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Flat-Response Neutron Detector Using Spatial Distribution of Thermal Neutrons in a Moderator

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Abstract

We propose a novel neutron detector that realized flat-response using information of a spatial distribution of thermal neutrons in a moderator. The proposed detector consists of a ^{3}He Position Sensitive Proportional Counter (PSPC) and a cylindrical moderator surrounding the ^{3}He PSPC. The cylindrical detector is irradiated by neutrons along the cylinder axis. The spatial response of the ^{3}He PSPC are used to correct the detector response into flat-response. We adopte a weighting method to achieve flat-response, in which detected neutrons weighted depending on their detected positions are accumulated as the detector response. Through Monte Carlo simulation studies, we confirm that the flat-response neutron detector can be realized by correcting the response of the proposed detector using the weights determined by a Multiple Least Square Method (MLSM). Additionally, fundamental property of the ^{3}He PSPC is experimentally investigated to check applicability to the proposed flat-response neutron detector. We conclude that we should take account of the end effect when determining the weights and correcting the detector response.

KEYWORDS: *neutron monitor, flat response, long counter, position sensitive proportional counter, MCNP*

1. Introduction

Detection efficiencies of neutron detectors generally depend on incident neutron energy. When an absolute neutron fluence is to be determined, outputs of neutron monitors should be corrected using information on a neutron energy spectrum. Therefore, neutron detectors with an detection efficiency independent of incident neutron energy are useful in many fields of neutron science and engineering [1]. This type of detectors is referred to as "flat-response neutron detector." The flat–response means that the response, which is defined as detected counts per incident neutron, is constant independent of incident neutron energy. The standard flat-response detector is based on neutron moderation through elastic and/or inelastic scatterings. Cross sections of most neutron capture reactions decrease according to the "1/v law." The most of neutron detectors, therefore, are more sensitive for slow neutrons than fast neutrons. To effectively detect fast neutrons, the neutron detectors should be covered with a neutron moderator consisting of light elements. The neutron moderator makes the detection efficiency high for fast neutrons. Slow neutrons, however, have the probability that they are captured in the moderator and escape from it before they reach the detector. Because both effects cancel out each other, the neutron detectors surrounded with the moderator tend to be insensitive to incident neutron energy. The long counter is a well known standard flat-response neutron detector. The combination of a BF_3 tube and the cylindrical moderator was firstly suggested as a flat-response neutron detector by A. O. Hansen and M. L. McKibben [2]. The direction of incident neutrons is restricted into a single direction by a boron oxide neutron shield surrounded with a paraffin moderator. The long counter, however, shows depression in the detection efficiency in low energy region. Some holes are provided on the front surface of the long counter to prevent this depression.

The energy-response of this type detector depends on various geometric parameters, such as a thickness of the moderator, a diameter and a depth of the holes and so on. To design the flat-response detector using these geometric parameters, a large number of trials using the Monte Carlo simulations and/or basic experiments are required. Therefore, the perfect flatness has not been achieved yet.

In the detectors described above, however, the incident neutrons penetrate some distance along the cylinder axis depending on incident neutron energy. The average penetration depth increases with increase of the neutron energy [3][4]. We have proposed utilization of the information on the spatial distribution of the detected neutrons by the thermal neutron detector in the long counter to achieve completely flat-response. The BF_3 counter in a long counter is replaced with the ^{3}He position sensitive proportional counter (PSPC) [5]. The neutron response of this detector can be corrected using the information on the thermal neutron distribution in the long counter obtained with the ^{3}He PSPC.

In this paper, we propose the response correction method using spatial distribution of detected neutrons by the ^{3}He PSPC to achieve the completely flat-response. We discuss the response correction algorithms for a flat-response neutron detector with the ^{3}He PSPC through MCNP Monte Carlo simulation studies [6]. We additionally discuss the property of the ^{3}He PSPC through basic experiments to check applicability to the proposed flat-response neutron detector.

2. Detector Response

Figure 1 shows the geometry of the designed detector. The BF_3 thermal neutron detector of a long counter was replaced with a 20 cm long ^{3}He PSPC. The PSPC was surrounded with a polyethylene moderator. Polyethylene is a useful moderator because of high content of hydrogen atoms and suitability for machining. Neutrons entered from the left surface of the detector in **Fig. 1**. We calculated the spatial neutron distribution detected by ^{3}He(n,p) reactions in the ^{3}He PSPC through Monte Carlo simulations using the MCNP code. The 20 cm long ^{3}He PSPC was virtually divided into 20 regions with a 1cm width. **Figure 2** shows the calculated spatial responses for parallel mono-energetic neutron beams with energies ranging from 10^{-3} to 20 MeV. The spatial response is defined as the number of detected neutrons per incident neutron at each position in the ^{3}He PSPC. In **Fig. 2**, the peak positions in the spatial response shift to deeper positions from the surface with increasing neutron energy. These results indicate that the peak positions depend on the incident neutron energies and we can estimate the information on incident neutron energies from the spatial distribution of the detected neutrons.

3. Discussion on Response Correction Algorithms

3.1 Weighting method

We propose the response correction method using the spatial response obtained with the ^{3}He PSPC to improve the flatness of the response. We have adopted the weighting method to achieve the flat-response. In the conventional long counter, the response R is obtained by summing up all spatial responses over the whole counter and is written as;

$$R = \sum_i R_i \qquad (1),$$

where R_i is the spatial response at ith position. On the other hand, in the weighting method, each detection position has an individual weight and each spatial response is multiplied by these weight. The whole response R_c of the detector is obtained by summing up all the corrected spatial responses as follows;

$$R_c = \sum_i R_i \times w_i \qquad (2),$$

where w_i is the weight at ith position. In this technique, the detected neutrons weighted depending on each detected position are summed up as the response.

3.2 Simple Least Square Method (SLSM)

We firstly adopt the simple least square method (SLSM) to determine the individual weights. **Figure 3** shows the conceptual drawing of determining the individual weights, where R_s is a "standard response" that is the target value of the corrected response. The weights are derived from the spatial responses at some standard energy points to reduce the residual errors Δ(E) between the standard and corrected responses by means of the least square algorithm given as;

$$\frac{\partial}{\partial w_i} \sum_j \left(R_s - R_c\left(E_j\right)\right)^2 = \frac{\partial}{\partial w_i} \sum_j \left(R_s - \sum_i R_i\left(E_j\right) \times w_i \right)^2 = 0 \qquad (3),$$

where E_j is jth standard energy. At eight standard energy points (10^{-3}, 10^{-2}, 10^{-1}, 1, 5, 10, 15 and 20 MeV), spatial responses were calculated by using MCNP code, where the detector were irradiated by 10^7 neutrons for each energy. These spatial responses were used to determine the weights using Eq. (3). **Figure 4** shows the corrected response using the derived weights. The corrected responses are constant for the standard energy points. However, uncertainties of these corrected responses are relatively large. The spatial responses were also calculated for the other energy points, as well as at the standard energy points. The corrected responses at the energy points that are not used for weight determination are drastically scattering. The derived weights are considered to be trapped into local solution that is not the true one. This is considered that the derived weights are determined to make responses strictly constant at the standard energy points despite the fact that raw responses used for weight determination have statistical uncertainties.

3.3 Multiple Least Square Method (MLSM)

To solve the problem discussed above, we tried to improve the weight determination algorithm. In the SLSM, the weights are determined to make the responses strictly constant using only one response having statistical uncertainty, that is not a strictly true value, at each standard energy point. This results in oscillation of corrected responses as shown in **Fig. 5 a)**. We, therefore, have proposed to use multiple responses with statistical fluctuation for each standard energy point as shown in **Fig. 5 b)**. A number of the independent responses, including the spatial responses, were calculated and used for determining the weights according to **Eq. (3)**.

The ten spatial responses were actually calculated for each standard energy point, where the detector was irradiated by 10^6 neutrons in each response calculation. The total statistical uncertainty for each energy point is consequently equal to the case of the SLSM. We determined the weights using 80 responses, *i.e.* 10 responses at 8 energy points. We refer to this weight determination method as a Multiple Least Square Method (MLSM). **Figure 6** shows the corrected responses using the weights determined by the MLSM. Oscillation of the corrected responses is dramatically suppressed as compared with the case of the SLSM. The flatness of the corrected responses is improved as compared with the raw responses. We confirm that the flat-response can be achieved by correcting the response of the proposed detector that has the ^{3}He PSPC at the center of the cylindrical moderator, using the weights determined by the MLSM.

4. Experimental Characterization of ^{3}He PSPC

In above simulation studies, a neutron detection position in the ^{3}He PSPC is just the position occurring ^{3}He(n,p) reaction. However there is in fact some difference between the actual reaction position and the position outputted from the detector. In this section, we discuss the properties of the ^{3}He PSPC that is important when correcting the detector response. We fabricated the ^{3}He PSPC to characterize its fundamental properties, such as pulse height spectra and spatial profile of detected neutrons. The active length and the inner diameter of the tube were 21.6 and 1.32 cm, respectively. The filling gas was 0.7 atm ^{3}He and 0.3 atm CF_4, which shortens the range of ^{3}He(n,p) reaction products. The anode was a resistive nickel-chromium alloy wire with a 10 μm diameter. The applied voltage to the anode wire was 850 V. The collected charge was read out from both sides of the anode wire. The relative position of a detected neutron along the tube is derived from $S_r/(S_l+S_r)$, where the origin is the left end of the tube, where S_l and S_r were output signals from left and right sides of the tube, respectively. Total deposition energy is the sum of these signals, *i.e.* S_l+S_r.

To verify the property on position sensing, the fabricated detector, covered by five Cd sheets with 2cm width and 2 cm spacing, was irradiated by neutrons from a ^{252}Cf neutron source surrounded by a polyethylene moderator. **Figure 7** shows the deposited energy spectrum. There are a clear full energy deposition peak and the structures caused by a wall effect and/or an end effect. Since the filling gas pressure was insufficient to fully stop the products of a neutron absorption reaction in the active region, the structure caused by events escaping both products, a proton and a triton, was observed. **Figure 8** shows the spatial profiles obtained only for the full energy deposition events and for events occurring the wall and/or the end effects. Both profiles have a similar trend in the center region but have an obvious difference in the edge regions. When a full energy deposition event occurs, both proton and triton produced by a neutron absorption reaction are fully stopped within the active region of the tube. Since the filling gas pressure was low, both products must be projected into a nearly parallel direction to the tube axis to deposit full energy. In other words, neutron absorptions must be occurred at the longer distance from the edge of the tube active region than the range of tritons, which have the shorter range than protons, for full energy deposition. Consequently, no full energy deposition events can occur within the edge region. When determining the weights and correcting the detector response, we should take account of these properties.

5. Conclusions

We proposed a novel neutron detector that realized flat-response using information of a spatial distribution of thermal neutrons in a moderator. The proposed detector consists of the ^{3}He PSPC and the cylindrical moderator surrounding the ^{3}He PSPC. The cylindrical detector is irradiated by neutrons along the cylinder axis and the spatial response of the ^{3}He PSPC are used to correct the detector response into flat-response. We adopted the weighting method to achieve flat-response, in which detected neutrons weighted depending on each detected position are summed up as the detector response. Through the MCNP Monte Carlo simulation studies, we confirmed that the flat-response neutron detector can be achieved by correcting the response of the proposed detector using the weights determined by the MLSM. We additionally performed the fundamental experiments using the fabricated ^{3}He PSPC to check applicability to the proposed flat-response neutron detector. We concluded that we should take account of the end effect to determine the weights and to correct the detector response.

As future works, we will try to experimentally verify the feasibility of the proposed flat-response neutron detector. For these purposes, we should make the fundamental experiments at mono-energetic and broad spectrum standard neutron fields.

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Captions

Figure 1 Fundamental Configuration of the proposed flat-response neutron detector.

Figure 2 Calculated spatial distribution of neutron detection position in the ^{3}He PSPC for various incident neutron energies.

Figure 3 Conceptual drawing of determining the individual weights

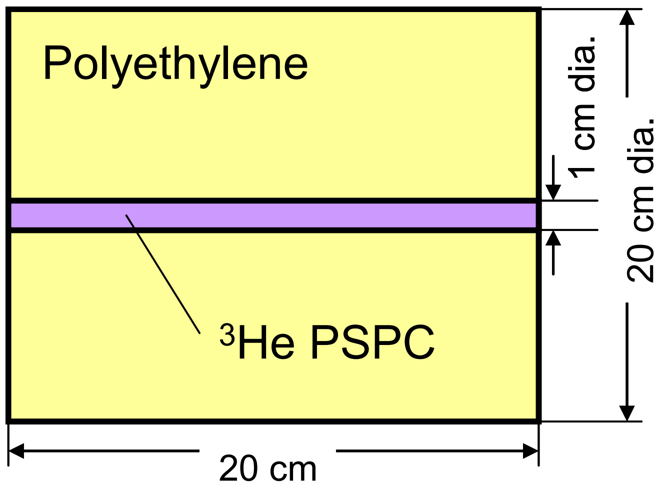
Figure 4 Corrected response using the weights derived from Eq. (3) by using SLSM a) at standard energy points (10^{-3}, 10^{-2}, 10^{-1}, 1, 5, 10, 15 and 20 MeV) and b) at other energy points.

Figure 5 Conceptual drawing of a) Simple Least Square Method (SLSM) and b) Multiple Least Square Method (MLSM).

Figure 6 Corrected response using the weights derived by using MLSM.

Figure 7 Energy deposition spectrum obtained by the fabricated ^{3}He PSPC.

Figure 8 Spatial profiles obtained by ^{3}He PSPC. Profiles obtained from full energy full energy deposition events and events occurring the wall and/or end effects are plotted for a comparison.



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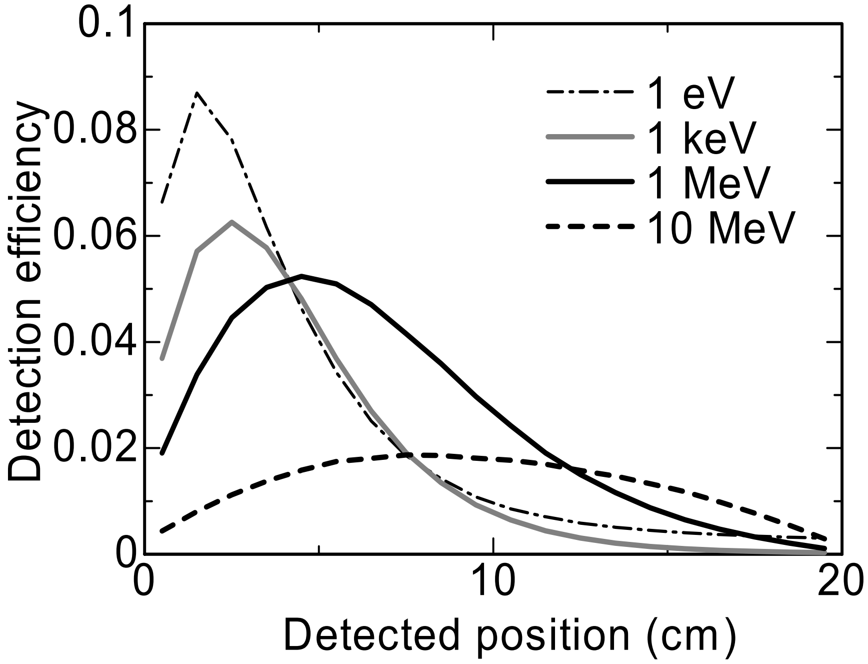
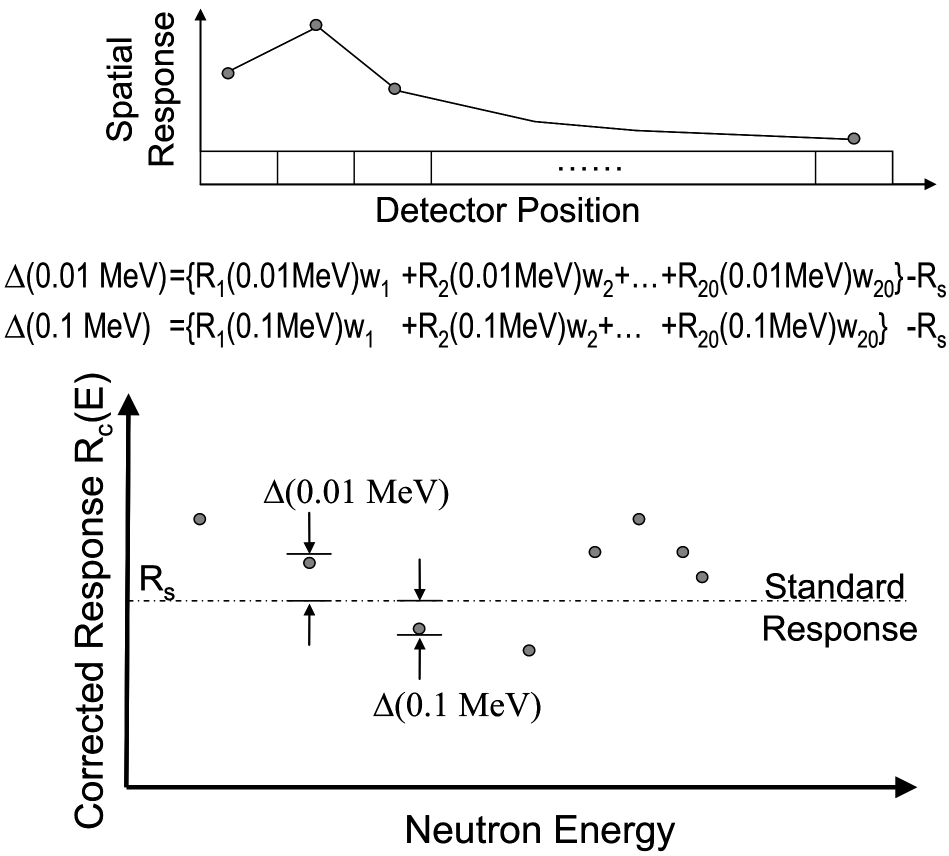


Figure 2 Calculated spatial distribution of neutron detection position in the ^{3}He PSPC for various incident neutron energies.



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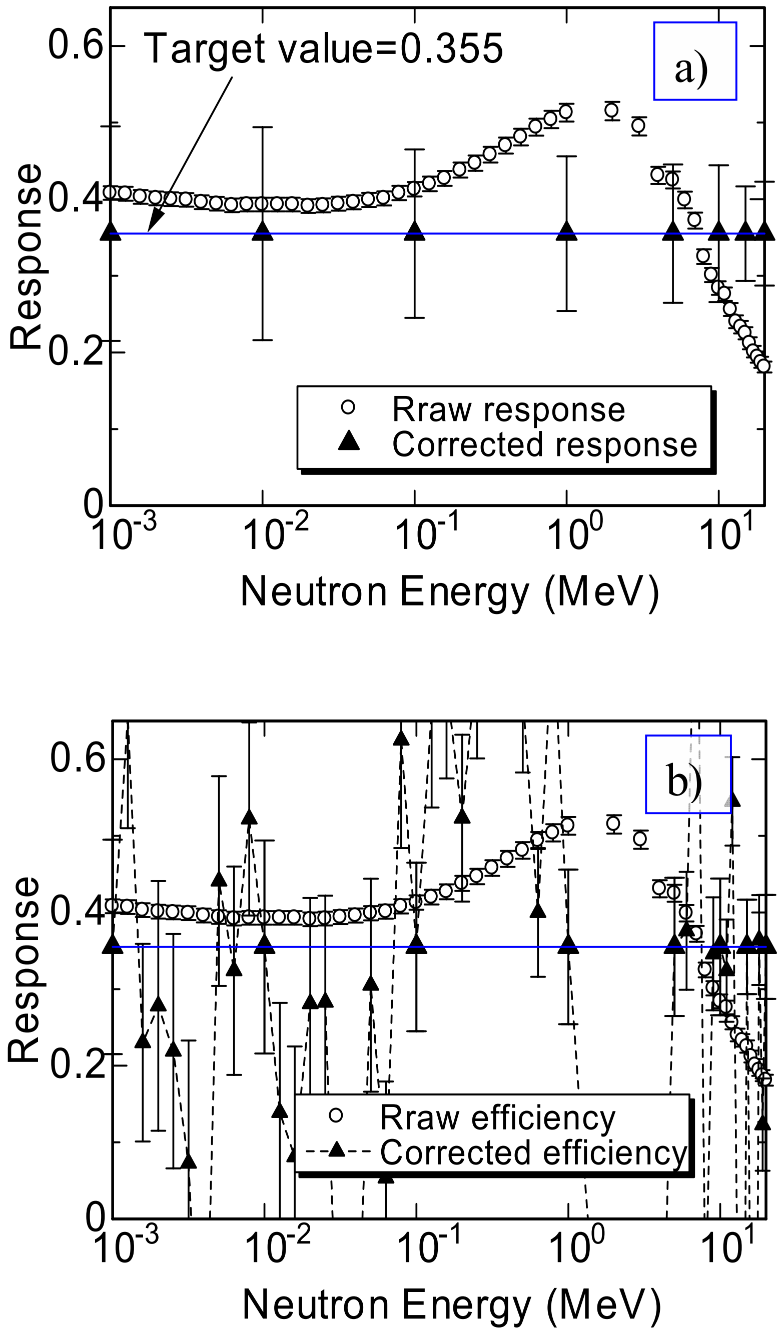
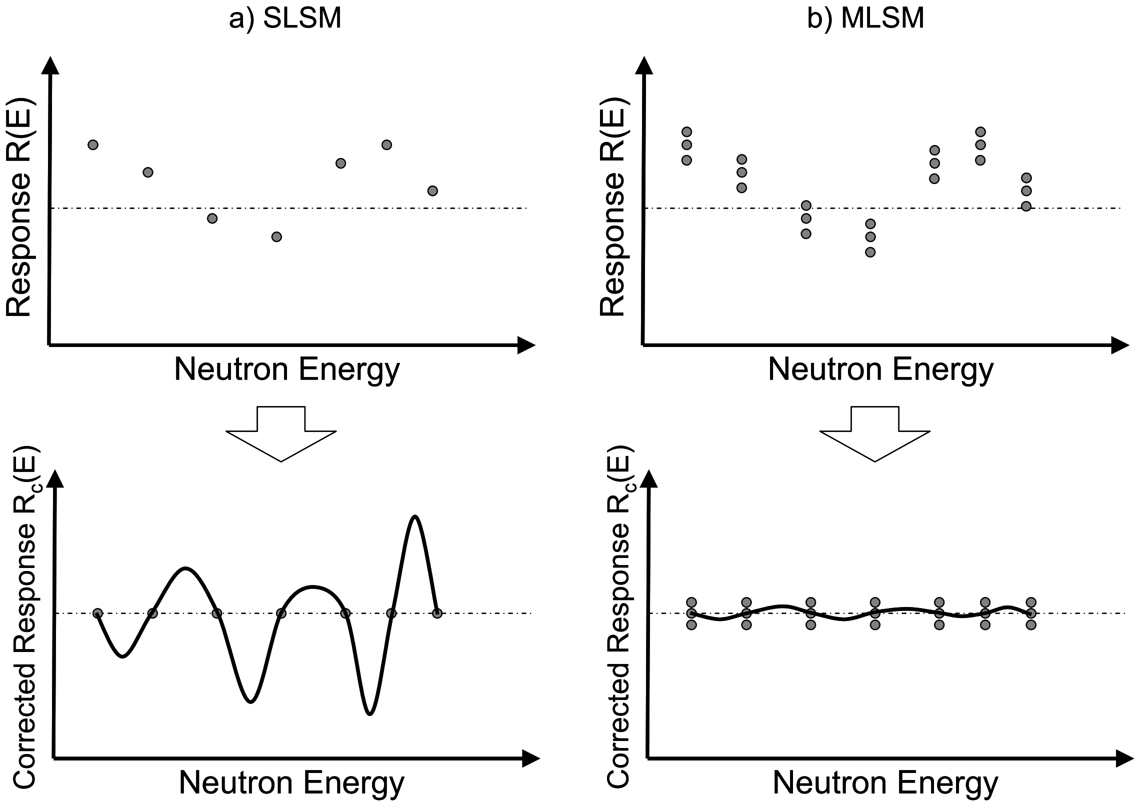


Figure 4 Corrected response using the weights derived from Eq. (3) by using SLSM a) at standard energy points (10^{-3}, 10^{-2}, 10^{-1}, 1, 5, 10, 15 and 20 MeV) and b) at other energy points.



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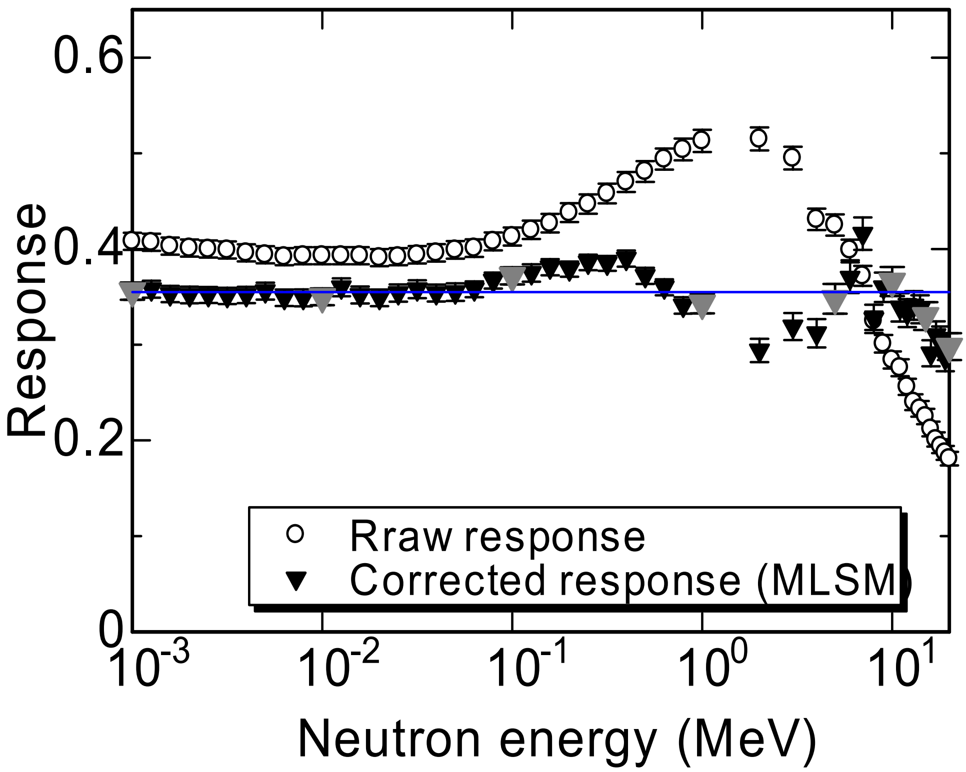

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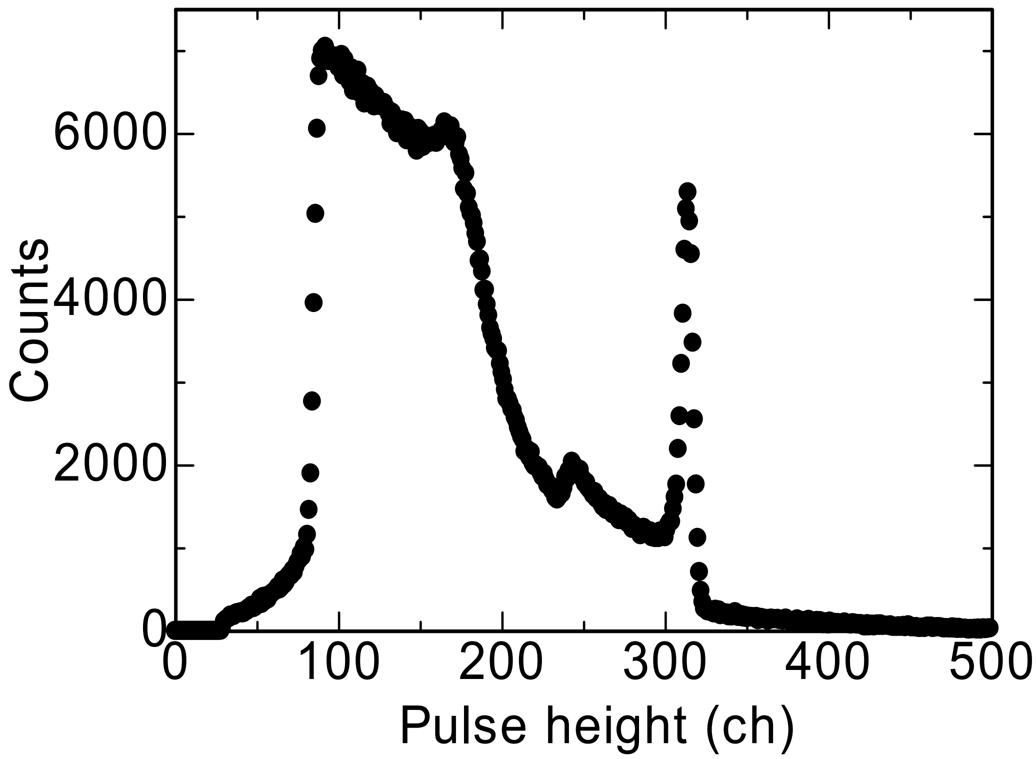

Figure 7 Energy deposition spectrum obtained by the fabricated ^{3}He PSPC.

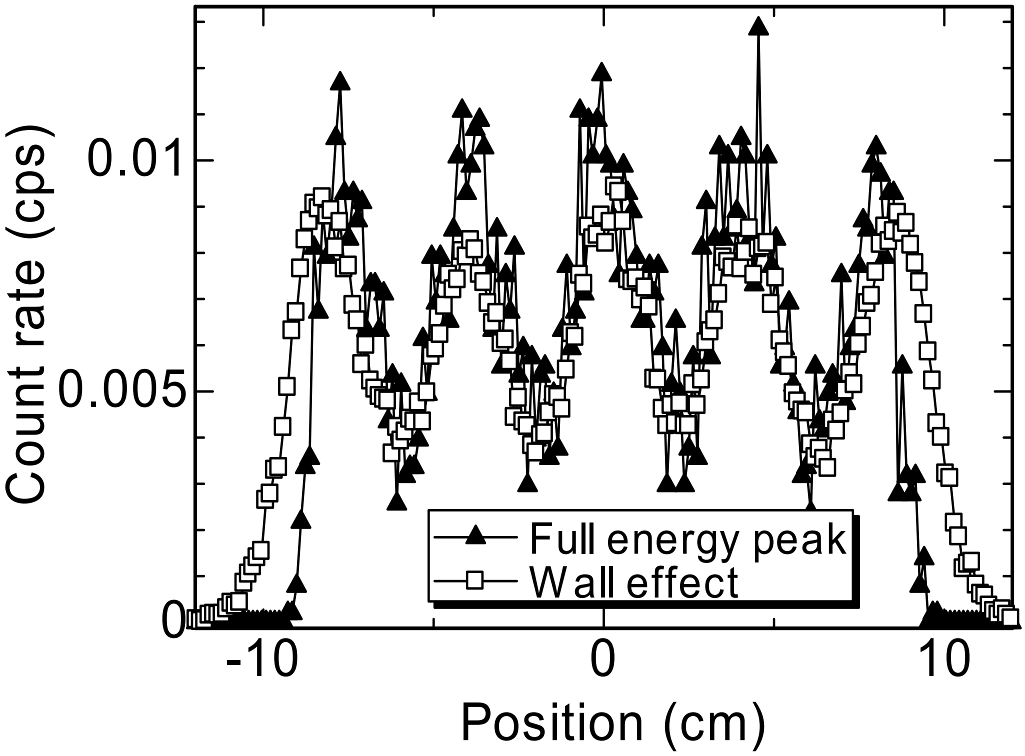

Figure 8 Spatial profiles obtained by ^{3}He PSPC. Profiles obtained from full energy full energy deposition events and events occurring the wall and/or end effects are plotted for a comparison.