ELSEVIER

Nuclear Instruments and Methods in Physics Research A 416 (1998) 109–114

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Response of liquid scintillator detectors to neutrons of $E_n < 1$ MeV

N. Colonna*, G. Tagliente[1]

INFN, Dipartimento di Fisica, Via Amendola 173, 70126 Bari, Italy

Received 28 January 1998; accepted 16 March 1998

Abstract

The response of liquid scintillator detectors to neutrons of energy $0.1 < E_n < 1$ MeV has been studied with a ^{252}Cf source. The measured light output is compared with the results of Monte-Carlo simulations performed with the GEANT/MICAP package. A good agreement is obtained with an empirically determined light-energy curve for recoil protons. For a threshold of 10 keVee on the light output, the high efficiency measured for neutron energies as low as 0.1 MeV makes liquid scintillator detectors adequate for studies of low-energy neutron sources.

1. Introduction

The search for sources of low-energy neutrons ($E_n < 1$ MeV) is a subject of current interest for the growing number of applications in different fields, such as neutron activation analysis, neutron radiography, antimine detection and Boron Neutron Capture Therapy (BNCT). In particular, large efforts are being devoted towards an accelerator-based neutron facility for BNCT, in the hope of providing epithermal neutron beams of superior quality relative to the ones currently available at nuclear reactors [1,2]. Ideally, neutrons produced in the reaction should be characterized by an energy spectrum as low as possible, by high yield, and by little or no contamination of high-energy neutrons and γ-rays. Furthermore, the energy of the primary beam should be appropriately chosen so as to minimize the size and costs associated with the accelerator.

The choice of the right reaction relies on the accurate determination of the energy spectrum and yield of emitted neutrons at different angles. Since the data available in literature are in some cases scarse or incomplete, it is often necessary to perform specific measurements of low-energy neutron production in proton- or deuteron-induced reactions. To this aim, liquid scintillator detectors, commonly used for higher energy neutrons, can still be used for $E_n < 1$ MeV, provided that their efficiency is determined. Such detectors offer the unique advantage of allowing time-of-flight (TOF) measurements and γ-rejection through standard pulse-shape discrimination techniques. Furthermore, their response can, in principle, be easily and accurately simulated since, in the energy region of

* Corresponding author. Tel.: + 39 80 544 2351; fax: + 39 80 544 2470; e-mail: colonna@bari.infn.it.

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

0168-9002/98/$19.00
PII: S0168-9002(98)00485-9

interest, it is mainly determined by the accurately known n–p elastic scattering. However, the efficiency of liquid scintillator detectors to low-energy neutrons has not been thoroughly studied. Besides, Monte-Carlo simulations may not be completely reliable since very little is known on the light output of low-energy recoil protons. Parameterizations of the proton light yield, such as those proposed by Cecil et al. [3] or Madey et al. [4], can only be considered valid for proton energies in excess of 1 MeV, so that their extrapolation to lower energy is somewhat arbitrary and may lead to large errors in the estimate of detection efficiencies for low-energy neutrons.

In this paper we report on a measurement of the response function of liquid scintillator cells to neutrons of energy $0.1 < E_n < 1$ MeV. In Section 2 the experimental procedure is discussed. In Section 3 the results are presented, together with a comparison with Monte-Carlo simulations. A summary of the results is presented in Section 4.

2. Experimental procedure

The response of liquid scintillator detectors to low-energy neutrons has been studied by means of a ^{252}Cf source. The procedure employed in the present measurement is described in more detail in Ref. [5]. It relies on the simultaneous detection of neutrons and γ-rays from fission events of the ^{252}Cf source. To trigger on prompt γ-rays, and to provide the start for the neutron time-of-flight (TOF) measurement, a 10 cm thick BaF_2 crystal was used. A high trigger efficiency on fission events was ensured by positioning the crystal very close to the source, and by keeping a low threshold on the detector, ~ 150 keV electron equivalent (keVee). Considering the large number of γ-rays emitted for each fission and the high intrinsic efficiency to γ's that characterizes BaF_2 crystals, a very high probability for the detection of at least one γ-ray per fission event was achieved in the setup.

The neutron detector consists of a BC501 liquid scintillator cylindrical cell 5 in diameter by 2 in thickness. The cell is read out by a Philips XP2041 phototube, operated with an EG&G 2041 voltage divider. To minimize the background from in-scattering caused by the floor or other surrounding materials, the detector was positioned at a height of 1.5 m and at a minimum distance of 3 m from the walls. A light structure made of hollow aluminum tubes was used as support and a lead shield 3 mm thick was positioned around the scintillator cell to suppress environmental γ-rays and reduce random coincidences. The neutron detector was mounted at a distance of 50 cm from the source, to minimize the contributions of background relative to direct neutrons, without significantly worsening the energy resolution. For an average time resolution of the whole setup of ~ 3 ns, as estimated from the fission γ peak, the energy resolution goes from approximately 7% for 100 keV neutrons to $\sim 10\%$ for neutrons of 1 MeV. To ensure the detection of neutrons of energy as low as 100 keV, the electronic threshold on the neutron detector during the measurement was kept around an estimated value of 10 keVee.

The event trigger was constructed by requiring a concidence between the BaF_2 detector and the scintillator cell. Both the neutron TOF and the integrated light output of the scintillator cell were recorded, together with the zero-crossing time from a standard pulse-shape discrimination circuit [6]. For absolute time calibration, the prompt γ–γ coincidence peak was used. The measured light output was calibrated in absolute units with ^{137}Cs and ^{241}Am sources.

3. Results

Fig. 1 shows the measured time-of-flight spectrum before performing γ rejection or background subtraction. A rejection based on pulse-shape discrimination was only applied for light outputs above 60 keVee, since for smaller signals a worsening in the time resolution prevents from distinguishing γ and neutron lines. The residual background, caused by low-energy γ-rays, was subtracted assuming a flat distribution, whose level was determined in the region above 200 ns.

Response functions were constructed for different gates on the neutron energy. A light output spectrum of the background was constructed with a gate on the flat region of the TOF spectrum

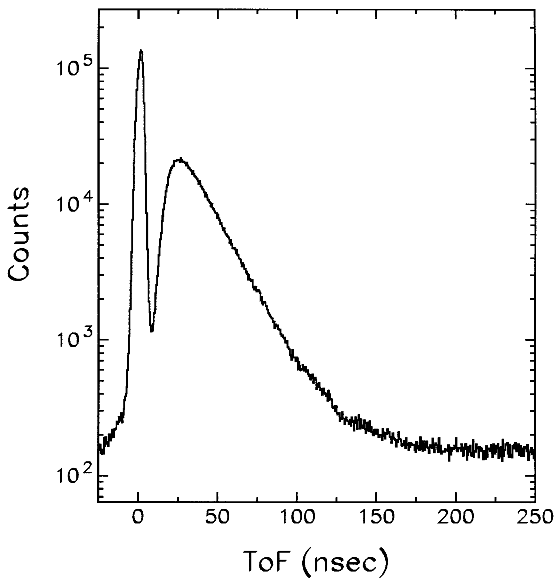

Fig. 1. Time-of-flight distribution from the ^{252}Cf source, measured with a BC501 scintillator cell. The start of the TOF was provided by a 5 cm thick BaF_2 crystal placed very close to the source. The distance of the neutron detector from the source was 50 cm.

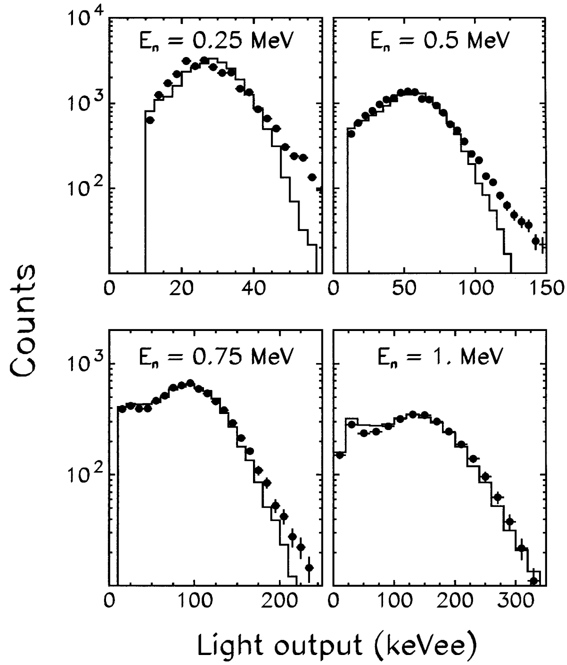

Fig. 2. Measured response functions (solid symbols) of the liquid scintillator cell to neutrons of energy between 0.2 and 1 MeV. The histograms represent the results of GEANT-based Monte-Carlo simulations.

($200 < \mathrm{TOF} < 250$ ns). This background was parameterized with two exponentials, which were then subtracted from the response functions at each neutron energy, after normalization for the corresponding width of the TOF gate. Fig. 2 shows the measured response functions for neutrons of four different energies between 0.2 and 1 MeV. For very low-energy neutrons, the response function is characterized by a pronounced peak, which is the result of the high probability for those neutrons to deposit a large fraction of their energy inside the scintillator volume. With increasing energy, complete absorption inside the cell becomes less likely (the probability for neutrons to deposit more than 80% of their initial energy inside the scintillator volume goes from approximately 70% for 0.1 MeV neutrons to $\sim 45\%$ at 1 MeV). As a consequence, the peak becomes progressively less important and the response function tends to a more typical close-to-flat shape.

The histograms in Fig. 2 represent the results of Monte-Carlo simulations performed with the CERN package GEANT [7]. In this package, a neutron is followed by the MICAP routine [8] until it escapes the detector or its energy falls below 100 eV. For each interaction the energy deposited by secondary products, in this case recoil protons, is converted into light by means of an appropriate light-energy curve. Together with the interaction cross section, the light yield of the scintillator to protons or other charged products is a fundamental ingredient in the simulation of the response function. However, contrary to the n–p scattering cross section, known with good accuracy at all energies, the light conversion process is not sufficiently well known for proton energies below 1 MeV. Two commonly used curves [3,4] dramatically understimate the light output distribution of low-energy neutrons. A recently proposed curve [9] produces more realistic response functions, though some discrepancy still exist at very low energy. To closely reproduce the detector response function for neutron energies as low as 100 keV we have slightly modified the parameters used in the functional form of Ref. [9]. The new emperically determined parameters of the light-energy curve are: $a_1 = 0.64723, a_2 = 0.96020, a_3 = 0.64180, a_4 = 1.0826$. Compared with Cecil's prescription, the new curve is characterized by a more gradual fall at low energy, thus indicating that saturation effects may be substantially less significant at these energies than previously believed.

For a meaningful comparison with the data, most experimental conditions were included in the simulations. Neutrons were generated with the theoretical energy distribution of Ref. [10], isotropic in space and at a distace of 50 cm from the detector. The simulated time of the interaction in the scintillator was recorded, so that a "reconstructed" energy could be obtained from the TOF with the same procedure used for the experimental data. Both the time resolution, measured from the γ–γ coincidence peak, and the light output resolution, estimated by means of the ^{137}Cs source, were included in the simulations.

The simulated response functions, shown by the solid histograms in Fig. 2, are normalized to the experimental ones with the same factor used for the efficiency (see discussion below). A satisfactory overall agreement can be observed between simulated and experimental distributions at all energies. Some discrepancy is observed on the tail of the distribution for the lowest energies, probably connected to an underestimate in the simulations of the light and time resolution or caused by a contamination in the data of higher energy in-scattered neutrons. The generally good agreement between the measured and simulated response functions constitutes a proof of the validity of the Monte-Carlo calculations, and ensures that the effect of the threshold on the detection efficiency can be correctly estimated by the simulations presented here.

In the present measurement, the efficiency of the neutron detector is given by the ratio between the measured energy spectrum and the normalized emission distribution. Fig. 3 shows the neutron energy distribution, reconstructed from the TOF (symbols), together with the contribution of the random background (dashed histogram). The solid histogram represents the predicted energy spectrum obtained by multiplying the emission probability reported in Ref. [10] by the neutron multiplicity per fission ($\nu = 3.77$) and by the number of source fissions integrated over the time of the measurement. This last number relies on the precise knowledge of the source activity. Contrary to Ref. [5], it was not possible in this experiment to accurately determine the fission rate of the source, because of the finite dimension of the source case. The use of the nominal source activity for normalization purposes results in a systematic discrepancy between simulated and experimental efficiency of $\sim 30\%$ (for $E_n > 1$ MeV). For this reason, it was decided to renormalize the experimental results to the Monte-Carlo predictions in the high-energy region ($1 < E_n < 3$ MeV), since at those energies the efficiency is not significantly affected by the threshold or by details of the light output of recoil protons.

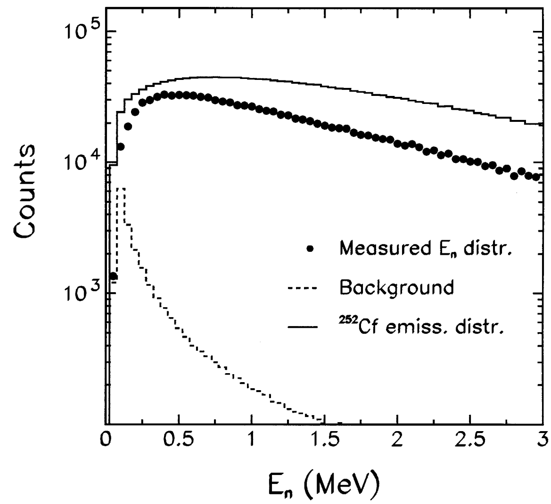

Fig. 3. Energy spectrum of neutrons emitted from the ^{252}Cf source (solid histogram), reconstructed from the measured TOF. The dashed histogram represents the contribution of the random background, modelled as a flat TOF distribution at the level measured above 200 ns (see Fig. 1). The dotted histogram represents the energy distribution of the emitted neutrons, from Ref. [10].

Fig. 4 shows the comparison between the measured efficiency (solid symbols) and the results of GEANT-based calculations, for three different

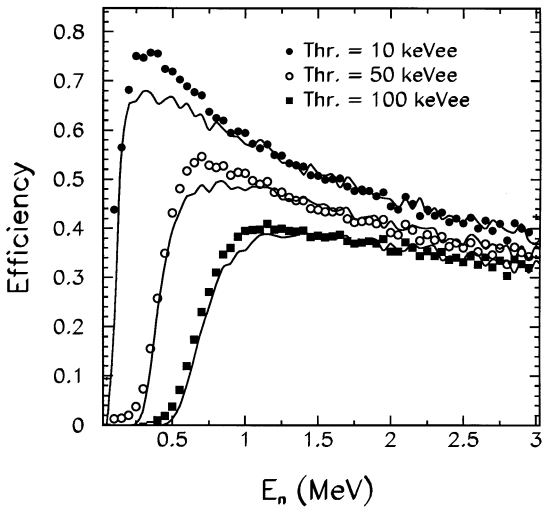

Fig. 4. Symbols: measured detection efficiency of 5 cm thick liquid scintillator cell as a function of neutron energy for three different values of the light output threshold. The curves represent the result of GEANT-based Monte-Carlo simulations. The experimental efficiencies are normalized to the simulations in the range $1 < E_n < 3$ MeV for the 10 keVee threshold. The same normalization factor is applied on both other cases.

values of the threshold on the light output. The general trend of the measured efficiency is well reproduced by the calculations, in particular, the sharp rise around $E_n = 100$ keV for the 10 keVee threshold. A small discrepancy is observed between the measured efficiency and the Monte-Carlo results for neutron energies below 800 keV. The observed difference could be the result of a possible inadequacy of the theoretical formula of Ref. [10] in describing the low-energy part of the emission spectrum from the Cf source. Furthermore, one cannot exclude minor shortcomings in the Monte-Carlo calculations. However, most probably the experimental efficiency is overestimated due to contamination of neutrons in-scattered from the BaF_2 trigger detector. An attempt to estimate the amount of in-scattering by means of a shadow bar did not give satisfactory results, possibly because the scattering material is very close to the source and a sizable fraction of scattered neutrons are also blocked by the shadow bar. However, simulations of the neutron interaction in the BaF_2 crystal indicate a contribution from in-scattering at a few percent level, qualitatively consistent with the observed difference.

4. Summary

The response function of liquid scintillator detectors to neutrons of $0.1 < E_n < 1$ MeV has been studied with a ^{252}Cf source. The light output of recoil protons at those energies is significantly higher than predicted by parameterizations generally used at higher energies. When a new light-energy curve is used, a close reproduction of the measured response function is obtained with a GEANT-based Monte-Carlo simulation. For a threshold of a few keVee, an efficiency higher than 70% is measured for the 2 in thick liquid scintillator cells. While for energies below 0.1 MeV the use of a different type of detector is certainly more appropriate [11], the high measured efficiency of standard liquid scintillator detectors for $E_n > 0.1$ MeV makes them still suitable for studies of low-energy neutron sources.

5. Acknowledgements

The authors wish to thank Mr. P. Cariola and A. Masciullo for their technical support in mounting the setup. The author also acknowledge Dr. A. Pantaleo and G. Lanzano' for useful discussions and comments.

References

[1] R.F. Barth, A.H. Soloway, R.M. Brugger, Cancer Investigation 14 (1996) 534.
[2] J.W. Kwan, O.A. Anderson, L.L. Reginato, M.C. Vella, S.S. Yu, Nucl. Instr. and Meth. B 99 (1995) 710.
[3] R.A. Cecil, B.D. Anderson, R. Madey, Nucl. Instr. and Meth. 161 (1979) 439.
[4] R. Madey, F.M. Waterman, A.R. Baldwin, J.N. Knudson, J.D. Carlson, J. Rapaport, Nucl. Instr. and Meth. 151 (1978) 445.
[5] G. Lanzano, E. De Filippo, M. Geraci, A. Pagano, S. Urso, N. Colonna, G. D'Erasmo, E.M. Fiore, A. Pantaleo, Nuovo Cimento A 110 (1997) 505.
[6] P. Sperr, H. Spieler, M.R. Maier, D. Evers, Nucl. Instr. and Meth. 116 (1974) 55.

[7] R. Brun, M. Hansroul, J.C. Lasalle, GEANT3, CERN DD/EE/84-1, 1986.
[8] J.O. Johnson, T.A. Gabriel, Technical Report TM-10340, ORNL, 1988.
[9] N. Colonna, L. Celano, G. D'Erasmo, E.M. Fiore, L. Fiore, V. Paticchio, G. Tagliente, G. Antuofermo, G. Iacobelli, M. Sacchetti, P. Vasta, A. Pantaleo, Nucl. Instr. and Meth. A 381 (1996) 472.
[10] J. Cub, E. Finckh, K. Gebhardt, K. Geissdorfer, R. Lin, J. Strate, H. Klein, Nucl. Instr. and Meth. A 274 (1989) 217.
[11] E.A. Kamykowski, Nucl. Instr. and Meth. A 317 (1992) 559.