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Neutron spectrometry with He-3 proportional counters

M Manolopoulou[1*], M Fragopoulou[1], S Stoulos[1], E Vagena[1], W Westmeier[2] and M. Zamani[1]
[1]School of Physics, Aristotle University of Thessaloniki, Thessaloniki 54124, Hellas
[2]Philipps-Universität, 35032 Marburg, Germany
[*]email: metaxia@auth.gr

Abstract. Helium filled proportional counters are widely used in the field of neutron detection and spectrometry. A review of some parameters and physical effects that influence the He-3 proportional counters response is presented through the experimental study of a commercially available counter. The impact of these effects is taken into account in the description of detector performance when the response is calculated with the Monte Carlo method. A method to determine neutron energy distribution with a bare He-3 counter in an unknown neutron field is presented. The neutron energy range extends up to about 7 MeV. The method does not require a hypothesis about neutron spectrum shape. It is based in the calculated counter response with Geant4, the validity of which is experimentally verified. A detailed description of the steps needed is presented.

1. Introduction

Application of He-3 counters in neutron detection and spectrometry has been long proposed mainly due to high cross section of ^{3}He interaction with neutrons though for spectrometry applications several causes like recombination, space charge and wall effect make response function calculation a difficult task [1-6]. In this work the response of a proportional He-3 counter is studied experimentally and simulated with the Geant4 code [7]. The calculated response of the system is used to determine neutron energy distribution in an unknown neutron field.

2. Experimental technique

Irradiations were performed with nearly mono-energetic neutron beams in the energy range from 230 keV to 10.7 MeV provided by a Tandem, Van de Graff accelerator facility at the Institute of Nuclear Physics, NCSR Demokritos, Athens, Hellas. Neutrons with energies up to 3.3 MeV were obtained via the ^{7}Li(p,n)^{7}Be reaction, from 3.75 to 10.7 MeV were produced via ^{2}H(d,n)^{3}He reaction while higher energies up to 22 MeV via ^{3}H(d,n)^{4}He reaction. Details about the irradiations can be found elsewhere [8]. The description of the counter and the operational characteristics obtained during the above irradiations are presented in Table 1.

Irradiations were also performed in a calibrated neutron field, in the low-scatter measurement hall of the Physikalish-Technische Bundesanstalt (PTB, Braunschweig) irradiation facility, in order to determine the response function of the counter. Neutron beam energies were 0.5, 1.2 and 2.5 MeV while irradiations were carried out additionally with a shadow cone between the target and the counter to determine the influence of the room returned neutrons to the spectra acquired. Irradiation time was scheduled to attain sufficient statistics in the spectra, around 1000 counts in the centroid of the full energy peak. The count rate was kept low, around 10^3 cps to avoid space-charge effect and/or pulse pile-up events in the counter.

Table 1. Description and operational characteristics of the counter.

Pressure [atm]	Gas content	Cathode material / thickness	Anode material / diameter	Effective length [cm]	Effective diameter [cm]	Operating Voltage [V]	Shaping Time [μs]
6	^{3}He 64.7% Kr 33.3% CO_2 2.0%	Stainless Steel 304 / 0.089 cm	Tungsten / 0.025 mm	15	5	1700	8

3. Results and Discussion

3.1 Pulse height distributions

Pulse height distributions obtained during irradiations for 8 neutron beam energies are presented in figure 1. This complex response is made up of (i) The "Full Energy" peak, at the end of each spectrum, formed when total kinetic energy of the ^{3}He(n,p)T reaction products is deposited in the effective gas volume. The reaction is exothermic, with Q=764 keV. The neutron kinetic energy is added to the Q value of the reaction, and the total kinetic energy is distributed among the two reaction products according to their emission angles in the lab frame. For neutrons with energies above around 7 MeV, as it is calculated by the SRIM/TRIM code [11], the proton/triton range becomes larger than the dimensions of the effective volume of the counter. Therefore the full energy peak cannot be formed (e.g. 7.7 MeV in figure 1).

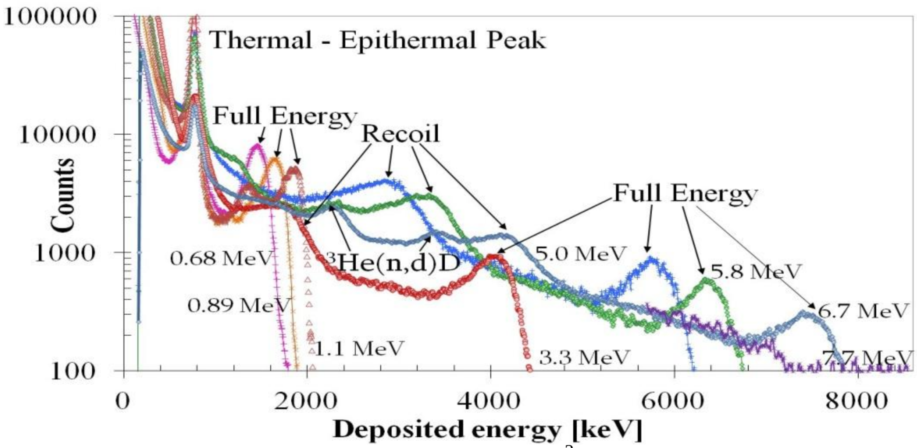

Figure 1. Pulse height distributions obtained with He-3 counter for several neutron beam energies. For the neutron beam energy of 7.7 MeV, only the last part of the spectrum is presented for clarity reasons.

(ii) The Recoil distribution is formed by the ^{3}He recoiling nuclei, due to ^{3}He(n,elastic) reaction. The energy E_R transferred to a ^{3}He nucleus via elastic scattering of a neutron of energy E_n is $E_R \approx 4E_n\cos^2\theta$ where θ is the scattering angle of the recoiling nucleus in the lab coordinate system [1]. As all scattering angles are allowed, in principle, the result in the spectrum is a continuum between a minimum of zero energy and a maximum of whenever the recoiling nucleus is emitted at 0° with respect to the neutron direction. This maximum energy is calculated to be 75% of the neutron energy for the ^{3}He nucleus and 29%, 22% and 5% for the C, O and Kr nuclei, respectively. It should be pointed out that although the cross-section of elastic scattering for fast neutrons is larger than the ^{3}He(n,p)T reaction, the result in the pulse height distribution is not so prominent as compared with the full energy peak, due to the distribution of the recoil events over a wide energy region of the spectrum (figure 1). (iii) Gamma-ray distribution. $\gamma-$rays interact mainly with the counter walls and Kr atoms producing electrons. Due to their long range, electrons can deposit a limited amount of energy (usually less than about 200-300 keV) in the counter, producing pulses with small amplitudes and long rise times. These pulses are recorded in the low-energy region of the pulse height distributions, presenting an exponentially decreasing function of which the exponent is a function of the $\gamma-$ray field intensity [5,8,9] (iv) Finally, in all spectra the Thermal-Epithermal peak is formed from scattered, low energy, neutrons. It should be noted here that as the counter was covered with 1 mm Cd foil, in the thermal-epithermal peak are registered neutrons with energies above about 1 eV up to several tenths of keV due to system resolution. (iv) Finally, for neutron energies above 4.3 MeV, the ^{3}He(n,d)D reaction contributes to the pulse height distributions, with Q=-3.27 MeV (figure 1).

3.2 Energy calibration and Resolution

The deposited energy of the ^{3}He(n,p)^{3}H reaction products which is registered in the full-energy peak area of the spectrum exhibits a linear relationship with the pulse height although a nonlinear behaviour is observed for recoil peak events as presented in figure 2(a). Moreover, when the recoil nuclei pulse height is converted to energy via energy calibration of the full energy peak, a significantly lower energy than the one expected from kinematics is calculated, mainly as a result of a recombination effect. The energy calibration equation for recoil events has been reported previously [10]. Resolution of the full energy peak is in the range of 4%-8% (figure 2(b)).

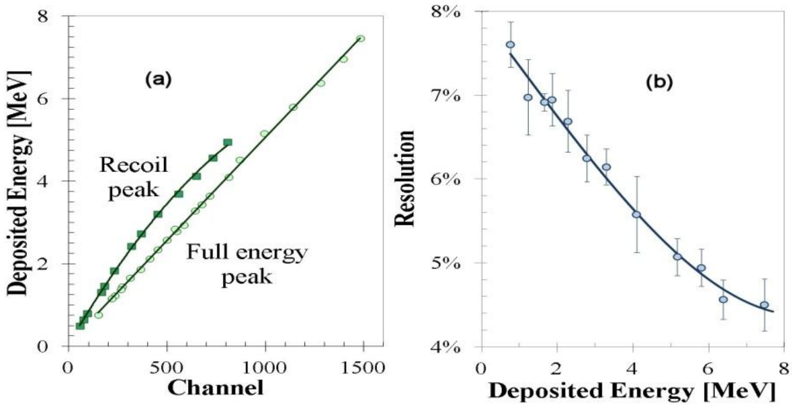

Figure 2. (a) Energy calibration of the system for the full energy and recoil peaks and (b) resolution as a function of neutron energy.

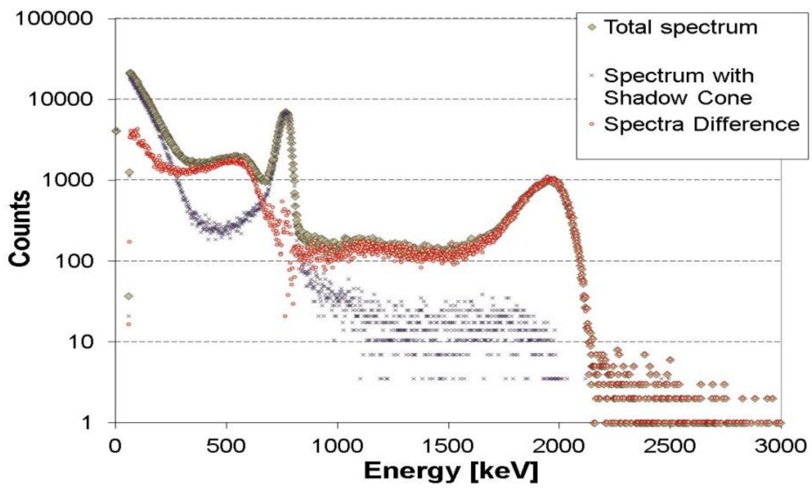

Figure 3. Pulse height distributions obtained during irradiations at PTB facility with 1.2 MeV neutrons. The original spectrum (Total) and the additional spectrum with a shadow cone between the target and the counter mainly due to room-returned neutrons. The difference is the calculated counter response from direct neutrons only.

3.3 Efficiency calibration measurements

The response of the system was measured for neutron energies: 0.5, 1.2 and 2.5 MeV. Irradiations were carried out at the low-scatter measurement hall of the PTB irradiation facility. In figure 3 the pulse height distributions obtained with and without the shadow cone, as well as the difference of the above two, are presented. Neutron fluencies were certified with uncertainties 4% to 8%. The efficiency of the system for the full energy peak is determined $1.64 \cdot 10^{-2}$ ±9.6%, $1.29 \cdot 10^{-2}$ ±5.2% and $7.2 \cdot 10^{-3}$ ±7.2% for neutron energies 0.5, 1.2 and 2.5 MeV respectively, for the irradiations conditions, thus when neutrons are crossing the face of the counter and are travelling parallel to the counter axis.

3.4 Simulation of counter response with GEANT4

Counter response was calculated using the Geant4 simulation kit (v.4.9). An accurate description of the counter regarding its geometrical characteristics, gas mixture and construction materials was provided by the manufacturer (LND Inc.). In order to take into account the displacement of the recoil events, namely the two different energy calibrations according to the origin of the events, during the calculation the particles that are found to deposit energy in the effective volume of the counter are identified and their deposited energy is scored to the corresponding calculated spectrum according to their identity. An example of the different calculated spectra coming from (n,p), (n,elastic) or other reactions with the above procedure is presented in figure 4. The spectrum originating from recoil events is first

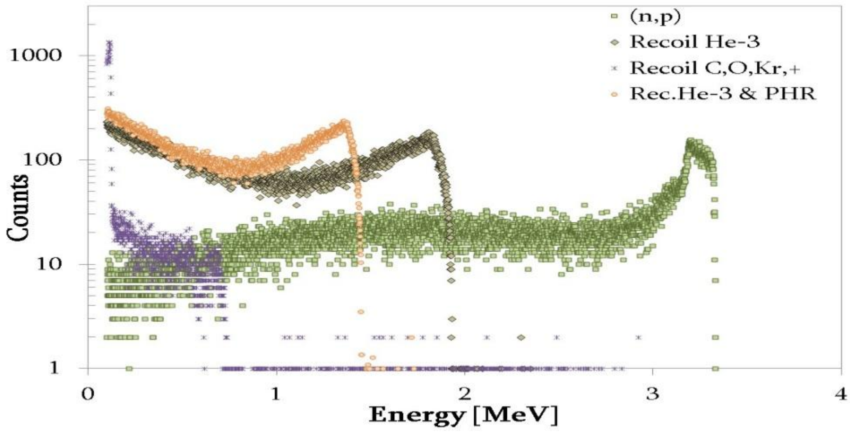

Figure 4. Calculated spectra originating from (n,p), (n,elastic) and other reactions for incoming neutron beam energy of 2.5 MeV. With dots the He-3 recoil spectrum after the application of the Pulse Height Reduction correction function.

treated with the correction function due to pulse height reduction (figure 4). Subsequently, each spectrum is folded with a Gaussian distribution according to the experimentally determined resolution function. It should be noted here that the resolution measured at recoil edges is about 3 times larger than that of the full-energy peaks. Finally, the spectra are added together with an exponentially decreasing function to account for gamma ray contribution in the lower part of the pulse height distribution. The parameters of this function are calculated from the counts registered in the first channels of the experimental spectra [8]. Comparison of the experimental spectra with the simulated ones is presented in figure 5.

3.5 Neutron spectrum unfolding.

The calculated response of the system can be used to unfold a spectrum in an unknown neutron filed. An example is provided below. Details about the neutron source and the irradiation are described in reference [12].Neutron energy range from 0.1 to 7 MeV is divided to several isolethargic bins. Counter response is calculated for each bin. Multiple regression analysis is performed between the experimental pulse height distribution data (independent variables) and the calculated counter response for each bin (dependent variables). Comparison of the experimental pulse height distribution with the simulated one using the determined neutron fluencies is presented in figure 6(a). The determined neutron fluencies are found in acceptable agreement with the expected ones obtained from the simulation with DCM-DEM code, figure 6(b) [13,14].

4. Conclusions

The response of a proportional He-3 counter was studied experimentally and the observed performance was implemented to the simulated response of the counter with Geant4. A satisfactory agreement between the calculated spectra and the experimental pulse height distributions obtained in calibrated neutron fields is observed. The calculated response of the counter was used to unfold spectra from an unknown neutron filed. The calculated neutron fluence distribution is in acceptable agreement with the expected from simulation for that field.

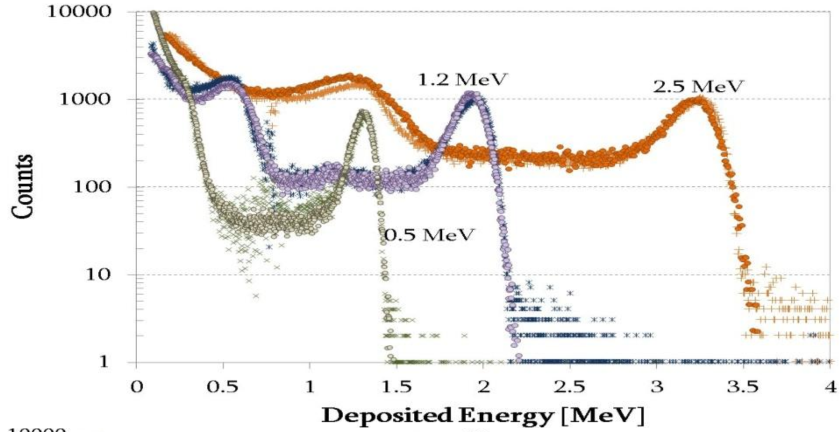

Figure 5. Experimental pulse height distributions (cross) and simulated spectra (dots) with GEANT4 for neutron beam energies 565 keV, 1.2 MeV and 2.5 MeV.

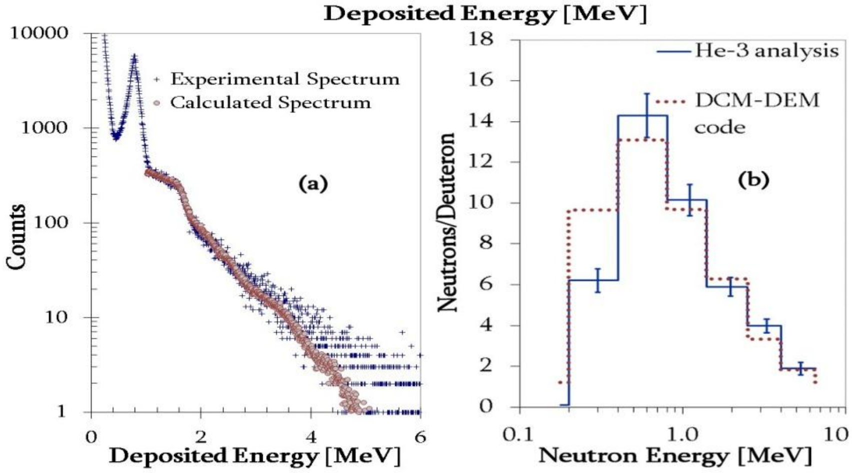

Figure 6. (a) Experimental (cross) and simulated with Geant4 (dots) pulse height distributions. (b) Energy distribution of neutron yield as it is figured out from the analysis of He-3 counter spectra and comparison with the calculated one by DCM-DEM code.

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