MONTE CARLO SIMULATION OF A CAPTURE-GATED FAST NEUTRON SPECTROMETER WITH SIMPLE GEOMETRY

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Abstract

A detailed GEANT4 based Monte Carlo simulation has been performed to evaluate response functions of the simple geometry neutron spectrometer on the base of boron loaded liquid scintillator. This simulation is performed as a first stage of a program creation for detailed description of neutron interactions in the developed segmented neutron spectrometer. The results of our simulations reproduce well the experimental spectra accumulated with the monoenergetic neutrons in the energy range up to 5 MeV in spite of the several simplifications. In addition the importance of taking into account the neutron scatterings in the detector surrounding was demonstrated. The suitability of the GEANT4 toolkit applied for simulation of response functions of the simple geometry neutron detector has been proved and can be used as a base for the simulation of the detectors with more complex configurations.

1 Introduction

The measurements of energy spectra and very weak fluxes of neutrons are very important task for experiments aimed to search for rare processes such as double beta decay, dark matter etc. The neutrons being one of the main sources of a background for these experiments are produced in surround rocks by (α, n) reactions and spontaneous fission as well as by cosmic ray muons.

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Several types of so called "capture-gated spectrometers" able to measure full neutron energy deposited in detector were developed. The main feature of such spectrometers is a possibility to use coincidence between preceding proton recoil pulses and delayed well defined neutron capture pulses. In such case a high background rejection (more than 10^3) can be achieved.

Development of a segmented neutron spectrometer on the base of organic scintillator is in progress now [1, 2] as an advanced version of capture-gated detectors. It was shown that such segmented spectrometer is able to measure energy of neutrons in the energy range from 1 to 15 MeV with considerable improvement of a pulse height resolution. In this work the Monte Carlo simulations of response functions of a simple geometry fast neutron spectrometer for monoenergetic neutrons is performed as a first stage of a program creation for detailed description of neutron interactions in the developed segmented spectrometer.

2 Design of a simple geometry spectrometer

In the work [3] pulse height spectra and detection efficiencies have been measured with monoenergetic neutrons (in the energy range between 1.2 and 14.6 MeV) for a full-energy-absorption neutron spectrometer with very simple design and geometry of experiment (see Fig. 1). In our simulation work we decide to use the experimental results obtained with this set up because the most part of these experimental input data can be easily reproduced in a simulation program without ambiguities connected with more complex geometry.

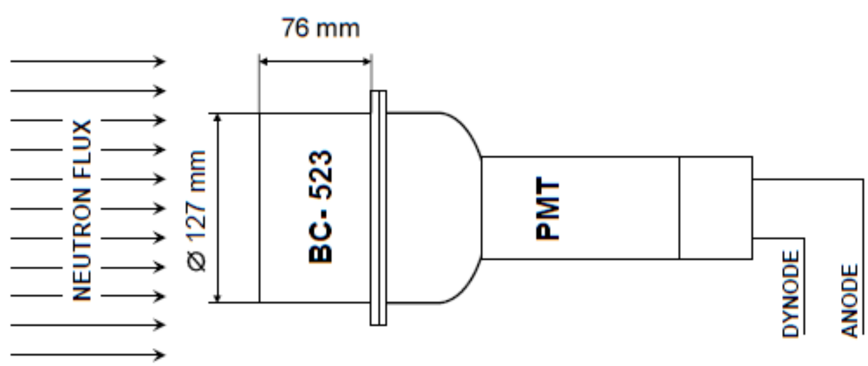

Figure 1: Schematic drawing of the simple geometry neutron spectrometer (adopted from the paper [3]).

The detector used in this work is based on 12.7 cm diameter and 7.62 cm long liquid scintillator made from BC-523, which is a 5% natural boron-loaded organic liquid with isotopic abundance of 80.2% ^{11}B and 19.8% ^{10}B, resulting in a ^{10}B content of about 1% by weight. This scintillator is viewed by one photomultiplier Hamamatsu R1512 (12.7 cm in diameter).

An electronic scheme of the experiment gives possibility to perform a delayed coincidence between a prompt signal which due to elastic scattering of fast neutrons on scintillator protons and a signal from reaction $^{10}B(n,\alpha)^7Li$ as a result of interaction of thermal neutron with detector material. Detection and energy measurement of the (n,α) reaction products provide second pulse that signifies the capture of neutron. The delayed capture occurs on a time scale of several microseconds. Such scheme measures the total energy lost of a neutron through multiple elastic scattering, i.e. the energy of the incident neutron.

In the experiment performed in work [3] the monoenergetic neutrons were generated by Cockcroft-Walton and Van de Graaf types accelerators and directed to a surface of the spectrometer in parallel with the detector axis.

Fig. 2 shows pulse height spectra measured for various energies of monoenergetic neutrons in work [3] as well as spectra simulated in our work by using GEANT4 .

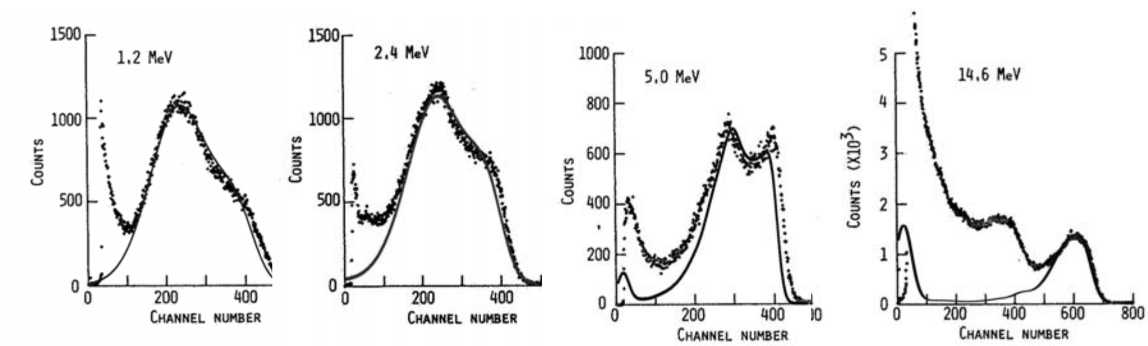

Figure 2: The pulse height spectra for neutron energies E_n equal to 1.2, 2.4, 5 and 14.6 MeV measured in work [3] (dots) and simulated in this work by using GEANT4 (solid line).

3 The Monte Carlo simulation

As one can see the pulse height spectra shown in Fig. 2 have complicated shapes starting from 5 MeV neutron energy. The origin of the complicated pulse height spectra observed for monoenergetic neutrons was examined using Monte Carlo simulation of fast neutrons entered into the detector. In the simulation total light outputs of recoil protons were summed up in the neutron slowing down process.

The Monte Carlo simulation of this neutron spectrometer response function has been carried out using Geant 4.8.2 package with neutron cross section set G4NDL 3.10 [4], and simulation results were analysed by using ROOT 5.14 package [5]. The interactions which a neutron undergoes in the detector are defined by the physics list of a GEANT4 toolkit. The GEANT4 physics list used in our program was optimized to handle low energy interactions of electrons, gammas and neutrons. The interactions of neutrons at low energies include radiative capture, elastic scattering, fission and inelastic scattering. All data are derived from evaluated data libraries obtained from ENDF/B-VI data [6].

For this version of GEANT4 the currently supported final states for inelastic scattering $nA \rightarrow$ are $n\gamma$s, np, nd, nt, n^3He, $n\alpha$, $nd\alpha$, $nt\alpha$, $nt2\alpha$, $n\alpha p$, $n3\alpha$, $2n$, $2np$, $2nd$, $2n2\alpha$, $3n$, $3np$, $3n\alpha$, $4n$, $4np$, $4n\alpha$, $d\alpha$, $d2\alpha$, dt.

In parallel with the GEANT4 program, which is a common tool suitable for simulation of passage of different kinds of particles, we have elaborated a code DGEOM specially designed for neutron transportation in media for more simple and fast treatment of the data when it is needed. This code uses the table DLC37 (100 group neutron cross sections) based on ENDF/B-VI neutron data base for sampling mean free path and interaction type. Elastic neutron scattering is calculated through kinematics and is isotropic in a centre mass system. For description of inelastic neutron scattering on carbon a simple approximation cross section was used (only two first levels of ^{12}C).

The following simplification are adopted for both GEANT4 and DGEOM :

- neutrons enter the detector perpendicular onto the flat front surface of the cylindrical detector and uniformly on one;
- light emission is solely due to recoil protons;
- neutrons scattered away from the scintillator never come back again;
- only for DGEOM program neutron scattering is considered as isotropic in the center-of-mass-coordinate system, in comparison with GEANT4 where is considered precise distribution.

As it will be shown below this difference doesn't play a considerable role for scatterings of neutrons with energies up to 15 MeV.

Since the light yield is nonlinear function of the proton energy, the total light yield differs depending on the history of neutron energy loss in the neutron slowing down process [7]. In such a case detector response is defined as a sum of separate light signals due to recoil proton energy deposition. Light yield as a function of recoil proton energy in the organic scintillator was taken from work [8].

Taking into account the above mentioned conditions the Monte Carlo simulations of pulse height spectra of neutrons with energies E_n equal to 1.2, 2.4, 5 and 14.6 MeV have been performed for the detector from [3] with using both GEANT4 and DGEOM .

In Fig. 2 the results of our Monte Carlo calculations in comparison with experimental spectra are shown. One can see that the shapes of spectra become more complicated with growing an initial neutron energy. Each spectrum looks like a composition of at least two components which get detached more and more with higher energies. The course of such behaviour of both experimental and calculated spectra came to light during MC simulations at tracing of each neutron passage through detector. This will be discussed in more details in the next section.

In Fig. 3 the results of simulations with GEANT4 and DGEOM for neutrons with energy $E_n = 14.6$ MeV are compared. Difference in energy region below 5 MeV is due to more simple approximation of cross sections for inelastic scatterings of neutrons on ^{12}C nuclei used in DGEOM .

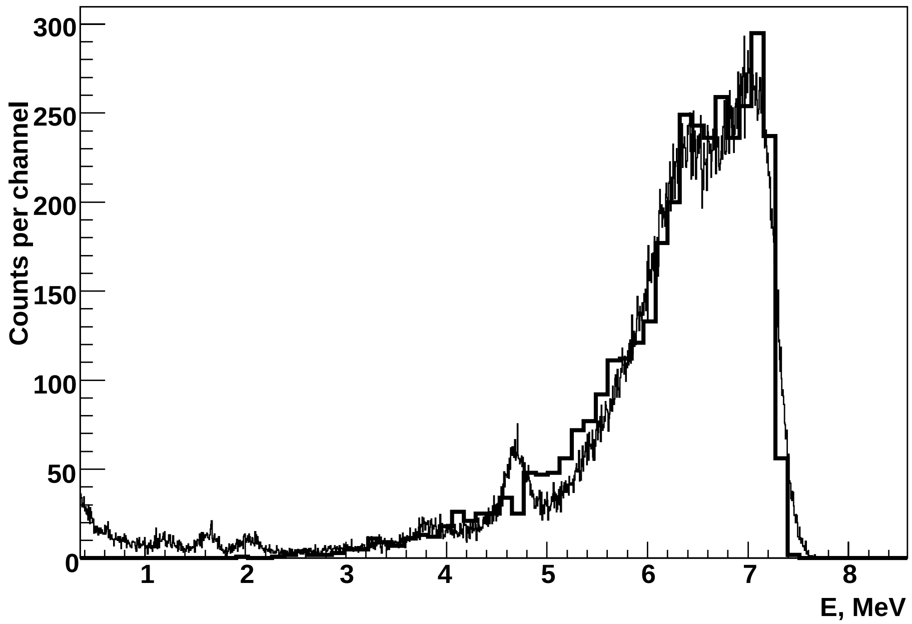

Figure 3: The spectra of neutrons with calculated by GEANT4 (thin line) and DGEOM (thick line), $E_n = 14.6$ MeV.

Authors of work [3] carried out also the Monte Carlo simulations of pulse height spectra of neutrons with energies E_n equal to 1.2, 2.4, 5 and 14.6 MeV but they used the light yield function for protons (keeping in mind a quenching factor) $L_p = 0.328 \times E_p^{1.5}$ in their simulations for all energy range. It should be noted that the factor 0.328 used in [3] don't allow to reproduce with enough accuracy both absolute and relative shapes of spectra for neutron energies above ≈5 MeV. That is why we used another light yield function for protons taken from paper [8] were the full proton light output function is described by a set of polynomials of third order for 6 energy regions of protons from 0 up to 16 MeV (see Fig. 4). For simplicity, this function can be approximated as $L_p = 0.183 \times E_p^{1.5}$ for proton energy below 5 MeV only.

4 Results and discussions

Due to quenching effects [7], the specific light-yield in organic scintillators is not proportional to the energy of a recoil proton. Therefore, from the point of view of a total light yield, the neutron moderation process consists of two main modes. One of these modes is the multiple recoil processes and the total light yield depends strongly on a way how the energy loss of each neutron was distributed among the recoil protons. The distribution of the total light yield, finally converted into the pulse height spectrum with a broad asymmetric peak, corresponds to a multiplicity of the neutron scattering process. In the other mode a neutron loses a total (or almost total) energy in a single collision only. In this

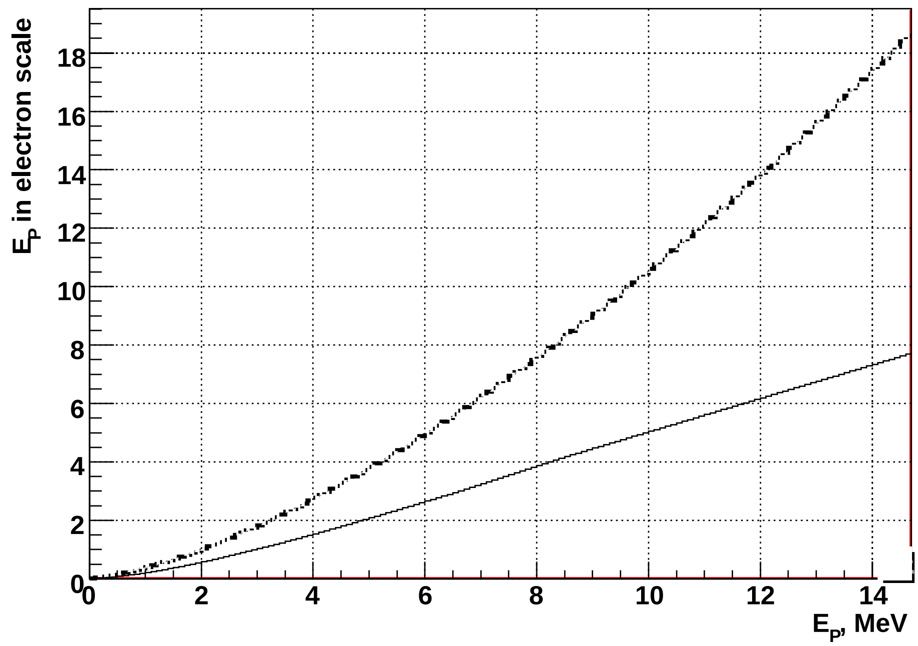

Figure 4: Proton light yield functions for liquid scintillator: dots — used in work [3]; solid — used in our calculations, taken from work [8].

case the light is emitted due to single proton recoil. The total light yield is unambiguous value because the energy of that recoils is fixed, therefore, this mode of moderation will contribute to the pulse height response as a separate and relatively narrow peak. This peak always appears from the right of the multiple peak because in this mode the recoil proton has its highest energy.

Relative increasing of a single scattering mode of moderation with growing of energy is demonstrated on Fig. 2 both for the experimental and calculated spectra and this is connected with a fact that the higher energy of neutron the lesser neutron scattering number in the detector, that is confirmed by our simulations.

It was also shown during this simulation that the existent difference between experimental and simulated spectra in their low energy parts is connected with some contribution of neutrons moderated and scattered outside of the detector. Unfortunately, no details about surrounding of the detector have been presented in the paper [3] and this gives no chance to include some additional parameters connected with the environment of this detector in our simulation. That is why we use for our simulation an "ideal case" where the described detector is placed in a "wall-less" space without any additions.

To demonstrate the importance of taking into account the neutron scatterings in the detector surrounding let us pay special attention on the comparison between experimental and simulated spectra for 14.6 MeV neutrons. Indeed, in the simulated spectrum for 14.6 MeV neutrons (Fig. 2, right) negligibility of the contribution of neutron scatterings in detector surroundings leads to considerably lower number of events for energy region be-

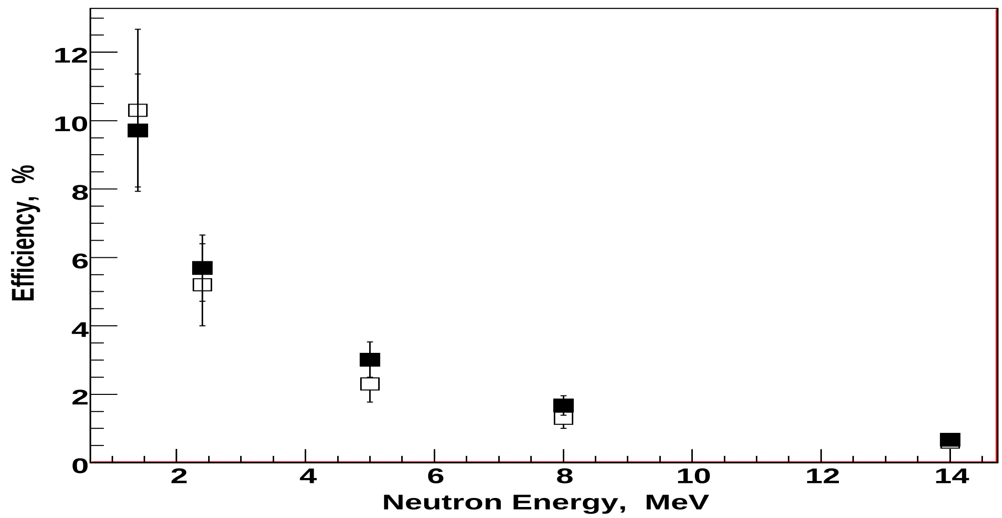

Figure 5: The efficiencies of neutron detection calculated by GEANT4 (filled rectangles) and experimental from work [3] (empty rectangles).

low 5 MeV (in the electron equivalent energy scale) in comparison with the experimental spectrum where an additional wide peak around 5 MeV is due to outside neutron scatterings. From the other hand the peak connected with multiple scatterings of neutrons in the detector practically disappear for a case of 14.6 MeV neutrons. That is, for neutrons with relatively high energy ($\geqslant$10 MeV) the peak connected with externally scattered neutrons appears in the spectrum instead of the peak due to multiple scatterings of the neutrons in the detector which becomes negligible at such energy. For neutrons with lower energies the contribution of the externally scattered neutrons decreases whereas the contribution of the multiple scatterings of neutrons in the detector medium becomes more and more considerable. This is demonstrated on Fig. 2 (central and left parts) for the 1.2, 2.4 and 5.0 MeV neutron spectra.

Both the GEANT4 and DGEOM programs demonstrated good enough agreement of the simulation results with experimental spectra for the energies of neutron at least up to $\approx$5 MeV where the contribution of the externally scattered neutrons is negligible and is not taken into account in our simulations.

Fig. 3 demonstrates agreement between the simulated spectra made by GEANT4 and DGEOM programs for 14.6 MeV neutron energy. Some differences in the spectrum details are connected with accuracy of the neutron — carbon cross section used in these simulations.

The efficiencies measured in work [3] as well as calculated on the base of our simulations are presented on Fig. 5. One can see the admissible agreement between experimental and calculated values of efficiencies, thus this additionally confirm the proper work of the programs and input parameters applied for our simulations.

Conclusions

The Monte Carlo simulations of response functions of the simple geometry neutron spectrometer on the base of boron loaded liquid scintillator have been performed for neutron interactions in the wide energy range from 0.025 eV to 15 MeV.

The performed MC simulations are based on the GEANT 4.8.2 package with the G4NDL 3.10 neutron cross section set and with taking into account nonlinearity of the light yield of recoil protons in organic scintillator.

It was shown that the results of our simulations of the neutron spectrometer response functions reproduce well the experimental spectra accumulated with the monoenergetic neutrons in the energy range up to 5 MeV in spite of the several simplifications adopted for this simulation. It was clearly demonstrated that for these neutron energies the complicated shapes of the spectra accumulated with the simple experimental set up used in work [3] are mostly due to a superposition of two wide peaks originated from the multiple and single scatterings of neutrons during their moderation in the detector medium. In addition the importance of taking into account the neutron scatterings in the detector surrounding was demonstrated by comparison the experimental and simulated spectra for 14.6 MeV neutrons.

Thus, the suitability of the GEANT4 toolkit applied for simulation of response functions of the simple geometry neutron detector has been proved and can be used as a base for simulation of the detectors with more complex configurations.

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