Fast neutron spectroscopy from 1 MeV up to 15 MeV with Mimac-FastN, a mobile and directional fast neutron spectrometer

N. Sauzet*, D. Santos, O. Guillaudin, G. Bosson, J. Bouvier, T. Descombes, M. Marton, JF. Muraz

Laboratoire de Physique Subatomique et de Cosmologie (LPSC) – Université Grenoble Alpes - CNRS/IN2P3 – 53, avenue des Martyrs, 38026 GRENOBLE cedex – France

Abstract

In the frame of direct dark matter search, the fast neutrons producing elastic collisions are the ultimate background. The MIMAC (Micro-tpc MAtrix Chambers) project has developed a directional detector providing the directional signature to discriminate them based on 3D nuclear tracks reconstruction. The MIMAC team of the LPSC has adapted one MIMAC chamber as a portable fast neutron spectrometer, the Mimac-FastN detector, having a very large neutron energy range (10 keV – 600 MeV) with different gas mixtures and pressures. The present paper shows its main features and functionality and demonstrates its potential in the energy range from 1 MeV to 15 MeV at the GENESIS neutron source facility of LPSC.

1 Introduction

In the frame of direct dark matter search, the fast neutrons producing elastic collisions on the nuclei of the active volume of the detector generate the same signals that an eventual WIMP (Weakly Interacting Massive Particle). These events as well as the neutrinons are the ultimate background for dark matter detection. In the frame of the MIMAC project (Micro-tpc MAtrix Chambers), a directional detector giving the directional signature to discriminate them [ref 1] has been developed. In such a way, the LPSC MIMAC team has explored the possibility to adapt one MIMAC chamber as a fast neutron spectrometer. Fast neutron spectroscopy is a challenge and required in many different domains, such as neutron dosimetry, identification of special nuclear material and nuclear physics. Some applications require measurements above 10 MeV and a large energy range. Among these applications, we can mention the secondary neutrons in radiotherapy, and the characterization of cosmic neutrons produced in the atmosphere by cosmic particles, going up to 100 MeV.

Neutron spectroscopy at high energies (above 1 MeV) is challenging for the present available detector technologies. Indeed, iterative moderation using neutron capture on converters leads to poor energy resolution and requires hypothesis on the expected neutron energy, the detection in solids through elastic collisions is limited due to the absorption of recoils in the converter, whereas detection in liquid scintillators results in a limited measuring range.

In the present paper, we describe the fast neutron spectrometer called Mimac-FastN, that tackles these issues for high neutron energies, based on the 3D detection of nuclear recoils becoming possible from a very fast sampled, self-triggered and low noise electronics developed at the LPSC [ref.3 and.4].

2 Detection principle

Mimac-FastN is a micro-TPC (Time Projection Chamber) based on a micro-pattern detector coupled to a fast self-triggered electronics [ref.1]. The chamber is filled with a gas that constitutes the converter of fast neutrons into charged particles. In the present paper, we describe the operation of Mimac-FastN with 2 liters of a gas mixture of 95 % of $^4$He and 5 % of CO$_2$ as a quencher, at 700 mbar, to measure neutron energies between 1 MeV up to 15 MeV. The gas mixture and the pressure can be modified depending on the application energy range [ref.11]. Fast neutron detection is performed through the tracking of the nuclear recoils that result from nuclear elastic scattering between incident fast neutrons and the gas nuclei. The nuclear recoils lose part of their kinetic energy by ionization in the detector gas. The primary electrons resulting from this ionization process are collected by an electrical field of 160 V/cm through a 25 cm long drift chamber, up to the micro-pattern detector (a square bulk Micromegas [ref.2] with a 512 µm gap, and sides of 10.8 cm). A high electrical field of 10.5 kV/cm between the grid and the anode of the Micromegas produces avalanches, that result in the signal amplification. Resulting secondary electrons are collected on the pixelated anode and the ions drifting toward the grid.

* Corresponding author: nadine.sauzet@lpsc.in2p3.fr
The Mimac-FastN electronic board [ref.3] manages two synchronized types of data. The first one is the energy released in ionization by the nuclear recoil, read through a charge preamplifier connected to the mesh of the micro-pattern detector. This preamplifier, developed at LPSC, has a gain of about 100 mV/pC (that is adjustable depending on the energy range required), and a time constant of 2 ms so that the rise time of the signal is small compared to the electronic decay time. The second type of data is the fired strips of pixels on the anode of the micro-pattern detector (512 strips, 256 in X and 256 in Y), which gives access to the 2D position of the charges.

The data on the grid and on the pixelated anode are read out at a sampling frequency of 40 or 50 MHz, depending on the length of tracks to be produced, and managed by the electronic board. In this way, each nuclear recoil track is sliced into samples. In the gas mixture, He/CO₂ (5%) at 700 mbar and at 40 MHz sampling, each sample has a perpendicular component to the anode of 241 μm (referring to a Magboltz simulation that gives a drift velocity of 9.65 μm/ns in this gas mixture, which leads to a length of 9.65 μm/ns x 25 ns). So the 3D nuclear recoil track is reconstructed thanks to the composition of the 2D picture on the pixelated anode, and the perpendicular component inferred from the electronic sampling.

The electronic board is coupled to the micro-pattern detector through an interface board that ensures the chamber tightness. This very low noise electronic board manages itself the triggering of each event acquisition through a FPGA. The acquisition triggering is done from the signal on the grid requiring a ionization energy threshold. Once triggered, the acquisition window remains open 25 μs at maximum.

The synchronization of the readout on the grid (ionization energy) and the readout on the pixelated anode (track data) is managed by the FPGA. The sampling time is the same for the pixelated anode reading, and for the charge profile on the grid. The two different types of information being the track coordinates and the deposited charges can then be synchronized for each time-slice.

The pixelated anode readout is performed by the 8 MIMAC ASICs, specifically developed by the MIMAC team of the LPSC [ref. 4].

A dedicated software controls the FPGA through a USB connection, and stores the data event by event in a text file or in a PostgreSQL database.

Analysing the event-by-event sampled data from the grid and the pixelated anode, the kinetic energy of the incident neutron can be measured.

The neutron kinetic energy is deduced from the kinetic energy of the nuclear recoil by the following equation:

\[ E_n = \left(1 + \frac{m_R}{m} \right)^2 \times \frac{E_R}{\cos^2(\theta_{RN})} \]

being \( E_n \) the incident neutron energy, \( E_R \) the kinetic energy of the nuclear recoil, \( \theta_{RN} \) the angle between the nuclear recoil track and the incident neutron direction, and \( m \) the nuclear recoil mass.

The kinetic energy of the nuclear recoil is determined from the measured ionization energy, corrected from the ionization quenching factor ([ref.7] and [ref.8]) in the considered gas mixture.

The angle \( \theta_{RN} \) is estimated from the 3D recoil track reconstruction, and from the neutron emitter position that gives the incident neutron direction (see Figure 1).

![Figure 1: Drawing of the detector structure at the top, and picture of Mimac-FastN at the bottom.](image)

3 GENESIS facility

Spectroscopy of the neutrons produced by the reactions D(d(220 keV,n)) and T(d(220 keV,n)) has been explored at the GENESIS facility [ref.9], with Mimac-FastN, for neutron mono-energetic measurements at 3 MeV and 15 MeV. A picture of the facility with the experimental set-up can be seen on Figure 2.

The GENESIS facility is enclosed by a concrete bunker.
4 Special features of nuclear elastic collisions with neutrons above 3 MeV

The angular distributions of the $^4$He recoils, resulting from elastic diffusions with fast neutrons, is a function of the neutron energy. Angular distributions in the laboratory frame have been calculated with the Monte Carlo code Geant 4 [ref. 5], version 10.10.01, with the physics list QGSP_BERT_HP_LIV, and a chamber filled with a gas mixture of $^4$He/CO$_2$ (5%) at 700 mbar (see Figure 3).

These angular distributions show that for neutron energies above 3 MeV, angles above 60° are more likely. This has two implications. The first one is that the most probable kinetic energy of the $^4$He recoil is 1.1 MeV for a neutron of 15 MeV. In a mixture of $^4$He/CO$_2$ (5%) at 700 mbar, a recoil track with this kinetic energy is 3.3 cm long according to SRIM [ref. 6], and so remains contained in the drift volume as described previously. From these simulations, we deduce that above 3 MeV, the higher the neutron energy is, the smaller the recoil track will be.

The second consequence is that a 3D geometry is required to detect recoils for neutron energies above 3 MeV. The advantage of a gaseous detector like Mimac-FastN with a cylindrical or cubic symmetry geometry, is that recoils can be detected whatever their direction is. The pixelated anode could represent a limitation, if the nuclear recoil tracks are parallel to this plane, since in this case, the 3rd dimension calculated by the electronic sampling will be limited to a few samples. However, knowing the position of the neutron emitter, the chamber can be orientated perpendicularly to the mean emission direction. In such a configuration, if the $\theta_{\text{rel}}$ angles are above 60°, the tracks' orientations are optimized compared with the anode plane (see Figure 4).

5 Nuclear recoil track direction

With a time sampling of 25 ns, Mimac-FastN gives access to a high resolution profile of the charges deposited in ionization as a function of time, for each event. The Figure 5 shows an example of such a charge profile lasting 300 timeslices, each bin (timeslice) having a width of 25 ns.
Figure 5: Charge profile integration on the grid of an $^4$He recoil, resulting from an elastic diffusion with a neutron of 15 MeV. This profile is composed of 300 time samples of 25 ns collected in the time range of 7.5 µs.

At energies below 1 MeV for $^4$He, the Bragg peak is located in the first half of the track. In such a way, a symmetry analysis of the charge profile, compared with its middle point in amplitude, can be performed as illustrated in Figure 6, in order to find the Bragg peak location for which the maximum number of primary electrons have been produced.

Figure 6: Definition of risetimes 1 and 2 on the charge profile of an $^4$He recoil.

The comparison of risetime$_1$ and risetime$_2$ measurements constitutes an observable to define the track direction. The Figure 7 shows a plot of risetime$_2$ as a function of risetime$_1$ for $^4$He recoils from elastic diffusions with neutrons of 3 MeV, in a perpendicular configuration of the beam. This plot reveals two distinct branches that are assigned to each track direction.

Figure 7: Comparison of risetime$_1$ and risetime$_2$ measurements for $^4$He recoils resulting from elastic diffusions with neutrons of 3 MeV, in a perpendicular configuration with respect to the beam.

The Figure 8 shows the first and last pixels of the tracks projected on the pixelated anode, for the selection of the lower branch of the plot of risetime$_2$ as a function of risetime$_1$, assigned to the tracks directed towards the anode. The Figure 9 shows the same plots for the selection of the upper branch, assigned to the tracks directed towards the cathode.

Figure 8: Position of the first and last point of the $^4$He recoil tracks, projected on the pixelated anode, for the tracks directed towards the anode.
For the tracks directed towards the cathode

![Neutron emitter]

Figure 9: Position of the first and last point of the $^4$He recoil tracks, projected on the pixelated anode, for the tracks directed to the cathode.

It can be seen on Figure 8 and Figure 9 that the coordinates of the extremity points of the $^4$He recoil tracks are consistent with the position of the neutron emitter and the forward scattering of the nuclear recoil, whether the recoil is directed towards the cathode or the anode. For the selection of the events directed towards the cathode, the interaction point (first point of the track) is the first time-slice read on the anode, whereas for events directed towards the anode, the first time-slice read on the anode corresponds to the last point of the nuclear recoil track.

The measured ionization energy loss per time-slice can be related to the measured nuclear recoil path length per time-slice, through the synchronization of the readouts on the grid and on the pixelated anode. It means that the Bragg peak time-slice can be found for each event.

The temporal position of the Bragg peak is plotted on Figure 10 for, on the one hand, tracks directed towards the anode, and on the other hand, towards the cathode. This plot represents, for each event, the time-slice for which the Bragg peak is reached, normalized to the charge collection duration, as read on the anode.

For the tracks directed towards the cathode, the Bragg peak is located at 40% of the time development of the track on average. For the tracks directed towards the anode, it is located at 60% on average in the reading direction on the anode, so at 40% from the track interaction point.

![Time slice Bragg peak / Event duration (percent)]

Figure 10: Position of the Bragg peak for $^4$He recoils resulting from elastic diffusions with neutrons of 3 MeV issued from D(d(220 keV),n) on GENESIS, for tracks directed towards the anode or the cathode.

A dedicated paper on this head-tail MIMAC measurement of nuclear recoil tracks will be published shortly.

### 6 Energy calibration

The charge profile is measured through a charge preamplifier connected to the mesh and sent to a Flash-ADC (on the electronic board) that digitizes the signal on 4096 channels. The Flash-ADC energy calibration is done through a natural boron coating fixed on the cathode and by means of the following capture reaction of thermal neutrons by the $^{10}$B isotope:

\[
\begin{align*}
  n + ^{10}B & \rightarrow ^4He + ^7Li + \gamma \quad (94\%) \\
  n + ^{10}B & \rightarrow ^4He + ^7Li \quad (6\%)
\end{align*}
\]

The boron coating consists in an IBS (Ion Beam Sputtering) deposit of 500 nm of $^{10}$B$_2$C on an aluminum sheet (see picture in Figure 11). The $^{10}$B isotope represents 20% of the natural boron. The coating has a specific shape in order to check the spatial resolution of the boron projection picture on the anode.

The energies deposited in ionization by the $^4$He and $^7$Li particles are measured on the Flash-ADC, and their tracks are imaged on the pixelated anode.

Figure 11 shows the anode projection of the detector exposed to a 3 MeV neutron field crossing 5 cm of high density polyethylene. The projection on the anode of the first point of all the tracks directed towards the anode, highlights the boron coating, due to neutron captures, that become predominant with respect to the total elastic diffusions on the gas nuclei, at low energies. The presence on this picture of the specific shape of the boron corner proves the
uniformity of the electrical field lines in the field cage and gives an estimation of the spatial resolution.

Figure 11: on the left, picture of the B4C coating used for energy calibration and spatial resolution measurements; on the right, projection on the pixelated anode of the first point of all the tracks, that highlights the boron shaped coating, in a neutron beam of 3 MeV moderated through 5 cm of HDPE.

A selection of all the tracks whose interaction points are located on the boron coating projection, leads to the energy spectrum of the particles issued from neutron captures on $^{10}$B, as presented on Figure 12. This measured spectrum can be compared to the ionization energy spectrum calculated with Geant 4, on Figure 13.

Figure 12: Measured ionization energy spectrum of the $^4$He and $^7$Li particles resulting from neutron captures on the boron coating, in a neutron beam of 3 MeV moderated through 5 cm of HDPE.

Figure 13: Simulated ionization energy spectrum of the $^4$He and $^7$Li particles resulting from neutron captures on the boron coating.

The Geant4 simulation embeds an ionization quenching factor, that is defined as the amount of ionization energy deposited by the particle, compared to its kinetic energy ([ref. 7], and [ref. 8]). In the energy ranges considered above, the mean ionization quenching factor considered by the GEANT4 simulation is 97.5 % for $^7$Li, and 98.8 % for $^4$He. These values will have to be checked by measure, and will be the object of a future paper.

The energy calibration of the Flash-ADC can be done comparing the simulation with the measurements taking into account the end-points or the mean peak values of the peaks issued from the branching ratio of 94 %. The peak issued from the alpha particle emitted in the case of a branching ratio of 6 % constitutes a checkpoint of the calibration equation. More details on this calibration energy will be done in a dedicated paper.

7 Discrimination of species and physical process

Elastic diffusions can occur on all the gas nuclei constituting the gas chamber, so recoils of $^4$He, $^{12}$C and $^{16}$O are detected. Besides, fast neutrons can interact with all the structures being part of the detector, mostly composed of aluminum, Kapton, PMMA and copper.

7.1 Fast neutrons on aluminum

Aluminum is the material of the ionization chamber.

On $^{27}$Al, fast neutrons can produce (n,p) and (n,α) reactions, respectively above 1.8 MeV and 3.1 MeV. For neutrons of 15 MeV, the cross-sections of these reactions are roughly 0.06 barn and 0.1 barn respectively, and protons are emitted with an energy up to 12.7 MeV, while alphas with an energy up to 10.2 MeV can be produced. These alpha particles are all absorbed by the materials crossed before
reaching the gaseous active volume (cathode and field cage), whereas protons having a residual energy are detected in the active volume.

7.2 Fast neutrons on Kapton and PMMA

Kapton and PMMA are components of the field cage that define the drift field and the active gaseous volume.

On Kapton and PMMA, fast neutrons can interact through elastic diffusion with hydrogen, or through inelastic (n,p) and (n,α) reactions.

Elastic diffusions on hydrogen have a cross section of 0.6 barn for neutrons of 15 MeV.

(n,p) reactions mainly occur on $^{16}$O and $^{14}$N for neutron energies above 9.6 MeV and 0.6 MeV respectively. For neutrons of 15 MeV, cross sections of such reactions are roughly of 0.04 barn, and protons are emitted with energies up to 5.08 MeV and 13.4 MeV. Then, proton recoils or protons issued from nuclear reactions can be detected in the gaseous active volume.

(n,α) reactions mainly occur on $^{12}$C, $^{16}$O and $^{14}$N, for neutron energies above 5.7 MeV, 2.2 MeV and 0.2 MeV respectively. For neutrons of 15 MeV, cross sections of such reactions are respectively of 0.05 barn, 0.14 barn and 0.08 barn, and alpha particles are released with energies up to 6.4 MeV, 9.8 MeV and 10.9 MeV. These alpha particles issued from nuclear reactions can be detected in the gaseous active volume.

All these particles leave some energy in the Kapton or the PMMA itself, before being released in the gaseous active volume. The specificity of all these particles is that they are emitted on the edges of the active volume, and as such, they can be discriminated by analysis of their projected track on the pixelated anode.

7.3 Fast neutrons on copper

Copper is the cathode material as well as a component of the field cage.

On $^{63}$Cu (69 % of natural copper), fast neutrons can produce inelastic (n,p) and (n,α) reactions, above 0.7 MeV and 1.7 MeV respectively. For neutrons of 15 MeV, the cross-sections of these reactions are 0.06 barn and 0.04 barn respectively, and protons are emitted with an energy up to 14 MeV, while alphas with an energy up to 12.5 MeV. All these particles can release their energy partially or totally in the active volume.

7.4 Summary of the main interactions with the detector structures, for neutrons of 15 MeV

| Interaction process | Max energy of the product | Major contribution |
|--------------------|----------------------------|-------------------|
| Aluminium (n,p)    | 12.7 MeV                   |                   |
| Kapton and PMMA    | (n,p) 13.4 MeV              | 10.9 MeV          |
|                    | (n,α) 15 MeV                | X                 |
| Copper             | (n,p) 14 MeV                | 12.5 MeV          |

7.5 Track length as a function of ionization energy

In our approach to calculate the neutron energies, we consider the $^4$He recoils only. So all the other recoil species and the contributions of nuclear reactions have to be discriminated. By means of the electronic synchronization of the pixelated anode with the grid, we can plot each event track length as a function of its energy deposited in ionization in the gaseous active volume. We performed both simulations and measurements of these distributions, as shown in the next paragraphs.

7.5.1 Simulations with Geant 4

The two-dimensional graph (track length as a function of ionization energy) opens the field to the discrimination of the different physical process, as can be assessed by the result of simulations with Geant 4, of Mimac-FastN in a beam of mono-energetic neutrons of 15 MeV, on Figure 16 and Figure 18 (associated respectively to the geometry configurations of Figure 14 and Figure 15).

Figure 14 : Mimac-FastN geometry modeled with Geant 4, in a configuration parallel to the mean beam emission.

Figure 15 : Mimac-FastN geometry modeled with Geant 4, in a configuration perpendicular to the mean beam emission.
Figure 16: Simulation of the track lengths as a function of ionization energy, with Mimac-FastN modeled with Geant 4, in a configuration parallel to the mean beam emission, with neutrons of 15 MeV.

On this two-dimensional plot resulting from simulation, different structures emerge, that are assigned as follows:

**Branch A**: protons issued from Kapton, PMMA, aluminum and copper, that do not release all their energy in the active volume, because their track lengths are much higher than the field cage length. This branch is broad because the length related to the energy deposited depends on the initial energy of the proton and the Bragg peak position.

**Branch B**: protons issued from Kapton and PMMA, that release all their energy inside the active volume.

**Branch C**: $^4$He recoils with a kinetic energy of more than 10 MeV that are scattered in a head-on collision along the longitudinal chamber axis (perpendicular to the pixelated anode), that release little energy in the gaseous volume with long path length, since the stopping power is small at the beginning of the recoil travel inside the gas (the Bragg peak is at the end of the track). See Figure 17 for a focus on these $^4$He recoils.

**Structure D**: $^4$He recoils of low energy that release part of their energy in the active volume before going outside.

**Branch E**: $^4$He recoils that release all their energy in the active volume.

**Branch F**: $^{12}$C and $^{16}$O recoils that release all their energy in the active volume.

Given the good separation of all these branches characterizing different physical process and nuclear recoil masses, we can easily select the branch E ($^4$He recoils) that is the main branch of interest for neutron energy measurements discriminating all the other ones. Only the directional information gives the possibility to discriminate them.

The two-dimensional plot of Figure 18 in the perpendicular configuration shows that the structure with multiple branches associated to different physical process is similar to the one obtained in the parallel configuration. The main difference concerns the branch C that is not observed in the perpendicular configuration: the $^4$He recoils scattered with a small diffusion angle go outside of the active volume in parallel to the anode, and are then discriminated. In the parallel configuration, the track lengths are longer, which is consistent with the size of the field cage (10.8 x 10.8 x 25 cm).

Simulations show that by means of 3D tracks synchronized with the ionization energy measurement, the neutron spectrometer Mimac-FastN presents an excellent ability to identify and discriminate different nuclear recoil species even those that do not remain fully contained inside the ionization active volume.

Figure 17: Focus on the simulation of the track lengths of $^4$He recoils as a function of ionization energy, in a configuration parallel to the mean beam emission, with neutrons of 15 MeV.

Figure 18: Simulation of the track lengths as a function of ionization energy, with Mimac-FastN modeled with Geant 4, in a configuration perpendicular to the mean beam emission, with neutrons of 15 MeV.
### 7.5.2 Measurements with 15 MeV neutrons

Measurements have been performed with Mimac-FastN at the GENESIS facility [ref.9] with the reaction T(d(220 keV), n), that results in the production of neutrons of 15 MeV at 0°. The set-up of the experiment is described in § 9 and 10.

Figure 19 shows the measured track lengths as a function of ionization energy for all the events detected. We observe on this plot the same structure as the one obtained by simulation, which allows the attribution of the measured branches to the physical process and species. The main $^4$He recoil branch is easily differentiable (branch E).

We have performed a measurement in the same conditions, with the chamber rotated of 90°, and so placed perpendicularly to the mean beam direction. Figure 20 shows the measured track lengths as a function of ionization energy in this second configuration.

![Figure 19: Measured track lengths as a function of energy, in a configuration parallel to a neutron beam of 15 MeV produced by the reaction T(d(220 keV),n) at GENESIS facility.](image)

![Figure 20: Measured track lengths as a function of energy, in a configuration perpendicular to a neutron beam of 15 MeV produced by the reaction T(d(220 keV),n) on GENESIS, for tracks directed toward the anode or the cathode.](image)

These two plots show the same structure and are fully consistent with the simulated plots, which proves the good track reconstruction whatever the orientation of the detector configuration compared to the mean beam axis.

The measured events showed on branch A attributed as the energetic protons going outside the active volume have a particularity compared to $^4$He recoils tracks on branch E: the tracks on the pixelated anode present many holes, whereas $^4$He tracks do not show this type of feature, as seen on Figure 21 for protons and Figure 22 for $^4$He. These holes are due to the low ionization energy deposited per time-slice (on average, 1.5 keV/25 ns (time-slice) for a proton of 400 keV) that is not enough to trigger all the strips of pixels that have a threshold defined individually as a function of their intrinsic noise. For comparison, a $^4$He of 400 keV deposits 8.5 keV/25 ns (time-slice) on average.

![Figure 21: A 400 keV proton recoil track issued from an elastic diffusion with a neutron of 15 MeV produced by the reaction T(d(220 keV),n) on GENESIS.](image)

![Figure 22: A 400 keV $^4$He recoil track issued from an elastic scattering with a neutron of 15 MeV produced by the reaction T(d(220 keV),n) at the GENESIS facility.](image)
8 Data analysis strategy

8.1 Gamma – neutron rejection

Compton electrons resulting from the interaction of few MeV gamma rays with the detector structures lose 70 keV at most in the Mimac-FastN gaseous active volume, as attested by a simulation with Geant 4 (see Figure 23).

The minimum ionization energy that can be detected is determined by the noise level on the grid of the micro-pattern detector. This lowest ionization energy threshold is 25 keV with the usual Mimac-FastN set-up. So referring to simulation, above 25 keV, we only have a residual of 0.3 % of electrons. The energy loss per time-slice of these electrons is so low (0.06 keV/time-slice on average) that measures lead to a similar phenomenon as the one observed for protons: the energy deposited by these electrons is not enough to trigger the strips of pixels, and so these events do not leave dense and clear tracks in the active volume being easily discriminated. However, the energy of all these events is measured on the grid of the micro-pattern detector, as shown on the profile on Figure 24, that has a typical signature with a charge deposit by clusters, compared to the energy profile of a nuclear recoil that is continuous with time (Figure 25).

A selection of the events that leave clear and dense tracks in the gaseous active volume represents an excellent discrimination of the events coming from the nuclear recoils produced by elastic diffusions with fast neutrons with respect to those resulting from electrons produced by gamma rays interactions [ref.12].
8.2 Selection of tracks produced in the gaseous active volume

As shown previously by Geant 4 simulations (cf. § 7.5.1), some nuclear recoil tracks go outside of the gaseous active volume, or enter to this volume when the particles are emitted from the chamber or field cage walls. All these tracks projected on the anode have the specificity to hit the edges of the pixelated anode, which creates an over-density of events on the volume periphery (see Figure 26). These events can be rejected in setting a condition on the coordinates of the first step of the track, in order to discriminate the anode periphery.

Figure 26: First step projection on the anode of nuclear recoils' tracks, resulting from elastic diffusions with neutrons produced by the reaction T(d(220 keV),n) on GENESIS.

8.3 Selection of $^4\text{He}$ recoils

The $^4\text{He}$ branch (E) has to be selected to reject protons, $^{12}\text{C}$ and $^{16}\text{O}$. Besides, we have to reject $^4\text{He}$ that go outside of the active volume along the chamber longitudinal axis, since they are not reliable for the neutron spectrum calculation, because of their incomplete track and energy released in the active volume.

All these discriminations are based on the analysis of the energy released in ionization normalized to the recoil track length as a function of ionization energy, as shown in Figure 27.

Figure 27: Measurement with Mimac-FastN in a perpendicular configuration, of the ionization energy normalized by the track length as a function of ionization energy, for nuclear recoils resulting from elastic diffusions with neutrons produced by the reaction T(d(220 keV),n) at GENESIS facility. This plot was drawn after discrimination of tracks going outside of the active volume through its lateral limits and rejection of tracks with holes (with more than 1% of empty timeslices).

Compared to Figure 20, branch A does not appear on this plot, since its related proton tracks go outside of the volume and have characteristics of density that lead to their discrimination. Structure D is constituted of $^4\text{He}$ recoils that go outside of the volume along the chamber longitudinal axis. Branch F is the branch that aggregates $^{12}\text{C}$ and $^{16}\text{O}$ recoils. A new branch emerges from the enhancement due to the normalization with the track length, branch G, that is constituted of CO recoils, that have track lengths of roughly 5 mm for a released ionization energy of 250 keV. The Figure 28 shows such a track of CO recoil. These CO molecules can have for origin a dissociation of the CO$_2$ molecules by the ionizing radiation inside the chamber during the measurements.

Figure 28: A 250 keV CO recoil track resulting from an elastic diffusion with a neutron produced by the reaction T(d(220 keV),n) at GENESIS.
Some of these molecular recoils are split along their path.

A fit of the main $^4$He recoil branch (branch E) is done to keep only recoils useful to the neutron spectrum reconstruction.

9 Measurement results from D(d(220)keV,n)

Spectroscopy of the neutrons produced by the reaction D(d(220 keV,n) has been performed at the GENESIS facility [ref.9], with Mimac-FastN placed at 0° degree with respect to the deuteron beam axis. In this configuration, the D(d(220 keV,n) nuclear reaction produces neutrons of 3.1 MeV.

The target is a solid target, composed of titanium loaded with deuterium, and evaporated on a 3 mm thick copper backing [ref.10]. The measurement has been done in one hour, with a deuteron current of 100 µA, in the configuration with the longitudinal axis of the detector perpendicular to the beam axis. The detector was positioned at 1 meter from the target. In this directional measurement, we consider the target location as the neutron source position. The spectrometer Mimac-FastN was filled with a gas mixture of 95 % of $^4$He and 5 % of CO$_2$ at 700 mbar.

Fast neutrons can be scattered on the concrete walls of the bunker. All the discriminations presented previously have been applied on the data, and the degrees of freedom brought by the 3D geometry have been explored to discriminate part of these scattered neutrons on the walls of the facility, and finally to reconstruct the neutron energy spectrum, plotted on Figure 30.

The measured neutron spectrum reveals a polyenergetic spectrum with 4 structures. This is explained by the target composition and the interaction of deuterons with all the components of the target.

The peak A is the expected production of neutrons of 3.1 MeV resulting from the reaction D(d(220 keV,n). The shoulder B is produced by neutrons resulting from $^{63}$Cu(d,n)$^{64}$Zn and $^{65}$Cu(d,n)$^{66}$Zn with energies between 5.5 MeV and 6.8 MeV, and from $^{48}$Ti(d,n)$^{49}$V with energies around 4.5 MeV. The shoulder C results from $^{64}$Zn(d,n)$^{65}$Ga with energies around 1.8 MeV. The structure D is a contribution of the residual scattered neutrons on the walls of the accelerator bunker.

These measurements reveal that cross sections of low energy deuterons on copper and zinc are not negligible, despite the lack of data reported in the literature on this subject. This measured neutron spectrum is associated to the measured angular distribution of $^4$He recoils related to the incident neutron direction. This measured angular distribution is presented in Figure 31 and shows the same feature as the simulated distribution given by Geant 4 in Figure 3, namely, a higher probability of elastic scattering between 50° and 75°, which confirms the Geant4 simulation features.
10 Experimental results with T(d(220)keV,n)

In the same facility and with the same experimental set-up, spectroscopy of the neutrons produced by the reaction T(d(220 keV,n) has been performed. At 0° degrees with respect to the deuteron beam axis, the T(d(220 keV,n) nuclear reaction produces neutrons of 15.1 MeV.

The target has the same structure as the one described previously with the deuterium loading replaced by a tritium loading.

The measurement has been done in 1 hour, with a deuteron current of 5 µA. The neutron spectrometer longitudinal axis is perpendicular to the beam axis. It is located at 1.7 meters from the target, and the gas mixture is the same as the one used for the reaction D(d(220 keV,n) experiment. See Figure 2 for a picture of the experimental set-up.

The Figure 32 shows the reconstructed neutron spectrum.

As in the precedent experiment, a polyenergetic spectrum is observed.

The peak A is the expected production of neutrons of 15.1 MeV resulting from the reaction T(d(220 keV,n). The peak B is populated by neutrons resulting from $^{63}$Cu(d,n)$^{64}$Zn, $^{65}$Cu(d,n)$^{66}$Zn and $^{48}$Ti(d,n)$^{49}$V. The peak C results from D(d,n) reactions following the implantation of part of the incident deuterons into the target backing. The peak D is a contribution of the residual scattered neutrons on the walls of the accelerator bunker.

This neutron spectrum is associated to the angular distribution of $^4$He recoils related to the incident neutron direction. This angular distribution is presented in Figure 33, and shows the same feature as the simulated distribution given by Geant 4 in Figure 3, namely, a higher probability of emission of the $^4$He recoil around 70°.

11 Conclusion

In the present paper, we have described the ability of Mimac-FastN to measure mono-energetic neutron spectra at 3 MeV and 15 MeV. Using the same gas mixture, with a threshold on the neutron energy as low as 200 keV, this directional fast neutron spectrometer gives a complete polyenergetic neutron spectrum exploring the material and eventual pollutions of the target or neutron sources.

This ability to provide polyenergetic neutron spectrum has already been applied to characterize...
the angular distribution of fast neutrons produced in a nuclear reaction proposed for a radiotherapy called Accelerator-Based Boron Neutron Capture Therapy (AB-BNCT) [ref.13].

With its high spatial resolution 3D track reconstruction associated with its large adjustable measuring range, Mimac-FastN is a versatile instrument that opens new fields for directional neutron spectrometry, for applications such as nuclear matter characterization, detection of target pollution, nuclear cross section measurements or monitoring the neutron production for radioprotection purposes.

Besides this study, preliminary measurements performed at CERF (CERN) [ref.14] with this instrument have recently shown a good potential for spectrometry at neutron energies as high as 200 MeV, a range covering atmospheric neutron production and high energy neutron monitoring.

12 Acknowledgments

This work has been funded by the “Prematuration” program of CNRS, by the LabEx Enigmass, and by Linksium SATT (Technology Transfer Accelerator Office).

We thank the LPSC accelerator team for the operation of the GENESIS facility labeled CNRS for their support during all the performed experiments.

References

[1] D. Santos et al., “MIMAC: A micro-TPC for directional detection of dark matter”, EAS Publications Series, vol. 53, pp. 25-31, 2012.

[2] I. Giomataris et al., “Micromegas in a bulk”, NIM A, vol. 560, pp. 405-408, 2006.

[3] O. Bourrion et al., “Data acquisition electronics and reconstruction software for real time 3D track reconstruction within the MIMAC project”, JINST 6 C11003, 2011.

[4] J. P. Richer et al., “Development of a front end ASIC for Dark Matter directional detection with MIMAC”, NIM A, vol. 620, pp. 470-476, 2006.

[5] S. Agostinelli et al., “GEANT4, a simulation toolkit”, NIM A, vol. 506, pp. 250-303, 2003.

[6] J.F. Ziegler and J.P. Biersack, SRIM - The Stopping and Range of Ions in Matter (Pergamon Press New York, www.srim.org, 1985).

[7] D. Santos et al., “Ionization Quenching Factor Measurement of $^4$He”, arXiv:0810.1137v1, Oct. 2008.

[8] O. Guillaudin et al., “Quenching factor measurement in low pressure gas detector for directional dark matter search”, EAS Publications Series, vol. 53, pp. 119-127, 2012.

[9] GENESIS facility: http://lpsc.in2p3.fr/index.php/fr/plateformes-technologiques/peren-energie-nucleaire

[10] C. Monnin et al., “Characterization of deuteride titanium targets used in neutron generators”, NIM A, vol. 453, pp. 493-500, 2000.

[11] D. Maire et al., “Neutron energy reconstruction and fluence determination at 27 keV with the LNE-IRSN-MIMAC microTPC recoil detector”, IEEE transactions on Nuclear Science, 63(3): 1934-1941, June 2016.

[12] Q. Riffard et al., “MIMAC low energy electron-recoil discrimination measured with fast neutrons”, JINST, August 2016, Vol.11 Issue 8, p1-1.

[13] M.E Capoulat, N. Sauzet et al., “Neutron spectrometry of the $^9$Be(d(1.45 MeV),n)$^{10}$B reaction for accelerator-based BNCT”, NIM B, vol.445, pp 57-62, 2019

[14] A. Mitaroff, M. Silari, “The CERN-EU high-energy reference field (CERF) facility for dosimetry at commercial flight altitudes and in space”, Radiation Protection Dosimetry, vol.102, n°1, pp 7-22, 2002