Recent progress in HYDE and GASPARD detectors

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The scientific perspectives generated by the new accelerators being built at Germany (FAIR, Darmstadt) and France (SPIRAL2, Caen) have motivated the construction of the HYDE and GASPARD silicon detector arrays to perform leading research in low energy nuclear reactions. Such studies should provide angular distributions of elastic, transfer and breakup reactions, providing unique information on shell evolution, collective phenomena and nucleon-nucleon correlations at the borderlines of nuclear stability. In this paper we present main topics concerning particle identification and detector design under development by our collaborations.

1. Introduction

Nuclear reactions involving unstable nuclei with low breakup thresholds and exotic structures display features remarkably different from those of well-bound stable nuclei. With the advent of recent radioactive ion beam (RIB) facilities, new nuclei far from the line of stability have been available for study. The construction of the new facilities FAIR (Darmstadt, Germany)[1] and SPIRAL2 (Caen, France)[2] has generated good perspectives in the experimental nuclear physics community.

The new exotic nuclear species are of great importance for nuclear structure studies as well as for providing a deeper microscopic picture of nuclear physics in a wide scope: isospin-symmetry breaking effects in heavy nuclei, proton-neutron pairing phase or for the study of rare decay modes, such as the recently observed two-proton radioactivity. On the other hand, the weaker binding may lead to a more diffuse mean field and a modified spin-orbit interaction, all of which lead to a modification of the shell gaps.

Such modifications of shell structure have an influence on the evolution of nuclear shapes and collective modes that should be investigated in detail. The possibility to produce of the most exotic isotopes offer direct access to the relevant astrophysics paths, leading to a fruitful synergy of nuclear structure and nuclear astrophysics.

The FAIR (Facility for Antiproton and Ion Research) is an extension of the existing RIB facility GSI in Darmstadt (Germany). It will allow for the production of radioactive nuclei of very short life, down to a few microseconds, with enough intensity to perform nuclear spectroscopy studies. At the Low Energy Branch of FAIR, the ions will be slowed down to energies of a few MeV/u, where direct nuclear reaction studies can be performed. This is the objective of the experiments foreseen for HISPEC collaboration at FAIR. The main instrument for such studies will be the HYDE (Hybrid Detector) array, which should be able to perform measurements of reaction cross sections induce by these very short-lived nuclei.

The development and construction of HYDE is made in collaboration with the research groups of GASPARD and FAZIA detectors for the SPIRAL2 facility, allowing for the exploitation of the existing synergies and providing common working groups for R&D activities.

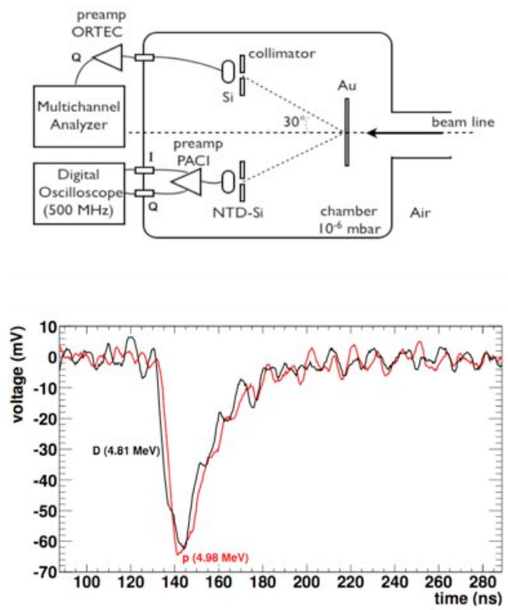

Fig. 1 Up: Experimental setup for DPSA studies. Down: Typical pulse shapes for low energy protons and deuterons.

2. Digital Pulse Shape Analysis for particle identification.

Charged particle identification has been normally achieved in the past by time of flight (TOF) and energy loss techniques with particle telescopes (PT). The former requires long flight paths, which translate into large, expensive and somewhat cumbersome arrays. The latter implies relatively high thresholds, which preclude the identification of low energy particles with large Z, and very fast particles leaving too low energy in the first stage detector. Digital Pulse Shape Analysis (DPSA) of both current and charge signals produced by charged particles impinging on silicon detectors has been proposed as a particle identification tool [3]. Preliminary results were very promising and therefore DPSA studies play an important role among the various R&D activities performed by our collaboration in the last few years. This technique is an important challenge from both experimental and instrumental points of view, with applications in many other fields. At present it appears that a suitable combination of these three techniques (TOF, PT and DPSA) should be implemented for the design and construction of the new generation of particle detectors.

The basic DPSA method consists on the digitalization of the signals produced in the silicon detectors using a large bandwidth preamplifier (300 MHz typical), together with a fast digitizer having a high sampling rate (~1GS/s). The digitalized pulses can be offline analyzed and classified according to the mass and charge of the impinging particles. The R&D activity must also cover a convenient design and implementation of the FEE electronics in the proximity of detector cells. Various parameters concerning the quality of the silicon wafers play an important role in this technique, like crystallographic orientation [4] and non-uniformity in thickness and resistivity [5].

An important issue is to determine the limits of DPSA technique: range of energies, masses and charges, optimal silicon thickness, strip effects and radiation degradation. For this purpose a database of digital pulses is being built using nuclear reactions with stable beams. In Fig. 1 (up) we show the experimental setup for DPSA studies prepared for a recent experiment carried out at Centro Nacional de Aceleradores (Seville, Spain). A high uniformity NTD (Neutron Transient Doped) silicon detector was bombarded by low energy, low intensity light ions after scattering on a gold target. The signals were collected by using a 300 MHz bandwidth preamplifier (PACI) [6] and driven to a digital oscilloscope with a 2GS/s sampling rate. A typical current signal for protons (red) and deuterons (black) are shown in Fig. 1 (down).

Analytical techniques for DPSA based on momentum expansion have been successfully applied for identifying heavy ions with both silicon and scintillation detectors [7]. An alternative method for particle identification is the implementation of artificial neural networks (ANN), which can take advantages of existing hardware already available in the market. An

ANN consists of a set of artificial neurons, typically organized into several layers with a high degree of interconnection. Among the different existing topologies of neural networks, a widely used architecture is the so called Feed-Forward or Multilayer Perceptron (MLP) network. Very good results could be obtained with MLP in many different applications where there is a complex, non-linear relationship between several variables.

The technique has been applied to analyze recent data obtained by the FAZIA collaboration using the CIME cyclotron facility at GANIL (Caen, France). In these experiments, a high quality NTD detector (500um thick) was bombarded with different isotopes, from 12C to 84Kr, in an energy range between 4 and 9 MeV/u. The detector was mounted in reverse injection configuration, connected to a PACI preamplifier, providing both charge and current outputs. Both signals were recorded using a commercial data acquisition system ACQUIRIS, with a 12 bit digitizer, 2 GS/s sampling rate. The result obtained with this technique is shown in Fig. 2 (down), where clear separation of isotopes has been achieved for isotopes of Argon, Sulfur, Kripton and Iron. The ANN used in this work had three layers with 8+8+2 structure giving a total of 18 neurons, as it is schematically shown Fig. 2 (up). We have used 300 points per current pulse, and the corresponding Levenberg-Marquardt back-propagation algorithm.

The artificial neural network can be implemented in a FPGA device. A basic system was built for this purpose, consisting on eight neural networks, an arbiter with rotary priority (to avoid that the same network puts its data in the output device), and a microcontroller PicoBlazeTM for communication with the output device. This system has been implemented in a Spartan-3AN700 device, using a simple LCD display as the output device. Tests have been performed with a frequency of 50 MHz, the architecture of 8x8x2 neurons and a pulse length of 100 points. With this configuration the PSA operation requires about twenty microseconds. A basic flow diagram for operation is shown in Fig. 3.

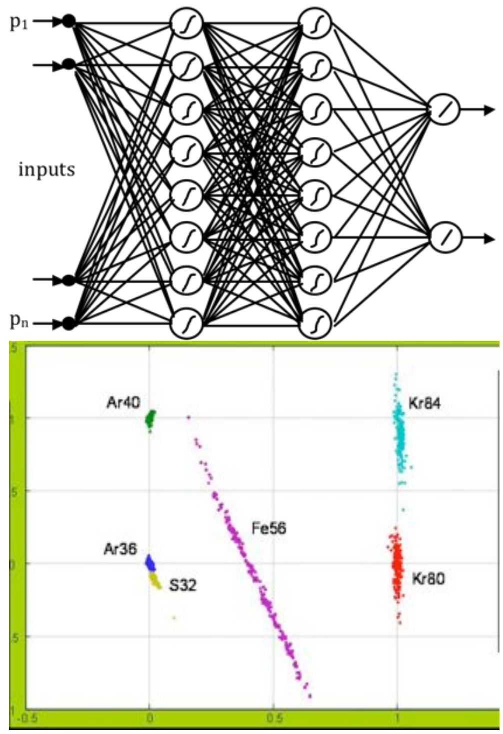

Fig. 2 Up: Simple neural network architecture. Down: Classification of pulses of several heavy ions impinging on NTD silicon detector. See text for details.

3. Innovations in Data Acquisition and Front End Electronics

The development of high performance front end electronics and signal acquisition systems represent a notable technological challenge since they demand conflicting requirements, among them:

- Low power consumption for the increased number of acquisition channels on the detector.

- Low supply voltage, as required by modern integrated circuits technologies and to reduce power consumption in digital circuits.

- More processing capability and wider bandwidth.

- Adaptation to different specifications to favor inter-operation.

- Lower size and cost of the systems, which implies a higher density of integration and the use of silicon technologies, in particular CMOS technologies allowing integration in the same substrate all the analog and digital functionality.

Due to the difficulty to achieve simultaneously all these characteristics, different technological solutions may coexist favoring some features at the expense of the others. In applications demanding wide bandwidth (like in DPSA), usually the analog signal is digitalized as soon as possible, and most of the signal conditioning formerly performed in the analog domain is now performed in the digital stage. This fact makes that the bandwidth and accuracy that the A/D converters must feature is becoming higher which lead to more power consumption and better performance, making these blocks a key element. Thus it is necessary to develop new design techniques allowing to satisfy these demands maintaining at the same time a reduce power consumption.

On the other hand, we are dealing with a extremely high granularity system, where several DSSSD detectors of 128x128 channels are going to be used for spectroscopy, thus generating about 512 signals per detection cell. The proposal made by the Huelva-Krakow collaboration is the construction of high-density front-end electronics, based on the spectroscopic chip of the VA-TA type produced by IDEAS (Norway). This commercial solution looks like a moderate cost in the project, easy chip replacement, large density of channels (64ch/chip) and a high dynamic range. For the moment we are in the production stage of 16 prototype boards, which will also be used for detector test and optimization of relevant parameters like dynamic ranges, trigger structure, time-stamping, data transmission rate and power dissipation.

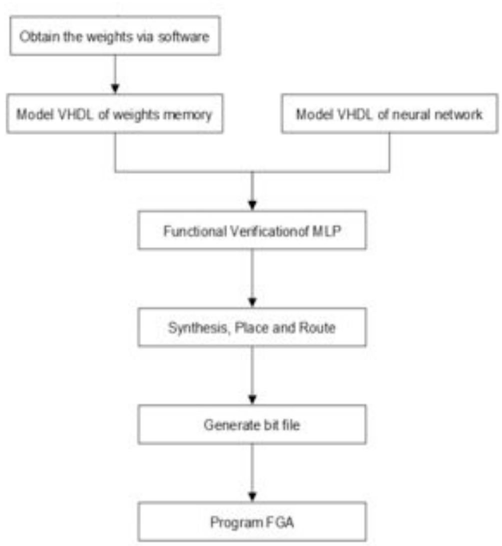

Fig. 3 Flow diagram for ANN implementation in an FPGA dedicated to DPSA. See text for details.

4. Mechanical design

The collaboration has realized a number of specific mechanical designs of the detection cells and reaction chamber for the HYDE detector array, everything integrated in the low energy beam line of FAIR.

The activities concerning the mechanics of HYDE are coordinated within the design group HYDE-GASPARD, which brings together the community for low energy reactions operating at FAIR and SPIRAL2. An important achievement of this working group has been the selection of the software, the so called CATIA design package. The choice was motivated by specific features of the analysis modules (temperature and mechanical stress, among others) which have shown high efficiency aerospace and automotive industry, where similar requirements are found. In addition, it is possible to export the mechanical designs to be used by the Montecarlo simulation code NPTool (Geant4 based) [8] for physics cases.

The mechanical design of the new charged particle arrays must consider the possibility of being used in combination with other gamma arrays like AGATA, the largest germanium based detector for gamma ray spectroscopy, or PARIS, a compact calorimeter based on LaBr3. These operation possibilities put some constraints on the size of the charged particle array to be built, to have about 400 mm maximum diameter, and to make a particular choice of low gamma absorption materials for the mechanical construction. On the other hand, in a first approach the preamplifier stage is sitting just over the surface of the reaction chamber, so that the corresponding temperature distribution must be calculated and the dissipated power minimized. Regarding the detection cells, the main constraint is determined by imposing four inches technology for the silicon wafers, so that the cost of the project is kept under limits. One of the proposed designs is shown in Fig. 4, where 54 detector cells of high granularity are placed in the corresponding vacuum vessel.

5. Detector cell

The goal of our detection system is to be able to study the fragments produced in the nuclear reactions, using radioactive beams with energies between 5 and 30 MeV/u. To do that, it requires charge particles detection with Z and A identification, and with an energy resolution better than 100 keV (average cell). This kind of system is composed by a set of silicon detectors forming a multistage particle telescope. The necessary information to identify reaction fragments is obtained by means of the three different techniques (TOF, PT, DPSA).

At present stage we are building a prototype of detection cell based on double-sided silicon strip detectors, (DSSSD). The first detector is only 20 micrometers thick and its active area is divided in 32 strips per side, having a reasonable angular resolution of about 5 degrees (lab) but still keeping a reasonable low capacitance. This layer will stop low energy heavy ions, and therefore DPSA techniques could be implemented to provide particle identification.

The second layer is a DSSSD detector 100 micrometers thick and 128 x 128 strips. The high segmentation can provide an angular resolution of about 0.5 degree (lab) so that a reasonable momentum reconstruction of reaction fragments can be achieved for kinematic studies.

The third detector is a DSSSD of 500 micron with 128 strips by side, with similar characteristics than previous stage.

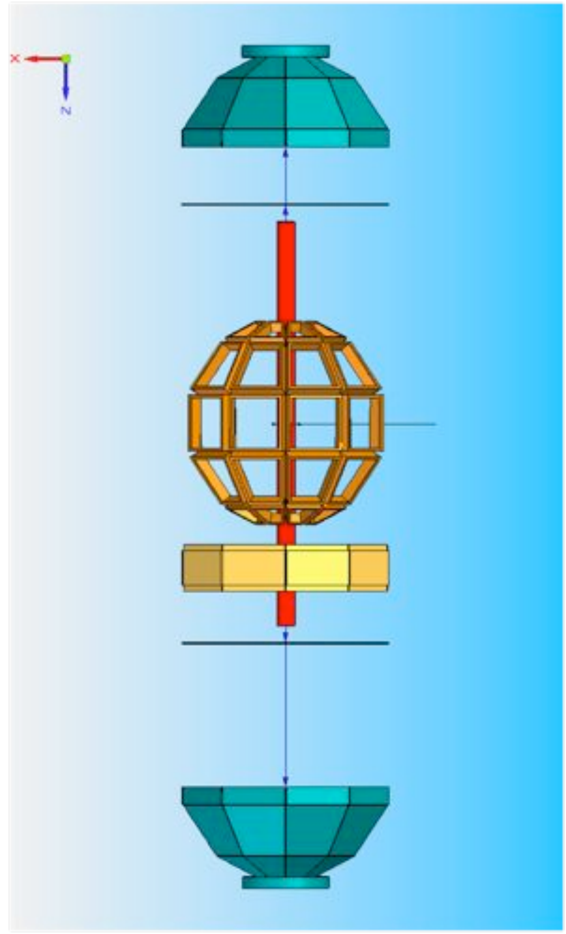

Fig. 4 One of the proposed mechanical designs of HYDE detector for FAIR. The vacuum vessel is divided in 3 parts to help operation and maintenance. The inner structure holds 54 detector cells, where DSSSD detectors of high granularity are mounted.

Finally, and with the mission of to track very energetic light particles, we have a DSSSD of 1500 micrometers thick and with a low granularity of 32 x 32 strips.

The detectors have been ordered to MicronSemiconductors Ltd according to our specifications. A sketch of the mechanical design of the prototype is given in Fig. 5.

6. Synergies of HYDE with other European projects

Along the last years there have been a number of initiatives to establish synergy groups between charge particle detection communities in the international frame. The main collaborations have been established between HYDE-FAZIA in the context of digital pulse shape analysis techniques, between HYDE-GASPARD concerning the physics of low energy radioactive beams and detector design.

3. Summary and conclusions

The new generation of radioactive beam facilities being built at FAIR and SPIRAL2 is demanding large particle detector arrays using the last advances in particle detection technology. The collaborations for construction of the detectors HYDE, GASPARD and FAZIA are leading important developments on digital pulse shape analysis, silicon production, front end electronics and data acquisition systems that will be used to build a new generation of particle detectors.

Acknowledgments

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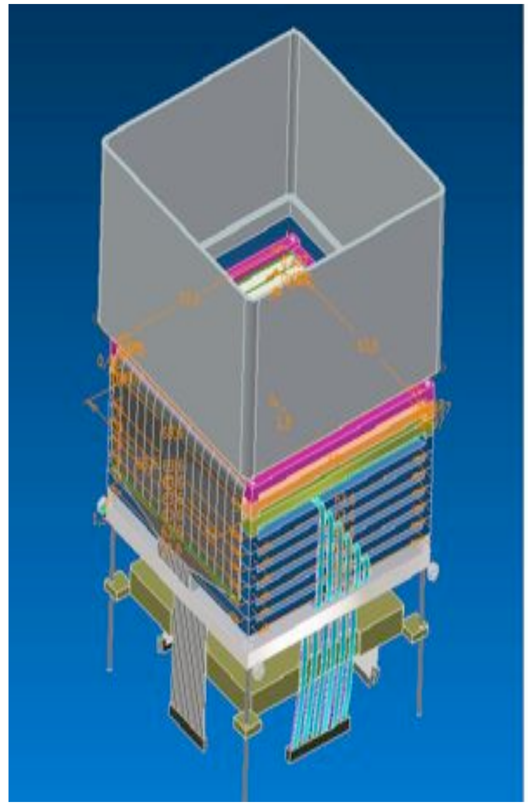

Fig. 5 Prototype of detection cell of the HYDE detector. The pink, orange, green and blue layers correspond to 40 µm, 100 µm, 500 µm and 1500 µm DSSSD detectors, respectively. The grey box on the top is foreseen to protect the silicon layers when manipulating the detector cell.