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A neutron detection efficiency study for BaF_2 crystal

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Summary. — A simple method for measuring the efficiency of BaF_2 crystal to neutrons of energy up to 11 MeV is here described. The method relies on the simultaneous detection of neutrons and gamma-rays from fission events of a ^{252}Cf source. The detection efficiency of a 5 cm thick BaF_2 crystal has been measured as a function of the neutron energy and threshold on the light output, and the experimental values have been compared with the results of a GEANT-based Monte Carlo calculation.

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1. – Introduction

Recently the use of BaF_2 crystals has become widespread for the detection of γ-rays [1] as well as light charged particles [2]. Furthermore their use as a phoswich for the detection of heavy ions has been recently proposed [3, 4]. As known, BaF_2 crystals have good timing properties [5] and high density, so that potentially they could also be used as neutron detectors, though in the past years this property was exploited only to reject neutron contamination in experiments involving BaF_2 crystals as γ-rays detectors. It is then clear that the possibility of using a BaF_2 phoswich as a unique detector has become very attractive, and an effort in this sense has been made with success during an experiment in Ganil, where all the reactions products from the reaction $^{40}Ar + ^{27}Al$ at 44 MeV/n were detected [6].

The use of a neutron detector usually requires the knowledge of the intrinsic neutron detection efficiency ε. As known, this efficiency depends upon many factors, like neutron energy, electronic threshold on the light output, shape and thickness of the crystal, etc... In recent years many authors have investigated this problem and measured the neutron detection efficiency in different energy ranges. In ref. [7] the efficiency was measured for neutron energies ranging from 0.5 to 10 MeV and for an electronic threshold of 60 keV-ee. In this measurement the neutrons produced by a ^{252} Cf source were detected by a 14 cm thick BaF_2 crystal in coincidence with the fission fragments detected by a silicon detector. The results show a neutron efficiency curve which strongly increases as a function of the neutron energy up to 3–4 MeV, and then reaches a plateau around a value of $\varepsilon = 0.3$. In ref. [8] the neutron energy was extended to 22 MeV, by using deuteron induced reactions on a thick LiF target. With respect to the previous study, on one hand the main features shown by the efficiency as a function of neutron energy were confirmed for two different electronic thresholds, 1 and 2 MeV, on the other hand an evolution of the reaction and detection mechanism was observed, involving mostly the reaction $(n, n'\gamma)$ for $E < 11$ MeV and more complicated reactions producing charged hadrons for $11 < E < 22$ MeV. In ref. [9] the efficiency was measured for neutron energies between 15 and 45 MeV, but with a threshold of 4.6 MeV-ee and introducing a neutron-gamma discrimination, which in fact cut all the neutrons leading in the crystal to reactions of the type (n, γ) and made ε increase as a function of the neutron energy in the whole range. Finally in ref. [10] the efficiency was measured for a 25 cm thick BaF_2 crystal between 15 and 150 MeV, with a threshold of 7 MeV-ee and n-γ discrimination.

Apart for ref. [8] from which absolute results can be extracted, it is in general very difficult to use these data for practical purposes, as they are greatly sensitive to the electronic threshold, the detection method, the thickness and shape of the crystal. Alternatively we propose a simple and practical method, similar to the one described in ref. [7], which allows to easily measure the detection efficiency of a BaF_2 crystal to neutrons of energy less than 12 MeV. In the following, after a description of the method, we shall present the results obtained for a 5 cm thick BaF_2 crystal.

2. – Experimental method

In the method here presented, the detection efficiency of a BaF_2 crystal to neutrons is measured by means of a ^{252}Cf source. As known, ^{252}Cf decays in two modes, with a half-life of 2.64 years: α-particle emission (96.91%) and spontaneous fission (3.09%). For each fission event, an average of $\nu = 3.77$ neutrons are emitted, accompanied by 6-8 prompt γ-rays [11]. In general fission events are selected by means of fragment detectors, which also provide the start for the neutron time-of-flight (ToF) measurement. However, because of the large number of γ's emitted in coincidence with neutrons in the fission process, one could also employ a γ-ray detector (such as a BaF_2 crystal) placed very close to the source to select fission events and as a start for the neutron time-of-flight. In fact, this choice has several important advantages: since no fission fragments have to be detected, a safer sealed ^{252}Cf source can be used; furthermore, the measurement does not require the use of an evacuated scattering chamber and can be performed in air. Finally, a trigger efficiency close to 100% can be easily achieved, since at least one γ-ray per event (out of the 6–8 emitted) is detected, provided that a sufficiently thick crystal is used and that a low threshold is kept on the detector. It should be mentioned, however, that in the proposed method the neutron detection efficiency cannot be obtained by simply dividing the number of n-γ coincidences by the number of singles (in this case the counts in the γ detector), because of the inevitable presence of environmental and delayed γ-rays from the source, of decay products originating from the contaminant nuclei present in the same BaF_2 crystal [12], and of cosmic-ray–induced reactions in the crystal. On the contrary, one has to use the source fission decay rate, which can be accurately determined by means of a dedicated measurement, as will be shown later on.

In the present experiment, carried out at the Catania Dipartimento di Fisica and INFN Laboratorio Rivelatori, two similar BaF_2 crystals were used, both of which had a 25 cm^2 hexagonal surface and were 5 cm thick. A sealed ^{252}Cf source, whose activity was approximately known, was placed in the middle of the front face of one of the two crystals (B_1), which acted as the trigger detector. The other crystal (B_2), whose detection efficiency to neutrons we planned to study, was positioned at 50 cm from the source. For each event, the PM signal of B_2 was used to start a time-to-amplitude converter (TAC), while the PM signal of B_1, properly time-discriminated and delayed, was sent to the stop of the TAC. The output of the TAC was sent to a multichannel analyzer. To ensure that at least one γ-ray for each fission event was detected in B_1, the

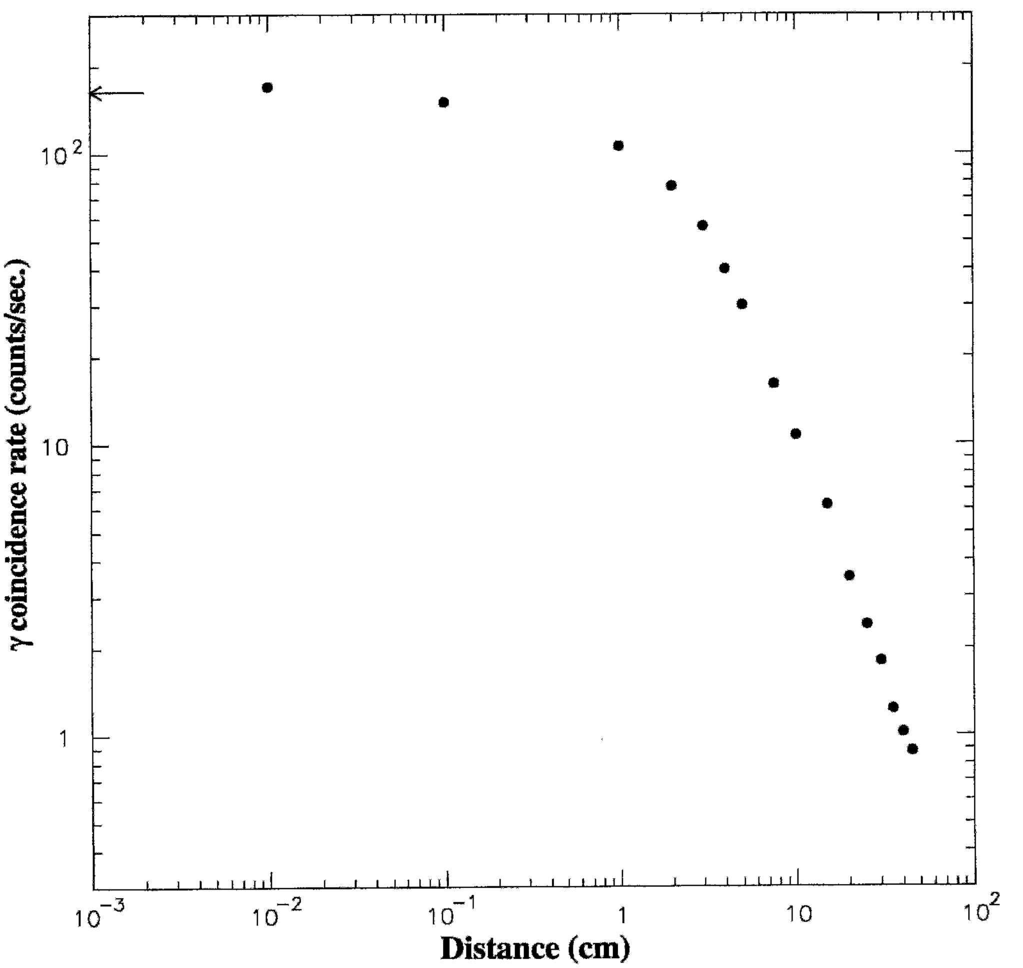

Fig. 1. – Coincidence rate between two BaF_2 crystals, measured with a ^{252}Cf source of ~ 170 fissions/s nominal activity (as indicated by the arrow on the Y-axis) as a function of the distance d. The source is placed in contact with one of the crystals, while the distance d of the other one from the source is varied between ~ 0 and 50 cm. The first point corresponds to the source sandwiched between the two detectors, for which a distance of ~ 0.1 mm has been approximately estimated.

threshold on this detector was kept as low as possible around ~ 200 keV-ee. Measurements were performed with different thresholds on B_2, from 500 to 1000 keV-ee. For the ToF calibration the γ-γ coincidence peak was used, while the threshold was calibrated with ^{22}Na and ^{60}Co sources. For the purpose of environmental background subtraction, a run was recorded in the same configuration but without the ^{252}Cf source.

On the assumption that B_1 triggered on all fission events, the efficiency of B_2 to neutrons emitted from the ^{252}Cf source is simply obtained by dividing the measured neutron spectrum $N_{\rm exp}(E)$, normalized to the total number of fission events, by the emission energy spectrum $P(E)$. This has accurately been studied and can be found in the literature (see, for example, ref. [13]). A special care instead has to be taken in calculating the total number of fission events, since for commercially available ^{252}Cf sources, like the one used in this experiment, the activity is not known with an accuracy generally better than 10-20%. Therefore we decided to perform a precise measurement of the activity by using the same experimental setup just described. In particular, we measured the number of coincidences between B_1 and B_2 for different distances (d) of B_2 from the source. In order to subtract a possible background not correlated to the source (the one, for instance, due to cosmic-ray reactions in the crystal or to the contaminant products in the same BaF_2 crystal, [12], see sect. **2**. «Results»), the experiment was repeated at the same distances without source. It should be mentioned that for this measurement it is essential to use two detectors with the same efficiency to fission γ-rays. To this aim, the crystal thickness and threshold of both detectors have to be the same. (In this case, therefore, the threshold on B_2 was lowered to the same value of B_1, ~ 200 keV-ee.) Figure 1 shows the results of the measurement. As expected from solid angle consideration, for sufficiently large distances a $1/d^2$ trend is observed. For smaller distances, however, the coincidence rate tends to saturate around a value consistent with the number of fission events expected from the source activity. This can be explained by considering that the large number of γ-rays emitted in each fission event leads to a coincidence probability of $\sim 100\%$ even for a partial coverage of the solid angle. The observed plateau in fig. 1 has two important implications: on the one hand it proves that the trigger detector (B_1) has an efficiency to fission γ-rays very close to 100%, since otherwise the coincidence rate would not tend to a saturation value. On the other hand, the value of the plateau provides a much more reliable estimate of the fission decay rate and has been used in the present analysis.

3. – Results

Figure 2a) shows the time-of-flight spectrum for a threshold on B_2 of 500 keV-ee. The two peaks in the figure are due to n-γ and (the more intense one) to γ-γ coincidences. From the latter, a time resolution of 700 ps at FWHM has been estimated. Few events in which a neutron is detected in the first BaF_2 crystal and a γ-ray in the second one are expected to lie in and to broaden the γ-γ peak. The origin of the peak on the right shoulder of the γ-γ peak is due to the x-γ coincidences generated either by cosmic-ray induced reactions in the two BaF_2 crystals or by the presence of impurities in the same crystals, where x stands for any nuclear products, like β-particles, α-particles or γ-rays, produced either in the interaction of a cosmic-ray with the crystal or in the disintegration processes of the contaminant nuclei present in the BaF_2 crystal [12]. This has been tested by measuring separately the same spectrum

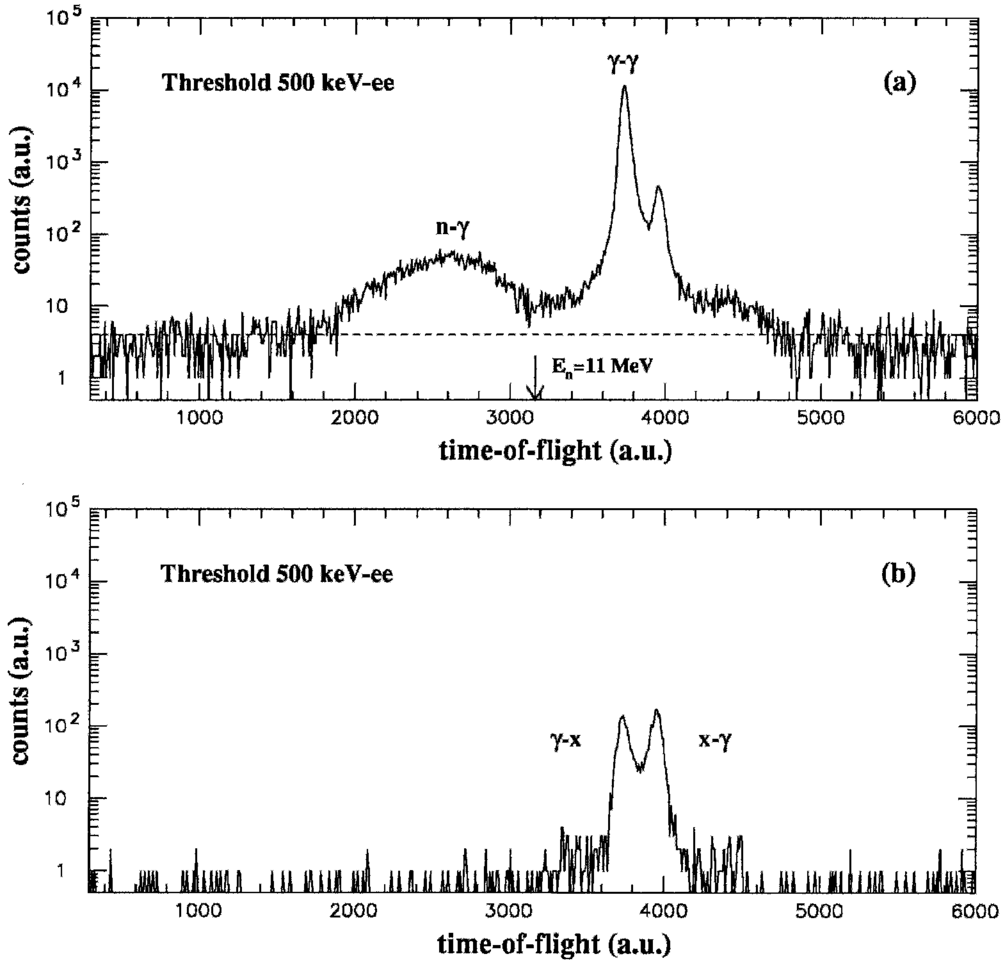

Fig. 2. – a) Time-of-flight spectrum with the ^{252}Cf source inserted, b) the same without source (background); see text.

without ^{252}Cf source, as reported in fig. 2b). The two observed peaks, indicated as x-γ and γ-x in fig. 2b), correspond respectively to the two cases in which a particle is produced and detected in the first detector and the associated γ-ray is detected in the second one, and viceversa. The time-of-flight difference between the two peaks is given simply by $2d/c$, where d is the distance between the two detectors and c the light velocity.

Also the different levels of background on the sides of the γ-x and x-γ of fig. 2b) can arise from second-order coincidences connected either with the same radioactive decay of BaF_2 impurities or with the cosmic-ray induced reactions in the crystal. To avoid a fine background analysis, that is beyond the aim of this work, the background in fig. 2a) has been subtracted as the flat dashed line and no neutron data has been used beyond the energy corresponding to the arrow shown in the same figure

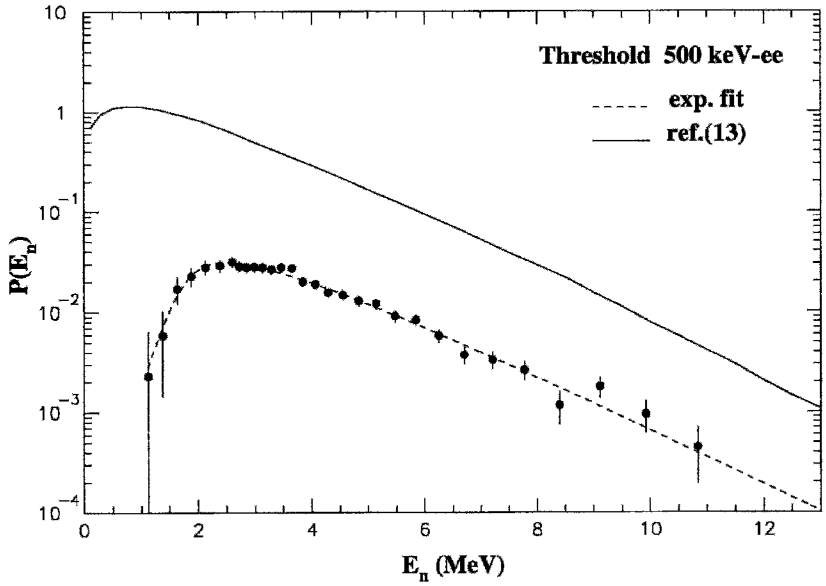

Fig. 3. – Neutron energy spectrum measured with an electronic threshold of 500 keV-ee. The spectrum has been normalized to the total expected neutron number. The smooth dashed-curve through the data has been obtained by a fit procedure (see text). The upper curve is the expected neutron spectrum from ref. [13] and is such that its area gives the total number of neutrons per fission event, $\nu = 3.77$.

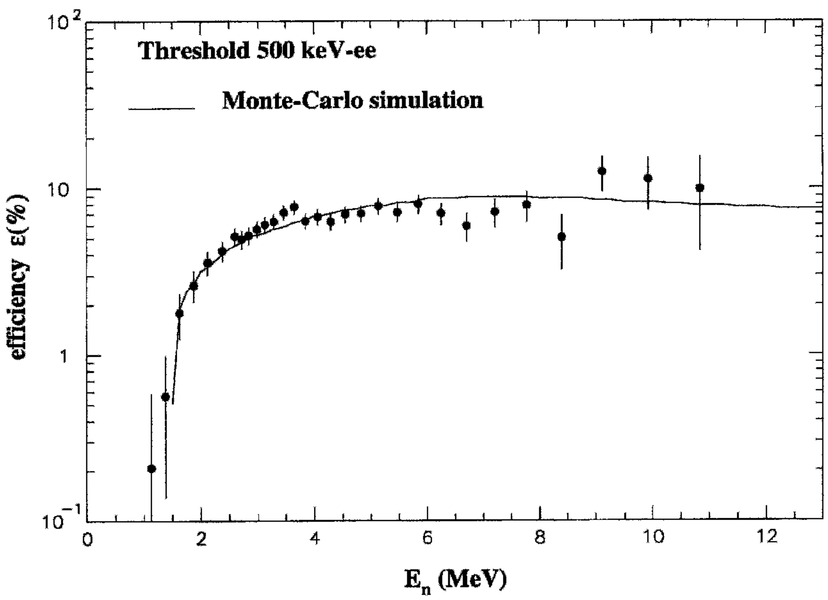

Fig. 4. – Experimental neutron efficiency as a function of the neutron energy and for a threshold value of 500 keV-ee. The curve is the result of a Monte Carlo simulation by the code GEANT, ref. [14].

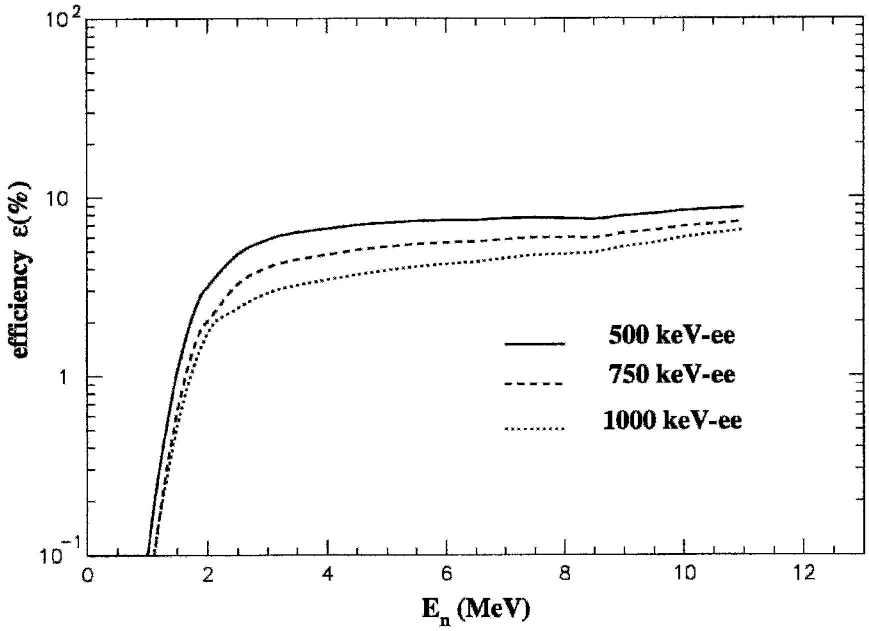

Fig. 5. – Experimental neutron efficiency curves as a function of the neutron energy and for three different values of the threshold, 500, 750 and 1000 keV-ee, respectively. The curves have been obtained by smoothening the experimental data.

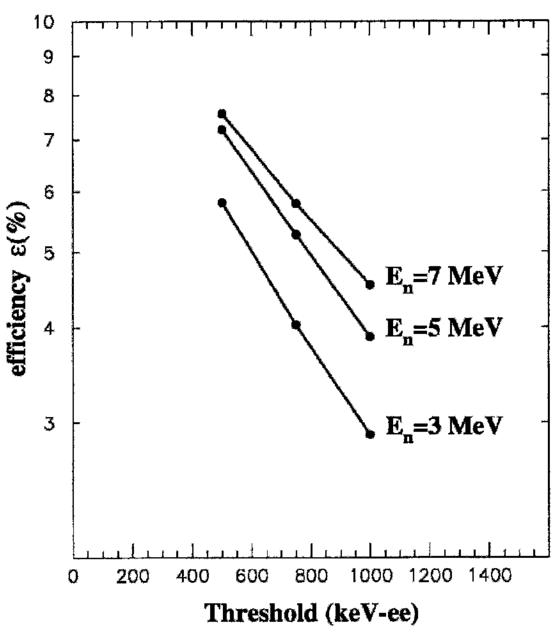

Fig. 6. – Neutron efficiency as a function of the electronic threshold and for different values of the neutron energy. The lines through the experimental points are only to guide the eye.

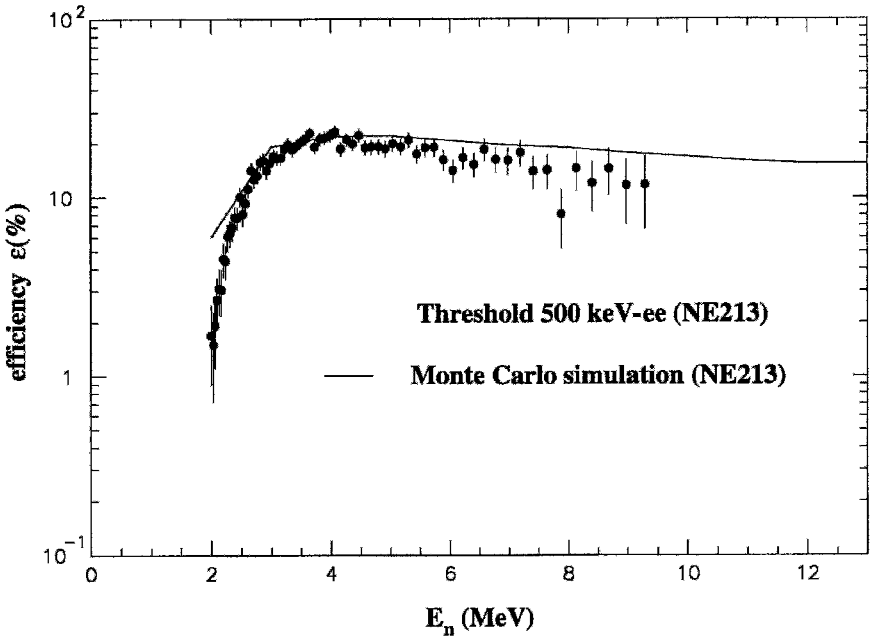

Fig. 7. – Neutron efficiency as a function of the neutron energy, for a 2″ thick NE213 liquid scintillator. The curve is the result of a Monte Carlo simulation, ref. [15].

(≈ 11 MeV), in the hypotesis that the γ-ray peak contribution completely vanishes below the same marked arrow.

Figure 3 shows the neutron energy spectrum obtained for an electronic threshold of 500 keV-ee, normalized to the total number of calculated fission events. The full line spectrum is taken from ref. [13] and is such that its area gives the neutron multiplicity in a fission event, $\nu = 3.77$. After fitting the experimental spectrum to two convenient different functions (one for the lower part of the spectrum near the threshold, and the other one for the plateau zone, dashed line), we have calculated the efficiency by simply dividing the two spectra. The results relative to an electronic threshold of 500 keV-ee are shown in fig. 4, where the measured efficiency is reported as a function of the neutron energy. In the figure, a Monte Carlo (MC) simulation performed with the code GEANT [14] is also shown. The observed behaviour of the efficiency as a function of the energy is very similar to the one reported in ref. [7, 8], *i.e.* very rapidly increasing for low energies (where the threshold is very important), and then approximately constant above $\simeq$ 4–6 MeV. The agreement of experimental data with the MC simulation is surprisingly good.

Figure 5 shows the efficiency as a function of the neutron energy, for the three electronic thresholds $E_s = 500, 750$ and 1000 keV-ee. The curves were obtained by fitting the data with the sum of two proper functions. The dependence of the efficiency on the threshold is shown in fig. 6, for some values of neutron energy. The trend is typically exponential, as already found by other authors [8].

As a validation *a posteriori* of the method here proposed, the neutron efficiency measurement has been repeated by replacing the second BaF_2 detector with a NE213 cylindrical liquid scintillation detector, 4″ wide, 2″ thick, triggered by the same BaF_2 detector described as B_1 in the text. The results, obtained with the method illustrated in the text and relative to a threshold of 500 keV-ee, are shown in fig. 7. We note that for neutrons of low energies the NE213 efficiency is higher than for the case of a BaF_2 crystal. However, starting at around 4 MeV the neutron efficiency for NE213 detector monotonically decreases as a function of the neutron energy, so that we expect that for neutrons of energy higher than ≈ 15 MeV the BaF_2 crystal neutron efficiency could be comparable or higher than the one of a NE213 liquid scintillator of the same thickness. Comparison with MC calculations performed following the methods of ref. [15] (thick line), shows a sufficiently good agreement, thus validating the method here proposed.

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