Neutron response function for a detector with $^{3}$He counters for the 0.39–1.54 MeV neutron energy range

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Abstract

An experimental study was carried out on the neutron response functions of two neutron detector arrays consisting of 39 $^{3}$He proportional counters with a polyethylene moderator for monoenergetic neutrons within the 0.39–1.54 MeV neutron energy range. Experimental data on the sensitivity of neutron counting to a change in neutron energy and the influence of the thickness of polyethylene moderator were obtained. The experimental efficiency curves were compared with the calculated response functions generated by a neutron transport code.

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1. Introduction

Studies of delayed neutron emission from neutron-rich nuclei are carried out by using different types of detectors. These studies require a neutron detection system of high efficiency, good energy and angular resolution and with the number of channels sufficient to enable multi-

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neutron decay measurements. The main advantages of a polyethylene moderated multi-counter neutron detector system are a practically zero energy threshold, the absence of cross-talk, a low sensitivity to gamma quanta and the fact that it can be made of detectors of high neutron sensitivity [1–4]. Systems with $^{3}$He proportional counters can be used for obtaining the average energies of the delayed neutron spectra for chemically and mass-separated sources [5] and the angular distributions of neutrons [6].

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Delayed neutrons from different emitters range in energy from hundreds of keV up to several MeV, for example, single delayed neutrons for $^{14}\text{Be}$ have energy of 290 keV [7], and the energy of delayed neutrons from $^{15}\text{B}$ takes several values, the main ones being 1.77 and 3.2 MeV [8]. This implies that the sensitivity of a neutron detector should remain constant in a broad energy range or the detector should provide information on neutron energy to correct measured results. Different approaches to the calibration of neutron detectors are described in papers: the neutron-sources Am/Li [3,4], RaBe, $^{124}\text{SbBe}$, $^{24}\text{NaBe}$, $^{24}\text{NaD}_2\text{O}$ [5] of spontaneous fission of $^{252}\text{Cf}$[5,10,11] or sources of delayed neutrons [9,10] were used.

In the present work, we have measured the response functions of two neutron detector arrays, with 39 $^3\text{He}$ proportional counters each, for monoenergetic neutrons within the 0.39–1.54 MeV neutron energy range. The main goals of the measurements were to obtain experimental data on the sensitivity of neutron counting to varying neutron energies and the influence of the thickness of the polyethylene moderator. The experimental data will be used for constructing optimal neutron detector arrays with modules [6] for studies of the properties of delayed neutrons from fission fragments within the framework of Dubna Radioactive Ion Beams (DRIBs) [12] and Accélérateur Linéaire auprès du Tandem d'Orsay (ALTO) [13] projects.

2. Neutron detector arrays

The detection assemblies are shown in Fig. 1, each array consisting of 39 modules [6] arranged in six layers. In the first assembly, all the modules were identical and each of them consisted of a hexagonal polyethylene unit (distance between parallel planes—50 mm) with a cylindrical cavity (diameter 32 mm) for a counter of neutrons. The length of the counter and the polyethylene moderator was 50 cm. The counters were filled with $^3\text{He}$ up to a pressure of 7 atm. Every counter of neutrons was supplied by a pre-amplifier which was hardly fastened directly on a counter in a cylindrical case; the cases of pre-amplifier were used for fixing of counters of neutrons in assembling.

In the second assembly, the polyethylene moderator was removed from the modules of the 2nd and 4th rows.

![Fig. 1. Scheme of $^3\text{He}$ neutron detector arrays: (a) with complete moderator and (b) without moderator in the 2nd and 4th rows. Gray hexahedrons are moderator units, black and white circles are counters.](image-url)
The detection assemblies were surrounded by a shield from boron-loaded polyethylene with a window in the front side; this window was covered by 1 mm cadmium foil.

3. Energies of neutrons and intensity monitoring

The experiments described here were performed with the Van de Graaf electrostatic accelerator HV2500AN at Charles University, Prague, Czech Republic.

Monoenergetic neutrons were produced as secondary particles from a \(^{3}\text{H}(p,n)^{3}\text{He}\) reaction on a Ti–T target (0.2 mg/cm\(^2\)) with a molybdenum backing. The target was mounted at an angle of 45\(^\circ\) to the incident beam of protons, so the real thickness of the target was about 0.28 mg/cm\(^2\). The energies of protons used and the corresponding neutron energies are shown in Table 1.

The energy spread of protons due to the energy loss in the target and the corresponding energy spread of neutrons were calculated to be not more than 30 keV.

The proton energy spread for the beam of the accelerator was not more than 2 keV. Each neutron detector array was mounted at a distance of 3 m from the tritium target and the center of the array was placed at 0\(^\circ\) to the beam axis, neutron counters were located perpendicularly to this axis and were seen at an angle of \(\pm 6^\circ\) from the target. The neutron energy spread due to the angular spread was about 10 keV.

Measurements of the energy of neutrons and relative intensity monitoring were made with a stilben crystal detector of diameter 3.0 cm and thickness 2.2 cm connected to a Philips XP-2020 photomultiplier tube and placed in front of neutron detector arrays. Using a stilben scintillation crystal gives an efficient way to discriminate between incident gamma rays and neutrons by means of pulse shape discrimination (PSD). We applied a PSD method, which is based on charge integration of the pulse current over two different time intervals using a charge-integrating QDC. The method is described in Ref. [14] and the same electronics was used in the current experiment.

Plotting the charge in the tail of a pulse against the total charge gives the two-dimensional spectra in Fig. 2 for incident proton energy of 1.7 MeV and a respective neutron energy of 0.93 MeV. One can see a separation between neutrons (top branch) and \(\gamma\)-rays (bottom branch) in the figure. Making a contour around the neutron branch and projecting it on the \(x\)-axes, we obtain a one-dimensional energy spectrum of neutrons. In other words, we determine the experimental neutron response function and can calculate the neutron counts for the respective branch. The corresponding one-dimensional spectrum is shown in Fig. 3.

The process of neutron scattering on protons at neutron energy of up to 10 MeV is isotropic in a center-of-mass coordinate system. So the response function of a detector based on the simple

![Figure 2](image)

**Fig. 2.** Two-dimensional spectrum of total charge versus charge in the tail of a pulse obtained on a stilben crystal for neutron with the energy \(E_n = 0.93\) MeV.

<table>
<thead>
<tr>
<th>(E_p) (MeV)</th>
<th>1.2</th>
<th>1.3</th>
<th>1.4</th>
<th>1.7</th>
<th>1.8</th>
<th>2.0</th>
<th>2.2</th>
<th>2.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_n) (MeV)</td>
<td>0.39</td>
<td>0.50</td>
<td>0.61</td>
<td>0.93</td>
<td>1.03</td>
<td>1.23</td>
<td>1.44</td>
<td>1.54</td>
</tr>
</tbody>
</table>
accuracy of determination of neutron energies with this method is quite good and we really have monoenergetic neutrons with an energy spread of not more than about 35 keV.

4. Neutron intensity monitoring with a $^3$He counter

We also used $^3$He proportional counters without a moderator for relative monitoring of intensity of incident neutrons at detector arrays. A $^3$He proportional counter was placed in front of neutron detector arrays along the line connecting the center of the array with the target. To estimate the neutron intensity, we integrated the amplitude spectra of the pulses from the counter. This integral is mainly connected with the thermal neutrons originating in the array, floor and walls in the experimental room because of the very small sensitivity of $^3$He-counter to neutrons of higher energies. But these thermal neutrons were originated from neutrons from reaction on tritium target, and so the intensity of these thermal neutrons reflects the intensity of primary neutrons. We obtained good agreement in neutron intensity monitoring for both types of detectors used.

5. Results

The counting rates of the separate groups of neutron counters arranged in the central part of each layer of a detection assembly and a monitor detector were measured at different energies of incident neutrons. In Fig. 1(a,b), these groups of neutron counters are marked with a black tone. The distributions of the counting rates (recalculated per one counter and normalized to the monitor counting rate) are shown in Fig. 5(a,b) for neutron detector arrays with a complete moderator and without a moderator in the 2nd and 4th rows, respectively. The error of every point of the response function is less than the point size. The good sensitivity of both arrays to the changing of neutron energies is clearly seen, so the valid correlation of count rate ratios for different rows of neutron counters with neutron energies was obtained. If the detection sensitivity versus

hydrogen scattering of monoenergetic neutrons in this energy range should have a rectangular shape, extending from zero to the full incident neutron energy [15]. But due to different distortion mechanisms [16], we can see that the one-dimensional spectrum has a significant deviation from a pure rectangular shape. The relative neutron energies determined using the crossing of the extrapolated right part of the spectra with the x-axes are shown in Fig. 4. One can see that the
neutron energy curve for one row of counters is quite different from that for another row of counters, the ratio of counts for the two rows will be a function of neutron energies.

It is seen from a comparison of the two response functions (Fig. 5a,b) that removing part of the moderator leads to the displacement of the maximum of the rate to the deeper layers of the counters and the total detector sensitivity drops with the decrease of the volume of the moderator.

Plots of the sensitivity of neutron detection versus incident neutron energy (in recalculation per one counter) independent of the number of detecting rows are shown in Fig. 6. The sensitivity of the first array with all its counters is taken as 100% at 1540 keV of incident neutron energy. As is visible, for detection assembly with a larger amount of moderator the sensitivity of registration is systematically higher for all neutron energies.

As neutron energy increases, neutron registration sensitivity increases. This can be explained by the fact that at low energies, a considerable fraction of neutrons is reflected by the front layers of a detector and does not penetrate into the assembly, neutrons of higher energies penetrate deeper into the assembly and their losses due to reflection are smaller. 4π detectors will register neutrons of small energies more effectively, because they do not abandon a detector due to the reflections in other internal layers, but neutrons of high energies will leave the assembly.

The experimental sensitivity curves were compared with calculated response functions generated using the MCNP code [17] version B. During calculations good agreement with experimental information was achieved, calculations with a larger amount of moderator in a detector were conducted, the distance between the parallel planes of polyethylene hexahedrons being changed from 5 to 6, 7 and 8 cm. In Fig. 7, the calculated dependences of the sensitivity of neutron registration on the thickness of the moderator for two neutron energies (0.61 and 1.54 MeV) are presented. As is obvious from the graphs, the distance between the parallel planes of polyethylene hexahedrons about 6.5 cm is optimal. Taking into account that in experiments with 4π detectors, neutrons get into a detector isotropically, the effective thickness of moderator in our modules is near optimal. It is also necessary to notice that an increase in the thickness of the moderator results in an increase in the neutron lifetime for a detector, and so experiments on studying delayed neutrons in coincidence with β-particles or γ-rays or in multiple neutron measurements result in an increase of the background from random coincidences.

Consequently, to ensure that neutron registration sensitivity depends weakly on the energy of incident neutrons up to an energy of 1.5 MeV, a detector of neutrons must consist of no less than 4–5 layers of modules, consisting of neutron detectors (7 atm He, 32 mm in diameter) and
 moderator surrounding one detector by a layer approximately 1 cm thick.

Neutrons of higher energies—from 3 to 5 MeV—can be obtained in a (d,d) reaction on the same accelerator and experiments on determination of the response function of an assembly of neutron counters for this range of energies will be conducted.

Fig. 6. Efficiency of neutron detection as a function of the energy of incident neutrons.

Fig. 7. Calculated efficiency of neutron detection as a function of the thickness of moderator.

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