LETTER OF INTENT

R&D-FAZIA: Prototype development Phase

(http://fazia.in2p3.fr)

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An R&D program devoted to new experimental concepts of identification in Atomic (Z) and Mass (A) numbers of light and heavy isotopes produced in nuclear reactions is the goal of the present R&D of the International FAZIA Collaboration (a full list of the members is given at the of this document). The aim is to build prototypes for a new detection array for coming European Radioactive Nuclear Beam facilities (SPIRAL-2/GANIL, FAIR/NUSTAR, LNL/SPES and EURISOL). The detection array will be used to study dynamical and thermodynamical aspects of nuclear collisions. It will then provide a unique capability to study isospin effects.

The basic idea is to develop a detector array for isospin-oriented reaction dynamics studies to be performed in a large bombarding energy range (from SPIRAL2 and SPES to EURISOL) in 4 steps:

1. FAZIA ***Prototype phase*** to define the basic telescope cell.
2. FAZIA ***Prototype-array phase***: on the basis of the conclusion drawn in the preceding phase, a prototype array will be designed and constructed. It will consist of about 20-30 basic telescope cells arranged in a compact array. The geometry of the array shall fulfill technical needs in terms of granularity and angular resolution for testing all the mechanical and electrical problems associated with the compactness of the system (dead zones, cross talks...). Also the DAQ should be tested in that phase.
3. FAZIA-***Array for SPIRAL2/SPES***: construction of a FAZIA-array apt to SPIRAL2 ans SPES beams with large solid angle coverage.
4. Final ***4π FAZIA-array***.

The Step 1 (prototype phase) is currently supported by INFN in Italy (in the framework of the Nucl-ex experiment) and IN2P3/CNRS and Agence Nationale de la Recherche for France. Step 2 (prototype-array phase) has been already approved by the IN2P3/CNRS scientific council. The completion dates are 2008 for step1, 2010 for step 2, 2012 for step 3 and 2015 for the final FAZIA-array. A Memorandum of understanding is in preparation, to be signed by INFN in Italy, IN2P3 and GANIL in France and by Polish, Romanian and Spanish Institutions.

The final detection array, which will be made of several modules like the prototype, will include several thousands of channels and thus cannot be conveniently instrumented with present day electronics. ASICs (Application Specific Integrated Circuits) can offer a high performance, compact, and integrated solution. The main challenges in the case of nuclear physics stem from the large energy ranges of the particles detected. We will therefore concentrate on the development of ASICs for a high-dynamic-range front-end, timing and shaping electronics. Efforts will also be directed towards ASICs for Digital Pulse Shape Analysis (DPSA), in close relation with the research on pulse shape analysis.

The benefits and exploitation connected to the development and study of new detectors are currently expected to be largely disseminated throughout the nuclear physics scientific community. The prototypes are expected to be characterized by an excellent charge resolution (up to 70) and mass resolution (up to 50) with low energetic identification thresholds, well beyond the capability of the existing instrumentation. This will be done by using Pulse Shape Analysis with novel detector configurations and novel ideas to simplify the electronic chain.
On the other side, namely of the development of fast digitizer, having high sampling rate (of the order of 2 GSample/s) and high resolution (effective bits larger than 10), one can reasonably foresee exploitation of the outcomes.

Objectives

The long term Physics goal of the Collaboration is the *Characterization of the Nuclear Equation Of State (NEOS) with respect to the the isospin degree of freedom.* In order to reach that objective it necessary to improve the Z and A identification performances of the detectors, with respect to the existing apparatuses.

The tool of heavy-ion collisions at intermediate energies (10-100 A·MeV) has proven its ability to extract fundamental microscopic and macroscopic properties of nuclear matter. These properties analysed with stable beams have to be studied on a wider isospin (N/Z ratio) range in order to extend our present knowledge to two component (neutrons, protons) systems in interaction.

On the one hand, studies of dynamical aspects of reaction mechanisms provide relevant information about incompressibility of nuclear matter when compared with models using effective interactions. This is done through the study of stopping, isospin density changing in collisions and characteristics of compressed nuclear matter. The Radioactive Nuclear Beams (RNB) facilities will provide a unique capability to study neutron-rich compressed matter and then to probe the isospin dependence of the NEOS which is largely unknown. This goal is connected with astrophysics since the asymmetry term plays a dramatic role in type-II supernova collapse and in the expected morphology of neutron-stars. On the other hand, with a careful selection of events, studies of the de-excitation schemes of nuclei at finite temperature are possible. The use of very exotic (in terms of N/Z ratio) beams are expected to reveal new phenomena and new signatures related to the isospin composition of the excited nuclear system (neutron enrichment of the gas-phase for example). The goals are connected with the study of phase transitions in finite systems, which is of broad

scientific interest and closely connected with the search for quark gluon plasma, Bose condensates and melting of solid clusters.
From an experimental point of view, it is obvious that to fully exploit the Radioactive Nuclear Beams (RNB) facilities and study the effects of large isospin variation, the accomplishment of both Z and A identification of particles and fragments over the largest possible ranges is necessary. The present identification techniques (Time of Flight, Telescope DE-E) do not allow fulfilling the identification requirement on a large dynamical range. Several multi-detector systems are currently being intensively exploited at European nuclear physics facilities and are generating major advances in the scientific fields described above. For the study of nuclear dynamics and thermodynamics at Fermi energies, current state of the art arrays include INDRA (1993, France) and CHIMERA (1999, Italy). At lower energies 4Pi apparatuses are also available at LNL (e.g. GARFIELD), where important upgrading have been recently implemented, mainly for the Digital Electronic treatment of the data. However mass and charge identification are currently very limited for all these apparatuses. To fully benefit from radioactive beams, complete identification is necessary up to A~50. This will only be achievable through the development of Digital Pulse Shape Analysis (DPSA) techniques and the corresponding electronics.

Mass and charge identification is one of the major challenges of particle detection systems. At present, two techniques are generally employed, time of flight and energy loss measurements. The former requires long flight paths which translate into large, expensive and somewhat cumbersome arrays. The latter implies high thresholds which preclude the identification of important low energy particles. More recently, particle identification through pulse shape analysis has been proposed and promising preliminary studies have been performed. The combination of the three techniques should open a path towards more compact and efficient arrays. We propose to intensively investigate the potential of mass and charge discrimination through pulse shape analysis in both Silicon and CsI detectors. Research in this area includes development of electronics (signal digitization), algorithms and materials (e.g. neutron transmutation doped silicon).

Multi-channel arrays comprising several thousands of channels cannot be conveniently instrumented with present day electronics. ASICs (Application Specific Integrated Circuits) can offer a high performance, compact, and integrated solution. The main challenges in the case of nuclear physics stem from the large energy ranges of the particles detected. ASICs will be developed for a high-dynamic-range front-end, timing and shaping electronics. ASIC for Digital Pulse Shape Digitization (DPSA) is also under consideration.

Project description

The detection array, which will be made of several modules like the prototype, has to be extremely compact and simple, in order to cover the whole solid angle. The number of detectors needed has to be sufficiently large to obtain a precise determination of the characteristics of the charged products emitted in the reaction, with special regards to the precision in the emission angle. Compact electronics has to be associated with an analog and a digital part. The analog part will allow a first (low-noise, high dynamic range) pre-amplification of the signal. The digital part will sample the signal and perform the pulse shape analysis on-line with a fast digital signal processor with subsequent recording of the results of the detection. A focused effort in the development of ASICs is planned. In parallel, a task will be directed at developing electronics and software algorithms for DSP (Digital Signal Processor), optimized for charged particles since a significant development of real time DSP-based software is required to perform the necessary Pulse Shape Analysis of the signals.

The benefits and exploitation connected to the development and study of new detectors are currently expected to be largely disseminated throughout the nuclear physics scientific community. The prototypes, which the present project aims at, are expected to be characterized by a charge and mass resolution well beyond the capability of the existing instrumentation. At the end of the R&D, it is expected that a proposal for an innovative large array will be submitted to the appropriate funding agencies. The individual elements of the array will be largely identical to the prototype, thus drastically reducing their development and construction time. This array, which should be portable to various experimental sites, will strongly enhance the quality of the research performed at several large scale European nuclear science facilities. Operation is foreseen with stable and in particular with radioactive nuclear beams. On the other side, namely the development of fast digitizers, having high sampling rate (of the order of 2 GSample/s) and high resolution (effective bits larger than 10), one can reasonably foresee exploitation of the outcomes, also in contexts external to the field of basic research.

The "state of the art" concerning the detection and identification in charge and mass of the reaction products of heavy ion collisions at intermediate energies (10-100 AMeV) is the following: the best resolutions in charge and mass are obtained with Silicon-Silicon or Silicon-CsI(Tl) telescopes (with preferred position sensitivity in order to properly correct the thickness inhomogeneities of the Delta E detector). The main limitations of this approach are the existence of both a low-energy threshold for charge identification (the particles must have enough energy to reach the second detector, punching through the first one, which for this reason should be thin) and of a high-energy threshold (high-energy particles produce small signals in the first detector, which for this reason should be thick). The measurement of the time-of-flight allows to determine the mass (but not the charge) of the particles stopped in the first detector. When the second detector is a CsI(Tl) scintillator (read out with a phototube or a photodiode) it is possible to perform a shape analysis of its signal and obtain an identification in charge and mass of the very fast charged particles (even though only up to charge 3 or 4): in fact it is well known that the fluorescence of CsI(Tl) depends on the ionization density of the detected particle, with fluorescence times varying from a fraction of to several microseconds. The shape analysis of the signals can also be used for charge identification of particles stopped in the first Silicon detector: in fact the shape of the signal depends on the ionization density of the detected particle in this kind of detectors too. The difficulty in this case is that the changes of the signal shapes occur on time scales of the order of few (or few tens of) nanoseconds, thus requiring particularly fast electronics. A better sensitivity to the ionization density can be obtained by mounting the Silicon detector in a "reverse" configuration with respect to the usual one, that is with the particles entering the detector from the rear side (the one opposite to the p-n junction) where the electric field is weak; the disadvantage is a general slowing down of the signals, with a corresponding worsening of the timing performances of the detector. All these identification methods require sophisticated electronic designs because, in order to obtain all necessary information, signal amplitudes (energy measurements) and arrival times of the particles (time-of-flight measurements) are to be determined as well as the shape analysis of the signals. Therefore a next generation detection setup with all these capabilities (shape analysis of the signals of the CsI(Tl) and especially of the Silicon Delta E detector) would be very complicated and very expensive if it were manufactured with the conventional approach, namely with analog electronics.

In order to fulfil the mentioned requirements, the prototype basic cell is a telescope consisting of 3 detection layers : Delta E1 – Delta E2 – E. The first two layers will be made of Silicon material (300 and 500 micrometers thick), the last one of 4 cm of CsI(Tl). Digital electronics will be used.

For shape analysis of the signals, the detector response has to be as much as possible independent of the particle impact location. Therefore nTD-Silicon material as Delta E detector has been chosen because of its intrinsic precise doping (better axial and radial uniformity): the doping of Silicon to create n-type Silicon is realized by neutron transmutation of ^{30}Si isotopes to ^{31}P after neutron capture and beta decay. This technique leads to resistivity fluctuations better than those attainable with standard FZ Silicon detectors.

A second novel idea is the following: the Delta E2 - E telescope consisting of a Silicon detector followed by a CsI(Tl) scintillator could be manufactured without photomultiplier or photodiode; in fact, in our approach the Silicon is used not only to measure the ionization produced by the particles passing through it, but also to read out the fluorescence produced in the CsI(Tl) by the particles. With this method the electronic chain can be greatly simplified and made much more compact. The junction side of the Si detector must be optically coupled to the CsI scintillator. Therefore the particles passing through the Si and the CsI detectors give a composite current (or charge) signal, having a fast component (developing over tens of ns) associated with the ionization produced in the Silicon material and a slower component (times of the order of microseconds) due to the fluorescence of the CsI(Tl). It is therefore possible, by properly filtering the output of the preamplifier connected to the Si detector, to separate the two aforementioned contributions. The digital electronics is expected to be particularly efficient for an accurate shape analysis of the signal. This will allow the design and implementation of a compact telescope, able to identify mass and charge of the particles in the desired large energy range.

Achievements

The International Collaboration FAZIA, recently formalized, started originally as the AZ4pi collaboration born in 2001 and supported (2002-2004) through a “Project International de Cooperation Scientifique” (PICS) CNRS-IN2P3/INFN between France and Italy. Physicists and Engineers have been working together to define the best technical solutions for a new European detection system. In 2004 the basic ideas for the prototypes using DPSA-techniques and associated electronics were envisaged and preliminary experimentation started. The FAZIA collaboration has been formalized in 2006 (http://fazia.in2p3.fr/) and the Project Management Board, as well as the Scientific Coordinators have been elected.

During the 2003-2006 period, several experiments and technical developments have been made:

- The goal of the experiments was to create a data-base of Pulse Shapes of different ions implanted in Silicon nTD material. For example, Mass number (A) discrimination is obtained from Pulse Shape Analysis of 80MeV ^{12}C and ^{13}C and also 313 MeV ^{36}Ar and ^{40}Ar stopped in an nTD-Silicon detector. In 2002 at LNL, using 250MeV ^{16}O beam, the first high-quality Digital Pulse Shape analysis was performed and showed indeed the possibility of discriminating IMF’s stopped in the Silicon detector. Channelling experiments were also performed at LNL in November 2006. They have been extremely important, since they demonstrated –as suspected by the collaboration-- that it is mandatory to control channelling effects in order to have stable shapes of the current/charge signals. In particular a clear improvement is expected for A- and Z-discrimination by “tilting” the Silicon detector and by using the <100> orientation instead of the usual <111>. We are presently performing an experiment at LNL meant to precisely determine the right “random” cut for the <100> detectors and to explore the sensitivity of the DPSA on the residual doping non-uniformity of the Silicon detectors.
- Realistic and parameter free simulations are being developed in the collaboration to reproduce the Pulse Shapes in Silicon detectors, for stopped highly-ionizing ions.
- Technical developments concern the implementation of a fast charge and current-sensitive preamplifier (PACI), of a custom ASIC (MAR) to sample the current signal with high speed and high resolution (2GS/s-12 bits conversion using a low-noise analog pipeline), also exploiting the expertise on fast acquisition systems based on fast ethernet network.
- A new Front-end electronics card, based with the mother board developed and used in GARFIELD is under construction. It includes the MAR-ASIC, ADCs and FPGA/DSP processing for digital treatment of current and charge signals from PACI-preamplifier. The acquisition system will be, for this phase 1, the system already in operation for the GARFIELD collaboration (Italy).

PROPOSED EXPERIMENTS

To compare the advantages and drawbacks of the different technical solutions 8 prototypes have been manufactured and have to be tested in 2007/2008 (Agence Nationale de la Recherche program, INFN and IN2P3/CNRS funds): test of reverse and direct mounted configurations (Time of Flight versus Pulse Shaping), telescopes with photodiode and without, possibility of using a strip nTD-silicon detector for Delta E1 and Delta E2, Csi with different Tl doping from different manufacturers. The new Front-end electronics card, under development, will be used.

After a series of implantations of fixed-energy, known-charge and known-mass ions to study the response of the silicon, real experiments are necessary to test the detection and identification capability of the prototypes for a continuous range of different (A, Z and Energy) reaction products.
A proposal for a first experiment using the ensemble of prototypes (see picture) and the associated electronics has been presented to the PAC of GANIL (for possible experimentation in spring 2008) for testing the telescopes at higher energies. This high-bombarding energy experiment should be complemented with lower energy experiments in order to test the whole capability of the prototypes. It is to be noted that the lower energy tests are very important because the most demanding identification requirements are those connected to detection of fully stopped heavy ions. Moreover low energy ions are those expected in the Physics cases which will be addressed by our Collaboration by medium-term RNB facilities, like SPIRAL2 ans SPES.
In particular the following issues related to our R&D must be addressed, exploiting the beams available at LNL:

- by using reactions induced on light targets by Sulphur and Nickel at the highest available energies we plan to produce light charged particles, intermediate mass fragments and heavier reaction products in a wide energy range. This campaign is complementary to the one foreseen at GANIL, which is mainly oriented in testing the prototypes using higher energy beams to copiously produce heavier fragments induced by fission on heavy targets.
- the Digital Pulse Shape Analysis performances of our system for selected isotopes of given Z, like Carbon, Sulphur, Nickel and Selenium as a function of the energy will be studied. This may serve to test the very limit (in terms of low-energy identification thresholds) of the FAZIA prototypes. The spanned energy range is covered by the Tandem and Tandem/Alpi combination. Measurements involving carbon can be complemented, in the very low energy side (of the order of ten MeV), with experiments already started at LABEC in Florence.
- by exploiting the beams well suited for the previous item, we plan to also address the issue of straggling. The recent results on channeling effects, obtained by our collaboration during an experiment in LNL, suggest that a deeper study on straggling is also necessary to experimentally verify the importance of this effect in limiting the identification performances. In fact, we remind that our identification approach for stopped ions (those which wil be mainly studied in LNL) is based on the penetration depth: different penetrations change the shape of the signal because of the difference in the experienced electric field. It is therefore clear that any effects which, for a given ion of a fixed energy, may influence its penetration produces an undesired modification in the signal. Our preceding experience suggests that the presently available formulae for estimating the straggling of heavy ions in the energy regime between 1-10 AMeV tend to overestimate the effect and therefore that an experimental study is necessary.

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