Neutron spectroscopy from 1 to 15 MeV with Mimac-FastN, a mobile and directional fast neutron spectrometer and an active phantom for BNCT and PFBT

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Abstract. In the frame of direct dark matter search, the fast neutrons producing elastic collisions on the nuclei of the active volume are the ultimate background. The MIMAC (MIcro-tpc MAtrix Chambers) project has developed a directional detector providing the directional signature to discriminate them from the searched events based on 3D nuclear tracks reconstruction. The MIMAC team of the LPSC has adapted one MIMAC chamber as a mobile fast neutron spectrometer, the Mimac-FastN detector, having a wide neutron energy range (10 keV – 600 MeV) working with different gas mixtures and pressures. This presentation will be focused on the MeV range with ^{4}He + 5% CO_2 gas mixture at 700 mbar. A boron coating inside the active volume used for calibration purpose opens the possibility to use the active volume as an active phantom for Boron Neutron Capture Therapy (BNCT) and Proton Fusion Boron Therapy (PFBT).

1. Introduction

To perform a fast neutron spectroscopy without a time flight measurement or without many ^{3}He counters is a real challenge and required in many different domains, such as neutron dosimetry, identification of fissile nuclear material and nuclear physics in general. 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.

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 [1]. The chamber is filled with a gas that constitutes the converter of fast neutrons into nuclear recoils able to ionize the gas in the active volume. In the present paper, we describe the operation of Mimac-FastN with 2 litres 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 [11,12]. 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 [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, which result in the signal amplification. Resulting secondary electrons are collected on the pixelated anode and the ions drifting toward the grid.

The Mimac-FastN electronic board [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 in samples. In the gas mixture ^{4}He/CO_2 (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 pixelated anode readout is performed by the 8 MIMAC ASICs, specifically developed by the MIMAC team of the LPSC [4].

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

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

$$E_n = \frac{(1+m_R)^2}{4m_R} \times \frac{E_R}{cos^2(\theta_{RN})}$$

being E_n the incident neutron energy, E_R the kinetic energy of the nuclear recoil, θ_{RN} the angle between the nuclear recoil track and the incident neutron direction, and m_R the nuclear recoil mass.

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

The angle θ_{RN} is estimated from the 3D recoil track reconstruction, and from the neutron emitter position that gives the incident neutron direction, see figure 1.

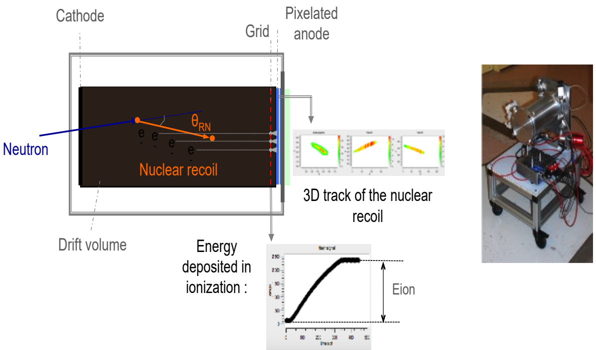

Fig. 1: Drawing of the detector principle at the left, and picture of Mimac-FastN at the right

3. 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:

$$n + {}^{10}_{5}B \rightarrow {}^{4}_{2}He + {}^{7}_{3}Li + \gamma \quad (94\ \%)$$

$$n + {}^{10}_{5}B \rightarrow {}^{4}_{2}He + {}^{7}_{3}Li \quad (6\ \%)$$

The boron coating consists of an IBS (Ion Beam Sputtering) deposit of 500 nm of $^{nat}B_4C$ on an aluminum sheet, see picture in figure 2 (left). 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.

The figure 2 (right) shows the anode projection of the detector exposed to a 3 MeV neutron field crossing a 5 cm thickness moderator of high density polyethylene (HDPE). 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 scatterings 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.

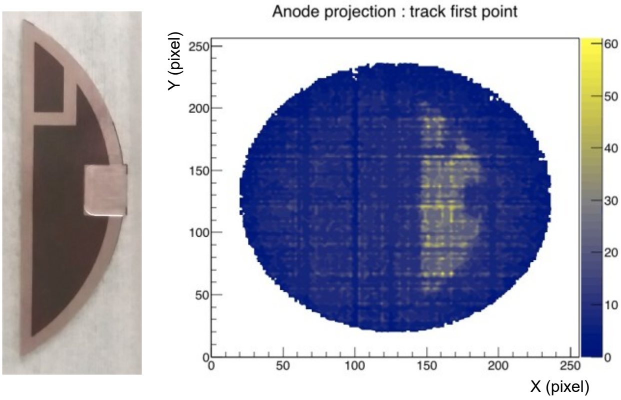

Fig. 2 : On the left, a picture of the B_4C coating used for energy calibration and spatial resolution measurements ; on the right, projection on the pixelated anode of the first point of all the tracks, that highlights the boron shaped coating, in a neutron beam of 3 MeV moderated through 5 cm of HDPE.

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 in figure 3. This measured spectrum can be compared to the ionization energy spectrum calculated with Geant 4, shown in figure 4.

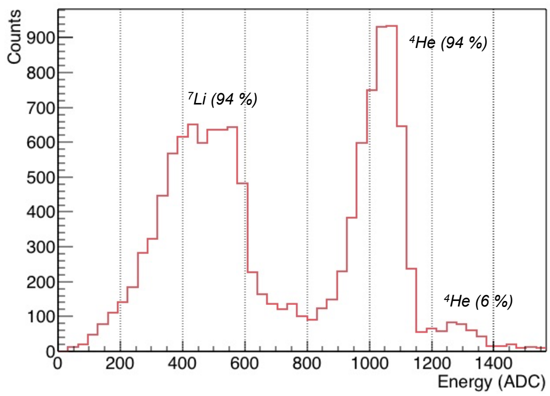

Fig. 3: Measured ionization energy spectrum of the ^{4}He and ^{7}Li particles resulting from neutron captures on the boron coating, in a neutron beam of 3 MeV moderated through 5 cm of HDPE.

The Geant4 simulation embeds an ionization-quenching factor, which is defined as the amount of ionization energy deposited by the particle, compared to its kinetic energy ([7] and [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.

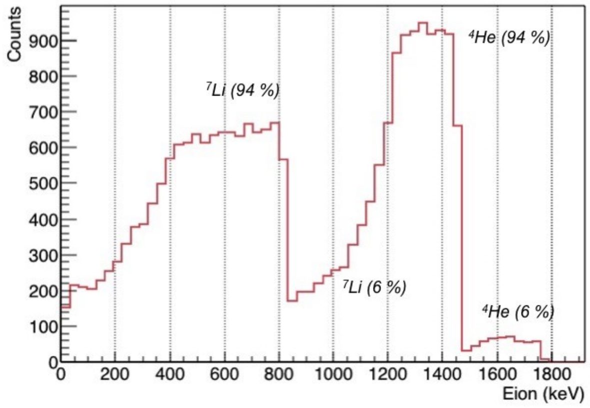

Fig. 4: Simulated ionization energy spectrum of the ^4He and ^7Li particles resulting from neutron captures on the boron coating.

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.

This measurement opens the possibility to use the detector as an active phantom for BNCT [15] placed in a high flux epithermal neutron field just after the moderator and counting the neutron captures produced at the coating level simulating the tumor and the amount of ^{10}B placed on it by a previous vectorization. In this way a dose calculation can be performed with a controlled amount of boron and with the thermal neutron field available. In addition, the active phantom can be used with a high energy proton beam during a PFBT (Proton Fusion Boron Therapy) counting the alpha particles produced on ^{11}B.

4. Experimental Results

The angular distributions of the ^4He recoils with respect to the neutron direction, resulting from elastic scattering with fast neutrons, is a function of the neutron energy.

These angular distributions, see figure 5, 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 ^4He recoil is 1.1 MeV for a neutron of 15 MeV. In a mixture of $^4He/CO_2$ (5%) at 700 mbar, a recoil track with this kinetic energy is 3.3 cm long according to SRIM [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 cylindric 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 θ_{RN} angles are above 60°, the tracks' orientations are optimized compared with the anode plane.

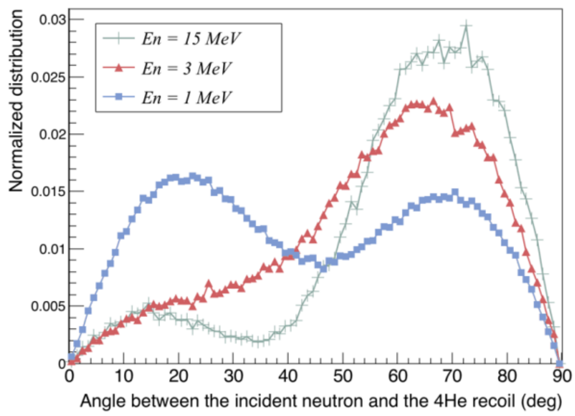

Fig. 5: The simulated angular distributions of ^4He recoils with respect to the neutron direction in the laboratory coordinate system, resulting from elastic scattering with neutrons of 1 MeV, 3 MeV and 15 MeV.

Angular distributions in the laboratory frame have been calculated with the Monte Carlo code Geant 4 [5], version 10.1.2, with the physics list QGSP_BERT_HP_LIV, and a chamber filled with a gas mixture of $^4He/CO2$ (5%) at 700 mbar.

4.1 Experimental 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 [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 was a solid target, composed of titanium loaded with deuterium, and evaporated on a 3 mm thick copper backing [10].

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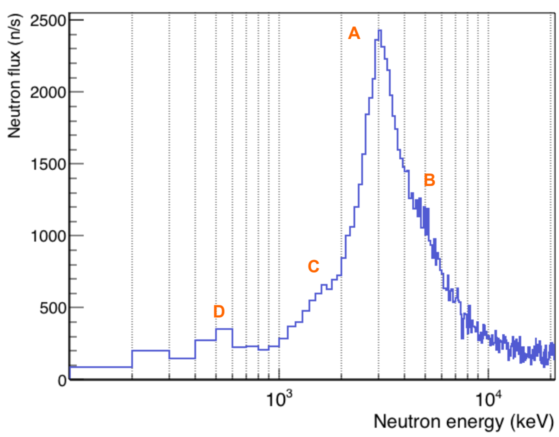

Fig. 6 : Measured neutron spectrum with the reaction D(d(220 keV),n) at GENESIS, with a binning of 120 keV/bin.

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 in figure 6.

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.

4.2 Experimental results from 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.

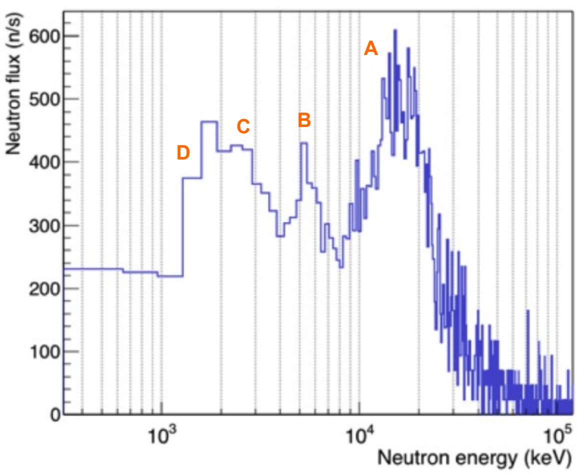

Fig. 7: Measured neutron spectrum with the reaction T(d(220 keV),n) at GENESIS, with a binning of 320 keV/bin.

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.

The figure 7 shows the reconstructed neutron spectrum.

5. Conclusions

In this presentation, 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) [13]. We have recently demonstrated the interesting active phantom application for BNCT (Boron Neutron Capture Therapy) and PFBT (Proton Fusion Boron Theapy) profiting of the calibration device.

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) [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.

For more details on this MIMAC-FastN data analysis see our recent publication [16]

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