Development of a Micromegas TPC for Low Energy Heavy Ions Measurement for Nuclear Fission and Astrophysics Applications

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Abstract. Time Projection Chambers are widely used since many years for tracking and identification of charged particles in high energy physics. We present a new R&D project to investigate the feasibility of a Micromegas TPC for low energy heavy ions detection. Two physics cases are relevant for this project. The first is the study of the nuclear fission of actinides by measuring the fission fragments properties (mass, nuclear charge, kinetic energy) that will be performed at different installations and in particular at the NFS facility to be built in the framework of the SPIRAL2 project in GANIL. The second physics case is the study of heavy ion reactions, like (α,γ), (α,p), (α,n) and all the inverse reactions in the energy range between 1.5 and 3 AMeV using both stable and radioactive beams. These reactions have a key role in p process in nuclear astrophysics to explain the synthesis of heavy proton-rich nuclei. Within the project, a large effort is devoted to Monte-Carlo simulations and a detailed benchmark of different simulation codes on the energy loss and range in gas of heavy ions at low energy has been performed. A new approach for simulating the ion charge state evolution in GEANT4 is also presented. Finally, preliminary results of an experimental test campaign on prototype are discussed.

Keywords: TPC, Micromegas, Fission, Astrophysics, GEANT4, SRIM.
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MOTIVATIONS

Gaseous detectors and Time Projection Chambers (TPC) in particular are widely used since many years in nuclear and particle physics. On one hand, they provide very good tracking performances with low material budget and they can be built to cover large surfaces, keeping a moderated cost. On the other hand, gaseous detectors show their best tracking performances on the detection of minimum ionizing particles in transmission mode. They have been only rarely used to perform tracking and identification of heavy ions at low energy [1-2].

The FIDIAS project (FIssion Detector at the Interface with AStrophysics) aims at the evaluation of the feasibility of a TPC based on the Micromegas detector [3] for the

full reconstruction and identification of low energy heavy ions. The physics case of the project is twofold. The first is the study of the nuclear fission by the characterization of the fission fragments. In particular, a precise and systematic measurement of the mass, nuclear charge and kinetic energy of fragments produced by the neutron induced fission of actinides in a large range of neutron energies is fundamental in order to improve phenomenological and microscopic models [4-7]. In addition, while quite a lot of data on fission yields are available for thermal energies, only few fissioning actinides have been studied in the keV-MeV range. The latter are very important for the design of future fast reactors and for the optimization of Radioactive Ion Beam facilities. This is the reason why, together with measurement in the thermal energies (at ILL or Orphée research reactors), we foresee to perform measurements in the epithermal and fast region, in particular at the NFS ToF facility that will be built in the framework of SPIRAL2 at GANIL [8]. This facility will provide the highest available neutron flux in the region between 1 and 20 MeV.
The second physics case is the study of alpha capture reaction relevant for the stellar nucleosynthesis. In particular, the study of the p-process is actually a key field in the understanding of the nuclear abundances and, despite the fact that the p nuclei is a bunch of only 35 stable nuclei, the modelisation of their production mechanism is based on a reaction network involving hundreds of nuclei and reactions (mostly γ-n, γ-p, γ-α and their inverse). These reaction cross sections are very difficult to measure and are quite badly reproduced by standard Hauser-Feshbach theory which needs precise knowledge of optical models, gamma strength functions and level densities. A well-established program has been already setup for the study of alpha-induced reactions in inverse kinematics at LISEIII in GANIL [9]. The aim of the project is to continue this program by using stable and radioactive beam available at ISOLDE, S-DALINAC and in the future at SPIRAL2 in the mass region 80-140 and 170-200 in the energy range between 1 and 3.5 AMeV.

THE FIDIAS PROJECT

The scope of the FIDIAS project is to explore the possibility to perform a full reconstruction of the ions using a Micromegas TPC in a magnetic field. The ionizing gas foreseen for the TPC is He, which is the only one fulfilling the requirements of the two physics cases. This is because the He gas gives the longest path for the fission fragments and it will allow the study of alpha-induced reactions in inverse kinematics, using the TPC gas volume as an active target. For the study of fission fragments, the detector will be arranged as a double-sided TPC, with the actinide target in the middle, in order to detect both fragments in coincidence (fig. 1). The main advantage of this setup is its full angular coverage, leading to high detection efficiency. This has to be compared with a “standard” two-arm setup [10] which has an efficiency rarely higher than 10%. The TPC ionization products are detected by a Micromegas detector [3], which has been chosen because it has been proven to achieve very high space resolution, even at high rate, thanks to its fast ion evacuation provided by the presence of the micromesh. Moreover, Micromegas is quite insensitive to gammas and its material budget is very low, providing radiation hardness.

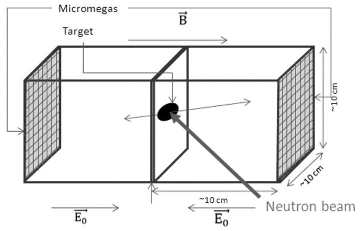

FIGURE 1. Sketch of the double-sided TPC detector for fission fragment measurement.

With the double-sided TPC, given the tracks of the two fragments and thanks to the presence of the magnetic field (and imposing momentum conservation of the two fragments), it is possible to extract the ion velocity and A/q, where A is the ion mass and q its ionic charge. Since the TPC dimensions are large enough to stop the ions, the total deposited energy will give a measurement of the fragment TKE (Total Kinetic Energy). Moreover, the nuclear charge of the fragment can be extracted by range measurement or ΔE-E correlation. One of the main difficulties comes from the fact that heavy ions at low energies show an evolving ionic charge along their path in the gas and, since the ion bending gives only access to A/q, it is necessary to know the ionic charge evolution in order to measure the ion mass. Although the project is in its early stage, a big effort has already been devoted both on simulation and prototyping.

Simulation: a GEANT4 benchmark

In order to make a full simulation of the detectors, given the presence of the magnetic field, the only suitable Monte-Carlo simulation code available on the market is GEANT4 [11]. This code, developed for high energy physics, has to be benchmarked in terms of energy loss, energy straggling and ionic charge evolution simulation. GEANT4 has been benchmarked against two other simulation codes, SRIM [12] and Lise++ [13], developed to correctly calculate the transport of heavy ions at low energy.

The energy loss, lateral straggling and range of fission fragments in different gases (helium, neon, argon) has been calculated with the three codes. As an example, the calculated range of four fragments (two light and two heavy) in helium and argon is showed in figure 2. The main result of this comparison is that the disagreement between GEANT4 and the other codes depends quite much on the gas type and on the ion mass but never exceeds 15%. Similar results are obtained looking at the energy loss and the lateral straggling, even for mixed gas like Ar-isobutane.

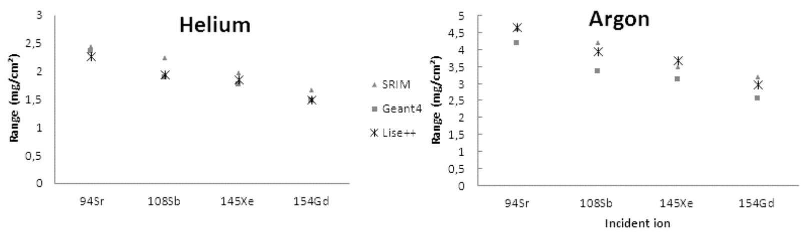

FIGURE 2. Range of 4 fission fragments in He and Ar calculated with GEANT4, SRIM and Lise++.

The calculation of the evolution of the ionic charge of the fission fragments in the gas has been performed with GEANT4 and Lise++. In fig. 3 the mean ionic charge as a function of the ion energy loss is showed for Sr-94 in argon. It can be seen that the GEANT4 calculation is fully incompatible with the Lise default model. On the other hand, in the Lise code one can choose on several models depending on the ion energy and on the target type. In particular, the Shima model [14] has been chosen to be the most able to fit experimental data on fission fragment ionic charge evolution in noble gases. This model has been integrated in GEANT4 and will be used as default for the completion of the TPC simulation.

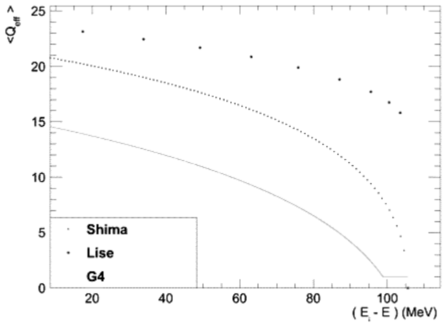

FIGURE 3. Mean ionic charge of Sr-94 in Ar as a function of its energy loss calculated with GEANT4, Lise (default model) and Shima model [14].

These results validate the use of GEANT4 for the simulation of the ion transport in the TPC gas and make possible the study of the tracking capabilities of the detector. On the other hand, GEANT4 has found to be unable to correctly simulate the electron production by primary and secondary ionization. Therefore, we have developed a stand-alone simulation code that can be linked to GEANT4 in order to simulate the electron production, drift and diffusion in gas. This code, based on a previous work developed by the Actar collaboration, provides the electron production from the ion energy losses at each interaction step and then calculates the electron drift and diffusion using the gas drift velocity and transverse diffusion coefficient calculated with the GARFIELD code [15]. Finally, the integrated charge is calculated at the anode, given a strip pitch or a pixel dimension and geometrical arrangement. Thanks to this code, the calculated charge will be compared to the results obtained during the test of a prototype (see next section) and will allow the optimization of the Micromegas readout granularity.

Test of a Micromegas TPC prototype

A TPC prototype has been built and tested with a Cf source but without magnetic field. The prototype was made of a 10x10x10 cm^3 drift box coupled with a Micromegas detector equipped with 96 strips in one dimension with a pitch of 250 μm (allowing an active area of only 2.5 cm). The TPC gas we used is a mixture Ar(90%)-Isobuthane(10%). The readout electronics is based on the After chip [16], developed for the TPC used by the T2K neutrino experiment, and provides the signal sampling with an adjustable frequency up to 50 MHz and a dynamical range of 2V coded on 12 bits. Despite the fact that the After FEE has been developed for MIP detection, the test results are very encouraging since, as can be seen in fig. 4, we could detect and code the signals from Cf spontaneous fission fragments and reconstruct tracks from the correlation between the time at maximum amplitude and the strip number. Moreover, no visible saturation has been observed on the whole energy and mass range. Therefore, we could measure the energy distribution of the fission fragments by summing the amplitudes of the signals associated to the identified tracks. One should take into account that, given the small active area of the prototype, only part of the fragment track could be detected.

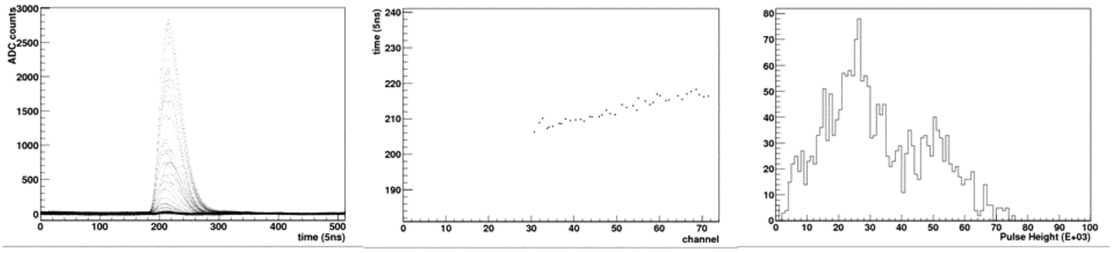

FIGURE 4. Time development of signals from Cf fission fragments (left). Correlation between time of signal and strip number (center). Distribution of the sum of signal amplitudes (right).

CONLUSIONS

A new R&D project of a Micromegas TPC for the full tracking and identification of heavy ions at low energy has started with a benchmark of the GEANT4 simulation code and a prototype test. The results are encouraging and the project will be pursued with the optimization of the detector granularity and its tracking and identification capabilities. Moreover, a test campaign of a 2D Micromegas TPC detector with a full active area is foreseen for the end of 2010 and a test in 8T magnetic field is foreseen for the beginning of 2011.

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