Dessin sur couverture réalisé par Céline Querniard
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Foreword

This activity report covers the 2006–2008 period which has been not only extremely successful concerning our scientific results and our technical realizations, but also extremely dynamic for what concerns the development and the organization of our activities. The common entry to all these activities is the Nuclear domain, whatsoever the most fundamental aspects are concerned or the more applied ones, with researches performed in nuclear physics and in nuclear chemistry. The wealth and the dynamism of our researches have aroused scientific programs beyond the usual perimeter of our core business. Interdisciplinary activities have been indeed developed in a pertinent scheme, allowing us to try to answer to the society expectations related for example to the nuclear energy or the medical research.

Besides the research activities, we are involved in education actions which benefit from the repercussions of our research: we are able to propose state-of-the-art courses, actions towards the general public and also promotions of our technical realizations, as the non intrusive control and investigation system gives an illustration.

The excellence that the physicists and chemists have instilled to our research programs has been possible thanks to the total involvement of our administrative and technical groups. This excellence is recognizable in the appointment of prizes to agents (Prize of the French Physics Society, Yvan Peychès Prize, two Prizes for Excellence in ph-d Theses, Cristal of CNRS, Legion of Honour), in the A+ highest-ranking of our lab in 2007 as well in the numerous positive answers received when we solicit funding agencies or respond to the various requests for proposal. This recognition at the national level shines at the local level since Subatech is now a major actor of the research in the Pays de la Loire region, in particular thanks to its involvement in the activities related to the ARRONAX cyclotron. These research activities are written down in this report. For each thematic, a general summary is first given before going in more detailed description through specific forms. As an introduction, we summarize in this foreword, the memorable facts that happened during these last three years.

Subatech is a “Unité Mixte de Recherche” (UMR 6457) affiliated to three funding agencies, CNRS (via IN2P3, its scientific institute), the “Ecole des mines de Nantes” and the University of Nantes. In the late of 2008, Subatech groups 164 persons, among them 50 researchers, professors and assistant professors, 29 ph-d students, 8 persons in postdoctoral position, 77 engineers or technicians as well as 20 persons with a fixed term contract. Since 2006, the number of permanent employees still increases, but at a lower rate than previously. One the one hand it could be inferred that Subatech has roughly reached the size with which we will live the next years. On the other hand we must keep in mind that, from 2009, new staff are foreseen to noticeably reinforce our teams (chairs,…). We also have to carefully consider the increase of the number of persons with fixed term contract, increase for which we can be very pleased since it is of course related to the significant enhancement of our contractual activity, but for which also, we can be enquired by the deviance to the job insecurity it suggests.

These last three years have been of particular importance for our lab since they correspond to the outcome of realizations for which our success was crucial. This is the case of the ARRONAX cyclotron or the dimuon spectrometer realizations that have been successfully installed in 2008 in the ALICE experiment at LHC collider thus rewarding years of effort. At present, the priority is naturally the analyses of the so-expected LHC data which will be performed in particular thanks to our computing “farm” successfully implemented within the LCG grid.

Some remarkable marches have been also performed in the radiodetection of cosmic rays of extreme energies with the CODALEMA experiment. The pertinence of this research program has allowed our official participation to the AUGER experiment in Argentina. The know-how of Subatech in the “nuclear reactor” activities is widely recognized and induces brilliant involvements in physics programs, education as well as in more instrumental activities related to sources and accelerators.
In radiochemistry, researches are at a level never reached before as it is highlighted by the amount of contractual funds or by the creation of chairs related to this activity at the Ecole des mines de Nantes. Thanks to the research themes that are explored, Subatech can be positioned as a reference lab for the major actors of the French electronuclear domain. SMART, our group in charge of radioactivity measurement in any environment just went through record years for the contractual level that has been reached.

The research programs that emerged in the previous activity report are now perennial. This is the case for the hard probe physics explored with the ALICE electromagnetic calorimeter currently under construction in Subatech as well as the theoretical developments in astronuclear domain. These recent activities have already won the bet that they were worthy of being supported as far as the instrumental level is concerned with the liquid xenon detectors or the theoretical level with the recent development on the energy loss of elementary constituents passing through a dense nuclear medium. The contribution of Subatech is also capital for the radioelement production for the ARRONAX cyclotron: the techniques that are developed and the related instrumental activities will offer to ARRONAX the possibility to have, in self-reliance, its own production techniques.

These selected remarkable facts highlight the fact that Subatech abilities lay over a large domain. Taking into account the recent societal issues, we had to organize our research with a different approach more oriented towards a grouping logic such as the federative structure GRIM3 (Groupement de Recherche Interdisciplinaire sur les Matériaux, les Molécules et la Matière) that emerged in the fall of 2008 and which assembles four labs in Nantes, among which Subatech. Currently under achievement, two other actions have been initiated and for which Subatech plays again a major role. One groups three departments of the CNRS (EDD, INSU and IN2P3) on the interdisciplinary program “Signal, Bruit, Alerte, Détection et Environnement”. The other one, together with the INSU institute, will allow our integration into the Observatory of the Sciences of the Universe in Nantes. These federative structure should allow to develop our interdisciplinary programs in a more accentuated and efficiently way.

Finally, 2008 corresponded to the start of the new quadrennial program of our UMR and despite we are already at its midway, we have to think about our future actions as well as to make sure to maintain our present activities and level of excellence. Our brainstorming has to take into account the research and high-level education context which has significantly evolved these last years. This context is complex and its outlines are nowadays still uncertain. As we already did it, we have to pursue our evolution into a grouping logic, to deal with the diversity of the requests for proposal, of the funding agencies, to answer to the new economical and societal issues and hence to propose adapted education for these new dynamics. Subatech clearly aims at demonstrating that fundamental and applied research, theoretical and experimental activities, and a strong contribution to education not only can harmoniously live together, but strongly complement each other. Especially today, it seems also worthwhile reminding the importance of a continuous stream of fundamental research, that prepares – in an rather unpredictable way – the field of applications.

To conclude and before to leave for the reading of this report, we would like to sincerely thank all the persons who contributed to the edition of this document.

Jacques Martino
Director of Subatech

Christelle Roy
Deputy-director
Avant-Propos

Ce rapport d’activité 2006–2008 couvre une période qui a été, non seulement extrêmement riche de succès au niveau de nos résultats scientifiques et de nos réalisations techniques, mais également extrêmement dynamique au niveau du développement et de l’organisation de nos activités. Le point commun de toutes ces activités est le Nucléaire, que ce soit dans ses aspects les plus fondamentaux que dans ses aspects davantage appliqués, avec des recherches que nous menons à la fois dans le domaine de la Physique Nucléaire et de la Chimie Nucléaire. La richesse et le dynamisme de nos recherches ont permis de susciter des programmes dépassant le périmètre habituel des activités qui constituent notre propre cœur de métier. Les activités interdisciplinaires se sont effectivement développées de manière pertinente, nous permettant de répondre aux attentes sociétales comme celles par exemple liées à l’énergie nucléaire ou encore à la recherche médicale. Outre les activités de recherche, nous menons des actions d’enseignement qui bénéficient des retombées de notre recherche et pour lesquelles nous proposons des filières de pointe, des actions envers le grand public ou encore de valorisation de nos réalisations techniques, comme le contrôle non destructif peut en être une illustration.

L’excellence que nos chercheurs ont pu donner à nos programmes de recherche a été possible grâce au plein engagement de nos services techniques et administratifs. Cette excellence se reconnaît dans l’attribution de prix aux agents (Prix de la Société Française de Physique, Prix Yvan Peychès, deux Prix d’excellence de thèses, Cristal du CNRS, Légion d’Honneur), dans le classement A+ de notre laboratoire en 2007 et dans les réponses positives que nous recevons lorsque nous nous adressons aux agences de moyen ou répondons aux divers appels à projet. Cette reconnaissance au plan national rayonne au plan local puisque Subatech est devenu un acteur majeur de la recherche ligérienne, grâce en particulier à son implication sur les actions autour du cyclotron ARRONAX.

Ce sont donc ces activités de recherche qui sont consignées dans ce rapport avec, pour chaque thématique, une description tout d’abord générale puis davantage détaillée au travers de fiches spécifiques. En guise d’introduction, nous résumons dans cet avant-propos les faits marquants de ces trois années.

Subatech est une Unité Mixte de Recherche affiliée à trois tutelles, le CNRS (par son institut scientifique l’IN2P3), l’Ecole des mines de Nantes et l’Université de Nantes. Fin 2008, Subatech regroupait 164 agents, dont 50 chercheurs et enseignants-chercheurs, 29 doctorants, 8 post-doctorants, 77 ingénieurs et techniciens ainsi que 20 personnes en contrat à durée déterminée. Depuis 2006, les effectifs des permanents évoluent très peu quel que soit le corps de métier considéré sous-tendant que Subatech a grosso-modo atteint la taille avec laquelle il fonctionnera les prochaines années. A cela, il faut tout de même opposer le fait que le nombre de personnes en contrat temporaire croît, ce dont on peut se féliciter car cela est évidemment lié à la très forte augmentation de notre activité contractuelle, mais aussi s’inquiéter par la déviance vers la précarité des embauches qu’il suggère.

Ces trois dernières années ont été particulièrement importantes pour notre laboratoire car elles ont vu l’aboutissement de réalisations pour lesquelles notre réussite était cruciale. C’est le cas du cyclotron ARRONAX, ou encore des réalisations pour le spectromètre à muons qui ont été installées avec succès en 2008 dans l’expérience ALICE auprès du collisionneur LHC, récompensant ainsi des années d’effort. A présent, la priorité est bien sûr l’exploitation des données tant attendues du LHC, en particulier grâce à notre ferme de calcul bien implantée au sein de la grille LCG.

Des avancées remarquables ont été réalisées dans le domaine de la radiodétection des rayons cosmiques de très haute énergie avec l’expérience CODALEMA. La pertinence de ce programme de recherche a permis la participation désormais officielle de Subatech dans l’expérience AUGER en Argentine. Le savoir-faire de Subatech dans les activités « réacteur » est largement reconnu et permet des implications brillantes que ce soit dans les programmes de physique, dans les enseignements ou encore dans les activités de sources et accélérateurs qui y sont liées.
En radiochimie, les recherches sont à un niveau d’activité jamais été atteint auparavant comme le dénote l’ampleur des financements contractuels ou encore la création de chaires de l’Ecole des mines liées à cette activité. Grâce aux thématiques des recherches développées, Subatech se place comme un laboratoire de référence pour les grands acteurs de l’électronucléaire français. SMART, notre service de mesure de la radioactivité, quant à lui, vient de vivre des années record au niveau contractuel.

Les programmes de recherche qui apparaissaient comme émergents lors de l’édition précédente de notre rapport d’activité sont aujourd’hui pérennes, comme la physique des sondes dures avec le calorimètre électromagnétique d’ALICE en cours de construction à Subatech, ou encore les développements théoriques en astro-nucléaire. Des activités récentes ont également d’ores et déjà remporté le pari qu’elles méritaient d’être soutenues, tant au plan instrumental avec les détecteurs au xénon liquide qu’au plan théorique avec les développements liés à la perte d’énergie des constituants élémentaires dans un milieu très dense. La contribution de Subatech est également essentielle pour la production de radioéléments auprès du cyclotron ARRONAX : les techniques développées, les instrumentations associées permettront à ARRONAX de posséder, en toute indépendance, ses propres techniques de production.

Ces quelques faits marquants prouvent que les compétences de Subatech se déclinent sur un large spectre. Devant les nouveaux enjeux sociétaux, il a fallu organiser la recherche différemment, s’orientant davantage vers une logique de regroupement. C’est ainsi que fin 2008 a été créée la structure fédérale GRIM3 (Groupement de Recherche Interdisciplinaire sur les Matériaux, les Molécules et la Matière) qui groupe quatre laboratoires nantais dont Subatech. Actuellement en cours de concrétisation, deux autres actions ont été menées pour lesquelles Subatech joue aussi un rôle moteur. L’une rassemble trois départements du CNRS (EDD, INSU et IN2P3) sur le programme interdisciplinaire « Signal, Bruit, Alerte, Détection et Environnement ». L’autre, avec l’INSU, permet notre intégration dans l’Observatoire des Sciences de l’Univers nantais. Au travers de ces regroupements, la mise en commun de programmes de recherche et de moyens devra permettre de développer davantage et efficacement nos programmes interdisciplinaires.

Enfin, 2008 marquait le départ du nouveau quadriennal de notre UMR et bien que nous soyons à son mi-parcours, il nous faut déjà réfléchir à ce que seront nos actions futures, tout en veillant à consolider celles que nous avons entreprises ces années passées et à garder notre niveau d’excellence. Cette réflexion se fait aujourd’hui dans un contexte de la recherche et de l’enseignement supérieur qui a très sensiblement évolué ces dernières années, qui est complexe et dont les contours sont aujourd’hui encore incertains. Nous avons dû et su nous adapter à une logique de regroupement, à la diversité des appels d’offres, des agences et de leurs guichets, répondre aux nouveaux enjeux sociaux économiques et donc proposer des formations adaptées à ces nouvelles dynamiques.

Pour conclure et avant de laisser place à la lecture de ce rapport, nous tenons à remercier vivement toutes les personnes qui ont contribué à la réalisation de ce document.
Subatech rapid presentation

Subatech is a joint laboratory (Unité Mixte de Recherche, UMR 6457) shared by the Ecole des mines de Nantes, the University of Nantes and the CNRS (IN2P3: Institut National de Physique Nucléaire et de Physique des Particules).

The research activities of Subatech mainly focus on nuclear physics and chemistry. These fields support the teaching contribution of the lab at the Ecole des mines and the University.

A strong specificity is the very broad research field, from very fundamental subjects (quark gluon plasma, astroparticles,...) up to very applied topics (non destructive control, radioactivity monitoring, nuclear wastes,...). Subatech aims at:

- a strong international and national positioning, on highly competitive fields;
- a strong local involvement, via the Arronax cyclotron, interdisciplinary collaborations (medicine, materials, planetology, environment,...);
- research contributions at a double intersection, “fundamental-applied” and “physics-chemistry”;
- displaying “nuclear” as a common denominator.

In 2009, Subatech gathers about 164 people: 50 researchers, 77 engineers, technicians and administrative people, 29 PhD, 8 postdocs, visitors and other temporary staff.

Subatech research can be described through its 3 main fields:

- **The universe at high energy**, through fundamental experimental and theoretical developments on quark gluon plasma, astroparticles and nuclear astrophysics. On the first two fields, Subatech aims, for its competences, at a clear leader positioning (Alice-dimuon at Cern, cosmic ray radiodetection at Nançay and Auger,...). These activities rely on European PCRD contracts, on French ANR and also more local financial supports. Strong contributions to the required experimental equipments are provided by the lab technical divisions. Dedicated analysis are prepared via a local computing farm connected to the Cern grid. Alice and Radiodetection involvements are the aimed French leader position.

- **Nuclear Energy and Environment**, with a focus on energy and materials. This field, both fundamental and applied, spans radiochemistry for nuclear waste storage, radiolysis, ADS transmutation and related ADS scenarios, nuclear core characterisation with anti-neutrinos, non destructive control, and, of course, the SMART environmental radioactivity measurement activity. These fields provide a large variety of industrial contacts as well as industrial, European, ANR, Carnot Institute... and regional research contracts. Subatech is involved in strong national and local collaborations, on material analysis, radioactivity measurement techniques and related environmental questions. These Nuclear Energy and Environment involvements are, for Subatech, high-priority developments axis.

- **Nuclear and Health**, mainly with the actions around the Arronax cyclotron, through study and production of radionuclides for nuclear medicine therapy and imaging, and development of novel detection techniques. This new thematic field for Subatech is strongly supported as a local specificity in Nantes. It will be a new but important development axis of the lab.
Fundamental research is for Subatech the essential ingredient without which more applied activities and educational actions cannot afford any pertinence. Subatech proves that no opposition can be found between fundamental and applied research. On the contrary, the broad field of activity shows the existing and rich complementarities between a forefront fundamental research and societal concrete applications: both “do feed” mutually. Besides the quark and gluon plasma, societal questions, like cancer or nuclear energy, are central challenges for Subatech.

All researches of Subatech imply long-term, multi-annual programs, in the framework of international collaborations, and with financial support from many sources: CNRS (IN2P3), Ecole des Mines, University, French ANR, European FP’s, local authorities, “competitiveness” poles,…

Subatech educational activities are performed at the Ecole des mines and at the University, in Nantes. At the Ecole des mines, through the existing engineering formation NTSE (Nuclear: Technology, Safety, Environment), through “modern physics” teaching (quantum mechanics, statistical physics, relativity, nuclear physics), electromagnetism. New formations are actively being prepared: Advanced Nuclear Waste Management, Reactor Physics and Technology, Nuclear Safety… At the University, through undergraduate and graduate teaching, and the MARS master with the Ecole des mines (Fundamental and Applied Nuclear Physics, with a strong medical physicist speciality).

Around 30 PhD students perform their doctoral research at Subatech. Here again, Subatech twofold duality: fundamental-applied and research-teaching, do provide the students with the present, concrete and modern image of the nuclear and subatomic domain.

Finally, the last “Visating Committee” which evaluated Subatech (2007) gave the highest ranking : A^†.
Research Activities

The UNIVERSE at HIGH ENERGY
- QG plasma
- radiodetection
- theory
- detectors

NUCLEAR - ENVIRONMENT
Energy and Materials
- radiochemistry
- storage
- cyclotron
- radiolysis
- transmutation
- reactors
- ND control
- detectors
- SMART

NUCLEAR - HEALTH
- cyclotron
- radionuclides
- imaging

Technical Support

Subatech
Two supermodules installed inside the ALICE detector (in blue white on the top of the picture)
Quark gluon plasma

Heavy ion collisions at ultra-relativistic energies are expected to offer, in the laboratory, the conditions suitable for a nuclear phase transition, from a hadronic to a partonic state. At sufficiently high temperatures and densities, quarks and gluons are deconfined and this particular state, called Quark Gluon Plasma (QGP), is supposed to be the state of the Universe a few fractions of second after the Big Bang.

The experimental search of the quark gluon plasma has really started in the eighties in the frame of challenging heavy ion programs at CERN (Conseil Européen pour la Recherche Nucléaire) in Europe and at BNL (Brookhaven National Laboratory) in the United States. Since the middle of the nineties, Subatech participates to these programs and more specifically to the PHENIX and STAR experiments at the RHIC collider in Brookhaven (USA) and to the ALICE experiment at the LHC collider at CERN (Geneva).

Starting operation for the first time in 2000, RHIC is the most powerful heavy ion collider in the world, until the LHC starts in 2008 with energies 30 times. The signatures of the plasma formation are investigated via different observables in adequacy with the instrumental performances of the detectors. But globally, the approaches and methods are almost always the same : an observable is measured in collisions offering the optimal conditions for the QGP creation, with the heaviest ions and the most central collisions. Then the observable is measured in collisions unable to offer a phase transition : lighter ions, peripheral collisions....

In the PHENIX experiment, electromagnetic probes (leptons and photons) are investigated with the aim to probe the QGP phase of the collision. In particular, photons are not affected by the nuclear medium they crossed, they provide a prime footprint of the extreme initial conditions under which the QGP may occur. Furthermore, the Subatech group has collaborated to the PHENIX electromagnetic calorimeter.

In STAR experiment, Subatech pursues three physics programs with the aim to obtain a complete description of the heavy ion collision. The first topic concerns the characterisation of the strange particle production, motivated by the fact that since strange quarks do not exist in the incident nucleons, their presence in the final state (as hadrons) allow to inform on the different steps of the collision. The second topic is related to particle correlations which provide information on the particle interaction potentials, size, lifetime of the emitting sources as well as the emission sequence if non-identical particles are considered. The third topic is dedicated to the search of exotica particles like pentaquarks for which a discovery would serve as a drastic test for the Standard Model.

Besides the physics programs, Subatech in collaboration with IPHC of Strasbourg has built the Silicon Strip Detector, part of the inner tracking system, installed in STAR in 2004. The SSD improves the tracking performances as well as the identification of short lived particles such as the strange and charm particles.

LHC has delivered its first proton beams in September 2008. Subatech has participated to the construction of two detectors of the ALICE experiment : the Inner Tracker System and the Dimuon Spectrometer. Concerning this latter, besides the technical realisations, a huge effort has been done on the offline developments associated to the detector functioning as well as for the physics analyses. The Dimuon Spectrometer is mainly dedicated to the charm and beauty production whose characterisation is expected to provide a strong signal of the deconfined phase. An original study is also performed on the electroweak boson W to characterise the parton distribution functions of the neutron and proton, and to establish an alternative baseline too the QGP studies.

The implication of Subatech in the ALICE experiment has been extended these last two years with two other involvements. One is related to the fact that Subatech is a secondary computing site (called Tier 2) of the LHC Computing Grid, CERN being a Tier 0, Lyon Computing Centre (CCIN2P3) being a Tier 1. The second involvement concerns the construction of a part of the new ALICE ElectroMagnetic

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Calorimeter (EMCal). This detector is composed by 11 ensembles which are the assembly of elementary modules. The goal is to complete one of these 11 ensembles in order to be installed in ALICE during the first LHC shutdown foreseen between January and March. The aim is to provide to

ALICE the necessary tools to study particles at very high energies which is a very interesting and informative topic by revealing the inner structure of the quark gluon plasma, as RHIC demonstrated it.
Tracking and trigger muon gas chamber separated by the iron wall
The LHC will explore the nuclear phase diagram via the collision of lead nuclei at 5.5 TeV per nucleon pair, hence at energies 30 times the collision energy of the Relativistic Heavy Ion Collider (RHIC). It will extend study of the Quark-Gluon Plasma (QGP) into a qualitatively new regime of temperature and density, dominated by hard processes.

One of the most striking results obtained at RHIC is the discovery of jet-quenching [1]. Jets (set of particles collimated in phase space) are produced in all types of high energy collisions but in the case of heavy ion nuclei, the hard scattering occurs in the dense and hot QGP midst. Jets consequently pass through the plasma, interacting with it and losing energy, before emerging into vacuum and “fragmenting” into the stable particles seen in the detector. This energy loss process in the plasma, called jet-quenching, modifies strongly the jet structure that is seen in pp collisions. Such modifications are calculable theoretically using perturbative QCD and thus jet studies provide a powerful tool to probe the early stages of the QGP.

After the publication of jet-quenching results, European (French and Italian) and American physicists explore the possibilities of such measurements in ALICE. Its baseline design did not include a large-area calorimeter which is essential for jet quenching study but it was nevertheless possible to add such an apparatus in ALICE. Here, contrary to high energy particle physics, a hermetic calorimetric coverage is not needed and since the jet quenching signal lies in the modification of the distribution of particles within each jet, it requires a powerful charged particle tracking and identification that are ALICE specialties.

A large Electromagnetic Calorimeter (EMCal) has been proposed to be built by this new European and American collaboration [2]. EMCal is a lead-scintillator sampling calorimeter with about 13 000 individual towers grouped into eleven SuperModules (SM) (Fig.1). The towers are readout by wavelength-shifting optical fibers in a “shashlik” geometry, coupled to the same Avalanche Photo-Diode sensors.

Fig. 1: The EMCal calorimeter on its support structure.
EMCal counts 100,000 individual scintillator tiles, 185 km of optical fiber and its total weight is about 100 tons. The project is now approved and under way to be ready for the major PbPb run in 2010, programming the two first SM (one from each side of the Atlantic) for early 2009. Three SM will be constructed in Europe, the remainder built in the U.S. Three French laboratories, IPHC-Strasbourg, LPSC-Grenoble and Subatech-Nantes (this latter ensures the French scientific and technical coordination) participate to the EMCal project. Up to now, the instrumental developments have concerned mainly the design of the modules, of their mechanical supports and electronics components. Some module prototypes (Fig. 2) have been mounted in Europe and United States and tested at CERN in October 07 allowing the validation of the technical choices. The project enters now in its construction phase for which Subatech plays a major role. Hence, since 2006, the EMCal project has required a strong involvement of Subatech mechanic team. Thanks to the quality of its realisations, both from its design office and from its workshop, the mechanical team has provided a recognition to Subatech both at the national and international levels. Since two years, more tasks and international responsibilities have been entrusted to Subatech. The consequences have been also visible in electronics developments since American engineers have requested the implication of two persons of Subatech for the design of EMCal electronics cards. For the module construction, a room dedicated to their assembly and tests has been equipped in Subatech Hall. The realisation of these modules will allow to understand their functioning and to interpret their data which are two unavoidable steps if we want to obtain, rapidly, significant results. About 300 modules will be mounted and tested in Subatech before their shipping to Grenoble for their final assembly in SuperModule and to CERN for their mounting in ALICE. In parallel to these instrumental tasks, simulations are performed by our team on various topics : elaboration of new algorithms for module characterizations, high pt photons and jets measurements and for the quantification of the improvement in the ALICE physics performances due to EMCal. EMCal will provide to the experiment a fast trigger for high energy jets, together with measurement of neutral particles in the jets that are not seen by the ALICE charged particle tracking system. EMCal covers the full length of the ALICE TPC and a third of its azimuth, and is situated back-to-back with the smaller, highly granular PHOS lead-tungstate calorimeter. With the fast trigger provided by the EMCal, ALICE will measure jets in PbPb and pp collisions to energies well beyond 200 GeV, enabling a comprehensive set of jet quenching measurements with ALICE unique capabilities.

Fig. 2: EMCal module prototypes assembled and tested at CERN SPS in October 2007. The mechanical supports have been designed and realized by the mechanic team of Subatech.

La physique des jets et des photons à haute impulsion transverse s’est révélée d’un intérêt majeur pour caractériser la matière dense et chaude créée dans les collisions d’ions lourds relativistes. A RHIC, cette matière s’apparente au plasma de quarks et de gluons recherchés depuis plus de 20 ans. Grâce à l’expérience ALICE, les propriétés de cette matière pourront être explorées au LHC avec des énergies bien supérieures à celles de RHIC. Mais pour que cette étude soit complète et pertinente, ALICE devait s’équiper du détecteur adéquat : un calorimètre électromagnétique. Subatech a participé à sa conception et débute à présent sa construction. Les premiers éléments seront insérés dans ALICE lors du prochain arrêt faisant suite de l’hiver 2009 et se verront compléter au cours des deux prochaines années.

References
γ-jet physics with EMCal at ALICE experiment.

G. Bourdaud, H. Delagrange, C. Roy

Les γ-jets sont des événements rares où un photon et un hadron sont créés par effet Compton ou annihilation. Le parton s'hadronise et forme une gerbe de particules appelée jet. Le photon et le jet sont émis dos-à-dos, on parle de γ-jet. L'intérêt des jets n’est plus à démontrer depuis RHIC qui l’a prouvé par l'observation de la suppression des hadrons de haute impulsion transverse (phénomène de « jet quenching »). Cette perte d’énergie, ou plus exactement la redistribution de l’énergie dans le jet, peut être mise en évidence par la modification de la distribution de l'énergie des particules appartenant au jet en collisions p-p et Pb-Pb (hump-backed plateau). Cette mesure nécessite de déterminer l’énergie initiale du jet, ce que les γ-jets permettent de faire de façon élégante et précise.

Comparing jets in Pb-Pb and p-p collisions will show the energy redistribution in the jet : due to strong interactions in quark and gluon plasma (QGP), high momentum particles radiate gluons, which leads to a decrease of high momentum particles and an enhancement of low momentum particles. This phenomenon is called “jet quenching” [2].

Fig. 1: Theoretical modification of the hump-backed plateau due to jet quenching in dense medium (dashed lines) and hump-backed plateau without quenching effect (solid lines), compared to experimental points (symbols) [3].

The hump-backed plateau [3] is an interesting observable to explore the modification in jet energy distribution induced by jet quenching. It is represented by the $\frac{d\sigma}{dx} = \ln(1/x)$ distribution, where x is defined as $x = p_T(\text{hadron})/p_T(\text{jet})$ for the jet particles. Its modification due to the medium is a promising observable for QGP study. Fig. 1 shows this experimental distributions, th so-called hump-backed plateau from different experiences[3] and a theoretical modifications due to a QGP.

Year 2008 will see the first LHC runs. For the 2010 Pb-Pb run, the EMCal will be partially installed and operational. This calorimeter will be dedicated to neutral particles detection in ALICE and will provide the opportunity to study γ-jet physics. EMCal will be used for the gamma reconstruction and the central tracking (ITS and TPC) for jet reconstruction. γ-jets are essential to assess the jet energy loss in a QGP by providing a jet energy calibration. Since photons penetrate the dense medium with greatly reduced interactions compared to hadrons, it provides an excellent measure of the energy and direction of the tagged jet.

The detectors and available beam energy at RHIC are not fully satisfactory for gamma-jet studies : due to the large amount of underlying background and limited acceptance, it is very difficult to identify both direct photon and tagged jet. The gamma-jet cross-section is small at RHIC, their detection and analysis is still very hard [6]. This study will be possible at LHC energies. In ALICE experiment, the predicted rate for γ-jets with an energy >30 GeV is about 10000 events per year.

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1 Large Hadron Collider.
2 Electro Magnetic CALorimeter
3 Inner Tracking System
4 Time Projection Chamber
5 Relativistic Heavy Ion Collider.
(considering the gamma in EMCal). This energy is the limit to be able to distinguish jets from the background.

EMCal offers the possibility to detect gammas over wide energy range up to 100 GeV, with a resolution lower than 3% for energy > 30 GeV. It also gives the possibility to identify photons by shower shape analysis with an efficiency more than 60% and a purity > 70% for $15<p_T(\gamma)<50$ GeV [4].

The tracking system can reconstruct tracks from charged particles from 100 MeV to 100 GeV with a resolution about 2% [1]. Combined with an efficient “UA1 like” cone algorithm, it is possible to reconstruct jets at the opposite of the gamma with an efficiency about 60% [4]. Previous reconstruction of the gamma reduces the searching area for the jet to a thin azimuthally ($|\Delta\phi|<0.5$) opposed strip and gives directly the energy of the jet.

Fig 2 shows the hump-backed plateau from simulated $\gamma$-jets and reconstructed in the ALICE environment. The background is not simulated her. For this study, 100 GeV gamma-jets were simulated using PYTHIA [5] Monte Carlo. Two samples of events were simulated: one with and on without quenching effect. The modification of the hump-backed plateau (Fig 2.), due to quenching effect, is viewable by an enhancement of high $\xi$ particles and a suppression of low $\xi$ particles. This modification can be used to measure the quenching effect.

The ratio for the hump-backed plateau is presented on Fig 3. The modification is not biased by underlying event for $\xi$ between 1.5 and 4. These results show that the ALICE experiment with the EMCal will be a well suited tool for $\gamma$-jet study and jet fragmentation : the hump-backed plateau can be measured and its modification between p-p and Pb-Pb collisions can be used to measure quenching effect.

![Fig. 2: Simulated modification of the hump-backed plateau due to jet quenching in dense medium in ALICE with full reconstruction.](image)

![Fig. 3: Measured ratio of hump-backed plateau with and without underlying events.](image)

Consequences of a $L_c/D$ enhancement effect on the non-photonic electron nuclear modification factor in central heavy ion collision at RHIC energy

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La suppression des électrons non-photoniques observée par les expériences de RHIC dans les collisions centrales Au+Au à 200 GeV pourrait être, en partie, expliquée par une augmentation du rapport baryon/méson dans le secteur du charme ($\Lambda_c / D$). En supposant un rapport $L_c / D$ de l’ordre de l’unité pour des impulsions transverses de 5 GeV/c, une suppression de 40% des électrons de la décroissance semileptonique du charme est prédite.

One of the most robust experimental evidence for the creation of a new state of matter in heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) is the large suppression of light hadrons at high transverse momentum ($p_t$). This phenomenon is well reproduced by models which take into account the radiative energy loss of high $p_t$ light quarks and gluons propagating through a dense medium of colored quarks and gluons. Further insights into the underlying mechanism can be obtained from the study of heavy hadrons. In contrast to intermediate-$p_t$ light hadrons which are predominantly produced by gluon fragmentation, charm and bottom hadrons originate from the fragmentation of heavy quarks. Quarks are supposed to lose less energy than gluons in the medium due to a smaller color charge coupling. In addition, radiative energy loss was predicted to be smaller for heavy quarks as compared to light quarks because of the so-called “dead-cone” effect which limits the medium induced radiative energy loss at forward angles. Surprisingly, recent data from the PHENIX and the STAR collaborations in Au+Au collisions at 200 GeV show that the quenching of heavy quarks, as studied indirectly via the so-called non-photonic electrons, is stronger than theoretical expectations and is as large as that of light mesons. Reconciling these data with model predictions is a real challenge which triggers a lot of theoretical activities nowadays.

In this work we investigate the possibility that part of the strong suppression of non-photonic electrons might be due to another source of electrons, namely charmed baryons. Indeed, whereas light mesons are largely suppressed in heavy ion collisions at RHIC, the suppression of non-strange and strange baryons is observed to be much less in the intermediate $p_t$ range ($2 < p_t < 4$ GeV/c). This anomalous baryon/meson enhancement is relatively well understood in the framework of the recombination model, which assumes that, at low and intermediate $p_t$, hadronization occurs via the coalescence of “free” quarks. An anomalous baryon/meson enhancement for charm hadrons leads naturally to a non-photonic electron $R_{AA}$ smaller than one. This is mostly due to a smaller semileptonic decay branching ratio of charm baryons ($\Lambda_c$) as compared to charm mesons. The main assumption we put forward is that, in a deconfined medium, charm baryon production is enhanced relative to charm meson production, as compared to the vacuum. This assumption is qualitatively justified in the framework of the recombination model. We will assume a baryon/meson ($\Lambda_c/D$) enhancement as a Gaussian shape. For $pp$ collisions, we use the predictions from PYTHIA. Our simulation framework is based on the PYTHIA-6.152 event generator. The PYTHIA input parameters were first tuned according to [1] and the PHENIX acceptance cut ($|n| < 0.35$) was applied in order to correctly reproduce the $p_t$ distribution of non-photonic electrons measured in $pp$ collisions at 200 GeV. As it can be seen in Fig. 1, the agreement between
the simulation and the data is rather good except in the high pt region where the simulation under-predicts the data.

Fig. 1: Invariant differential cross-section of non-photonic electrons (dots) measured in pp collisions at 200 GeV. The solid curve shows the result of the PYTHIA simulation as described in the text.

The following Gaussian parameters of $\Lambda_d/D$ ratio have been chosen: Mean: 5 GeV/c, constant: 0.9 and sigma: 2.9 GeV/c. The constant of 0.9 is justified since the resulting $\Lambda_d/D$ ratio of 0.9 is of the same order of magnitude as the non-strange and strange baryon/meson ratios measured by the STAR collaboration. The enhancement is applied such that the pt-differential charm cross-section is conserved. The latter is an arbitrary choice that could be justified since most of the charm hadron transverse momentum is given by the charm quark whatever, baryon or meson, this hadron is. We finally compute the RAA ratio from the non-photonic electron pt spectra assuming that the only medium induced effect is the $\Lambda_d/D$ enhancement. The results are shown in Fig. 2 together with the PHENIX data. One can see that the $\Lambda_d/D$ ratio close to unity in central collisions at pt = 5 GeV/c can already explain 40% of the suppression of non-photonic electrons in the 2–4 GeV/c pt range. Even in the high pt region (8–9 GeV/c) the $\Lambda_d/D$ enhancement results in a significant suppression of electrons from charm semileptonic decay.

Fig. 2: Nuclear modification factor of non-photonic electrons (dots) measured in central (0 – 10%) Au+Au collisions at 200 GeV. The crosses correspond to the results of the simulation described in the text for a $\Lambda_d/D$ enhancement factor of 12 ($\Lambda_d/D$ equal to unity at 5 GeV/c).

La distribution en impulsion transverse des électrons non-photoniques est évaluée avec le générateur PYTHIA. Ces calculs sont en accord avec les mesures réalisées par la collaboration PHENIX (voir Fig.1). Le facteur de modification nucléaire des électrons de la décroissance semi-leptonique du charme a été calculé en supposant qu’une surproduction de baryons a lieu dans le secteur du charme dans les collisions centrales Au+Au à 200 GeV. Nous observons qu’une suppression de jusqu’à 40% du facteur des modification nucléaire des électrons procédant de la décroissance semi-leptonique du charme, peut être compris par un mécanisme de surproduction de baryons charmés comme il a été observé pour les baryons contenant quarks légers. Ce travail a été publié dans la revue internationale Physics Lettes B, volume 663 page 55.

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ALICE-EMCAL Beam Test Analysis

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EMCAL, le détecteur électromagnétique de grande acceptance d’ALICE, qui est en cours de construction et d’assemblage, va permettre d’améliorer la résolution en énergie des jets et de mesurer des photons de haut moment transverse. Des tests sous faisceau préalables sont nécessaires de façon à qualifier les modules finaux et mesurer leurs performances. Une campagne de tests sous faisceau a été réalisée en Septembre-Octobre 2007 au CERN sur des modules prototype final. Les résultats de ces tests, en termes de qualité des données extraites et de calibration relative, sont présentés ici.

The ALICE ElectroMagnetic CALorimeter EMCAL is designed to measure the deposited energy of particles interacting electromagnetically such as photons and electrons that are absorbed almost completely in the volume of the detector from 5 MeV to 100 GeV. EMCAL will cover a region of 110 degrees in azimuth and +/- 0.7 units in pseudorapidity, located in front of the PHOton Spectrometer: PHOS. EMCAL is segmented into 11 super modules. One super module is composed of 24 strip modules of 12 modules each. Each individual module contains 2 x 2 = 4 towers built up from 77 alternating layers of 1.44 mm Pb and 1.76 mm scintillator. The scintillation light produced in each tower is collected by an array of 36 wavelength shifting fibres (WLS) which are connected to the photosensor (Avalanche Photo Diode : APD) at the back of the module. The APDs are directly connected to the back of a Charge Sensitive Preamplifier (CSP) that converts the charge signal into a voltage step that is transformed by a Shaper In the Front End Electronics into a semi-Gaussian pulse shape of 100 ns shaping time. Each shaper channel is split via a low noise gain buffer into high and low gain shapers. The full scale energy range for an EMCAL tower is chosen to be 250 GeV, which sets the the low gain range from 250 MeV to 250 GeV and the corresponding high gain range from 16 MeV to 16 GeV, with a gain ratio 1/16.

The EMCAL beam test measurements made in autumn 2007 at CERN (PS and SPS) used a stacked 4x4 array of prototype EMCAL modules (8x8 towers) with final design and electronics chain. The goals of the beam test measurements are to measure the EMCAL intrinsic energy resolution and position resolution and to measure the linearity and uniformity of the detector response, using electron beams. The beam tests are also aimed at developing calibration tools (gain stability, time dependence), using electron beams, MIPs (Minimum Ionizing Particles) from hadron beams, and LED events. Using a LED calibration system, in which all towers view a calibrated pulsed LED light source, and MIPs allows to track and adjust APD gains (to match the relative tower energy calibration online to better than 5%). In order to minimize the EMCAL energy resolution for high energy electromagnetic showers it is important to obtain and maintain a tower-by-tower relative energy calibration of better than 1% in the offline analysis. The tests at SPS were made with electron and hadron beams over an energy range from 5 to 100 GeV/c and at PS, from 0.5 to 6.5 GeV/c. The beam position was measured by scintillators and tracking chambers.

One of the SUBATECH commitments is to study the fitting of pulse shape distribution and high-low gain correlation, and to investigate the relative calibration with hadron beam. The figure 1 shows an example of a pulse shape obtained with an electron beam at 80 GeV/c, for one tower, represented by ADC counts as a function of time. The digitized time samples have amplitude, as a function of time t that can be described by a $\Gamma_n$-function:

$$\Gamma_n = P + A x^n e^{a(t-t_{\text{max}})}$$

with

$$x = \frac{(t-t_{\text{max}}+\tau)}{\tau}$$

where $t_{\text{max}}$ is the time value where the function peaks, $\tau$ is the decay constant, A the amplitude, P the pedestal and n is the power parameter of the fit that is fixed to 2. An important fea-
ture in the test beam analysis is to check if the parameters extracted from the raw data are well evaluated. This will condition, in future, the quality of the data, because the amplitude and time, that will be used, come directly from the fit of the raw data.

On the figure 1, the signal is fitted using that $\Gamma_2$-function. The fitting parameters indicated are: $A$, $t_{\text{max}}$, $\tau$, and $P$.

Fig. 1: Typical fitted (black line) pulse shape (red line and full points) with an electron beam at 80 GeV for one tower in High gain.

To quantify the fit quality, one can define a variable $Q$, which is the average value of absolute relative difference between the signal (ADC counts) and the fit function. This variable, studied for an electron beam, has been estimated, in percentage, between 2% and 20% for amplitudes between 100 and 1050 ADC, and enables to conclude on a good fit quality. In order to improve the fitting quality, we will also study this variable as a function of the fitting interval.

The High-Low gain correlation can be studied for several towers. The aim of that study is to determine a threshold value of amplitude for which we will use low gain, rather than high gain, when saturation in high gain occurs (at 1024 ADC counts). We studied this correlation by plotting fitted amplitude in high gain as a function of the one in low gain for one tower. A good correlation is found, with a ratio 16 between both gains, until 1050 ADC counts approximately. This enables to conclude that the high gain can be used up to 1050 ADC counts.

One has also investigated the relative tower calibration we can obtain with hadron beam triggers. Such particles being at Minimum Ionisation, their energy loss in the towers is known. By selecting events where one and only one tower has signal amplitude above a given threshold we can obtain a fixed reference for each tower. The figure 2 presents the amplitude of the signal extracted from the fit with the $\Gamma_2$-function described previously.

Fig. 2: Amplitude of the signal in one tower for MIPs. The amplitude corresponds to high gain signal. The blue curve corresponds to the fit (see text).

The Maximum Probable Value (MPV) of the tower response to the MIPs is then evaluated by a fit with a Landau function convoluted by a Gaussian function. The same procedure has been repeated for the 32 central towers that where scanned with SPS hadron beam. This allowed to extract a relative tower calibration. This calibration has been applied on 80 GeV/c electron beam showing an energy resolution of 2.5%. This calibration must now be applied on all electron data and all towers to extend this analysis to the overall energy range.

Le Calorimètre Electromagnétique EMCAL va permettre la mesure et la détection des photons et des pions neutres dans l’expérience ALICE. Ce détecteur, devenu crucial pour l’étude du Plasma de Quarks et de Gluons au vu des résultats du RHIC, est actuellement en cours de construction à SUBATECH et dans plusieurs laboratoires français, italiens et américains. Il doit être installé pour le run Pb Pb à grande luminosité du LHC. Des tests sous faisceau de modules prototypes ont été réalisés à l’automne 2007 afin de caractériser leurs performances en termes de qualité des données mais également afin d’étudier et de développer les techniques de calibration. Leur analyse a permis de qualifier les modules et d’obtenir une première calibration relative.

References
Neutral particle identification in EMCal

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Au LHC, la mesure de la production de particules de haute énergie permettra de caractériser le milieu dense formé lors de collisions d’ions lourds. Le calorimètre électromagnétique EMCal de l’expérience ALICE détectera en particulier les photons et les pions neutres jusqu’à des énergies de 100 GeV. Les différentes techniques qui sont utilisées pour identifier ces particules ont été étudiées et les intervalles en énergie pour lesquels le détecteur est apte à les identifier ont été déterminés.

The observation of a strong suppression of high \( p_T \) hadrons in ultra-relativistic heavy ion collisions at RHIC [1] has reinforced the idea that hard processes are pertinent probes to characterize the deconfined medium created. At LHC, the high expected rates for hard probes will open the possibility to quantify the effect of partonic energy loss in the medium with the measurement of high \( p_T \) jets and hadrons. To improve the ALICE capabilities for measuring jets and neutral particles, the electromagnetic calorimeter EMCal, located back to back with and covering a larger acceptance than the Photon Spectrometer (PHOS), will be partly installed in 2009 for the first heavy ion collisions. Of particular interest, the direct high \( p_T \) photons and \( \pi^0 \) will be measured. Both measurements will provide a test of Quantum Chromodynamic (QCD) theory with \( p-p \) collisions at a center of mass energy of \( \sqrt{s}=14 \) TeV. It will also serve to probe the confined medium created in \( Pb+Pb \) collisions at \( \sqrt{s}=5.5 \) TeV per nucleon pair. However direct photons are highly contaminated by decaying photons (mainly issued from \( \pi^0 \)) and the studies presented here show that the EMCal characteristics allow for a separation between those two sources of photon.

In order to identify the photon and the neutral pion, two different analysis are performed according to the kinematical range: at low transverse momentum \( p_T \), the decaying photons are detected by the calorimeter as two separated signals/clusters and the technique of the invariant mass can be used to reconstruct the neutral hadron. At larger \( p_T \), the two decaying photons lead to one single cluster in the calorimeter but the resulting transversal shape of the electromagnetic shower allows the distinction between the two particles. Finally at even larger \( p_T \), the neutral meson gives rise to the same signal than the photon in the calorimeter and it is not possible anymore to identify the direct photons independently of the event characteristics.

The feasibility of detecting direct photons and \( \pi^0 \) with EMCal was studied using full simulations of the ALICE experimental setup as a function of \( p_T \).

Figure 1 shows the invariant mass for two photons detected with EMCal obtained from \( \pi^0 \) generated with energy of 9 GeV in \( Pb+Pb \) environment. The invariant mass peak is fitted using a Gaussian function and a 2nd order polynomial for the combinatorial background:

\[
\frac{E}{E}\sqrt{s} = 9 \text{ GeV} \\
\sigma/m = 12\% \\
\]

\[
\text{Fig. 1: Invariant mass for two detected photons obtained from generated } \pi^0 \text{ with energy of 9 GeV in } Pb-Pb \text{ environment.}
\]
mean value obtained for the Gaussian function corresponds to the mass of the \( \pi^0 \) and its resolution is 12%.

The technique of the invariant mass allows determining statistically the yield of \( \pi^0 \) for \( p_T \) from 1 to 15 GeV/c with a maximal efficiency of 80% at \( p_T=9 \) GeV/c. At lower \( p_T \), the efficiency is smaller as one of the two decaying photons has energy smaller than the clusterization energy cut. At larger \( p_T \), as the two photons merge into a single cluster in the calorimeter, the efficiency decreases. Once the \( \pi^0 \) yield is measured using that technique, the decaying photon yield can be obtained from Monte Carlo and be used to extract from the inclusive photon yield the direct photon one.

The transverse electromagnetic shower shape can be parameterized by an ellipse. The main axis of that ellipse is used here to identify in an event by event basis the photon and the \( \pi^0 \). A Bayesian method has been developed in order to add into the global ALICE Particle Identification the information based on the EMCAL shower shape [2]. For studying the shower shape capabilities to suppress the \( \pi^0 \) yield, realistic simulations from QCD Next To Leading Order calculations [3] in p-p and Pb-Pb collisions have been used. Figure 2 shows the ratio between prompt photons and \( \pi^0 \) detected as a single cluster in EMCAL as a function of \( p_T \) in Pb-Pb central collisions. The full (open) points show the ratio with (without) a selection cut on the shower shape. It is shown that the shower shape cut allows increasing the ratio of prompt photons to \( \pi^0 \) by a factor from 5 to 10 to reach a ratio up to 1 for \( p_T \) from 15 to 30 GeV/c.

The photon efficiency for that method is larger than 70%. However the \( \pi^0 \) rejection is not sufficient in that \( p_T \) range and also for higher \( p_T \), another method, which is not discussed here, is necessary: the isolation method [3]. This method depends on the event characteristics requiring no other particles around the selected photon. From the \( \pi^0 \) point of view, the shower shape selection allows also to select them with efficiency larger than 80% and to measure the \( \pi^0 \) yield up to 40 GeV/c with less than 10% contamination from direct photon in Pb-Pb collision and 1% contamination in p-p collision.

To summarize, the ALICE electromagnetic calorimeter EMCAL will allow to measure and identify the photons (neutral pions) from \( p_T=1 \) (0.5) GeV/c up to 30 (40) GeV/c using two techniques: the invariant mass technique at low \( p_T \) and up to 15 GeV/c and the shower shape analysis at larger \( p_T \). These measurements in p-p and Pb-Pb collisions will allow testing the QCD theory and will help to characterize the dense medium formed in heavy ion collision.

Fig. 2: Ratio of direct photon over \( \pi^0 \) before (open points) and after (full points) a selection on the shower shape of the detected clusters in EMCAL.
\( \pi^0 \) production in p-p collisions in ALICE: efficiency and acceptance of the Photon Spectrometer

L. Benhabib, C. Roy, Y. Schutz

Les photons et les mésons neutres de grande impulsion transverse constituent des sondes privilégiées pour signer la formation du plasma de quarks et de gluons dans les collisions d’ions lourds à des énergies ultra-relativistes. Les photons, permettent d’une de part de tester les prédictions de la Chromodynamique Quantique perturbative (pQCD), et d’étudier d’autre part les propriétés thermodynamiques (température) du plasma formé par l’intermédiaire du rayonnement thermique émis lors de la collision. La production des pions neutres dans les collisions p-p fournit un test direct des prédictions de la pQCD, et sert de référence pour explorer la modification des processus durs dans les collisions d’ions lourds. Le spectromètre de photons PHOS de l’expérience ALICE nous permettra de mesurer la production des mésons neutres \( \pi^0 \), à partir de leur désintégration en deux photons, sur un large domaine en moment transverse au LHC. Une estimation de la section efficace différentielle de production des pions neutres prédite par des calculs pQCD « next-to-leading order » (NLO) pour des collisions p-p à 10 TeV, ainsi que l’acceptance géométrique et l’efficacité de reconstruction des \( \pi^0 \) avec des analyses de masse invariante seront présentés.

Amongst the main RHIC discoveries is the suppression of hadrons with large transverse momentum in central nucleus-nucleus (A-A) collisions at 200 GeV. The \( R_{AA}(p_T) \) ratio, which compares the production yield in A-A collisions with respect to p-p ones, shows almost no change for photons from peripheral to central A-A collisions within errors. However, high-\( p_T \) neutral pions are strongly suppressed (\( R_{AA} \approx 0.2 \)) in central A-A collisions. The strong suppression and the different behaviour between photons and \( \pi^0 \) supports the idea that the scattered partons loose energy by gluon emission in the hot and dense medium produced. High-\( p_T \) hadron production in p-p and A-A collisions at the LHC is thus a key measurement to determine the properties of hot QCD matter (gluon density, transport coefficient parameter) at the highest energies ever studied.

In this report I will first briefly describe the ALICE PHOton Spectrometer PHOS which allows us to measure neutral pions via their \( \gamma\gamma \) decay channel. In a second stage, I will discuss the feasibility of the \( \pi^0 \) measurement, in terms of statistics, for the first proton-proton run conditions at the LHC (\( \sqrt{s} = 10 \text{ TeV} \)). Finally, I will detail the Monte Carlo-based method used to obtain the \( \pi^0 \) geometrical acceptance and reconstruction efficiency.

The ALICE PHOton Spectrometer (PHOS) consists of the combination of PbWO\(_4\) (PWO) crystals and Avalanche Photon Diodes (APDs) for the scintillation-light readout. In total, 17920 channels cover 100° in azimuthal angle and ± 0.12 in pseudo-rapidity. PHOS contains 5 modules consisting of 64x56 crystals each. Each crystal is a 18cm long parallelepiped, with 20 radiation lengths (\( X_0[\text{PbWO4}] = 0.89 \)). PHOS has an energy resolution of 3.3%/\( \sqrt{E} \) + 1.1% and a granularity resolution \( \Delta \Phi \times \Delta \eta = 0.004x0.004 \) [2]. The first module of the ALICE PHOS detector was installed in May 2008 and it will take data during the first year of operation at the LHC.

The expected \( \pi^0 \) production yield per \( p_T \) bin can be estimated using the counting rate formula

\[
\frac{dN}{dp_T} = L_{\text{int}} \times \frac{d \sigma}{dp_T} \times A_{\pi^0} \times \varepsilon
\]

where: \( L_{\text{int}} \) is the integrated luminosity, \( \frac{d \sigma}{dp_T} \) the differential cross section, \( A_{\pi^0} \) the geometrical acceptance of the detector, and \( \varepsilon \) the \( \pi^0 \) efficiency reconstruction has been calculated by INCNLO program.
[1] which allows to compute perturbatively the photon and hadron differential cross sections in QCD hard processes at Next-to-leading-Order (NLO) accuracy. The figure 1 presents the expected rates one should achieve in the first proton-proton run assuming 30 days of collisions at $\sqrt{s}= 10$ TeV, with a luminosity $L=0.5 \times 10^{29}$ cm$^{-2}$s$^{-1}$ and 1 PHOS module ($\Delta\eta \times \Delta\phi = 0.24 \times 20^\circ$) with a $\pi^0$ reconstruction efficiency of $0.9 \times 0.9$ (corresponding to photon reconstruction efficiency squared).

We conclude from this calculation that – assuming that the LHC will perform as expected – we can measure pions up to 25 GeV/c. We have now to estimate more accurately the acceptance and efficiency correction factors.

**Reconstruction efficiency correction factor:**
This correction factor $C_{\text{efficiency, rec.}}$ can be calculated after performing an analysis of the $\pi^0$ invariant mass spectrum and a background subtraction which relies on fitting the signal with a gaussian and a 2-polynomial function. $C_{\text{efficiency, rec.}}$ is defined as the number of reconstructed pions around $2\sigma$ (or $3\sigma$, where $\sigma$ is the width of the Gaussian fit of the invariant mass distribution) of the $\pi^0$ peak over the number of generated pions which have 2 decaying photons in PHOS. The efficiency correction factor presented on Fig. 3 increases with the generated $\pi^0$ energy to reach 85% (resp 65%) for $3\sigma$ (resp $2\sigma$) above $E_{\pi^0}$~10 GeV.

![Fig 3: Efficiency correction factor $C_{\text{efficiency, rec.}}$ for $\pi^0$ in PHOS detector.](image)

These results allows us to conclude that ALICE will allow to measure neutral pions up to 25 GeV in the first year of operation.

**Geometrical acceptance correction factor:**
The acceptance for $\pi^0$ detected in their $\gamma\gamma$ decay is defined as the number of neutral pions with both decay photons in PHOS acceptance over the number of total $\pi^0$ actually produced in $|y| < 0.5$ and $\Phi = 2\pi$. This acceptance depends on $\gamma\gamma$ due to the varying opening angle between the two decay photon as a function of the pion “boost” as seen on Fig 2. Above $E_{\pi^0}$~10 GeV, the $\pi^0$ acceptance in PHOS flattens out at about 1%.

![Fig 2: Geometrical acceptance for $\pi^0$ in PHOS as a function of the $\pi^0$ energy.](image)

Afin de déterminer la section efficace de production des $\pi^0$ dans l’expérience ALICE, la mesure expérimentale de leur taux de production devra être corrigée par des facteurs d’acceptance géométrique et d’efficacité de détection qui ont été estimés à partir de simulations Monté Carlo. Le facteur d’acceptance géométrique sature autour de 1% ce qui correspond bien à $\Delta\phi \times \Delta\eta = 0.24 \times 20^\circ$ (un module PHOS).

Le facteur d’efficacité de reconstruction estimé avec des analyses de masse invariante quant à lui croit jusqu’à atteindre 85%. Si le LHC et le spectromètre de photon d’ALICE réalisent les performances attendues nous pourrons mesurer à l’aide de PHOS des pions neutres atteignant des énergies jusqu’à 25 GeV/c lors des premières collisions proton-proton à 10 TeV.

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CERN/LHCC 99-4
The main objective of the muon spectrometer is to trigger and track muons to examine heavy flavour production via their muon decay channels. To separate different states of the $\bar{\nu}$ family an invariant mass resolution of about 100 MeV/c$^2$ is required. The equivalent spatial resolution is of the order of hundreds of $\mu$m in the tracking system bending plane and a few mm in the non bending one.

The chambers in the last 3 stations of the spectrometer present an anomalously high level of noise that will affect the performances of the detector. While we are working to track the origin of the noise and to reduce it, this study [1] has been carried out to evaluate its real impact on the spectrometer performances and determine the maximum level of noise that is acceptable from the physics point of view.

The project is carried out with the ALICE software “AliRoot”, by simulating and reconstructing 5000 $\bar{\nu}$ with different level of uniform noise. The noise is applied channel by channel on the last 3 stations of the spectrometer during the simulation process by adding a randomly generated charge to the measured one. For the first 2 stations, the noise is fixed to 2 ADC which is the averaged value observed during the last cosmic runs. A dispersion of the electronic gain fixed to 10% (which is realistic according to the electronic tests performed so far) is also applied to each channel on the 5 stations at the beginning of the simulation. Another part of this project [1], not describe in this report, have shown that the gain dispersion has a relatively small effect on the spectrometer performances compared to the effect of the noise (bending resolution multiplied by 2, +10 MeV/c$^2$ on the $\bar{\nu}$ mass resolution and no loss of reconstruction efficiency). The reconstruction parameters are set in such a way that even the worst reconstructed cluster can still be taken into account when reconstructing the muon tracks, thus maximizing the tracking efficiency and making it independent of the level of noise. The drawback is the formation of fake tracks (random association of clusters), which are discarded by requiring the matching with the tracks reconstructed in the trigger chambers.

The spectrometer performances are characterized by the chamber resolution (i.e. the resolution of the reconstructed clusters determined by the dispersion of the residuals between them and the track they belong to) and by the reconstruction efficiency and accuracy of $\bar{\nu}$.

Le but de cette étude est d'évaluer l'impact du bruit électronique observé sur les trois dernières stations du spectromètre sur les performances de ce dernier, et d'en extraire une limite supérieure acceptable.

![Fig. 1](image)

Fig. 1 : $\bar{\nu}$ mass resolution as a function of the electronic noise on bending (red) or non bending (blue) plane, and on both (black).

Five different levels of noise have been tested: 0, 12.5, 25, 37.5 and 50 ADC. The chamber resolution increases by a factor 2 in the non bending plane and by a factor 7 in the bending one when increasing the noise from 0 to 50 ADC, reaching 700 $\mu$m in the bending plane. At the same time, the $\bar{\nu}$ mass resolution goes from 100 to 300 MeV/c$^2$ while the reconstruction efficiency drops from 92 to 40.
% as shown by the black points on figures 1 and 2 respectively. Further studies have shown that this loss of efficiency is independent of the transverse momentum and the rapidity of muons.

Fig. 2 : Reconstruction efficiency as a function of the electronic noise on bending (red) or non bending (blue) plane, and on both (black).

The two cathodes of the tracking chambers give information preferentially in either the bending or the non bending direction. The noise is then expected to have a different impact on the spectrometer performances depending on the affected cathode. Since the level of noise measured on both cathodes is different, the simulations have been performed again by applying the noise on one cathode at a time. The noise on the other cathode is fixed to 2 ADC like for stations 1 and 2. The effects observed on the reconstructed \( \gamma \) will allow to extract a maximum acceptable value of noise on both cathodes separately.

Results presented on figures 1 and 2 clearly show that the detector performances are much more sensitive to the noise in the bending plane (red points) than in the non bending one (blue points). In the second case, the mass resolution increase to 140 MeV/c^2 and the efficiency is not affected. When the noise is on the bending plane, the mass resolution increase to 300 MeV/c^2 and the efficiency drops to 75%. We can also note that the combined effect of the noise on both cathodes has a dramatic effect on the reconstruction efficiency, while the mass resolution is more or less determined by the resolution in the bending plane only.

From these results, we can fixe the maximum acceptable level of noise to about 5 ADC in the bending plane and about 20 ADC in the non bending one. Recent works done to reduce the electronic noise have revealed a problem of stability in the low voltage power supplies. This problem has been fixed and the level of noise observed is of the order of the limitation determined by this study. Under these conditions, all the physics studies foreseen with the MUON spectrometer are achievable.

Un des principaux objectifs du spectromètre est d’étudier la production des résonances de quarks lourds via leur canal de désintégration en deux muons. Une résolution en masse invariante de l’ordre de 100 MeV/c^2 est nécessaire pour identifier les paires de muons provenant des particules de la famille de l’\( \Upsilon \), ce qui correspond à une résolution spatiale du spectromètre de l’ordre de la centaine de microns dans la direction de courbure des traces et de l’ordre du millimètre dans la direction perpendiculaire.

Certains des chambres de trajectographie du spectromètre présentent un bruit électronique anormalement élevé qui va affecter ses performances. Tandis que l’on travail à identifier l’origine de ce bruit et à le réduire, cette étude a été menée afin de déterminer l’impact exacte de celui-ci pour en extraire une limite supérieure acceptable du point de vue de la physique.

Les résultats montrent une grande sensibilité des performances lorsque le bruit est situé sur le plan de la chambre mesurant la position de la trace dans sa direction de courbure. Dans ce cas une limite d’environ 5 canaux ADC de bruit semble raisonnable, tandis qu’environ 20 canaux ADC reste acceptable sur l’autre plan.

Les derniers travaux effectués sur l’électronique des chambres, et notamment sur les générateurs de basse tension, ont permis de réduire le bruit au niveau des limites déterminées dans cette étude. Les performances attendues du spectromètre devraient donc être atteintes.

[1] C.Bianchin et al., « Effects of electronic noise on the spectrometer performances », To be published as an ALICE Internal Note
Effect of heavy-quark energy loss on the muon differential production cross section in Pb-Pb collisions at 5.5A TeV

Z. Conesa Del Valle 1, A. Dainese 2, H. Ding 3, G. Martinez, D. Zhou

Heavy quarks are regarded as effective probes of the strongly-interacting medium produced in ultra-relativistic heavy-ion collisions, since they are produced in the initial hard-scattering processes and they may subsequently interact with the medium. Heavy-quark medium-induced energy loss will be one of the most captivating topics to be addressed at LHC. In hadron–hadron collisions at LHC energies, muons are predominantly produced in semi-leptonic decays of heavy-flavoured hadrons, mostly beauty for muon $p_T \sim 4$ GeV/c. Thus, in heavy-ion collisions, the muon $p_T$ distribution is sensitive to $b$-quark energy loss effects. The muon $p_T$ distributions in pp and Pb–Pb collisions at LHC energies are calculated considering the semi-muonic decays of heavy-flavoured hadrons and the muonic decay of $W$ and $Z$ bosons. The $p_T$ and rapidity distributions of $W/Z$ and of their decay muons are obtained from the PYTHIA event generator. The resulting $p_T$ distributions are normalized to the NNLO cross sections that are a cross section per nucleon–nucleon collision of $6.56 (7.34)$ nb for the $W$ and $0.63 (0.68)$ nb for the $Z$ in Pb–Pb (pp) collisions at 5.5 TeV, including the muonic branching ratios (10.6% for $W$ and 3.4% for $Z$).

We use the NLO pQCD calculation implemented in the HVQMNR program to obtain the heavy-quark $p_T$–$y$ double-differential cross sections, with the following parameters values: for charm, $m_c = 1.2$ GeV and factorization and renormalization scales $\mu_F = \mu_R = 2\mu_0$. For beauty, $m_b = 4.75$ GeV and $\mu_F = \mu_R = \mu_0$. Finally, we decay the hadron into a muon according to the spectator model. The muon production cross sections per nucleon–nucleon collision from charm (beauty) at $\sqrt{s_{NN}} = 5.5$ TeV that we obtain are 0.415 mb (20 $\mu$b) in Pb–Pb collisions and 0.637 mb (23 $\mu$b) in pp collisions. A charm (beauty) semi-muonic branching ratio of 9.6% (11.0%) has been considered.

We compute the muon $p_T$ distribution taking into account the heavy quark energy loss in the strongly-interacting medium that is expected to be formed in central Pb–Pb collisions at LHC energies. For modelling the energy loss of heavy quarks by medium-induced gluon radiation, we used the quenching weights in the multiple soft scattering approximation.

We start by presenting, in Fig. 1, the muon production cross-section as a function of transverse momentum in the 10% most central Pb–Pb collisions, when only nuclear shadowing is included. The contributions from charm, beauty and weak gauge bosons are shown separately. Due to their large masses, $W$ and $Z$ bosons are mainly produced with small transverse momentum. Therefore, the decay muons...
have typically $p_t \approx \frac{m_{W,Z}}{2}$. In the range 4–30 GeV/c beauty decays prevail, and at larger $p_t$ the W decays represent the largest contribution to the muon spectra.

These muon nuclear modification factors could provide the first experimental observation of the $b$ quark medium-induced suppression in Pb–Pb collisions at the LHC. The presence of a medium-blind component (muons from W and Z decays) that dominates the high-$p_t$ muon yield will allow an intrinsic calibration of the medium-sensitive probe (heavy quarks), because it will provide a handle on the strength of the initial-state effects that may alter the hard-scattering cross sections in nucleus–nucleus collisions at the unprecedented energies of the LHC.

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Silicon Strip Detector during its installation inside STAR expérience

Layers of the silicon strip detector
The STAR experiment at RHIC, Brookhaven Laboratory, USA, studies hadronic matter under extreme conditions of density and temperature. Up to 2005, the STAR group of Subatech has been involved in construction and software aspects of a Silicon Strip Detector (SSD), in two particle correlations, and in strange particle analysis. In 2005 the SSD took first data with full acceptance. We summarize in the following the main developments in the group, from 2006 to 2008, in chronological order:

**2006 overview:** the Subatech group consisted by one Prof. (S.Kabana) and one PhD student (J. Bouchet). We had no senior person to be on site at BNL for the SSD, during the 2006 p+p run. In 2006 we therefore concentrated our efforts in the calibration of SSD in the Cu+Cu data taken in 2005. J. Bouchet was sent to BNL to work in collaboration with the reconstruction group. Subatech’s responsibility was the SSD calibration and Monte Carlo. These efforts, lead to the successful calibration of SSD in the Cu+Cu data. J.Bouchet has been named software coordinator of SSD. STAR convenors required from us studies on a preliminary candidate for a new N0 or ΛK0s state, found in 2001 data. This work was given to 2 master students (preliminary results). The candidate was found also in 2004 data (master A.Ghouam). Furthermore, the search for the isospin partner N+→ΛK+ resulted in a possible candidate at nearby mass (master H.Ricaud). While these results are very promising, much more work (rather at PhD level) is needed to complete the required studies. In fall 2006 a new student (A.Geromitsos) started a co-tutelle PhD Thesis with BNL, to work on heavy flavour and the SSD. He was sent for the first half of co-tutelle to BNL, with co-supervisor J. Dunlop, physics coordinator of STAR in 2006, and deputy spokesperson at present.

**2007 overview:** the Subatech group consisted by one Prof. and two students (J.B., A.G.). The students both participated in the SSD run of spring 2007. The senior support of SSD run on site was assured by LBNL, BNL and Strasbourg (J.Baudot, D.Bonnet). We concentrated on the SSD calibration task. Two master students from TU Warsaw have been sent to BNL during the 2007 run as part of the Warsaw-Nantes collaboration (J.Plebanek and R.Pieniazek). J.Bouchet and the 2 polish students assured the calibration of SSD in Au+Au 2007 data, which succeeded quite fast, within 2007. It was found (J.B.) that the efficiency of the SSD in the reconstructed data can be as low as 50% depending on wafer. We therefore concentrated efforts of A.Geromitsos in 2007 on a new SSD Cluster Finder, to enhance the SSD efficiency, which shows promising results. A.Geromitsos started also heavy flavour (D0) analysis in Cu+Cu data. In summer 2007, the SSD has been taken out of STAR, and was later transferred to Subatech, for reparations and the upgrade. J Bouchet defended successfully his Thesis in oct. 2007, and took a post doc at Kent State University (STAR).

**2008 overview:** the Subatech group consists of one Prof., one post doc (R Sahoo) and one student (A.G.). We work on D0 analysis and electron-D0 correlations, allowing to disentangle beauty and charm contributions. The microvertexing techniques are still under ‘quality assurance tests’. The SSD detector tests in 2008 were successful, retaining all modules 95% working. (S. Bouvier, Ch. Renard). A capacitor problem causing current leakage was identified and will be repaired. Work on two particle correlations (p-p, p-pbar, pbar-pbar) with supervisor B.Erazmus and co-supervisor J.Pluta from TU Warsaw (co-tutelle PhD Thesis, H.Zbroszczyk), has been completed, leading to new important insights on source size in Au+Au collisions at RHIC. H. Zbroszczyk defended successfully her Thesis in 2008, and took a permanent position in TU Warsaw (STAR, ALICE).

**Future plans:** Our primary project for the next 1-2 years is heavy flavour (e-D0 and D0) analysis using microvertexing methods in Cu+Cu and Au+Au collisions. This project will help disentangle charm/beauty contribution and resolve the jet quenching puzzle at RHIC. The project on new particle searches can reach publication stage, with one PhD Thesis. The SSD will be part of the future STAR Heavy Flavour Tracker (~run 2011). The SSD efficiency can be significantly enhanced by the new cluster finder. An electronics upgrade of SSD under way by our expert engineers in Subatech, will allow higher event rates to be taken by the SSD, integrating it well into the new STAR trigger upgrade.
Electron–D0 correlations in Cu+Cu collisions at 200 GeV with STAR at RHIC

A. Geromitsos, S. Kabana, R. Sahoo

Heavy quarks are expected to lose less energy than light quarks due to the so-called dead cone effect [1]. The sum of charm and beauty produced in Au+Au collisions at 200 GeV at RHIC, measured through the yield of non-photonic electrons, is found to show more ‘quenching’ than theoretically expected (fig. 1). In order to understand this observation the direct measurement of charm and/or beauty separately and in the relevant transverse momentum range is needed.

The work presented here concerns the measurement of the $D^0 \to K\pi$ (B.R. 3.84%) in Cu+Cu collisions at 200 GeV taken in 2005 with the STAR experiment at RHIC. This analysis can take advantage of the silicon detectors of STAR (SVT and SSD). We apply a novel analysis technique to identify and separate charm and beauty via leading electron azimuthal correlations with open charm mesons, which has been already successfully applied in p+p collisions at 200 GeV in STAR [2]. The STAR electromagnetic calorimeter provides a unique opportunity to identify electrons online and to select a sample of events with a large enhancement of heavy-flavor production. Moreover, this correlation method reduces significantly the combinatorial background in the reconstruction of D0 mesons. Due to momentum conservation, the heavy-quark-antiquark pairs are correlated in relative azimuth ($\Delta\phi$), leading to the characteristic back-to-back orientated sprays of particles. The branching fraction for charm and bottom decays into electrons is ~10%. While triggering on the leading electron, the balancing heavy quark, which is identified by the D0 meson, can be used to identify the underlying production mechanisms. In particular, a charge-sign requirement on the trigger electron and decay Kaon provides a powerful tool to separate charm and bottom quark events (fig.2).

Fig. 1: Nuclear Modification Factor vs pT

Fig. 2: Schematic view of fragmentation of $b\bar{b}$ (left) and $c\bar{c}$ (right).
PYTHIA simulations [2]. The azimuthal correlation in combination with the charge-sign requirement allows the clear separation of charm and bottom quark events.

The electron identification is being performed by combining the information from the TPC and the calorimeter. The calorimeter, situated behind the TPC, covers an acceptance of $\eta < 1$ and full azimuth.

Photon conversions in the detector material and $\pi 0$ and $\eta$ Dalitz decays represent the dominant source for the electrons from heavy quark decay. Here, each electron candidate is combined with the tracks passing the de/dx cut (fig. 4) and candidates with an invariant mass $m(e^+e^-)$ less than 150 MeV are disregarded. Fig. 5 shows the $K \pi$ invariant mass after a first selection of electron candidates and a cut on de/dx, and superimposed an estimate of the background based on the rotational method. The shape of the estimated background (red), describes well the shape of the signal plus background distribution (blue).

Fig. 3: Pythia simulation: Delta(phi) of electrons and D0 mesons for e-K like-sign (left) pairs and unlike sign pairs (right). Green is for beauty and red for charm [1].

Fig. 4: Invariant Mass of like-sign (blue) and unlike sign (red) electron/positron pairs, in Cu+Cu collisions at 200 GeV.

Fig. 5: Invariant mass $K \pi$ (blue) and estimate of rotational background (red).

Fig. 6: DCA(xy) of charged tracks to main vertex for 0,1,2,3,4 hits in silicon detectors: from outwards (blue) towards inwards (black).

One of the most important goals of STAR is the measurement of flavour dependence of jet quenching. We present the first analysis of heavy-quark pairs correlated in relative azimuth ($\Delta \phi$) leading to the characteristic back-to-back orientation of their decay products in particular electron-D0 correlations in Cu+Cu collisions at 200 GeV. This analysis allows to reduce the combinatorial background for the $D0 \rightarrow K\pi$ invariant mass, as well as to estimate the charm and beauty contributions separately.

The invariant mass of $K \pi$ has been investigated after a preliminary electron selection. The background estimate describes well the shape of the signal plus background distribution. The improved DCA using the silicon detectors of STAR is illustrated. Future work will focus on optimization of cuts, simulation studies, improvement of electron identification, as well as on microvertexing techniques.

Proton femtoscopy in STAR

B. Erazmus, H. Zbroszczyk

The results of proton-proton, antiproton-antiproton and proton-antiproton femtoscopy measurements by the STAR collaboration at RHIC for Au+Au collisions at two CMS energies: 62 and 200 GeV per nucleon are presented. Thanks to large data statistics, all the analysis was performed for three centralities. Correlation functions for systems including antiprotons were measured for the first time. Strong impact of residual correlations, coming from heavier two-particle systems, was observed and taken into account in the analysis. The final results are consistent for all measured systems within each centrality and energy. Proton and antiproton source sizes, extracted with a very good accuracy, systematically increase with the collision centrality for both energies. Extracted radii for central collisions follow the \( m_T \) dependence confirming flow phenomena observed for different particle species. All radii from proton femtoscopy scale with \( (dN_{ch}/d\eta)^{1/3} \) as was seen earlier for mesons. We also detect a small but clear asymmetry in the emission process between protons and antiprotons. It indicates that antiprotons are emitted earlier and/or closer to the system edge than protons.

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) was designed to measure the properties of hot and dense matter created in heavy ion collisions at ultrarelativistic energies. One of the detectors operating at RHIC is Solenoidal Tracker At RHIC (STAR). Analysis of two-particle correlations at small relative velocities is a part of STAR physics program. The correlation effect is determined by the distance separating emission points in space and time and by the relative momentum of particles. Thus, analysis of particle correlations is able to access the information about space-time development of particle emission process which cannot be measured directly. Correlations of identical particles reflect the effects of quantum statistics (QS) and of the final state interactions (FSI): Coulomb and strong. Non-identical pairs are sensitive to the final state interactions only. We measure the correlations as a function of \( k^* \), the momentum of one particle in the rest frame of the pair.

From the experimental point of view, many secondary protons and antiprotons are indistinguishable from the primordial ones. This effect should be taken into account, to avoid the misinterpretation of the measured results, if correlations between other particles are taken as the correlations of protons.

Together with experimental analysis we use the theoretical model Therminator (THERMal Heavy IoN GenerATOR). The generator was designed to study particle production at SPS, RHIC and LHC energies. It implements the thermal model of particle production with a single freeze-out. The geometry of the freeze-out hypersurface is chosen according to hydro-inspired Cracow model. The space-time emission point, as well as information about “parents” is stored for each generated particle. The aim of this study is to analyse the proton-proton correlations after removing the the residual ones.

Fig. 1: Proton-proton (top panel), antiproton-antiproton (middle panel), proton-antiproton (bottom panel) correlation functions for three centralities (see data points): central collisions (0-10% of the total hadronic cross-section for the Au+Au collision) (bright grey), midcentral (10-30%) (dark grey), peripheral (30-80%) (black) with their theoretical fits.
Figure 1 presents correlation functions for all systems composed of protons and antiprotons, corrected for detector effects and residual correlations. Figure 2 shows the compilation of all measured source sizes versus collision centrality expressed by $(dN_{ch}/d\Delta N)^{1/3}$. The results are consistent within statistical and systematic uncertainties. The nature of $(dN_{ch}/d\Delta N)^{1/3}$ scaling ($N_{ch}$ number of charge particles), seen earlier for pions, is observed also in proton femtoscopy. Studying of such dependence is motivated by the relations to the final geometry through particle density at the freeze-out.

The extracted baryon radii for central collisions confirm hydrodynamical description of source evolution (see Fig. 3), where heavier particle species are expected to be emitted from smaller area. The system’s collective expansion produces such differences in the length of homogeneity because the emission points of massive particles emitted with close velocities are less dispersed and on average more pushed towards the edge of the system than it is the for the lighter ones. The results in Figure 3 conform the “universal” $m_T$ scaling established with other particle species.

Nonidentical particle correlations allow one to measure which particle is emitted earlier and/or closer to the system edge. According to hydrodynamical description, the difference in particle emission is naturally expected for particles with different masses. However, studies of proton-antiproton correlations show that such asymmetry exist for such system as well. In order to extract this information, all pairs were divided into two groups: first group contains pairs, when protons are faster than antiprotons (left-hand side of the Fig. 4, $k^*(\text{sign}(k^{*\text{out}}))>0$) and the second groups is composed of pairs, when protons are slower ($k^*(\text{sign}(k^{*\text{out}}))<0$). In the case, when ratio of both functions is not equal the unity (see right-hand side of the Fig. 4), an asymmetry in particle emission is detected. The observed effect in $\text{out}$ component indicate that in average antiprotons are emitted closer to the edge of the emitting system and/or earlier. By comparison with model predictions (UrQMD, EPOS) we claim, that it can be the consequence of antiproton annihilations.

The results of proton-proton, antiproton-antiproton and proton-antiproton femtoscopy measurements by STAR experiment at RHIC for Au+Au collisions at two SMS energies: 62 and 200 GeV per nucleon are presented. Thanks to large data statistics, all the analysis was performed for three centralities. Correlation functions for systems including antiprotons were measured for the first time. Strong impact of residual correlations, coming from heavier two-particle systems, was observed and taken into account in the analysis. The final results are consistent for all measured systems within each centrality and energy. Proton and antiproton source sizes, extracted with a very good accuracy, systematically increase with the collision centrality for both energies. Extracted radii for central collisions follow the $m_T$ dependence confirming flow phenomena observed for different particle species. All radii from proton femtoscopy scale with $(dN_{ch}/d\Delta N)^{1/3}$ as was seen earlier for mesons. We also detect a small but clear asymmetry in the emission process between protons and antiprotons. It indicates that antiprotons are emitted earlier and/or closer to the system edge than protons.
Search for new hadronic states decaying into $\Delta K^+$ and $\Delta K^0 s$ with STAR at RHIC

A. Ghoulam, S. Kabana, H. Ricaud

One of the most spectacular results of RHIC, is that hadrons in heavy ion collisions, appear to be produced mainly through quark coalescence. Exotic multiquark states, allowed by QCD, can therefore form through quark coalescence, and be enhanced as compared to elementary collisions, in which coalescence does not prevail as production mechanism. A preliminary peak, candidate for a new $N^0$ or $\Xi^0$ state has been measured near 1730 MeV in STAR and two other experiments in the $\Delta K^0 s$ and the $\Sigma-K^+$ invariant masses. The latter if confirmed, excludes the $\Xi^0$ hypothesis. If this peak is a true $N^0$ state, the isospin partner $N^+$ should exist at same mass. We present preliminary results on a possible candidate peak for the expected isospin partner, namely the $N^+ \rightarrow \Delta K^+$ at nearby mass. Furthermore we present new studies for the $\Delta K^0 s$ peak which have been requested by STAR.

One of the most spectacular results of RHIC is the elliptic flow versus transverse momentum scaling with the number of constituent quarks observed in heavy ion collisions at RHIC, suggesting that the majority of midrapidity hadrons in Au+Au collisions at RHIC are formed through quark coalescence out of a partonic source, possibly representing an sQGP. Exotic multiquark states can therefore form through quark coalescence, and be enhanced in heavy ion collisions as compared to elementary particle collisions, in which coalescence does not prevail as production mechanism. Heavy ion collisions at RHIC and LHC may therefore be a unique source of QCD exotics.

Exotics are allowed by QCD, however lattice QCD and different QCD models lead to contradictory predictions, as of their existence and characteristics, reflecting the difficulties in such calculations, touching on non perturbative QCD aspects.

The STAR experiment is the only RHIC experiment able to measure many strange hadrons in a large acceptance. STAR accumulated by now a very high statistics of events over 8 years of long dedicated runs of 6 months each. Therefore, STAR offers at the moment a unique advantage for searches for exotic with high strangeness content, formed at midrapidity, through parton coalescence.

A preliminary narrow peak, candidate for the states ud$\bar{s}$d$\bar{s}$bar ($N^0$) or ud$\bar{s}$d$\bar{s}$bar ($\Xi^0$) has been measured near 1730 MeV (Fig. 1) in STAR, in the $\Delta K^0 s$ inv. Mass, in Au+Au collisions at 200 GeV, with S/$\sqrt{N}$ of 5-6 (hep-ex/0406032), as well as in two other experiments, in the $\Delta K^0 s$ and $\Sigma-K^+$ decay channels. The latter if confirmed, would exclude the $\Xi^0$ hypothesis. If this peak is a true $N^0$ or $\Xi^0$ state, the isospin partner, $N^+$ for $N^0$, or $\Xi^+$ for the $\Xi^0$ should exist at same mass.

Here we present preliminary results on a candidate peak for the expected isospin partner of the $N^0$, namely the $N^+ \rightarrow \Delta K^+$ at nearby mass (master thesis, H. Ricaud). The data analysed are part of Au+Au collisions at 200 GeV taken with a minimum bias trigger in run 2004. The key new feature of the method used for both $\Delta K^+$ and $\Delta K^0 s$ analysis as compared to other analysis done within STAR, is the unprecedentedly hard identification cuts, Fig. 2: Energy loss of particles versus momentum.
leading to excellent K+, K0s and Λ identification. In other analysis of STAR such high purity of Λ, K+ and K0s is not required. The K+ are identified through their De/dx (Fig. 2). We select the K+ in the low momentum range below 0.45 GeV and De/dx>-2 (fig. 2 and fig. 3 left). Taking larger momenta of K+, the pion contamination from the left is increasing (Fig. 3 middle and right).

The Λ are identified through topological cuts and Armenteros cuts. Only unambiguous Λ candidates are taken in the analysis. Good candidates which can be also K0s are excluded. The invariant mass of ΛK+ after the selection cuts is shown in fig.4 left. In fig. 4 right, a rotated background estimate is shown before normalization, to demonstrate that the background estimate describes approximately the form of the left plot, and that no peak appears in the background near 1700 MeV.

A possible peak near 1700 MeV mass is perceived in the left plot, while background normalization and subtraction is needed for this to be claimed as a statement, and for the significance to be qualitatively assessed.

Fig. 3: De/dx in σ away from Kaon mean dE/dx. for different momenta (σ) of the K+.

Fig. 4: Invariant mass m(ΛK+) in Au+Au collisions at 200 GeV. Left : signal+background, right : rotational background

If these candidates are confirmed, they do not need to be pentaquark states. New such multiquark states, can be in several new multiplets, e.g. new 27-plet by J Ellis et al, etc. The STAR collaboration and the Strangeness Group convenors, requested from us, to finalize the analysis, firstly, using the full available STAR statistics, in order to enhance the significance, and secondly, by doing certain proposed systematic studies. The required work, needs human resources (a PhD) in order to be completed towards a publication.

QCD exotics, if produced through quark coalescence, can show dramatic enhancement in HI collisions at RHIC and LHC. A preliminary peak in ΛK0s inv. Mass, candidate for the states N0 or Ξ0, has been measured near 1730 MeV in Au+Au coll. at 200 GeV in STAR in 2001 data and two other experiments in ΛK0s and ΣK+ decay channels. The latter if confirmed, supports the N0 hypothesis. If this peak is a true state, the isospin partner N+ should exist at same mass. We present preliminary results on a candidate peak for the expected isospin partner namely the N+ \( \rightarrow \Lambda K^+ \) at nearby mass. The peak is seen for the highest purity Λ and K+ samples. It diminishes progressively with enhanced π contamination as expected for a real signal and so it does. Many more systematic studies are needed.

Following requests of the STAR convenors, we searched if the ΛK0s possible peak is seen also in 2004 data (master thesis, A. Ghoulam). The peak is seen also in the 2004 data in the low and medium luminosity sample. The overall new significance (2001+2004 data together) remain to be assessed.

Fig. 5: Invariant mass m(ΛK+). From upper left to down right, the pion contamination in the K+ sample is increasing.
A new Cluster Finding method for the Silicon Strip Detector in the STAR experiment at RHIC

J. Bouchet, A. Geromitsos, S. Kabana

The Silicon Strip Detector has been successfully included in the heavy ion runs of STAR that took place after its full installation in the experiment, namely the runs taking data from Cu+Cu collisions at 200 and 62 GeV in 2005, and from Au+Au collisions at 200 GeV in 2007. The inclusion of the SSD is important for charm and beauty identification using microvertexing techniques. The efficiency of the SSD varies and can reach values as low as 50%.

We propose here a new method of Cluster finding, based on the TSpectrum [1] ROOT Class, which is developed and investigated with the goal to improve the efficiency of the SSD.

In the present situation the Cluster Finder used for the SSD inside the STAR reconstruction software (which we will call here Standard Cluster Finder (SCF)), is being performed by checking both the P and N sides of the SSD for topological correlation between strips as well as “charge-matching”. At the same time it has been observed and studied [2] that the N side presents a rather noisy behavior. As a result, many of the fired strips in P side do not match with the strips in the opposite side, and it is expected to have a negative impact on the detector’s global tracking efficiency.

In the present study we investigate for the first the cluster finding efficiency on each side and compare the efficiencies of the presently used method (SCF) and the new method. The new method consists of the following steps. Every wafer and every side (P and N) is treated independently regardless of it’s neighboring opposite side.

A first scan is being performed on the strips that have noise $rms < 15$. We accept only the clusters that fulfill the following condition:

$$\frac{A}{\delta A} > 5$$

**Fig. 1:** Upper plot: Cluster candidates found by the new method in one event (black open circles on x-axis) and measured ADC counts of fired strips (red stars). Bottom plot: cluster candidate (zoomed) found by the SCF method in the same event (blue star).
where \( A \pm \delta A \) are the values of the area and error, beneath the Gaussian fit that is performed via this method to each cluster candidate.

Here we show first results on the peak finding efficiency on each side separately, independent of P/N matching. An analysis has been performed on a small event sample for every wafer, side and ladder. The number of clusters found with the two different methods, have been compared.

Fig. 1 upper plot shows the 3 clusters found by the new method in one SSD event (open black circles set indicatively in the x-axis), and the corresponding ADC counts in red, while fig. 1 down plot, shows that in the same event only one of those clusters has been found by the ‘present’ method SCF (blue point) (this plot is zoomed around the only found peak).

In fig. 2 we plot the number of clusters found by SCF as a function of the number of Clusters found by the new method. The blue line shows the result of a linear fit to the data. The red line represents the case in which the results coincide. The difference of the slopes between the blue and the red line indicate that the new method finds approximately 43% more Clusters than the old method for the N side and 51% for the P side (preliminary result).

Future plans include analysis with Monte Carlo, and estimate of the fakes rate and the SSD efficiency, including the tracking, on a high statistics sample. The method can be used in future reproductions of already taken events with the SSD, in particular for the data of 2007 and 2005. The future runs with the SSD upgrade and the Heavy Flavour Tracker (HFT), will of course also benefit, from an improvement in the SSD peak finding efficiency.


Le détecteur en Silicium de l’expérience STAR (SSD) permettre pour la première fois, d’utiliser la technique du microvertexing dans les collisions d’ions lourds dans le but d’identifier les saveurs lourdes. L’efficacité du SSD varie et peut attendre des valeurs assez bas (e.g. 50%). Dans ce rapport, nous avons présenté les premiers résultats d’une nouvelle méthode de Cluster Finder pour le SSD, en utilisant les données de 2007 (Au+Au a 200 GeV). Grâce à cette méthode, nous avons trouvé approximement un taux de 40 % de clusters de plus que avec la méthode présente sur la piste P, et 50 % de plus sur la piste N. Ces résultats sont preliminaires. Des études Monte Carlo sont aussi à réaliser et l’efficacité et les ‘fakes’ du SSD dans la reconstruction sont à etudier avec les deux methodes. Cette nouvelle methode peut etre utiliser pour la reproduction des donnees existants (2005 et 2007) et aussi pour les futures run du STAR avec le SSD upgrade et le future Heavy Flavour Tracker (HFT) du STAR dans le quelle le SSD fait partie.
Status of the STAR Silicon Strip Detector Hardware

S. Bouvier, G. Guilloux, C. Renard, L.M. Rigalleau

Le Silicon Strip Detector (SSD) est la quatrième couche du détecteur de vertex de l'expérience Solenoid Tracker At Rhic (STAR) auprès du collisionneur Relativistic Heavy Ion Collider (RHIC). Après une installation complète été 2004, suivi d'une opération de maintenance été 2005, le SSD est resté opérationnel jusqu'à l'été 2007. Pour des raisons de programme de physique, il a été décidé de démonter le SVT et le SSD de STAR pour réduire la quantité de matière en son centre. Cette opération va nous permettre de procéder à un changement complet des cartes électroniques des échelles afin que le SSD soit compatible avec le nouveau système d’acquisition de STAR et soit utilisé par le HFT (Heavy Flavour Tracker) comme couche externe faisant la liaison avec la TPC. Mais avant de procéder à cette mise à jour, il était judicieux de faire la bilan complet des différentes échelles.

The SSD (Fig.1) completes the inner part of STAR, named SVT (Silicon Vertex Detector); both are based on silicon technology. The SSD was proposed to enhance the tracking capabilities in the central region of STAR. It consists of a barrel with a radius of 23 cm inserted between the SVT and the Time Projection Chamber.

320 detector modules are arranged in 20 carbon epoxy ladders (Fig.2), which lead to a total sensitive area of about 1 square metre and half a million analogue channels. One detection module is composed of a double-sided silicon strip detector and its front-end electronics (FEE). The 7.5 x 4.2 cm² silicon wafer contains 1536 microstrips (768 per side) and has a resolution of 30 μm in azimuth (RΦ) and 700  μm in the beam direction (z). The FEE of each module is composed of 12 ALICE128C readout chips and 2 control chips (COSTAR), supported by 2 hybrid circuits made up of one flex circuit and one carbon stiffener (Fig. 3).

The SSD was installed completely in 2004 and in spring 2007 several ladders started to have running problems. Moreover the STAR physics program of 2009 needed to reduce the material in the centre of the experiment. This is why it was decided to remove both SVT and SSD and to perform an upgrade of the ladders in order to be compatible with the STAR readout system DAQ1000.
Before starting the new design, a complete test of the 22 ladders has been performed at SUBATECH in order to evaluate if the SSD will be sufficiently in good shape to run with the HFT.

All the ladders dead or partially dead during the last STAR run are working well now after the test and several minor repairs. The problems were mainly due to damaged ADC or connection boards. The results of the tests are the following:

- 6 fully good ladders.
- 7 ladders with one bad hybrid (half module).
- 6 ladders with several bad modules.
- 3 ladders with a high voltage trip.

Several bad hybrids and bad modules were already identified during the construction of the SSD and can be forced to run (the test software will be improved to be able to do it). The high voltage trip of the 3 last ladders comes from a high leakage current due to one module on the ladder. After several investigations, it has been discovered that this leakage current comes from one of the decoupling capacitors located on the hybrids of the module (Fig.4). The objective now is to develop a tool and a procedure to remove this capacitor from the module without removing the module from the ladder, which is a risky operation.

Without any repair and modules forced to work the active area is still more than 90%, which is still acceptable by the experiment.

The schedule of the repair and the upgrade of the ladder is the following:

- Repair and test (after software improvement) of all the ladders: end of 2008.
- Prototype of the upgrade 2009 (3 ladders).
- Installation of the SSD in 2010.

The goal for the SSD is being operational again with the HFT (Heavy Flavour Tracker), the new pixel silicon tracker, from the run starting end of 2010, beginning of 2011.

Les tests complets des échelles ont montré que toutes les échelles sont encore en état de marche. Le problème de fonctionnement de certaines échelles provenait des cartes ADC et/ou de connexion qui vont être changées pour rendre le système de lecture des échelles compatibles avec le nouveau système d’acquisition de STAR. 3s échelles présentent un courant de fuite important. Il a été mis en évidence que ce courant provenait de capacités de découplage équipant les modules. Une procédure de réparation est en cours d’élaboration.

Un calcul brut (sans aucune réparation des échelles) montre que la surface active du SSD est d’environ 90% ce qui est acceptable de la part de la communauté STAR.

The Silicon Strip Detector (SSD) is a fourth layer of silicon detectors of the STAR experiment, thus completes its inner tracking device. The goal of STAR is to study heavy ion collisions in order to probe the existence of the Quark Gluon Plasma (QGP), a deconfined state of nuclear matter. Strangeness enhancement, such as $K_S^0$, $\Lambda$, $\Xi$ and $\Omega$ particles production, has been proposed as one of the signatures of formation of the QGP [1]. STAR central tracking device is a large cylindrical Time Projection Chamber (TPC), which provides momentum measurement and allows particle identification. Closer to the beam axis, the inner tracking system is dedicated to precise measurement of the primary vertex and increase of detection efficiency of secondary particles. It includes the Silicon Vertex Tracker (SVT) arranged in 3 layers surrounded by the SSD.

The SSD was proposed to enhance the tracking capabilities at mid-rapidity by improving the pointing resolution from the TPC through SVT. It uses double-sided silicon microstrip sensors and consists of 320 detector modules arranged on 20 ladders, forming a barrel at a radius of 23 cm from the beam, inserted between the SVT and TPC [2].

The RHIC run of 2005 (run V) with Cu+Cu collisions at $\sqrt{s} = 62$ and 200 GeV was the first time where the inner tracking device was fully operational. Performances and offline Calibrations tasks of the detector are presented here. To take advantage of the high spatial resolution given by the silicon strip technology in the data reconstruction, several corrections like the charge calibration and Lorentz effect correction have to be done. Software development has been done to implement these tasks. The charge calibration corrects for the difference between charges collected by strips on each side (namely P and N side strips), due to electronic readout. Since SSD uses double sided detectors, the same charge deposit is expected for each side for a given detection module. Fig. 1 shows the correction of the charge deviation before (left) and after (right) applying a gain correction for hits in a given wafer. The distribution after gain correction is centered on 0.
The charge matching (comparison between the charge collected on P and N sides) is used to disentangle ambiguities due to the hit reconstruction in a high particle environment. One impact of the charge calibration is to reduce the number of ambiguous reconstructed hits due to geometrical association of clusters [3]. Another correction implemented for the first time in the software was to take into account of the Lorentz effect [4], present in silicon detector because of the presence of a magnetic field of 0.5 T (created by the magnet that surrounds the TPC) and the electric field imposed to deplete a silicon wafer.

After alignment of the silicon detectors with respect to the TPC, we studied the tracking efficiency of the SSD. The improvement due to the SSD was confirmed by a better distance of closest approach of tracks to the primary vertex of the collision (DCA). The DCA resolution has 3 components (the vertex resolution, depending on the number of tracks used for its calculation, the track pointing resolution, depending on the detection and alignment resolution and by the multiple coulomb scattering (MCS) in silicon detector which evolves as the inverse of the momentum of track). It can be expressed by:

\[ \sigma_{DCA}^2 = a^2 + \left(\frac{b}{p}\right)^2 \]

where \( a \) parameterizes the 2 first contributions and \( b \) the MCS contribution [5].

Fig. 2 shows the DCA resolution as standard deviation of track DCA to primary vertex using TPC only (black) and adding the SSD (red) then the 3 layers of the SVT.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>TPC</th>
<th>TPC + SSD</th>
<th>TPC + SSD + SVT(1)</th>
<th>TPC + SSD + SVT(2)</th>
<th>TPC + SSD + SVT(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{DCA}^{XY} )</td>
<td>253</td>
<td>865</td>
<td>378</td>
<td>283</td>
<td>272</td>
</tr>
<tr>
<td>( \sigma_{DCA}^Z )</td>
<td>176</td>
<td>1000</td>
<td>350</td>
<td>239</td>
<td>216</td>
</tr>
</tbody>
</table>

**TAB.1**: DCA resolution in \( \approx m \) at \( P = 1 \text{GeV/c} \) vs. number of silicon hits in track fit

Contribution from tracking (parameter \( a \)) is comparable with MCS at \( P = 1 \text{GeV/c} \) thus confirmed the good alignment required for such precise detectors (see details in [5]). One can see from Tab.1 the improvement in the DCA resolution in both transverse and longitudinal directions by adding at least the hit from the SSD.

The tracking efficiency (defined as the ratio of the number of tracks including a SSD hit over all the tracks within the SSD acceptance) has been measured to 48% for the entire run V. However the efficiency varies locally sensors by sensors, as shown in Fig. 3 that represents the tracking efficiency of each individual wafers due to different level of electronic noise.

**Fig. 3**: Tracking efficiency and as a function of \((\eta,\phi)\) of tracks

The noise dependence has been simulated on Fig. 4 that shows the impact of noisy strips (then occurring more dead areas in the detector). The tracking efficiency, represented as a function of momentum, is decreasing when the level of strip noise increases.
One of the original goals of the SSD is an improvement of the detection of short-lived particles decaying before reaching the TPC. The SSD hit should then increase the signal-to-background (S/B) of reconstructed secondary vertices. Based on the run V data, we see an improvement in terms of $K_S^0 \rightarrow \pi^+ \pi^-$ and $\Lambda \rightarrow p\pi$ invariant mass reconstruction [6].

From Fig. 5, one can see the reduction of the combinatorial background in the $\{\pi^+,-\pi^\mp\}$ association due to a better track DCA resolution.

The signal is obtained by using a simultaneous fit of the signal and the background. The S/B has been evaluated to $6.22\pm0.03$ for TPC only (Fig. 5 left) and to $13.93\pm0.13$ when using the SSD (Fig. 5 right).

Requiring a SSD hit improves also the mass resolution of $K_S^0$ for high $p_T$ compare to TPC only (Fig. 6). This reflects the improvement of the single-track momentum resolution at high $p_T$ when adding a SSD hit.

[3] B. Hippolyte et al., Silicon Strip Detector Reconstruction Chain for the STAR experiment, STARNOTE 0427
[5] Y. Fisyak et al., Overview of the inner silicon detector alignment procedure ad techniques in the RHIC/STAR experiment, CHEP 2007

Les données du run V au RHIC ont clairement montrées ce qu’apporte le SSD en terme de trajectographie dans l’expérience STAR. Associé au SVT, une amélioration de la reconstruction des particules étranges est observée. Les futures données des collisions Au+Au du run VII où la mesure du charme et de la beauté ouverte ($D^0, D^{\pm}, B^{\pm}$) sont en cours d’analyse.
Example of structural transition (crystals, patches, ropes, sponges, ...) dynamics for the nuclear matter inside neutron star.
Study of decay mechanisms in nucleon-induced reactions around the Fermi energy

F. Sébille, V. de la Mota, I.C. Sagrado Garcia, J.F. Lecolley, V. Blideanu

Nous avons réalisé une étude des réactions induites par des neutrons dans le cadre du modèle DYWAN en comparaison avec les données expérimentales. Les résultats sont clairement sensibles au champ moyen auto-cohérent, notamment à la dépendance en isospin de l’équation d’état nucléaire, et à la nature des particules détectées.

In this work, we have performed a comparative study between theoretical and experimental results in nucleon-induced reactions at incident energies in the Fermi energy domain. Theoretical calculations were made in the framework of the DYWAN model [1,2] which is a quantum extended-Hartree Fock description accounting for density fluctuations at the lowest order in the interaction, without any adjustable parameter.

The effects of the isospin dependence of the nuclear interaction on the emitted particle cross-section has been addressed considering different reactions in order to see whether the nature of incident and outgoing particles could play any role in our analysis.

In Fig. 1 are plotted the differential cross-sections in $^{208}$Pb(p,Xp) reaction at 62 MeV together with the experimental results of Ref. [3] (crosses). Calculations involve the soft Zamick force with isospin-dependent term (red line) and without this term (blue line). We observe a clear difference between both calculations, the one performed with the isospin-dependent force being in better agreement with the data.

In Fig. 2 is depicted the proton simple differential cross-section in $^{208}$Pb(n,Xp) reaction at 96 MeV. Experimental results (diamonds) are extracted from Ref. [4] and the theoretical ones involve the same forces as in Fig. 1. Now both calculations follow closely the experimental results in the range of energies 1080 MeV. At the same time we observe that in this case the theoretical results are not strongly modified by the contribution of the asymmetry term in the nuclear field. The calculations seem to be rather insensitive to the isospin degree of freedom at least in the particular case where the nature of incoming and outgoing nucleons is different.

Fig. 1: Differential cross-section form Ref. [3]. Theoretical calculations with (without) isospin dependence in red (blue).

The characteristics of emitted protons in Fig. 2 could suggest that the principal mechanisms involved in the reaction are direct diffusions. In that case the mean field should have less influence on the evolution of the emitted particles and consequently both versions of the effective force give roughly the same result, in good agreement with the experiment.
On the other hand, the strength of proton spectra in Fig. 1 is higher than the strength of protons spectra in Fig. 2 and the influence of the force appears now more clearly. Keeping in mind the fact that neutronproton free scattering cross-section is large compared with the corresponding neutronneutron or protonproton values [5], only the occurrence of multiple diffusions inside the target can explain these results. Indeed, in these processes the incident protons should interact more with other target nucleons in such a way that they have enough time to feel the effects of the mean field.


Fig. 1 : Differential cross-section form Ref. [4]. Theoretical calculations with (without) isospin dependence in red (blue).

Nous avons réalisé une étude comparative des résultats théoriques obtenus avec le modèle DYWAN et des données expérimentales récentes dans le domaine des réactions induites par des nucléons aux énergies de Fermi. Le but de ce travail a été d’avancer dans la compréhension des mécanismes microscopiques impliqués dans ces réactions afin d’extraire des informations sur les caractéristiques de l’interaction nucléaire.

Nous nous sommes intéressés en particulier aux effets d’asymétrie en isospin dans les sections efficaces de diffusion de neutrons et de protons. L’effet marquant de nos résultats est que l’influence des termes d’asymétrie est appréciable seulement dans le cas où la nature des particules incidente et diffusée est la même. Dans ce cas on obtient un très bon accord avec l’expérience lorsque la force tient compte des effets s’isospin.

Ces résultats suggèrent qu’un plus grand nombre de diffusions nucléon-nucléon ont lieu dans la cible lorsque les particules dans la voie d’entrée et de sortie sont identiques. Ces résultats soulignent également le caractère répulsif du terme dépendant de l’isospin, comme il a été suggéré par des travaux précédents [6].

Nous avons montré que les spectres des particules issus des réactions nucléon-noyau sont des observables très sensibles à la dépendance en isospin de la force effective, en conséquence ce type de réactions constituent une opportunité d’approfondir notre connaissance de l’interaction nucléaire dans le domaine d’énergies intermédiaires.

Probing the nuclear matter isospin asymmetry by nucleon-induced reactions at Fermi energies

F. Sébille, V. de la Mota, I. C. Sagrado Garcia, J. F. Lecolley, V. Blideanu, S. Figerou

Even though an exhaustive experimental systematic in nucleon-induced reactions is far from being achieved at intermediate energies, the available nuclear data open new opportunities to the theoretical models which aim at addressing either reaction mechanisms or nuclear interaction characteristics. The theoretical description of these processes with a microscopic approach constitutes a difficult task. One difficulty is the treatment of composite particle emission, which in most models, gives unrealistic results.

Nevertheless at intermediate energies, the production rates of light charged particles are important, and require a relevant evaluation, even if we are mainly interested by nucleonic probes in the incoming and outgoing channels. In this work we investigate nucleon-induced reactions in the framework of the Dynamical Wavelets in Nuclei (DYWAN) model, which has been proven to give a good description of the nuclear dynamics in nucleon on nucleus or in nucleus on nucleus reactions. The purpose of the model is to tackle efficiently the out of equilibrium mechanisms contributing to the observables.

In a few words, the essential aspects of our model are the quantum treatment of nucleons in terms of Slater determinants of wavelets which evolve through an ETDHF-type equation. Density fluctuations, responsible of the breakup of the system, are generated by unfolding the averaged density on many Slater determinants of single nucleons, each of which undertaking a particular path in the available space of states of the system

The measured free nucleon-nucleon diffusions evidence that proton-neutron cross sections are higher than proton-proton and neutron-neutron ones. Cross sections provided by nucleon-induced experiments are higher in the \( ^{208}\text{Pb}(p,Xp) \) reaction than in the \( ^{208}\text{Pb}(n,Xp) \) one. This states that mean-field effects strongly compete with direct diffusions, and even they can become predominant. Theoretical simulations exhibit a strong sensitivity to the isospin asymmetry of the effective local Skyrme interaction in \( ^{208}\text{Pb}(p,Xp) \) reactions. It means that in \( (p,Xp) \) channels compared with \( (n,Xp) \) ones, on the average, the emitted protons stem from a greater number of diffusions, and therefore experience the nuclear mean field longer, becoming more sensitive to the nuclear interaction properties governing the mean field, especially to the isospin asymmetry.

Nucleon-induced experiments show that cross sections of emitted nucleons are rather similar in \( ^{208}\text{Pb}(p,Xn) \) and in \( ^{208}\text{Pb}(p,Xp) \) reactions. This indicates, in this case, that the contribution of the mean-field is at least of the same order as direct diffusions. The current theoretical simulations exhibit an overestimation of \( ^{208}\text{Pb}(p,Xn) \) spectra for the higher emission energy. This is essentially due to the overestimated residual interactions and to the implemented local interaction.
Fig. 1: Integrated differential cross sections on iron (top) and on lead (bottom) targets for two different angles and two incident energies. The results for different channels are reported, the abscissa represents, in arbitrary units, the channels 1: \((n,Xp)\), 2: \((p,Xn)\), 3: \((p,Xp)\), and 4: \((n,Xn)\). Points correspond to experimental results and the dashed line joins the theoretical values.

Nevertheless, related in-medium effects and a more realistic effective interaction should be accessible in forthcoming refined and quantitative investigations.

Finally nucleon-induced experiments emphasize that the emitted nucleon cross sections are clearly higher in \(208\text{Pb}(n,Xn)\) than in \(208\text{Pb}(p,Xp)\) reactions. Since, the effect of the residual interactions is expected to be the same in both cases the previous result shows that the mean field acts more repulsively in the \((n,Xn)\) channel than in the \((p,Xp)\) one. From here we can infer the presence of a neutron skin for the heavy target. This is coherent with the fact that the energy involved in these nucleon-induced reactions favor the interaction of the incoming projectile mainly with the nuclear matter located at the surface of the target. All these coherent and convergent experimental as well as theoretical indications strongly suggest that nucleon-induced reactions in the Fermi energy domain are valuable probes of the isospin asymmetry of both the nuclear matter in exotic nuclei and of the nuclear interaction.

The current investigation points out that refinement in experiments and theoretical simulation could provide the opportunity to extract stringent and quantitative information about the characteristics of the nuclear force.

References

Self-consistent investigation of structural transitions in neutron star crust

F. Sébille, S. Figerou, V. de la Mota

Neutron stars have fascinated physicists since their prediction in the early years of the XXth century. They have been conceived as remnants, composed of essentially densely-packed neutrons, which is left behind the explosion of massive stars. A considerable effort has been done by different theoretical models [1,2,3] in order to understand the properties of this extreme state of matter and to describe the observed phenomena.

It is usual to divide the neutron star into three different density regions. The outermost layer, which has been extensively studied, extends up to around 3 \(10^{11}\) g/cm\(^3\) and is supposed to be composed of essentially a crystalline lattice of neutron-rich nuclei immersed in a degenerate electron gas. The second region extends from there up to a density of \(~1.5 \times 10^{11}\) g/cm\(^3\) and in addition to the neutron-rich nuclei it is composed by both degenerate electron gas and neutron gases [4]. In the last region, at still higher densities the matter consists of a uniform liquid of neutrons, protons and electrons and other elementary particles start to appear, as density increases.

In this work we present a new dynamical model for the description of the outer layer of a neutron star. The foundations of the dynamical description are based on the DYWAN approach of heavy-ion collisions [5]. In this framework, the stellar crust is self-consistently determined starting from an infinite periodic crystal of nuclei surrounded by a uniform electron gas. The principal static properties of nuclear matter have been compared with other theoretical calculations. Energy density and chemical potentials in a lattice of oxygen nuclei are shown to be correctly described even with a simplified effective force.

Owing to the fact that we focus the investigation on matter at zero temperature in the crust, currently in the model the evolution of the system is ruled by the nuclear mean-field. A variety of structural phases, the so-called “pasta phases”, are shown to be built self-consistently from the microscopic nuclear motion. The morphology of these structures has been analysed using integral geometry techniques, revealing their complexity. Beyond spherical nuclei, rod-like, slabs, cylindrical bubbles, slabs with holes, connected slabs and sponges have been found. These phases are formed dynamically allowing the transitions...
between different kinds of structures having ground state energies close to each others. We also have evidenced that, at variance with common macroscopic interpretation, the wave functions spreading is characterized by the coexistence and imbrications of different geometrical structures each one appearing for well defined values of the threshold density. The threshold density is the density at which we draw iso-surfaces extracted from matrix density, for visualized structures in fig 1. A clear sensitivity to the EOS has been evidenced for the low proton fraction, while for symmetric nuclear matter the results are almost independent of it. There is a conspicuous increase of the region of spherical and sponge-like structures against those of slabs and cylinders as the effective force is stiffer. In this case, the neutrons are dripped preferentially in the three dimensional geometries instead of one and two dimensional ones.

The bound particles fill discrete energy levels, whose densities are compelled by the involved effective interaction, therefore in this framework it will be possible to investigate aspects such as shell effects as well refined properties of the nuclear interaction like non-local effects. It will provide the opportunity to probe dynamical paths on a complex energy manifold, where the lattice type fingerprints on different phases as well as the coexistence of various lattice geometries could be analysed.

Physical correlations and fluctuations will be firstly addressed according to a statistical description in term of least biased mixture of Slater determinants, their time evolution being ruled by a master equation.

References

Les étoiles à neutrons sont des astres compacts, naissant suite à l’effondrement gravitationnel d’une étoile massive donnant lieu a une supernovae. On peut distinguer trois grands domaines de densité, l’écorce supérieure se situe à des densités de 3 \(10^{11}\) g/cm\(^3\), elle est principalement composé d’un réseau coulombien de \(^{56}\)Fe immergé dans un gaz d’électrons dégénéré. La seconde région atteint des densités de 1.5 \(10^{10}\) g/cm\(^3\). Une partie des neutrons a été éjectée des noyaux pour former une gaz de neutrons. A ces densités la compétition entre l’interaction coulombienne et l’interaction nucléaire crée des modifications de forme des noyaux appelées « pasta phases ». La dernière partie, la plus dense, est composée de matière nucléaire uniforme, fortement peuplée en neutrons, avec la présence possible d’autres particules selon les modèles utilisés pour la caractériser. Bien que représentant une faible fraction de l’étoile, l’écorce est une interface entre l’étoile et les observations. Une bonne connaissance de celle-ci est donc indispensable. La non reproductibilité de ces conditions physiques en laboratoire, fait des étoiles à neutrons un sujet d’étude privilégié pour extraire les propriétés fondamentales de la matière nucléaire, notamment ses propriétés iso-vectorielle.

Dans ce contexte un modèle dynamique et quantique a été développé pour étudier ces transitions structurales et leur impact sur les propriétés de transport de la matière nucléaire.
The in-medium effects and a window of the fusion process

Z. Basrak, Ph. Eudes, F. Sébille, V. de la Mota

Parameterisation of the in medium nucleon-nucleon (NN) cross section \( \sigma_{NN} \) is a key quantity for the theoretical models describing heavy-ion collisions at low and intermediate energies. Recent works emphasised that \( \sigma_{NN} \) has a conspicuous influence on different observables like the fusion process [1] and the double differential cross sections [2] in nucleon induced reactions on nuclei. These investigations seem to point out that the in-medium effects play a crucial role below the Fermi energy where they appear to be dominant.

In this work, we studied the \( ^{36}\text{Ar} + ^{58}\text{Ni} \) system at 18, 21, 24 and 30 MeV/u for all impact parameters from central to peripheral collisions. We decided to address the fusion process since we have shown [1] that the threshold energy at which fusion disappears is clearly dependent on the value of the NN cross section \( \sigma_{NN} \).

This study has been carried out within the framework of the semi-classical Landau-Vlasov model (LV) with the momentum-dependent Gogny interaction D1-G1. In our model, \( \sigma_{NN} \) is the Metropolis parameterisation of the free nucleon-nucleon cross section with energy and isospin dependence. \( \sigma_{NN} \) is assumed to be isotropic and density independent, a well justified hypothesis at energies under study. The in-medium effects are taken into account by multiplying \( \sigma_{NN} \) by a corrective constant factor \( F \). In the present study, \( F \) varies from 0 up to 1, noting that the value 0 corresponds to a pure mean field approach.

Figure 1 gives an insight into the reaction mechanism observed in each simulation as a function of the value of coefficient \( F \) and of the impact parameter. The contours are obtained by performing a bi-dimensional interpolation between the calculations performed on discrete set of \( F \) values and impact parameters. The orange zones are regions where one observes the fusion while the white zones correspond to binary processes. The labels a, b, c and d denote the incident energies of 18, 21, 24 and 30 MeV/u, respectively.

For \( F \) values close to 1, the fusion is dominant on a large interval of impact parameters, the later one being reduced when the incident energy rises. This aspect is in agreement with the experimental results which exhibit that the fusion cross-section strongly diminishes with the increase of beam energy.
What is more surprising is the appearance of a fusion window for the weakest values of the constant F (typically below 0.5). The term “fusion window” means that fusion is observed in the semi-peripheral collisions rather than for the central collisions where it is generally admitted to occur. The window becomes larger when F gets smaller. This well evidenced window at 18 and 21 MeV/u, is progressively washed out with the increasing projectile energies. In the current theoretical model, this mechanism stems from the cooperative actions of the residual interactions and the Pauli blocking. At lowest energies the in-medium effects reduce tremendously the transition probability between different energy levels, and therefore the energy dissipation. In addition, the transition probability is governed by the available phase space through the Pauli blocking, so that at low incident energy transition probability vanishes except for the most peripheral collisions.

The in-medium effects on fusion cross section at incident laboratory energies below 20 MeV per nucleon need more investigations both experimentally and theoretically. As a matter of fact they have a crucial importance in different fields like for example the physics of compact stars. A better understanding of the fusion process induced either by stable or radioactive beams will be especially valuable to further improve our knowledge on the nuclear interaction properties with respect to the isospin degree of freedom. The study of fusion process under conditions of decreasing proton fraction particularly deserves deeper investigations. The heating from nuclear reactions at moderate densities in the crust of compact stars should play an essential role in the temperature profiles and therefore on outstanding phenomena like the ignition of X-ray burst or neutron star cooling. It even could influence strongly the structure of the nuclear matter in the crust through the expected fusion barrier lowering, and consequently the strength of the heat capacity.

**Fig. 2** : Ratio between the Metropolis nucleon-nucleon cross section and an in-medium [4] nucleon-nucleon cross section for n-p, n-n and p-p elastic scattering.

The in-medium effects on fusion cross section at incident laboratory energies below 20 MeV per nucleon need more investigations both experimentally and theoretically. As a matter of fact they have a crucial importance in different fields like for example the physics of compact stars. A better understanding of the fusion process induced either by stable or radioactive beams will be especially valuable to further improve our knowledge on the nuclear interaction properties with respect to the isospin degree of freedom. The study of fusion process under conditions of decreasing proton fraction particularly deserves deeper investigations. The heating from nuclear reactions at moderate densities in the crust of compact stars should play an essential role in the temperature profiles and therefore on outstanding phenomena like the ignition of X-ray burst or neutron star cooling. It even could influence strongly the structure of the nuclear matter in the crust through the expected fusion barrier lowering, and consequently the strength of the heat capacity.

**References**

Impact of the in-medium nucleon-nucleon cross section on early-reaction-phase heavy-ion dynamics below 100 MeV/u

Z. Basrak, Ph. Eudes, F. Sébille

It has been shown theoretically [1-3] and confirmed experimentally [4-6] that heavy ion reactions (HIR) at intermediate energies, especially for central collisions, are strongly dominated by the midrapidity emission, a component which is emitted early during the dynamical reaction phase. We have shown in previous studies that this prompt and copious dynamical emission (DE) is proportional to the impact parameter b \([1,2,7]\). The prompt DE particles evacuate a large amount of available system energy. Since this emission occurs in the early compact phase of HIR, it is crucial to study details of the early transformation of the initial relative motion of the entrance reaction channel into other forms of energy.

This study has been carried out within the framework of the semi-classical Landau-Vlasov model (LV) \([8]\) with the momentum-dependent Gogny interaction D1-G1 \([9]\). In this model, \(\sigma_{NN}\) is the free nucleon-nucleon cross section with its usual energy and isospin dependence. For the sake of simplicity, \(\sigma_{NN}\) is assumed to be isotropic and density independent, an approximation which is fully justified in HIR below 100 MeV/u. The in-medium effects are taken into account by multiplying \(\sigma_{NN}\) by a corrective constant factor \(F\). In the present study, \(F\) takes the values 0.8, 1, 1.2, and 1.5.

A quantitative previous study of the main energy components that are responsible for the observed copious midrapidity emission, namely, heat and compression energy, has recently been reported \([10]\). Here, we investigate how the change of \(\sigma_{NN}\) influences the early energy transformation and, in particular, how heat and compression energy behave as a function of the factor \(F\).

Two systems were studied: \(^{36}\text{Ar} + ^{58}\text{Ni}\) and \(^{58}\text{Ni} + ^{58}\text{Ni}\) reactions at 52, 74, and 95 MeV/u (52, 74, and 90 MeV/u for the latter reaction) at all impact parameters from central to peripheral collisions. These systems have been extensively studied experimentally by the INDRA collaboration at GANIL.

Fig. 1: The value of thermal (left) and compression energy (right) maxima as a function of the factor \(F\) at 52 (open circles), 74 (full circles), and 90 MeV/u (triangles) in head-on collisions of \(^{58}\text{Ni}\) and \(^{58}\text{Ni}\) nuclei.
The results of the simulations show that the time evolution of heat $E_h$ and compression $E_{compr}$ during the early dynamical reaction phase present maxima at all incident energies. These maxima are function of the factor $F$. The dependence on $\sigma_{NN}$ is more important in the head-on regime. For other impact parameters, it is weaker and vanishes for grazing collisions. It is worth noting that $E_h$ increases with $\sigma_{NN}$ whereas $E_{compr}$ decreases. This is clearly visible in the behaviour of the above energy components maxima shown in Fig.1 for the Ni+Ni reaction. As expected, the value of the energy maxima increases with the entrance channel energy. It should be noticed that the instant at which these maxima are reached is almost independent of $\sigma_{NN}$ and decreases with increasing relative velocity of colliding nuclei. One also sees that $E_h$ reaches its maximal value a few fm/c before $E_{compr}$ reaches its.

We have also quantitatively studied the dynamical emission (DE). We defined the quantity $D_{em}$ which corresponds to the amount of charged particles emitted before $t_{sep}$ divided by the total charge of the system. $t_{sep}$ is the time at which the quasiprojectile and the quasitarget emerge and separate in the exit reaction channel.

Figure 2 shows how DE depends on the reaction centrality as a function of $\sigma_{NN}$. As a reference, shown is a curve which represents the size of the overlapping region between the target and the projectile in a fully geometrical assumption. The centrality of the reaction is expressed via the relative impact parameter. The value of DE is evidently proportional to the value of $\sigma_{NN}$. This observation may be used to constrain the factor by which the free NN cross section $\sigma_{NN}$ has to be modified in order to account for the modifications of the elementary NN scattering process caused by the presence of nuclear surroundings.

To experimentally disentangle the contribution of the so-called nuclear equation of state from the possible effects coming from the in-medium distortion of elementary free-particle scattering is an extremely difficult problem. The aim of the present work is to contribute to unravelling the very complex heavy-ion-reaction mechanisms in the intermediate energy regime by studying how the change in $\sigma_{NN}$ affects the early reaction phase, in particular the thermal and compression energy and the so-called dynamical emission.

![Figure 2](image)

**Fig. 2**: Simulation results for the evolution of dynamical emission as a function of the reduced impact parameter for the Ni+Ni reaction at 74 MeV/u as a function of $\sigma_{NN}$. Different symbols used denote different values of $F$: circles for $F=1.5$, triangles $F=1.2$, filled circles $F=1$, and diamonds $F=0.8$.

L’objectif de cette étude est d’apporter des informations sur la façon dont la section efficace nucléon-nucléon dans le milieu peut affecter les premiers instants de la collision. Nos résultats montrent que $\sigma_{NN}$ influence la façon dont se répartit l’énergie disponible au départ sous forme de compression et de chaleur. Elle a également une incidence sur la quantité de particules émises dans la phase dynamique, composante qui emporte avec elle une grande quantité d’énergie.

References
Parton collisional energy loss in a QGP

S. Peigné, A. Peshier, T. Sami

L’atténuation nucléaire des spectres hadroniques à grand $p_T$ dans les collisions d’ions lourds à haute énergie, appelée « jet-quenching », est attribuée à la perte d’énergie partonique dans le milieu chaud (le plasma de quarks et de gluons, ou QGP) créé lors de la collision. Les données de RHIC montrent qu’à grand $p_T$, le quenching est aussi important pour les saveurs lourdes que légères. Ceci est difficile à comprendre si la perte d’énergie partonique est, comme on le pense, principalement radiative, et plus petite pour les saveurs lourdes du fait de l’effet de « cône mort » (« dead cone effect »). Dans ce contexte, il est important de réexaminer la perte d’énergie due aux collisions élastiques. Bien qu’il soit difficile de voir comment cette contribution pourrait augmenter le quenching des saveurs lourdes sans simultanément augmenter celui des saveurs légères, il est crucial, du point de vue théorique, d’établir les formules correctes pour la perte d’énergie collisionnelle d’un quark lourd.

At the Relativistic Heavy Ion Collider (RHIC), the $p_T$ spectrum of light hadrons has been observed [1] to be strongly suppressed in central ultrarelativistic heavy-ion collisions, as compared to proton-proton (pp) collisions. This is illustrated by the suppression factor $R_{AA}$ to be much smaller than unity. For pions $R_{AA} \approx 0.2$ for $p_T > 0.4$ GeV. This nuclear attenuation of hadron production has been quoted as jet-quenching, and is one of the most important signals for the new state of matter — referred to below as a quark-gluon plasma or QGP — produced in a (central) heavy-ion collision.

The effect of jet-quenching was anticipated by Bjorken [2], as a consequence of medium-induced partonic energy loss in the QGP. Although Bjorken illustrated his idea by performing an estimate of the collisional loss of light partons, parton energy loss generally arises from both collisional and radiative processes. In fact, for a parton energy $E >> M, T$, where $M$ is the parton mass and $T$ the plasma temperature, the radiative component is believed to be dominant, due to either its dependence on $E$ at large medium size $L$ [3], or to its proportionality to $L^2$ at small $L$ [4]. Thus it seems legitimate to neglect collisional losses in phenomenological studies of light hadron quenching, and to attribute hadron quenching solely to the radiative energy loss.

The data on heavy flavour quenching [5], obtained indirectly by observing the electrons and positrons arising from D and B meson semi-leptonic decays, show that the nuclear attenuation of heavy c and b quarks is as strong as that of light partons. This is difficult to explain when assuming that heavy quarks, similarly to light partons, lose energy dominantly through radiation. Indeed, for heavy quarks, gluon radiation at an angle $\theta_{\text{rad}}<M/p_T$ is suppressed [6]. This is the so-called dead cone effect, leading to a strong suppression (at not too large $p_T$), of the average radiative loss of a heavy quark compared to a light parton,

$$\Delta E_{\text{rad}}(b) < \Delta E_{\text{rad}}(c) < \Delta E_{\text{rad}}(q,g) .$$

If the electrons and positrons from heavy flavour decays observed in the experiment would arise dominantly from D mesons, then the dead cone effect would not be too drastic, due the moderate value of the charm quark mass. In this case explaining the heavy flavour quenching with purely radiative c quark energy loss might still be possible [7]. However, the relative contributions from D and B decays are likely to be of the same order, as in pp collisions [8]. The dead cone effect being stronger for b than for c quarks, this leads to a reduction of the effective radiative loss. Hence, with similar c and b contributions, the current models tend to underestimate heavy flavour quenching.

Thus for heavy quarks, purely radiative energy loss seems insufficient to explain the observed attenuation. This has renewed the interest in the collisional part $\Delta E_{\text{coll}}$ of the parton energy loss. Could the collisional loss be much larger for a heavy quark than for a light parton, which would increase heavy flavour quenching without spoiling the reasonably good description of light hadron quenching with purely radiative loss?
We have reconsidered the average collisional loss of a heavy fermion, both in QED [9] and in QCD [10]. Our QCD result for a fast heavy quark \( Q = c, b \) includes the effect of the running coupling and is thus fully predictive. Since the very definition of parton energy loss is different in the tagged heavy quark case and in the untagged light parton case [11], the heavy quark collisional loss contains an additional term — a collinear logarithm \( \sim \log(\mathcal{E}/M^2) \) arising in the limit \( \mathcal{E} \gg M^2/T \) from u-channel exchange — which had been previously overlooked. This term makes the heavy quark collisional loss slightly larger than the light quark loss, but is however small compared to the well-known soft logarithm \( \sim \log(\mathcal{E}/m_D^2) \) (\( m_D \) being the Debye mass of the QGP) arising from t-channel scattering. Hence:

\[
E > M^2/T \Rightarrow \Delta E_{\text{coll}}(Q = c, b) \approx \Delta E_{\text{coll}}(q = u, d, s) .
\]

We stress that the latter estimate holds in the ultra-high energy limit \( E > M^2/T \). However, taking \( E(Q) \sim p_T \sim 20 \text{ GeV} \), and \( T \sim 200 \text{ MeV} \), we see that the data of Ref. [5] correspond to the region \( E > M^2/T \) for the c quark, but not for the b quark for which \( E \ll M^2/T \). Since \( \Delta E_{\text{coll}}(Q) \) is an increasing function of \( E \) we must have \( M_b/T \gg E \gg M_c/T \Rightarrow \Delta E_{\text{coll}}(b) < \Delta E_{\text{coll}}(c) \).

Thus under the present RHIC experimental conditions we expect both collisional and radiative contributions to the b quark energy loss to be suppressed compared to the c (and light quark) case. In this respect the observed strong heavy flavour quenching, with an important contribution from b quarks, remains a puzzle. This conclusion should however be considered as preliminary. Indeed, an average loss smaller for b than for light quarks is a priori not incompatible with heavy and light flavour quenching being of similar magnitudes, due to the different energy loss probability distributions in both cases.

Finally, we stress that in phenomenological studies of jet-quenching, parton collisional loss should not be added independently to the radiative loss. For instance, at small \( L \) the light quark radiative loss reads [4]

\[
\Delta E_{\text{rad}} \sim \alpha_s \hat{q} L^1 ,
\]

where \( \hat{q} \) is the transverse momentum squared transferred per unit length to the fast parton. From the simple relation [12]

\[
\hat{q} = 3.4 T \left( \frac{dE_{\text{coll}}}{dx} \right) ,
\]

we infer that at small \( L \) we have

\[
\Delta E_{\text{rad}}(q) / \Delta E_{\text{coll}}(q) \approx 3.4 \alpha_s L T .
\]

Radiative and collisional losses are not independent. This is quite intuitive, radiative losses being induced by elastic collisions.

Le plasma de quarks et de gluons (QGP), état de la matière prédit par la théorie des interactions fortes, peut être produit dans les collisions d'ions lourds ultrarelativistes. Un des « signaux » essentiel de QGP est l'atténuation des jets hadroniques (jet-quenching) due à l'énergie perdue par les partons (= quarks et gluons) produits dans la collision d'ions lourds, du fait de leur passage à travers le plasma.

Bien que la perte d'énergie partonique explique qualitativement le phénomène observé de jet-quenching, une compréhension quantitative fait encore défaut. Le calcul théorique de la perte d'énergie partonique, même dans un cadre idéal (où le QGP est supposé à l'équilibre), n'est en effet pas clos.

Dans cet article nous discutons la perte d'énergie collisionnelle d'un quark lourd, et présentons une relation simple entre perte collisionnelle et perte radiative dans le cas d'un quark léger.

Liquid drop model mass formula and nuclear radius

G. Royer, C. Gautier

Les coefficients de différentes formules de masse dérivées du modèle de la goutte liquide ont été déterminés par un ajustement sur 2027 noyaux. Les masses peuvent être reproduites avec un écart-type de 0.6 MeV. Différentes expressions permettant de calculer le rayon nucléaire ont été ajustées à partir de 782 rayons de charge expérimentaux. La proportionnalité à $A^{1/3}$ donne $R = 1.2257 A^{1/3}$ fm.

To predict the stability of new nuclides in the superheavy element region and the regions close to the proton and neutron drip lines continuous efforts are needed to determine the nuclear masses of such exotic nuclei and then their binding energies. Within a modelling of the nucleus by a charged liquid drop, semi-macroscopic models including a pairing energy have been firstly developed to reproduce the experimental masses. To reproduce the non-smooth behaviour of the masses (due to the magic number proximity, parity of the proton and neutron numbers,...), macro-microscopic approaches have been formulated, mainly the finite-range liquid drop model and droplet. Nuclear masses have also been obtained accurately within the statistical Thomas-Fermi model with an effective interaction. Microscopic Hartree-Fock self-consistent calculations using mean-fields and Skyrme or Gogny forces and pairing correlations as well as relativistic mean field theories have also been developed to describe these nuclear masses.

The experimental binding energy may be derived from the experimental atomic masses [1]. The fission and fusion potential barriers are governed by the evolution of this nuclear binding energy with deformation. Four basic terms are sufficient to describe roughly these barriers: the volume, surface, Coulomb and nuclear proximity energy terms while the introduction of the shell and pairing energy terms is needed to explain structure effects and improve quantitatively the results. Other terms have been proposed to determine more accurately the binding energy: the curvature, $A^{0}$, proton form factor correction, Coulomb exchange correction and Wigner terms.

Different subsets of the following expansion of the nuclear binding energy have been considered [2,3]

$$B_{\text{nucl}}(A,Z) = a_v (1 - k_v I) A^{2/3} - a_s (1 - k_s I) A^{1/3} - a_k (1 - k_k I) A^{1/3} - a_0 A^{0} - 0.6 e^2 Z^2 / R_0 + f_p Z^2 / A + a_{c, \text{exc}} Z^{4/3} / A^{1/3} - E_{\text{pair}} - E_{\text{shell}} - E_{\text{Wigner}}.$$ 

The first term is the volume energy and corresponds to the saturated exchange force and infinite nuclear matter. In this form it includes the asymmetry energy term of the Bethe-Weizsäcker mass formula via the relative neutron excess $I = (N - Z) / A$. The second term is the surface energy term. It takes into account the deficit of binding energy of the nucleons at the nuclear surface. The dependence on $I$ is not considered in the Bethe-Weizsäcker mass formula. The third term is the Coulomb energy. It gives the loss of binding energy due to the repulsion between the protons. The curvature energy in $A^{1/3}$ is a correction to the surface energy appearing when the surface energy is considered as a function of the mean local curvature. The $a_0 A^0$ term appears when the surface term is extended to include higher order terms in $A^{1/3}$ and $I$. The three other Coulomb terms are respectively the usual Coulomb energy, the proton form-factor correction to the Coulomb energy which takes into account the finite size of the protons and the charge exchange correction term. The theoretical shell and pairing effects given by the Thomas-Fermi model have been selected. The last term is the Wigner energy which appears in the counting of identical pairs. The coefficients have been determined by a least square fitting procedure to the 2027 experimental atomic masses.
verifying the two conditions: N and Z higher than 7 and the uncertainty on the mass lower than 150 keV. The nuclear proximity energy term does not appear since its effect is not effective around the ground state. The root-mean-square deviation between the experimental and theoretical masses has been used to compare the different selected sets of terms.

To follow the non smooth variation of the nuclear masses with A and Z the introduction of the shell energy is obviously needed as well as that of the pairing term though its effect is smaller. The proton form factor or the charge exchange correction plays the main role to improve the accuracy of the mass formula. The curvature energy and the Wigner term have separately a strong effect in the decrease of $\sigma$ but their coefficients are very unstable. The introduction of an III dependence in the surface and volume energies improves slightly the efficiency of the expansion and is more effective than an $I^4$ dependence. A value of $\sigma = 0.60$ MeV can be reached while $a_s$ is around 15.5 MeV and $a_v=17-18$ MeV. The figure shows that the difference between the theoretical and experimental masses can be lower than 2.25 MeV and less than 1.15 MeV when $A$ is higher than 100.

**Fig. 1:** Difference between the theoretical and experimental masses for 2027 nuclei.

The coefficients of the used different formulas given the nuclear radius have been fitted on 782 ground state nuclear charge radii allowing to obtain $\sigma = 0.052$ fm for the most precise formula. The simple proportionality to $A^{1/3}$ leads to $R = 1.2257 A^{1/3}$ fm.

Pour prédire l’existence des noyaux exotiques et superlourds il est nécessaire de déterminer précisément l’énergie de liaison de ces noyaux et donc d’avoir une formule de masse nucléaire très fiable pour faire des prédictions crédibles. Les modèles purement microscopiques donnent lieu à des calculs très longs et il est difficile alors d’ajuster les coefficients sur les 2000 masses nucléaires précisément connues. Aussi les modèles macro-microscopiques de type goutte liquide avec corrections de couches et d’appariement sont les plus utilisés. Les valeurs des coefficients varient beaucoup d’un modèle à l’autre; par exemple le coefficient de surface varie de 16 MeV à 21 MeV selon les versions. Le nombre de paramètres ajustables varie beaucoup aussi.

Différentes formes possibles de la formule de masse nucléaire ont été étudiées. En plus des termes indispensables d’énergie de volume, de surface, d’énergie Coulombienne et des effets de couches et d’appariement, ces formules contiennent ou non des termes de courbure, de Wigner, de congruence, de facteur de forme du proton, de correction d’échanges de charges ou différentes puissances de l’excès de neutron relatif $(I=N-Z/A)$. Le coefficient $a_s$ de l’énergie de surface demeure toujours proche de 17-18 MeV et $r_0$ voisin de 1.22-1.23 fm.

L’écart-type entre les masses expérimentales et théoriques peut être inférieur à 0.6 MeV quand on prend en compte assez de termes. Les deux termes Coulombiens additionnels jouent un rôle essentiel et identique pour améliorer la précision. La courbure et le terme de Wigner permettent aussi l’amélioration de la précision mais leurs coefficients sont très instables. Le terme en $|I|$ n’améliore que légèrement la précision et le terme en $I^4$ encore moins.

Indépendamment, différentes formules reproduisant le rayon nucléaire ont été ajustées sur 782 données expérimentales. La plus simple $R=r_0A^{1/3}$ donne $r_0=1.2257$ fm, en très bon accord avec la valeur déduite des masses nucléaires. Cela remet sans doute en cause les valeurs comprises entre 1.12 et 1.18 fm utilisées dans certains modèles bien que l’hypothèse utilisée d’un noyau de densité constante et à bord abrupt soit très simpliste.

Alpha-decay half-lives and predictions for the superheavy nuclei

G. Royer, H. F. Zhang

The $\alpha$ decay process has been described within a quantum tunneling through the potential barrier determined from a generalized liquid drop model including the proximity effects between the $\alpha$ particle and its daughter nucleus and adjusted to reproduced the experimental Q value. The $\alpha$ emission half-lives were deduced from the WKB barrier penetration probability as for a spontaneous asymmetric fission with a constant assault frequency and no preformation factor [1]. The rms deviation between the theoretical and experimental values of $\log_{10}[T_{\alpha}]$ was only 0.63 for a data set of 373 emitters having an $\alpha$ branching ratio close to one and 0.35 for the subset of 131 even-even nuclides. A fitting procedure led to the following empirical formulas respectively for the 131 even(Z)-even(N), 106 even-odd, 86 odd-even and 50 odd-odd nuclei. A and Z are the mass and charge numbers of the mother nucleus.

\[
\log_{10}[T_{1/2} (s)] = -25.31 - 1.1629 A^{1/6} \sqrt{Z} + \frac{1.5864Z}{\sqrt{Q_\alpha}}.
\]

\[
\log_{10}[T_{1/2} (s)] = -26.65 - 1.0859 A^{1/6} \sqrt{Z} + \frac{1.5848Z}{\sqrt{Q_\alpha}}.
\]

\[
\log_{10}[T_{1/2} (s)] = -25.68 - 1.1423 A^{1/6} \sqrt{Z} + \frac{1.592Z}{\sqrt{Q_\alpha}}.
\]

\[
\log_{10}[T_{1/2} (s)] = -29.48 - 1.113 A^{1/6} \sqrt{Z} + \frac{1.6971Z}{\sqrt{Q_\alpha}}.
\]

The rms deviation are respectively 0.285, 0.39, 0.36 and 0.35.

New $\alpha$ decay half-lives have been obtained recently and the predictions derived from the formulas are compared in the first table with the experimental data. The good agreement confirms the accuracy of the formulas and their usefulness for new predictions.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$Q_{\alpha,exp}$ (MeV)</th>
<th>$T_{1/2}$ exp (s)</th>
<th>$T_{1/2}$form. (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{105}$Te</td>
<td>4.9</td>
<td>$0.7 \times 10^{-6}$</td>
<td>$0.37 \times 10^{-6}$</td>
</tr>
<tr>
<td>$^{152}$Er</td>
<td>3.49</td>
<td>$2.3 \times 10^{-10}$</td>
<td>$1.6 \times 10^{-10}$</td>
</tr>
<tr>
<td>$^{176}$W</td>
<td>4.51</td>
<td>$1.6 \times 10^{-6}$</td>
<td>$3.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>$^{185}$Hg</td>
<td>7.52</td>
<td>$4.2 \times 10^{-4}$</td>
<td>$2.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{185}$Hg</td>
<td>4.71</td>
<td>$5.3 \times 10^{8}$</td>
<td>$2.0 \times 10^{8}$</td>
</tr>
<tr>
<td>$^{172}$Pb</td>
<td>7.79</td>
<td>$2.3 \times 10^{-4}$</td>
<td>$2.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{172}$Pb</td>
<td>5.22</td>
<td>$3.6 \times 10^{6}$</td>
<td>$2.1 \times 10^{6}$</td>
</tr>
<tr>
<td>$^{195}$Po</td>
<td>7.69</td>
<td>$2.5 \times 10^{-3}$</td>
<td>$1.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$^{208}$Po</td>
<td>5.41</td>
<td>$1.2 \times 10^{7}$</td>
<td>$1.0 \times 10^{7}$</td>
</tr>
<tr>
<td>$^{195}$Rn</td>
<td>7.35</td>
<td>$6.5 \times 10^{-2}$</td>
<td>$9.6 \times 10^{-2}$</td>
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<tr>
<td>$^{205}$Ra</td>
<td>7.64</td>
<td>$5.9 \times 10^{-2}$</td>
<td>$5.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>$^{210}$Th</td>
<td>8.05</td>
<td>$1.7 \times 10^{-2}$</td>
<td>$1.3 \times 10^{-2}$</td>
</tr>
<tr>
<td>$^{220}$U</td>
<td>10.3</td>
<td>$6.0 \times 10^{-8}$</td>
<td>$5.8 \times 10^{-8}$</td>
</tr>
<tr>
<td>$^{238}$Cm</td>
<td>6.62</td>
<td>$2.3 \times 10^{5}$</td>
<td>$3.3 \times 10^{5}$</td>
</tr>
<tr>
<td>$^{252}$Hs</td>
<td>9.02</td>
<td>$2.2 \times 10^{1}$</td>
<td>$1.03 \times 10^{1}$</td>
</tr>
</tbody>
</table>

The second table focuses on the heaviest nuclei for which the uncertainties both on the experimental Q value and $\alpha$ decay half-lives are larger because only some $\alpha$ cascades have been observed [2-3].

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$Q_{\alpha,exp}$ (MeV)</th>
<th>$T_{1/2}$ exp (s)</th>
<th>$T_{1/2}$form. (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{298}$118</td>
<td>11.8 MeV</td>
<td>1.8 ms</td>
<td>0.39 ms</td>
</tr>
<tr>
<td>$^{299}$116</td>
<td>10.67</td>
<td>53 ms</td>
<td>308 ms</td>
</tr>
<tr>
<td>$^{300}$116</td>
<td>10.80</td>
<td>18 ms</td>
<td>27 ms</td>
</tr>
</tbody>
</table>
Thus predictions of the partial $\alpha$ decay half-lives of still unknown superheavy nuclei within the formulas seem reliable [4-5] and are displayed in the last table. The assumed $\alpha$ decay energies are calculated from the atomic mass evaluation of Audi, Wapstra and Thibault [6].

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$Q$ (MeV)</th>
<th>$T_{1/2\text{ GLDM}}$</th>
<th>$T_{1/2\text{formula}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{293}_{118}$</td>
<td>12.3</td>
<td>77 $\mu$s</td>
<td>187 $\mu$s</td>
</tr>
<tr>
<td>$^{292}_{117}$</td>
<td>11.6</td>
<td>1.3 ms</td>
<td>6.47 ms</td>
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<td>$^{291}_{115}$</td>
<td>10.00</td>
<td>4.33 s</td>
<td>4.8 s</td>
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<tr>
<td>$^{290}_{113}$</td>
<td>9.34</td>
<td>102 s</td>
<td>99.4 s</td>
</tr>
<tr>
<td>$^{289}_{112}$</td>
<td>9.3</td>
<td>64.7 s</td>
<td>25.1 s</td>
</tr>
<tr>
<td>Rg</td>
<td>8.96</td>
<td>6.01 min</td>
<td>5.5 min</td>
</tr>
<tr>
<td>Ds</td>
<td>8.96</td>
<td>3.05 min</td>
<td>4.6 min</td>
</tr>
<tr>
<td>Mt</td>
<td>8.7</td>
<td>10.35 min</td>
<td>7.72 min</td>
</tr>
<tr>
<td>Hs</td>
<td>8.4</td>
<td>49.7 min</td>
<td>65.2 min</td>
</tr>
<tr>
<td>Bh</td>
<td>8.5</td>
<td>9.94 min</td>
<td>48.4 min</td>
</tr>
</tbody>
</table>

The preformation factor of the $\alpha$ particle in the different nuclei has been extracted from the data [7] and it has been found that the more the nucleon number is close to the magic numbers, the more the formation of $\alpha$ cluster is difficult inside the mother nucleus.


Ternary cluster decay of hyper-deformed $^{56}$Ni and $^{60}$Zn nuclei at high angular momenta

G. Royer, W. von Oertzen, C. Beck

Deux expériences conduisant à la formation des noyaux $^{56}$Ni et $^{60}$Zn ont été analysées. Des corrélations hors plan ont été observées dans les voies de sortie binaire et ternaire. Les barrières de potentiel décrivant ces fissions binaires et ternaires ont été calculées dans le cadre d’un modèle de la goutte liquide généralisé. Pour de faibles moments angulaires, la fission ternaire semble exclue. La fission ternaire devient compétitive par rapport à la fission binaire aux grands moments angulaires (45-52 $\hbar$). La désintégration en trois fragments des noyaux $^{56}$Ni et $^{60}$Zn indique la formation de noyaux hyperdéformés à grands moments angulaires.

Two experiments have been performed with a binary reaction spectrometer in combination with $\gamma$-detector arrays, the first at the HMI (Berlin) with a $^{36}$Ar beam of 195 MeV on a $^{24}$Mg target and the second with a $^{32}$S beam of 165.3 MeV at the VIVITRON accelerator of the IRES (Strasbourg) [1-2]. It was possible to measure two heavy fragments in coincidence with respect to their in-plane and out-of-plane scattering angles, time of flight and energy. For binary exit channels with two excited heavy fragments which evaporate particles, very broad out-of-plane distributions have been observed. These events have the largest cross section. In addition narrow out-of-plane correlations are observed in binary channels and ternary events with larger missing charges. Using the out-of-plane correlations the exclusive differential cross sections for broad and narrow components have been extracted. Both the binary and the coplanar ternary decays are characterised by the number of missing $\alpha$-particles. Quite remarkable odd-even effect is observed in the yields, which is a clear indication of a statistical decay from an equilibrated compound nucleus. From general kinematic considerations it can be concluded that the ternary fission process occurs from a stretched configuration and the decay is collinear.

The potential barriers governing the binary and ternary fission have been calculated within a generalised liquid drop model taking into account both the asymmetry and the proximity effects between the nascent fragments. For the binary and ternary fission the saddle-point of the macroscopic potential barriers corresponds always to two separated fragments maintained in unstable equilibrium by the balance between the repulsive Coulomb forces and the attractive proximity forces (see Figs. 1 and 2). The ternary fission barrier height increases with the symmetry of the decay. At low angular momenta the ternary fission seems excluded. The saddle-point for the ternary fission corresponds to very high moment of inertia and, as a consequence, the rotational energy is much weaker than the binary one at high angular momenta (45-52 $\hbar$) and the ternary fission.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Barrier heights (MeV)</th>
<th>Barrier heights (MeV)</th>
<th>$Q$ (MeV)</th>
</tr>
</thead>
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<td>$^{32}$S+$^{40}$Si</td>
<td>39.5</td>
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</tr>
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<td>$^{30}$P+$^{30}$P</td>
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<td>77.6</td>
<td>-3.76</td>
</tr>
<tr>
<td>$^{30}$Si+$^{28}$Si</td>
<td>40.9</td>
<td>55.2</td>
<td>-6.64</td>
</tr>
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<td>$^{28}$Al+$^{28}$Al</td>
<td>66.2</td>
<td>79.4</td>
<td>-24.59</td>
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<td>$^{28}$Si+$^{28}$Mg</td>
<td>55.3</td>
<td>68.5</td>
<td>-13.58</td>
</tr>
<tr>
<td>$^{24}$Mg+$^{3}$Mg</td>
<td>61.2</td>
<td>74.4</td>
<td>-23.57</td>
</tr>
</tbody>
</table>
Deux expériences conduisant à la formation des noyaux $^{60}$Zn et $^{56}$Ni ont été réalisées. La 1ère au HMI de Berlin utilisait un faisceau $^{36}$Ar de 195 MeV et une cible de $^{24}$Mg. La 2ème utilisait un faisceau de $^{32}$S de 165.3 MeV au Vivitron de Strasbourg [1-2]. Deux fragments lourds étaient détectés en coincidence dans le plan ou en dehors du plan de diffusion. Les sections efficaces des différentes voies de fission avec différentes pertes de charge ont été obtenues. Des étroites corrélations hors plan ont été observées dans les voies de sortie binaires et des voies où la charge manquante fait penser à une fission ternaire. Cette charge manquante indique que des clusters d’un, deux, trois ou quatre particules alpha ont été émis. Un effet pair-impair remarquable a été observé ce qui indique clairement qu’un noyau composé a bien été formé et qu’il s’est désintégré de façon statistique.

Les barrières de potentiel décrivant ces fissions binaires et ternaires ont été calculées dans le cadre d’un modèle de la goutte liquide généralisé prenant en compte les effets de proximité nucléaire entre les fragments naissants. Pour la fission binaire et ternaire le point-selle de la barrière correspond à deux fragments séparés mantenus en équilibre instable par la balance entre les forces Coulombiennes répulsives et les forces de proximité nucléaire attractives. Pour de faibles moments angulaires la fission ternaire semble exclue. Le point-selle pour la fission ternaire correspond à de grands moments d’inertie si bien qu’aux grands moments angulaires (45-52 $\hbar$) l’énergie de rotation est beaucoup plus faible que dans le cas binaire et la fission ternaire devient compétitive par rapport à la fission binaire ; l’état d’équilibre ayant même une énergie plus basse que dans le cas binaire même si le Q de réaction est plus défavorable [3-4].

En conclusion la désintégration en trois fragments des noyaux $^{56}$Ni et $^{60}$Zn est la signature de la formation de configurations nucléaires hyperdéformés à grands moments angulaires.

As a conclusion the ternary cluster decay observed in the present N = Z nuclei $^{56}$Ni and $^{60}$Zn is a signature of the formation of nuclear hyperdeformed configurations energetically favoured at high angular momenta. In these states a strong clusterisation into $\alpha$-clusters is predicted, giving rise to ternary cluster decay.


Toward an understanding of the RHIC single non photonic electron data

P.B. Gossiaux, J. Aichelin

High transverse momentum ($p_T$) single non-photonic electrons which have been measured in the RHIC experiments come Dominantly from heavy meson decay. The ratio of their $p_T$ spectra in pp and AA collisions ($R_{AA}(p_T)$) reveals the energy loss of heavy quarks in the environment created by AA collisions. Using a fixed coupling constant and the Debye mass ($m_D = gT$) as Infrared regulator perturbative QCD (pQCD) calculations are not able to reproduce the data, neither the energy loss nor the azimuthal ($v_2$) distribution. Employing a running coupling constant and replacing the Debye mass by a more realistic hard thermal loop (HTL) calculation we find a substantial increase of the collisional energy loss which brings the $v_2(p_T)$ distribution as well as $R_{AA}(p_T)$ to values close to the experimental ones without excluding a contribution from radiative energy loss.

The model to describe the momentum spectra of heavy quarks or heavy mesons produced in ultrarelativistic heavy ion collisions has three major parts which we will describe one after the other: 1) the initial distributions of the heavy quarks, 2) the description of the expanding quark gluon plasma and 3) the interaction of the heavy quarks with the plasma. For the momentum space distribution as well as for the relative contribution of charmed and bottom quarks we use the pQCD results in fixed order + next to leading logarithm (FONLL) of Cacciari et al [1]. The heavy quarks are isotropically distributed in azimuthal direction and therefore their $v_2$ is zero. Any observed anisotropy of heavy meson is due to the interaction of their constituents with the medium, and can therefore be used to reveal the strength of this interaction. In coordinate space the initial distribution of the heavy quarks is given by a Glauber calculation. The expanding plasma is described by a hydrodynamical approach. We use the boost invariant model of Heinz and Kolb which has been described in detail in [2]. This model reproduces a variety of experimental findings. Corresponding to two different equations of state this approach allows to calculate two distinct scenarios of the expansion. Here we use the approach with a mixed phase.

The novelty of the approach is the description of the interaction between the heavy quarks and the plasma. As compared to former pQCD calculations we have introduced a) An effective running coupling constant, $\alpha_{\text{eff}}(Q^2)$, determined from electron positron annihilation and non leptonic decay of $\tau$ leptons. b) A infrared regulator in the t channel which is adjusted to give the same energy loss as calculated in a hard thermal loop approach. We find a substantial increase of the collisional energy loss which brings the $v_2(p_T)$ distribution as well as $R_{AA}(p_T)$ to values close to the experimental ones without excluding a contribution from radiative energy loss.
Fig. 1: Comparison of the experimental and theoretical results for $R_{AA}$ for central Au+Au collisions. We display $v_2$ of single non-photonic $e^-$ as a function of the heavy quark momentum $p_T$. The purple line shows $R_{AA}$ for $e^-$ from B-meson and the red line that of D-meson decay for the K values indicated in the figure. The blue line is the sum of both. We assumed hadronization at the end of the mixed phase on the right hand side at the end of the mixed phase.

The results for $R_{AA}$ in central Au+Au collisions are compared to the experimental data in fig. 1. For a constant coupling constant and the Debye mass as IR regulator one has to employ K-factors of the order of 10-12. The combination of both new ingredients of our model, the running coupling constant and the new infrared regulator brings the K factor close to an acceptable value of 1-2, leaving nevertheless still room for radiative energy loss. Also for minimum bias events we can observe that the new model reproduces quite well the experimental $R_{AA}(p_T)$ distribution as may be inferred from fig.2.

Fig. 2: Comparison of the experimental and theoretical results for $R_{AA}$ for minimum bias Au+Au collisions. We display $v_2$ of single non-photonic $e^-$ as a function of the heavy quark momentum $p_T$. The purple line shows $R_{AA}$ for $e^-$ from B-meson and the red line that of D-meson decay for the K values indicated in the figure. The blue line is the sum of both. We assumed hadronization at the end of the mixed phase on the right hand side at the end of the mixed phase.

In conclusion, this new approach shows that collisional energy loss is most likely to play a substantial role in the equilibration of heavy quarks with the medium formed at RHIC (provided coupling constant and infrared regulator are properly adjusted) and that the present single non photonic $e^-$ data could be well described using pQCD calculation that would include both collisional and radiative contributions.


Theory
Bimodality

A. Le Fèvre, J. Aichelin

Recently, the INDRA collaboration has discovered [1] that, in collisions of heavy ions - Xe+Sn and Au+Au between 60 and 100 A.MeV incident energy --, in a small interval of the total transverse energy of light charged particles (Z< 2), ET, a quantity which is usually considered as a good measure for the centrality of the reaction, two distinct reaction scenarios exist. In this ET interval, in forward direction -- i.e. quasi-projectile --, either a heavy residue is formed which emits light charged particles only, or the system fragments into several intermediate mass fragments. This phenomenon has been named "bimodality". In addition, as shown in [1], the mean ET value of this transition interval scales with the projectile energy in the center of mass of the system for Au+Au reactions, between 60 A.MeV and 150 A.MeV. This observation has created a lot of attention because it could be interpreted as a sign that in a heavy ion reaction a first order phase transition can be observed [2].

In order to verify whether bimodality is a 'smoking gun' signal for a first order phase transition in a finite system, we have performed numerical simulations with one of the dynamical models which has frequently been used to interpret the multifragmentation observables, the Quantum Molecular Dynamics (QMD) approach [3,4]. This approach simulates the entire heavy ion reaction, from the initial separation of projectile and target up to the final state, composed of fragments and single nucleons. Here, nucleons interact by mutual density dependent two body interactions and by collisions.

To quantify the bimodality, one may define as in [1] \( a_2 = \frac{Z_{\text{max}} - Z_{\text{max}-1}}{Z_{\text{max}} + Z_{\text{max}-1}} \) where \( Z_{\text{max}} \) is the charge of the largest fragment, while \( Z_{\text{max}-1} \) is the charge of the second largest fragment, both observed in the same event in the forward hemisphere.

In QMD [5] bimodality has nothing to do with the final state interaction. Whether we find a multifragmentation or a heavy residue event is determined when projectile and target nucleons still overlap almost completely in coordinate space [4].

One may conjecture that, due to the random character of the scattering angle, events with the same ET decelerate differently, and, therefore, a different behavior of the average momenta may be at the origin of the different \( a_2 \) values. For this purpose, we study with Au+Au at 150 A.MeV incident energy, at 60 fm/c, when \( a_2 \) is decided, the dependence with the final \( a_2 \) of the average momentum of all target nucleons which are at the end entrained in A>4 fragments. We find no dependence(fig.2)
Fig. 1: Top: most probable value of $a_2$ in the quasi-projectile angular range $\theta_{\text{cm}} < 90^\circ$ as a function of the total transverse energy $ET$ in the quasi-target angular range $\theta_{\text{cm}} > 90^\circ$, scaled by $E_{\text{cm}}$, the energy per nucleon of the system in the center of mass. We display INDRA experimental results (left panels) extracted from [1] and QMD simulations [5] (right panels) for the Au+Au collisions at three different bombarding energies. Bottom: differential reaction cross-section (linear color scale, arbitrary unit) of $a_2$ as a function of $ET$, in the transition region, for Au+Au at 100 A.MeV incident energy. We show the INDRA experimental data and the filtered QMD simulations (left and right panels respectively). As in [1], for calculating $a_2$, in both experimental and QMD results, it is required that at least 80 % of the total charge of the projectile is detected by the INDRA set-up in the forward hemisphere.

It is interesting to see the differences and similarities of the origin of bifurcation in a statistical model as compared to the analysis of QMD events. In both cases, the energy is the essential quantity. In the statistical model, there is, for a given number of nucleons in a given volume, a small range of total energies for which the number of micro-states with one residue is of the same order of magnitude as the number of micro-states with many fragments. (In order to count the micro-states, it is assumed that the fragments are in one if their eigenstates, sometimes parameterized by a level density formula.) In this energy range, bimodality appears as a global property of the systems which is dependent on the total energy of all nucleons present in the reaction. In QMD events, the essential quantity is the total binding energy of the nucleons bound in medium size or large clusters. As explained above, in the transition region, this energy is almost identical for a multifragment and for a residue configuration. Therefore, both configurations appear, and we see bimodality. The fragments are not in the ground state, their nucleons are not isotropic neither in coordinate space nor in momentum space. Thus, bimodality is a local quantity in QMD simulations, depending only on the total binding energy of a subset of the nucleons. Therefore, in QMD, bimodality makes no reference to a statistical or thermal equilibrium, neither of the system nor of the population of the excited states of the fragments.

Fig. 2: QMD simulations of Au+Au at 150 A.MeV incident energy, at 60 fm/c: differential cross-section (colored contour levels, linear scaled) of the longitudinal (left) and transverse momentum (right) of all nucleons which are finally entrained in a fragment of size $A > 4$ as a function of final (at 200 fm/c) $a_2$. The symbols represent the mean values of momentum.

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Modelling an expanding plasma in the Nambu Jona-Lasinio approach

F. Gastineau, L. Gerland, J. Aichelin

Lattice gauge calculations predict that at high density/high temperature a new state of matter, a plasma of quarks and gluons (QGP), is formed. In the detectors, however, only hadrons are observed. Hadronic matter is separated from the QGP by a confinement/chiral phase transition. If one wants to learn something about the properties of the new state of matter, it is therefore necessary to understand how the system passes this phase transition and which information the hadrons carry about the plasma phase. This information is also highly desirable because, up to now, the dynamics of the entire reaction is not well understood. Hydrodynamical models describe many details of the reaction but have to assume that the system reaches a state of local equilibrium very fast. This is not understandable in terms of the perturbative cross-section, which should be applicable for the entrance channel and which predicts a much slower equilibration. Therefore, it is worth using another phenomenological model, the Nambu Jona-Lasinio (NJL) model [1], which has been shown to be quite successful in regions where it can be compared with QCD. In its SU (3) version and supplemented by a t’Hooft determinant, the NJL Lagrangian has the same symmetries as that of the QCD. These symmetries are known to be the basis of many properties of quark and hadronic matter. They allow meson masses to be described at low density and low temperature and provide a simple approach to study the chiral phase transition. It also predicts the tricritical point in the r-T phase diagram, which has recently been discovered by lattice QCD calculations [2].

We use this Lagrangian to investigate three topics:
1) Does it predict the colour-flavour locked states for low temperature high-density matter? In ref. [3], we have shown that this state is indeed produced as predicted by pQCD and that the condensates are of the order of a hundred MeV. This observation may have important consequences for the interior of neutron stars.

2) How do baryons behave at finite temperature/finite density? [4]. In the NJL approach, baryons are made from diquarks and quarks, bound by the exchange of quarks between both. If one concentrates on the dominant scalar diquarks, one obtains the baryon masses as a function of the temperature and for $\mu=0$. They are shown in Fig. 1.

![Fig. 1: Masses of hyperons and the proton as a function of the temperature for $\mu=0$. The dotted lines give the sum of the masses of the diquarks and the quarks.](image)
We see that baryons exist up to the critical temperature, which in our model is around $T = 225$ MeV but they change their mass considerably. A similar behaviour is observed for the mass as a function of the chemical potential for $T=0$.

3) One of the current central questions is why the quark gluon matter reaches equilibrium in a very short time. This is concluded from the comparison of hydrodynamical calculations with the experimental results. pQCD cross-sections would require a much longer time for the system to come to equilibrium.

Using the NJL model, we have shown that, due to the interplay between the quark and meson masses (see Fig. 2) close to the chiral phase transition, the system may develop a critical opacity [5] where all s-channel transition rates become very large. This is true for the elastic (see Fig. 3) as well as for the hadronization cross-sections (Fig. 4).

These large cross-sections equilibrate very efficiently the expanding plasma (which is here more a liquid than a plasma) and create a gas of mesons (see Fig. 5) although confinement is absent in the NJL Lagrangian [5]. Since the equilibration takes place during the expansion, a strong radial flow develops, which is seen in the data.

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**Fig. 2:** Quark and meson masses as a function of the temperature for $\mu = 0$ in the NJL model.

**Fig. 3:** Feynman diagrams (t and s channels) for the elastic quark-antiquark cross-section.

**Fig. 4:** Energy dependence of the cross-section for $u + u \to \pi^+ + \pi^-$, for different values of $T$ and $\mu = 0$.

**Fig. 5:** Number of pions and quarks as a function of time for an expanding plasma [5].

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F. Gastineau, L. Gerland, J. Aichelin

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Therefore, it is worth using another phenomenological model, the Nambu Jona-Lasinio (NJL) model [1], which has been shown to be quite successful in regions where it can be compared with QCD. In its SU(3) version and supplemented by a t’Hooft determinant, the NJL Lagrangian has the same symmetries as that of the QCD. These symmetries are known to be the basis of many properties of quark and hadronic matter. They allow meson masses to be described at low density and low temperature and provide a simple approach to study the chiral phase transition. It also predicts the tricritical point in the p-T phase diagram, which has recently been discovered by lattice QCD calculations.

Recently this Lagrangian has been improved by adding a mean field, calculated by a Polyakov loop [2]. It has been named PNJL. The Polyakov loop make the transition sharper and, even more important has not only the symmetries of the QCD Lagrangian but reproduces also quantitatively the thermodynamical properties which have been calculated on the lattice.

We use this Lagrangian to investigate two topics:
1) The masses of the scalar and pseudo scalar mesons at zero and finite chemical potential.
2) The cross sections between quarks as well as the hadronization cross sections q+q —> meson+meson, obtained in a Nc (number of colors) expansion of the Lagrangian.

Fig. 1: Masses of pseudo scalar mesons as well as of the quarks in the standard NJL as compared with the the PNJL for the same set of parameters as a function of the temperature for μ=0.
The pseudo scalar meson masses as a function of the temperature and for $\mu=0.$ are shown in Fig. 1 for NJL and PNJL. We see that at very low and very high temperatures there are no differences. The additional mean field pushed the phase transition towards higher temperatures. Close to the phase transition the form of the PNJL and of the NJL results are rather similar. However, if we observe quark masses, we see that chiral symmetry restoration takes place more rapidly (in other words, the domain in temperature where transition takes place is smaller) in PNJL than in NJL.

A very similar behaviour can also be observed for the scalar mesons which play an important role in the scattering between quarks because they are the particles which are exchanged between the quark lines. Also here we observe a higher temperature for the phase transition in the PNJL model but otherwise little changes in the functional form.

Using these results we can calculate the elastic scattering between quarks. The results are shown in fig.3. We see that the form of the cross sections are quite different for a same temperature. But let remember that the transition temperature $T_c$ is not the same for the NJL and the PNJL model in the figures. In fact, you can choose temperature transition in PNJL. Here, we chose $T_c = 270$ MeV because that's the prediction of lattice calculations. Finally, normalised to $T_c$, results are quite similar.

![Fig. 2: Masses of scalar mesons as well as of the quarks in the standard NJL as compared with the PNJL for the same set of parameters as a function of the temperature for $\mu=0$.](image1)

![Fig. 3: Quark elastic cross section between an u and an s quark in NJL and PNJL for $\mu=0$ and for two different temperatures.](image2)

Effects of gluon thermal mass on heavy quark energy loss

J. Aichelin, C. Brandt, P.-B. Gossiaux, T. Gousset, S. Peigné

Les relations de dispersion des gluons sont différentes dans un milieu thermique et dans le vide. La probabilité de rayonnement de gluons par un quark énergétique produit dans un plasma de quarks et de gluons s’en trouve affectée, donnant lieu à deux effets contribuant à la perte d’énergie radiative : l’effet Ter-Mikaelian et le rayonnement de transition. Pour un quark lourd, nous montrons que ces deux effets, combinés à la perte purement collisionnelle, sont responsables d’un effet de retard apparent de celle-ci.

Collisional energy loss has recently attracted some attention [1,2] due to the single electron puzzle observed in ultrarelativistic heavy ion collisions [3]. When incorporating collisional loss into quenching scenarii, one usually assumes that a heavy quark produced in a QGP immediately undergoes stationary energy loss. In Ref. [4], it was however argued that the reaction of the medium on the heavy quark (of mass $M$ and energy $E >> M$) can only set in after some ‘retardation time’ $t_{ret}$. In the present work we explain why for purely collisional loss we have $t_{ret} \sim 1/m_D$, with $m_D$ the Debye mass of the QGP, in agreement with the diagrammatic approach of Ref. [5]. We also recall the study of Ref. [6], which presents for the first time a consistent calculation of heavy quark energy loss at zeroth order in an opacity expansion [7]. In other words we discuss initial bremsstrahlung and transition radiation in addition to purely collisional processes. (Gluon radiation induced by quark rescattering in the QGP is not considered here.)

We assume the heavy quark to be produced in a static QGP of high temperature $T$. The latter hypothesis implies the hierarchy $1/T \ll r_D \ll \lambda$, where $1/T$ is the average distance between two constituents of the QGP, $r_D \sim 1/m_D \sim 1/(gT)$ is the Debye radius and $\lambda=1/(g^2 T)$ is the mean free path of the heavy quark. Under these hypotheses, we can describe the QGP via its collective response to the current [8], where the dielectric functions are obtained from the gluon polarization tensor.

Let us first consider the case of an infinite plasma. When the heavy quark is produced at initial time $t_{prod} \sim 1/E$ in a hard subprocess and $E$ is much larger than all other scales (in particular $1/E \ll 1/T$), the production of the bare quark factorizes from subsequent evolution. The kinetic energy loss of the quark travelling the distance $L$ reads:

$$-\Delta E_{\text{kin}}(L) = E_{\text{kin}}(t_{\text{prod}}) - E_{\text{kin}}(t = L/v) = -\int dt \left[ \int d'x v \cdot \vec{E} \right]$$

where $v$ is the heavy quark velocity, $j_1$ denotes the spatial component of the quark current, and the subscript "m" denotes the mechanical work done on the quark. In fact, this work already differs from zero for a quark produced in vacuum since initial bremsstrahlung, induced by the sudden acceleration of the quark, leads to the reduction of $E_{\text{kin}}$ after $t_{\text{prod}}$. This vacuum contribution should be subtracted.

When discussing jet quenching observables such as nuclear attenuation factors $R_{AA}$, only the vacuum-subtracted medium-induced energy loss matters. For this energy loss we get:

$$-\Delta E_{\text{ind}}(L) = -\Delta E_{\text{kin}}(L) + \Delta E_{\text{rad}}(L) = \int \frac{d^2 x d'x v \cdot \vec{E}}{r_{D}}$$

where the induced electric field enters the expression of $W$.

Our results for $\Delta E_m(L)$ are shown in Fig.1 (dashed line), for a charm quark of momentum $p=10$ GeV. The main feature is that the curve for $\Delta E_m(L)$ lies below the asymptote $\Delta E_m(L)$, by the amount (for $L \rightarrow \infty$)

$$\Delta E_m \approx \frac{\alpha_s \alpha}{m_D \gamma \sqrt{2}},$$

where $\gamma = E/M >> 1$. As a consequence, there is a significant delay before the onset of
stationary (linear) energy loss. This delay is not a
genuine retardation of purely collisional loss,
since various physical effects contribute to this
delay. First, part of the work done on the
charge from $t_{prod}$ to $t=\frac{L}{v}$ is due to initial
radiation. Due to the difference between the
gluon dispersion relations in medium and in
vacuum, the energy radiated in QGP differs
from that in vacuum. This is the QCD analog of
the Ter-Mikayelian (TM) effect, studied in [9]
and also identified in [4]. The radiated gluon
being timelike, the in-medium gluon dispersion
relations can be simply modelled by the gluon
thermal mass. It is more difficult to radiate a
massive gluon than a massless gluon, and we
intuitively understand why the TM effect
contributes negatively to the medium-induced
energy loss.

In order to single out the contribution specific
to collisional loss, we subtract the TM contribu-
tion, and find after subtraction that the curve
for $\Delta E_\text{coll}(L)$ is raised by the amount $d_4/2$
(exactly in the limit $E \to \infty$), see the
dash-dotted line in Fig.1. About half of the apparent
"retardation" is due to the TM effect.

As can already be seen in the case of a charge
with $v \approx 1$ produced in vacuum, the radiated
energy represents only ~ half of the mechanici-
work done on the charge after its produc-
tion. Using Poynting’s theorem we can show
that the other half is associated with the
creation of the charge's proper field. Obviously,
this self-energy contribution should not be
counted as "energy loss" as it is part of the
charge asymptotic state. Therefore, an
accurate definition of energy loss (to be used for
values of $L$ large enough so that the proper
field can be disentangled from other compo-
ents) is $\Delta E(L) = \Delta E_\text{coll}(L) - \Delta E_\text{self}$, where $\Delta E_\text{self} =
E_\text{self, vac} - E_\text{self, med}$. Although the self-energies,
deferred as the integral of the energy density
$(\varepsilon E + B^2)/2$, are separately ultraviolet
divergent, $\Delta E_\text{self}$ is convergent and $\approx d_4/2$ for $\gamma
\gg 1$. In Fig.1, the plain line represents $\Delta E(L)$
(after subtraction of the TM effect), i.e. the
genuine collisional energy loss in the case of an
infinite QGP. The shift compared to $\Delta E_\text{self}(L)$
appears to be $\sim \alpha_2 m_0$. Since the slope of
$\Delta E_\text{self}(L)$ is $\sim \alpha_2 m_0^5$ [8], we infer that the
retardation time due to purely collisional pro-
cesses is $t_{ret} \sim \frac{1}{m_0} \sim r_0$.

Finally, we consider the more realistic situation
where the quark is produced in a hard sub-
process in a finite size QGP, and travels the
distance $L_p$ before escaping the medium. In
this case the "asymptotic quark" (we assume
the quark to hadronize long after escaping the
medium) self-energy equals that in vacuum,
i.e., $\Delta E_\text{self} = 0$. It is thus legitimate to evaluate
the (induced) energy loss using (1), provided
one includes the transition radiation field in the
electric field. As for the TM effect, the presence
of transition radiation is due to the velocity of
light being different in medium and in vacuum,
in other words to the gluon thermal mass.

In Fig.2, the plain line includes all energy loss
contributions (collisional + TM effect + transi-
tion) in our model [6]. The shift with respect to
$\Delta E_\text{coll}(L)$ is $\sim d_4/3$, in particular it scales with $\gamma$.
This is due to a non-compensation between the
TM effect and transition radiation. As a
result, $\Delta E(L)$ suffers from a large effective
"retardation time", $t_{ret} \sim \gamma r_0$. Numerically
$(d_4/3)/E \approx 3-5\%$ for $L_p \approx \gamma r_0$, implying $t_{ret} \approx 4$ fm
before the stationary regime.

We have obtained the energy loss of a heavy
quark produced in a hard subprocess and
crossing a finite size QGP, at zeroth order in
an opacity expansion, by defining the energy
loss in terms of proper asymptotic states. The
retardation time of purely collisional loss turns
out to be $t_{ret} \sim r_0$. However, we find a large
"retardation time" $t_{ret} \sim \gamma r_0$, when collisional
loss is combined with initial bremsstrahlung and
transition radiation.

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Prompt photon production in \( p-A \) collisions and gluon shadowing

F. Arleo (LAPTH Annecy), T. Gousset

Nous avons examiné la possibilité d’étudier le shadowing des gluons au moyen de la production des photons prompts dans les collisions proton-noyau à haute énergie. Cette voie est prometteuse au LHC comme au RHIC.

Parton densities of nucleons are objects of utmost importance for predicting production rates in \( p-p \) collisions at high energy. Their modifications when the nucleon sits in a nucleus affect production rates in \( p-A \) and \( A-A \) collisions. The possibility to extract gluon shadowing from prompt photon production in \( p-A \) collisions is analyzed.

1. Modification of parton densities

In a nucleus, parton densities of nucleons are modified: \( u(x, Q^2) \rightarrow u_A(x, Q^2) \) for \( u \) quarks and \( G(x, Q^2) \rightarrow G_A(x, Q^2) \) for gluons. Thanks to dedicated experiments in deep inelastic scattering (DIS) and Drell-Yan production the modification for quarks and antiquarks is fairly well known. Since virtual photons couple only indirectly to gluons, the constraining of gluon shadowing is very weak. In addition the region of \( x \) where the parton density can be extracted is of relevance. Fig. 1 indicates this region for the nuclear DIS experiment.

2. Shadowing extraction in prompt photon production

Prompt photons are those produced at the parton level. They do not result from the decay of a produced hadron such as a neutral pion. At leading order, prompt photon production at large transverse momentum has a cross section

\[
\frac{d\sigma}{dy}(p+p \rightarrow \gamma+X)=u_1^*ubar_2^*d\sigma(u+ubar \rightarrow \gamma + g) + u_1^*G_2^*d\sigma(u+g \rightarrow \gamma + u + g) + \ldots
\]

On the right-hand side, the first two lines are examples of direct production, whereas the third line shows a fragmentation channel. In the kinematical region discussed below, direct production and fragmentation are of comparable importance. For direct production, the Compton channel (second line) is one order of magnitude stronger than the annihilation one (first line).

The differential cross section can be studied as a function of center of mass energy, transverse momentum, and rapidity. It has been measured at several energies, with various projectiles, giving a rather rich phenomenology. Collider data are fairly well described by pQCD at NLO.

The ratio

\[
R_{pA}=\frac{d\sigma(p+A \rightarrow \gamma+X)}{d\sigma(p+p \rightarrow \gamma + X)}
\]

is studied at \( \sqrt{s}=8.8 \) TeV as a function of \( x_f=2p_T/s \) and \( y \) with INCNLO, assuming either proton or nuclear parton densities. The result is shown in Fig. 2. The process is sensitive to modifications of parton densities and to the change of isospin composition.
In order to cut out the neutral pion background, it is often useful to select prompt photon candidates by way of an isolation criterion. This also eliminates to a large extent the fragmentation component. As a consequence, a direct extraction of shadowing ratios can be devised [1].

The nuclear ratio for isolated photons was computed with JETPHOX, using an isolation criterion. The result is shown in Fig. 3 (open circles) and compared with the approximate form 0.5 ($R_S + R_{F2}$) (dash-dotted line), showing that the cross section ratio gives direct access to the shadowing function of gluons $R_G$.

3. Outlook

Nuclear modifications up to 20% are expected from the extrapolation of the fits made to NMC data and used here to predict nuclear production ratios in prompt photon production at the LHC. Counting rates turn out to be sufficient to access such deviations.

Fig. 2: Ratio of inclusive photons at $y=0$ and $y=3$ in $p$-Pb over $p$-$p$ collisions at 8.8 TeV.

Fig. 3: Ratio of isolated photons produced at $y=0$ in $p$-Pb over $p$-$p$ collisions at 8.8 TeV.

Le shadowing nucléaire, que l’on peut traduire par phénomène d’ombrage nucléaire, est la modification de la distribution des quarks ou des gluons dans un nucléon lorsque ce dernier est au sein d’un noyau par rapport à la situation où il est isolé. Le shadowing est assez bien connu pour les quarks mais l’est beaucoup moins pour les gluons. Nous avons montré comment extraire ce shadowing pour les gluons dans les collisions proton noyau en mesurant la section efficace de production des photons dans ces réactions.

References
F. Arléo, T. Gousset
Generation of complete events containing very high pt jets

S. Porteboeuf, K. Werner

Nous étudions l'implémentation des processus durs, observable du Plasma de Quarks et de Gluons, dans la globalité d'un événement, aux énergies du LHC.

The study of very high transverse momentum jets will be an important issue at the LHC (1), in particular since the corresponding cross sections will be considerably larger than at RHIC energies. Jets are expected to provide information on the QGP formation, due to the energy loss of fast partons in the medium. Jet cross sections can be in principle compared to simple pQCD calculations, based on the hypothesis of factorization. But often it is useful or even necessary to not only compute the production rate of the very high pt jets, but in addition the "rest of the event".

We try to construct an event generator -- fully compatible with pQCD -- which allows to compute complete events, consisting of high pt jets plus all the other low pt particles produced at the same time. Whereas in "generators of inclusive spectra" like Pythia one may easily trigger on high pt phenomena, this is not so obvious for "generators of physical events", where in principle one has to generate a very large number of events in order to finally obtain rare events (like those with a very high pt jet). The topics of my research is to overcome these difficulties in the framework of the EPOS model.

A compact description of EPOS can be found in (2), many technical details about the physical basis of EPOS are described in (3), where we also discuss in detail the parameters of the model and how they are fixed. Concerning the basic features of this approach: EPOS is a consistent quantum mechanical multiple scattering approach based on partons and strings, where cross sections and the particle production are calculated consistently, taking into account energy conservation in both cases (unlike other models where energy conservation is not considered for cross section calculations). Motivated by the very nice data obtained by the RHIC experiments, nuclear effects related to Cronin transverse momentum broadening, parton saturation, and screening have been introduced into EPOS. Furthermore, high density effects leading to collective behaviour in heavy ion collisions are also taken into account. It appears that EPOS does very well compared to RHIC data (4), and also all other available data from high energy particle physic experiments (ISR,CDF and especially SPS experiments at CERN). As a result, EPOS is the only model used both for Extensive Air Shower simulations and accelerator physic which is able to reproduce consistently almost all data from 100 GeV lab to 1.8 TeV center of mass energy, including antibaryons, multi-strange particles, ratios and pt distributions.

Fig. 1: A Parton Ladder
One can see on Fig.1 a description of a parton ladder. In the initial stage of proton-proton collisions or heavy ion collision multiple interactions occur in parallel. The total energy is split between different ladder which lead to energy conservation. This phenomenon represents in EPOS an exchange of parton ladder in parallel. In the two limits, a parton ladder could either be soft or hard. This representation allows us to consider semi-hard cases. What is important to remark is that both soft, hard and semi-hard interactions are computed in the same formalism. Finally, this picture produces hard scattering regarding the complete event.

If one wants to compare with pQCD, one has to keep in mind that the parton model with factorisation computes only inclusive cross section: \(P+P \rightarrow \text{Jet} +X\), with no possibility to investigate the X part. And, the jet production is uncoupled from the rest of the event (soft production). As a consequence event generators based on this approach cannot compute complete events, they only compute jets and add the underlying by other means.

Once we understand the need of an event generator of complete events with both soft and hard physics, one can ask how to proceed. If one want to generate complete events, it's not possible to trigger on one process to study this particular contribution to the whole event. One has to generate every cases with his respective probability. So if we look at rare processes (like high pt partons), one needs many events in order to have sufficient statistics. The goal is to have an event generator of complete events (the hard process is produced within a complete event), and a low CPU time.

As already said, our work is based on EPOS, perfectly formulated as a multiple scattering model. As a first step we consider inclusive spectra. In the EPOS framework, we are able to compute the distribution \(N(K,x^+,x^-)\) of the number of elementary scatterings with light cone momentum fractions \(x^+\) and \(x^-\) and characteristics \(K\) (soft/hard,...). We also obtain a conditional probability distributions \(S(K,x^+,x^-,t)\) for particular hard processes with momentum transfer squared \(t\). We presently develop numerical techniques which allow us to generate randomly these variables, such that we can set kind of trigger conditions to generate easily even very rare hard scatterings.

So far we still talk about the generation of inclusive spectra, whereas our real aim is to go beyond this and generate real events. To do so, we replace the above-mentioned distribution \(N(K,x^+,x^-)\) by the usual Markov Chain simulation procedure, which generates complete events, with many elementary scatterings in parallel. For a given elementary interaction characterized by the light cone momentum fractions \(x^+\) and \(x^-\) and characteristics \(K\), we employ the techniques discussed above to generate individual hard events.

This is a work in progress. Some LHC prediction on our preliminary work could be found in (5).

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New facts about muon production in Extensive Air Shower simulations

T. Pierog, K. Werner

Nous étudions la production de muons dans les gerbes atmosphériques issues de rayons cosmiques.

Whereas air shower simulations are very valuable tools for interpreting cosmic ray data, there is a long standing problem: it seems impossible to accommodate at the same time the longitudinal development of air showers and the number of muons measured at ground. Using a new hadronic interaction model (EPOS) in air shower simulations produces considerably more muons, in agreement with results from the HiRes-MIA experiment. We find that this is mainly due to a better description of baryon-antibaryon production in hadronic interactions. This is an aspect of air shower physics which has been neglected so far.

Since more than ten years, detailed extensive air shower (EAS) simulations play a decisive role in interpreting measurements from ground based cosmic ray measurements. This concerns for example the chemical composition of cosmic rays in the KASCADE experiment (1) or the primary energy determination from AGASA (2). Using the currently employed hadronic interaction models (QGSJET01 (3), QGSJETII (4), and SIBYLL2.1 (5), experiments like KASCADE (6) or HiRes-MIA (7), show inconsistencies between experimental data and simulations. Furthermore, AUGER finds a discrepancy between the energy reconstruction of the primary cosmic rays from two different methods, which could be explained partly by a lack of muons in the simulations. Many attempts have been made to force the models to increase the muon production without changing Xmax (well constrained by data) -- without success.

Here we discuss the consequences of introducing EPOS -- a recently developed high energy hadronic interaction model -- into the air shower simulation models CORSIKA and CONEX. A compact description of EPOS can be found in (8), many technical details about the physical basis of EPOS are described in (9), where we also discuss in detail the parameters of the model and how they are fixed. Concerning the basic features of this approach: EPOS is a consistent quantum mechanical multiple scattering approach based on partons and strings, where cross sections and the particle production are calculated consistently, taking into account energy conservation in both cases (unlike other models where energy conservation is not considered for cross section calculations). A special feature is the explicit treatment of projectile and target remnants, leading to a very good description of baryon and antibaryon production, as measured in proton-proton collisions at 158 GeV at CERN. Motivated by the very nice data obtained by the RHIC experiments, nuclear effects related to Cronin transverse momentum broadening, parton saturation, and screening have been introduced into EPOS. Furthermore, high density effects leading to collective behavior in heavy ion collisions are also taken into account. It appears that EPOS does very well compared to RHIC data (10), and also all other available data from high energy particle physic experiments (ISR,CDF and especially SPS experiments at CERN). As a result, EPOS is the only model used both for EAS simulations and accelerator physic which is able to reproduce consistently almost all data from 100 GeV lab to 1.8 TeV center of mass energy, including antibaryons, multi-strange particles, ratios and pt distributions. Since this model is applied to accelerator physics, many data are considered which are not a priori linked to cosmic rays and air showers.
This is a very important aspect, which finally led to the discoveries discussed here. For our analysis, CONEX and CORSIKA are used to simulate the air shower development. For the high energy interactions (above 80 GeV) EPOS 1.6 is used, and as a reference the most commonly used interaction model QGSJET01. One of the most important observables in air shower physics is the electron number as a function of the depth \( X \), the latter one representing the amount of air traversed by the shower, expressed in g/cm\(^2\). The maximum \( X_{\text{max}} \) of this distribution is a function of the energy and of the mass of the primary particle, as shown in Fig. 1.

A complementary observable is the muon number at ground, for example expressed via the density \( \rho(600) \) of muons per squared meter at a lateral distance of 600 m from the shower core (impact point). We show results from the MIA detector as a function of the primary energy in Fig. 2 together with shower simulations for proton and iron from EPOS and QGSJET01, using the same notation as in Fig. 1. The HiRes-MIA data are compatible with the EPOS results, showing a heavy primary composition at \( 10^{17} \) eV and a lighter one at \( 10^{18} \) eV. Compared to QGSJET01, it is a shift of about 25% in the number of muons at ground. So for the first time, both \( X_{\text{max}} \) and muon data are well in between the two extremes proton and iron, with a tendency towards lighter primaries at higher energies.

Evidence for soft hadronic matter

C. Hartnack, J. Aichelin

An important challenge in nuclear physics is the search for the nuclear equation of state (EoS), i.e. the determination of the energy per nucleon in nuclear matter in thermal equilibrium as a function of density and temperature. A very promising method for this quest is the analysis of the production of strangeness in heavy-ion collisions below the elementary threshold, i.e. at energies where such a reaction is not possible in proton-proton collisions.

The production of a kaon requires an energy of at least 671 MeV in the nucleon-nucleon CM-system. For this large amount of energy, nucleons have to accumulate energy in multiple collisions. The most effective way to do this is the conversion of a nucleon into a resonance, which, in a second step, produces a kaon in another collision:

\[ N+N \rightarrow \Delta+N \quad \text{and} \quad \Delta+N \rightarrow K^+ + \Lambda+N. \]

This reaction chain is in concurrence with the decay of the resonance. For this reason, the production of kaons is favoured by high density where the mean free path is small enough to allow for multiple-step processes. Thus, kaon production is linked to the nuclear equation of state. A weak repulsion of compressed matter (called a soft equation of state) allows for higher densities and therefore for more kaon production than a strong repulsion (i.e. a hard equation of state).

However, kaon production is sensitive to many other parameters. Namely, the exact cross-section of the kaon production by a resonance is not known yet.

For this reason, it was suggested \[1\] to look for the ratios of the kaon yields in light systems (where there is only little compression) and in heavy systems. In such ratios, it is hoped that uncertainties like the unknown cross-sections may cancel. First comparisons of theoretical models \[2\] with experimental data \[1\] showed a tendency towards a soft EoS, as shown in Fig. 1 comparing experimental data of the KaoS collaboration \[1\] with previous calculations of Fuchs et al. \[2\] and results of the IQMD model \[3,4\].

IQMD could also demonstrate the robustness of the kaon ratios versus various parameters\[5\].

![Fig. 1: Ratio of the kaon yields in Au and C for a hard and a soft EoS in comparison of KaoS data and theoretical calculations.](image-url)
Fig. 2: Ratio of the kaon yields in Au+Au and C+C as function of the compression modulus K at low incident beam energies.

We see that for getting compatible with experimental data (hatched area) we have to assume small values of K i.e a soft EoS. There is another possibility to access information about the nuclear equation of state: when we analyse the kaon yield as a function of the system size A, we find an exponential scaling law $M(K) = M_0 A^\gamma$ with a normalization factor $M_0$ depending on various unknown parameters and an exponent $\gamma$ depending on K.

Fig. 3 shows the comparison of IQMD calculations of this slope parameter (lines) with experimental values (bullets) obtained by the KaoS collaboration [6]. Also an analysis using participant numbers $\alpha$, square, see [5,6]) has been included. Again we see a preference for a soft EoS. This is fully compatible with the findings in Fig. 1 and refs. [2] and supports the claim for a soft equation of state.
Radio detection of Ultra High Energy cosmic rays

Codalema dipole antenna
Ultra broad bandwidth active dipole used in the Codalema experiment. Schematic drawing of the ASIC amplifier (insert).
Astroparticles


Since many years, the origin of non-thermal cosmic radiation is a very stimulating field of researches. Recent results at the Pierre Auger Observatory have maybe opened a new window in the domain of Ultra High Energy Cosmic Rays: the arrival directions of the charged cosmic particles (above $10^{19}$ eV) can be correlated to the locations of active galactic nuclei (The Pierre Auger collaboration, Science 318, November 2007). These objects could be the source of the radiation but definite conclusions can only be made when more statistic and better detection performances can be obtained. To gain fairly quickly this necessary vault, improvement of the Extensive Air Showers (EAS) detection in term of surface, duty cycle and cost could be required.

High-energy cosmic rays are detected indirectly by the observation of the giant shower of secondary particles they induce in the atmosphere, with particle detectors on the ground or fluorescence/Cherenkov light detectors. Their characterization requires the simultaneous measurement of several parameters and high statistics. Radio detection of electric field pulses, with or without the associated use of other methods of detection, may provide a major and decisive contribution to high-energy cosmic ray research. The potentialities of this detection technique are the possibility to determine the direction, energy and nature of the primary, together with a high duty cycle and a relatively low cost.

In 2003, the Astroparticle group in Subatech was the promoter of the CODALEMA project in association with a few people from the LESIA (Observatoire de Meudon) and from the radio decametric array at the Nançay Radioastronomy Station. In 2005, a grant from the French ANR (Agence Nationale de la Recherche) allowed to extend the former experimental array of few antennas and particle detectors up to the current 24-dipole antennas and 17 scintillator arrays. Several laboratories were involved in this ANR project (in alphabetical order): ESEO (Angers), LAL (Orsay), LESIA (Observatoire de Meudon), LPCE (Orléans), LPSC (Grenoble), Observatoire de Besançon, Station de radioastronomie de Nançay. Besides, a subsequent effort has been made in testing the technique at the Auger Cosmic Ray Observatory (Malargüe, Argentina). Those tests had led to the setting of a prototype of self contained, self triggered and autonomous radio station which prefigures the future of cosmic ray radio-detection for deployment over very large areas.

The activities of the Astroparticle group during the 2 past years thus cover several aspects, which are discussed with some detail in the specific reports:

- Results of the CODALEMA 2005-2006 and 2006-2007 measurement campaigns in Nançay
- Pure radio detection performances of the CODALEMA experiment
- Since 2006, upgrade of the CODALEMA experiment in Nançay
- First tests and results at the Pierre Auger Observatory Southern site
- Design and tests of various active dipole antennas and associated electronics
- Design and tests of a self contained radio station (the two latter parts can be found in the Electronics Department contributions)
- Modelization of air shower radio electric fields (in collaboration with the Theory group)

CODALEMA is currently offering a calibration of the method around $10^{17}$ eV. For subsequent years, the plan is to set-up an extended array of autonomous radio stations in Nançay, spanning 10 km$^2$ together with an extension of the ground particle detectors array. In parallel, most of the groups of the CODALEMA collaboration are involved in the radio@Auger international project, aiming to set up a 20 km$^2$ “super hybrid” detector on the Auger Southern site, which will combine information from ground, fluorescence and radio detectors. Those parallel developments would open the way to the extension of the radio detection method to energies above $10^{18}$ eV.
Results of the CODALEMA 2005-2006 measurement campaign


The configuration of the CODALEMA experiment in late 2005 is presented Fig. 1. It was constituted of 11 log-periodic, conical helix antennas from the decametric array of Nançay, triggered by a 4-particle detector array. The year 2005 has been devoted to the accumulation of events to determine the performances provided by this new method of radio-detection.

Though very simple, this configuration led to important results. In the previous activity report of SUBATECH, we showed that CODALEMA had already provided firm evidence for a radio emission counterpart of EAS with an estimated energy threshold of ~ 5 \( \times 10^{16} \) eV [1]. In 2005 and 2006, we have opened a more thorough characterization of EAS radio signals [2]. It starts by comparing arrival times and incident directions as determined by the antenna array on the one hand, and the particle detector array on the other hand. The radio wave arrival time at any particular location is first extracted from off-line triangulation of multi-antenna events. The corresponding time distribution can then be compared with the particle front time reference supplied by the scintillator signals. The time difference distribution obtained by this procedure is shown in Fig. 2. A sharp peak, a few tens of nanoseconds wide, is clearly visible, showing an unambiguous correlation between some radio events and particle triggers. Outside of the coincidence peak, the flat distribution corresponds to accidental radio transients which are not associated with air showers but which randomly occurred in the 2 µs time window where the search is conducted. EAS candidates are those for which the arrival time difference between the two detector systems satisfies the relation \( |Δt| < 100 \) ns, corresponding to the peak.

Fig. 2: Distribution of time delays between the radio plane front and the particle plane front. The time of passage of the radio wavefront through a reference point is compared, for all events, to that of the particle front.

If the time-correlated events actually correspond to EAS, the arrival directions reconstructed from both scintillator and antenna data should be close to each other. Fig. 3 shows the distribution of the angle between the two reconstructed directions, without the time cut.
(grey histogram) and with a time cut of |Dt| = 100 ns around the peak displayed in Fig. 2 (black histogram). When selecting candidates in the peak, some chance events remain and can be clearly identified by plotting the angular difference distribution between radio pulses and particles. Most of the chance events have a large angular difference value and therefore true radio-particle coincidences can be selected using a small-angle cut on this distribution.

**Fig. 3:** Distribution of relative angles between particles and radio-pulses without time cut (grey histogram) and with a time cut around the coincident peak of the time difference distribution (black histogram).

The electric field variation in the antenna-based coordinate system depends on the arrival direction, in particular on the zenith angle. This makes comparisons between different showers or between the E-W and S-N axis difficult. For this purpose, it is thus preferable to reformulate the lateral dependence of the electric field profile (EFP) in a shower-based coordinate system, obtaining the shower axis orientation from the reconstructed arrival direction. To carry out this analysis an exponential profile fit \( E(d) = E_0 \exp(-d/d_0) \) has been used, where \( d \) is the distance between the shower axis and each fired antenna in the event considered. Fig. 4 exhibits illustrative EFIs from a sample of antenna events with multiplicity > 4.

At last, as long as the maximum of the field distribution is observed along one of the sampling axis, indications of core positions can be extracted, even if they lie outside the active area delimited by the antennas. Core locations extracted from the exponential fits are shown in Fig. 5 for a subset of 64 events. From the examination of the quality of the fits obtained for the profiles (see examples in Fig. 4), we estimate the uncertainty on the E-W position around 10~m for the strongest radio events falling close to the array centre.

**Fig. 5:** Core positions calculated for true EAS events with antenna multiplicity > 4. Each cross corresponds to a radio-reconstructed shower core position. Gray circles correspond to the positions of antennas.


Results of the CODALEMA 2006-2007 measurement campaign

Les données collectées depuis novembre 2006 dans la nouvelle configuration de CODALEMA (comprenant des antennes dipolaires et de nouveaux détecteurs de particules) sont actuellement en cours d’analyse. Ces modifications ont permis de calculer l'efficacité de radio-détection en fonction de l'énergie des gerbes et de mettre en évidence le rôle prépondérant de l'effet géomagnétique dans l'émission radio. Une analyse préliminaire concernant les profils de champ électromagnétique indique aussi une corrélation forte entre l'énergie de la gerbe et le champ radio-électrique.

In 2006 several important modifications of CODALEMA have opened the possibility of simultaneous measurements of the particle and radio characteristics ([1] and other contributions to this report). This upgrade has lead to deduce the radio detection efficiency in function of the energy of the shower and to demonstrate the role of the geomagnetic field in the radio emission processes [2]. The results have been deduced from a sample of events corresponding to 104 effective days of data acquisition, composed of 15029 internal events (the 5 central particle detectors flagged, with 1 having the maximum signal). Among these events, 101 coincidences between the radio and the particles were identified using criteria in arrival time and in direction. Fig. 1 shows the energy distribution measured for the both detectors, indicating an energy threshold around $10^{15}$ eV for the particle detection and around $10^{17}$ eV for the radio detection.

Because of the low number of events available we do not establish the detection efficiency at higher energy, nevertheless we should expect a full efficiency around $10^{18}$ eV with one single East-West polarization.

Fig. 2 exhibits a sky map of the arrival direction of the radio events, which shows a pronounced asymmetry between the North and South sectors, while the distribution of the scintillator events is approximately uniform in azimuth, reflecting the uniformity of the cosmic ray distribution. The South to North ratio of the events is approximately 15%. This South deficit is not observed using an autonomous radio trigger, i.e., when statistics is not dominated by cosmic rays. The interpretation of this effect is that the showers coming from North and South do not generate radio signal in a symmetric way. An obvious candidate for a symmetry breaking of the generation of the electric field is the geomagnetic field, oriented in Nançay at 27° to the South from the zenith. The Lorentz force acting on the charged particles in the shower causes the electric field emission from the cosmic air showers. This electric field magnitude should follow the variations of the vector cross product $V \times B$, where $V$ is the velocity of the shower particle and $B$ the geomagnetic field. With this hypothesis, the predicted sky map is very similar to the sky map recorded by the antenna. Improved statistics for “internal events” and an experimental study of the signal polarization will enable confirming this assumption.
Fig. 2: Sky map of observed radio events (10 degrees Gaussian-smoothed map). The zenith is at the centre, East is at 270°, West at 90°. The direction of the geomagnetic field in Nançay is indicated by the red dot.

The last aspect, which is certainly one of the keys to the success of the technique, is related to the correlation with the energy. Although this analysis is still regarded as preliminary, for the “golden events” in the 37-84 MHz frequency band, a satisfactory dependence for the electric field amplitude to the shower axis distance was obtained using the formula $E = E_0 \exp(-d/d_0)$ which allows to deduce $E_0$ after fitting the parameters (Fig. 3).

This should make possible to establish the correlation between the energy of the primary cosmic ray deduced from the particle analysis and the electric field amplitude (Fig. 4) using $E_0$ as a calorimetric estimator of the energy of the shower. First investigations seem to indicate that $E_0 \sim \sin \alpha \cdot \cos \theta \cdot E_p^{1.1}$, where $\alpha$ is the so-called “geomagnetic angle” existing between the arrival direction of the shower and the geomagnetic field direction, and $E_p$ the primary particle energy estimation. With the assumption that the number of particles in the shower follows $N = E_p^{0.9}$, this relation becomes $E_0 \sim \sin \alpha \cdot \cos \theta \cdot N_p^{0.99}$, suggesting that the radio-emission could be coherent in the used frequency band.

Fig. 3: EAS electric field amplitude versus distance to the shower axis for the higher energy event. The inset displays the topology of the ground field with the reconstructed direction and core location of the shower.

Dans sa nouvelle configuration, l’expérience CODALEMA permet la mesure simultanée des caractéristiques radio (grâce aux dipôles), et particules (grâce aux scintillateurs) des gerbes cosmiques. Cela a permis de mettre en évidence un déficit d’évènements dans la direction du champ magnétique terrestre qui pourrait être attribué à un effet géomagnétique prépondérant dans les mécanismes d’émission radio. Une dépendance exponentielle du champ électrique à la distance à la gerbe est également observée et permet d’établir une corrélation entre l’énergie du primaire et la l’amplitude du champ électrique.

Radio-detection performances of CODALEMA using astronomical phenomena

La sensibilité de détection et les performances de l'expérience CODALEMA ont été évaluées en utilisant deux phénomènes naturels : l’observation d’une éruption solaire permet d’estimer la résolution angulaire inhérente à la méthode de triangulation, et l’observation du signal de fond radio galactique permet d’estimer la sensibilité des antennes en termes de champ électrique détecté.

During an initial phase of studies of the CODALEMA experiment at Nançay, conical helix log-periodic antennas from the Nançay Decameter Array [1] have been associated to 4 particle detectors, allowing to provide firm evidences for a radio emission counterpart of EAS [2, 3]. A good understanding of this detection method has been achieved taking advantage of two natural phenomena: the accuracy in the reconstruction of the arrival directions has been estimated using a radio emission from the sun; the calibration of gains and sensitivities of the antennas have been deduced from the analysis of the galactic signal modulation [4].

Solar flare radio observation: on January the 15th 2005, the mean squared signal seen by our antennas as a function of time was about 20 times higher than a typical day.

Fig. 1: CODALEMA set-up on Jan 15th 2005 during the sun emission.

In parallel, the Nançay Decameter Array detected a particularly intense solar activity during almost the whole day. Since the duration of the transient signals corresponding to EAS don’t exceed a few tenths of nanoseconds, we have suspected that our 10 µs recorded signals mainly come from the sun emissions. To confirm this hypothesis, the arrival directions of the waveforms were calculated using the triangulation method developed for the shower detection with the current sep-up at that time (Fig. 1).

Fig. 2: Reconstructed directions (crosses) obtained using 3 (left circular polarized) of the 6 log-periodic antennas, compared to the Sun trajectory from ephemerides (solid line).

The result of triangulation is plotted on Fig. 2 and compared to the exact trajectory of the Sun from ephemerides. The angular distance distribution, after correction for systematic errors, fitted by the expected function (a Gaussian centred on zero multiplied by a sine function coming from the solid angle factor) was then calculated. A standard deviation of about 0.7°, which is the angular resolution related to point-like source detection by three log-periodic antennas, was obtained.
**Galactic radio signal:** as the distance between the source and the receiver must be higher than several wavelengths, the antenna calibration in the 1-100 MHz band is tricky. One way to perform it is to use the galactic background radio signal, provided that electronic noise and local emitters are not dominant. This is the case in the 37-70 MHz band at Nançay. Indeed, the signal standard deviation, averaged over all antennas, for each local sidereal hour has been calculated over a six months period (Fig. 3).

![Fig. 3: Averaged signal as a function of the local sidereal time over 6 months. Red solid line represents the expected galactic background signal.](image)

The signal dependence as a function of the local sidereal time (LST) demonstrates that our antenna setup is sensitive to a galactic signal (otherwise it would have been constant). Simulation of the radio signal intensity along the galactic plane was deduced using data from [5]. Using the formula discussed in [2] to convert voltage into electric field, the measured galactic signal corresponds to a field $E = 7.7 \, \mu \text{V/m}$. Assuming the galactic frequency spectrum in the 37-70 MHz band to be flat, the Fourier coefficient in this band is $(\langle E \rangle)_{\text{meas}} = 0.23 \, \mu \text{V/m/MHz}$ which is of the same order of magnitude as the theoretical expectation $(\langle E \rangle)_{\text{th}} = 0.14 \, \mu \text{V/m/MHz}$). This indicates that the response of our antennas for the galactic noise can be used for voltage conversion into electric field. In addition, the galactic radio signal can be used to make a more precise relative calibration between all antennas requesting that LST signal variations must be the same for each antenna. This relative calibration has indicated that the fluctuations between antennas are lower than 15%. Finally, the galactic signal is also a way to test the antenna directivity, as the antenna lobe is included in the simulation.

Upgrade of the CODALEMA experimental setup

The CODALEMA research program aims to the characterization of the Extensive Air Shower (EAS) radio profile, by measuring simultaneously its particle and radio contents in a hybrid mode. Significant results from the CODALEMA experiment have been already reported [1, 2 – see also contributions to this report]. The present objective of radio detection is to obtain the most achievable characterization of the shower radio emission content with shower location, direction and size. For this purpose two sets of overlapping detection arrays were deployed on the site of the Radio Observatory in Nançay, France, and were gradually improved and extended over the years (Fig. 1).

The ground particle array is dedicated to the characterization of the arrival time, direction, size and core location of the shower by a measurement of the particle density at the ground level. Moreover it provides a logic signal to trigger the antenna digitization and acquisition systems. It consists in 17 scintillator stations located on a grid of approximately 85m of pitch. It covers a 340×340m² surface whose center roughly matches the radio array center [2]. Each station includes a thick plastic scintillator seen by two photomultipliers, all inserted in stainless steel box, finally housed in a plastic container for weather protection (Fig. 2). The two photomultipliers have their high voltage supply set to work at different gains (high gain (HG) and low gain (LG)), in such a way to have an overall dynamics from 0.3 VEM to 3000 VEM, switching the signal analysis from HG to LG when the HG is near saturation.

The first attempt to detect radio signals in coincidence with ground detectors was realized successfully by using few of the conic logarithmic antennas taken away from the 144 phased antennas of the Decametric Instrument (DAM) [1]. However their huge size prevented any further utilization as a fast and cheap element to be deployed later on in an open field array.

Emphasis on simplicity, size, coast and performance was used as guideline to develop a short active dipole. It is made of two 0.6 m long and 0.1 m wide aluminum slats, separated by a 10 mm gap. It is hold horizontally at 1 m above ground by a plastic mast (Fig. 2). This antenna is loaded by a high input impedance dedicated low noise 34 dB amplifier whose 3 dB bandwidth is 100 kHz-220 MHz [3].

The core of the radio array is made of 14 antennas, around 90 m spaced, and forming a cross of two 600 m long arms oriented in the North-South and East-West directions. These antennas are themselves oriented in the East-West direction. 7 antennas were recently added in order to sample the radio signal associated to EAS in a diagonal direction and at smaller distance. 3 dipoles were installed near the array center, close to existing...
antennas and oriented in the North-South direction to study the polarization of the electric field.

All the detectors and antennas are wired to a central shelter that protects power supplies, racks of electronics and computers for data taking. In the standard acquisition mode, the particle detection system acts as a master EAS trigger while the antennas are configured in a slave mode. Signals from both array detectors are directed to 4 channel 6U VME waveform digitizer boards [4]. The so-called Matacq board performs a fast 12-bits digitalization of the waveforms with a 300 MHz analog bandwidth, at a sampling rate of 1 Gs/s and in a memory depth of 2560 points (2.5 μs of signal). The maximum excursion at 1 V analog input of these ADCs defines a LSB at 250 μV.

The noise of the antenna chain (antenna + preamplifier + cable) measured at the input of the digitizer is less than 200 μV rms. All the ADC boards are externally triggered by a dedicated 16-fold multiplicity circuit. This circuit discriminates the HG photomultiplier signals with a threshold corresponding to 0.3 VEM and compares the resulting multiplicity to a remotely controlled level. In standard data taking conditions, we require the 5 central stations to trigger within a 600 ns gate width. These trigger conditions lead to an event rate of about 8 events/hour.

The data acquisition software is running under the LabView environment installed on two conventional commercial PC. Subroutines have been developed to interact with the Matacq boards via GPIB interfaces allowing initializing and programming the boards, to calibrate and readout the data. On line monitoring and data transmission over the network for storage and further processing are also performed from those computers.

The CODALEMA experiment is running and taking data without any major interruption or extended failures since October 2006. These stable running conditions are required in order to cumulate large statistics of events and to allow refined analysis of radio signals associated to EAS. Extending further out the CODALEMA setup at Nançay requires a complete change in the installation strategy. The current strategy (all detection devices connected by underground cables to the central container) clearly reaches its limits in terms of infrastructure workload and cost and in terms of time propagation and attenuation of the signal in the cables. New radio station prototypes are currently built and feature a

trigger system, power supply and data transfer autonomous from the wired arrays and able to work in a standalone mode. They will be tested at Nançay and could be integrated in the existing array in order to increase its coverage. This would mark a new milestone towards a large scale radio detection array.

Fig. 2: A dipole near the central container located on the south side of the DAM (left). A dipole antenna and a scintillator station (right).

En amélioration et extension continue depuis ses débuts, l’expérience CODALEMA à Nançay a atteint maintenant une taille permettant des analyses détaillées des signaux radios associés aux gerbes atmosphériques. Deux réseaux de 17 scintillateurs et de 24 antennes dipolaires constituent le dispositif expérimental en place depuis Janvier 2008. Deux bras de 7 antennes forment le cœur du dispositif radio. 10 dipôles supplémentaires permettent de mesurer le signal radio sur de plus courtes distances et d’étudier la polarisation du champ électrique. L’expérience fonctionne sans aucune interruption importante depuis Octobre 2006. Des prototypes de station autonome seront prochainement testés sur site pour une possible intégration à terme dans le réseau actuel.

RAuger: a fully autonomous station for radio detection at Auger

The CODALEMA experiment has demonstrated the possibility to detect radio signals associated with high energy cosmic rays air showers and use them to determine some important air shower characteristics [1, 2]. However, the current size of CODALEMA limits exploration to energies around some $10^{17}$ eV. To get a better knowledge of these radio signals and their dependences on other primary characteristics at higher energies, a natural subsequent stage is to associate antennas to larger ground detector arrays as the Pierre Auger Observatory, in Malargüe, Argentina. Besides our own processes, the Auger collaboration has also engaged a reflection in this way, permitting both requirements to meet.

In December 2006, we have installed an array of 3 autonomous, self triggered radio detectors (stations) [3]. Each of these stations is solar powered and automatically transmits its data by a WiFi link to a central acquisition system located 1 km away from the array. On each station, the trigger is made on a simple voltage threshold set on a filtered part of the EW signal. Taking advantage of the great purity of the radio sky over Auger’s site, very broadband (1-100 MHz) signals can be recorded on both the East-West and North-South polarizations. In order to keep maximum of flexibility, the station is built as simple as possible using off-the-shelf equipments. The complete setup of this pre-prototype is as follow:

- 8-bit Analog to Digital converter electronics adapted to large band wave form analysis, working at 500 MS/s for a 5 µs registered waveform; the ADC is a Tektronix THS730A handheld scope, 1 GHz bandwidth,
- GPS receiver for event time tagging at the 10 nanoseconds level,
- 100 W solar panels and 100 A.h, 12 V batteries for power supply,
- the local acquisition system is the standard Unified Board developed for the Cerenkov tanks in Auger; it masters the local data streams and manages the communication with the distant Radio Central Data Acquisition System (RDAS),
- standard WiFi system (115 kb/s) to send antenna data to the RDAS.

The total power budget is 18 W. A synoptic sketch of a single station is given Fig. 1.

![Fig. 1: Sketch of the electronics of a single station.](image-url)
The complete array (called RAuger, for Radio@Auger) is depicted on Fig. 2. It is located in the middle of the surface detector (SD) array of Auger, and in the middle of an elementary mesh of the 1600 water tanks whose it is constituted. The RDAS PC is located on side of the Central Laser Facility (CLF) shelter, where an internet link to the outer world allows to download the data from France. Fig. 3 shows a picture of one of the stations, surrounded by a fence protecting them against animals.

Fig. 2: Location and set up of the 3-radio detector array. The radio stations named A1, A2 and A3 surround the central tank Appolinario added specifically in the middle of the elementary mesh of tanks Mage-Tania-Celeste.

Fig. 3: Picture of a station. The electronics is placed inside the box on side of the solar panel in background. On foreground, the two dipoles in crossed polarization, identical to those used in CODALEMA.

Radio events are time-tagged by the same GPS system as in Auger. This allows recognizing real cosmic ray events from noise by searching time coincidences between particle events detected by Auger’s SD and radio events.

Main results obtained with RAuger are described in the next contribution to this report. Operation of this prototype array has been stopped in 2008, but the goal was achieved to demonstrate the ability of self triggered radio detection [4]. For the coming years, a new generation of autonomous stations (described elsewhere in this report) will be installed on the CODALEMA and RAuger sites, with the mid-term objective of covering a 20 km² array at Auger, opening the way to a super-hybrid (SD, fluorescence and radio) cosmic ray detector.

La démonstration de la radiodétection des gerbes cosmiques autour de $10^{17}$ eV ayant été faite par CODALEMA, l’étape suivante concerne la gamme d’énergie supérieure (à partir de $10^{18}$ eV). La conception et la construction d’un réseau d’antennes travaillant à ces énergies nécessite des phases de tests auprès d’un détecteur permettant la validation et la calibration des signaux radio obtenus, tel l’Observatoire Pierre Auger (Malargüe, Argentine). Après avoir validé la qualité radio du site d’Auger grâce à des mesures de bruits effectuées en janvier 2005, nous avons installé sur le site de l’Observatoire un petit réseau de 3 stations de radio détection entièrement autonomes, dont l’objectif était la détection indépendante des signaux radio à haute énergie. Ces tests ont été concluants et ont pour la première fois au monde permis de démontrer la faisabilité de la détection radio non déclenchée par un détecteur de particules. Une version évoluée de ce prototype de station autonome est en cours de construction et sera installée d’une part sur le site de CODALEMA, d’autre part sur le site d’Auger en vue d’une extension future à une centaine d’antennes sur une vingtaine de km².

Results of the RAuger experiment

Pour la première fois au monde, le réseau prototype RAuger installé à l’Observatoire Pierre Auger (Argentine) a permis la détection complètement indépendante d’événements radio associés à des gerbes atmosphériques générées par des rayons cosmiques. Les résultats correspondant à environ un an d’exploitation de l’instrument sont présentés ici.

The principle of the RAuger experiment has been described in the previous contribution to this report and in ref. [1]. As cosmic ray air shower transients exhibit the same characteristics as most of man-made transient interferences, it is for the moment very difficult to recognize them by the only radio signal. With a large antenna array, this difficulty should be overcame, but RAuger extends only over a few hundred of m² and needs an independent confirmation for cosmic ray identification. This is the reason why radio events are time-tagged by the same GPS system as in Auger, which allows recognizing real cosmic ray events from noise by searching time coincidences between particle events detected by Auger’s SD and radio events. Fig. 1 shows an example of such a coincident signal.

In about one year of operation, corresponding to some 6 months of effective time (because of breakdowns and adjustment periods), 25 coincident events have been detected between radio and Auger, above an energy threshold very similar to the one observed on CODALEMA [2]. Those events constitute the first ever detection of cosmic ray events by an independent, self triggered radio system, definitively demonstrating the ability of radio to be a very complementary technique for Ultra High Energy Cosmic Ray (UHECR) studies.

Besides this technical breakthrough, and though low statistics has been reached, a very important result has also been found. In the northern hemisphere, a clear event density depletion has been observed in the distribution of radio detected cosmic ray events in the South direction, where the Earth magnetic field is oriented (see the CODALEMA contribution to this report). In the southern hemisphere, the magnetic field is directed toward North and such depletion would thus be expected in the northern part of the sky. Indeed, such an asymmetry has clearly been observed by the RAuger system (Fig. 2), undoubtedly confirming a geomagnetic origin for the
shower’s electric field production process, at least at this energy level.

Unfortunately, no 3-fold antenna coincidences could have been detected for various reasons (breakdown of individual station, high dead time...), and cosmic ray direction reconstruction by triangulation of radio data is thus not possible on those events. However, numerous storm events have also been detected by the antennas, among them a large amount being “triangulable”. Fig. 3 shows the map over a 6 months period of stormy episodes, whose location and path in the sky have been reconstructed by using the radio data of the 3 antennas.

Fig. 5: Sky map of the radio 3-fold events triangulated over a 6 months period. All of them are identified as storm transient events, and two storms with an especially important accumulation of events appear on North and South. The weak occurrence probability of a storm just above the array explains the few number of events detected at low zenith angles: most of the storms develop far from the array, and appear closer to the horizon.

Such a map confirms, if needed, the ability of this method of radio detection of fast transients to give important information on the arrival direction of any transient event, and especially of cosmic ray air shower events. Moreover, the remarkable homogeneity in azimuth of this map (where two specially strong stormy episodes clearly appear on North and South) demonstrates that the system is able to detect in any sky direction: the observed depletion in the North direction for cosmic ray events has thus a physical origin, intrinsic to the shower electric field generation processes, called “geomagnetic effect”.

Though RAuger was a prototype system, it really gave some fundamental features of what could and will be an autonomous radio detection station and its use in a larger array. The results obtained are closely related to the ones of CODALEMA and are very encouraging for the subsequent activities of our group.

En un peu plus de 6 mois de fonctionnement, effectif, l’expérience prototype RAuger de radio détection autonome à l’Observatoire Pierre Auger a pu observer 25 événements radio clairement identifiés comme ayant pour origine une gerbe atmosphérique initiée par un rayon cosmique. Malgré la faible statistique, la répartition des directions d’arrivée de ces événements dans le ciel confirme l’origine géomagnétique du processus de création du champ électrique dans la gerbe de particules. Comme attendu, la densité d’événements observée autour de la direction du champ magnétique terrestre (au Nord pour l’hémisphère sud, au Sud pour l’hémisphère nord) est clairement plus faible. Ce résultat, dont la carte de détection d’événements transitoires liés à des orages vient confirmer l’origine physique et non instrumentale, vient en appui des découvertes réalisées par l’expérience CODALEMA en France. L’activité future du groupe Astroparticules de SUBATECH autour de la radiodétection s’appuiera fortement sur ces expériences pour le développement de futurs grands réseaux d’antennes de radio détection des rayons cosmiques.


Radio-electric fields from cosmic-ray air showers at large impact parameters

High-energy electrons and positrons in cosmic ray air showers generate transient electric fields in the radio frequency domain. Estimates of pulse magnitudes, together with their time scales and behaviors are useful ingredients for the design of a radio-detection experiment. For a very large scale experiment it seems unrealistic to expect a sampling of the air shower electric field on a scale much smaller than a kilometre. This defines the typical impact distance at which electric field estimates are needed. At such distances, a simple model of the shower can be used to investigate various aspects of air shower electric field phenomenology.

The formulation of this model is thoroughly discussed in [1]. A preliminary report on this work was given at the 30th International Cosmic-Ray Conference [2].

1. Electric field estimates
Several mechanisms of charge separation in the shower may lead to a radio electric field component. Here the so-called transverse current component is singled out. At large impact parameter \( b \), the electric field for this component received at time \( t \) at observation point \( A \) reads

\[
E(t,A) = 4(c t')^2 (N_{ee}(t') + t' N'_{ee}(t')) J / b^4
\]

where \( N_{ee} \) is the number of electrons and positrons in the shower at emission time \( t' = -(b/c)^2/(2t) \), and \( J \) is in proportion of the drift velocity of positrons and electrons as a consequence of their deflection in the geomagnetic field.

A sample of pulse shapes is shown in Fig. 1 for showers with energy \( 10^{19} \) eV and \( X_{\text{max}} = 770 \) g/cm\(^2\). They are coming from the South azimuth with various zenith angle. The field is always EW in this situation and the eastward projection is shown. The observer is located at \( b = 1 \) km.

The conversion from the emission time \( t' \) to the reception time \( t \) (Doppler-like effect) distorts the time dependence, early times (corresponding to \( t' \) negative and large) getting more contracted than later times. This explains the sharp rise, the slower decay, and the even slower undershoot of the pulse shown in Fig. 1. The variation of rise time with zenith angle \( T \) is a specificity of radio emission by air showers at large impact parameters. The probing of earlier stages when \( T \) increases affects pulse shape and has the tendency to give larger fields. To get the complete change this increase has to be combined with the overall amplitude modification coming from the variation of the drift velocity, which is proportional to \( \sin D(T, \theta) \), where \( D \) is the angle between the shower axis and the geomagnetic field.

![Fig. 1: Electric field pulses simulated at 1 km from the observer.](image-url)
2. Efficiency

Given a detection criterion it is straightforward to count the number of antennas that see a given cosmic ray shower event, once the distribution of antennas is fixed. The geometry considered is that of a hexagonal array on a horizontal ground located at sea level and the detection efficiency is studied as a function of the antenna spacing. Our detection criterion is that the electric field magnitude is above a threshold to be defined on at least three antennas belonging to the same elementary triangle. The threshold is first fixed to the root mean square of the galactic noise below 100 MHz:

\[ E_T = \sigma_{sky} = 30 \, \mu V/m. \]

A look at Fig. 1 indicates that an antenna located at 1 km receives an electric field magnitude above this threshold for a vertical shower. For such vertical events and an antenna spacing \( d = 1.5 \) km, Fig. 2 depicts the area spanned by impact parameters of \( E_p = 10^{19} \) eV events seen by 3 antennas. The proportion of detected events is simply given by the ratio of the area of one filled region to that of a basis triangle. For \( 10^{19} \) eV vertical shower and \( d = 1.5 \) km this is about 35 %. Fig. 3 displays efficiency integrated over arrival directions from vertical to 60-inclined showers with a weight \( \sin \theta \times \cos \theta \). As explained in Sect. 1, inclined showers are in general more effective at large impact parameters, making them easier to detect than vertical ones. As a consequence the efficiency for \( d = 1.5 \) km is now 90 %.

3. Perspectives

Current investigations are dedicated to small impact parameters. This is the situation of interest for a small antenna array such as CODALEMA. As already mentioned, computations of electric fields are much more difficult in this case.

Fig. 2: Hexagonal array and area of detection.

Fig. 3: Efficiency vs antenna spacing.

Ce travail théorique présente l’évaluation du champ électrique créé lors de la traversée de l’atmosphère terrestre par un rayon cosmique de grande énergie, en vue d’aider à la conception d’un système de détection par un réseau d’antennes. La géométrie du réseau est déduite de l’efficacité de détection, calculée pour une antenne sous diverses conditions de distance à la gerbe et d’orientation de celle-ci.


NDT bench for testing the weldings of Airbus fuselage stringers
PARI: nuclear physics, applications and interdisciplinary research

The work of the PARI group is dedicated to experimental nuclear physics and applied radiation science, developing instrumental approach and simulation tools. The concerned fields are radioisotope production, biomedical imaging, nuclear energy and non destructive evaluation. Fundamental physics is also addressed in relation with these topics. These activities were previously developed in the former PACCA and INCADE groups.

First, the group develops detectors for biomedical imaging. In the field of autoradiography, the gaseous PIM structure is used for beta imaging, allowing large area devices and very high spatial resolution. Regarding medical imaging, a liquid xenon gamma camera is developed, expected to be able to localize the position of a radiotracer ($\gamma$ emitter) in the three dimensions with a good spatial resolution in counting mode. A 30 kg xenon prototype is successfully conceived, built and tested in the lab, including for the first time a MICROMEGAS structure immersed in liquid xenon to detect the ionization signal. The scintillation signal is presently detected by a photomultiplier tube (PMT), to be replaced by a gaseous photomultiplier (GPM) under development. This novel imaging technique requires a new kind of radiotracer (scandium-44), foreseen to be produced by ARRONAX.

Actually, radioisotope production on ARRONAX (accelerator for research in radiochemistry and oncology in Nantes Atlantique), to be turn into operation at the end of 2008, is under study. A pluridisciplinary team is in charge of the definition and the implementation of methods for the production of selected radionuclides, mainly for medical application. Firstly, special attention is paid to $^{54}$Cu, produced form $^{64}$Ni irradiation: high radionucleidic purity (>99,8%) is achieved using single step radiochemical separation.

In the nuclear energy domain, the group established an important R&D activity in the development of ADS spallation targets. Subatech contributed to the design of the MEGAPIE target (demonstration of the feasibility of the coupling of a high-power proton accelerator with a liquid-lead-bismuth spallation target) and the necessary associated nuclear assessment. A second issue is the production of volatile radioactive elements (Hg, Xe) via the spallation reaction in the liquid lead-bismuth. In order to assess the production rates of these elements and to compare them with the prediction of Monte Carlo simulations, the group participated in the ISOLDE experiments at CERN. The next step towards producing an ADS for nuclear waste transmutation is the development of a demonstrator. This is one of the objectives of the EUROTRANS integrated project of FP6. The group, together with the engineering design office of Subatech, is heavily implicated in the development of the spallation target of the future ADS demonstrator.

The group is also involved in the DOUBLE CHOOZ experiment, dedicated to neutrino physics, in relation with the feasibility study requested by the IAEA on the use of anti-neutrino detectors for NUCLEAR SAFEGUARDS (non-proliferation). Extended numerical simulations and experiments are ongoing. While in the first step only the far detector will be used in the Double Chooz experiment, accurate simulations of the antineutrino energy spectrum are essential. A full core simulation of a PWR reactor is performed with the MURE package (Monte-Carlo based code). In the same way, the team is involved in the NUCIFER experiment. The French Nuclifer detector, under development, will be dedicated to non-proliferation and thermal power applications. The aim is to have a relatively small antineutrino detector, portable, fulfilling all safety regulations to be operated near a nuclear reactor.

All the activities of the group rest on skills and knowledge in several fields of physics and engineering sciences. Finally, mainly as technological transfer activity, the group develops collaborations with regional companies in non-destructive evaluation and control, in relation with the EMC2 competitiveness cluster. If special attention is first turned on thermography, the aim is to build a multi-modality facility, including ultrasonic, optical, infrared thermographic and X-ray devices.
Development of a digital beta imager based on a Parallel Ionization Multiplier (PIM) device.

R. Berny, H. Carduner, J. Donnard, P. Leray, E. Morteau, N. Servagent, D. Thers

L’autoradiographie est une technique d'imagerie médicale qui permet de visualiser la localisation de molécules marquées avec des traceurs radioactifs dans des coupes de tissus biologiques ou dans des cultures de cellules. Le savoir-faire du laboratoire Subatech dans le domaine des détecteurs gazeux à microstructure a abouti au développement d’un prototype de petite surface dédié à l’imagerie d’une demi-lame histologique. Les résultats ont montré de très bons résultats en terme de résolutions spatiales (25 μm FWHM avec du ³H) démontrant que la structure PIM est adaptée à de l'imagerie de très haute résolution. Le développement d’un appareil multi-modalité de grande surface dédié à l'imagerie de tous types de traceurs radioactifs est actuellement en cours.

Autoradiography is a widely applied technique in research fields such as pharmacology and genetics. It is used to follow the progress of a medicine or to identify genes with great accuracy. The two-dimensional localization of the distribution of a molecule labeled with ³H or ¹⁴C in tissue samples is a rather difficult challenge from the point of view of radiation detection. We have developed a micropattern gaseous detector based on the Parallel Ionization Multiplier structure dedicated to high spatial resolution β imaging on small surfaces of a half microscope slide. Images obtained show a spatial resolution of 25 μm FWHM in two dimensions with ³H with a possibility of double labelling ³H /¹⁴C. The real time imaging is possible thanks to specific software developed for this application. Thanks to these encouraging results, we started to build a new prototype dedicated to multi-modality imaging of all different type of β emitters. It has a large surface able to process an image of 10 microscope slides in the same time. The good characteristics of spatial resolution in ³H are still present.

The PIM detector for beta imaging

PIM is a modular structure incorporating micromeshes allowing a large number of different configurations. Differing electric fields can be applied in order to create different stages in the detector like amplification stages and spread stages.

The source (radioactive sample) is placed directly in the gas and the microscope slide is used as a cathode. To overcome the isotropic emission of the source, a small amplification stage is placed directly in contact with the sample. The first stage is a 200 μm thick amplification gap defined by an insulating FR4 spacer placed between the microscope slide and a very thin nickel micromesh. The primary electrons are amplified by an electric field close to 30 kV/cm. The second stage is a thick diffusion gap in which the first stage avalanche is spread into a large cloud thanks to the transverse diffusion into gas. The third stage is finally a second amplification.
The induced signal created by the motion of charge is collected by a segmented anode. Each readout strip is connected to a front end electronic based on the GASSIPLEX chip. A specific real time software analysis was developed to monitor the different parameters of the acquisition such as the counting rate, the efficiency of reconstruction, the collected charge and allow the real time analysis process.

The performance

The first prototype developed is dedicated to the very high spatial resolution on a small surface of a half microscope slide. Results obtained show a spatial resolution of 25 μm FWHM [1]. Figure 2 shows an image obtained with this micro Imager of 3 slices of mousse brain labelled with ³H.

![Figure 2. Image of biological sample](image1)

Thanks to these encouraging results we built a second prototype [2] dedicated to high spatial resolution on large area with low energy β emitters such as ³H. With a multi-modality solution we should be able to image all different types of βemitters. Figure 3 shows a complete image of 10 microscope slides labelled with ³H obtained with the new prototype.

![Figure 3.10 microscope slides labelled with ³H](image2)


[2] Donnard J. et al., NDIP08, to be published in NIMA

L’autoradiographie est une technique d’imagerie largement répandue dans le domaine de la recherche biomédicale car elle permet de localiser dans un organisme une molécule marquée par un isotope radioactif émetteur. Nous avons développé un prototype dédié à une imagerie très haute résolution (25 μm) sur une surface d’une demi-lame histologique. Fort de ces résultats, nous nous sommes lancés dans la réalisation d’un appareil multi-modalité permettant d’imager avec le même appareil des émetteurs de basses énergies (³H ou ¹³C) ou de hautes énergies (¹³¹I, ¹⁸F ou ⁴⁶Sc). Les deux appareils sont basés sur une structure PIM dans laquelle un espace d’amplification très fin est placé au contact de l’échantillon utilisé comme cathode. Un espace de dérive permet ensuite aux électrons créés par le processus d’avalanche électronique d’être étalé. Une seconde amplification a lieu pour rendre le signal compatible avec le dispositif de lecture électronique. L’anode chargée de collecter tous ces électrons est segmentée en de très fin pixels. Un astucieux multiplexage permet de coder la charge présentée sur l’anode dans deux plans de projections X et Y réduisant ainsi le nombre de voies de lecture. Avec ce dispositif nous avons obtenu une résolution spatiale (finesse de l’image) de l’ordre de 25 μm.
Development of a liquid xenon $\gamma$ camera for medical imaging.

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Collaboration: Centre de recherche en cancérologie de Nantes (Inserm U601), Weizman Institute of Science (Israël), KEK Institute (Japon).

Une étude approfondie de $\gamma$ cameras comprenant du xénon liquide est en cours d’investigation afin d’élargir le champ et les applications de l’imagerie fonctionnelle clinique. Cette technologie, rarement utilisée jusqu’à présent, offre en effet de nombreuses opportunités pour l’imagerie médicale. Elle est ainsi à l’origine d’une proposition innovante d’imagerie à 3 photons du scandium-44 dans laquelle la position du point d’émission est mesurée désintégration par désintégration avec une bonne résolution spatiale. Un prototype de petite dimension est en cours de tests au laboratoire Subatech. La liquéfaction ainsi que la purification d’une grande quantité de xénon (30 kg) a été réalisée avec succès ; les premiers signaux de scintillation et d’ionisation issus de la détection de photons $\gamma$ ont été mesurés. Pour la première fois, une structure de type Micromegas immergé dans le liquide a été mise en œuvre pour collecter le signal d’ionisation.

1. Introduction

Gamma detection with liquid xenon has been studied at Subatech for 5 years, with the goal of improving PET (Positron Emission Tomography) imaging and diagnosis. Such a device allows the tracking of Compton vertices, thus offering the possibility of accessing the incident angle of each $\gamma$ ray. Then, by simulation we demonstrated that a full-size whole-body liquid xenon camera must be considered to improve energy resolution, spatial resolution and sensitivity in the case of PET imaging [1].

Moreover, Compton imaging with a liquid xenon telescope is of particular interest regarding trends in medical diagnostics and functional imaging because it offers unique possibilities when associated with a new type of radionuclide that emits a positron accompanied by a quasi-simultaneous $\gamma$-ray. We call this new technique $3\gamma$ imaging.

2. $3\gamma$ imaging

The basic idea is to use a new radionuclide and a liquid xenon Compton telescope to measure, event by event, the three coordinates of the decay position. The desirable properties of the new radionuclide are: low $\beta^+$ energy, and a third $\gamma$-ray with energy around 1 MeV emitted in coincidence in most of the $\beta^+$ decay. The 3-dimensional localization of the emission point is achieved by the intersection of the direction cone of the $\gamma$-ray with the reconstructed line of response of the positron annihilation (figure 1).

![Fig. 1: Principle of the $3\gamma$ imaging](image-url)

A new generation of camera and an ad hoc radionuclide are thus the foundations of this new imaging technique, allowing the localization of the radiotracer with a spatial resolution of the order of 1 cm, disintegration by disintegration. For both these elements, we have carried out extensive research to identify suitable candidates. We are now very confident about the association of a liquid...
xenon Compton telescope with scandium-44 as the radionuclide for this new imaging technique. A simulation of a Compton telescope associated to a micro PET camera for small animal imaging has been done. A detail study of the performances of 3γ imaging for a rat phantom can be found in references [2],[3]. The main result is that, in the case of small animal imaging, a precision on the localisation of each E+γ emitter along the line of response of the order of the centimetre can be reached (figure 2). Simulations of human whole body 3γ imaging are under progress to evaluate the performances of the proposed technique in terms of image resolution and quantification of the fixed activity.

### 3. Construction of the XEMIS1 prototype and first results

A first prototype of size 3x3x12 cm³ active area named XEMIS1 (Xenon Medical Imaging) has been built at Subatech and is currently being tested (figure 2). To benefit fully from the characteristics of liquid xenon, this prototype integrates, in a liquid xenon proportional chamber, the recent progress made in gaseous devices for detecting both ionization and scintillation [3]. The ionization signal is detected by a PIM/Micromegas device, developed at Subatech, immersed in liquid xenon for the first time and the scintillation contribution is detected by a Hamamatsu PMT. In parallel, a GPM (Gaseous Photo Multiplier), developed by the Weizmann Institute of Sciences [5] is expected to be tested in XEMIS1 in the coming months. This device allows covering large surfaces with very few dead areas.

We succeed to liquefy, using a PTR device [6], a large quantity of liquid xenon (30 kg) at a rate of 1.5 kg/h. The gaseous xenon is continuously circulating for purification purpose. The temperature regulation is working well and permits to have very stable conditions during data taking for days. Scintillation and ionisation signals from 511 keV γ-rays were measured using a collimated sodium-22 source. To select annihilation γ-rays coming from the source, a time coincidence with a CsI detector was realized. A typical event is depicted on figure 4. The ionisation signal is read through a home made preamplifier connected to a non segmented anode. The measured anode noise of ~1600 electrons RMS will be decreased by using a segmented anode needed to localise in 3 dimensions each interaction points.

**Fig. 2:** Distribution of the residuals along the LOR for small animal 3γ imaging

**Fig. 3:** Picture of the liquid xenon prototype XEMIS1 built at Subatech.

**Fig. 4:** Typical 511 keV γ-ray event in XEMIS1. The ionisation signal is detected 10 μs after the PMT signal which is used for triggering purpose and drift time measurement.
4. Conclusion and Outlook

We are performing researches on medical imaging with a liquid xenon telescope associated with the scandium-44 radionuclide. In this way, we expect to be able to localize the position of the radionuclide in the three dimensions with a good spatial resolution in counting mode. The liquid xenon prototype XEMIS1 is operational and has delivered its first scintillation and ionisation signals from a γ-ray source.


Nous proposons de développer une nouvelle imagerie fonctionnelle basée sur la détection en coïncidence de trois photons afin d’obtenir une image précise où la position de chaque point d’émission est mesurée désintégration par désintégration dans les trois dimensions avec une précision le long de la LOR proche de 1 cm. Cette technique d’imagerie médicale se caractérise par la nécessité de développer en parallèle un nouveau type de radio-traceur, le scandium 44 (émetteur de 3 photons), et un nouveau type de détecteur, un télescope Compton au xénon liquide. Nous avons construit un prototype de télescope Compton au xénon liquide afin de montrer la faisabilité et l’intérêt de cette nouvelle imagerie fonctionnelle. Nous projetons ensuite la construction d’une γ caméra comprenant 20 litres de xénon liquide afin de réaliser des images sur de petits animaux avant d’envisager une adaptation des dimensions de la caméra à celles de l’homme.
Class 1000, clean room at SUBATECH
Radioisotope production on ARRONAX

C. Alliot, V. Bossé, C. Bourdeau, F. Haddad, N. Michel, S. Ndong, M. Mokili, N. Sidqi et le service mécanique de SUBATEC

Une liste comprenant une dizaine d’isotopes d’intérêt pour la médecine a été établie en vue d’une production par le cyclotron ARRONAX (Nantes). Une équipe pluridisciplinaire a été mise en place pour définir et mettre en œuvre les méthodes de production de ces éléments. Pour le démarrage d’ARRONAX, nous nous sommes concentrés sur la production des isotopes de Cuivre-64 ($^{64}$Cu), Rubidium-82 ($^{82}$Rb), Cuivre-67 ($^{67}$Cu) et Astate-211 ($^{211}$At). Chacun de ces isotopes radioactifs fait appel à des conditions d’irradiation, des techniques de fabrication de cibles et d’extraction chimique différentes.

ARRONAX (Accelerator for Research in Radiochemistry and Oncology in Nantes Atlantique) will turn into operation in the last quarter of 2008 in Nantes (France). It is a high energy (70 MeV) and high intensity (700μA proton) multi-particle cyclotron ($p$, $d$, $D$). Its main characteristics are summarized in the table 1.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Accelerated particles</th>
<th>Energy Range (MeV)</th>
<th>Intensity (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>H-</td>
<td>30-70</td>
<td>&lt;350</td>
</tr>
<tr>
<td>Deuterons</td>
<td>D-</td>
<td>15-35</td>
<td>50</td>
</tr>
<tr>
<td>$\alpha$-particles</td>
<td>He++</td>
<td>70</td>
<td>&lt;35</td>
</tr>
</tbody>
</table>

Table 1. Main characteristics of the ARRONAX cyclotron.

A large part of the ARRONAX beam time will be devoted to the production of radionuclides mainly for medical application. A priority list of 10 isotopes for both diagnosis and therapy has been established and validated by the scientific committee. This list is presented in table 2. Each isotope has its own application domain:

- $^{124}$I, $^{64}$Cu, $^{86}$Y, $^{44}$Sc can be used in pretherapeutic PET dosimetry for an evaluation of tumor and normal organs (liver, kidney, and lung) doses before injection of their $\beta^+$ emitting counterparts ($^{131}$I, $^{67}$Cu, $^{86}$Y, $^{47}$Sc).

- $^{82}$Rb is an analog of potassium used in cardiology. It is obtained from a $^{82}$Sr/$^{82}$Rb generator.

- $^{68}$Ga can be daily available from a generator $^{68}$Ge/$^{68}$Ga.

- $^{52}$Fe has been used in nuclear medicine mainly for imaging in haematology.

- $^{67}$Cu and $^{47}$Sc are intended to be used in $\beta^+$therapy.

- $^{211}$At is a $\alpha$-emitter which seems particularly appropriate for alpha-therapy due to its half-life.

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Radioisotope</th>
<th>Half life</th>
<th>Use</th>
<th>Beam type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta^+$</td>
<td>$^{64}$Cu</td>
<td>12.7 h</td>
<td>Diagnostic in oncology</td>
<td>p</td>
</tr>
<tr>
<td></td>
<td>$^{124}$I</td>
<td>4.2 j</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{44}$Sc</td>
<td>4 h</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{68}$Ga</td>
<td>68 mn</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{86}$Y</td>
<td>14.7 h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$^{82}$Rb</td>
<td>1.2 mn</td>
<td>Diagnostic in Cardiology</td>
<td>$\alpha$ or p</td>
</tr>
<tr>
<td>$\beta^+$</td>
<td>$^{67}$Cu</td>
<td>2.6 j</td>
<td>Therapy</td>
<td>p</td>
</tr>
<tr>
<td></td>
<td>$^{47}$Sc</td>
<td>3.4 j</td>
<td>Peptide-therapy</td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$^{211}$At</td>
<td>7.2 h</td>
<td>Alpha-immuno-therapy</td>
<td>$\alpha$</td>
</tr>
</tbody>
</table>

Table 2. Radioisotopes of interest for a production on ARRONAX.
In order to produce these radioisotopes, a multidisciplinary team has been created which contains nuclear and material science physicists, radiochemists, radiopharmacists and mechanic engineers.

For the first year of operation of ARRONAX, we have focused our work on 4 isotopes which allow to take advantages of the whole capacity of the machine: the Copper isotopes (64 and 67), the Rubidium-82 and the Astatine-221.

**Copper-64**

It is produced through the $^{64}\text{Ni}(p,n)^{64}\text{Cu}$ reaction at low energy. The target is obtained by electroplating of enriched nickel onto a gold support. Over last twelve months, a dozen irradiations have been performed at CEMHTI (Orléans). High radionucleidic purity is achieved (> 99.8 %) using a single step radiochemical separation. The target production, the chemical extraction procedure as well as the reprocessing of the nickel target are on the validation process (see contribution in this report).

**Copper-67**

In this case, we plan to use the $^{68}\text{Zn}(p,2p)^{67}\text{Cu}$ reaction which requires a high proton beam energy (above 30 MeV). In addition, the production cross section is small (few tens of mb) and the use of highly intense beam is necessary if ones wants to make it available at a reasonable cost. These constraints fit well with ARRONAX characteristics. The target will be also electroplated on a support. Tests are being made to determine the best one between Ag, Au, Pt and Al. Since we used again enriched material, a recovery process has to be set. The chemistry is close to that developed for Copper-64. Collaborations are being set with the Brookhaven national Laboratory (USA) and PSI (Switzerland).

**Rubidium-82**

Due to its short half life (see table 2), this isotopes is proposed as a Strontium-82/Rubidium-82 generator to the medical community. It is then necessary to produce the Strontium-82 using the $^{89}\text{Sr}(\alpha,4n)^{89}\text{Sr}$ reaction. This process required a high energy proton beam (>40 MeV) which is available only on few accelerator worldwide including ARRONAX. A project financed by the “Région des Pays de la Loire” has started in 2007 for 3 years within the CPER in order to make this radionuclide available on ARRONAX for the European medical community. The target will be made of pressed pellet of rubidium chloride (RbCl) (see figure 1).

A dedicated target system is being designed in the mechanical department of Subatech (see contribution in this report).

The main challenge associated to this production is the heat removal from the target. Meanwhile, we have performed irradiation tests at the cyclotron MEDiCYC (centre A. Lacassagne, Nice) in order to have samples of irradiated material to set up the separation and extraction method. From those irradiations, an overall separation yield greater than 90% has been obtained using a “Chelex 100” resin. Reproductibility of the process has been also verified.

Two other irradiation tests are schedule for the end of 2008 to study the elution properties of the generator.

We expect to irradiate our first target at low intensity on ARRONAX during the first semester of 2009. We will then slowly increase the intensity and run at high intensity by the end of 2010 with a new dedicated targetry system.

**Astatine-211**

This isotope requires the use of the alpha particle beam. The production is achieved using the $^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$ around 30 MeV. Since ARRONAX is only able to deliver 70 MeV alphas, a degrader system is being built at Subatech (see contribution of the Mechanical group in this report).

At the moment, 100 MBq of Astatine-211 is produced every week at CEMHTI. The Bismuth is melted in a cup and then machine to get a homogeneous surface. The target is placed perpendicular to the beam which requires a thick Bi layer (of the order of 200μm). Since Bismuth has bad thermal properties, this system imposes to run at low intensity (few µA). On ARRONAX, we expect to produce large amount of Astatine-211 and then we need to increase the beam current on target. To do so, we have decided to use a tilted thin bismuth target. The support will be made of...
ceramic with good thermal properties and the bismuth will be evaporated under vacuum.

The target will be tilted at 15° with respect to the beam direction and the bismuth thickness (40μm) optimised to take into account the energy threshold of the (α,2n) reaction. An example of our target is presented in figure 2. Works are in progress to determine the best parameters to be used to evaporate the bismuth.

For extraction of astatine, a wet extraction method has been set and is used on a regular basis [2]. Works has started on the distillation method which allows to get highly pure Astatine within half an hour.

**Figure 2:** Thin bismuth layer on a AlN support.

**Bibliography**

Test system made at Subatech for strontium production installed at MEDiCYC (centre A. Lacassagne, Nice)
**64**Cu Production for PET Imaging

N. Michel, C. Alliot, V. Bossé, M. Mokili, F. Haddad et le service mécanique de SUBATECH  
Collaboration: CEMHTI (CNRS - Orléans)

Copper-64 (**64**Cu) is a positron emitter with an intermediate half life (T½=12.7 h) which may be used for diagnosis or pre-therapeutic PET dosimetry for an evaluation of tumor and normal organs (liver, kidney, and lung) doses before injection of its **E**-emitting counterpart Copper-67. A collaboration has been set with CEMHTI to make this radionuclide available for medical use.

Irradiation parameters

Among the different possible production route, the **64**Ni(p,n)**64**Cu reaction gives highly pure product in large amount. **64**Ni is a small fraction of the isotopic composition of the natural Nickel. To reduce copper contaminants and enhance the **64**Cu production, the target is made of highly enriched material and contains 99.63% of **64**Ni, 0.23% of **65**Ni, 0.005% of **61**Ni, 0.035% of **60**Ni and 0.07% of **58**Ni. Based on the (p,xn) production cross sections, we set the beam energy to 12 MeV. This energy maximizes the production of **64**Cu and minimizes contribution from other copper isotopes. A 10 μA proton beam is used on a tilted,15°, water cooled target.

In these conditions, the main contaminants are **61**Cu coming from (p,n) on **61**Ni and **61**Co, **59**Co, **55**Co and **58**Co from (p,α) reaction on Ni isotopes, **57**Ni. The other products are either stable or have short half lives making them disappearing rapidly.

Target preparation

The target is obtained by electroplating the Nickel onto a Gold support. The deposit has an elliptic shape of 1.29 cm² (see figure 1).

**Figure 6:** Ni film electrodeposited on Gold support

![Figure 6: Ni film electrodeposited on Gold support](image)

**Figure 5:** Deposit profile of Ni film along the small axis.

![Figure 5: Deposit profile of Ni film along the small axis](image)
Using our home made electroplating device, we have studied the effects of composition of plating solutions, pH, plating temperature, stirring, plating voltage and current density on the quality of the deposit. A set of parameters has been defined which gives good target homogeneity. The performance of our process is illustrated on figure 2 which represents the thickness, measured by profilometry, along one axis of the target for a 17μm deposit. Using our set of parameters, 40 μm thick deposit can be obtained within 7 hours. It has to kept in mind that this value in our target design, which is inclined at 15°, is equivalent to a 154 μm deposit perpendicular to the beam.

**Chemical extraction**

Only ion-exchange process is suitable for the separation of no-carrier-added $^{64}$Cu. We have developed a single step method using an anion-exchange column resin which allows separation of copper from cobalt and nickel. This method is also well adapted for automation.

After the bombardment, the plated nickel was dissolved by 1 mL of concentrated HNO$_3$ and evaporated to dryness. The activity was recovered by HCl 9 M and loaded onto anion exchange column previously equilibrated with the same solution. Nickel was eluted using HCl 9 M, then cobalt with a HCl/ethanol mix and finally copper with HCl 0.1 M.

**Target recovery**

Considering the relatively high price of the enriched $^{64}$Cu stable isotope, the recovery of non-reacted $^{64}$Ni has also been investigated. We studied both a simple method using evaporation to dryness and a method using a selective extraction on DMG resin. They both give a recovery yield greater than 93 %. Based on these results and our whish to recycle as many times as possible the $^{64}$Ni, we are currently working on a strategy combining both methods.

**Conclusion**

$^{64}$Cu is produced on a regular basis at CEMHTI using the $^{64}$Ni(p,n)$^{64}$Cu reaction at low energy. Over the last twelve months, a dozen irradiations have been performed. High radionuclide purity is achieved (> 99.8 %) using a single step radiochemical separation. Recovery of the expensive nickel material for reprocessing is operational.

Adaptation to ARRONAX which will use larger target (14 cm$^2$) is under way.

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**Le Cuivre-64 est un élément radioactif émetteur de positons dont la période physique (12,7h) est bien adaptée au marquage de peptides ou d’anticorps. Il peut être utilisé soit pour faire du diagnostique en utilisant la technique de tomodigraphie à émission de positon (TEP) soit pour des études dosimétriques avant l’utilisation du Cuivre-67 en thérapie.**

La production du Cuivre-64 à partir de Nickel enrichie en Nickel-64 a été mise en place en collaboration avec le laboratoire CEMHTI d’Orléans. Elle est opérationnelle et en cours de validation, Une grande pureté radioisotopique a été obtenue (>99.8%) qui le rend conforme à une utilisation médicale.

Depuis mai 2007, une dizaine d’irradiation a été réalisée à Orléans permettant la fourniture de Cuivre-64 aux équipes de L’INSERM U892 de Nantes et au laboratoire CIPA du CNRS à Orléans.
The MEGAPIE Initiative

A. Guertin, N. Thiollière et al.

The MEGAPIE project is an international endeavour, with the aim to design, build, operate and explore a liquid metal spallation target (figure 1) on the basis of Lead-Bismuth-Eutectic (LBE) for a beam power approaching 1 MW. The main goal of the initiative is to:

- Increase the neutron flux at SINQ
- Demonstrate the feasibility of a liquid metal target for high-power ADS applications

MEGAPIE was realised and commissioned at PSI by PSI (Switzerland), CEA, Subatech and ATEA (France), ENEA, CRIOTEC and Ansaldo (Italy), IPUL/Riga (Latvia), SCK-CEN (Belgium), Fz-Karlsruhe (Germany), DoE (USA), JAEA (Japan) and KAERI (Korea).

Beam commissioning

On the 21st of August 2006 the PSI neutron user program started after an extended shut down, in which a new liquid metal target, the MEGAPIE target, was installed. PSI is thereby the first facility World-wide to operate in user mode with a high power liquid metal target.

At a relatively stable and constant beam current of 40 μA, which corresponds to about 25 kW of beam power, the target accumulated a total charge of 60 μAh.

The second phase of the start-up procedure was successfully accomplished on the 15th of August, where the power was stepwise increased to 150 kW (250 μA proton current). The goal of this phase was to check and verify the response of the heat removal system at power conditions comparable to those used, when operated out of beam at the test stand in the autumn of 2005.

The third and final phase of the start-up procedure was successfully accomplished on the 17th of August, where the power was stepwise increased to full power 700 kW (1200 μA proton current). After some 10 minutes time with stable proton beam at each step, the beam was interrupted to follow the temperature transients in the target.
All systems operated very stable at all power levels – and after a final review of the target performance and a monitoring of radiation levels around the target station and around the instruments it was concluded that normal user operation could be started. Normal user operation was started on August 21st around 8:30 and is planned to continue until the normal annual winter shut-down starting on December 23rd 2006.

The first 12 hours of proton beam is seen in the figure 2.

**Fig. 2** : The first 12 hours of proton beam on Target in SINQ at PSI (Switzerland)

All along the MEGAPIE project, started at the end of the nineteen’s, main SUBATECH laboratory activities performed by the PARI group were focused on:

- Target assembly sequence and associated drawing preparation,
- Engineering calculation checking and report writing,
- Feasibility study concerning lead-bismuth leak detector,
- Target neutronic and nuclear assessment with dedicated simulations and experiments.

**MEGAPIE performances and PIE**

Based on earlier Monte Carlo simulations the liquid metal target was expected to provide a 40% increase in neutron flux (at identical current). Initial measurements at selected instruments confirmed an increase in neutron flux: while the powder diffractometer HRPT at the thermal beam port reported 41%, very close to the prediction, the SANS-I instrument at the cold guide quoted a flux increase as high as 70 to 80%. Meanwhile gold foil activation measurements have confirmed flux increases between 80 and 85% at both, a thermal beam port (NEUTRA) and a cold beam port (ICON), and 70% at sector 80 (thermal water scatterer). Revised calculations with more detailed target and moderator geometry reproduce these results.

At this stage, Post Irradiation Examination is prepared with particular attention on sample cutting and preparation, analyses to be performed during the next years until 2011. The stable and reliable operation of the MEGAPIE target together with the tremendous neutron flux gain of 80% strongly emphasizes the wish of the user community to permanently install a liquid metal target. A project to evaluate this option has already been started. In 2007 SINQ will be operated as planned with an upgraded solid lead target, for which a moderate flux increase compared to the previous solid targets is expected.

**MEGAPIE, MEGAwatt Pilot Experiment, est une collaboration internationale entre le PSI (Suisse), le CEA, le CNRS, l’ENEA (Italie), le FZK (Allemagne), le SCK/CEN (Belgique), le JAERI (Japon), la DOE (Etats-Unis) et KAERI (Corée), ayant pour objectif de réaliser, opérer et analyser une cible de spallation au plomb – bismuth liquide pour une puissance faisceau de 1MW au PSI en Suisse. MEGAPIE sera la première démonstration expérimentale du couplage d’un accélérateur à une cible de spallation, afin de contribuer à la validation d’une option technologique importante dans le cadre du développement des systèmes hybrides pour la transmutation des déchets nucléaires. Le but de la transmutation est de soumettre ces éléments radioactifs à un flux de neutrons qui les transformerait en des éléments stables ou dont la durée de vie serait beaucoup plus courte, ce qui permettrait un stockage plus facilement gérable à long terme. La réalisation d’un système hybride de démonstration est prévue pour la période 2016-2025. La mise en oeuvre d’un prototype industriel dédié à la transmutation est attendue pour la période 240-2050.**

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Measurements of volatiles and gas production rates in Pb and Pb-Bi thick targets for ADS

Y. Tall, S. Cormon, M. Fallot, Y. Foucher, A. Guertin, T. Kirchner
Collaborations: MEGAPIE and IS419

IS419, an experiment to cope with the volatiles products
Within the frame work of the IP EUROTRANS (integrated project in the 6th programme EURATOM on the transmutation of nuclear waste), lead bismuth eutectic is chosen as the spallation target for the XT-ADS (eXperimental Transmutation in an Accelerator Driven Sub-critical system). Thus several projects such as MEGAPIE (MEGAwatt PlOt Experiment) were initiated in order to evaluate the behaviour of the target under irradiation by a strong protons beam. The irradiation of the target involves a spallation reaction which, in addition to neutrons, generates volatiles and radioactive spallation residues. To determine experimentally the production rates of gas and volatile elements following spallation reaction of 1.4/1.0 GeV protons on LBE target, the experiment IS419 was performed at the ISOLDE facility at CERN. The obtained results and their comparison with obtained data from Monte Carlo simulations (MCNPX [2] coupled with CINDER, ORIHET [3] and FISPACT) are of interest for the developments of ADS spallation targets.

A large scale facility dedicated to a production of radioactive ion beams
ISOLDE is one of the largest scientific installations using the technique of the on-line mass separation. It is dedicated to the production of a large variety of radioactive ion beams which are generated in thick target via spallation, fission or fragmentation. Isotopes will be ionised by the ionisation source, then extracted and accelerated by a field of 30 kV and sent to the on-line separator: the HRS (High Resolution Separator) and the GPS (General Purpose Separator). The GPS is designed to allow three different beams within a certain mass range to be selected and delivered simultaneously into the experimental hall via three different beam lines (central mass, low mass and high mass beam line). The second separator, the HRS, is equipped with two bending C-magnets with bending angles 90° and 60° degrees and it can only provide one beam at the same time with a very high resolution in mass.

Volatile measurements
The group PARI in SUBATECH took part actively in the two last experiments realized in 2004 and 2005 at ISOLDE. These experiments consisted to the irradiation of a lead bismuth target contained in tantalum cylinder filled at 75% with energetic protons of 1.0 and 1.4 GeV. The mass of the target is set to 547 g and in order to obtain good efficiency release rates the target temperature is fixed around 600 °C.

Measurements procedure overview
Various techniques of measurements are available at ISOLDE and can be subdivided in two ways according the half life of the isotopes. The off line measurements (spectroscopy): it concerns isotopes with lower range half life (5 minutes to some few days).
The online measurements (two types of procedure can be used to collect data): the Faraday Cup and the tape station measurements. The Faraday cup is most useful for measuring stables isotopes or long-lived radioisotopes. The tape station allows to measure the production rate of radioisotopes ($\beta$ emitter) with a very short half life.

**Results**

The experiment analysis has been carried out in the framework of the IS419 collaboration. The obtained results have been compared to simulations done with MCNPX coupled with the various models and options implemented in the code (BERTINI, ISABEL, INCL4, ABLA, CEM2K ...) and evolution codes (CINDER, ORIHET and FISPACT).

Figures 1 and 2 show, for example, the production rates of xenon at 600°C measured at 1 and 1.4 GeV [1] compared with MCNPX simulations.

At 1 GeV, we have an overall good agreement between measurements outside the molten lead-bismuth and simulations inside the material. At 600°C and 1 GeV, the Xe behaviour seems to be well reproduced by the codes. This is not the case at 1.4 GeV, Bertini/Dresner option overestimates the production rate. INCL4/ABLA option still well reproduces the experimental data. The discrepancy between the two options could be attributed to a better fission description in INCL4/ABLA and a too big excitation energy in Bertini/Dresner at the end of the cascade stage.

Le projet intégré EUROTRANS du 6e Programme Cadre de Recherche et Développement européen cherche à démontrer la faisabilité technique de la transmutation des déchets radioactifs dans un réacteur hybride dit XT-ADS. Un réacteur hybride est composé de trois éléments : l’accélérateur, la cible (préférentiellement de numéro atomique élevé), le cœur maintenu sous critique et rempli en partie d’actinides mineurs dédiés à la transmutation. Chacun de ses composants doit être validé expérimentalement ainsi que leur couplage. Ainsi le projet MEGAPIE (MEGAwatt PIlot Experiment) a été initié afin d’étudier une cible de Pb-Bi liquide soumise sous forte irradiation par un faisceau de protons (574 MeV, 1.75 mA). Afin de prévoir des dispositifs adéquats de confinement et d’extraction des produits radioactifs et volatiles produits par spallation, l’expérience IS419 a été réalisée auprès de l’installation ISOLDE. L’expérience IS419 consiste à une irradiation d’une cible de Pb-Bi liquide contenue dans un cylindre en tantale remplie à 75 % par un faisceau de protons d’énergie de 1,0/1,4 GeV. Les résultats obtenus ont permis de mettre en place de déterminer les taux de production des radio-isotopes très contraignants sur le plan de la sûreté et de mener une comparaison avec les résultats obtenus par les simulations Monte Carlo.

**References**

EUROTRANS: European Research Programme for the Transmutation of High Level Nuclear Waste in Accelerator Driven System

A. Guertin, N. Thiollière et al.
Collaboration: EUROTRANS integrated project of Euratom FP6

The integrated project EUROTRANS [1] of the 6th Euratom Framework Programme (fig 1.) focuses on the transmutation (the nuclear conversion of long-lived and/or toxic elements, such as plutonium and the minor actinides, into short-lived or stable elements) of radioactive waste and will initiate work on a European Transmutation demonstration (ETD) based on the accelerator driven systems (ADS, fig2). It will carry out a first advanced design of a 50-100 MWth experimental facility to demonstrate the technical feasibility of transmutation in an Accelerator Driven System (XT-ADS). It will also produce a generic conceptual design (several 100 MWth) of a modular European Facility for Industrial Transmutation (EFIT). Both designs will bear the same fundamental systems characteristics in order to allow scalability between XT-ADS and EFIT.

The strategic outcome of the EUROTRANS project will provide a state-of-the-art, reliable basis for the assessment of the technical feasibility of transmutation by ADS and a first cost estimate of an ADS-based transmutation system. It is also expected to provide important input elements to the appropriate decision-making authorities to decide whether to embark on the detailed engineering design of an ADS for transmutation (being the XT-ADS) and its eventual construction after completion of this project.

Fig. 1 : 30 partners and 17 universities from 14 different countries are involved in the IP EUROTRANS.

Fig. 2 : Principle of an ADS: a high power proton beam accelerator is coupled to the spallation target inserted in the center of a sub-critical reactor core.
The project started on April 1st, 2005 for a duration of five years. Subatech contributed to the preparation of the contract and is responsible for the work-package on the proof of feasibility of the spallation target for the XT-ADS.

The main work performed up to the beginning of 2006 was the preparation of a detailed work plan on the spallation target, taking into account the feed-back from previous FP5 projects, the interfaces of the target with the primary system of the reactor and the accelerator, the available R&D results and possible contributions form the European partners involved in the work.

The spallation target of an ADS feeds the sub-critical reactor core with the required number of neutrons. It is located in the centre of the reactor core at the end of the proton beam line. The concept of the XT-ADS spallation target is based on the pre-design study performed by SCK•CEN within the MYRRHA project [2]. The design of the target must fulfill a number of requirements determined by the expected performances of the ADS. The target should produce $3 \times 10^{17}$ primary neutrons per second to feed the sub-critical core at its $k_{\text{eff}} = 0.95$ and has to support the 350 MeV, 5 mA proton beam from the accelerator. Due to the available space and the proton beam current density of 125-175 $\mu$A/cm$^2$ a liquid lead-bismuth eutectic (LBE) window-less target with forced convection heat removal (1.43 MW of heat deposited in the target) was selected as reference concept (fig. 3).

They are:
- The layout and mechanical design of the spallation target LBE loop (pumps, heat exchanger, piping ...);
- The vacuum system design with particular attention to the interaction zone of the proton beam with the free LBE surface;
- The nuclear assessment via detailed Monte Carlo simulations.

En France la gestion actuelle des déchets nucléaires à vie longue fait appel à des solutions d’entreposage sûres, mais non définitives. La loi de 1991 (loi Bataille) a demandé non seulement d’étudier le stockage en formation géologique, mais aussi d’explorer les possibilités d’un entreposage de longue durée et d’une réduction de la nocivité de ces déchets par séparation-transmutation.

La transmutation consiste à transformer un déchet radioactif à vie longue en un déchet non radioactif ou de durée de vie courte. Une des options actuellement à l’étude est la transformation des déchets dans des systèmes hybrides. Il s’agit d’un accélérateur de protons couplé à un réacteur sous-critique qui contiendrait dans son cœur les éléments radioactifs à transmuter (fig. 2).

L’objectif du projet EUROTRANS est la conception avancée d’une installation expérimentale de système hybride pour démontrer la faisabilité technique et économique, ainsi qu’une conception préliminaire pour un ‘transmutateur’ industriel.

SUBATECH intervient plus particulièrement dans la conception et l’étude de faisabilité de la cible de spallation qui constitue la source de neutrons nécessaire à la transmutation des déchets dans le cœur du réacteur. Les travaux de conception et les études en physique nucléaire sont menés en collaboration avec les partenaires européens du projet.

References
The Double Chooz experiment

M. Fallot, L. Giot, B. Guillon, J. Martino, S. Cormon
and the Double Chooz collaboration

During the last decade, our knowledge on neutrinos has impressively increased. By measuring solar and atmospheric neutrinos, several experiments have shown that neutrinos are massive particles and as a consequence can oscillate from one flavor to another [1]. But several open questions remain, as what is the nature of the neutrino: Dirac or Majorana?, their mass hierarchy, neutrino absolute masses, what is the intensity of the CP symmetry violation in the leptonic sector ?. Concerning the CP violation, a first hint could come from the determination of the less constrained oscillation parameter \( \theta_{13} \) as, if it revealed to be null, no CP violation could be observed in the leptonic sector. The best constraint on \( \theta_{13} \) comes from the reactor Chooz experiment [2], which gives \( \sin^2(2\theta_{13})<0.02 \pm 0.00 \) @ 90% C.L. for \( \Delta m_{12}^2 = 2.0 \times 10^{-3} \). The aim of the Double Chooz experiment is to measure this mixing angle, reaching the sensitivity limit of \( \sin^2(2\theta_{13})<0.02-0.03 \), assuming \( \Delta m_{12}^2 = 2.0 \times 10^{-3} \). To this purpose, two identical detectors will be placed respectively at 400 m (“Near detector”), before the oscillation may occur, and 1050 m (“Far detector”) from the reactor cores of the Chooz power plant in the Ardennes, France [3]. Two types of experiments can access this parameter ; disappearance and appearance experiments. Reactor experiments are disappearance experiments. The disappearance probability is quasi free from correlations and degeneracies with other oscillation parameters and will thus provide very complementary results to appearance experiments using neutrino beams such as T2K or Nova [4]. The use of two identical detectors will allow to eliminate most of the systematic errors when computing the ratio between the two measured antineutrino energy spectra, provided a very good energy calibration of both detectors. The Double Chooz detector concept (Fig. 1) consists in a cylindrical acrylic target filled with Gd-doped liquid scintillator. Antineutrinos are detected through their interaction by inverse beta decay : \( q_e + p \rightarrow e^+ + n \). The positron energy is directly related to the antineutrino energy, and the neutron is captured in the Gd nuclei of the target. After a neutron capture, Gd emits 8MeV gammas detected in a delayed coincidence (50\(\mu\)s) with the positron signal. The target is surrounded by a \( \gamma \)-catcher filled with non-doped liquid scintillator, to catch escaping gammas from the target, and a non scintillating stainless steel buffer to isolate the center of the detector from background arising from residual activity of the PM tubes (390 10''PMTs), and a inner veto filled with mineral oil equipped with 70 8'' PMTs. In the case of the far detector, located under an overburden of 300 m.w.e. in the former Chooz experiment pit, a steel shielding surrounds the whole, to isolate the detector from gammas arising from the rock, made with demagnetized low activity steel rods. 15000 events per year are expected in the Far detector. The Far detector should be operational in mid-2009. As regards the Near detector, an overburden of more than 45m of rock (115m.w.e.) will decrease the cosmic ray background. 150000 events per year are expected in this latter detector. The Near detector will be operational in 2011. The calibration devices will consist in \( \gamma \) and neutron sources, LEDs and lasers, inserted into the target or into the buffer through the glove box and the chimney. Calibrations will be
performed as often as necessary to obtain a relative energy scale calibration identical within 1% between both detectors. The expected energy resolution is 7% at 1 MeV. Cosmic muons induce accidental and correlated background. Indeed, they create neutrons through different processes: $\mu$-capture by nuclei of the target, but also electromagnetic nuclear break-up. The energetic neutrons produced will be slowed down by multiple scattering on protons whose recoil energy will give a signal similar to positron energy. At the end, the thermalized neutron will be captured by Gd, giving a signal similar to an antineutrino. Some light beta delayed neutron emitter nuclei may be produced also ($^4$He, $^6$Li) from $^{12}$C break-up and create as well a correlated background signal. The former Chooz experiment data have confirmed the validity of the simulations of these backgrounds and give reliable experimental results to extrapolate. In order to tag correctly the muons, an external veto made of co-extruded plastic bars equipped with scintillating fibers will be positioned on top of the detector, assuring redundancy with the internal veto and allowing $\mu$-tracking.

In the first phase of the experiment, only the far detector will take data. The measured antineutrino energy spectrum will have to be compared with a simulation of the emitted spectrum by the PWR N4 cores of the Chooz power plant, as precise as possible in order to set already a more stringent limit on $\theta_{13}$. The SUBATECH and CEA/IRFU/SPhN teams have focussed their efforts on this calculation. The chosen method takes advantage of the huge amount of decay data accumulated on fission products in the last decade. The antineutrino energy spectrum is computed within 2 stages. A simulation of the PWR N4 core is first performed computing the fission product concentrations, as will be explained in the next report. A specific database constituted of different subsets of different databases has been constituted (BESTIOLE) and completed using Gross Theory spectra and experimental beta spectra [5]. The overall beta energy spectrum is obtained through a weighted sum of the beta spectra branch by branch by the fission product concentration. The antineutrino energy spectrum is then deduced unambiguously thanks to energy conservation. A complete treatment of errors and correlations has been performed. Results are also detailed in one of the following reports. Reactor antineutrinos could constitute also a new reactor monitoring tool. SUBATECH is also very involved in these applied antineutrino physics aspects, as will be presented in next reports.


![Fig. 1: The Double Chooz far detector.](image)
Double Chooz : Reactor antineutrino spectrum simulation

M. Fallot, L. Giot, B. Guillon, J. Martino and the Double Chooz collaboration

Au cours de la première phase de l’expérience Double Chooz, qui va débuter en été 2009, seul le détecteur lointain prendra des données. Il faudra donc comparer les mesures à un spectre d’émission d’antineutrinos par les réacteurs de Chooz simulé le plus précisément possible afin de réduire dès la première phase l’incertitude sur le paramètre $\theta_{13}$. En outre, la détermination précise du spectre en énergie des antineutrinos des réacteurs est indispensable également pour la surveillance des réacteurs avec les antineutrinos.

To simulate as accurately as possible the antineutrino energy spectrum coming from nuclear power plants represents a trial. This is our aim in order to better constrain the $\theta_{13}$ value already with the far detector alone from the Double Chooz experiment [1]. In the eighties, several approaches were followed to access the antineutrino spectra of fissile isotopes. Schreckenbach et al. measured integral beta spectra from $^{235}$U, $^{239,241}$Pu at the ILL Grenoble [2]. They performed very precise measurements up to 8 MeV, but their conversion procedure induced an important shape uncertainty on the obtained antineutrino spectra. Up to now their measured beta spectra remain the most precise ones, and were used in previous neutrino experiments such as the Bugey and Chooz ones [3,4].

The numerous informations on the fission products contained nowadays in databases can be directly used to build branch by branch integral beta spectra and convert them into antineutrino ones without any ambiguity. Moreover the knowledge of individual contributions of fission products allows to simulate the precise time evolution of the antineutrino spectrum emitted by the nuclear power plant due to the large pannel of involved half-lives and simulate the burn-up of the fuel, when coupled to a precise simulation of the core.

We have therefore developed generic simulation tools that can be used to simulate the antineutrino spectrum from any reactor type. A careful computation of the errors on the obtained antineutrino spectrum and their propagation is also carried out. The aim is, at the end, to bring new tools in order to make a performant analysis of the oscillations in the first phase of the experiment.

The SUBATECH team started a simulation work using the widely used particle transport code MCNPX [5] coupled with an evolution code solving the Bateman equations for the fission products within a package called MURE (MCNP Utility for Reactor Evolution) [6]. The time evolution of the isotopic composition of the core is then only driven by the initial fuel composition and the input of the thermal power given by the operators in the case of a power plant. We adapted the code to the needs of the Double-Chooz experiment [7]. The code MURE, giving the total amount of each fission product produced in the experimental conditions, is coupled to the ENSDF database containing beta decay properties of a large number of fission products. The overall beta spectrum is then given as :

$$N(E_\nu, t) = \sum_i Y_i(Z,A,I,t) \sum_j b_{ij}(E_\nu) P_{ij}(E_\nu, E_\nu, Z)$$

The first term $Y_i(A,Z,I,t)$ correspond to the $\beta$-decay rates of the isotopes $Z$, $A$, in the isomeric state $I$, at instant $t$. The terms $b_{ij}(E_\nu)$ and $P_{ij}(E_\nu, E_\nu, Z)$ are the branching ratio and the antineutrino spectral shape for the $j_{th}$ branch with the end-point energy $E_\nu$. A package called BESTIOLE has been developed by the CEA/IRFU/SPhN to read these informations from ENSDF and give them as an input to a code inspired from the BETA-S code from Oak Ridge, computing the beta
spectrum shapes, taking into account the type of the transition [7].

When simulating the $^{235,238}$U and $^{239,241}$Pu beta spectra using MURE and the BESTIOLE packages, no data can be found in the ENSDF database for a non negligible amount of very neutron-rich fission products. Beta spectra measured by Rudstam et al. [8] were then included when they could not be reproduced correctly by the BESTIOLE code. But there still remains a large number of nuclei for which no information at all is available. Our strategy to solve this problem is twofold: improve the simulation of the beta spectra of exotic nuclei, and develop a mixed approach that relies on the precise beta spectrum measured by Schreckenbach et al. and also on our simulation to perform the conversion to the antineutrino spectrum [9]. New measurements are also foreseen.

The high energy part problem could also originate partially from the "Pandemonium effect" [10]. Indeed in databases some experimental information are biased due to the detection apparatus used to perform the measurements of the beta-gamma branches, leading to an overestimation of the high energy part of the Pandemonium nuclei beta energy spectra. To complete the amount of decay data already available, the JENDL database supplies Gross Theory [11] spectra for unknown nuclei and also corrects a selected set of nuclei assumed to suffer from the Pandemonium effect. The changes in our simulated overall beta spectrum when including these JENDL corrected individual spectra are under study.

A lot of different combinations of the different databases can be performed. The TAGS collaboration [12] has also performed re-measurements of nuclei which data were suspected to suffer from the Pandemonium effect. The inclusion of these data in our computation is under study as well. We have also studied the influence of 4 individual fission yields databases, JEFF3.1, JENDL2000 and ENDFB/VI and VII. The fig. 1 and 2 show the case of the $^{235}$U beta spectrum simulations compared with data from [2]. These preliminary spectra are obtained with the best combination of individual spectra from the cited above databases. One can see that the influence of the different fission yields is more pronounced above 5MeV, when short-lived nuclei are involved. In the case of $^{235}$U, JEFF3.1 seems to give better results, but this is not always the case as regards the other fissile nuclei. Similarly to the fission product beta spectra, we have to select the accurarest individual fission yields in the databases, depending on the fissile nucleus.

![Fig. 1: $^{235}$U beta spectrum from [2], compared with different simulations using ENDF, JEFF and JENDL fission yields databases.](image1)

![Fig. 2: ratio of the difference between simulation and data from [2] over data from [2] for different simulations (corresponding to fig.1).](image2)

As regards the computing of errors, the results obtained on the total $^{235}$U spectrum when propagating the errors on the branching ratios and the end-points are lower than 2% below 4MeV, lower than 4% between 4 and 5.5MeV and lower than 6% up to 6.5 MeV [9]. At low energy the computed errors are compatible with the ones of the ILL data, then they become larger. The correlations are large, despite missing the fission yield correlations. These results are promising for a performant oscillation analysis.
Pour pouvoir repousser les limites de notre connaissance des neutrinos, les expériences qui étudient les antineutrinos produits par les réacteurs nucléaires doivent connaître très précisément le spectre en énergie des antineutrinos émis. En effet, même si elles utilisent plusieurs détecteurs identiques, la présence de plusieurs cœurs de réacteur par centrale, présentant en outre un historique de puissance différent, empêche une comparaison directe des spectres mesurés par les détecteurs. L’équipe mène des calculs pour caractériser le plus précisément possible ce spectre en énergie. Pour cela, des simulations de réacteur ont été effectuées ainsi que des études sur la décroissance béta des produits de fission, dont les plus exotiques sont mal connus. Nous présentons ici succinctement ces dernières études. Le spectre des antineutrinos est simulé en sommant branche béta par branche béta toutes les contributions des produits de fission. Cette méthode permet notamment de convertir le spectre béta global en spectre d’antineutrinos sans ambiguïté, de simuler l’évolution en temps du spectre et de propager les erreurs associées. Des comparaisons de bases de données nucléaires avec les mesures existantes des spectres béta issus de la fission des isotopes d’Uranium et de Plutonium sont effectuées. Les calculs d’erreurs sur les spectres béta globaux montrent des erreurs comparables aux mesures utilisées par les expériences de neutrinos jusqu’à présent, sans l’ambiguïté due à la conversion de béta à antineutrino.

The Double Chooz far detector.
Reactor monitoring with antineutrinos: The Nucifer experiment

Collaboration: IN2P3-APC, CEA/DAM, CEA-DSM-IRFU, IN2P3-Subatech

Les antineutrinos pourraient constituer un nouvel outil de mesure de la puissance thermique des réacteurs nucléaires, complémentaire des méthodes actuelles. SUBATECH s'investit dans le projet Nucifer, la construction d'un petit détecteur d'antineutrinos destiné à surveiller à distance et de façon non intrusive l'activité d'un réacteur nucléaire.

Since the discovery of neutrinos more than 50 years ago, tremendous progresses have been achieved on the fundamental knowledge and detection of neutrinos which give new opportunities of applied neutrino physics [1]. Among them, antineutrinos could be exploited for two nuclear reactor monitoring applications: the thermal power measurement and the control of the isotopic composition of the reactor fuel. This is greatly supported by the International Atomic Energy Agency (IAEA) as a potential new safeguard tool. The large quantities of antineutrinos produced, about $10^{21} \bar{\nu}_e$ per second in a 1 GW$_e$ reactor core, arise from the $\beta$ decays of the fission products. The distribution of fission fragments depends on the fissile isotopes ($^{235}$U, $^{238}$U, $^{239}$Pu and $^{241}$Pu). The average number of emitted antineutrinos and their mean energy depend also on the fissile isotope that undergoes fission, such as for the released power which lead to significant differences in the associated antineutrino spectrum.

Mikaelian et al. have first demonstrated the direct relation between the antineutrino flux and energy spectrum with the thermal power and fuel content of a reactor core [2]. If a fixed fuel composition is considered, the neutrino flux is directly proportional to the thermal power of the reactor. On the other hand, at fixed power, the neutrino flux and the shape of the energy spectrum are affected by any change of the fuel composition. These two correlations are the key concepts for reactor monitoring with neutrinos. The measurement of the thermal power of a reactor is currently based on two methods which are both prone to uncertainties: the measurements of the heat evacuated through the steam generators or the measurement of the neutrons emitted by the core. The neutrino method without aiming replacing other methods will allow performing a complementary measurement with different systematic errors. Huber and Schwetz performed a sensitivity calculation and quote that, considering the actual error on the known antineutrino fluxes from U and Pu isotope fissions, thermal power can be measured with a 3% precision with a 10t detector at 10m within 1 day [3]. Recently, thanks to a cubic meter sized antineutrino detector with Gd-doped liquid scintillator installed at the San Onofre commercial power plant, Bowden et al. have confirmed that it is possible to monitor precisely the thermal power over hour-to-month-time scales with a non intrusive and unattended mode but also to have information on the plutonium content of the reactor core [4]. Other similar projects are under development in Brazil and in Japan. The Nucifer detector, under development in France, will also be dedicated to non-proliferation and thermal power applications [5].

The Nucifer project is developed in synergy with the Double Chooz collaboration, taking advantage of their expertise in the neutrino detection. The aim is to have a relatively small detector, portable, fulfilling all safety regulations to be operated at a nuclear reactor and remote controlled with a simple design to...
be built and tested within the next two years. If the concept is validated, it could be deployed at any reactors across the world and be operated by a non-neutrino physicist like a power plant operator or an IAEA inspector.

The preliminary design of the Nucifer detector is presented on Fig. 1. The antineutrinos will be detected in the hydrogenous scintillator via the inverse $\beta$ decay process: $\nu_e + p \rightarrow e^+ + n$. The detector will be a cylindrical steel vessel filled with about 1.5 m$^3$ of Gd-doped liquid scintillator. Photomultipliers tubes (PMTs) optically coupled to the liquid target will be located at the top of the detector vessel. Most of the incident neutrino energy above the reaction threshold (1.8 MeV) is carried out by the positron through the annihilation $\gamma$ rays. This produces a prompt light signal recorded by the PMTs. The neutron is thermalized in the scintillator and tagged by its capture on gadolinium ($\sim$50 ns). Such a delayed coincidence between the gamma rays and the neutron allows a strong rejection of the single events, due to natural radioactivity. A polyethylene layer doped with boron and a lead shield will respectively absorb the thermal neutron flux impinging the detector surface and reduce the external gamma background. A plastic scintillator veto will surround all these components to avoid triggering on the muons coming from the cosmic rays. The overall foot print including shielding is about 2.5 $\times$ 2.5 m$^2$. An energy resolution of 35 % and a detection efficiency of 50% are expected from GEANT4 simulations. SUBATECH is responsible for the design, the development and the realization of the muon veto and its associated DAQ. The design of the veto is an on-going study. This detector should be able to handle a rather high $\gamma$-ray rate environment without penalizing the muon detection.

A first prototype called Module-0 will be installed in 2009 at CEA-Saclay to characterize all the detection chain using sources. Then the detector will be deployed late 2009 at the 70 MW$_{th}$ research reactor OSIRIS (Saclay) to perform first antineutrino measurements. The lower power of this research reactor is compensated by a shorter distance to the core, an easier access to the reactor history and operation and the possibility of dedicated tests. 2000 events per day are expected in the detector. A set of background measurements (neutrons, gamma, muons) have already been performed on the OSIRIS site with the reactor off and at full power. The measured fluxes will set the minimal amount of shielding required to reduce this background below the signal level. These measurements already confirmed the Geant 4 muon rate simulations of 73 m$^{-2}$s$^{-1}$.

A possible second test is foreseen at the ILL reactor (Grenoble, France) to set an accurate absolute normalization before a final validation at a power station. Moreover, the fuel enriched at 97% in $^{235}$U and the short cycle duration of 50 days guarantees a pure $^{235}$U antineutrino spectrum suppresses all systematic errors associated to the control of the burnup effect. After the commissioning phase of NUCIFER, large statistics measurements of the antineutrino spectrum can be foreseen to provide reference spectra for studies of the sensitivity to the thermal power and the plutonium content of the core.


L’expérience Nucifer s’appuie sur l’expertise de la collaboration Double Chooz dans la détection des antineutrinos. Le but est de développer un détecteur de petite taille, transportable, simple dans son utilisation et sa maintenance, qui permettrait de monito-rrer la puissance thermique d’un réacteur avec les antineutrinos émis lors de la décroissance des produits de fission présents dans le cœur. SUBATECH a la responsabilité de la conception, construction et mise en place du véto à muons de Nucifer et de l’électronique associée. Ce détecteur véto sert à dis- socier les événements « antineutrinos » de ceux provenant des rayons cosmiques. Des projets simi-laires sont actuellement en cours au Brésil, Japon et aux USA. Les premiers tests du prototype seront réalisés auprès du réacteur de recherche OSIRIS à Saclay dès fin 2009.
Monte-Carlo simulation of Pressurized Water Reactors


Les deux Réacteurs à Eau Pressurisée (REP) de la centrale nucléaire de Chooz dans les Ardennes, émettent plus de $10^{20}$ antineutrinos/sec lorsqu’ils délivrent le maximum de leur puissance de 4.27 GWth. Ce sont ces antineutrinos que l’expérience Double Chooz va étudier dès 2009, pour repousser la limite de la connaissance du paramètre de mélange $\theta_{13}$. Pour déterminer précisément les caractéristiques des antineutrinos émis, une simulation des cœurs de REP (de type N4) de Chooz est nécessaire. Nous présentons dans ce contexte une simulation de REP complète effectuée avec le code MCNP Utility for Reactor Evolution (MURE). Une étude de sensibilité de l’inventaire aux paramètres d’entrée de la simulation est également présentée.

In the first phase of the Double Chooz experiment [1], only the “far detector”, placed at 1050m from the cores, will be available, thus requiring an accurate knowledge of the antineutrino spectrum emitted by the core. By the means of Monte-Carlo, our work consists in the simulation of the complete history of the Chooz reactor cores during the years of operation. The direct application will be an accurate normalization of the first phase of Double Chooz. The overall antineutrino spectrum is given as:

$$N(E_{\nu},t) = \sum_{i} Y_i(A, Z, I, t) \sum_{j} b_{ij}(E_{\nu}) P_{ij}(E_{\nu}, E_{o,j}, Z)$$

The first term $Y_i(A, Z, I, t)$ correspond to the $\beta$-decay rates of the isotopes $Z$, $A$, in the isomeric state $I$, at instant $t$. The terms $b_{ij}(E_{\nu})$ and $P_{ij}(E_{\nu}, E_{o,j}, Z)$ are the branching ratio and the antineutrino spectral shape for the $j_{th}$ branch with the end-point energy $E_{o,j}$. A specific database containing beta decay properties of a large number of fission products has been compiled from existing databases (ENSDF, JENDL….) to compute the antineutrino decay spectra (see next contribution). A full core simulation of a PWR reactor of type N4 corresponding to the reactors of the Chooz power plant (France), has been performed to compute the fission product $\beta$-decay rates with the MURE package [2]. MURE provides a convivial interface between the widely used particle transport code MCNP (Monte-Carlo N-Particle) [3] and an evolution code solving the Bateman equations. The evolution in time of the isotopic composition of the core is only driven by the initial fuel composition and the input of the thermal power. It is perfectly adapted to take into account the physics of a reactor core, especially the neutronics as neutron capture in various nuclei in the core give non-negligible distortion of the total energy spectrum [4] and the large effect due to long half-life fission products. This package constitutes an efficient tool for non-proliferation and thermal power scenario studies (for more details see [5]).

The core of N4 reactors has been fully simulated. The initial fuel consists of enriched uranium assemblies placed in the core with different $^{235}$U enrichments : 1.8, 2.4 and 3.1% in order to flatten the neutron flux. Each assembly constitutes a square lattice of 289 cells (17x17). In each assembly, 25 guide tubes are present for instrumentation (central rod) or absorbant or burnable poison rods. At the moment, the simulation of the control rods has not been performed as it would induce huge CPU times. Then, in our simulation, the criticality is only controlled with Boron diluted in the moderator, which is about 1000 ppm and constant over time. The water and cladding temperature is 600 K, and the effective fuel temperature considered is 900 K. Fig. 1 shows the burn-up simulation of a standard N4-PWR loaded with fresh fuel and without refueling. The power is maintained constant to 4.27 GWth. As soon as the reactor is operating, reactions of neutron capture on $^{238}$U produce $^{239}$Pu and $^{241}$Pu, which then also contribute to the energy production. The main contribution comes from the two isotopes $^{239}$U and $^{238}$Pu, which contribute to 90 % of the fission rates.
Since the neutron flux is mostly thermal, and due to the very low relative evolution of $^{238}\text{U}$ present in the core, $^{238}\text{U}$ makes a small and constant contribution.

Fig. 1. Time evolution of fission rates for the 4 most important isotopes contributing to the total power.

The effects on the inventory and fission rates of important inputs of a reactor core simulation: boron concentration, temperature effects, geometrical approximations and evolution control are directly related to the neutrino observable. Important uncertainties on the inventory and fission rates can arise from the uncertainties associated to temperatures of materials, cf Table 1.

<table>
<thead>
<tr>
<th>$\Delta N_{\text{f}}$</th>
<th>$\Delta T_m = 30\text{ K}$</th>
<th>$\Delta T_f = 200\text{ K}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}\text{U}$</td>
<td>&lt; 0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>&lt; 0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>0.8</td>
<td>1.5</td>
</tr>
<tr>
<td>$^{241}\text{Pu}$</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 1: $\Delta C_B$: effect of a 200 ppm variation of the B concentration on the U and Pu isotopes number of fissions per second. $\Delta T_m$: effect of a 30 K variation of the coolant temperature. $\Delta T_f$: effect of a 200 K variation of the fuel temperature.

An increase of the moderator temperature, keeping its density constant, results in a displacement of the thermal neutron bump towards higher energies. This effect decreases mean thermal fission cross sections. A 30 K variation of the moderator temperature around 600 K results in an effect smaller than 1% on the main fission rates after one year. Increasing the temperature of the fuel affects the effective cross-section through the Doppler effect. It results in an increase of the resonant capture mean cross sections in the fuel i.e. a negative reactivity coefficient. The effect on the fission rates of a 200 K variation around 900K is shown in Table 1; it is still below 1% except for $^{241}\text{Pu}$, because of its still low concentration after one year.

As absorbant rods are not simulated with MURE, the reactivity excess is compensated at the start of the cycle by the use of borated water. Since the boron (B) capture cross-section follows the $1/v$ law at low neutron energies, higher B concentrations harden the neutron energy spectrum and affect mainly the thermal neutrons. Indeed the effect of B modifies deeply the shape of the neutron energy spectrum in an homogeneous manner in the reactor core. Our simulations show that an uncertainty of 200 ppm on the boron concentration induces a non negligible uncertainty on the inventory and the fission rates of the main four fissile isotopes, of the order of 1 to 2% (cf. Table 1).

Other effects such as the sensitivity of the inventory to geometry approximations and $k_{\text{eff}}=1$ evolution have been studied, results can be found in [6]. These studies will be pursued in order to give an estimation of the precision one can get from such simulations, by the computation of uncertainties and their propagation. Using the presented tools, scenario studies for reactor monitoring with antineutrinos will be soon performed.

L’expérience Double Chooz, présentée précédemment, a pour but d’affiner nos connaissances sur les neutrinos, particules passe-muraille qui interagissent très peu avec la matière. Pour cela, elle utilise l’intense flux d’antineutrinos émis par les 2 Réacteurs à Eau Pressurisée (REP) de la centrale nucléaire de Chooz. Cette expérience qui cherche un signal très faible, a besoin de connaître le plus précisément possible le spectre en énergie des antineutrinos émis par les réacteurs, via la décroissance béta de produits de fission dans le coeur. Ce travail présente les simulations de cœur de REP effectuées à SUBATECH dans ce contexte, et qui serviront notamment à normaliser la première phase de l’expérience.

Pulsed thermography, experimental results and simulation

E. Lys, X. de La Bernardie, V. Métivier, N. Servagent

La thermographie infrarouge active est une méthode de contrôle et d’évaluation non destructive des matériaux. Elle consiste à mesurer le rayonnement infrarouge en provenance du matériau étudié. L’émission d’un rayonnement infrarouge est stimulée en augmentant localement la température du matériau à l’aide d’une source de chaleur externe. Le rayonnement émis par la source est partiellement absorbé par la surface du matériau pour être transformé en chaleur, qui va diffuser dans le matériau. Les défauts rencontrés agissent comme des obstacles à cette diffusion et provoquent des variations locales de la température, observables avec une caméra infrarouge.

Pulsed thermography (PT) is an active method which consists in “lighting” a material on a short duration and in a most uniform possible way, spatially and temporarily (see Fig. 1). The evolution of the surface temperature is observed with an infrared (IR) camera. This temperature variation, named thermal contrast, can reveal defects inside the material.

![Fig. 1: Pulsed thermography experiment.](image1)

Time of heating and duration of acquisition of the images are linked to the thermal conductivity of the material. The measure of the maximum contrast and of the time \( t_{\text{ref}} \) in which it is observed gives information about the nature and the depth of the defect [1]. This time \( t_{\text{ref}} \) is proportional to the square of the depth of defect. To determine the time \( t_{\text{ref}} \), it is necessary to assess the thermal contrast \( C(t) \) in the course of time from pictures of temperature given by the infrared camera.

**Experimental results and simulation**

The goal of the experiment is to quantify how PT with Flir A40M camera can find defects in composite C/PEEK material. A composite plate (2mm thick) with six blind holes (1mm depth and 10, 8, 6, 4, 3, 2mm diameter) is used within the setup shown in Fig. 1 to evaluate the minimal size of detectable defect.

![Fig. 2: thermal imaging of C/PEEK composite plate.](image2)

Fig. 2 presents a direct observation with IR camera and Fig. 3 presents the differential absolute contrast (DAC) correction of temperature measurement to eliminate nonuniform heating at the surface [2]. The DAC method allows seeing the six blind holes.

![Fig. 3: Results of the DAC application.](image3)

The whole experiment is simulated with a finite element software, including thermal and physical properties of C/PEEK (see Fig. 4).
For a semi-infinite medium, the time-dependent surface temperature $T_{surf}$ response to an instantaneous heat pulse is given by the following equation, where $Q$ is the input energy per unit area, $\kappa$ the thermal conductivity, $\rho$ the density and $C_p$ the specific heat of the sample:

$$\Delta T = T_{surf}(t) - T_{surf}(t = 0) = \frac{Q}{\kappa \rho C_p \sqrt{\pi t}}$$

The observation of the cooling of the tested material after the initial heat pulse perturbation thus allows observation of defects: when the heat applied to the surface propagates into the plate and encounters a discontinuity, a deviation from standard evolution (sound area, $-\frac{1}{2}$ slope in the Fig. 5 representation) is observed.

Further investigations are in progress in order to refine the default assessment and evaluation accuracy.

Le groupe PARI de SUBATECH mène des activités de recherche et développement dans le domaine de l’investigation et du contrôle non destructifs (ICND), qui s’insèrent naturellement dans le cadre régional lié au pôle de compétitivité EMC2 et au Technocampus : assemblage multimatériaux (MP32), soude thermo-plastique (MP16T5), contrôle santé matière (TSCNG/LUCIE),…

Les matériaux et assemblages à contrôler sont essentiellement des composites.

Les méthodes utilisées mettent en œuvre les ultrasons, l’optique (profilométrie laser, lumière structurée, interférométrie) et la thermographie infrarouge ; un moyen ultrasons laser est en cours d’évaluation avec EADS IW.

Dans le cadre de l’axe matériaux du CPER 2007-2013, le groupe va mettre en place une plateforme multimodale de contrôle non destructif, regroupant les méthodes optiques, ultrasonores, la thermographie infrarouge ainsi qu’un banc RX.

Pour en savoir plus :

http://www.pole-emc2.fr/
http://www.technocampusemc2.fr/

[1] Xavier P. V. Maldague, Theory and practice of infrared technology for non destructive testing, a Wiley-interscience publication, 2001

Summary of the activities in radiochemistry

The work of the radiochemistry group is dedicated to fundamental and applied questions, related to the behaviour of radioactive substances in the environment, in the nuclear fuel cycle and in medical applications.

The radiochemical and geochemical analysis of the long-term behavior of disposed high-level radioactive waste products in its engineered barrier environment in the geosphere is still at the center of interest of the radiochemistry group. Large research contracts exist with the French nuclear waste management agency ANDRA in the domain of radionuclide transfer in clay host rock of a potential repository site, considering as well the interactions between clay, nuclear waste glass and iron. Increasingly important is the study of graphite as waste material. Key processes studied were the mechanisms, which determine the mobility (transport) and the retention of radionuclides in a natural aquatic medium at the interfaces to solid phases such as waste matrices (glass, spent fuel), host rock minerals and near field materials: dissolution and diffusion mechanism, solubility constraints, coprecipitation, sorption mechanism, solution complexation and activity coefficient corrections, effect of natural organic materials, of micro organisms etc.. The effect of $\alpha$ and $\gamma$ irradiation on certain of these reactions (“radiolysis”) was studied as well. A principal characteristic of the work of the radiochemistry group is the intimate coupling of a multidisciplinary experimental approach with modelling.

Of increasing importance are medical applications of radiochemistry both for imaging and therapy. The arrival of the new 30-70 MeV Cyclotron in 2008 demands a strong coordination and structuring of research in the area of nuclear physics, radiochemistry, biology and nuclear medicine. With projects on At-211 production and on At chemistry and on radiolabelling and with a strengthening of its efforts in studying radiolytic reactions the group has taken a strong engagement in this direction.

Additionally, research on future generations of nuclear energy systems has been initiated focussing on the radiochemical aspects of the management of the waste streams from the HTR reactor concept, which can produce both electricity and hydrogen.

Close interaction exists between research in radiochemistry and the measurement of radioactivity by the service SMART in samples of urban, medical and industrial environments. Here a system of quality assurance has been established since many years, which provides important spin-offs as well for procedure developments in research.

The research has been accomplished by permanent exchange of experience with worldwide leading laboratories. This is documented by five research contracts in the 6th framework programme of the european commission (ACTINET, NF-PRO, RAPHAEL, FUNMIG, MICADO) and three projects in the 7th FWP (CARBOWASTE, RECOSY, TARC) as well as by many joint publications with researchers from Pacific Northwest National Laboratory (US), Forschungszentrum Karlsruhe, Forschungszentrum Jülich, Université Louis Pasteur Strasbourg, the cyclotron CERI of Orleans, Royal Insitute of Technology, Studsvik, CEA, ANDRA, SCK.CEN, ENRESA, Universidad Polytécnica de Catalunya, CIEMAT and PSI. The research is well integrated in the national research structure. This results in funding of research by the IN2P3, by the GdR PARIS and MATINEX, by the Canceropôle Grand Ouest, by the Agence Nationale de Recherche and by the region “Pays de la Loire”.

Today we have some evidence that the large quantity of research projects of international importance carried out by the radiochemistry group did not lead to dispersion or exhaustion of resources but to interesting synergism and innovative approaches: in fact the group is today one of the few institutions in the world, capable to assess the major question of the radio- and geochemistry of nuclear waste disposal and particular of its near field in a systematic manner. The international recognition is documented among others by the coordination of the MICADO project (19 european partners + US-DOE), by the organisation of international workshops on mobile radionuclides in nuclear waste disposal in 2007, La Baule, and on cements in nuclear waste management in 2008, Le Croisic.
Analytical Developments for colloids characterization

A. Piscitelli, S. Huclier, G. Montavon, B. Grambow

Les colloïdes et en particulier la matière organique naturelle, jouent un rôle primordial dans le comportement des radionucléides dans l'environnement. Il est donc indispensable de bien les caractériser pour bien comprendre ensuite leurs interactions. Un certain nombre d'outils analytiques ont donc été développés au laboratoire afin d'étudier ces colloïdes.

AF4 coupled to MALS/QELS:
For an accurate characterization of Natural Organic Matter and Colloids, and in particular to get information on the size distribution and weight distribution Flow Field Flow Fractionation (AF4) analysis coupled to light scattering (MALS/QELS) are usually performed. This technique whose aim is similar to Size Exclusion Chromatography, has been used for the characterization of polyacrylic acids (1200 < Mw < 50000 Da) and humic and fulvic substances as well as colloids from natural seawaters.

ESI-(IT) MS:
The samples are usually analyzed by mass spectrometry with an electrospray ionization (ESI-(IT) MS) in order to get structural information on macromolecules and in some cases on the complexed species formed with metal ions.

LIBD:
The LIBD (Laser Induced Breakdown Detection) is a very sensitive method of colloid detection: up to 5nm in size and some ppt in concentration. Therefore, the installation of such technology was a major stake for the laboratory.
The principle of the method is based on the generation and counting of breakdown events (i.e. creation of plasma) on colloidal particles in liquids. More precisely, when a pulsed laser is focused into a medium and exceeds a certain threshold irradiance, a so-called breakdown occurs in presence of a colloid: process for which the detection of colloids is made either in a photo-acoustical way or in a optical way.
From there, by varying the energy and measuring the corresponding breakdown probability ($H_{bd}$), some so called “S curve” are plotted which give the size (threshold) and the concentration (slope) of the colloidal suspension.

The calibration of the apparatus was made by the use of several types of standards: nanospheres of polystyrene (cf. fig. n°3), of oxide of zirconium,... which sizes vary between 11 and 1000nm and for concentration going up to the ppt.

Fig. 3: Nanosphere of polystyrene, for a diameter of 20nm and several concentrations

From there, first analysis on "real" samples are nowadays performed and first results are therefore acquired: they concern studies, for the time being, on transport of colloids, on size for chromium (cf. fig. n°4) and zirconium colloids.

Fig. 4: LIBD analysis of chromium particles (6nm in diameter) and comparison with polystyrene (20nm – 10ppb)

A partir des différentes techniques d’analyse développées au laboratoire (AF4 & MALS/QELS, ESI-(IT) MS et LIBD), des colloïdes, organiques ou non, sont étudiés et caractérisés dans des conditions extrêmes. Les données ainsi récupérées permettent alors un meilleur compréhension des phénomènes mettant en jeu les radionucléides dans l'environnement.
Complexation properties of At(x)$^+$ species

J. Champion, S. Huclier, A. Beasse, G. Montavon

Alpha-radioimmunotherapy is an innovative technique for the treatment of cancers complementary to current approaches. The principle is to use tumor-specific vectors labeled with alpha-radioisotopes. Astatine 211 is a very promising candidate if one considers the energy of the α particles emitted as well as its physical half-life (7.2 h). In spite of its interest, only few studies have been undertaken with astatine. This is explained by its poor availability (production with accelerators capable of accelerating alpha particles to high energies). The results available in the literature show that the labeling performed by substitution reactions, as it is the case with iodine, is not always efficient due to the weak stability of the C-At bond inducing a rapid deastatination in the organism.

Another way of labeling is to use astatine at a higher oxidation state as a “metal cation”. In this case, bifunctional chelating agents (BCA) are used: one function is used to form a stable complex with the radioisotope whereas the other allows for the connection with the vector. This way of labeling has never been explored. This can be explained by the fact that the astatine chemistry is nearly unknown.

The objectives of the project, carried out in a research consortium implying the radiochemistry group of Subatech and researchers from Nantes (CEISAM, CRCNA) and Strasbourg (IPHC) Universities are:
1/ to define and prepare the astatine species at ultra-trace concentrations (10$^{-13}$ - 10$^{-15}$ M);
2/ to define a methodology characterizing the interaction of organic molecules with astatine species at ultra-trace concentrations (10$^{-13}$ - 10$^{-15}$ M);
3/ to explore the coordination properties of the astatine species based on a step by step approach;
4/ to synthesize or define suitable bifunctional chelating agents and to assess the in-vitro stability of the labelled compounds.

The results linked to the two first objectives are presented in this report.

PRODUCTION OF ASTATINE

Astatine is produced by the CNRS cyclotron of Orléans via the nuclear reaction $^{209}$Bi(α,2n)$^{211}$At with alpha particles of 28 MeV. After production, $^{211}$At is isolated from the irradiated target using a wet extraction procedure [1].

CATIONIC FORMS OF ASTATINE

Astatine (At), element 85, has the electronic configuration [Xe]4f$^{14}$5d$^{10}$6s$^2$6p$^5$ and is below iodine in the Periodic Table of the Elements. The chemistry of astatine, one of the most difficult elements to investigate from a chemist’s point of view, is not well understood. There are no stable isotopes of astatine, with its longest-lived isotope having a half-life of 8.3 h. As a result, all chemical information has been derived from radiochemical studies at trace concentrations, typically 10$^{-11}$ to 10$^{-15}$ M. The astatine pourbaix diagram in non-complexing medium is still a matter of discussion considering the oxydation states as
well as the nature of the species [2]. The results of the present work show the existence of both At⁺ and AtO⁺ (At(\(x\))\(^+\)) forms that may be used for the chelation approach.

**QUANTITATIVE DESCRIPTION OF THE INTERACTION OF At(\(x\))⁺ WITH COMPLEXING AGENTS**

A displacement method is proposed to determine the complexation constants between astatine species At(I) and At(III) and complexing agents. The method, tested with SCN⁻ and a thia-calix[4]arene is based on solid / liquid or liquid / liquid separation procedures. For the solid / liquid separation, the cationic exchanger Dowex 50X8 was used. The interaction of At(I) and At(III) with the cationic exchanger is specific but could not be described by the cation exchange process expected. Most probably, At(I, III) interact with a “strong” site (in weak amount) to form a surface complex at the surface of the resin organic skeleton. For the liquid / liquid separation, chloroform, toluene and hexane were used. The solvents extract astatine species with distribution coefficients varying between 0.7 and 120. The extraction process was shown to be independent of aqueous phase characteristics (pH, ionic strength) and was explained by the solvation of astatine species by the organic solvent. The effect of the addition of the thia-calix[4]arene on the solid / liquid separation coefficients could be well described by the formation of a 1:1 At:thia-calix[4]arene complex with logK constants of 4.5 and 3.3 for At(I) and At(III), respectively. The higher constant measured for At(I) may be explained by a macrocyclic effect. For SCN⁻, the data measured in the presence of the organic solvents are explained by the formation of both 1:1 and 1:2 At:SCN complexes. In the case of the solid / liquid separation, data analysis was hampered by the probable formation of a ternary complex between At(I, III), SCN⁻ and the sites of the resin. The interaction strength appears slightly higher for At(I) (logK=5.9 and 3.8 for 1:2 and 1:1 complexed species, respectively) than for At(III) (logK=5.3 and 2.8 for 1:2 and 1:1 complexed species, respectively).

The constants obtained between At(III) and SCN⁻ are in good agreement with published data obtained using an electromigration method.

**PERSPECTIVES**

The work related to objectives 3 and 4 is being made.

**ACKNOWLEDGEMENT**

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Colloids effect on the migration of U(VI) in a sandy geological formation.

P. Le Cointe, S. Huclier, S. Azdani, A. Piscitelli, B. Grambow, G. Montavon

Les colloïdes sont des petites particules qui peuvent faciliter le transport des éléments toxiques dans l'environnement. Nous nous intéressons dans ce travail à l'effet de colloïdes naturels (argiles, substances humiques) sur le transport de U(VI) dans une formation géologique constituée de sable.

Colloïds are small particles / soluble polyelectrolytes that may affect or facilitate the transport of contaminants in soils. The effect of natural colloïds (clay material, natural organic matter (NOM)) on the transport of the uranyl ion UO$_2^{2+}$ in a sandy geological formation is studied in the present work. Transport experiments realized in the laboratory are quantitatively described with the objective to de realize a predictive numerical model.

System characterization

Sampling of the sediment (50 L) and the groundwater (210 L) were done in March and December 2007. A scheme of the geological formation is presented below:

![Figure 1: Geological background of the studied site.](image)

The sediment is made of three main components: quartz (90%), a clay fraction (10%) and Natural Organic Matter (2 ppm in solution). Quartz is an immobile fraction whereas the clay can be considered as an immobile or mobile (colloidal) fraction depending on the ionic strength of the aqueous medium. Regarding the Natural Organic Matter, ESI-MS (ElectroSpray Ionisation Mass Spectrometry) experiments showed that it is mainly made of fulvic acids. The content of NOM found in the sediment (< 0.3%) indicates that it can be considered as a colloidal fraction. The different phases were separated and isolated from the sediment and the water samples to be used in the transport studies.

Physical transport

The objective of this part is to define the hydrodynamic parameters characterizing the transport of the particles and solutes as well as the parameters describing the porous compacted medium (porosity, size filtration). This was assessed by imaging and transport studies realized with inert Polystyrene colloids.

Imaging

It was done with X-Ray Microtomography on the raw sediment compacted in a capillary of 5mm in diameter. The figure presented below shows an output picture. A mean pore diameter of about 15 μm is estimated.
Figure 2: Image of the compacted sediment done with X-Ray Microtomography

Transport studies
The studies were realized with two columns, one containing the raw sediment, the other the separated quartz phase. The effective porosities of both columns were determined by tracer experiments with HTO and Cl-36. The colloids detection was performed by Laser Induced Breakdown Detection (LIBD), a system developed in our laboratory. The principle is described below.

Nanocolloids of 500 nm in diameter pass through both columns without significant difference in speed as compared to HTO and Cl-36 tracers. For the colloids of 5 μm in diameter, they could not be detected at the exit of the column made of raw sediment. Regarding the quartz column, the colloids are not filtered out but they are significantly delayed compared to the conservative tracers. The size exclusion appears therefore around 5 μm. This value is in the same order of magnitude as the one obtained from imaging. The results show as well that porosity and size exclusion of the compacted sediment is strongly dependent on the content of clay. This was confirmed from the results of the tracer experiments: the effective porosities increase when the content of clay decreases.

Perspectives
The geochemical model describing U(VI) behaviour in the system is under construction and reactive transport experiments with U(VI) are foreseen with the quartz column in the presence or absence of the colloidal phases of interest (clay colloids, Natural Organic Matter).

ACKNOWLEDGMENTS
The work is financed by the French National Agency for Radioactive Waste Management (ANDRA).

Figure 3: LIBD principle
A typical result is reported in Figure 4.

Figure 4: Quartz column; Comparison of the breakthrough curves obtained with nanocolloids of 500 nm in diameter and conservative tracers.

Le but de ce travail est de comprendre si les petites particules (colloïdes) que l’on trouve dans les nappes phréatiques peuvent contribuer à faciliter le transport des éléments toxiques dans l’environnement.
Model uncertainty for the mechanism of dissolution of spent fuel in a nuclear waste repository (MICADO)

B. Grambow

Direct geological disposal of used fuel from nuclear energy production is a waste management strategy for many European member states. If the highly radioactive used nuclear fuel is placed within a thick-walled metallic container directly into a repository the corrosion of the container and access of slow flowing deep groundwater to the fuel is likely to occur after some thousands of years. But what happens if deep groundwater comes in contact with the fuel? For some 25 years research has been developing predictive procedures, accumulating experimental data and creating theoretical models. The coordinated action MICADO will assess the uncertainties in models describing the dissolution mechanism of spent nuclear fuel in a repository for geological time periods.

Nature and goals: Reliable models for predicting underground stability

MICADO’s objective is to find out whether international research has now provided sufficient reliable models to assess the corrosion resistance of spent fuel in groundwater and to contribute to answering the question whether radioactive used fuel from nuclear reactors can be stored safely for hundreds of thousands of years in a geological repository. Coordinated by SUBATECH/ARMINES this coordinated action brings together the efforts of many European waste management agencies, technical support organisations for regulators, universities and research organisations in Europe. Together with the involvement of the US American Department of Energy, this means that most of the world’s leading experts are participating in the project representing a variety of approaches to the prediction of the performance of disposed spent fuel over very long time periods.

Issues and activities: Assessing uncertainty, identifying needs

The key actions undertaken by the project concern the assessment of uncertainties in the experimental database as well as in models used. Direct extrapolation of empirical data to the long-term is not currently possible due to the difficulty of simulating the radiation exposure history of the spent fuel and the large time gap between an experiment conducted for few years in a laboratory and the real time horizon for disposal of hundreds of thousands of years. The mechanistic models, which translate the experimental observations to such long times, are also uncertain.

The project compares the different approaches and underlying hypotheses in the context of an evaluation of the quality of key experimental data. Two types of uncertainties will be assessed: uncertainties governed by the divergence between the various models and the experimental databases and uncertainties in predictions that arise from comparison of the outcomes of the various models. Detailed descriptions of the various models have already been produced and they will be compiled and com-
pared in a common document. Knowledge on the various approaches and methodologies used in spent fuel performance analyses will be shared between the various participating organisations via events such as the “teaching workshop” organised in February 2007 in Madrid. From these comparisons future research needs will be identified to reduce the observed uncertainties.

**Anticipated achievements: Reliable models and their limits**

It is known that certain fractions of the radionuclide inventory are very mobile and may become released almost instantaneously upon groundwater contact. This release may provide a very significant contribution to the expected dose from disposed spent fuel in the first 10 000 years. The size of these mobile fractions may depend on fuel evolution during the thousands of years prior to water access. The project will tell us how reliable our models and the underlying experimental data are in predicting these labile radionuclide inventories. Furthermore, although the project may not tell us exactly how long it will take for complete dissolution/corrosion of the remaining irradiated fuel matrix, it will organise the expert-judgement to assess the uncertainties inherent in such estimations.

It is finally expected that the project will provide a clear distinction between real uncertainties (missing data, ill-defined models, uncertain boundary conditions etc.) and apparent uncertainties caused by various simplification schemes in the models. For example, it will be assessed whether one can ignore the reactions of radiolytic radicals with the spent fuel surface without reducing the precision in the calculations. The exchange of knowledge organised in the project will increase the mutual understanding of the current state of knowledge and allow identification of gaps to be addressed in the FP7.

**Impact on Society: Confidence building and transferring knowledge**

In the absence of a broadly agreed approach to the management and disposal of long-lived waste in geological repositories the project takes a very important step in confidence building by assess the remaining uncertainties in spent fuel behaviour.

The MICADO project provides a unique opportunity by facilitating knowledge transfer between research institutions and universities working on fundamental fuel stability data and model development, waste management organisations trying to assess long term spent fuel stability, and technical support organisations working for regulators in charge to evaluate these assessments, as well as with other stakeholders, by creating a common well-reviewed database, by exchanging model approaches, by testing model application to this database and by assessing the implications of these uncertainties on uncertainties in long-term safety evaluations.
Transport through callovo-oxfordian argilite: Percolation experiments

C. Landesman, C. Bailly, N. Bessaguet, D. Durce, V. Baty, K. Perrigaud, B. Grambow

The understanding of the long-term behaviour of high-level radioactive wastes in a geological environment is of great importance for the acceptance of a future deep repository site. One of the key issues is the understanding of the transport mechanisms of mobile radionuclides through the barriers of the repository and especially through the Callovo-Oxfordian (COx) argillite, which is currently under investigation in France as potential host rock formation.

Transport properties of radionuclides through argillite can be influenced by several factors such as local variability of minerals within the argillite (clay minerals, carbonates, quartz,...) or existence of colloids which may promote the migration of radionuclides. Our objectives are i) to obtain macroscopic transport parameters of radionuclides (diffusion/dispersion coefficient, porosity, permeability,...) and ii) to determine the particle size cut-off for colloid filtration by the porosity of the argillite rock.

Our research took place in the framework of the R&D ANDRA collaborative project “GL Transfert”.

Experimental description

Argillite samples from deep boreholes at – 445 m/- 490 m of depth, well protected against air oxidation and dehydration, were used to fabricate cylindrical samples of 2 to 6 cm of diameter and a tolerance of 10 µm. Stainless steel flow through reactors of 70 µm smaller inner diameter where fabricated as well. After placing the argillite sample in the reactor small volumes of synthetic COx water were allowed to enter the reactor, leading to swelling of the argillite core and the closure of remaining void spaces at the reactor wall. Thereafter, percolation experiments were started. A high pressure pump has been used to push the synthetic COx water through the argillite core. Radionuclides of interest are then injected into samples via a injection loop connected to a valve. Typically, for small samples (diameter = 21 mm; length = 40 mm), the working pressure is fixed to 100 bars and the output flow rate is very low (around 40 µl/day). For these operating conditions, percolation experiments could last several months.

In order to reduce the duration time and to operated at a lower pressure (more representative of the COx argilite layer pressure around 40 bars), large reactors are used for argillite samples with a high diameter/thickness ratio, R, typically equal to 4 (see figure 1). This ratio can only be obtained with argillite samples containing more than 80 % of clay minerals.

Fig. 1: large reactor (left) and its argilite sample (right)
For that kind of samples (diameter = 60 mm; thickness = 15 mm), the working pressure is 5 bars and the output flow rate is around 720 µl/day. Figure 2 shows a typical experimental setting.

**Results**

First experiments (without injection of radionuclides) were devoted to the determination of the hydrodynamic parameters of the sample. Synthetic COx water was allowed to percolate through argillite sample at flow rates ranging from 0.5 to 5.5 µL/min and pressure was registered. The results are shown figure 3. The linear variation between pressure and flow rate shows that the Darcy’s law is valid over the studied range.

Injection of radionuclides (HTO and 36Cl) allows determining water accessible porosity and anion accessible porosity respectively. These parameters are of great importance for transport modelling. Figure 4 shows the breakthrough curve of HTO.

**Perspectives**

In order to investigate the influence of the mineralogy, experiments will be performed on argillite samples with variable amounts of carbonate minerals (ie: less amounts of clay minerals). Moreover, injection of variable size colloids (solid particles, polycarboxylic acids of variable molecular weight, natural organic acids,...) are planned to determine the cut-off of intact argillite.

**ACKNOWLEDGEMENTS**

The work is financed by the French National Agency for Radioactive Waste Management (ANDRA).

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Le but de cette étude est de comprendre les propriétés de transport des radionucléides au sein d’une argillette intacte (non fissurée) et de déterminer le pouvoir de filtration de cette roche vis à vis des colloïdes naturels pouvant exalter leur migration, radionucléides.
La venue prochaine du cyclotron ARRONAX à Nantes (septembre 2008) est l’occasion de répondre à plusieurs problématiques scientifiques posées dans le cadre du stockage des déchets nucléaires. L’oxyde d’uranium a été étudié durant de nombreuses années en tant que solide de référence car présent en majeure partie dans le colis de déchet. Malgré la multitude de données sur UO₂, les mécanismes d’oxydo-réductions et de dissolution ne sont pas clairement définis. De plus, peu de données existent sur les effets de la radiolyse de l’eau (initiée par le rayonnement α de l’UO₂) et de la présence de H₂, en tant que gaz issu de la dégradation du colis de déchets radioactifs. Cette étude permet d’analyser indépendamment chacun de ces paramètres pour définir leur influence sur les mécanismes de dissolution d’UO₂ à l’interface solide/solution.

Dissolution of TRISO-coated spheres UO₂ has been studied under α irradiation. The aim of this work is to understand the link between UO₂ α emitter potential fuel, H₂O₂ α water radiolysis product and H₂ gas present in the depth waste storage. 30 UO₂ spheres (without coating) were put in 30 ml of aqueous solution ([NaCl] = 1E-3 mol/l and [NaHCO₃] = 4 E-2 mol/l) with 0.76 g/l ratio. The system was controlled under reducing conditions with electrochemical materials. α irradiation has been performed using the CERI/CNRS cyclotron site in Orléans. One irradiation experiment used a 28 Mev α beam (7 MeV in solution) with a dose rate of 100 Gy/min for 2 hours. Moreover, we used Ar and Ar/H₂ gas to fill the system in order to improve the oxygen-free conditions and to study H₂ gas effect on UO₂ dissolution. In fact, these experimental conditions were successfully used in our laboratory to study the dissolution of UO₂ colloids under α radiolysis [1]. U concentration in solution was measured by ICP-MS and H₂O₂ concentration using the Ghormley method with a UV spectrometer. Table 1 shows U and H₂O₂ concentrations results for each sample:

- “ref-Ar”: without solids under Ar gas.
- “ref-Ar/H₂”: without solids under Ar/H₂ (95/5%) gas.
- “TRISO-Ar”: with 30 UO₂ spheres under Ar gas.
- “TRISO-AR/H₂”: with 30 UO₂ spheres under an α beam and Ar/H₂ gas.

Under Ar gas, U concentration increases (0 to 1.86 E-8 mol/l) at the same time that H₂O₂ concentration decreases (1.01 E-5 to 0.86 E-5 mol/l). So, the link between H₂O₂ consumption and UO₂ dissolution is established. When we add H₂ gas to the system we obtain some important data. H₂O₂ production increases with a ratio close to 2. Thus, there is a link between H₂O₂ and H₂ gas.

<table>
<thead>
<tr>
<th>Sample</th>
<th>[U] (mol/l)</th>
<th>[H₂O₂] (mol/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>“ref-Ar”</td>
<td>0</td>
<td>1.01 E-5</td>
</tr>
<tr>
<td>“ref-Ar/H₂”</td>
<td>0</td>
<td>2.09 E-5</td>
</tr>
<tr>
<td>“TRISO-Ar”</td>
<td>1.86 E-8</td>
<td>0.86 E-5</td>
</tr>
<tr>
<td>“TRISO-AR/H₂”</td>
<td>3.36 E-8</td>
<td>1.27 E-5</td>
</tr>
<tr>
<td>“TRISO-α-Ar/H₂”</td>
<td>3.37 E-6</td>
<td>1.34 E-5</td>
</tr>
</tbody>
</table>

Table 1: [U] and [H₂O₂] in solution after dissolution under a irradiation

Moreover, as shown in figure 1, UO₂ dissolution increases with a ratio close to 2. Thus, there is a non-negligible influence of H₂.
gas as it relates to UO₂ dissolution: H$_₂$ gas improves UO₂ dissolution. Finally, among samples under Ar/H$_₂$ gas we can check that when spheres are under an α beam the effect on UO₂ dissolution is very important (3.36 E-8 to 3.37 E-6 mol/l) while H$_₂$O$_₂$ consumption is the same (about 0.7 E-5 mol/l). Under an α beam many of the water radiolysis products (e- , OH$^-$,…) can affect the UO₂ dissolution and probably local H$_₂$O$_₂$ concentration is much higher that we have measured by the Ghormley method. Consequently, we need to measure these radiolysis product concentrations with an in situ technique.

\[
\frac{[U]_{H_2}}{[U]} = \frac{[U]_{H_2}}{[U]} = \text{In order to improve detailed solid characterization, we will perform μ-Raman in situ spectroscopy onto the cyclotron ARRONAX. This supply will be able to analyse solution by UV spectrophotometry and solid by μ-Raman spectroscopy. We want to carry out a project to install this supply into cyclotron ARRONAX (see figure 3).}

\[
\text{Fig. 1: [U]} \text{ in solution vs. α irradiation time}
\]

The cyclotron ARRONAX answers many questions requested by this experiment. Moreover, α pulse beam (not provided by CERI cyclotron) will be used to measure directly in situ radical species concentrations. Concerning the solid, we have obtained pictures by Scanning Electron Microscopy (SEM). This picture is presented in figure 2. We observe that UO₂ dissolution occurs locally in particular into grains boundaries.

\[
\text{Fig. 2: SEM pictures of UO₂ spheres after dissolution under α irradiation}
\]

\[
\text{Fig. 3: μ-Raman and UV facilities in UO₂ dissolution under irradiation α in cyclotron ARRONAX}
\]

\[
\text{Le cyclotron ARRONAX, disponible bientôt à Nantes, est un outil de choix pour l’étude des mécanismes de dissolution des solides sous irradiation α. Dans cette optique, Subatech met en place depuis 2 ans une étude sur un autre cyclotron français (CERI/CNRS) à Orléans concernant l’effet de la radiolyse α et du dihydrogène sur les mécanismes de dissolution de l’oxyde d’uranium. La finalité de cette préparation est la mise en place d’un système de caractérisation in situ de l’interface solide/solution sur le cyclotron ARRONAX utilisant la spectrophotométrie UV et la spectroscopie Raman.}

The method is based on the electrochemical reduction of U(VI) into U(IV), using a galvanostat (Radiometer Voltalab 21). All experiments were performed during several days inside a reaction vessel containing 1 mol/l NaCl at ambient temperature. All solutions were prepared with degassed Milli-Q water (Millipore, 18 MΩ.cm) and all chemicals used were of analytical purity. Stock solution of U(VI) was prepared by dissolving UO₂(NO₃)₂.6H₂O in 1 mol/l NaCl. The HCl stock solution was prepared in a glove box (MBraun, MB-200 with an extension model MB-200 MOD-E 1250/1000) under a nitrogen atmosphere, using the degassed water. The U(IV) stock solution was prepared in the glove box by electrolytic reduction of the initial U(VI) nitrate solution in the absence of O₂. The pH of this solution was kept lower than 1 to ensure the stability of U(IV). The redox and U(IV) stability were controlled periodically by a UV-Vis spectrophotometer (Shimadzu, UV-2401PC) connected by optical glass fibers directly to the glove box.

Irradiations

The samples were submitted to γ irradiation in a panoramic IL60PL (Cis Bio International, LCP Orsay) ⁶⁰Co source. The dose rate was about 3000 Gy/h (determined by Fricke’s dosimeter). Alpha irradiation was performed at the CERI cyclotron (CNRS-Orleans). This cyclotron generates alpha particles (⁴He⁺) in an energy range from 5 MeV to 45 MeV. Energy of 28 MeV was chosen for all the Tc experiments. The calculations from SRIM2000 code indicated that ⁴He⁺ (28 MeV) passed into the cell carrying energy of 5-6 MeV and a penetration depth in solution about 45 µm. The rest of energy was absorbed by the cell window and by the titanium windows of the ionization chamber. The alpha beam was monitored during the experiments as a function of the measured ⁴He⁺ current on the ionisation chamber. During all the experiments, the current of ⁴He⁺ flux in solution was fixed in the range from 10 nA to 50 nA. The irradiation time depending of experience, vary between 5 mn to 40 mn. The duration of an experiment is around 1h30.

Fig. 1: Set-up used for alpha radiolysis experiment, performed at the CERI cyclotron, Orleans, France.
Alpha and gamma radiolysis of U(IV)

The oxidation mechanism of U(IV) to U(VI), through unstable U(V) oxidation state is investigated in acid solutions. Under this high concentration of scavengers (H+, Cl−), the solvated electron and hydroxyl radical, formed by radiolysis of the solution, react in the spurs before diffusion, and generate the two major oxidizing species in the medium: ClOH•° and Cl2−°. The formation of ClOH•° and Cl2−° have been studied using ps pulse probe experiments [1]. From the kinetics observed at 690 nm and at 345 nm, G(OH•), G(ClOH•°) and G(Cl2−) were determined. These measurements are combined with a study of the U(IV) into U(VI) using alpha and gamma irradiations (Fig. 2, Fig. 3). The radiolytic yields (Tab. 1) measured by stationary radiolysis are interpreted with the initial yields of production of the radicals measured at the ps time-scale[1].

<table>
<thead>
<tr>
<th>G(-UIV) μmol J−1</th>
<th>Gamma</th>
<th>Alpha</th>
<th>Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.42 ± 0.03</td>
<td>0.09 ± 0.03</td>
<td>N2 / Ar</td>
<td></td>
</tr>
<tr>
<td>0.87 ± 0.03</td>
<td>0.12 ± 0.03</td>
<td>N2O</td>
<td></td>
</tr>
<tr>
<td>0.90 ± 0.03</td>
<td>0.06 ± 0.03</td>
<td>O2</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 1: G(-UIV) values, gamma and alpha irradiations, atmosphere Ar/N2, N2O, O2.

Les solutions concentrées de l’uranium(IV) sont de couleur verte et relativement stables en milieux acides. En présence de rayonnements gamma ou alpha, ces solutions vertes deviennent incolores. Ceci implique que les rayonnements peuvent modifier le contenu d’une solution. En effet, les rayonnements en traversant la solution de l’uranium déposent une quantité d’énergie comparable à celle déposée par la chaleur. Cette énergie déposée dans la solution modifie la composition chimique de celle-ci. Les rayonnements sont très présents dans les sites de stockage des déchets et ils peuvent modifier les formes chimiques des déchets et par conséquent leur comportement dans ces sites. Le but de notre étude est de regarder l’effet des rayonnements gamma et alpha sur le comportement des déchets radioactifs comme exemple : l’uranium et le technétium.

Scandium complexes for medical applications in a new PET/3γ camera and radio labelling studies

S. Huclier, G. Montavon

Il s’agit d’étudier les propriétés de complexation de ligands polyaminopolycarboxyliques, déjà utilisés comme radiopharmaceutiques, avec le scandium. Cet élément, dont plusieurs isotopes seront produits par le cyclotron Arronax, pourra être utilisé dans le cadre du développement d’une nouvelle caméra TEP et pour des applications de radio-immunothérapie.

INTRODUCTION

Among the various types of imaging techniques available for diagnosis of diseases, Immuno-PET as a scouting procedure before radio-immunotherapy (RIT) and the associated radiopharmaceutical are powerful tools. A new nuclear medical imaging technique based on the measurement of the emitter location in the three dimensions with a few mm spatial resolution using β+/γ emitters, has been developed by our team [1]. Such measurement could be realized thanks to a new kind of radio-nuclides which emit a γ-ray quasi-simultaneously with the β+ decay whose the most interesting radio-nuclide candidate is 44Sc (T1/2=3.97h, β+=94.27%, γ=99.9%). In addition to this, 47Sc is planned by the nuclear medicine teams for its potential interest for the β-RIT [2,3,4]. Such applications strictly demand that metallic radionuclide remain intimately associated to the targeting protein to minimize the toxicity derived from the dissociation and the delivery of radiation to normal, non targeted body tissues. A crucial aspect of these techniques is that the metal ions form thermodynamically stable and kinetically inert complexes with the selected compounds.

A number of macrocyclic chelators have been proposed as bifunctional agents for labeling antibodies and peptides with several radionuclides [5]. Owing to their structural features, tetraazamacroyclic derivatives form metal complexes with the required properties for these applications. The high affinity shown by some polyaminocarboxylic acids has been exploited to form very stable complexes (up to log KML > 20) [6]. For instance, metal complexes of DOTA and numerous DOTA derivatives have been developed for a variety of purposes, generally involving the use of the metal ions as probes [7].

The chelating ligand DOTA has been shown to bind transition metals and rare-earths with extreme stability under physiological conditions, leading to its use in vivo [6]. A DOTA derivative (NBD i.e. (S)-2-(4-nitrobenzyl)-DOTA) was tested with lanthanides and Sc³⁺ for its complexation properties and with the monoclonal antibody 2D12.5 [8]. A team [9] has discovered that this antibody bound specifically the DOTA chelates of all lanthanides with similar affinities, potentially making it a molecular docking station for medical imaging and therapy and other biotechnological applications. Nevertheless, the same team showed that the NBD-Sc chelate bound the 2D12.5 antibody with a much lower affinity than the strongest binding rare earth complex, perhaps because Sc³⁺ has a much smaller ionic radius [9]. The aim of this paper is to report the stability constant values for Sc³⁺ with DOTA, DTPA and TETA and their behaviors in serum conditions as well as for in vivo conditions for PET imaging with “Sc and radio-immunotherapy with “Sc.
RESULTS

Determination of the protonation constants

The protonation constants of DTPA, TETA and DOTA were calculated using the speciation code CHESS [10]. The protonation constants determined in the present study are summarized in Table 1 together with values obtained previously in 0.1 M of Me4NCl [11] and 0.1M of Me4NNO3 [6] for comparison purposes. Those values of log Kn are in quite good agreement with those obtained at 298 K for different background solutions as reported in a critical compilation of equilibrium constants [11].

Kinetics and Stability constants

The curve of the potentiometric titration of Sc-L in NaClO4 0.1 M presented a significant deviation from the curve of the respective L alone in the same conditions (Figure 6). The pKa values determined previously for L and the hydrolysis constants for Sc3+ alone were fixed and only the stability constant of Sc-L were fitted. From literature [12], it was shown that the stoichiometry of the complex was 1:1 described by the following equilibrium.

\[ mM + hL + hH^+ \rightarrow M_n L L_h H_h \]

\[ \beta_{mth} = \left[ \frac{[M][L][H]}{[M][L][H]} \right]^h \]

Table 1: protonation constants of DTPA, DOTA, TETA.

<table>
<thead>
<tr>
<th></th>
<th>DOTA</th>
<th>DTPA</th>
<th>TETA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Delgado et al., 2005 0.1M NaClO4</td>
<td>Bonin et al., 2008 0.1M NaClO4</td>
<td>Delgado et al., 2005 0.1M NaClO4</td>
</tr>
<tr>
<td>Log K1</td>
<td>12.09</td>
<td>10.3-10.4</td>
<td>10.2</td>
</tr>
<tr>
<td>Log K2</td>
<td>9.68</td>
<td>9.7-9.8</td>
<td>8.5</td>
</tr>
<tr>
<td>Log K3</td>
<td>4.55</td>
<td>4.5-5.1</td>
<td>4.23</td>
</tr>
<tr>
<td>Log K4</td>
<td>4.13</td>
<td>4.2-4.3</td>
<td>3.7</td>
</tr>
<tr>
<td>Log K5</td>
<td>2</td>
<td>1</td>
<td>1.84</td>
</tr>
</tbody>
</table>

From TRLFS kinetics experiment, it was deduced that the equilibrium of Eu3+ complexation with DOTA was reached after 2 hrs (Fig. 1). This seems to be too long for radiopharmaceutical applications. For DTPA and TETA, the interaction was found to be immediate.

In addition to this, some modifications of the shape of the emission spectra were observed as a function of time indicated some evolution in the complex symmetry properties.

The stability constants determined by potentiometric titrations are summarized in Table 2 together with data available from literature for Eu [6] have shown that the compounds DOTA and TETA form thermodynamically stable and kinetically inert complexes with di- and trivalent metal ions.

Reversibility

For RIT applications, metallic radionuclide must remain intimately associated to the targeting protein to minimize the toxicity derived from the dissociation. A point of interest is thus to study the reversibility of the equilibrium. To this aim, we have performed, in vivo like conditions, dissociation experiments in the presence of apotransferrine at pH = 7 and with carbonates. We also have used a complex to protein ratio of 2 since the protein has 2 metallation sites. The potential dissociation of Sc from the complex to the protein was monitored by UV after having verified that free Sc goes into the iron site of the protein and the Sc-ligand complexes do not absorb in the area of interest of the protein.
For DOTA and DTPA Sc complexes, nothing happens at least during the experimental time of 2 hours. Sc remains associated to the organic molecule. For TETA, it has a different behaviour. The spectrum (Fig. 2) recorded at 2 minutes indicates that Sc goes into the protein. The differential spectra in the inset show the 2 peaks of the tyrosine groups of the transferrine modified by the scandium.

Fig. 2: UV spectra monitoring Sc-TETA interaction with apotransferrin

Les 3 ligands étudiés présentent de fortes constantes de stabilité avec le scandium. Seuls les ligands DTPA et TETA ont des cinétiques d’interaction rapides et compatibles avec des applications médicales alors que les ligands DTPA et DOTA sont les seuls à être stables dans un milieu biologique extrêmement simplifié. Les prochaines étapes seront de valider ces données en procédant à des tests in vitro puis in vivo de manière à appréhender le comportement de ces complexes Sc-L dans des conditions plus proches de celles utilisées par les radiopharmaciens.

REFERENCES


10 Van der Lee


Automatic potentiometric titration set-up
Speciation of Technetium in acidic and non-complexing medium: Eh-pH effect

N. Vongsouthi, M. Fattahi, B. Grambow

Technetium-99 ($^{99}$Tc) is present in large quantities in nuclear waste, and properties related to its chemical behaviour and migration in geological environments are therefore of considerable interest. The knowledge of the solubility and speciation of Tc is an important clue to predict its mobility, in the safety assessment of nuclear waste repository, especially in the case of dissolution of nuclear wastes by groundwater. The mobility of Tc in the environment depends on its oxidation state. Under oxidizing conditions, the technetium is expected to exist in oxidation state (VII) as the pertechnetate anion $\text{TcO}_4^-$, which is not correctly sorbed and thus highly mobile in aqueous solutions. Under reducing conditions, the technetium exists mostly under the Tc(IV) oxidation state, and forms a soluble hydrous oxide, $\text{TcO}_2\cdot x\text{H}_2\text{O}$. The Tc(IV) is supposed to be relatively immobile without complexing agents.

The $\text{TcO}_2\cdot x\text{H}_2\text{O}$ is originally from the hydrolysis Tc(IV) species. But actually, the Pourbaix diagram of Tc is subject to questions. In fact, at acidic pH, $\text{TcO}_2^{2+}$ is preponderant but its form, and its charge, is not spectroscopically verified. The stable Tc(IV) species considered in acidic solution is $\text{TcO(OH)}^{2+}$. Moreover, no data considers a possible presence of polymers.

Although, depending on reducing conditions and pH, recent studies [2, 3, 5] show the possibility to have Tc(III) and Tc(IV) under hydrolyzed polymers in acidic and non-complexing medium. It represents a significant interest on its chemistry because the known Tc-polymers are all formed in presence of complexing agents (Cl$^-$, EDTA, CO$_3^{2-}$...).

This work focuses on the chemical behaviour and speciation of Tc in very acidic aqueous solution without complexants.

Electrochemical reduction of $\text{TcO}_4^-$ in an acidic and non-complexing medium

Some electrochemical experiments on $\text{TcO}_4^-$ were conducted to determine the speciation in acidic aqueous solutions without complexants. They were achieved in two steps: (1) potentiometric reduction (imposed current) of Tc in an electrochemical cell, (2) imposed potential switched off, to study the stability of reduced species. All experiments were done in different concentrations of HTFMS to have a pH display, under argon bubbling to avoid O$_2$ presence and monitored by UV-vis spectroscopy. $\text{TcO}_4^-$ can be reduced to Tc(V), Tc(IV) and Tc(III) species depending of the pH, the time of reduction and the concentration of Tc.

In HTFMS 1M solutions (pH = 0), the reaction leads directly to Tc(III). The characteristics peaks of Tc(VII) – 244 and 287 nm – disappear to give a spectrum without characteristics peaks. This last compound is stable only within a potential. Without imposed potential, Tc(III) directly oxidizes into Tc(IV) with small amount of Tc(VII). The re-oxidation of reduced species Tc(III) gives also a polymeric form of Tc, which was already observed in the presence of complexing ligands. The figure 1 shows the spectra of these different species.
The polymer form is characterised by Uv-bands at 250 nm, 320 nm and 495 nm. The band at 495 nm corresponds to a charge transfer between Tc atoms. The Tc(IV) polymer is suggested to be under the form $\text{Tc}_n\text{O}_y^{(4n-2y)+}$ with $n$ and $y > 0$. For instance, no evidence of its nuclearity was found but we supposed an $n = 2$, 3 or 4. The figure 1 shows the different spectra of the Tc species: Tc(VII), Tc(III) and Tc(IV) polymer form (with hypothesis that $n = 2$).

In more acidic solutions, the TcO$_4^-$ reduced into Tc(V), which is immediately goes to Tc(IV) polymer.

In both case, the polymer proportion depends on the concentration of Tc. In fact, if the concentration exceed at least 3E-4M, the reduction of TcO$_4^-$ gives directly the Tc(IV) polymer form. The Tc(IV) polymer form is a precursor of TcO$_2$ at more weak pH (near pH 2.5-4).

**Speciation of Tc in an acidic and non-complexing medium**

Previously, the reduced species were assigned to an oxidation state by comparison with literature and characteristic peaks. But a chemical or spectroscopic method must to be used to confirm the redox oxidation state. The redox titration, by permanganate ions, was used. The ions MnO$_4^-$ oxide the reduced species and the solution was monitored by UV-vis spectroscopy to correlate the dosage with characteristic peaks. At pH 0, the titration gives evidences that the reduced species was Tc(III). Then, it gives the Tc(IV) polymer form and finally Tc(VII). This titration is shown on figure 2.

**Fig. 1:** UV-vis spectrum of TcO$_4^-$, Tc(III), Tc(polymer) with $n = 2$ and the reoxidized Tc species. Concentration = 9.75E-5 M, pH = 0

**Fig. 2:** Redox titration of reduced Tc ($c = 1.87E-4$M) by permanganate ion ([MnO$_4^-$] = 1E-4M) at pH 0.

In more acidic solutions, the titration confirms well the presence of Tc(V) and Tc(IV) polymers.

To find the nuclearity, the structural appearance and the chemical environment of the polymer, XAS (X Absorption Spectroscopy) was used. Previous studies [1, 4], in chloride and sulphide media, demonstrated a polymer with a [Tc(µ-O)$_2$Tc]$^{4+}$ structure. The first results tented to show the same core structure.

Dans le cadre d’un stockage des déchets en couches géologiques profondes, le technétium fait partie des éléments susceptibles de migrer dans la bio-géosphère. Il est donc important de connaître sa chimie et donc sa spéciation en solution. En milieu acide non complexant, la spéciation du Tc est sujette à discussion. Seules les formes monomères sont considérées mais certaines données spectroscopiques manquent pour prouver leur forme chimique. Certains proposent l’existence de forme polymères sans réelle preuve. Ainsi cette étude a pour but d’étudier la spéciation du technétium en milieu non-complexant et de déterminer la présence d’une forme polymère et de son domaine de stabilité.

Specific conditioning of cesium in hollandite: alteration and irradiation effects

T. Suzuki, A. Abdelouas, J. Vandenborre, K. Perrigaud, B. Grambow

Hollandite, with about 5 wt.% Cs₂O, formulated as Ba₁Cs₀,₂₈Al₁,₄₆Fe₀,₈₂Ti₅,₇₁O₁₆, required specific chemical, physical, mechanical, thermal properties for the specific conditioning of cesium. The matrix will accept cesium atoms substituting barium atoms, located in the tunnel of the structure. The disintegration scheme of caesium follows the reaction

$$\ce{{}^{55}Cs + \beta + e \rightarrow {}^{55}Ba}$$

with beta emission responsible of the amorphisation of hollandite. Among the inventory of caesium radionuclides, 135-Cs is a long-live radionuclide with $T_{1/2} = 2.3 \times 10^6$ y, and 137-Cs ($T_{1/2} = 30.17$ y) is one of the major radiotoxic radionuclide contributor. We have shown through dissolution experiments and $\gamma$-irradiation of altered hollandite experiments at various pH that hollandite has a good chemical and physical durability. Notably, no amorphisation of the mineral phase is expected under storage conditions. The amorphisation by $\beta$-irradiation necessitated a dose thousand times higher than that encountered in storage conditions ($10.10^{11}$ Gy) [1].

Alteration of hollandite

In literature, a few data is available on the systematic study of hollandite in solution [2-3], compared to a numerous studies realized on the solid structure [4-6]. Our first objective was to understand the hollandite behaviour in solution, from acidic to basic pH prior any irradiation studies. Batch and dynamic systems were conducted in parallel at pH 2.5, 4.4 and 8.6, in HCl, NaCl and borate buffer solutions, respectively, at 95°C during 240 days. The surface of solid to volume of solution ratio was fixed to 500 and 5000 m⁻¹. The caesium release in solution presents two steps described as (Figure 1):

1- The earlier dissolution of hollandite releases one type of caesium, coming from grain boundaries or residual caesium from precursors during the synthesis, with a high release rate: $NLRC_{cs} = 1 \times 10^{-2}$ g/m²/d;
2- The long dissolution of hollandite is characterised by the release of caesium coming from the structure even, with a low release rate: $NLRC_{cs} = 5 \times 10^{-6}$ g/m²/d.

The final dissolution rates remain fairly low ($5\times10^{-6}$ g/m²/d) compared to the values measured for a nuclear borosilicate glass such as the French glass SON68 (containing about 1 wt.% Cs₂O) devoted for the confinement of a whole set of radionuclides, and which is one of the most durable nuclear waste form ($1.10^{-4}$ g/m²/d) [7].
Under gamma-irradiation, hollandite presents a good mechanical durability. The combination of solution radiolysis and solid irradiation does not modify the release of caesium in solution. The production of H$_2$O$_2$, stable molecular product of water radiolysis and known to be a strong oxidant, is not sufficient to affect the hollandite surface.

**At the interface solid-solution**

To better probe the hollandite surface the photoelectron X-ray spectroscopy (XPS) was used in addition to isotopic exchange experiments with 137-caesium:

1- At the surface, hollandite presents initially two different chemical environments of Cs ($E_l 738.0$ eV and $736.4$ eV). After alteration one of the two caesium ($E_l 738.0$ eV) disappears. The loss of one type of Cs could be associated to the earlier release rate observed during the hollandite alteration.

2- For the isotopic exchange experiments, the added radioactive 137-Cs did not react with the solid surface for all the pH-values studied and SA/V ratios. This may suggest that after reaching a steady state, the caesium in the hollandite tunnels is not exchangeable with the external solution in the scale of time of the experiments. Finally, caesium release from the hollandite would then be governed by either diffusion or by hollandite matrix dissolution without any significant back-reaction incorporating Cs into the structure of altered solid surface.

Dans le projet de loi 1991 sur la gestion des déchets nucléaires de hautes activités et à vie longue, il a été envisagé de séparer le césium du reste des produits de fission et de le confiner spécifiquement dans une phase minérale, la hollandite. Le but de ce travail a été d'étudier et de décrire le comportement du césium contenu dans la hollandite dans les conditions d'altération et d'irradiation. Au cours de ce travail, nous avons pu montrer la bonne durabilité chimique avec de faibles vitesses de relâchement et une bonne durabilité physique avec une résistance sous irradiations gamma et bêta. La hollandite est donc une bonne phase pour l’accueil du Cs radioactif en vue d’un stockage géologique.

Figure 8: Normalized release rates (NLR, g/m²/d) of Cs in hollandite, altered in dynamic system at pH 4.4 during 240 days at 95°C.

Gamma irradiation of hollandite altered

Gamma irradiation was carried with a 60-cobalt disposal at SCK/CEN (Mole, Belgium). The cumulated dose was $2.4 \times 10^6$ Gy during 5 days of irradiation. The container was purged under Ar-atmosphere with a temperature maintained at 60°C. All the samples were conditioned in Ar-atmosphere glove box.

Gamma irradiation of hollandite in alteration experiments had no effect on release rates of Cs ($\sim 5 \times 10^{-6}$ g/m²/d) (Figure 2).

Figure 9: Normalized release rates (NLR, g/m²/d) of irradiated and pristine hollandite as a function of alteration time (days) at pH 4.4, for SA/V ratio at 5000 m⁻¹.

Transmission electron microscopy observation of irradiated and altered hollandite confirmed the results obtained in solution, since no amorphous layer is formed (Figure 3).

Figure 10: (a) Transmission electron microscopy observation of hollandite surface after alteration and gamma-irradiation.

Dans le projet de loi 1991 sur la gestion des déchets nucléaires de hautes activités et à vie longue, il a été envisagé de séparer le césium du reste des produits de fission et de le confiner spécifiquement dans une phase minérale, la hollandite. Le but de ce travail a été d'étudier et de décrire le comportement du césium contenu dans la hollandite dans les conditions d'altération et d'irradiation. Au cours de ce travail, nous avons pu montrer la bonne durabilité chimique avec de faibles vitesses de relâchement et une bonne durabilité physique avec une résistance sous irradiations gamma et bêta. La hollandite est donc une bonne phase pour l’accueil du Cs radioactif en vue d’un stockage géologique.
Analysis of a colloidal suspension LIBD (Laser Induced BreakDown Detection).
Modeling R7T7 glass behavior and corrosion product properties

S. Ribet, B. Grambow

La modélisation des réactions chimiques des radioéléments en solution aqueuse et de sorption à la surface de matériaux d’environnement est une étape nécessaire dans l’interprétation quantitative des données expérimentales. Nous avons développé des modèles couplant des réactions chimiques avec les contraintes du transport hydrodynamique, permettant la prédiction du comportement des matrices de déchets nucléaires en cas de stockage en couche géologique profonde.

Modeling is used to predict the long-term evolution of the underground water composition in contact with rocks in case of infiltration of water in the nuclear waste disposal installation. Geochemical codes taking into account all possible reaction and speciation in solution, including precipitation and kinetic reactions are useful tools.

A large part of the modeling is based on laboratory scale experiments in view of extending results on field space and time scale, inaccessible otherwise.

PHREEQC is one of the geochemical/transport code used by the radiochemistry group. In order to model the diffusion of water through the engineered barriers disposal concept for nuclear waste glasses, behavior of each individual system (glass, corrosion product, bentonite) in solution need to be understood before coupling.

Modeling glass leaching behavior

The R7T7 glass dissolution kinetic was characterized by an initial rate $R_0$ in the order of $2 \text{ g m}^{-2} \text{ d}^{-1}$ and a final residual rate $R_f$ of about $10^{-4} \times R_0$.

A kinetic equation of the first order is used:

$$R = A \times [k_0 \cdot (1 - Q/K)_{\text{GiHyd}} + k_f]$$

The transition between these two processes is linked to the formation of a gel layer that can be modelled by the precipitation of a solid solution phase. End-members of this solid solution are chosen among metasilicate and oxyhydrate phases. One aim of this “amorphous phase” was also to retain the most non-congruent elements like calcium or aluminium. Figure 1 shows an application of this law to the leaching experiment of R7T7 glass ($S/V=50 \text{ cm}^{-1}$; $90^\circ\text{C}$) (Glamor European Project).

**Fig. 1:** R7T7 dissolution in pure water, $90^\circ\text{C}$ and $S/V=50 \text{ cm}^{-1}$. Experimental data (symbols), and modeling results (lines).

Silicon will be the main element controlling the leaching rate of the glass.
Modeling magnetite properties

Magnetite (Fe₃O₄) is predicted to be the main phase due to the corrosion of the iron steel container. Potentiometric titration data have been obtained with a batch method on a commercial magnetite, characterized by a specific surface area of 1.9 m² g⁻¹. Modeling of these results used the classical double diffuse layer model and two equations of protonation and deprotonation of SOH groups on surface:

\[
S_1OH_2^+ = S_1OH + H^+ \quad pK_a_1
\]
\[
S_1OH = S_1O^- + H^+ \quad pK_a_2
\]

Experimental data (C. Mayant contribution) can be fitted with Phreeqc geochemical code when attributing a site density of 2.4 /nm² and values of 3.5 and 5.1 for pK_(a1) and pK_(a2) respectively (Figure 2).

These sorption sites are more acid compared to literature data.

Silica sorption data have been obtained on both synthesized and commercial magnetite (K. Ferrand) and can be modelled with adding a second type site (S₂) of lower density (0.3/nm²) and sorption equation of the kind:

\[
S_1OH + H_4SiO_4 = S_1OSi(OH)_3 + H_2O
\]
\[
2S_2OH + H_4SiO_4 = (S_2O)_2Si(OH)_2 + 2H_2O
\]

Results are shown on Figure 3 as the moles of silicon sorbed by surface area as function of the silicon aqueous concentration.

**Fig. 3:** Silicon sorption on magnetite at three different pH values: experimental data and modelling

**Modeling diffusion for glass / corrosion product / clay system**

These models have been applied in the study of migration of major cations in a diffusion cell containing clay, magnetite and glass layers, for the European project NF-PRO.

Sensitivity analysis have been performed in order to identify the more influent parameters on the glass altered thickness (coefficient of diffusion, CO₂ partial pressure, silicon addition...)

The main results are a high glass dissolution rate as long as the corrosion products sites are not saturated.

Porosity and thickness of the corrosion product seem to be the less detrimental parameters for the glass dissolution.
Study of selenium behaviour in a soil-plant-microorganisms system

J. Muller, A. Abdelouas, Y. Thiry, M. Van Hess, B. Grambow

Le sélénium (Se) est produit lors des réactions de fission nucléaire sous la forme de plusieurs isotopes radioactifs, dont le $^{79}\text{Se}$ qui est un produit de fission à vie longue avec une demi-vie d’environ $1 \times 10^6$ années. Au cours du temps, les radioéléments à vie longue, comme le $^{79}\text{Se}$, peuvent engendrer une contamination de l’environnement. En effet, la migration du sélénium peut se produire via l’eau souterraine des sols et ainsi venir affecter la zone racinaire des végétaux. Cette étude vise à déterminer qualitativement et quantitativement les processus impliqués dans le transfert des sélénites ($\text{SeO}_3^{2-}$) pour deux sols (Bure et Mol) localisés à la surface de deux sites éventuellement destinés au stockage des déchets radioactifs en milieu géologique profond.

Performance assessment analysis of a deep geological repository for nuclear waste done by ANDRA has shown that $^{79}\text{Se}$ provides a significant contribution to potential long term radiation exposure. In this context, research efforts on radionuclides migration are required in order to determine the risks associated with the geological waste disposal option. Selenium can be present in soils under the four oxidation degrees (-II), (0), (IV) and (VI) and under various forms which determine its mobility and bioavailability. In most of soils, the forms selenite $\text{SeO}_3^{2-}$ and selenate $\text{SeO}_4^{2-}$ are the most frequent. These anionic forms are very soluble, mobile, bioavailable and potentially toxic (1). Selenium concentration in plants is estimated at 0.1 ppm and can reach 15000 ppm, according to the presence and the adaptation of the vegetation to soils which are more or less seleniferous or deficient in selenium (2). The rooting zone incorporation and redistribution of selenium in plants is very fast and depends on the plant species and on physiological conditions. Selenium also belongs to the elements susceptible to be methylated or reduced by microorganisms. The major metabolite formed via methylations and reductions are the DMSe (di-methyl Se) and Se(0), respectively. Selenium can also be methylated by plants. Biomethylation of selenium gives less toxic volatile forms (3).

In this report, we have focused on:
- Selenium uptake and transport in plant
- The influence of microorganisms on selenium behaviour
- Volatilization of selenium by plants and/or microorganisms

All these parameters influence selenium behaviour and have important implications in strategy dealing with environmental Se contamination.

SELENIUM ASSIMILATION BY RYEGRASS

Selenium assimilation by ryegrass does not depend on the type of soil. Indeed, the percentages of the initial selenium activity recovered in ryegrass for both studied soils have no significant differences. In non sterile conditions, assimilation rates of Se are 13.3 and 17.4 % for the soil of Bure and Mol, respectively. In sterile conditions, assimilation rates are 17.4 and 18.4 % for the soil of Bure and Mol, respectively. Moreover, there are no significant differences between sterile and non sterile conditions for both soils. Despite differences in soil compositions (Bure: clay loam; Mol: sandy loam), it seems that Se assimilation are the same for ryegrass, indicating in this case that soil composition does not play a key role on selenium assimilation by plants.
In our experiments, soil\textsubscript{dry} → plant\textsubscript{dry} transfer factors (TF = [Se\textsubscript{plant}] / [Se\textsubscript{soil}]) are comprised between 5.4 and 7.5 which are in the same order of magnitude than recommended ratios given by Coughtrey et al., (2) and Johnsson (4).

**TRANSFER FACTOR OF SELENIUM TO PLANT**

Selenium soil-plant transfer factor depends on plant species and on their physiological state (5), soil type, concentration and form of Se supply (6,7). Moreover, the distribution of radio-selenium artificially provided to plants would differ from native selenium (2,8). Transfer factors for several plant different parts are presented in table 1.

For both soils, Se transfer factors from soil to roots are higher than Se transfer factor from soil to seeds and leaves. Arvy (9) have already demonstrated that within 3 h, 50 % of the selenate uptake by roots moved to shoots, whereas in the case of selenite, most of the Se remained in the root and only a small fraction was found in the shoot. Selenite is rapidly transformed in organic forms of Se, which are retained in the roots (7). Transfer factors follow the order TF roots Mol > TF roots Bure > TF seeds Bure and Mol = TF leaves Bure and Mol. These transfer factors are in the same range of those reported for grasses by Coughtrey et al. (10).

**SELENIUM VOLATILIZATION**

Guo et al. (11) reported that significant fraction of Se in soils could be lost through volatilization of methylselenide such as DMSe (dimethylselenide) and DMDSe (dimethyldiselenide) and detectable concentrations of atmospheric Se were found by Chau and Wong. (12). Our experimental results show that ryegrass is the main factor for Se volatilization in both soil treatments (sterile and non sterile conditions).

Se volatilization is in the range of 0.07 to 0.21% of the initial selenium activity in experiments with ryegrass whereas Se volatilization is in the range of 0.001 to 0.04 % in experiments without ryegrass. In non sterile conditions, Se volatilization appears to be more important than in sterile condition, indicating that soil microorganisms participate to Se volatilization. Terry et al., (8) have shown that plants volatilized low amounts of selenite and selenate in absence of bacteria, these results demonstrating that microbial biomass (in particular in the rhizosphere) is one of the most important environmental factor affecting Se volatilization.

Le but de ce travail est de décrire les relations entre le sélénium, le sol, les plantes et les microorganismes afin de pouvoir prédire son comportement en cas de migration de celui-ci vers la biosphère. Cette étude est focalisée sur le comportement des sélénites car cet état d’oxydation du sélénium est très mobile et souvent présent à la surface des sols.

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**Table 1.** Transfer factors from soils to roots, seeds and leaves of ryegrass

<table>
<thead>
<tr>
<th></th>
<th>TF roots</th>
<th>TF seeds</th>
<th>TF leaves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bure non sterile</td>
<td>4.2 ± 0.8</td>
<td>0.7 ± 0.2</td>
<td>0.8 ± 0.3</td>
</tr>
<tr>
<td>Bure sterile</td>
<td>4.0 ± 1.6</td>
<td>0.6 ± 0.2</td>
<td>0.8 ± 0.4</td>
</tr>
<tr>
<td>Mol non sterile</td>
<td>6.6 ± 2.4</td>
<td>0.7 ± 0.2</td>
<td>1.1 ± 0.4</td>
</tr>
<tr>
<td>Mol sterile</td>
<td>8.1 ± 1.6</td>
<td>0.9 ± 0.2</td>
<td>1.2 ± 0.3</td>
</tr>
</tbody>
</table>

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(4) Johnson, L. Selenium uptake by plants as a function of soil type, organic matter content and pH; Springer Netherlands, 1991; Vol. 133.
Silicic acid retention of compacted magnetite powder

C. Mayant, B. Grambow, A. Abdelouas, S. Ribet, S. Leclercq


In France, the concept of deep geological disposal of vitrified high-level radioactive waste includes the steel canister with the nuclear glass surrounded by an iron overpack. In contact with groundwater and repository rock the iron overpack is expected to corrode in confined space into highly compacted corrosion products including magnetite (Fe_3O_4) and siderite (FeCO_3). These corrosion products may play a key role in radionuclide retention via sorption, reduction and precipitation processes. Also, they may enhance glass dissolution via sorption of silicon resulting from glass leaching.

Philippini et al. [1] studied the sorption of Si on a variety of iron corrosion products including magnetite and siderite in batch systems (in NaCl or in NaClO_4 as aqueous solution) with a specific surface area of 1.8 m^2.g^-1 and they found a sorption capacity of magnetite with respect to Si of 1.9 x 10^-2 mol_{Si}g^-1-magnetite (6.4 sites_{Si}nm^-2). According to these authors, silica sorption reached a maximum value between pH 7 and 9.

The objectives of the present work were to compare the silicic acid adsorption on both dispersed and compacted magnetite.

Silicic acid retention on dispersed magnetite

To provide a base for comparison with compacted magnetite, batch adsorption experiments with dispersed magnetite were conducted in plastic vessels at room temperature in an anaerobic glove box. The sorption distribution coefficient K_d was determined according to the equation (1):

$$K_d = \frac{[\text{H}_4\text{SiO}_4]_{\text{solid}}}{[\text{H}_4\text{SiO}_4]_{\text{supernatant}}} \times \frac{V}{m}$$  \hspace{1cm} (1)

where \([\text{H}_4\text{SiO}_4]_{\text{supernatant}}\) is the silicic acid concentration in the supernatant after adsorption; \([\text{H}_4\text{SiO}_4]_{\text{solid}}\) the difference between the silicic acid concentration in the stock solution and the silicic acid concentration in the supernatant; \(V\) the total volume of the suspension and \(m\) the magnetite mass.

The number of sites accessible to the silicic acid was calculated by using:

$$N_{\text{H}_4\text{SiO}_4} = \frac{[\text{H}_4\text{SiO}_4]_{\text{solid}} \times V \times N_{\text{A}}}{m \times S \times 10^{18}}$$ \hspace{1cm} (2)

where \(N_{\text{A}}\) the Avogadro number and \(S\) the specific surface area (m^2.g^-1) of the magnetite powder prior to compaction.

At pH 7.8, 18 % of the silicic acid was adsorbed on the magnetite surface leading to a final Si concentration of 1.03 mM. The sorption distribution coefficient \(K_d\) has been determined with
the equation (1): the average \( K_d \) for the five batches is \( 7 \pm 1 \text{ mL} \cdot \text{g}^{-1} \) \[2\]. The formal number of sites adsorbing \( H_4SiO_4 \) on the magnetite surface was determined using equation (2): a value of \( H_4SiO_4 \) \( 2.2 \pm 0.2 \text{ sites per nm}^2 \) \( (7.0 \times 10^{-6} \text{ mol}_\text{H}_4\text{SiO}_4\cdot\text{g}^{-1}_\text{magnetite}) \) was obtained \[2\]. These values may be compared to literature data. Our results are lower than the mean value but still in the error margin of the maximal sorption values reported by Philippini et al. \[1\] of \( 19 \pm 14 \times 10^{-6} \text{ mol}_\text{Si} \cdot \text{g}^{-1} \cdot \text{magnetite} \) at pH 8.5 corresponding to sorption sites densities for dispersed magnetite with respect to total dissolved Si of 6.4 sites\text{Si} \cdot \text{nm}^{-2}.

Silicic acid retention on the compacted magnetite

The silicic acid adsorption was studied in two percolation cells containing 30 g of magnetite compacted at 120 bars. The inlet silicic acid stock solutions were \( 4.5 \times 10^{-4} \text{ M} \) (case of first column) or \( 1.6 \times 10^{-3} \text{ M} \) (case of second column) with an adjusted pH of 8.5. The solutions were passed through the magnetite columns using the peristaltic pump at 10 \( \mu \text{L} \cdot \text{min}^{-1} \). A daily outlet sample was collected, its pH was measured and its monomer silicon concentration \(([\text{Si}]_\text{outlet})\) was determined by the UV-Vis method as described above.

The sorption distribution coefficient for the silicic acid \((L \cdot \text{g}^{-1})\) was determined with the following equation:

\[
K_d = \frac{\sum ([\text{H}_4\text{SiO}_4]_{\text{outlet}} - [\text{H}_4\text{SiO}_4]_{\text{inlet}})}{m \times [\text{H}_4\text{SiO}_4]_{\text{tot}}} \tag{3}
\]

with \( ([\text{H}_4\text{SiO}_4]_{\text{outlet}}) \) is the measured number of moles of monomer silicon in the collected sample volume \( V_{\text{outlet}} \), \( ([\text{H}_4\text{SiO}_4]_{\text{inlet}}) \) the hypothetical total number of moles of monomer silicon in the collected sample if silicon concentrations would have been at the inlet value, \( m \) the magnetite mass \((\text{g})\) and \( [\text{H}_4\text{SiO}_4]_{\text{tot}} \) the silicon concentration in the inlet stock solution \((\text{mol/L})\). For each collected sample, \( ([\text{H}_4\text{SiO}_4]_{\text{outlet}}) \) and \( ([\text{H}_4\text{SiO}_4]_{\text{inlet}}) \) are calculated as following:

\[
([\text{H}_4\text{SiO}_4]_{\text{outlet}}) = [\text{H}_4\text{SiO}_4]_{\text{outlet}} \times V_{\text{outlet}} \tag{4}
\]

\[
([\text{H}_4\text{SiO}_4]_{\text{inlet}}) = [\text{H}_4\text{SiO}_4]_{\text{tot}} \times V_{\text{inlet}} \tag{5}
\]

The number of active surface sites for silicic acid sorption was determined with the equation (6):

\[
N_{\text{H}_4\text{SiO}_4} = \frac{\sum ([\text{H}_4\text{SiO}_4]_{\text{inlet}} - [\text{H}_4\text{SiO}_4]_{\text{outlet}}) \times N_A}{m \times S \times 10^{18}} \tag{6}
\]

The results of \( H_4SiO_4 \) sorption on compacted magnetite at pH 8 are given in Fig 1. Final solution concentrations are about 90 to 95% of the initial value indicating close to equilibrium conditions for the distribution coefficients and very little concentration gradients of Si in the percolation reactor. The determined \( K_d \) (equation 3) is \( 16 \text{ mL} \cdot \text{g}^{-1} \) for the sorption experiment with \( 4.5 \times 10^{-4} \text{ M} \) \( H_4\text{SiO}_4 \) and \( 9 \text{ mL} \cdot \text{g}^{-1} \) for the experiment using \( 1.6 \times 10^{-3} \text{ M} \) \( H_4\text{SiO}_4 \). Compacted magnetite adsorbed about \( 7.0 \times 10^{-6} \text{ mol}_\text{H}_4\text{SiO}_4 \cdot \text{g}^{-1} \cdot \text{magnetite} \) \( (2.2 \pm 0.2 \text{ sites}_\text{H}_4\text{SiO}_4 \cdot \text{nm}^{-2}) \) for the \( 4.5 \times 10^{-4} \text{ M} \) experiment, and \( 1.4 \times 10^{-5} \text{ mol}_\text{H}_4\text{SiO}_4 \cdot \text{g}^{-1} \cdot \text{magnetite} \) \( (4.4 \pm 0.4 \text{ sites}_\text{H}_4\text{SiO}_4 \cdot \text{nm}^{-2}) \) for the \( 1.6 \times 10^{-3} \text{ M} \) experiment \[2\].

![Fig. 1: Silicic acid adsorption on the compacted magnetite at pH 8 with an inlet stock solution of (?) 4.5x10^{-4}M; (◊) 1.6x10^{-3}M. Comparison with the transfer of the tritiated solution (solid line) in the percolation cell containing compacted magnetite. Thus, the first experiment leads to the same density of accessible sorption sites (2.2± 0.2 sites\text{H}_4\text{SiO}_4 \cdot \text{nm}^{-2}) than the experiment of Si sorption on the dispersed magnetite. Thus, magnetite does not lose accessible surface sites when compacted at 120 bars. The second experiment leads to a number of sites (4.4 sites\text{H}_4\text{SiO}_4 \cdot \text{nm}^{-2}) close to the maximum sorption values reported by Philippini et al. [1].](image-url)


En France, les déchets nucléaires sont probablement destinés à être stockés en profondeur dans une formation géologique. Ils seront alors immobilisés dans des matrices solides : un verre, un conteneur en acier inoxydable et un sur-conteneur en acier faiblement allié. Malgré la présence de ces barrières pour la protection contre la dispersion de la radioactivité, le transfert de la radioactivité vers l’Homme via les eaux souterraines n’est pas exclu. Nos travaux concernent l’étude des phénomènes de rétention de l’acide silicique et du sélénium sur la magnétite compactée, principal produit formé lors de la corrosion du sur-conteneur par l’eau.
Glove box under inert atmosphere.
Thorium oxide solubility

J. Vandenborre, A. Abdelouas, K. Perrigaud, B. Grambow

The dissolution properties and/or solubility equilibria of ThO$_2$(crystallized), and/or Th(OH)$_4$(amorphous) were studied for many years. At neutral to basic pH, solubilities of ThO$_2$(cr) and Th(OH)$_4$(am) are at a value between 1-10 nM, whereas at acid pH, the solubilities of these two forms differ by as many as 7 orders of magnitude. According to equilibrium thermodynamics, large discrepancies in solubilities should also persist at neutral pH. The similarity of solubility values at neutral pH was then explained by the formation of a non-detectable amorphous surface phase on ThO$_2$(cr). A study of surface reactivity at close-to-equilibrium conditions may provide further insight into the processes controlling solubility. Kinetically, solubility equilibria can be interpreted as being governed by equal rates of attachment and detachment of surface species. These rates are not known under close-to-equilibrium conditions. If they are fast, rapid and continuous reconstruction of the surface would be expected and amorphous products will easily become redissolved to become incorporated into the crystalline surface. In contrast, if these rates are slow, amorphous products may survive and even in the absence of amorphous products, high energy surface sites may control overall solids solubility. The present work is carried out to shed some light on the relation between surface reactivity and solubility of ThO$_2$(cr). The ThO$_2$(cr) particles used are spherical with an average diameter of 500 μm. These spheres originate from TRISO-coated (Tri-isotropic or multi-layered high- and low-density pyrolytic carbon and silicon carbide coatings) fuel particles of the german HTR (High Temperature Reactor) test programme. In fact, only a few data exist concerning dissolution properties of these spheres. We have chosen these materials because they were made using a well defined protocol allowing to obtain spherical solid samples with similar and strictly controlled surface, presented onto figure 1. In this work [1], we have examined, in the first part, the dissolution properties of these particles and, in the second part, the role of surface reactivity in the establishment of dynamic solubility equilibria.

Fig. 1: SEM picture of ThO$_2$ kernel surface

The present work is a part of a large project on solubility/surface properties of oxides including ThO$_2$(cr) and ZrO$_2$(cr) with the aim of establishing a database of thorium oxide dissolution with detailed description of surface properties of each solid. The work described here focuses mainly on aqueous dissolution.
of ThO$_2$(cr) in acidic media. Moreover, detailed characterization of the ThO$_2$(cr) surface is presented to improve understanding of surface/solubility relation. First results show that “solubility values” are not thermodynamic values but governed by kinetics of exchange reactions between solution and solid surface (see figure 2). In fact, in this graphic, we can see that Th concentrations (full and empty spots) are far from thermodynamic data (straight line) in particular in neutral and alkaline media.

So, “solubility” data found in literature depends on surface properties. The red dotted line fits “solubility” data for Th(OH)$_4$(am) and the blue dotted line fits ThO$_2$(cr) data.

Detailed solid characterization by XPS, AFM and SEM techniques reveal much information about surface properties. In figure 3, AFM picture shows clearly that a dissolution process implies grains boundaries at first (kinetic effect). On XPS spectra (figure 4) we can see two Th peaks for two chemical environments. One of them disappears after dissolution process (named Th2). We assume that Th1 belongs to Th atoms localised into ThO$_2$ grains and Th2 belongs to grains boundaries first attacked by dissolution. At last, we conclude that “solubility curves” of figure 2 can be considered as a function of grains boundaries density with Th(OH)$_4$(am) > ThO$_2$(cr) > ThO$_2$ kernel.

Curves in figure 2 correspond to kinetic processes and not thermodynamic ones. The dissolution process is not the only one implied in solubility equilibrium. Solubility equilibrium is composed by all forward and backward reactions between solution and solid surface (= atoms exchange reactions).

**Fig. 2:** ThO$_2$ “solubility” curves data from literature [2] (black and white spots) and from this work (green spots).

**Fig. 3:** AFM picture of ThO$_2$ kernel particles after dissolution process

**Fig. 4:** Th XPS spectra before and after dissolution process

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Sorption of selenite in a multi-component system using the “dialysis membranes” method

J. Muller, A. Abdelouas, K. Perrigaud, B. Grambow

Radioactive selenium is produced in fission reactors in the form of several isotopes including $^{79}\text{Se}$, which is a long-lived fission product with a half-life of about $1 \times 10^6$ years. Performance analysis done by ANDRA (French Agency for Radioactive Waste Management) of a potential deep geological repository for nuclear waste has shown that $^{79}\text{Se}$ may provide a significant contribution to potential long-term radiation exposure. Indeed, a sensibility analysis based on an analysis of control of the performances of a nuclear waste storage concept showed that selenium can have a significant effect on the accumulated radioactive dose if it is transported through the geosphere without being delayed. The study was focused on the selenite anion ($\text{SeO}_3^{2-}$) sorption on several components largely represented in most of soils (smectite, Fe-oxyhydroxides and humic substances), since it is expected that this redox state of Se is rather mobile and prevails near the soil surface. This paper describes and validates the dialysis membranes method which aimed to test if the additivity of sorption holds true in a case of multi-components system. In such a separated system, the contribution of each mineral and organic phase on selenite sorption can be evaluated. The association of goethite and bentonite can be a first step to report phenomena of adsorption which can occur in soils but also in a system constituted by corrosion products (iron container) and clay constituting the barrier in a geologic disposal of radioactive waste. We will present experimental $K_d$ with one and two solid phases (bentonite and/or goethite) to validate our experimental procedure and to test selenite sorption additivity. Then, effect of humic substances on selenite sorption onto each single phase will be discussed.

SELENIUM RETENTION

By using the “dialysis membrane” method it is possible to determine a $K_d$ for each solid in a system composed of several mineral phases while with the “batch method”, we only measure a $K_d$ for the mixture. Results obtained at pH 7.0 for experiments with one and two solid phases are given in table 1.
Radiochemistry

Table 1 shows that on a mixture of solid phases (goethite-bentonite), Se sorption strongly decreased on goethite. Indeed, the average sorption coefficients dropped from 9411 to 614 L.kg⁻¹ in the presence of bentonite. Therefore, the concept of Se sorption additivity does not hold and data from single phase cannot be directly applied to estimate Se sorption on a multi-components system, e.g. soil. The decrease of Se K_d on goethite in presence of bentonite may be explained by a competition effect due to Si released by bentonite (1.1×10⁻⁵ M).

INFLUENCE OF SI CONCENTRATION ON SE RETENTION

To better understand the role of Si on Se sorption on goethite, we studied the Si sorption on goethite with and without Se(IV). The Se K_d’s on goethite as a function of Si concentration are given in Table 2.

Table 2. Influence of Si concentration on K_d (L.kg⁻¹) of selenium on goethite

<table>
<thead>
<tr>
<th>Si concentration</th>
<th>K_d goethite</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Si] = 7.56×10⁻⁶ M</td>
<td>838 ± 80</td>
</tr>
<tr>
<td>[Si] = 1.07×10⁻⁵ M (Si released by bentonite)</td>
<td>613 ± 69</td>
</tr>
<tr>
<td>[Si] = 6.57×10⁻⁵ M</td>
<td>734 ± 62</td>
</tr>
<tr>
<td>[Si] = 6.56×10⁻⁴ M</td>
<td>691 ± 4</td>
</tr>
</tbody>
</table>

Comparing these data with Se K_d obtained in the absence of Si (K_d = 9411 L.kg⁻¹) it is clear that Si competes for sorption sites on goethite. The Se K_d (613 ± 69 L.kg⁻¹) in the presence of 1.07×10⁻⁵ M Si, corresponding to the Si concentration obtained in water equilibrated with bentonite, is similar to that obtained with a similar Si concentration (838±80 L.kg⁻¹). Silicic acid is known to sorb well onto Fe-oxyhydroxides (1-3). These authors suggested that the presence of Si decreases the goethite surface availability for sorption by modifying the electrical double layer or by forming chemical bonds with surface groups.

INFLUENCE OF HA ON SELENIUM RETENTION

In a first step, HA were put into the same dialysis membranes which already contain the mineral. Results showed that HA sorb well onto goethite and bentonite and their concentrations decreased by 73 % and 39.2 % for goethite and bentonite, respectively. Selenium sorption experiments performed with HA outside of the dialysis membrane showed that HA did not complex selenite. Indeed, addition of HA in the outer volume of synthetic water did not affect selenite diffusion in dialysis membrane (no interaction) and consequently the obtained K_d with the two solid phases were similar to those obtained without HA. However, addition of HA to the solid phase inside the dialysis membrane showed a drastic decrease of Se sorption on goethite from 9411 to 3215 L.kg⁻¹ (figure 1) while the sorption capacity of bentonite with respect Se was not affected (data not shown).

![Figure 1. Selenium K_d values with and without HA and with HA inside and outside the dialysis membrane at pH 7.0 and [Se] = 1.26×10⁻⁷ M.](image-url)

These results suggest that HA and Se compete for the same sites on goethite, namely –SOH₂⁺, while Se and HA sorb on two different sites on bentonite. In a recent work by Salman et al. (4) the authors suggested that adsorption of HA on bentonite is mainly due to the interlayer structure rather than complexation with the smectite edge sites (5).

Le but de ce travail est de mieux comprendre la sorption des sélénites dans un système composé de plusieurs phases minérales. La méthode des « membranes de dialyse » a été utilisée et validée pour montrer la compétition entre les différentes phases solides et organiques lors de la sorption des sélénites.


Analysis electrophorèse capillary
SMART (Group for Radioactivity Measurement and Analysis in the Environment)

P. Chardon


Au sein du groupe de Radiochimie de Subatech, SMART assure une activité de prestations analytiques et d’expertises dans le domaine de la mesure de la radioactivité dans l’environnement. SMART est structuré pour répondre aux préoccupations environnementales émanant de tout acteur de la société (industriel, administration, autorités locales ou nationales, association, particulier,....). Laboratoire reconnu au plan national, SMART dispose d’agrément des Ministères de la Santé et de l’Environnement et est accrédité COFRAC depuis 1998.

One of the specific originalities of the Radiochemistry Group of Subatech is the analytical entity SMART. The aim of SMART is to answer any request from society connected with the measurement of radioactivity in the environment.

SMART offers analytical services and expert evaluations in a very large domain. The analysis of any kind of radioactive emitter ($\alpha$, $\beta$ and $X/\gamma$) in any kind of matrix (natural or industrial) can be performed.

Over the years, the competence of SMART has been successfully demonstrated in the following fields:

- measurement of radioactivity in natural samples (water, soil, sediment, plant, bio-indicator) and in food (fish, cereals).

Since mid-2004, French legislation has imposed a control of all sources of water intended for human consumption (i.e. groundwater, river water coming in and treated water coming out of water cleansing plants). SMART was one of the first laboratories in France to receive the agreement jointly of the French Departments for Health and for the Protection of the Environment.

- regulation controls of the liquid effluents coming from nuclear power plants, nuclear medicine departments and/or from their associated research labs.

- characterization of the radioactive wastes coming from (i) the dismantling of old nuclear plants or university nuclear labs (concrete, steel) (ii) incineration or (iii) kitchen/industrial waste plants.

- regulation controls of radon gas in public buildings.

- expert evaluation of the impact of old industrial sites contaminated by radioactive elements (in situ screenings and sampling, low level laboratory analysis and writing of expert evaluation reports).

- expert evaluation relating to the presence of radioactivity in the natural environment (radiological state of reference, supervision of the environment, calculation of the dose).

The strong analytical capacity of SMART is based on a large set of high-performance analytical equipment, including:
- alpha spectrometers with silicon (PIPS) detectors,
- hyper pure Ge gamma spectrometer with samplers,
- X-ray spectrometer,
- gaseous flowing proportional counters with very low background,
- liquid scintillation counters with very low background

Additionally:
- $\alpha$ spectrometer (PIPS detectors)
- specific combustion device for the determination of $^{14}$C and $^3$H in various matrices,
- devices for the determination of radon,
- an ICP-MS spectrometer for the analysis of non-radioactive trace level elements,
- an ionic chromatography system for the determination of non-radioactive major elements.

In a field where the independence of the judgement and the quality of the services are of great importance, SMART certifies impartial and highly reliable measurements. This ability is based on an accurate process of Quality Assurance in conformity with the requirements of the ISO 17025 norm.

SMART’s organization and documentary system first received the accreditation of the COFRAC (the French Committee for Accreditation) in 1998 for the following analysis (program # 135 on liquid matrix): $\gamma$ spectrometry, gross alpha and beta counting, $\alpha$ spectrometry for uranium and trans-uranium isotopes (in solid matrix also) $^{226}$Ra and $^{210}$Po, liquid scintillation for $^{14}$C, $^{210}$Pb and $^3$H determination. This accreditation was renewed in 2008.

During recent years, a great effort has been made to extend the area of accreditation, especially towards the analysis (i) of solid matrices and (ii) of natural radioactive emitters such as $^{226}$Ra, $^{41}$Ca,$^{93}$Mo, $^{210}$Po and $^{210}$Pb.

Moreover, for many years, SMART has actively participated in national and/or international inter-laboratory tests. For example, four times a year, SMART participates in the inter-laboratory tests organized by IRSN (the French Institute for Radioprotection and Nuclear Safety).

The very high quality results obtained during these tests allow SMART to:

i) receive the agreement for the measurement of radioactivity in the environment, jointly delivered by the French Departments for Health and for the Protection of the Environment,

ii) be a full member of the National Network for the Supervision of the Environment.

Lastly, SMART is an active member of the BNEN, which is the French office of standards dealing with normalization in the domain of nuclear techniques.

SMART : laboratoire de mesure de la radioactivité dans l'environnement d'un très haut niveau de compétence.

SMART a pour vocation de répondre à la demande sociétale relative à la mesure et à l’expertise de la radioactivité dans l’environnement. Ces clients sont tout autant des particuliers, des industriels, des autorités locales (mairies, préfectures) ou des administrations.

SMART a développé un périmètre analytique très étendu qui lui permet d’analyser toutes les formes de radioactivité ($\alpha$, $\beta$ $X/\gamma$) dans des échantillons aussi différents que l’eau, les denrées alimentaires, les sols, les végétaux, les matériaux industriels, avec la même fiabilité.

Ces capacités analytiques étendues reposent sur un parc d’équipement analytique moderne et conséquent.

SMART travaille sous Assurance Qualité. La qualité de ces prestations est officiellement reconnue par son accréditation COFRAC et par les divers agréments octroyés par les ministères de la Santé et de l’Environnement.
NTSE Students visiting the Civaux power plant

17 students (EMN NTSE option) at the Civaux nuclear power plant at (near Poitiers). Instructors from EDF gave a lecture on the power plant operation followed by an on-site exercises on the control room simulator.
Teaching Activities

Subatech is involved in several teaching activities at levels ranging from undergraduate to PhD. The proposed courses are mainly dealing with physics, electronic and mathematical sciences. The teaching activities take place at the University of Nantes and the Engineer school of “Ecole des Mines de Nantes”. At the University of Nantes, the Professors and Assistants are in charge of subatomic and physics, numerical methods, quantum and mathematical physics and participate to the teaching in general physic and computer science. They have been deeply involved in the commissions preparing the transition to the European LMD organization in Universities. The University teachers actively contribute to the administrative jobs and responsibilities at the faculty of sciences of Nantes. They are in charge of two Masters:

- The Subatomic Physic Master of Science, to prepare students to PhD in Subatech labs.

- The Master in Applied Radiation Sciences (“RIA”). This Master has been opened in September 2006.

The Subatech teaching team is also in charge of designing new cycle of courses. The teachers (and researchers) participate to conferences and seminars to promote the general physics and particularly the subatomic physics and to answer to the questions of the population relative to nuclear waste, energy production, astrophysics,...

The Ecole des Mines de Nantes trains engineers in the methods necessary for the design, development, optimisation, management, control and maintenance of industrial systems. The EMNantes engineer possesses : strong project management skills, an international profile, creative and proactive skills, a multidisciplinary background, a thorough preparation for efficient integration in the corporate world. The Subatech group is involved in teaching all underpinning knowledge's and understanding of science, mathematics and engineering fundamentals.

The competences-oriented teaching program lays special emphasis on personal development to enable students to build their own professional project.

A specialized courses in the field of Nuclear Systems (technology, safety, and environmental issues) is proposed by Subatech. These courses lays on a two years Master cycle:

1. Fundamentals in subatomic physics and principle of interaction radiation matter is proposed at the beginning of the first year. These part include a lot of practical trainings in order to well understand radioactive phenomena. During the second semester, more specialized courses are realized: an introduction to Radiochemistry, Monte-Carlo methods, Interaction of radiation with water and environment, basics of nuclear instrumentation.

2. The second year is more dedicated to nuclear production of energy, nuclear fuel cycle and radioactive wastes reprocessing. A large part of courses deal also with applications of nuclear method to medicine and radioelement production with accelerator. A lot of people from Subatech are involved in this training associated with specialists from the corporate world. A six month training in company complete these engineer diploma.

Since 1997 more than eighty engineers have obtained a diploma in Nuclear Science at the EMN, and we have to keep in mind that the interest of student for nuclear had clearly increase (+100%) in the last two years.
Information-Technology Division

J. Andrianavaly, J. M. Barbet, K. Chawoshi, P. Le Corre, J. Pinot

The IT service of SUBATECH is currently composed of five people and is in charge of:

- evolution and maintenance of the computing equipments of the laboratory (about 300 machines)
- management and protection of the local area network
- support to users
- researching the IT solutions needed by scientific projects

During the 2006-2008 period, as for previous years, the IT service has answered to the development of SUBATECH and the needs of its (staff) by acquiring adequate IT equipment: servers for computing and data analysis, office workstations, CAO workstations for the electronics/mechanics engineering, printers, etc.

The following points are summarising the various activities of the IT service:

Scientific Computing

In addition to the CCIN2P3 resources, the SUBATECH’s research groups are also using the local computing and data analysis (storage) resources for their scientific activities in order to prepare their national or international experiments. For this purpose, we have upgraded local PC/Linux cluster by replacing its working nodes (workers) with last generation’s PC and adding new nodes. This cluster is now currently composed of 45 Intel Xeon servers (260 Cores) running at 3GHz.

The SUBATECH laboratory is operating a Tier-2 center of the LHC Computing Grid (LCG), supporting the Alice experiment virtual organisation. The site, certified in January 2006, is now fully operational and actively used for Monte-Carlo production and storage. In 2007 112,072 Alice production jobs have been completed at the site for a total of 1,358,000 KSI2K*hours. The site is taking part to most LCG computing exercises, including the recent Common Computing Readiness Challenge of 2008 (CCRC08).
Data storage

The capacity of our SAN storage system has been augmented up to 60To to both the needs of the laboratory itself and the LCG-Tier-2 project commitments. A study has also been led for the installation of a high capacity (up to 140To) scalable storage system, in order to fulfil the needs of the laboratory for 2008-2010.

Management of IT

The laboratory’s assets count more than 300 workstations, desktop or laptops, running the Linux or Windows operating systems. During the period covered by this report, the following actions have been taken in order to help to their evolution and management:
- upgrade of all HEP supported Scientific-Linux 3 based computers to the SL4,
- upgrade of all Windows computers to Windows-XP,
- installation of a new NAS-SAN server (NetApp FAS3020) with a NDMP backup library,
- installation of management tools enabling automation of software installation and updates (used for Xlab, Firefox, Anti-viral software, patches, etc) for Windows workstations,
- installation of a Nagios based monitoring system for servers and network equipments.

Concerning the general purpose servers (mail, web, printing, AD, etc,) we have replaced a dozen of servers by virtual machines running inside a couple of physical machines by the means of VMware-ESX.

Local Area Network and Internet connection

The use of distributed resources located at CERN or at the CCIN2P3 and the experiment’s data transfers require high speed networks. Aiming at this, the local area network has been improved and the outside Internet connection is now based on a 1Gb/s link with the RENATER-III NRD.

In order to guaranty the safety of our network, we installed a firewall on the network entrance point. We have also defined a separate VLAN network to connect occasional visitors or workshops involving outside people in a secure way.

Computer security

Computer security rules and actions are taken according to an IN2P3 existing organisation known as the « Security Group» and in the framework defined by the CNRS. Apart from monitoring actions and reinforcing internal computer security, the laboratory has taken a very active part in a current thinking in the IN2P3 which aims at defining an IT Security Policy in consistency with the CNRS. Subatech organized the annual meeting of the IN2P3 Computers Security Group in September 2007.

User support

Considering that quality and well managed equipment are offering the best return on investment only if they used in the best possible way and that the evolution of the IT technologies requires the users to be helped, the IT service wants to provide a quality service to all users. In this view, the installation of a new request tracking system named Request-Tracker (RT) has allowed to improve this service even more.

Les chercheurs de Subatech, ainsi que ses services administratifs et techniques utilisent des moyens informatiques modernes et performants pour leur activité de recherche et de développement. Le réseau du laboratoire et sa connexion externe avec les autres réseaux de recherche leur permettent également d’accéder à des ressources distantes disponibles dans les centres de calcul nationaux et internationaux comme CCIN2P3, CERN, BNL.

Le service informatique de Subatech a la responsabilité d’étudier leur besoins, de proposer des solutions adéquates et d’en assurer la maintenance. Dans cet objectif, il est nécessaire de suivre les évolutions des technologies informatiques, en particulier dans les domaines suivants :
- Systèmes de stockage de haute capacité,
- Serveurs de calcul intensif en grappe,
- Réseau de communications haut-débit,
- Gestion centralisée des machines,
- Sécurité des systèmes d’information.
Mechanical Division


Le service mécanique de SUBATECH a en charge la conception et la réalisation des appareillages nécessaires aux projets dans lesquels le laboratoire est impliqué. Il participe également aux projets éducatifs des élèves de l’Ecole des Mines et assure un soutien technique aux groupes de radiochimie.

The aim of mechanical team of Subatech is to provide mechanical engineering for scientific projects of the laboratory. The principal projects in which the team is involved are the following:
- ALICE EMCcal
- ARRONNAX
- Nuclear and health
- CODALEMA
- Radiochemistry
- Detectors

The mechanical team is also involved in projects from engineer students.

Staff
The team is constituted of 8 engineers and 5 technicians, shared in 10 for the design office and 3 for the workshop.

Software (Design office)
The main software used in the design office is CATIA V5, a 3D CAD application. For structural and thermal analysis engineers use 2 Finite Element analysis applications, SAMCEF and ANSYS.

Hardware
The equipment in the workshop is made of 3 CNC Milling machines, 2 CNC and 1 classic lathe. The workshop is also able to lay out welding, to cut and drill mechanical pieces. The 3 CNC milling machines are interfaced with CATIA CADF post-processor application allowing these machines to work with files sent directly from the CAD software. This process allows to machine complex shapes.
The Electromagnetic Calorimeter for ALICE is the heaviest detector of the experiment, 120 tons for 7m length and 5 m radius. One of the first tasks involved to the mechanical team was to re-build and to update the 3D CAD model of the detector. This work allowed the design of the Super Module’s support, the rails. They have been manufactured by a French company and assembled first in SUBATECH and finally at CERN.

**Strongback**

The second very important point is the study and the realization of the strongback, support of the modules. This part ensures the fixation of 12 modules and integrates the optics path for the light transfer and the Front End Electronic to obtain a Strip-module.

To minimize the cost, a solution by moulding and machining has been chosen. This solution allows obtaining complex forms and minimizes the machining time.

**Crate**

The collaboration ALICE EMCal asked SUBATECH to design the 3D CAD model of the Super Module’s crate, big box dedicated to receive 24 Strip-modules.
Insertion Tooling

The tooling, dedicated to the insertion of the crates equipped with their detectors in the support structure, is able to support a weight of 8 tons, to turn and move it on the rails in working place. The design has been made by the mechanics team and realized by several companies in France.

Fig. 10: Tooling in the workshop before transport at CERN

The workshop also carried out various parts of the approach system for the Super modules as well as the alignment target for the support rails. The fixing of the support rails on support structure and the tests of the insertion were ensured by us on the site of the CERN in June 2008.

Modules and Strip-modules assembly.

As for the project Dimuon project, the mechanical service is in charge to assemble 288 detection modules into 24 Strip-modules (equivalent to one Super-module’s crate). This task requires the installation and the organization of several assembly lines.

CODALEMA

Radio detection of ultra high energy cosmic ray air showers. A study has been made by the design office and the workshop has realized 10 antennas in June 2006 and 12 in June 2007.

Fig. 11: Antenna in a meadow

MYRRHA

Subatech takes part in the design of a windowless liquid lead-bismuth target, within the framework of the project ADS. The experience gained by Subatech in the project MEGAPIE (lead-bismuth target, with window) has a major importance for this new project.

SPIRAL 2

Subatech currently study a liquid target (deuterium), in alternative to the current solution of solid target planned for the Spiral2 neutron converter. This original target will allow the deposits of high thermals powers at the interaction area of the 200kW beam of Spiral2. One of the engineers participates also in the committee of expert charged to evaluate the feasibility of a solid target.

ACTIVITIES RELATED TO CYCLOTRON

ARRONAX

In collaboration with cyclotron team the mechanical group has to study and realize several set up for the machine. Degraders of energy for alpha and proton beam, thermal simulation, mechanical design and Integration in the beam line.

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NUCLEAR AND HEALTH

Irradiation of rubidium Chloride

Design and realization of an experimental equipment to test the irradiation of rubidium chloride on a beam. The final goal is to produce Sr82 generator for medical imagery application. The first beam was carried out in February 2008 at Nice.

Fig. 15: Integration on the beam line.

RADIOCHEMISTRY

Cells for high pressure diffusion

The rack, equipped with a reactor, is able to accommodate ten high pressure cells. The material is dedicated to test samples of clay taken on the sites planned for the storage of nuclear wastes (Bur).

Cells for electroplating application

Set up to deposit nickel 64 on a gold target. These types of targets have been irradiated on the Cyclotron of Orleans and will be used later on ARRONAX.

Fig. 18: ARRONAX type

Fig. 16: The set up for the experiment at Nice

Fig. 17: Orléans Type

Fig. 19: Rack of 10 cells

To accelerate and improve the studies of propagation velocity of radionuclide under high pressure, the workshop machined cells with different diameter (21, 42 and 60mm).

Cell of percolation

Cell of percolation are used to study the argillaceous material porosity. These cells must resist strong pressures as much as 120 bars.
Again with an aim of checking the propagation velocity of the radionuclide in a material, we designed and carried out a cell of diffusion for granite sample. We also realize a prototype of cell for iron sample to measure oxidation velocity.

Cell of diffusion « LUCO »

For materials as cements the study of the propagation velocity requires different equipment. It must be made with polymer but does not withstand pressure.

Fig. 20: Cell for 42mm diameter sample

Fig. 21: Prototype machining in our workshop

DETECTOR

Beta imager

This gaseous detector is dedicated to molecular imagery on cut of body tissues. The design was made by PARRI group. The adaptation the realization and the assembly were made by the mechanical team.

Fig. 22: Beta imager

XEMIS

Gamma detection with liquid xenon has been studied at SUBATECH with the goal of improving PET (Positron Emission Tomography). The key idea is to integrate in liquid xenon a proportional chamber. Recent progresses have been made with gaseous devices for detecting both ionization and scintillation. For reasons of purity of xenon and thermal dilatation of the detection structure, the main part of the structure is made of machinable ceramics. This constraint enabled us to acquire the techniques of machining for this type of materials.

Fig. 23: Detection area

GPM

In collaboration with the Weismann Institute of Tel-Aviv, we are working on a Gaseous Photo Multiplier using THGEM (THick Gas Electron Multiplier). This detector is designed and will be made at SUBATECH (except THGEM realized by the Weismann Institute). The gas detector will be installed in a vacuum chamber plunged in liquid xenon.

Fig. 24: GPM
Technical groups and administration

Mechanical workshop

CNC Milling machine
RAAMO
(Robot Anguille Autonome en Milieu Opaque)

S. Bouvier, P.B. Gossiaux, L.M. Rigalleau, N. Servagent

RAAMO est un projet ANR piloté par le département Automatique et Productique de l’école des Mines de Nantes. Subatech a pris en charge les lots 3 et 4 du projet qui sont le développement des modèles physiques liés à l’électrolocation, la mise en œuvre d’une méthode de mesure et la conception du système électronique associé.

Theoretical and simulation part :
Physically, the weak electrical fishes achieve electro-location by creating a controlled electrical current (associated to some electrical field due to Ohm’s local law) that flows from the “emitter” pole to the “receivers”, through a conductive medium (water). Isolating or conductive obstacles located in this medium then get polarized, what creates in return an induced electrical field which implies a modification of the current at the receiver sensors, modification referred as the “electrical image” (EI) of the environment. One ultimate achievement of the RAAMO project would be the ability to evaluate EIs’ with quick analytical model for a large class of environments, However, due to its non-local nature, such a problem is non trivial and the only analytical solutions that can be found in the literature mainly concern the influence of small objects.

Noticing that an intermediate goal of RAAMO would be to have the eel-robot circulate in a close tank, we have restricted ourselves, as a first task, to the case of the EI of an isolating infinite wall. For this purpose, we have modelled the eel by an electrical dipole (+: emitter; -: receiver) and resorted to the image-method to implement the boundary condition (current density parallel to the wall). Within this model, the external conductance $\Gamma_{env}$ admits a simple expression ($\gamma$ being the conductivity): 
$$
\Gamma_{env} = \frac{\gamma}{2\pi R(1 + \frac{1}{2\pi}) - \frac{3d}{\gamma L_{env}^2} - \frac{\gamma}{\sqrt{4d^2 + 2L_{env}^2}}}
$$
which was used to analyse the achievable sensitivity of electro-location ($\approx$1% for a wall located at “half-length” $L/2$ in front of the eel) as well as to design “observers” for observation and detection based on Extended Kalman Filter algorithm (cf publication).

Although the image method might be very convenient, it only applies to limited cases of environments and only provided the distance to the wall is large compared to the transverse size of the eel fish. In order to circumvent these limitations, we have developed numerical simulations based on the “Boundary Element Method” (BEM) and compared the results for the realistic situation our prototype (see next part) immerged into a water tank.

Experimental set up
The experimental set-up is given by Fig.1. A bipolar probe is immerged in water. One of its electrodes is connected to a signal generator and the other to a 50 $\Omega$ load resistor. The frequency $f = 20$KHz of the signal ($U_0$) avoids ion migration to the electrodes. (direct current does not allow measurements). Reception signal ($U_1$) is proportional to the current travelling through the water between the two stainless steel electrodes of the bipolar probe (Fig. 2).
The electro-location is based on the equivalent resistance obtained by the voltage measurement on a load resistor (fig.3) or by the current measurement. It has been demonstrated by calculation and confirmed by the experimental measurement that a direct current measurement is more sensitive to resistance variation.

Due to the very low level of variation, around 0.4% at a distance corresponding to twice the length of the probe, a differential measurement is under investigation. Moreover, the variation of the conductivity from one medium to another has to be taken in account too.

**Future prospects**

A multi-polar probe is already study. It has the same geometry than the bipolar one. It is composed of one exiting electrode and twelve reception electrodes. Such a probe will be able to locate the wall position of the water tank. Using a cartesian robot (XY) with rotation stage (around Z) to motorised this probe, it will be possible to follow any movement law in XY plane (respecting low speed). Our first goal is to make the probe doing a complete round of the tank at a fixed distance of the walls. To do that, the electrodes signals will be processed in real time using algorithm based on the theory part to determine the instantaneous position and the new position to be reached at the next step. This new position will be transmitted from the computer to the cartesian robot which will move the probe.

Un prototype d’électrolocalisation basé sur un algorithme BEM appliqué à une simple sonde bipolaire a permis la détection des parois d’un aquarium 0.4x0.55x1m³ (préc. sig. 5%). Afin de discriminer la position de ces parois, une sonde multi-polaire a été réalisée. En motorisant cette sonde à l’aide d’un robot cartésien (XY) équipé d’un axe de rotation (Z), il sera possible d’effectuer une trajectoire quelconque à hauteur fixe. Notre premier objectif d’électrolocalisation consiste à traiter en temps réel les signaux de cette sonde par un algorithme BEM spécifique pour qu’elle réalise un tour complet à vitesse constante dans un aquarium de 1x1x1m³ à une distance fixe des bords.

[1] Reference publications
ALICE-Dimuons read out card with its FPGA modules
Les principales compétences du service :  
- Pré-étude  
- Cartes électroniques de type numérique rapide haute densité.  
- Cartes électroniques de type mixte analogique/numérique.  
- Cartes électroniques de type anode pour détecteur gazeux.  
- Circuits programmables (VHDL.)  
- Simulation VHDL multi carte, multi FPGA.  
- ASIC analogique bas bruit, large bande  
- Simulation ASIC analogique  
- Conception, simulation et mesure d’antenne  
- Soudure sous binoculaire  
- Déverminage, validation, réparation de cartes électroniques.  

- Intégration système sur site.  
- Développement de bancs de test  
- Développement de programmes d’acquisition  
- Bases de données avec PHP/mysql

Les principaux outils du service :  
- Cadence (Linux)  
- Synplify_pro (Linux et Windows)  
- QuartusII (Linux et Windows)  
- ModelSim (Linux et Windows)  
- Matlab  
- LabVIEW  
- Oscilloscope numérique  
- Analyseur logique  
- Générateur de pattern  
- Analyseur de réseau  
- Analyseur de spectre
CODALEMA: From autonomous station installed at AUGER-south to the new one tested at NANCAY

S. Acounis, J.L. Béney, D. Charrier

Pour la mesure du champ électromagnétique associé au rayonnement cosmique entrant dans l'atmosphère, 3 stations autonomes (utilisation de cartes de déclenchement autonome) ont été conçues, fabriquées et installées sur le site d'AUGER sud (Malargüe, Argentine). A partir des retours techniques et scientifiques, une nouvelle architecture a été choisie. Cette nouvelle station autonome est intégrée et testée actuellement au radiotélescope de Nançay (France).

In 2006, 3 autonomous test stations were installed in Malargüe (Argentina). Subatech developed the antennas and the trigger board of these stations. All the other parts are “off the shelf”: UB card from Auger, Tektronix portable oscilloscope, standard Wifi access point. After a debugging period, the stations performed well and good results showed up.

Based on this experience, a new architecture of the station is being developed. The hardware part is composed of one trigger board (SUBATECH), 2 acquisition boards (LAL), one GPS board (LAOB) and one controller board (Station de Radioastronomie de Nançay) integrated into a crate in “Europe” format. See Fig.2.

The trigger board has been redesigned to be fully programmable. The thresholds and the trigger logic have a serial link with the controller board (Rabbit card). See Fig 3.

Two different versions based on the same electronic will exist: one that can be plugged in a chassis (currently being tested at Nançay observatory) and a stand-alone version equipped with a Rabbit controller card.
The controller board based on a Rabbit processor manages the data acquisition of the station by exchanging data with a PC through an Ethernet link. A client/server software has been developed by Nançay and Nantes. The client executed on PC is able to send commands to the server in order to configure the acquisition. The server executed on the controller sends science event to the client when an autonomous trigger is generated. It sends it also an acknowledge event systematically after having received and executed a command. All events are stored by the client under binary files. See Fig. 4.

The new station and its associated PC is being integrated and tested at Nançay. See Fig. 5.
The CODALEMA active dipole antenna

D. Charrier

In 2006, 500 Low Noise Amplifier (LNA) were produced for the need of the CODALEMA extension at Nançay (France) and Malargüe (Argentina). They are still exactly the same ASIC as those designed in 2004 [1], but packaged in a low cost plastic box. This is why a new PCB (Fig. 1) and a test bench were built for a quality control of the produced LNA. Since the beginning of CODALEMA, 30 antennas [2] have been produced and installed on the field (see also the contributions from the Astroparticle group in this report).

Fig. 1: The antenna preamplifier board.

To enhance the detection performance of the antenna, the following goals should be achieved: (a) galactic noise dominated antenna; (b) perfect linearity LNA; (c) constant and poor directivity; (d) three polarizations measurement possibility without any cross-talk and finally; (e) cheap and reliable antenna. Few studies using a NEC2 algorithm software were performed in order to design the optimum antenna radiator shape. A good compromise seems to be a V-shape closed loop dipole antenna (Fig. 2). This antenna radiator is very simple: it uses only copper wires, and is crossed in order to measure the X and Y linear polarizations. The vertical polarization is not measured separately but detected thanks to the V-shape.

Fig. 2: A V-shape prototype antenna.
Measurements were performed at Nançay to verify the validity of simulations. The methodology to design the antenna lies in four steps: (a) the antenna is created by using EZNEC software and divided in a suitable number of segments for a finite element method computation; (b) the antenna impedance is extracted; (c) the galactic background detected by the antenna is computed using few MATLAB functions; (d) the antenna radiator is built (Fig. 2); (e) finally, measurements of the galactic noise are performed and compared to the simulations (Fig. 3). By this way, the validity of the simulation is checked using the galactic background as a reference. This allows to characterize the response of the antenna.

Fig. 3: Comparison of galactic noise between measurements (blue: V-shape, red: 1.2 m dipole) and simulations (solid line: perfect ground plane, dotted line: real ground plane).

This response depends on the antenna’s height above the ground, and on its electrical constants. The real system to be studied is thus a dipole antenna held horizontally above an infinite and varying reflector. This is why a theoretical study of the ground effect has been performed and implemented in MATLAB functions, taking into account the fact that the electric field to be detected is not an infinite sine wave but a finite pulse. Fig. 4 shows the CODALEMA antenna effective length in the zenith direction for frequencies between 10 and 200 MHz. The decrease of the antenna length with the frequency leads to a flat Fourier spectrum of the detected pulses.

Fig. 4: Simulation of CODALEMA antenna effective length. Red and blue lines are simulations taking into account the ground reflector. Pink line is for a free space antenna and the green line is the response of the perfect ground reflector.

At Nançay, a test bench has been installed in collaboration with the radio astronomers in order to characterize a set of antennas by measurement of the galactic background variations. This test bench is composed of a spectrum analyser, an analog switch, a band pass filter and an amplifier. On Fig. 5 the sky temperature variations detected by the CODALEMA antenna can be seen. Note that there are no intermodulation effects of the LNA during the 44 hours of run.

Fig. 5: Spectrum (10 to 100 MHz) versus time of the 1.2 m CODALEMA antenna (44 hours).
Simulations of the existing LNA (designed with the AMS BiCMOS 0.8 mm technology) with the same antenna radiator as Fig. 2 were computed with EZNEC and MATLAB softwares for the antenna impedance extraction and conversion to a CADENCE format. They give the following features: (a) the linearity is poor since the input IP3 is only -13 dBm at 10 MHz and -16 dBm at 100 MHz; (b) the sensitivity defined as the minimum galactic background over the LNA noise is 10 dB from 28 to 74 MHz; (c) the gain temperature drift from -40°C to 100°C is -3.3 dB. A new LNA with an up to date technology (the low cost AMS CMOS 0.35 μm) is under study and gives much better features: (a) the input IP3 is excellent (17.5 dBm at 10 MHz and 16 dBm at 100 MHz); (b) the sensitivity is 10 dB from 15 to 166 MHz with a much simpler antenna radiator; (c) the gain temperature drift is only 0.38 dB from -40°C to 100°C. Those features are better than those required for the low frequency radio astronomy (e.g. LOFAR project). This means that the new LNA becomes versatile, and could be used both for the cosmic ray radio detection and the radio astronomy.

Des préamplificateurs à bas bruit (LNA) ont été produits à 500 exemplaires. Une étude combinant des simulations et des mesures montre que la forme d’antenne optimale serait celle d’un « V-shape » à boucles fermées. La réponse de l’antenne CODALEMA a été étudiée et modélisée. Un nouveau LNA aux qualités prometteuses, compatible avec la radioastronomie, est en cours de conception.


[2] D. Charrier et al., IEEE antennas and propagation, Id. 10.1109/APS.2007.439
Technical groups and administration

Test station in the fields in Argentina
Alice DiMuon-Trigger On-Line Software and its integration with Electronics

J.L. Béney

Un groupe de programmes (MTS package) a été développé à SUBATECH afin d'interfacer les différents logiciels on-line génériques (DAQ, CTP, ECS) et spécifiques (CP, DQM, DA) entre eux ainsi qu'avec les électroniques de lecture et d'acquisition qui nécessitent dans le cas du Muon Trigger le chargement d'un nombre important de paramètres en début de Run. Il a apporté en plus une série de diagnostics sur le fonctionnement des électroniques qui en a fait un des outils principaux pour l'intégration du détecteur sur le site du CERN.

The ALICE on-line software is mainly composed by the Detector Control System (DCS), the Central Trigger Processor (CTP), the Data Acquisition (DAQ) and finally the Experiment Control System (ECS). The ALICE Muon Trigger is interfaced with these 4 systems. See Fig.1.

Fig. 1: ALICE On-Line Architecture for Muon Trigger

Its electronics exchanges data directly with CTP and DAQ through Global and DARC boards. The overall electronics can be configured through JTAG board and their inputs be fired on front-end side through FET board.

These 5 boards are integrated in the Global crate and can be configured and monitored by the associated VME CPU (VP315).See Fig. 2.

Fig. 2: ALICE Muon Trigger Electronics

The MTS package is the set of programs and libraries which are used on the VME CPU to test, configure and monitor the electronics. It is composed of several softwares: One test program associated to each VME board and the MtsProxy.

The test programs are used to test and validate their associated board when it is integrated in the Global Crate. The MtsProxy is started before any ALICE Run in which the Muon Trigger is set in the Global Partition. The ECS controls the MtsProxy through a FSM (Finite State Machine) and can request to test, configure or monitor the electronics. The MtsProxy is able also to set the mode of each L0 trigger signal on CTP request. See Fig.3.
When a configuration is required, it gets the active setup from the DAQ data base as the 3 other specific on-line software (Control Panel, Data Quality Monitoring and Detector Algorithm). See Fig.1. The development of the MTS package has been done under Linux, in C language using an object methodology. The access to the VME bus has been performed in using either the CCT driver or the CERN driver. The MTS package uses the DIM package for TCP/IP communication, the SMI package for state machine control and mysqlclient package for data base access. It has been tested first on a test bench built at SUBATECH before being installed and tested at CERN with the overall electronics.

Les logiciels «on-line» d’ALICE sont principalement composés du DCS, du CTP, de la DAQ et de l’ECS. Le détecteur Muon Trigger est interfacé avec ces 4 systèmes. Voir Fig.1. Son électronique échange des données directement avec le CTP et la DAQ à travers les cartes Global et DARC. L’ensemble des électroniques peut être configuré grâce à la carte JTAG et activé par la carte FET. Ces 5 cartes sont intégrées dans le châssis Global et peuvent être configurées et surveillées par le processeur VME associé (VP315) Voir Fig.2. Le paquetage MTS est un ensemble de programmes et de bibliothèques qui sont utilisés sur le processeur VME pour tester, configurer et surveiller les électroniques. Il est composé par plusieurs logiciels: un programme de test associé à chaque carte VME et le MtsProxy. Les programmes de test sont utilisés pour tester et valider leur carte associée quand elle est intégrée dans le châssis Global. Le MtsProxy est démarré avant chaque démarrage d’ALICE auquel participe le Muon Trigger. L’ECS contrôle alors le MtsProxy et peut lui demander de tester, configurer ou surveiller les électroniques. Le MtsProxy est aussi capable de configurer le mode de chaque ligne de déclenchement de niveau 0 sur demande du CTP. Voir Fig.3. Quand une configuration est demandée, il va chercher la dernière qui est active dans la base de données de la DAQ comme les 3 autres logiciels spécifiques (CP, DQM et DA). Voir Fig.1. Le développement du paquetage MTS a été fait sous Linux, en langage C et en utilisant une méthodologie objet. L’accès au bus VME a été réalisé en utilisant le driver CCT et le driver du CERN. Le paquetage MTS utilise les paquetages DIM pour la communication via TCP/IP, SMI pour le contrôle par machine à état fini et mysqlclient pour l’accès à la base de données. Il a été testé en premier sur un banc de test construit à Subatech avant d’être installé et intégré au CERN.
Alice DiMuon-Trigger DARC card

R. Berny, P. Pichot, Ch. Renard

Le service Electronique a développé une carte VME capable de prendre en compte les consignes et messages de déclenchement de l’expérience Alice (CERN), de lire les données du DiMuon-Trigger afin de former un événement au standard d’Alice et enfin d’envoyer cet événement vers l’acquisition centrale d’Alice.

The DARC board is the interface between the DiMuon-Trigger detector (Front-End boards, Local-Trigger boards, Regional-Trigger boards and Global-Trigger board) and the Alice experiment (Central-Acquisition and Central-Trigger). See Fig. 1.

The DARC board decodes the commands coming from the Alice-Central-Trigger, generates a signal to freeze the sensor data, reads and temporarily stores the data from height Regional-Trigger boards, the Global-Trigger board and the Alice-Central-Trigger. Finally, it transmits these data (1.28 Giga bit per second) to the Alice-Central-Acquisition when required. See Fig. 2.

Fig. 1: DiMuon-Trigger readout and trigger electronics, block diagram

Fig. 2: DARC, block Diagram

The DARC board has two extension slots. See Fig. 3:
- One for a DCS board, developed in Germany, which receives the commands via optical fibre from the Alice-Central-Trigger.
- One for an SIU board, developed in Hungary, which transmits the data via optical fibre to the Alice-Central-Acquisition.
The size of the DARC printed circuit is 367 mm x 400 mm x 1.6 mm (VME triple Europe format, double depth). It contains 14 layers on which the conductor minimum width is 120 µm and the minimum gap between conductors is 120 µm (class 6). 2700 of the almost 4000 holes have a diameter of 350 µm.

The DARC board contains more than 400 components, distributed on both sides of the printed circuit. One component is soldered on a thermal-drain. The six BGA components have a density of 100 pins per cm². See Fig. 4.

The prototype that interfaces to only one Regional-Trigger board is used for the acquisition of the Alice Zero Degree Calorimeter (ZDC).


STAR SSD Upgrade

S. Bouvier, Ch. Renard, L. M. Rigalleau

De 1998 à 2004, nous avons développé et installé, en commun avec l’IPHC (anciennement IRES) à Strasbourg (F), le détecteur au silicium à micro pistes (ou SSD pour Silicon Strip Detector) pour l’expérience STAR, installée auprès de l’accélérateur RHIC (BNL, USA). En prévision de l’augmentation de luminosité de RHIC, les chercheurs américains (LBL USA) qui ont pris la responsabilité du SSD nous ont demandé de proposer une solution technique afin d’adapter l’électronique de celui-ci au nouveau système d’acquisition (DAQ1000) de STAR et de diviser par au moins 70 le temps d’acquisition des données. Pour des raisons de coût et de délai, cette solution ne doit pas nécessiter de modifier les modules (capteurs et électronique de Front-End) ni leurs bus.

From 1998 to 2004, we have developed and installed, in common with IRES laboratory (renamed IPHC) from Strasbourg (F), the Silicon Strip Detector (SSD) in the STAR experiment, on the RHIC accelerator (BNL, USA).

Anticipating RHIC luminosity increase, American physicists (LBL, USA), in charge of the SSD upgrade asked us to propose a technical solution in order to adapt the SSD to the new STAR acquisition system (DAQ1000) and to divide by a factor of 70, at least, the SSD acquisition time.

For cost and time to market reasons, this solution must not need to change the modules (sensor and Front-End electronics) nor their bus cable.

The new STAR acquisition system (DAQ1000): The DAQ1000 system is based on the DDL link, developed for the acquisition of ALICE (LHC, CERN) experiment.

We have implemented this link on two different printed circuits (DARC_vadorh and DARC) that participate to data taking respectively for ZDC and Dimuon-Trigger detectors in ALICE.

Reducing the acquisition time:

In the actual version of the SSD, the data readout is multiplexed at a low frequency: 768 channels x 16 modules x 10 ladders on a 10 bit bus at 30MHz. See Fig.1. The readout time (4ms) is longer than the transfer time to the acquisition (1.8ms) but the acquisition requests us to transfer many other filling words (3ms), bringing the total to 7ms.

Progress in integration and power dissipation for analog to digital converters and serial transmissions permitted us to propose a solution mixing parallel readout: 16 modules x 5 ladders at 50MHz and GHz serial transfer on optical fibre. See Fig.2. The readout time (154µs) becomes shorter than the transfer time to acquisition (410µs).

To decrease this transfer time, we consider implementing a zero suppression mechanism (the expected occupation rate would permit us to divide by 3 the transfer time).
Le nouveau système d’acquisition de STAR : DAQ1000
Le système DAQ1000 utilise le lien DDL, développé pour l’acquisition de l’expérience ALICE (LHC, CERN). Nous avons implémenté ce lien sur deux circuits imprimés différents (DARC, vadorh et DARC) qui participent aux prises de données respectivement des détecteurs ZDC et Dimuon-Trigger d’ALICE.

La diminution du temps d’acquisition :
Dans la version actuelle du SSD, la lecture des données est multiplexée à basse vitesse : 768 voies x 16 modules x 10 échelles sur un bus 10 bits à 30MHz. Voir Fig.1. Le temps de lecture (4ms) est plus grand que le temps de transfert vers l’acquisition (1,8ms) mais l’acquisition réclame le transfert de beaucoup de mots de remplissage supplémentaires (3ms), portant le temps total à 7ms.

Les progrès en intégration et puissance dissipée des convertisseurs analogique vers numérique et des transmissions série nous permettent de proposer une solution mixant lecture en parallèle : 16 modules x 5 échelles à 50MHz et transfert série sur fibre optique à 1GHz. Voir Fig.2. Le temps de lecture (154µs) devient plus petit que le temps de transfert vers l’acquisition (410µs).

Afin de réduire le temps de transfert vers l’acquisition, nous envisageons d’implémenter un mécanisme de suppression de zéro (le taux d’occupation attendu nous permettrait de diviser par 3 ce temps de transfert). L’implémentation d’une mémoire interne pouvant contenir 4 événements est aussi envisagée afin de découpler la lecture des capteurs du transfert vers l’acquisition.

Intégration avec les nouveaux détecteurs de STAR :
En parallèle à l’augmentation de luminosité de RHIC, de nouveaux détecteurs vont s’installer dans STAR (HFT, IFC, FGT). Certains seront tout près du SSD et demandent que des câbles et le câblage du SSD soient modifiés. Voir Fig.3.

État des échelles :
Toutes les échelles (20 + 2 de réserve) sont à SUBATECH pour la maintenance. Les premiers tests ont montré que plus de 90% des modules sont bons.

Fig. 2: SSD readout proposal, block diagram
To decouple the readout of the sensors from data transfer to the acquisition, implementing an internal memory that could contain 4 events is also studied. The SSD acquisition time would then only be due to the readout time of the sensors.

Fig. 3: SSD proposed and old cabling
Integration with new STAR detectors:
Aside RHIC Luminosity increase, some new detectors will install in STAR (HFT, IFC, and FGT). Some of them will be very close to the SSD and ask for cable and cabling modification. See Fig.3.

Ladder status:
All the ladders (20 + 2 spares) are actually at SUBATECH for maintenance. The first tests report that more than 90% of the modules are good.

CENTre AUtomatique de REceuil d’événements (CENTAURE)

D. Roy

The “Centaure” acquisition software previously developed at Subatech is always used locally and is also exported to other laboratories. This generic software is particularly well suited for new detector tuning. It permits to operate acquisition with CAMAC/VME modules, including namely CAEN v551/v550 couple. The last version corrects some imperfections at the level of command synchronisation. We were asked to produce a “light” version of Centaure, it is now available. The goal was to shorten the set up time, by guiding the user at each step or proposing more intuitive commands:
- Now, a single pop-up menu (See Fig.1) permits to create the I/O file, re-open an existing file, launch an off-line acquisition with the I/O file, or automatically commute to “replay” mode.

Fig. 1: pop-up menu

- The way to create the I/O command file has been simplified. Now, you pass through a step-by-step menu (See Fig.2) to produce a complete command file.

Fig. 2: I/O list editor step-by-step menu

- Write and test of treatment function is now eased by the “mini-projets” feature that user can adapt then test directly with LabVIEW before compiling it to create the DLL for Centaure.

Le logiciel d’acquisition de données “Centaure” développé à Subatech, continu d’être utilisé localement et s’exporte vers d’autre laboratoires.
Finally, the function catalogue was enriched with read functions that exploit the "bloc transfer" mode of the interfaces. This mode highly increases the acquisition speed.

Alice Electro Magnetic Calorimeter (EMCal)

P. Pichot, D. Roy

Nous avons pris en charge la réalisation de plusieurs cartes prototypes pour EMCal : TCard, lpcb_top, lpcb_bottom, GTLbusDataA, GTLbusDataB, GTLbusControlA, GTLbusControlB.

We had in charge to realize some electronic board prototypes for EMCal: TCard, lpcb_top, lpcb_bottom, GTLbusDataA, GTLbusDataB, GTLbusControlA, and GTLbusControlB.

We started from requirements issued by EMCal people and documents published on the web to study the new boards, adapted from those used by Alice-PHOS detector.

Il nous fallait à partir de demandes émanant des acteurs d’EMCal et de documents publiés sur le web, étudier de nouvelles cartes adaptées de celles du détecteur Alice-PHOS.

Nous avons proposé les “avant-projets” puis réalisé les prototypes de ces cartes.

Nous les avons expédiées au CERN, ou elles ont pu être validées.

Stacking up of plates of scintillateurs and of lead composing the heart of a module of the Emcal calorimeter of Alice
Construction of the SUBATECH building

October 2004

December 2005
Administration


Le service administratif de SUBATECH (11 personnes) apporte son soutien aux activités de recherche en assurant:
- l'accueil et la gestion administrative des personnels permanents et temporaires
- la gestion financière de l'ensemble des crédits et les procédures d’achats et de marchés publics
- l’organisation et la gestion des missions des personnels scientifiques, techniques et administratifs

The administrative staff of SUBATECH (11 people) supports the research activities by:
welcoming and administratively managing both permanent and temporary staff
financially managing all the allocations as well as both the purchasing procedures and public contracts procedures
organizing and administrating the trips and journeys of scientific, technical and administrative staff

Human resources management
The personnel division is responsible for the laboratory 149 agents (2006) and 164 agents (2007), with permanent or temporary status, regardless of their employer (National Centre for Scientific Research : CNRS, Nantes University, Nantes School of Engineering, or private associations).

Fig. 1: Manpower per employer on 31/12/2007

Fig. 1 shows that most engineers, technicians and clerical staff (ITA) come from CNRS whereas the breakdown of researchers and teaching researchers is more or less balanced.

If we compare permanent staff growth between 2003 and 2007 (Fig. 2), the laboratory continues to expand (8% within 3 years), although this expansion has slowed down since the laboratory was created (113% since 1995).

As far as temporary staff (PhD students & post-docs) is concerned, there is a 15% increase between 2005 and 2007.
Trainees

The number of trainees in the laboratory increased by 35% between 2005 and 2007.

Financial management and purchasing procedures

The administrative division is in charge of purchases and controls the laboratory budget whose funds come from the IN2P3 (National Institute for Nuclear and Particle Physics), Nantes University, and Nantes School of Engineering as well as its own resources.

Trainees

Own resources : 2 357 705 €
National Founds : 1 417 516 €

Missions

The laboratory agents carry out approximately 1300 missions per year with destinations that clearly reflect the international dimension of its research collaborations:

- missions at CERN (European Organization for Nuclear Research)
- missions in France
- missions in EU and outside EU countries (Germany, Italy, Belgium, United States of America, Japan...)
Technical groups and administration

Scientific collaborations

The EUREA GDRE (European Research Grouping) involves the following countries: Poland, Ukraine, Russia and the Czech Republic.

Continuing education

Most seminars are presented by French scientists (fig. 10), and a quarter by European scientists.

Seminars

Fig. 12: Origin of scientists presenting seminars
Hygiene and safety

K. Perrigaud (ACMO), G. Blain (PCR)

Subatech, Mixed Research unity 6457 (CNRS, EMN, University of Nantes) is installed in the premises of EMN of Nantes since 1995. From the point of view of the safety, the integration in new buildings, as well as the construction of an extension of laboratory for the radiochemistry in May, 2007, allowed to facilitate the application of the rules of Hygiene and Safety. Notably, for the construction of the hall of experience, of the mechanical workshop and of the rooms dedicated to the radiochemistry, every risks were able to be considered from the initial arrangement.

The Hygiene and the Safety to Subatech

A commission of Hygiene and Safety is instructed, twice a year, to make a census of the diverse problems of every service and to propose solutions. A report of this commission is exposed by the ACMO (Agent in Charge of the Implementation of the Hygiene and the Safety) to the Committee of Hygiene and Safety of the Ecole des Mines de Nantes. This report is also communicated to the various supervisors: Inspector Hygiene and Safety IN2P3, Inspector Hygiene and Safety CNRS of the Regional Delegation 17, Engineer of Prevention of the Faculty of Science of Nantes and Person in charge Safety Armines. The laboratory sets up a Hygiene and Safety team to meet the needs in the various fields of activity of Subatech.

Census of the risks within the unit

Mechanical workshop
All the machines are in conformity. Only the trained persons are authorized to use them. The specific safety regulations in the use of machines are posted on each working station.

Compressed gases
A large number of gas bottles are used for various applications: test of detectors, radiochemistry and welding. Systems of safety concerning the use of gases (O₂ detector and explosion-proof system) are installed in the rooms of experiment.

Gases present in the laboratory:
- Inert gas: nitrogen, helium, argon, CO₂ conditioned in bottles of 10m³
- Hydrogen and oxygen conditioned in bottles of 3m³
- Acetylene conditioned in bottle of 6m³
- Gas mixtures: argon-CO₂; argon-methane; neon-hydrogen, conditioned according to the needs.

All these gas bottles are the object of an annual rental agreement, in order to avoid prolonged storage involving a time limitation of the test in pressure of the bottle. Platforms of distribution were installed outside of buildings in the year 2007 to limit the number of bottles present inside the rooms of experiment.

Radioactive risks
The Subatech laboratory is an “Installation Classée pour l’Environnement” (ICPE) subject-ed to declaration since July 7, 1995. The laboratory has authorization DGSNR T440 325 valid until May 6, 2010 to hold and use radioelements in sources sealed and not sealed. The holder of the authorization is J. Martino, Director of the laboratory.

The “Personne Compétente en Radioprotection” (PCR) is G. Blain. The sealed sources are micro sources of ¹³⁷Cs, ⁹⁰Sr, ²²Na, ²⁴¹Am, ⁶⁰Fe, ⁶⁰Co, ¹⁵²Eu…, with an activity lower than 4 MBq, necessary to the calibration of measurement apparatus of the radioactivity used in metrology and to the tests of detectors fabricated by the laboratory.

The not sealed sources are mainly radiochemical ⁹⁹Tc solutions, ⁵¹Nor, ⁹⁰Sr, ¹⁵²Eu, ⁷⁵Se, ³⁷H, ¹⁴C, ²³⁵Pu, ²⁴¹Am, ²³⁸Pu, ²⁴²Pu, ²⁴³Am, ²３⁸U, ²³³Th, ²²⁶Ra, ²¹⁰Pb…, with an activity lower or equal to 5 MBq used as radiochemical markers or tracers in the experiments of radiochemistry, and in the measurements of radioactivity in the samples analyzed by the laboratory.
For the uses of these sources the personnel of the laboratory is mainly classified of category B and the buildings are in supervised zone where the risks of internal and external exposure are very limited in normal situation of exploitation. In more of the measurement apparatus of the radioactivity the laboratory is equipped with material with protection against radiation:
- probes and meters of radioactivities alpha, beta and gamma
- hand-foot-clothing controller
- surface contamination controller
- radiation meter, portable spectrometer

To build all of the features of protection against radiation, the laboratory set up a dedicated team.

Chemical risks
The chemicals used for the treatments of samples, the cleaning of material and the chemical separations are:
- Usual solvents: ethanol, acetone, no benzene and not or few of cyclic
- Organic solvents: chloroform, twinkling liquids
- Solid: various salts (total 150 kg)
- Acids and bases: 100 litres / year of hydrochloric acid, nitric, sulphuric acid, ammonia water, and little hydrofluoric acid.

The laboratory was equipped with safety shower, system of eye rinsing and of portable autonomous showers Hexafluorine and Diphotérine to avoid chemical damages of the users.
The toxic products are followed up and weighted after every use.

Risks related to the Lasers
Lasers are used for the research in optical metrology of high degree of accuracy: micro-movements (2µm), flatness of small and great surface and characterization in size and concentration (2nm) of solutions (solid particles in suspension). In order to respect the regulation related to the use of the lasers the rooms of experiment are protected with adapted indication, access control and safety glasses are available. The rules of use are posted as well as the instructions in case of emergency.

Prevention of the risks
Every agent makes a medical examination once a year (twice a year for the staffs classified in DATRA). The fire safety is integrated with the one of the EMN with regular exercises and training of volunteers to the techniques of evacuation and fire fighting.

A large number of persons are trained in the first aid at work. This training was developed by the introduction of the use of a semi-automatic defibrillator (D.S.A) with which the E.M.N is equipped since 2007. A training of new entrants is given by the PCR for the radioprotection part and by the ACMO for all the other risks present in the laboratory.

For the working zones where the risk is more important, the staffs have at their disposal equipments of individual protection: blouses, combinations, gloves, glasses, masks, and ear-protection headsets.

For some of the laboratories dedicated arrangements were necessary:
- Classification in zone watched: 10 rooms
- Specific equipment: sorbones ventilated and filtered, limp in gloves

A control of the application of safety instructions is made by regular visits of premises by the responsible persons (Director, ACMO and PCR).

For environmental protection and respect for the rule, the waste management takes an important place in the prevention of the risks. The radioactive waste is collected and stored for elimination by the ANDRA and the chemical waste is eliminated through the Ecole des Mines in contract with a specialized company.

The industrial accidents
The zero accident is the objective to be reached and, the whole of the actors of the prevention takes part in it.

On the graph above one can observe the industrial accidents according to the place where they occurred. The accident on the way to work are most difficult to control. The ones occurring within the laboratory make the reconstitution of the event possible, allow to learn the lessons from them and to lead to actions of prevention.
## Summary table

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Publications

2006

1. Title: Study of the interaction of Ni^{2+} and Cs^{+} on MX-80 bentonite: Effect of compaction using the "capillary method"
Author(s): Montavon, G; Alhajji, E; Grambow, B
Source: ENVIRONMENTAL SCIENCE & TECHNOLOGY Volume: 40 Issue: 15 Pages: 4672-4679 Published: AUG 1 2006
Times Cited: 3

2. Title: Heavy quarks thermalization in heavy-ion ultra-relativistic collisions: elastic or radiative?
Author(s): Gossiaux, PB; Guiho, V; Aichelin, J
Conference Information: International Conference on Strangeness in Quark matter, Date: MAR 26-31, 2006
Univ Calif Los Angeles Los Angeles CA
Times Cited: 2

3. Title: Nuclear surface effects in heavy-ion collisions at RHIC and SPS
Author(s): Werner, K
Conference Information: International Conference on Strangeness in Quark matter, Date: MAR 26-31, 2006
Univ Calif Los Angeles Los Angeles CA
Source: JOURNAL OF PHYSICS G-NUCLEAR AND PARTICLE PHYSICS Volume: 32 Issue: 12 Pages: S159-S163 Published: 2006
Times Cited: 1

4. Title: Oxidation and dissolution rates of UO_2(s) in carbonate-rich solutions under external alpha irradiation and initially reducing conditions
Author(s): Suzuki, T; Abdelouas, A; Grambow, B, et al.
Conference Information: 10th International Conference on Chemistry and Migration of Actinides and Fission Products, Date: SEP 18-23, 2005 Avignon FRANCE
Source: RADIOCHIMICA ACTA Volume: 94 Issue: 9-11 Pages: 567-573 Published: 2006
Times Cited: 1

5. Title: Recent astrophysical and accelerator-based results on the hadronic equation of state
Author(s): Hartnack, C; Oeschler, H; Aichelin, J
Conference Information: International Conference on Strangeness in Quark matter, Date: MAR 26-31, 2006
Univ Calif Los Angeles Los Angeles CA
Source: JOURNAL OF PHYSICS G-NUCLEAR AND PARTICLE PHYSICS Volume: 32 Issue: 12 Pages: S231-S239 Published: 2006
Times Cited: 1

6. Title: Baryon-baryon correlations in Au+Au collisions at root S-NN=62 GeV and root S-NN=200 GeV, measured in the STAR experiment at RHIC

Author(s): Gos, HP; STAR Collaboration
Conference Information: Conference on Relativistic Heavy-Ion Physics, Date: 2005 Budapest HUNGARY
Source: NUKLEONIKA Volume: 51 Pages: S59-S63 Published: 2006
Times Cited: 0

7. Title: Sorption of Cs, Ni, Pb, Eu(III), Am(III), Cm, Ac(III), Tc(IV), Th, Zr, and U(IV) on MX 80 bentonite: An experimental approach to assess model uncertainty
Author(s): Grambow, B; Fattahi, M; Montavon, G, et al.
Conference Information: 10th International Conference on Chemistry and Migration of Actinides and Fission Products, Date: SEP 18-23, 2005 Avignon FRANCE
Source: RADIOCHIMICA ACTA Volume: 94 Issue: 9-11 Pages: 627-636 Published: 2006
Times Cited: 1

8. Title: Correlation between X-ray chemical shift and partial charge in Tc(IV) complexes: Determination of Tc partial charge in TcnOy(4n-2y)^+
Author(s): Poineau, F; Fattahi, M; Grambow, B
Conference Information: 10th International Conference on Chemistry and Migration of Actinides and Fission Products, Date: SEP 18-23, 2005 Avignon FRANCE
Source: RADIOCHIMICA ACTA Volume: 94 Issue: 9-11 Pages: 559-563 Published: 2006
Times Cited: 1

9. Title: Coprecipitation of thorium and lanthanum with UO_2+x(s) as host phase
Author(s): Rousseau, G; Fattahi, M; Grambow, B, et al.
Conference Information: 10th International Conference on Chemistry and Migration of Actinides and Fission Products, Date: SEP 18-23, 2005 Avignon FRANCE
Source: RADIOCHIMICA ACTA Volume: 94 Issue: 9-11 Pages: 517-522 Published: 2006
Times Cited: 0

10. Title: Comparison of complexed species of Eu in alumina-bound and free polyacrylic acid: A spectroscopic study
Author(s): Montavon, G; Hennig, C; Janvier, P, et al.
Source: JOURNAL OF COLLOID AND INTERFACE SCIENCE Volume: 300 Issue: 2 Pages: 482-490 Published: AUG 15 2006
Times Cited: 3

11. Title: Codalema: A cosmic ray air shower radio detection experiment
Author(s): Ardouin, D; Belletoile, A; Charrier, D, et al.
Conference Information: International Workshop on Acoustic and Radio EeV Neutrino Detection Activities, Date: MAY 17-19, 2005 Zeuthen GERMANY
Source: INTERNATIONAL JOURNAL OF MODERN PHYSICS A Volume: 21 Pages: 192-196 Published: 2006
Times Cited: 0
12. Title: Uranium mill tailings: Geochemistry, mineralogy, and environmental impact  
Author(s): Abdelouas, A  
Source: ELEMENTS Volume: 2 Issue: 6 Pages: 335-341 Published: DEC 2006  
Times Cited: 3

13. Title: Water diffusion in the simulated French nuclear waste glass SON 68 contacting silica rich solutions: Experimental and modeling  
Author(s): Ferrand, K; Abdelouas, A; Grambow, B  
Source: JOURNAL OF NUCLEAR MATERIALS Volume: 355 Issue: 1-3 Pages: 54-67 Published: SEP 1 2006  
Times Cited: 7

14. Title: Ghost-free higher-derivative theory  
Author(s): Smilga, AV  
Source: PHYSICS LETTERS B Volume: 632 Issue: 2-3 Pages: 433-438 Published: JAN 13 2006  
Times Cited: 2

15. Title: The Muon Spectrometer of the ALICE experiment  
Author(s): Finck, C; ALICE Muon Spectrometer collaboration Conference Information: 5th International Conference on Physics and Astrophysics of Quark Gluon Plasma, Date: FEB 08-12, 2005 Saha Inst Nucl Phys Salt Lake City UT  
Source: 5th International Conference on Physics and Astrophysics of Quark Gluon Plasma Volume: 50 Pages: 397-401 Published: 2006  
Times Cited: 2

16. Title: Physics of the muon spectrometer of the ALICE experiment  
Author(s): Martinez, G; ALICE Collaboration Conference Information: 5th International Conference on Physics and Astrophysics of Quark Gluon Plasma, Date: FEB 08-12, 2005 Saha Inst Nucl Phys Salt Lake City UT  
Source: 5th International Conference on Physics and Astrophysics of Quark Gluon Plasma Volume: 50 Pages: 361-370 Published: 2006  
Times Cited: 0

17. Title: Nuclear waste glasses - How durable?  
Author(s): Grambow, B  
Source: ELEMENTS Volume: 2 Issue: 6 Pages: 357-364 Published: DEC 2006  
Times Cited: 3

18. Title: Photochemical behaviour of Tc2OCl104- and TcnOY4n-2y+ in chloride media  
Author(s): Poineau, F; Fattahi, M; Grambow, B  
Source: RADIOCHIMICA ACTA Volume: 94 Issue: 2 Pages: 91-95 Published: 2006  
Times Cited: 1

19. Title: Speciation of technetium and rhenium complexes by in situ XAS-electrochemistry  
Author(s): Poineau, F; Fattahi, M; Den Auwer, C, et al.  
Source: RADIOCHIMICA ACTA Volume: 94 Issue: 5 Pages: 283-289 Published: 2006  
Times Cited: 0

20. Title: Condensation mechanisms of tetravalent technetium in chloride media  
Author(s): Poineau, F; Fattahi, M; Montavon, G, et al.  
Source: RADIOCHIMICA ACTA Volume: 94 Issue: 5 Pages: 291-299 Published: 2006  
Times Cited: 1

21. Title: Radioelectric field features of extensive air showers observed with CODALEMA  
Author(s): Arduin, D; Bellalcal, A; Charrier, D, et al.  
Source: ASTROPHYSICAL PHYSICS Volume: 26 Issue: 4-5 Pages: 341-350 Published: NOV-DEC 2006  
Times Cited: 10

22. Title: Immobilization of inert TRISO-coated fuel in glass for geological disposal  
Author(s): Abdelouas, A; Noirault, S; Grambow, B  
Source: JOURNAL OF NUCLEAR MATERIALS Volume: 358 Issue: 1 Pages: 1-9 Published: NOV 15 2006  
Times Cited: 1

23. Title: Parton ladder splitting and the rapidity dependence of transverse-momentum spectra in deuteron-gold collisions at the BNL Relativistic Heavy Ion Collider  
Author(s): Werner, K; Liu, FM; Pierog, T  
Source: PHYSICAL REVIEW C Volume: 74 Issue: 4 Article Number: 044902 Published: OCT 2006  
Times Cited: 18

24. Title: Coefficients and terms of the liquid drop model and mass formula  
Author(s): Royer, G; Gautier, C  
Source: PHYSICAL REVIEW C Volume: 73 Issue: 6 Article Number: 067302 Published: JUN 2006  
Times Cited: 8

25. Title: Conformal properties of hypermultiplet actions in six dimensions  
Author(s): Ivanov, EA; Smilga, AV  
Times Cited: 0

26. Title: Retardation effect for collisional energy loss of hard partons produced in a QGP  
Author(s): Peigne, S; Gossiaux, PB; Gousset, T  
Source: JOURNAL OF HIGH ENERGY PHYSICS Issue: 4 Article Number: 011 Published: APR 2006  
Times Cited: 10

27. Title: Hadronic matter is soft  
Author(s): Hartnack, C; Oeschler, H; Aichelin, J  
Source: PHYSICAL REVIEW LETTERS Volume: 96 Issue: 1 Article Number: 012303 Published: JAN 13 2006  
Times Cited: 0

28. Title: Leaching behaviour of non-irradiated and irradiated HTR UO2-ThO2 fuel particles under reducing conditions  
Author(s): Alliot, C; Grambow, B  
Conference Information: 29th International Symposium on the Scientific Basis for Nuclear Waste Management, Date: SEP 12-16, 2005 Ghent BELGIUM  
Source: SCIENTIFIC BASIS FOR NUCLEAR WASTE MANAGEMENT XXIX Volume: 932 Pages: 497-503 Published: 2006  
Times Cited: 0
29. Title: Coupling of chemical processes in the near field  
  Author(s): Grambow, B; Giffaut, E  
  Conference Information: 29th International Symposium on the Scientific Basis for Nuclear Waste Management,  
  Date: SEP 12-16, 2005 Ghent BELGIUM  
  Source: Scientific Basis for Nuclear Waste Management XXIX Volume: 932 Pages: 55-66 Published: 2006  
  Times Cited: 3

30. Title: First results of fast one-dimensional hybrid simulation of EAS using CONEX  
  Author(s): Pierog, T; Alekseeva, MK; Bergmann, T, et al.  
  Conference Information: 13th International Symposium on Very High Energy Cosmic Ray Interactions,  
  Date: SEP 06-12, 2004 Pylos GREECE  
  Source: NUCLEAR PHYSICS B-PROCEEDINGS SUPPLEMENTS Volume: 151 Pages: 159-162 Published: 2006  
  Times Cited: 8

31. Title: Proton-Lambda correlations in central Au+Au collisions at root s(NN)=200 GeV  
  Author(s): Adams, J; Martin, L, Roy, C; Star and al.  
  Source: PHYSICAL REVIEW C Volume: 74 Issue: 6 Article Number: 064906 Published: DEC 2006  
  Times Cited: 2

32. Title: Microscopic calculations of double and triple giant resonance excitations in heavy ion collisions  
  Author(s): Fallot, M, Lanza, EG; Catara, F; Andres, MV, et al.  
  Source: PHYSICAL REVIEW C Volume: 74 Issue: 6 Article Number: 064906 Published: DEC 2006  
  Times Cited: 12

33. Title: Directed flow in Au plus Au collisions at root s(NN)=62.4 GeV  
  Author(s): Adams, J; Erazmus, B, Estienne, M; Star and al.  
  Source: PHYSICAL REVIEW C Volume: 73 Issue: 3 Article Number: 034903 Published: 2006  
  Times Cited: 12

34. Title: Multiplicity and pseudorapidity distributions of charged particles and photons at forward pseudorapidity in Au plus Au collisions at root s(NN)=62.4 GeV  
  Author(s): Adams, J; Erazmus, B, Estienne, M; Star and al.  
  Source: PHYSICAL REVIEW C Volume: 73 Issue: 3 Article Number: 034906 Published: 2006  
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35. Title: Experimental evidence for the influence of the excitation wavelength on the value of the equilibrium constant as determined by Time-Resolved Emission Spectroscopy (TRES)  
  Author(s): Billard, I; Montavon, G; Markai, S, et al.  
  Source: RADIOCHIMICA ACTA Volume: 94 Issue: 5 Pages: 275-282 Published: 2006  
  Times Cited: 0

37. Title: Measurement of High-p(T) single electrons from heavy-flavor decays in p+p collisions at root s=200 GeV  
  Author(s): Adare, A; Delagrange, H, d’Enteria, D; Afanasiev, S; Aida, C, PHENIX et al.  
  Source: PHYSICAL REVIEW LETTERS Volume: 97 Article Number: 252002 Published: 2006  
  Times Cited: 43

38. Title: Evidence for a three-phonon giant resonance state in Ca-40 nuclei  
  Author(s): Fallot, M; Scarpaci, JA; Frascaria, N, et al.  
  Source: PHYSICAL REVIEW LETTERS Volume: 97 Issue: 24 Article Number: 242502 Published: DEC 15 2006  
  Times Cited: 0

39. Title: Pion freeze-out time in Pb plus Pb collisions at root s(AGeV)=158 studied via pi(-)/pi(+) and K-/K+ ratios  
  Author(s): Aggarwal, MM; Delagrange, H, Martinez, G; Retiere, F; Ahamed, Z, Angelis, ALS, WA98 et al.  
  Source: EUROPEAN PHYSICAL JOURNAL C Volume: 48 Issue: 2 Pages: 343-352 Published: NOV 2006  
  Times Cited: 0

40. Title: ALICE: Physics Performance Report, Volume II  
  Author(s): Aphecetche, L, Cussonneau, J-P, Delagrange, H, d’Enteria, D, ALICE et al.  
  Source: JOURNAL OF PHYSICS G-NUCLEAR AND PARTICLE PHYSICS Volume: 48 Issue: 2 Pages: 343-2040 Published: 2006  
  Times Cited: 45

41. Title: Jet properties from dihadron correlations in p plus p collisions at root s=200 GeV  
  Author(s): Adler, SS; Aphecetche, L, Cussonneau, J-P, Delagrange, H, d’Enteria, D; PHENIX et al.  
  Source: PHYSICAL REVIEW D Volume: 74 Issue: 7 Article Number: 072002 Published: OCT 2006  
  Times Cited: 26

42. Title: Direct observation of dijets in central Au plus Au collisions at root s(NN)=200 GeV  
  Author(s): Adams, J; Erazmus, B, Estienne, M; Aggarwal, MM; Ahamed, Z, STAR et al.  
  Source: PHYSICAL REVIEW LETTERS Volume: 97 Issue: 15 Article Number: 152301 Published: OCT 13 2006  
  Times Cited: 45

43. Title: Identified baryon and meson distributions at large transverse momenta from Au plus Au collisions at root(S)(NN)=200 GeV  
  Author(s): Abelev, BI; Erazmus, B, Estienne, M; Boucher, J, STAR et al.  
  Source: PHYSICAL REVIEW LETTERS Volume: 97 Issue: 15 Article Number: 152301 Published: OCT 13 2006  
  Times Cited: 39

44. Title: Forward neutral pion production in p+p and d+Au collisions at root(s(NN)=200 GeV  
  Author(s): Abelev, BI; Erazmus, B, Estienne, M; Boucher, J, STAR et al.  
  Source: PHYSICAL REVIEW LETTERS Volume: 97 Issue: 15 Article Number: 152302 Published: OCT 13 2006  
  Times Cited: 20
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Author(s): Abelev, BI; Erazmus, B, Estienne, M, Bellingeri-Laurikainen, A, Martin, L, STAR et al.
Source: PHYSICAL REVIEW LETTERS Volume: 97 Issue: 13 Article Number: 132301 Published: SEP 29 2006
Times Cited: 12

46. Title: Multiplicity dependence of inclusive p(t) spectra from p-p collisions at root s=200 GeV
Author(s): Adams, J; Erazmus, B, Estienne, M, Bellingeri-Laurikainen, A, Martin, L, STAR et al.
Source: PHYSICAL REVIEW D Volume: 74 Issue: 3 Article Number: 032006 Published: AUG 2006
Times Cited: 5

47. Title: Nuclear effects on hadron production in d plus Au collisions at root S-NN=200 GeV revealed by comparison with p plus p data
Author(s): Adler, SS; Cussonneau J-P, Delagrange H, Finck C, Germain M, PHENIX et al.
Source: PHYSICAL REVIEW C Volume: 74 Article Number: 024904 Published: 2006
Times Cited: 21

48. Title: Quantum entanglement via nilpotent polynomials
Author(s): Mandilara, A; Akulin, VM; Smilga, AV, et al.
Source: PHYSICAL REVIEW A Volume: 74 Article Number: 022331 Published: 2006
Times Cited: 4

49. Title: Dense-medium modifications to jet-induced hadron pair distributions in Au+Au collisions at root(NN)-N-S=200 GeV
Author(s): Adler, SS; Delagrange H, d'Enteria D, Martinez G, PHENIX et al.
Source: PHYSICAL REVIEW LETTERS Volume: 97 Article Number: 052301 Published: 2006
Times Cited: 115

50. Title: alpha decay half-lives of new superheavy elements through quasimolecular shapes
Author(s): Royer G, Zhang, HF; Li, JQ; Zuo, W, et al.
Source: CHINESE PHYSICS LETTERS Volume: 23 Pages: 1734-1737 Published: 2006
Times Cited: 1

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Author(s): Royer G, Zhang, HF; Zuo, W; Li, JQ, et al.
Source: PHYSICAL REVIEW C Volume: 74 Article Number: 017304 Published: 2006
Times Cited: 11

52. Title: On the efficiency of Fermi acceleration at relativistic shocks
Author(s): Lemoine, M; Pelletier, G; Revenu, B
Source: ASTROPHYSICAL JOURNAL Volume: 645 Issue: 2 Pages: L129-L132 Part: 2 Published: JUL 10 2006
Times Cited: 10

53. Title: Transverse-momentum p(t) correlations on (eta, phi) from mean-p(t) fluctuations in Au-Au collisions at root(s)(NN)=200 GeV
Author(s): Adams, J; Erazmus B, Estienne M, Martin L, STAR et al.
Times Cited: 26

54. Title: Minijet deformation and charge-independent angular correlations on momentum subspace (eta, phi) in Au-Au collisions at root S-NN=130 GeV
Author(s): Adams, J; Erazmus B, Estienne M, Martin L, STAR et al.
Source: PHYSICAL REVIEW C Volume: 73 Issue: 6 Article Number: 064907 Published: JUN 2006
Times Cited: 45

55. Title: Effect of aqueous acetic, oxalic, and carbonic acids on the adsorption of europium(III) onto alpha-alumina
Author(s): Alliot, C; Bion, L; Mercier, F, et al.
Times Cited: 3

56. Title: Azimuthal angle correlations for rapidity separated hadron pairs in d+Au collisions at root s(NN)=200 GeV
Author(s): Adler, SS; Cussonneau J-P, Delagrange H, Finck C, Germain M, PHENIX et al.
Source: PHYSICAL REVIEW LETTERS Volume: 96 Article Number: 222301 Published: 2006
Times Cited: 12

57. Title: Identified hadron spectra at large transverse momentum in p+p and d+Au collisions at root(NN)-N-S=200 GeV
Author(s): Adams, J; Erazmus, B, Estienne, M, Aggarwal, MM; Ahammed, Z, STAR et al.
Source: PHYSICS LETTERS B Volume: 637 Issue: 3 Pages: 161-169 Published: JUN 8 2006
Times Cited: 61

58. Title: Improved measurement of double helicity asymmetry in inclusive midrapidity pi(0) production for polarized p+p collisions at root s=200 GeV
Author(s): Adler, SS; Cussonneau J-P, Delagrange H, Finck C, Germain M, PHENIX et al.
Source: PHYSICAL REVIEW D Volume: 73 Issue: 9 Article Number: 091102 Published: MAY 2006
Times Cited: 18

59. Title: Jet structure from dihadron correlations in d+Au collisions at root S-NN=200 GeV
Author(s): Adler, SS; Cussonneau J-P, Delagrange H, Finck C, Germain M, PHENIX et al.
Source: PHYSICAL REVIEW C Volume: 73 Issue: 9 Article Number: 091102 Published: MAY 2006
Times Cited: 23
61. Title: Common suppression pattern of eta and pi(0) mesons at high transverse momentum in Au plus Au collisions at \( \sqrt{s_{NN}}=200 \) GeV
Author(s): Adler, SS; Aphecetche L, Cussonneau J-P, Delagrange H, Finck C, Germain M, PHENIX et al.
Source: PHYSICAL REVIEW LETTERS Volume: 96 Issue: 20 Article Number: 021301 Published: MAY 26 2006 Times Cited: 36

62. Title: Hadronization geometry from net-charge angular correlations on momentum subspace (eta, phi) in Au-Au collisions at \( \sqrt{s_{NN}}=130 \) GeV
Author(s): Adler, SS; Delagrange H, d'Enterria D, Adler, SS; Afanasiev, S; Aidala, C, PHENIX et al.
Source: PHYSICAL REVIEW LETTERS Volume: 96 Issue: 1 Article Number: 012304 Published: MAY 26 2006 Times Cited: 36

63. Title: Hydrodynamic source with continuous emission in Au plus Au collisions at \( \sqrt{s}=200 \) GeV
Author(s): Adler, SS; Delagrange H, d'Enterria D, Adler, SS; Afanasiev, S; Aidala, C, PHENIX et al.
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Author(s): Adler, SS; Aphecetche L, Cussonneau J-P, Delagrange H, Finck C, Germain M, PHENIX et al.
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Author(s): Adler, SS; Aphecetche L, Cussonneau J-P, Delagrange H, Finck C, Germain M, PHENIX et al.
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Author(s): Montavon, G; Bouby, M; Huclier-Markai, S, et al.  
Source: JOURNAL OF COLLOID AND INTERFACE SCIENCE Volume: 327 Issue: 2 Pages: 324-332 Published: 2008  
Times Cited: 0

3. Title: ALPHA DECAY POTENTIAL BARRIERS AND HALF-LIVES AND ANALYTICAL FORMULA PREDICTIONS FOR SUPERHEAVY NUCLEI  
Author(s): Royer, G; Zhang, HF  
Conference Information: Workshop on State of the Art in Nuclear Cluster Physics, Date: MAY 13-16, 2008 Strasbourg FRANCE  
Source: INTERNATIONAL JOURNAL OF MODERN PHYSICS E-NUCLEAR PHYSICS Volume: 17 Issue: 10 Pages: 2270-2274 Published: 2008  
Times Cited: 0

4. Title: Discrepancies in thorium oxide solubility values: a new experimental approach to improve understanding of oxide surface at solid/solution interface  
Author(s): Vandenborre, J; Abdelouas, A; Grambow, B  
Conference Information: 11th International Conference on Chemistry and Migration Behaviour of Actinides and Fission Products in the Geosphere, Date: AUG 26-31, 2007 Munich GERMANY  
Source: RADIOCHIMICA ACTA Volume: 96 Issue: 9-11 Pages: 515-520 Published: 2008  
Times Cited: 0
5. Title: Structural investigation of coprecipitation of technetium-99 with iron phases  
Author(s): Llorens, IA; Deniard, P; Gautron, E, et al.  
Conference Information: 11th International Conference on Chemistry and Migration Behaviour of Actinides and Fission Products in the Geosphere, Date: AUG 26-31, 2007 Munich GERMANY  
Source: RADIOCHIMICA ACTA Volume: 96 Issue: 9-11 Pages: 569-574 Published: 2008  
Times Cited: 0

6. Title: Surface site density, silicic acid retention and transport properties of compacted magnetite powder  
Author(s): Mayant, C; Grambow, B; Abdelouas, A, et al.  
Conference Information: 11th International Conference on Chemistry and Migration Behaviour of Actinides and Fission Products in the Geosphere, Date: AUG 26-31, 2007 Munich GERMANY  
Source: PHYSICS AND CHEMISTRY OF THE EARTH Volume: 33 Issue: 14-16 Pages: 991-999 Published: 2008  
Times Cited: 0

7. Title: Cryptogauche symmetry and cryptoghosts for crypto-Hermitian Hamiltonians  
Author(s): Smilga, AV  
Source: JOURNAL OF PHYSICS A-MATHEMATICAL AND THEORETICAL Volume: 41 Issue: 24 Article Number: 244026 Published: 2008  
Times Cited: 3

8. Title: ARRONAX, a high-energy and high-intensity cyclotron for nuclear medicine  
Author(s): Haddad, F; Ferrer, L; Guertin, A, et al.  
Times Cited: 0

9. Title: Kaon production at subthreshold energies: what do we learn about the nuclear medium?  
Author(s): Hartnack, C; Oeschler, H; Aichelin, J  
Conference Information: International Conference on Strangeness in Quark Matter, Date: JUN 24-29, 2007 Levoca SLOVAKIA  
Times Cited: 0

10. Title: QCD running coupling and collisional jet quenching  
Author(s): Peshier, A  
Conference Information: International Conference on Strangeness in Quark Matter, Date: JUN 24-29, 2007 Levoca SLOVAKIA  
Source: JOURNAL OF PHYSICS G-NUCLEAR AND PARTICLE PHYSICS Volume: 35 Issue: 4 Article Number: 044028 Published: 2008  
Times Cited: 0

11. Title: On the coefficients of the liquid drop model mass formulae and nuclear radii  
Author(s): Royer, G  
Source: NUCLEAR PHYSICS A Volume: 807 Issue: 3-4 Pages: 105-118 Published: 2008  
Times Cited: 0

12. Title: Collisional energy loss of a fast parton in a QGP  
Author(s): Peigne, S  
Conference Information: 9th Joint Meeting of Heidelberg-Liege-Paris-Wroclaw, Date: MAR 06-08, 2008 Univ Liege, Fundamental Interact Phys & Astrophys Grp Spa BELGIUM  
Source: HADRONIC PHYSICS Volume: 1038 Pages: 139-148 Published: 2008  
Times Cited: 0

13. Title: Toward an understanding of the single electron data measured at the BNL Relativistic Heavy Ion Collider (RHIC)  
Author(s): Gossiaux, PB; Aichelin, J  
Source: PHYSICAL REVIEW C Volume: 78 Issue: 1 Article Number: 014904 Published: 2008  
Times Cited: 0

14. Title: Selenide retention onto pyrite under reducing conditions  
Author(s): Liu, X; Fattahi, M; Montavon, G, et al.  
Source: RADIOCHIMICA ACTA Volume: 96 Issue: 8 Pages: 473-479 Published: 2008  
Times Cited: 1

15. Title: Macroscopic treatment of radio emission from cosmic ray air showers based on shower simulations  
Author(s): Werner, K; Scholten, O  
Source: ASTROPARTICLE PHYSICS Volume: 29 Issue: 6 Pages: 393-411 Published: 2008  
Times Cited: 2

16. Title: Collisional energy loss of a fast heavy quark in a quark-gluon plasma  
Author(s): Peigne, S; Peshier, A  
Source: PHYSICAL REVIEW D Volume: 77 Issue: 11 Article Number: 114017 Published: 2008  
Times Cited: 1

17. Title: Effect of heavy-quark energy loss on the muon differential production cross section in Pb-Pb collisions at root S-NN=5.5 TeV  
Author(s): del Valle, ZC; Dainese, A; Ding, HT, et al.  
Source: PHYSICS LETTERS B Volume: 663 Issue: 3 Pages: 202-208 Published: 2008  
Times Cited: 0

18. Title: Recent alpha decay half-lives and analytic expression predictions including superheavy nuclei  
Author(s): Royer, G; Zhang, HF  
Source: PHYSICAL REVIEW C Volume: 77 Issue: 3 Article Number: 037602 Published: 2008  
Times Cited: 7
19. Title: Physics of crypto-Hermitian and crypto-supersymmetric field theories
Author(s): Smilga, AV
Source: PHYSICAL REVIEW D Volume: 77 Issue: 6
Article Number: 061701 Published: 2008
Times Cited: 2

20. Title: Collisional energy loss of a fast muon in a hot QED plasma
Author(s): Peigne, S; Peshier, A
Source: PHYSICAL REVIEW D Volume: 77 Issue: 1
Article Number: 014015 Published: 2008
Times Cited: 3

21. Title: Effects of ionizing radiation on the hollandite structure-type: Ba$_{0.85}$Cs$_{0.26}$Al$_{1.35}$Fe$_{0.77}$Ti$_{5.90}$O$_{16}$
Author(s): Abdelouas, A; Utsunomiya, S; Suzuki, T, et al.
Source: AMERICAN MINERALOGIST Volume: 93 Issue: 1 Pages: 241-247 Published: 2008
Times Cited: 0

22. Title: SEARCH FOR A LONG LIVING GIANT SYSTEM IN U-238+U-238 COLLISIONS NEAR THE COULOMB BARRIER
Author(s): Giot L, Golabek, C; Villari, ACC; Heinz, S, et al.
Conference Information: Workshop on State of the Art in Nuclear Cluster Physics, Date: MAY 13-16, 2008 Strasbourg FRANCE
Source: INTERNATIONAL JOURNAL OF MODERN PHYSICS E-NUCLEAR PHYSICS Volume: 17 Issue: 10 Pages: 2235-2239 Published: 2008
Times Cited: 0

23. Title: Thermodynamic interpretation of neptunium coprecipitation in uranophane for application to the Yucca Mountain repository
Author(s): Murphy, WM; Grambow, B
Conference Information: 11th International Conference on Chemistry and Migration Behaviour of Actinides and Fission Products in the Geosphere, Date: AUG 26-31, 2007 Munich GERMANY
Times Cited: 0

24. Title: Zero degree Cherenkov calorimeters for the ALICE experiment
Author(s): Yerma F, De Falco, A; Arnaldi, R; Chiavassa, E, et al.
Conference Information: 6th International Workshop on Ring Image Cherenkov Counters (RICH 2007), Date: OCT 15-20, 2007 Trieste ITALY
Source: NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT Volume: 595 Issue: 1 Pages: 267-269 Published: 2008
Times Cited: 0

25. Title: WEBEXP: Windowless target electron beam experimental irradiation
Author(s): Guertin A, Cadiou A, Buhour J-M, : Dierckx, M; Schuurmans, P; et al.
Conference Information: International Workshop on Materials for Heavy Liquid Metal Cooled Reactors and Related Technologies, Date: MAY 21-23, 2007 Rome ITALY
Source: JOURNAL OF NUCLEAR MATERIALS Volume: 376 Issue: 3 Pages: 302-306 Published: 2008
Times Cited: 0

26. Title: Consequences of a Lambda(c)/D enhancement effect on the non-photonic electron nuclear modification factor in central heavy ion collisions at RHIC energy
Author(s): Martinez-Garcia, G; Gadrat, S; Crochet, P
Source: PHYSICS LETTERS B Volume: 663 Issue: 1-2 Pages: 55-60 Published: 2008
Times Cited: 3

27. Title: The hadronic interaction model EPOS
Author(s): Werner, K
Conference Information: 14th International Symposium on Very High Energy Cosmic Ray Interactions, Date: AUG 15-22, 2006 Weihai PEOPLES R CHINA
Source: NUCLEAR PHYSICS B-PROCEEDINGS SUPPLEMENTS Volume: 175 Pages: 81-87 Published: 2008
Times Cited: 1

28. Title: Physics process of cosmogenics Li-9 and He-8 production on muons interactions with carbon target in liquid scintillator
Author(s): Zbiri, K
Source: NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT Volume: 597 Issue: 2-3 Pages: 219-221 Published: 2008
Times Cited: 0

29. Title: Charged hadron multiplicity fluctuations in Au+Au and Cu+Cu collisions from root S-NN = 22.5 to 200 GeV
Author(s): Adare, A; Aphecetche L, :Cussonneau J-P, Delagrange H, Finck C, Germain M, PHENIX et al.
Source: PHYSICAL REVIEW C Volume: 78 Issue: 4 A Article Number: 044902 Published: 2008
Times Cited: 0

30. Title: Hadronic resonance production in d+Au collisions at root S-NN = 200 GeV measured at the BNL Relativistic Heavy Ion Collider
Author(s): Abelev, BI; Bouchet J, Erazmus B, Estienne M, Aggarwal, MM; STAR et al.
Source: PHYSICAL REVIEW C Volume: 78 Issue: 4 A Article Number: 044906 Published: 2008
Times Cited: 1
31. Title: System-Size Independence of Directed Flow Measured at the BNL Relativistic Heavy-Ion Collider
Author(s): Abelev, BI; Bouchet J, Erazmus B, Estienne M: Aggarwal, MM; STAR et al.
Source: PHYSICAL REVIEW LETTERS Volume: 101 Issue: 25 Article Number: 252301 Published: 2008 Times Cited: 0

32. Title: The ALICE experiment at the CERN LHC
Source: JOURNAL OF INSTRUMENTATION Volume: 3 Article Number: S08002 Published: 2008 Times Cited: 2

33. Title: Forward Neutral-Pion Transverse Single-Spin Asymmetries in p plus p Collisions at s=200 GeV
Author(s): Abelev, BI; Bouchet J, Erazmus B, Estienne M: Aggarwal, MM; STAR et al.
Source: PHYSICAL REVIEW LETTERS Volume: 101 Issue: 22 Article Number: 222001 Published: 2008 Times Cited: 1

34. Title: Suppression Pattern of Neutral Pions at High Transverse Momentum in Au plus Au Collisions at root S-NN=200 GeV and Constraints on Medium Transport Coefficients
Author(s): Adare, A; Aphecetche L, d'Enterria,D, Delagrange H, Finck C, Germain M, PHENIX et al.
Source: PHYSICAL REVIEW LETTERS Volume: 101 Issue: 23 Article Number: 232301 Published: 2008 Times Cited: 1

35. Title: Fission decay of N=Z nuclei at high angular momentum: Zn-60
Author(s): Royer G, von Oertzen, W; Zherebchevsky, V; Gebauer, B, et al.
Source: PHYSICAL REVIEW C Volume: 78 Issue: 4 Article Number: 044615 Published: 2008 Times Cited: 0

36. Title: How sensitive are di-leptons from rho mesons to the high baryon density region?
Author(s): Achelchin J, Vogel, S; Petersen, H; Schmidt, K, et al.
Source: PHYSICAL REVIEW C Volume: 78 Issue: 4 Article Number: 044909 Published: 2008 Times Cited: 0

37. Title: Muon Production in Extended Air Shower Simulations
Author(s): Pierog, T; Werner, K
Source: PHYSICAL REVIEW LETTERS Volume: 101 Issue: 17 Article Number: 171101 Published: 2008 Times Cited: 0

38. Title: Onset of psi(0) Suppression Studied in Cu plus Cu Collisions at root s(NN)=22.4, 62.4, and 200 GeV
Author(s): Adare, A; Aphecetche L, :Cu+Cu collisions
Source: PHYSICAL REVIEW LETTERS Volume: 101 Issue: 16 Article Number: 162301 Published: 2008 Times Cited: 2

39. Title: Spacetime scales and initial conditions in relativistic A+A collisions
Author(s): Sinyukov, YM; Karpenko, IA; Nazarenko, AV
Source: JOURNAL OF PHYSICS G-NUCLEAR AND PARTICLE PHYSICS Volume: 35 Issue: 10 Article Number: 10471 Published: 2008 Times Cited: 0

40. Title: Saturation of E-T/N-ch and freeze-out criteria in heavy-ion collisions
Author(s): Cleymans, J; Sahoo, R; Mahapatra, DP, et al.
Source: JOURNAL OF PHYSICS G-NUCLEAR AND PARTICLE PHYSICS Volume: 35 Issue: 10 Article Number: 104147 Published: 2008 Times Cited: 0

41. Title: Consequences of a Lambda(c)/D enhancement effect on the non-photonic electron nuclear modification factor in central heavy ion collisions at RHIC energy (vol 663, pg 55, 2008)
Author(s): Martinez-Garcia, G; Gadrat, S; Crochet, P
Source: PHYSICS LETTERS B Volume: 666 Issue: 5 Pages: 533-533 Published: 2008 Times Cited: 0

42. Title: Dihadron azimuthal correlations in Au+Au collisions at root s(NN)=200 GeV
Author(s): Adare, A; Aphecetche L, :Cu+Cu collisions
Source: PHYSICAL REVIEW LETTERS Volume: 101 Issue: 1 Article Number: 014901 Published: 2008 Times Cited: 7

43. Title: Particle-species dependent modification of jet-induced correlations in Au plus Au collisions at root s(NN)=200 GeV
Author(s): Afanasiev, S; Aphecetche L, :Cu+Cu collisions
Source: PHYSICAL REVIEW LETTERS Volume: 101 Issue: 8 Article Number: 082301 Published: 2008 Times Cited: 0

44. Title: J/psi production in root s(NN)=200 GeV Cu+Cu collisions
Author(s): Adare, A; Aphecetche L, , Delagrange H, Germain M, PHENIX et al.
Source: PHYSICAL REVIEW LETTERS Volume: 101 Issue: 12 Article Number: 122301 Published: 2008 Times Cited: 0

45. Title: Scavenging of e(s)(-) and OH center dot radicals in concentrated HCl and NaCl aqueous solutions
Author(s): Atinault, E; De Waele, V; Schmidhammer, U, et al.
Source: CHEMICAL PHYSICS LETTERS Volume: 460 Issue: 4-6 Pages: 461-465 Published: 2008 Times Cited: 3

46. Title: Spin alignment measurements of the K*(0)(892) and phi(1020) vector mesons in heavy ion collisions at root S-NN=200 GeV
Author(s): Abelev, BI; Bouchet J, Erazmus B, Estienne M: Aggarwal, MM; STAR et al.
Source: PHYSICAL REVIEW C Volume: 77 Issue: 6
47. Title: Quantitative constraints on the transport properties of hot partonic matter from semi-inclusive single high transverse momentum pion suppression in Au plus Au collisions at root S-NN=200 GeV
Author(s): Adare, A; Aphecetche L, Delagrange H, Germain M, PHENIX et al.
Source: PHYSICAL REVIEW C Volume: 77 Issue: 6 Article Number: 064907 Published: 2008 Times Cited: 4

48. Title: Suppression of high-p(T) neutral pion production in central Pb+Pb collisions at root s(NN)=17.3 GeV relative to p+C and p+Pb collisions
Author(s): Aggarwal, MM; Delagrange H, Martinez G, Retiere F, Ahammed, Z, Angelis, ALS, PHENIX et al.
Source: PHYSICAL REVIEW LETTERS Volume: 100 Issue: 24 Article Number: 242301 Published: 2008 Times Cited: 2

49. Title: Longitudinal double-spin asymmetry for inclusive jet production in (p)over-right-arrow + (p)over-right-arrow collisions at root s=200 GeV
Author(s): Abelev, BI; Bouchet J, Erazmus B, Estienne M, Aggarwal, MM; STAR et al.
Source: PHYSICAL REVIEW LETTERS Volume: 100 Issue: 23 Article Number: 232003 Published: 2008 Times Cited: 3

50. Title: Source breakup dynamics in Au+Au collisions at root s(NN)=200 GeV via three-dimensional two-pion source imaging
Author(s): Afanasiev, S; Aphecetche L, Delagrange H, Germain M, PHENIX et al.
Source: PHYSICAL REVIEW LETTERS Volume: 100 Issue: 23 Article Number: 232301 Published: 2008 Times Cited: 3

51. Title: alpha particle preformation in heavy nuclei and penetration probability
Author(s): Zhang, HF; Royer, G
Source: PHYSICAL REVIEW C Volume: 77 Issue: 5 Article Number: 054318 Published: 2008 Times Cited: 0

52. Title: Centrality dependence of charged hadron and strange hadron elliptic flow from root s(NN)=200 GeVAu+Au collisions
Author(s): Abelev, BI; Erazmus B, Estienne M Abelev, BI; Aggarwal, MM; Ahammed, Z, STAR et al.
Source: PHYSICAL REVIEW C Volume: 77 Issue: 5 Article Number: 054901 Published: 2008 Times Cited: 6

53. Title: The MEGAPIE-TEST project: Supporting research and lessons learned in first-of-a-kind spallation target technology
Author(s): Cadiou A, Guertin A, Fazio, C; Groschel, F; Wagner, W, et al.
Source: NUCLEAR ENGINEERING AND DESIGN Volume: 238 Issue: 6 Pages: 1471-1495 Published: 2008 Times Cited: 1

54. Title: Enhanced strange baryon production in Au+Au collisions compared to p+p at root s(NN)=200 GeV
Author(s): Abelev, BI; Bouchet J, Erazmus B, Estienne M Abelev, BI; Aggarwal, MM; STAR et al.
Source: PHYSICAL REVIEW C Volume: 77 Issue: 4 Article Number: 044908 Published: 2008 Times Cited: 1

55. Title: Supersymmetry versus ghosts
Author(s): Robert, D; Smilga, AV
Source: JOURNAL OF MATHEMATICAL PHYSICS Volume: 49 Issue: 4 Article Number: 042104 Published: 2008 Times Cited: 0

56. Title: rho(0) photoproduction in ultraperipheral relativistic heavy ion collisions at root s(NN)=200 GeV
Author(s): Abelev, BI; Bouchet J, Erazmus B, Estienne M Abelev, BI; Aggarwal, MM; STAR et al.
Source: PHYSICAL REVIEW C Volume: 77 Issue: 3 Article Number: 034910 Published: 2008 Times Cited: 2

57. Title: Elastic scattering of 96 MeV neutrons from iron, yttrium, and lead
Author(s): Eudes P, Lebrun C, Haddad F, Ohm, A; Blomgren, J; Andersson, P, et al.
Source: PHYSICAL REVIEW C Volume: 77 Issue: 2 Article Number: 024605 Published: 2008 Times Cited: 0

58. Title: Cold nuclear matter effects on J/psi production as constrained by deuteron-gold measurements at root S-NN=200 GeV
Author(s): Adare, A; Aphecetche L, Cussonneau J-P, Delagrange H, Finck C, Germain M, PHENIX et al.
Source: PHYSICAL REVIEW C Volume: 77 Issue: 2 Article Number: 024912 Published: 2008 Times Cited: 16

59. Title: Radio pulses from cosmic ray air showers - Boosted Coulomb and Cerenkov fields
Author(s): Meyer-Vernet, N; Lecacheux, A; Ardouin, D
Source: ASTRONOMY & ASTROPHYSICS Volume: 480 Issue: 1 Pages: 15-25 Published: 2008 Times Cited: 2

60. Title: Bimodality: A sign of critical behavior in nuclear reactions
Author(s): Le Fevre, A; Aichelin, J
Source: PHYSICAL REVIEW LETTERS Volume: 100 Issue: 4 Article Number: 042701 Published: 2008 Times Cited: 2

61. Title: Centrality dependence of charged hadron production in deuteron plus gold and nucleon plus gold collisions at root S-NN=200 GeV
Author(s): Adler, SS; Aphecetche L, Cussonneau J-P, Delagrange H, Finck C, Germain M, PHENIX et al.
Source: PHYSICAL REVIEW C Volume: 77 Issue: 1 Article Number: 014905 Published: 2008 Times Cited: 0
62. Title: A macroscopic description of coherent geomagnetic radiation from cosmic-ray air showers  
   Author(s): Scholten, O; Werner, K; Rusydi, F  
   Source: ASTROPARTICLE PHYSICS Volume: 29 Issue: 2 Pages: 94-103 Published: 2008  
   Times Cited: 2

63. Title: Identification of photon-tagged jets in the ALICE experiment  
   Author(s): Conesa, G; Delagrange, H; Diaz, J, et al.  
   Times Cited: 3

64. Title: Study of processes involving selenite immobilization in a soil-plant-microorganisms system  
   Author(s): Muller, J; Abdelouas, A; Grambow, B, et al.  
   Conference Information: 8th Annual V M Goldschmidt Conference, Date: JUL, 2008 Vancouver CANADA  
   Source: GEOCHIMICA ET COSMOCHIMICA ACTA Volume: 72 Issue: 12 Pages: A662-A662 Published: 2008  
   Times Cited: 0

65. Title: Micro-canonical pentaquark production in e(+e(-)) and pp collisions  
   Author(s): Liu, FM; Werner, K  
   Conference Information: 14th International Symposium on Very High Energy Cosmic Ray Interactions, Date: AUG 15-22, 2006 Weihai PEOPLES R CHINA  
   Source: NUCLEAR PHYSICS B-PROCEEDINGS SUPPLEMENTS Volume: 175 Pages: 58-61 Published: 2008  
   Times Cited: 0
Invited talks and conferences

2006


3. Aichelin J., “Transport theories in the Fermi energy domain” Introductory talk at the workshop on simulation of heavy ion reaction, achievement and challenges, ECT, Trento (Italie) 10-14 avril 2006

4. Aichelin J., "Tomography of the Quark Gluon Plasma by charmed mesons" Workshop on Heavy Ion Reactions at Ultrarelativistic Energies ECT, Trento (Italie), 26-30 juin 2006

5. Aichelin J., "Bimodality a smoking gun Signal for a first order phase transition", Nucleus Nucleus conference 2006, Tio de Janeiro (Brésil), 26 août au 1er septembre 2006

6. Aichelin J., “Challenges for Transport theories to describe high density systems” Workshop on Physics at high baryon density, Strasbourg (France) 19 septembre 2006


12. Hartnack C., “Description of low energy heavy ion collision within the Isospin Quantum Molecular Dynamics Model”, ECT, Workshop on simulation models for heavy ion collisions close to the Fermi energy, Trento (Italie), avril 2006


29. Smilga A. «Superconformal higher-dimensional field theories and the Theory of Everything», Quark 2006, St Petersbourg (Russie), mai 2006


32. Werner K., “Nuclear Surface Effects in AUAU@RHIC”, 22rd Winter Workshop on Nuclear Dynamics, La Jolla (USA), mars 2006

33. Werner K. “Core-corona separation in heavy ion collision at RHIC and SPS”, I3 network workshop, Trento (Italie), Juin 2006

2007


3. Aichelin J., “Tomography of the Quark Gluon Plasma by Heavy Quarks”, Memorial Workshop for the 75th Birthday of J. Zimanyi, Budapest (Hongrie) 2-5 juillet 2007


5. Aichelin J., “What have we learnt from dilepton Spectra and what do we have to measure to learn even more”, Collaboration Meetong of the HADES Collaboration, Ayia Napa (Chypre) 30 octobre au 4 novembre 2007


2008

1. Aichelin J., “Collisional energy loss of heavy quarks in a Quark Gluon Plasma”, 24th Winter Workshop on Nuclear Dynamics, South Padre Island (Texas, USA), 5-12 avril 2008


7. Hartnack C. “Description of heavy ion collisions within the Isospin Quantum Molecular Dynamics Model”, Joint ICTP-AIEA advanced workshop on model codes for spallation reactions, Trieste (Italie), février 2008


26. Werner K., “Macroscopic of Radio Emission based on Shower Simulations and a Realistic Index of Refraction”, Workshop Radio at Auger, Nantes (France), janvier 2008


33. Werner K., “Hydrodynamic Evolution : o the role of Initial Conditions and Freeze Out (thermal or not)”, International Conference on Strangeness in Quark Matter 2008 (SQM 2008), Pékin (Chine), octobre 2008
Publications

2006


19. Royer G., «Multiple-humped fission and fusion barriers of the heaviest elements and ellipsoidal deformations», 11th International Conference on nuclear reactions mechanism, Varenna (Italie), juin 2006


2007


l’enseignement supérieur, les pédagogies actives : enjeux et conditions» Louvain-la-Neuve (Belgique), 24-26 janvier 2007


15. Porteboeuf S., «Particle Production at the LHC: Prédictions from EPOS,» Heavy Ion Collisions – Last Call for Predictions, Cern, Genève (Suisse), 2007


2008


24. Royer G., «Alpha decay potential barriers and half-lives and analytical formula predictions for the superheavy nuclei», State of the Art in Nuclear Cluster Physics, Strasbourg (France), mai 2008


**Conference Communications (not published)**

**2006**


27. Royer G. et al, «Multiple-humped fission and fusion barriers of the heaviest elements and ellipsoidal deformations», 11th International Conference on Nuclear Reaction Mechanisms Varenna Italie (2006)


31. Suzuki T. et al, Gdr Nomade, Palais des Papes, Avignon (France), 2006


34. Suzuki T. et al, 13èmes journées d’Etudes de Chimie sous Rayonnement, Domaine de Port au Rocs, Le Croisic (France), 2006


2007


5. Eudes P. et al, Heavy-Ion at the Fermi energy, a theoretical point of View, Eurons/Ewon meeting, Prague (république Tchèque), 2007


27. Schutz Y., L’origine et la structure ultime de la matière, Conférence de l’Académie des Sciences, Arts et Belles Lettres de Caen, 17 juin 2007


2008


14. Gossiaux P.B. et al, «Towards an understanding of the RHIC single electron data», 20th


32. Peigné S., Seminar at the University of Jyvaskyla, Finlande “Parton collision energy loss in a quark-gluon plasma” Avril 2008


34. Porteboeuf S., «Generation of complete event containing very high pT jets», Workshop on the Network I3HP, Villasimus, Sardinia (Italie) 2008


38. Sahoo R., Kabana S., " The QCD Phase Transition and the thermal properties of the $\phi$ mesons", Excited QCD Meeting, Zakopane, Poland Fev 2009.


43. Thiollière N. et al, «Gas production and activation calculation in MEGAPIE», 9th Technical Review Meeting MEGAPIE, Aix en Provence (France), 2008

45. Vandenborre J.et al, «Combustibles pour les réacteurs VHTR (UO$_2$ et THO$_2$) : Etude de l'influence de la surface et de l'irradiation sur les propriétés de solubilité »

PHD Theses

2006


2007


7. Isabelle Llorens, «Etude de la coprécipitation des éléments ; Tc, Se et Am(Eu) avec les phases d’accueils ; FeCO3, Fe3O4, FeSiO3, Fe2SiO4, FeS et FeS2», Université de Nantes

8. Laeticia Kasprak, «Quantification et spéciation du 99Tc dans les matrices environnementales» Université de Nantes

2008


5. Thomas Saugrin, «Analyse de l’expérience CODALEMA de radio détection des grandes gerbes cosmiques atmosphériques» Université de Nantes

6. YoroTall «Etude des caractéristiques nucléaires d’un système hybride de 300 MW(th) pour la gestion des déchets radioactifs». Université de Nantes

7. Sandra Valcares, «De la mesure des champs électriques par l’expérience CODALEMA aux caractéristiques des rayons cosmiques», Université de Nantes
8. Jérôme Donnard «Développement d’un dispositif d’imagerie bêta à très haute résolution spatiale». Université de Nantes

9. Liu Xiaolan, «Absorption du Se (IV ; VI) sur la pyrite et la transformation cristalline de la pyrite» Université de Nantes

10. Elodie Atinault «Étude de l’oxydation radiolytique de l’uranium degré d’oxydation +IV par radiolyse pulsée et stationnaire induite par divers rayonnements : hélium, électrons accélérés et gamma”» Université de Nantes
Lectures and schools


L. Aphecetche : «La grille de calcul au LHC»
Cours de l’école Internationale Joliot Curie 2008
