NUMERICAL STUDY OF THE PARTICLE TRANSPORT IN FAST NEUTRON DETECTORS WITH CONVERSION LAYER

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1. Introduction

Neutron detectors based on thin-film neutron reactive coatings (or "conversion layer") in close proximity to semiconductor materials are of great interest for many applications in material science and nuclear physics [1,2]. Fast neutrons with energy range from 100 keV to several tens of MeV can be detected through elastic scattering on light atoms, mainly hydrogen, due to the similarity between the neutron and hydrogen nucleus, favoring the energy transfer from the neutron to the hydrogen [3]. Commonly used reactive material for thin-film-coated detectors is high density polyethylene (HDPE) with high concentration of hydrogen, where fast neutrons are scattered and energetic recoil protons (hydrogen nuclei) are produced. Secondary generated protons which carry information about neutrons can be directly detected by a charged particle detector based on Si, SiC, GaAs, CdTe, etc.. GaAs detector has been shown as a perspective candidate for charged particle measurements due to its good detection and spectrometric performances, low price of the base material and high radiation resistance [1,2,4].

This paper deals with fast neutron and recoil proton transport simulation using statistical analysis of Monte Carlo radiation transport code (MCNPX). Its possibilities in the detector design and optimization are presented.

2. Experimental details

2.1. Fast neutron detection with conversion layer

Generally, the methods used to recognize neutron interactions within a detector rely on second-order effects. A very common neutron interaction that is often used for *fast* neutron detection is (n,p) reaction. The charged-particle reaction products emitted as a result of neutron interaction in the so-called conversion layer can be easily detected with a charged-particle detector. Electrons and holes generated in the volume of detector during slowing-down of proton are separated by the high electric field between detector electrodes and the electric signal can be measured at the output.

Low atomic number materials having relatively high elastic scattering cross sections for fast neutrons are usually manipulated for fast neutron detection. A hydrogen-rich coating, such as HDPE will produce relatively good detection efficiency [1]. It was shown that neutron detection efficiency can be 4 times larger when a converter layer is used [5].

Optimum thickness of the HDPE converter material is an important parameter to be established. The thicker the conversion layer, the higher elastic recoil rate and consequently, the more protons are produced. On the other hand, if the thickness of the conversion film gets closer to the range of protons in HDPE, some of the recoil protons are stopped as they pass through the rest of the layer and cannot reach the active region of the detector.

2.2. Calculation method

Optimum conversion film thickness can be specified by measurements; however, a much more efficient method of its determination is using a computer calculation technique. One of the most used computer codes for simulation of neutron transport through converter layer is MCNP code. The versions employed in the calculations up to the present allow tracking the whole history of interacting particle (neutron), such as interaction type, energy, direction and position. The PTRAC option of the MCNP code is often used as output information and the neutron energy and its direction before and after elastic scattering listed in the PTRAC file is recalculated using the interaction kinematics to output information on the recoil protons. This specification of recoil protons represents an input for some ion-transport code (e.g. SRIM - The Stopping and Range of Ions in Matter [6]) to simulate the proton transport through the converter [7-9].

In our calculations, the extended version of Monte Carlo radiation transport computer code, i.e. MCNPX (Monte Carlo N-Particle eXtended, version 2.5.0 [10]) was employed. A great advantage of the extended version lies in its capability to track not only neutrons but also recoiled charged particles, in our case protons, at nearly all energies by mixing and matching of nuclear data table and model physics. This approach restricts the task to usage of only one computer code without the need of other supporting software or computer programs.

3. Results

The proton projected range in HDPE calculated using the SRIM code is shown in Fig. 1. Taking as example the protons with highest energy of about 12 MeV one can find out the respective range in HDPE to be of about 1.9 mm. Accordingly, the maximum detection efficiency for 12 MeV neutrons is limited to HDPE film of 1.9 mm thickness. Though, the source neutrons and consequently the recoil protons are distributed in energy (as described above) and hence, different ranges of protons in HDPE have to be considered in the simulations. The differential flux of ^{239}Pu-Be radionuclide source of fast neutrons has been modeled as depicted in Fig. 2.

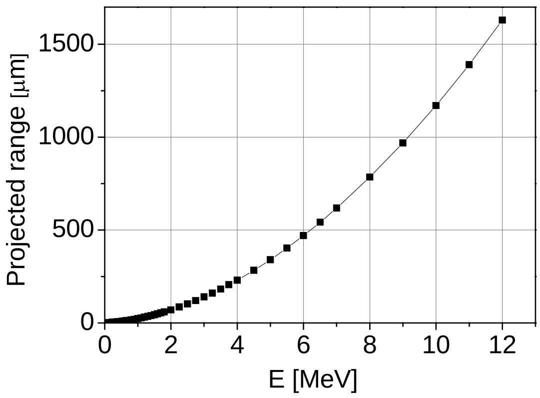

Fig.1: *Proton projected range in HDPE converter layer calculated by SRIM.*

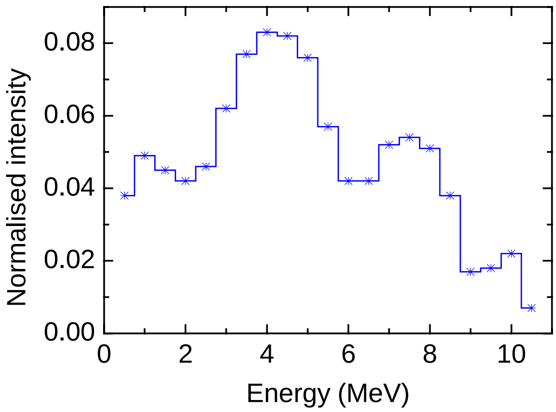

Fig.2: *The neutron spectrum from the ^{239}Pu-Be source used for MCNPX modeling [11].*

The results from MCNPX calculations show that increase of the converter layer thickness increases the (n, p) reaction rate and consequently, the number of recoil protons in the converter volume. As the recoil protons are transported through HDPE conversion layer, some of them are stopped and consequently, the integral flux density of protons entering the active volume of the detector reaches its maximum value for a specific conversion film thickness. The energy distributions of flux density of the protons entering detector after passing the HDPE conversion film of different thicknesses are shown in Fig.3. The conversion efficiency, i.e. the ratio of the proton flux density on the output side of the HDPE conversion layer to neutron flux density on the input side, calculated for different conversion layer thicknesses in dependency of the incident neutron energy is depicted in Fig.4. In the graphs one can follow the tendency of both the integral proton flux density and conversion efficiency to grow with increasing conversion film thickness until about 500 µm, followed by the decrease of respective quantities with further increase of conversion film thickness.

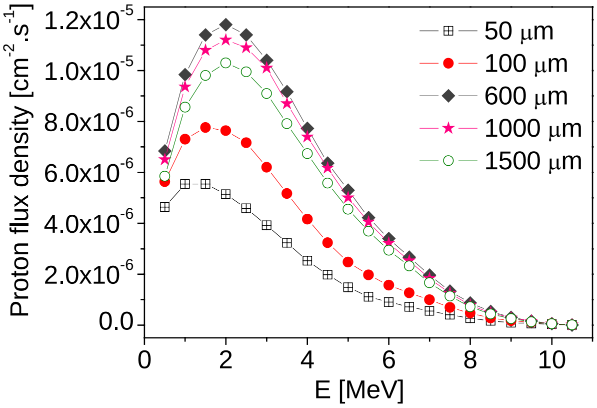

Fig.3: *The proton flux density on the HDPE layer output.*

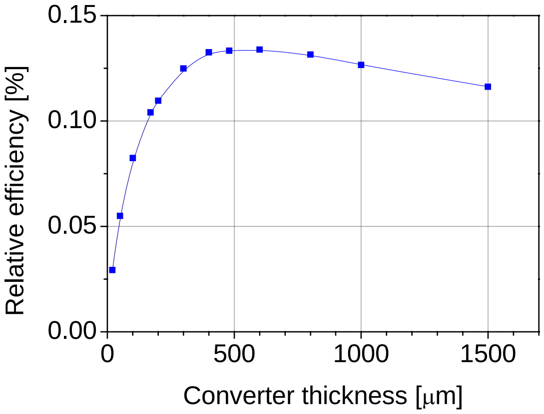

Fig.4: *Calculated detection efficiency of fast neutron detection.*

The intrinsic detection efficiency of any device operated in pulse mode is defined as the probability that a quantum of radiation incident on the detector will produce a recorded pulse. For a given detector, efficiency values depend on the type and energy of the incident radiation. For incident charged particles, many detectors have a total efficiency that is close to 100%. Therefore, the detection efficiency (ε) was assumed to be consistent with integral conversion efficiency, i.e. the ratio of the integral flux density (P_{out}) of protons entering the active region of the detector to the integral flux density of neutrons entering the HDPE layer (N_0) [6], i.e.:

$$\varepsilon = \frac{P_{out}}{N_0} \tag{3.1}$$

The optimal thickness of the conversion film has been derived from the dependency of detection efficiency on the conversion film thickness. According calculations, the highest detection efficiency of about 0.135 % can be reached for about 500 µm thick conversion film.

In further, the energy deposited by recoil protons in the active volume of the detector based on GaAs was calculated (f6 tally in MCNP code) and its dependency on the detector active thickness has been followed. The results are presented in Fig.5. As obvious, the energy deposited saturates for active volume thickness of about 300 µm. In thinner active regions, not all recoil protons are able to deposit the whole carried energy and consequently, the signal to noise ratio will be decreased. Fig.6 depicts the f8 tally, e.g. the pulse height tally which provides the energy distribution of pulses created in a cell that models a physical detector. The energy distributions of pulses were calculated for different thicknesses of the active region. Only the energy deposited by recoil protons was assumed. As visible from Fig.6, the proton spectra shape agrees with that of the incident proton flux density for the active volume thicknesses above 270 µm.

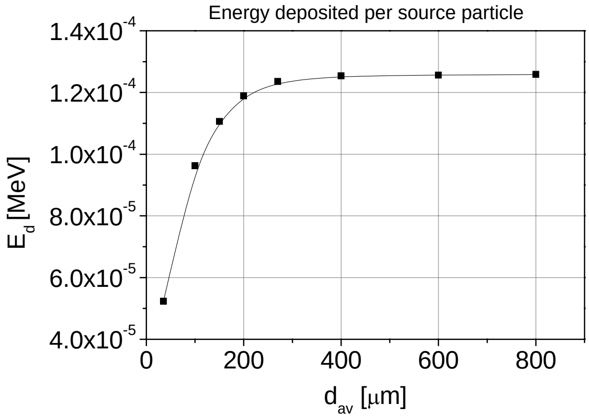

Fig.5: *Proton energy deposition averaged over an active volume of GaAs detector (f6 tally in MCNPX code).*

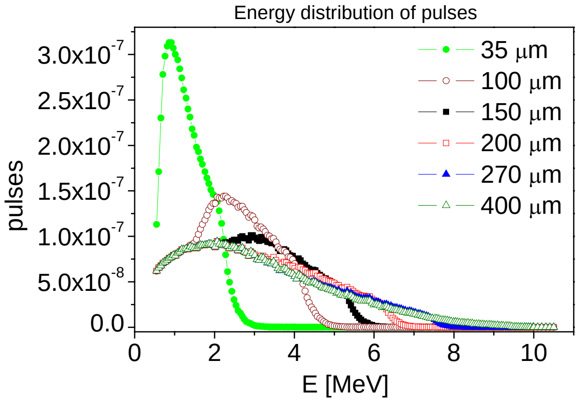

Fig.6. *Energy distribution of pulses created in a detector (f8 tally in MCNPX code).*

4. Conclusion

In this article the application of the MCNPX calculation code for fast neutron semiconductor detector design was demonstrated. MCNPX proved as a very advantageous self-contained simulation program for fast neutron and secondary proton tracking. Simulations of respective particle transport through conversion layer of HDPE and further in the active volume of detector let us to follow important characteristics as neutron/proton flux density, reaction rate of elastic scattering on hydrogen nuclei and deposited energy as well as their dependencies on incident neutron energy and conversion layer/active region thickness. The efficiency of neutrons to protons conversion has been calculated and its maximum was reached for 500 μm thick conversion layer. The minimum active region thickness has been estimated to be about 300 μm.

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5. References

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