Performance of a long plastic scintillator detector for neutron studies

L. Celano, G. Tagliente [1], G. D'Erasmo, A. Pantaleo, N. Colonna, E.M. Fiore,

INFN and Dipartimento di Fisica dell'Universita', V. Amendola 173, 70126 Bari, Italy

R. Rui

Dipartimento di Fisica dell'Universita', V. A. Valerio 2, 34127, Trieste, Italy

We present the performance of a very long position-sensitive plastic scintillator detector, to be used in hypernuclei studies with the Finuda apparatus at the Daϕne accelerator of Frascati, Italy. The detector response to neutrons of 40<E<100 MeV was measured in a dedicated experiment at Triumf, Vancouver. By comparing the measured response functions with the results of a Geant-based simulation, we have estimated the detector efficiency as a function of energy, light output threshold and impact position.

1 Introduction

Long position-sensitive plastic scintillator detectors are becoming popular in neutron studies, since they can provide, at relatively low cost, an efficient solid angle coverage together with continuous position identification [1–4]. In general, the low light attenuation and good timing properties which characterize many scintillator materials currently available, allow to obtain reasonably good energy, position and light output resolution even for very long position sensitive scintillator bars. For this reason, a barrel of 72 position-sensitive plastic scintillator detectors (the "Tofone" array) is under construction to be used, in conjunction with other subdetectors of the Finuda apparatus [5], in

[1] Present address: University of British Columbia, Vancouver, B.C., Canada, V6T 2A6

the trigger of the event and to measure non-mesonic decays of λ-hypernuclei at the Daϕne ϕ-factory in Frascati, Italy.

For an accurate measurement of the neutron λ-hypernucleus decay, it is of fundamental importance to determine the detector efficiency to neutrons in the energy range between 40 and 100 MeV (the energy of neutrons from the non-mesonic λ-hypernucleus decay is around 80 MeV). For long position-sensitive detectors, such efficiency is a function not only of the neutron energy and applied threshold, but also of the impact position, and therefore has to be characterized as a function of all three parameters. To this aim, we have performed an experiment at Triumf, Vancouver, Canada, in which we have measured the response of the Tofone module to neutrons of different energies. We have then compared the measured response functions to Montecarlo simulations based on the Geant simulation package, and in which the light production and attenuation properties of the detector have been included. From such simulations we have estimated the efficiency and its dependence on neutron energy, applied threshold and impact position.

2 The neutron detector

The basic module of the Tofone array consists of a trapezoidal bar of Bicron BC408 plastic scintillator 255 cm long, 10 cm thick and with the two bases of 10.7 and 11.6 cm respectively. For position reconstruction, the produced light is read out at both ends of the scintillator. The detector is wrapped with aluminum foil for a more efficient light collection, and sealed against external light with black tape. To keep the photomultipliers (PMT) outside the magnetic field of the Finuda apparatus, the produced light is deflected by 90 degrees by means of a lucite prism and transported to the PMTs via cylindrical light guides of 5 cm radius and 1 m long. The PMTs are the Philips XP2020 with the Cern type LE238 voltage devider, operated at a voltage of $\sim$ 1900 V. The impact position (X) and time-of-flight (ToF) of a particle hitting the detector are reconstructed with the following expressions:

$$X = c_0(T_R - T_L) + c_1 \qquad ToF = c_2(T_R + T_L) + c_3 \tag{1}$$

Here T_R and T_L are the measured time of the "right" and "left" PMT signals. For convenience, c_1 is chosen so that X represents the distance from one of the scintillator edges.

One of the fundamental problems associated with long scintillator detectors is the dependence of the collected light on the neutron impact position. Because of its effect on the detection efficiency, it is of of crucial importance to experimentally characterize the light attenuation process for the scintillator bar used. To this aim, we have performed a measurement of the light ouput produced by cosmic-rays traversing the 10 cm depth of the scintillator bar at various positions along the detector. The direction of the cosmic-rays was selected with two scintillator pads 5 cm wide, placed on opposite faces of the detector. Fig. 1 shows the measured light output as a function of the position. The light output was calibrated in MeV electron equivalent (MeVee) by assigning the deposited energy to the light output produced in the central position. The observed trend is well described by the following expression [4]:

$$PH(X) \propto e^{-\frac{X}{a}} + be^{-\frac{2L-X}{a}} \tag{2}$$

Here X is the distance of the impact point from the detector edge and L is the length of the detector. The line in fig. 1 represents the results of a best fit of the measured light output with eq. (2). The following values of the parameters were obtained from the fit: $a = 181$ and $b = 1.29$.

3 Response functions and efficiency

To measure the detector response function to neutrons in a wide energy range, we have employed the π^- absorption reaction at rest on ^{12}C. As a result of the reaction, neutrons of energy up to 100 MeV are produced, mainly from the quasi-free π^- absorption on a nucleon pair inside the ^{12}C nucleus [6]. The experiment was performed in the pion channel M8 at TRIUMF Vancouver, Canada, which delivered a 180 MeV/c π^- beam. The beam was degraded to an energy of a few MeV by means of a series of plastic degraders placed 2 m before the target. Pions were then stopped in 1 cm thick plastic scintillator acting as target. The beam direction was defined with the help of a scintillator counter placed between the degraders and the target at a distance of 1 m from the latter. A third scintillator placed immediatelly after the target and slightly bigger than it, was used as a veto counter to select only stopped particles. The neutron detectors used in the experiment were two prototype modules of the ToF array (Tofone) of the Finuda apparatus. They were monted at a distance of 127 cm from the target. Two long veto counters made of plastic scintillators 0.5 cm thick, were placed in front of the neutron detectors in order to reject charged particles produced in the reaction. Analog and timing signals of each PMT of the neutron detectors were recorded, with the ToF start provided by the scintillator target. The background, caused by random coincidences between stopped π^- and uncorrelated particles (environmental γ-s or cosmic-rays), was measured by delaying the neutron trigger by 2 RF periods of the Triumf cyclotron. The ToF, used to measure the neutron energy, was calibrated with prompt γ-rays emitted in the reaction, while a ^{60}Co source and cosmic-rays were used to calibrate the scintillator light output.

Figure 2 shows the background-subtracted response functions for neutrons of 70 MeV energy and for different positions along the scintillator bar. The solid and open symbols in the left panels represent the individual response functions for each end of the scintillator. The effect of the light attenuation is clearly visible for progressively increasing distances from one of the two extremes. However, the strong position dependence of the individual light outputs is overcome by constructing the geometric average L_g of the two recorded light outputs ($L_g=\sqrt{L_R \times L_L}$). A spectrum of L_g is shown, together with the prediction of a Montecarlo simulations (later described) in the right panels of the figure for the different positions. As indicated in ref. [4], L_g is essentially independent on the neutron impact position. On the contrary, the "effective" threshold on L_g shows a variation for progressively increasing distances from the center. This dependence results from the combination of the light attenuation process and of the requirement of a coincidence between the two PMTs signals. Though a unique value of the threshold for the whole detector cannot be defined, it is possible, by using eq (2), to estimate the threshold at any position, once its value is known for the central region of the detector. Therefore, in the following the value of the threshold in MeVee is given only for the central position.

Figure 3 shows the measured response functions for neutrons of 40$\pm$7, 60$\pm$12, 80$\pm$17 and 100$\pm$23 MeV energy. For simplicity, the geometric average L_g is shown only for the central position. The solid line represents the results of Montecarlo simulations performed with the package Geant [7]. In the calculations, we have included the light output of protons and other charged particles produced by the neutron interaction, as given by Cecil et al. [8]. The light output resolution, estimated from cosmic-ray measurements, was included in the simulations, together with the resolution of the neutron energy associated with the uncertainty in the interaction point inside the detector volume and the ToF resolution. Finally, the light attenuation process was introduced in the Montecarlo by means of eq. (2), with the experimentally determined values of the parameters. The measured and simulated response functions were normalized, similarly to ref. [9], to the same number of counts above threshold.

The reasonable agreement between the measured response functions and the Geant-based simulations in the whole energy range studied, validate the use of such simulations to estimate the efficiency of the scintillator bar as a functions of the energy, light output threshold and impact position. A comprehensive view of the results, for the detector configuration used (i.e. for a distance of 127 cm from the interaction region), is shown in figure 4. In particular, in panel (a) the efficiency is plotted as a function of neutron energy for a 4 MeVee threshold while in panel (b) it is shown as a function of the threshold on the measured light output, for 70 MeV neutrons. In both cases the efficiency refers to the central position. In panel (c) the efficiency is plotted as a function of the position for 70 MeV neutrons and a threshold of 4 MeVee.

It is interesting to speculate on this last observed trend, which is the result of two competing factors: on the one hand, for increasing distances from the center, the effective scintillator thickness traversed by the neutrons increases, because of the non-normal impinging direction. On the other hand, as previously mentioned, the effective threshold on the light output increases, thus causing a corresponding decrease of the efficiency (see panel b). Both effects can be quantitatively estimated on the basis of simple geometrical and light attenuation considerations. In particular, the effective threshold (Th) and thickness (S) can be expressed as a function of the impact position X by the following:

$$Th \propto \frac{Th_c}{e^{-\frac{x}{a}} + be^{-\frac{2L-x}{a}}} \qquad S = \frac{S_c}{cos(arctg(\frac{|X-X_C|}{d}))} \tag{3}$$

with Th_c the threshold at the detector center, x the distance from the farthest extreme and a and b the attenuation parameters relative to the scintillator bar used.

The above considerations indicate that it is possible to estimate the efficiency at any given position from the one relative to the detector center, but applying the appropriate threshold and thickeness corresponding to the new position, as extracted from (3). The dashed curve in fig. 4 represent the result of the method just described. The reasonably good agreement with the result of the complete simulation (solid curve), leads as a consequence, that the efficiency of a long scintillator bar to neutrons can be expressed solely as a function of neutron energy and light output threshold, since the dependence on the impact positions can be easily calculated for any experimental configuration from the light attenuation and geometrical factors of eqs. (3). A look-up table of the efficiency, currently in preparation, will be used in the reconstruction package of the Finuda apparatus.

4 Summary

We have studied the performance of a very long position sensitive plastic scintillator bar as a neutron detector. An array of such detectors will be used in the Finuda apparatus at Daϕne, to study neutrons emitted in non-mesonic decays of λ-hypernuclei. The light attenuation in the detector, which strongly affects the efficiency and its position dependence, has been characterized with cosmic-rays. The response functions to neutrons of energy between 40 and 100 MeV have been measured in a dedicated experiment at Triumf, Vancouver, and have been compared with the results of Geant-based simulations. After including the light attenuation property of the detector and all relevant resolutions, a close reproduction of the measured response functions is obtained. From the simulations, the efficiency has been estimated as a function of neutron energy, light output threshold and impact position. The authors wish to thank G. Antuofermo, A. Boggia, P. Cariola, G. Iacobelli, M. Sacchetti, G. Casamassima and P. Vasta for their technical support in setting up the experiment, and dr. N. Grion for useful suggestions and comments.

References

[1] S. Cierjacks et al., Nucl. Instr. and Meth. A 238 (1985), 354.

[2] R.C. Byrd et al., Nucl. Instr. and Meth. A 313 (1992) 437.

[3] A. Ahmidouch et al., Nucl. Instr. and Meth. A 326 (1993) 538.

[4] L. Lüdemann et al., Nucl. Instr. and Meth. A 334 (1993) 495.

[5] M. Agnello et al., Nucl. Phys. A585 (1995) C271.

[6] R. Madey et al., Phys. Rev. C25, 3050 (1982) and references therein.

[7] R. Brun et al., GEANT3, CERN DD/EE/84-1 (1986).

[8] R.A. Cecil et al., Nucl. Instr. and Meth. 161 (1979) 439.

[9] N. Nakao et al., Nucl. Instr. and Meth. A 362 (1995) 454. 285.

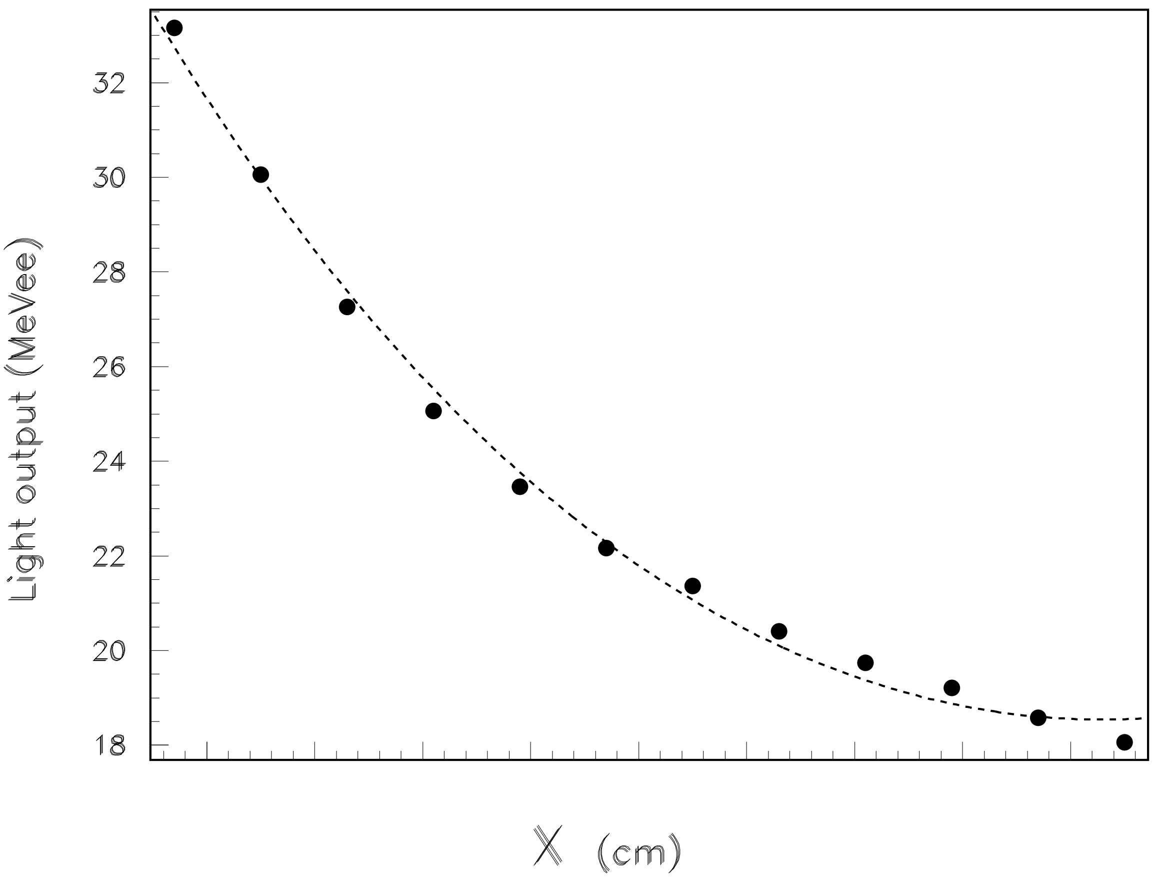

Fig. 1. Measured light output (symbols) produced by cosmic-rays traversing the 10 cm thickness of the detector at various positions along the scintillator bar. The abscissa represents the distance from one of the scintillator ends. The light output is calibrated in MeVee so to correspond to the deposited energy at the detector's center. The line is the result of a fit with eq. (2).

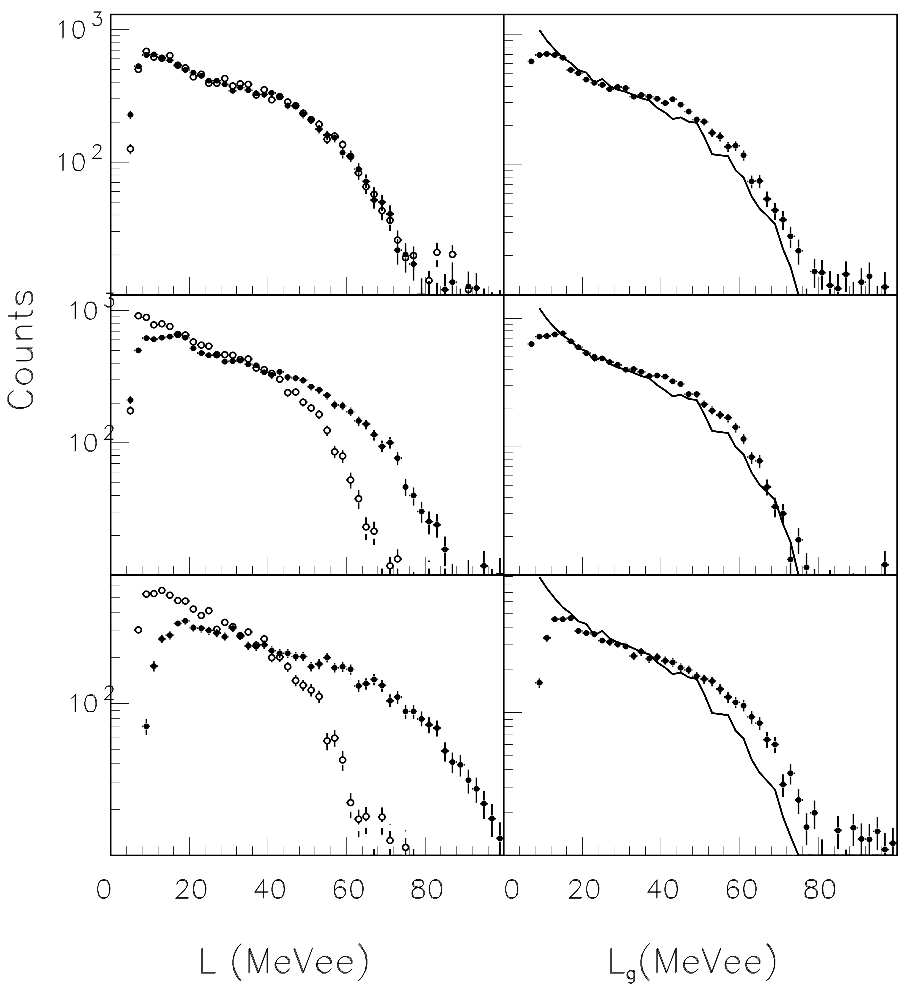

Fig. 2. Response functions of the scintillator bar to neutrons of 70 MeV energy, measured at different positions along the detector. In the left panels, the light output is plotted separatelly for the right and left ends (solid and open symbols respectively). The symbols in the right panels show the geometric light ouput L_g, compared with the results of a Montecarlo simulation (line).

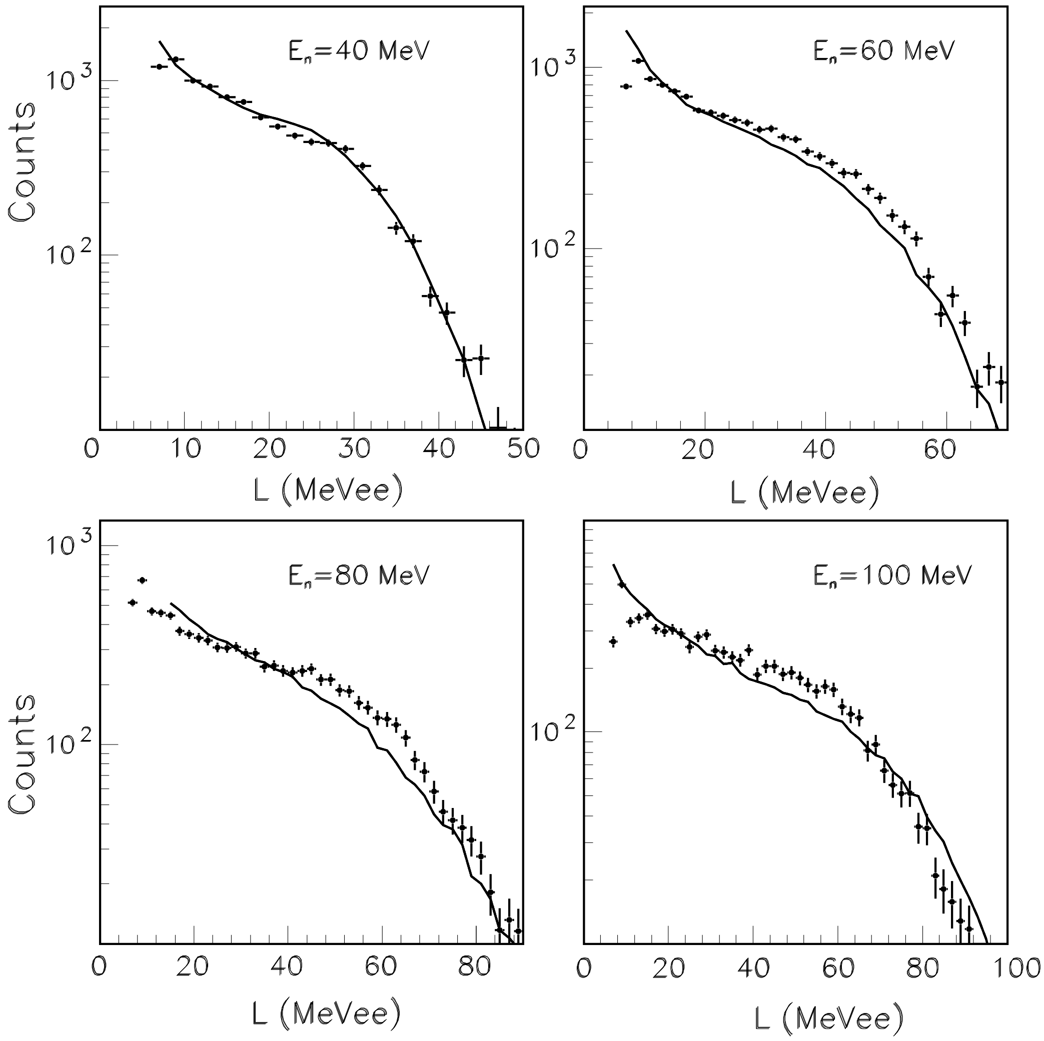

Fig. 3. Response function of the scintillator bar to neutrons of different energies detected in the central position. The line represents the results of Montecarlo simulations performed with a Geant-based code.

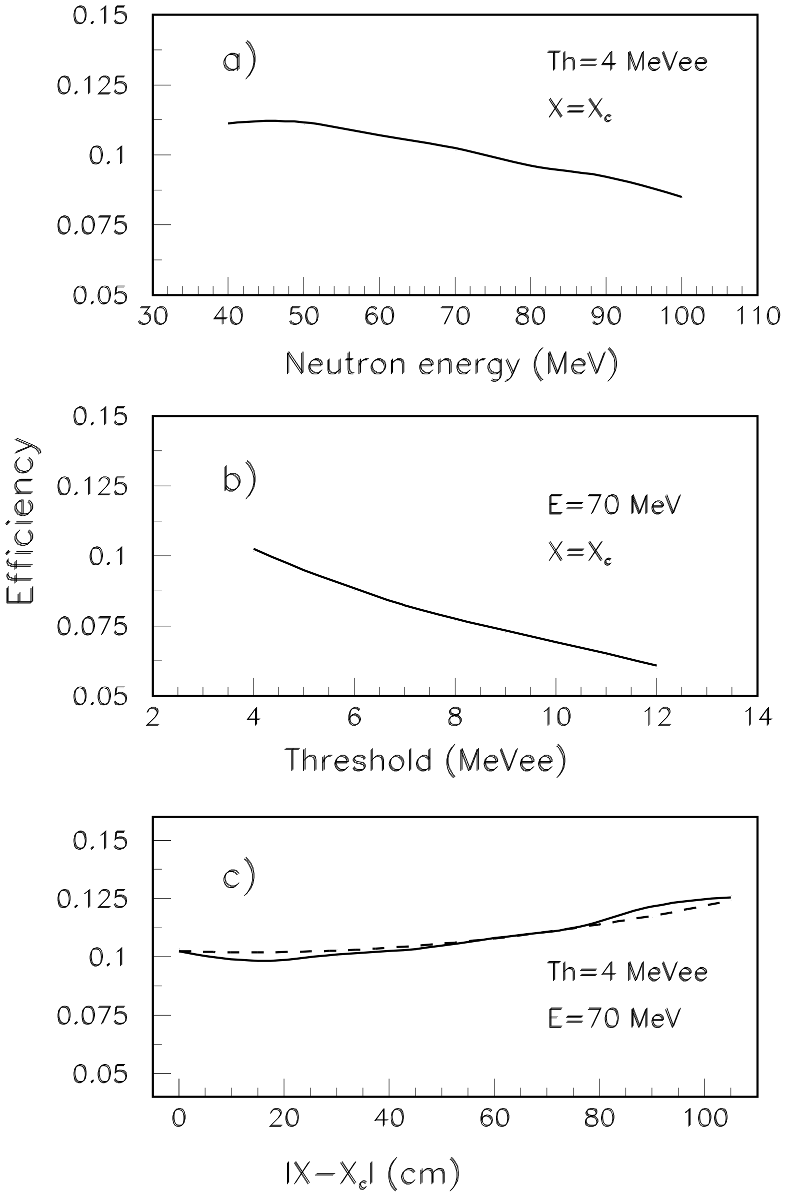

Fig. 4. The efficiency of the neutron detector predicted by the simulations, as a function of neutron energy (a), threshold (b) and impact position. The dashed line in panel (c) represents the efficiency for different positions as estimated from the one at the detector center corrected for the effective thickess and threshold (see text).