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Development of a gaseous proton-recoil telescope for neutron flux measurements between 0.2 and 2 MeV neutron energy

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HIGHLIGHTS

- A new recoil proton detector for neutron flux measurement below 1 MeV
- Low sensitivity to other particles to operate in intense electron/γ-rays fluxes

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ABSTRACT

Absolute measurements of neutron fluence are an essential prerequisite of neutron-induced cross section measurements, neutron beam lines characterization and dosimetric investigations. The H(n,p) elastic scattering cross section is a very well known standard used to perform precise neutron flux measurements in high precision measurements. The use of this technique, with proton recoil detectors, is not straightforward below incident neutron energy of 1 MeV, due to a high background in the detected proton spectrum. Experiments have been carried out at the AIFIRA facility to investigate such background and to determine its origin and components. Based on these investigations, a gaseous proton-recoil telescope has been designed with a reduced low energy background. A first test of this detector has been carried out at the AIFIRA facility, and first results will be presented.

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1. Introduction

Five out of the six concepts of new generation nuclear reactor studied in the framework of the Generation IV international forum are based on fast neutron spectra. These concepts rely on simulations based on high quality nuclear data (Aliberti et al., 2006). It is expected that the evolution of the GenIV system analysis, and the focusing on a few preferred concepts, will motivate designers to define the relevant target accuracy. Despite the experimental efforts, large discrepancies and uncertainties still exist in the actinide region (Chadwick et al., 2011). Fission cross sections are of primary importance to determine reactor behavior and incineration capabilities. As fast neutron spectra

are peaked between 100 keV and 2 MeV, new cross section measurements have to be performed in this energy range (NEA, 2016). For neutron-induced fission cross section measurements, the accurate knowledge of the neutron flux impinging on the studied sample is mandatory. This is usually obtained measuring the fission rate of isotopes such as ²³⁵U, ²³⁸U or ²³⁷Np whose reaction cross section is well known (Paradela et al., 2010, Tsinganis et al., 2014, Salvador et al., 2015, Matei et al., 2017). However, this introduces a strong correlation between independent measurements based on the same standard reactions. In addition, the accuracy of these standard reactions is limited (0.5% at best, and up to 10%). An independent and well known standard reaction is the H(n,p) elastic scattering reaction. Indeed, the detection principle is completely different from the fission

detection, nullifying correlations between the measured cross section and the standard one. Moreover, its accuracy is about 0.2% in the MeV energy range, compared with typically few percents for the fission cross section standards mentioned above. Different concepts of proton-recoil detectors are available, depending on the type of measurements, the facility environment, the neutron energy range and the target accuracy of the measurement.

Plastic scintillators (Kovash et al., 2011) and proton-recoil proportional counters (Babut and Gressier, 2007, Nolte and Thomas, 2011) are suited to measure low energy neutron flux, down to few 10 keV. However, the scintillators require the use of time-of-flight technique to infer the neutron energy (Beyer et al., 2007), and thus can be used only in specific facility. On the other side, proportional counters provide a good accuracy of the neutron flux (2-3%), but they totally rely on simulations of the detector response.

The use of proton-recoil telescope method is more straightforward: the neutron flux is converted into a recoil-proton flux, by mean of a hydrogenous foil called radiator. The charged protons can be easily detected, using single or multiple staged Silicon detectors (Asai et al., 2006, Donzella et al., 2010, Naitou et al., 2011, Kessedjian et al., 2012), as well as diamond detectors (Hassard et al., 1998). Nevertheless, such technique is challenging when dealing with low energy neutrons, due to background and by the energy lost in the radiator.

2. Proton-recoil detection with Si detector below 1 MeV

A cross section measurement was carried out by the ACEN group of the CENBG institute between 1 and 2 MeV neutron energy, produced via T(p,n) nuclear reaction at 4MV Van De Graaff facility at Bruyères-Le-Châtel, CEA, France. The proton-recoil telescope consists of a collimated 4 μ m-thick polypropylene foil (PP foil) and a collimated 50 μ m-thick Si detector placed 8 centimeters far away. The protons detected in the silicon are emitted close to 0° with respect to the incoming neutron direction, and have therefore a kinetic energy close to the incident neutron energy. They produce a peak in the proton-recoil spectrum, with a good signal-to-noise ratio. Therefore, the number of counts in the proton peak is used to determine the incident neutron flux. A detailed description of the method and of the detector itself can be found in Marini et al. (2016, 2017). Previous studies at higher energies (using multiple staged Si detector) showed that a precision of the order of 1% could be achieved in the proton peak integral (Kessedjian et al., 2012). Around 1 or 2 MeV, the accuracy is only about 3% due to a high contribution in the low energy part of the proton spectrum, as can be seen in Fig. 1. Below 1 MeV, it becomes impossible to determine the neutron flux with acceptable uncertainties. Dedicated experiments were performed on the AIFIRA facility (Sorieul et al., 2014) to investigate the origin of such background and to find solutions to reduce it. Simulations have also been carried out with the MCNP5 code, in order to improve our understanding of the observed phenomena. Results were presented in Marini et al. (2016) and are briefly summarized here.

The results of the MCNP simulations show that low energy γ -rays emitted at the neutron production source are responsible for the observed background. Indeed, they generate a large amount of electrons via Compton scattering or photoelectric effect when interacting with surrounding materials in the setup (especially the copper beam dump). Additional tests performed on the AIFIRA facility showed that this background is strongly reduced when no neutrons are produced (by using a CaF target instead of a LiF target), indicating that most of these γ -rays are generated by neutron radiative capture or inelastic scattering reactions, especially in the beam dump

Fig. 1. Proton spectrum in the Si detector (standard and background measurements) for 2MeV incident neutron energy. The proton peak is visible on the right, as well as the intense background at low energy.

where the neutron flux is the highest. Electrons deposit much less energy in matter than protons due to their lower stopping power. Nevertheless, an electron of few 100 keV deposits energy in the whole thickness of the detector (here 50 μ m), whereas the ranges of 700 keV and 200 keV protons-recoil in silicon are around 10 μ m and 2 μ m respectively. In addition, simulations show that many electrons reach the Si detector with a high incident angles, further increasing the effective thickness and thus the energy deposition.

3. Development of the Gaseous Proton-Recoil Detector (GPRD)

To perform accurate neutron flux measurement at energies below 1 MeV without relying on detector-response simulations, the ACEN group has developed a new concept of proton recoil telescope with a reduced sensitivity to γ -ray/electron flux. The target accuracy is 3% for neutron energies between 200 keV and 2 MeV, taking into account proton counting uncertainty, geometry uncertainty and radiator thickness uncertainty. To adapt the thickness of the detector to the proton energy, the choice was made to build a gaseous detector. The pressure can be adjusted for the total proton range in the gas to fit the detector geometry. The detector concept is similar to one of the MIMAC detector (Mayet et al., 2012), however the neutron scattering does not occur in the gas itself but in a radiator, to avoid issues specific to proportional counter detectors as presented in section 1. The detector has the capability to discriminate direct neutrons from scattered neutrons, as well as to reject contaminant events (protons emitted by other sources than PP foil, cosmic rays...), thanks to a proton track analysis. To perform accurate neutron flux measurements, the detector requires a well-defined efficiency. A scheme of the detector is presented in Fig. 2.

The detector is constituted by a hydrogenous radiator made of polypropylene or mylar foil and a segmented ΔE -E ionization chamber (4x4x12cm³). The chamber is filled with CF₄ gas with a pressure ranging from few tens of mbar to slightly above 1 bar. The gas has been chosen free of hydrogen, to prevent additional recoil protons emission from the gas itself. Structures and collimators of the Gaseous Proton Recoil Telescope are made of Macor ceramic for the same reason. A special care was taken to build the detector with a reduced amount of material, in order to minimize the neutron scattering which seriously complicates the cross section measurement upstream the neutron flux measurement. The coincidence between the ΔE and E sides of the ionization chamber enables a first discrimination between recoil protons and background events (such as cosmic rays or recoil proton emitted by surround H-rich materials) to be made. The track reconstruction permits the discrimination between direct and scattered

Fig. 2. Scheme of the GPRD. Objects, materials and actions are detailed. The sample disk is shown separately for clarity purpose.

Fig. 3. (up) Picture of the segmented Micromegas detector; (middle) scheme of a proton track for a 1 MeV incident neutron energy; (down) scheme of a proton track for a 300 keV incident neutron energy

Fig. 4. Signal amplitude on pads in the ΔE region as a function of the time of irradiation

These different features validate the new principle of this detector. However, under the present experimental conditions, it was not possible to measure the proton detection efficiency of the detector, and in particular that every acceptable recoiling proton is actually detected. It would have required a quantitative experiment, with the addition of a reference fissile target.

On the other hand, this experiment shed light on several issues, which prevent considering the GPRD to be operational in its current status.

Static discharges: at few tens of mbar of gas pressure, the high voltage breakdown is strongly reduced due to the Paschen law (Škoro, 2012; Marić et al., 2014). This effect was under-estimated for the design of the detector, and discharges occurred at certain regimes (pressure/voltage). Special care will be taken to modify the detector design according to this constraint.

Non-homogeneous electric field: The detected signal amplitude of the side pads was quite lower when compared to the central pads.

Moreover, the positioning of the collimators (see Fig. 2) also affected the signal amplitude of the neighboring pads. This is due to electric field lines not strictly perpendicular to the Micromegas and the cathode. Some of the primary electrons then drift along the field lines out of the Micromegas detection plane. To solve this issue, a field cage will be designed for the GPRD upgrade.

Signal weakening: Under neutron irradiation, the signal amplitude of many pads quickly decreases. As can be seen on Fig. 4, the signal is nearly lost after few minutes of irradiation. As said in section 2, a large number of low energy electrons are generated with the neutron production source. These electrons may be deposited on the surfaces of the collimators or samples disk. This induces a strong local electric field distortion, and greatly reduces the collection of primary electrons by the pads or affect their spatial distribution. Indeed, by electrically grounding the entrance collimator, the signal loss was less severe (see Fig. 4) as part of the background electrons deposited on the collimator surface are collected and removed. The addition of a field cage will solve this issue, as it will help to collect the parasitic charges and reduce the electric field lines distortion.

4. Conclusion

The use of the H(n,p) standard reaction to accurately determine the neutron flux below 1 MeV without relying on detector response simulation is challenging, because the use of radiator with solid detectors is very sensitive to the high background contribution, mostly due to γ -rays/electrons produced in the neutron production target. To overcome this issue, a new double chamber gaseous proton-recoil telescope was designed and tested at the CENBG, with the aim of reaching an accuracy of 3% in the neutron flux determination. It has a very low sensitivity to γ -rays/electrons, which enables to detect recoil protons generated by incident neutron energies as low as 300 keV. Improvements have still to be made to meet the initial requirement of 200 keV neutron energy.

The ΔE -E coincidences, coupled to a proton track analysis, enables the discrimination between direct neutrons impinging on the PP foil, scattered neutrons impinging on the PP foil, and cosmic rays or recoil proton from other H-rich surrounding materials.

However, the electric field is slightly distorted by surrounding materials, and heavily distorted by the space charge accumulation on ceramic pieces of the detector. New studies based on electrostatic simulation code to add a field cage are undertaken in order to overcome both issues. A new prototype is currently designed and will be tested in the near future.

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