

Study of n- γ discrimination for 0.4–1 MeV neutrons using the zero-crossing method with a BC501A liquid scintillation detector

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Abstract: An experimental system aimed at n- γ discrimination using the zero-crossing method with a $\phi 3'' \times 2''$ BC501A liquid scintillation detector was established and tested with an Am-Be neutron source. Two-dimensional plots of energy versus zero-crossing time were obtained. The quality of n- γ discrimination was checked by the figure-of-merit (FOM), the neutron peak-to-valley ratio, and the proportion of leaked neutrons over all neutron events. The performance of n- γ discrimination in terms of FOM was compared with previous work done by other groups. The n- γ discrimination in four different energy regions with an interval of 0.1 MeV between 0.3 MeV and 0.7 MeV was studied, and the results indicate that the n- γ discrimination threshold can go down to 0.4 MeV.

Key words: n- γ discrimination, BC501A liquid scintillator, neutron energy spectrum

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1 Introduction

The measurement of neutron energy spectra is of great importance in many basic research studies and applications, such as in nuclear reactor control, accelerator design, nuclear radiation protection, and nuclear structure research. It has been found that all neutron fields coexist with an associated γ -ray background, and that this arises as a result of the scattering reactions of the neutrons with materials in the environment and as direct byproducts of the primary reaction producing the neutron field. Thus an effective n- γ discrimination technique is necessary for neutron detection. One of the most effective methods is the use of a liquid scintillator coupled with a photomultiplier tube (PMT) together with the n- γ discrimination technique.

The BC501A liquid scintillator is widely used in fast neutron detection and energy spectra measurements for its high detection efficiency and excellent n- γ pulse-shape discrimination property [1, 2]. The key feature of BC501A for fast neutron detection in the presence of γ -rays is that it shows different scintillation components depending on the specific energy loss of the ionizing particle. Appropriate pulse shape analysis methods allow the discrimination of incident neutrons from γ -rays by the use of such differences in the light emission. Furthermore, the relationship between the deposited energy and the total ionization depends on the types and en-

ergy of the ionizing particles. For this reason, this ionization is usually described in keVee or MeVee, where the ee stands for the electron-equivalent energy units [3]. There are usually three methods used to carry out n- γ discrimination based on pulse shape analysis: the rise-time method, the zero-crossing method, and the charge comparison method [4–6]. The first two utilize the difference in the time information of neutron and γ -ray events to separate them. The charge comparison method is implemented by integrating each signal over two time intervals by QDC. D. Wolski and M. Nakhostin compared the quality of n- γ discrimination between the zero-crossing method and the charge comparison method [7, 8]. They found that the zero-crossing method shows a better n- γ discrimination compared with the charge comparison method. Additionally, J. Yan compared the performance of the rise-time method with the zero-crossing method and the zero-crossing method was also expected to work better [9].

In this paper, an experimental system that uses the zero-crossing method to perform n- γ discrimination was set up. The two-dimensional (2D) plots of n- γ discrimination showed an excellent performance of n- γ discrimination in our interested energy range (0.05–1.4 MeVee). We calculated the figure-of-merit (FOM) for different energy thresholds and regions, and it was found to be improved compared with the work done by M. Nakhostin and J. Yan in recent year. The quality of n- γ separa-

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tion in four neutron energy regions (0.3–0.7 MeV with a 0.1 MeV interval) was checked by the FOM, the neutron peak-to-valley ratio, and the proportion of leaked neutrons over all neutron events. The results indicated that the threshold of the n- γ discrimination can go down to 0.4 MeV.

2 Experimental setup

A cylindrical BC501A liquid scintillator of 3" in diameter and 2" in height coupled to a PMT was used to carry out the n- γ pulse shape discrimination. A diagram of the experimental setup which implemented the zero-crossing technique and the neutron energy measurement is shown in Fig. 1. The Am-Be neutron source was placed 82.5 cm away from the front surface of the scintillator on its central axis. The PMT is mounted on the back surface of the scintillator with silicon oil.

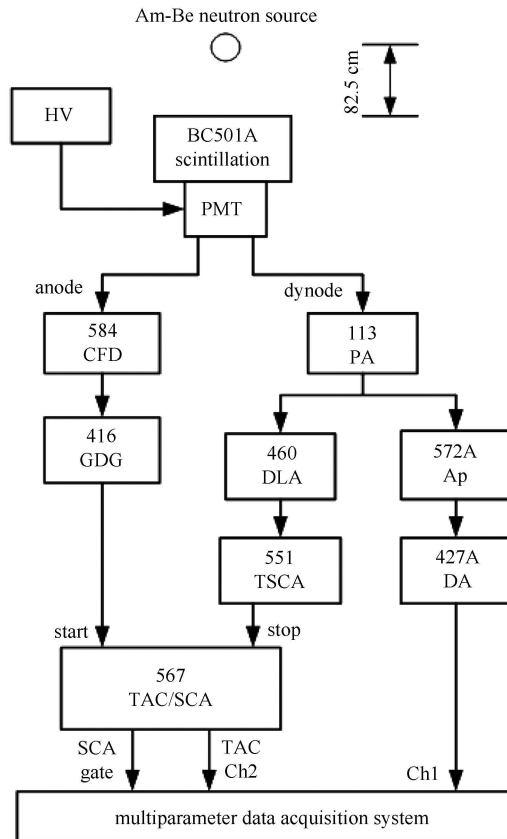


Fig. 1. The experimental setup.

The measurement circuit consists of two branches: Ch1-for the energy spectrum measurement and Ch2-for the zero-crossing discrimination. An SCA (single-channel analyzer) output of 567TAC/SCA was used as the gate signal for the system. The different zero-crossing times of signals produced by neutrons and γ -rays can be obtained by recording the time intervals between the start and stop pulses.

In this work, the lower thresholds of 584 and 551 were set to 0.1 so that the energy threshold was extended to a lower level. The delay of 416 was adjusted to 1.4 microseconds to shorten the interval between the start and stop pulses in order to satisfy the range of 567TAC (200 nanosecond). The n- γ discrimination performed best with an INTEG time of 0.25 microseconds for 460, and a shaping time of 1 microsecond for 572 A. The output of 572 A had to be delayed by 1 microsecond with 427 A so that Ch1 and Ch2 satisfied the coincidence time of the multiparameter data acquisition system.

3 Results and discussion

Two different energy ranges were selected for the measurement. The corresponding high PMT voltage for the two energy ranges was -1670 V and -1370 V.

As the light output of the electron is known to be linear, with its energy in the range of $0.04 \text{ MeV} \leq E_e \leq 1.6 \text{ MeV}$ [10], Compton electrons induced by standard γ -ray sources ^{133}Ba ($E_\gamma=0.356 \text{ MeV}$) and ^{60}Co ($E_\gamma=1.332 \text{ MeV}$) were selected to perform the energy calibration for the two energy ranges, respectively. The energy calibration was done using the channel number at 50% of the Compton edge maximum. The 2D plots of n- γ discrimination using the zero-crossing method for the two energy ranges are shown in Fig. 2 and Fig. 3.

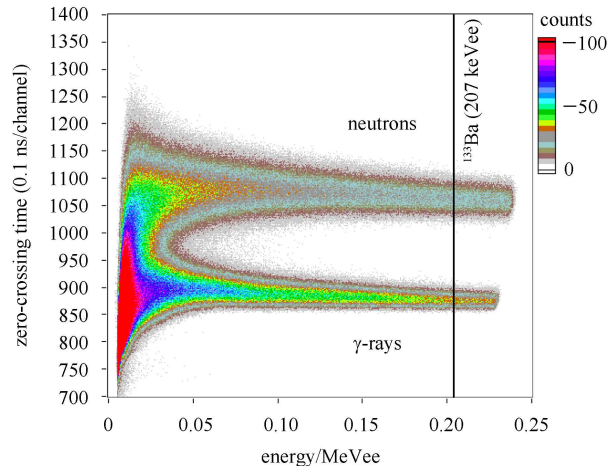


Fig. 2. 2D plot of energy versus zero-crossing time for the lower energy range.

The quality of n- γ separation was checked by the FOM, which is defined as

$$\text{FOM} = \frac{S}{\text{FWHM}_n + \text{FWHM}_\gamma}, \quad (1)$$

where S is the separation between the peaks of the neutron and γ -ray events, and FWHM_n and FWHM_γ are the full-width at half-maximum of the neutron and γ -ray peaks, respectively [11]. As a consequence, a greater FOM value means better n- γ discrimination quality.

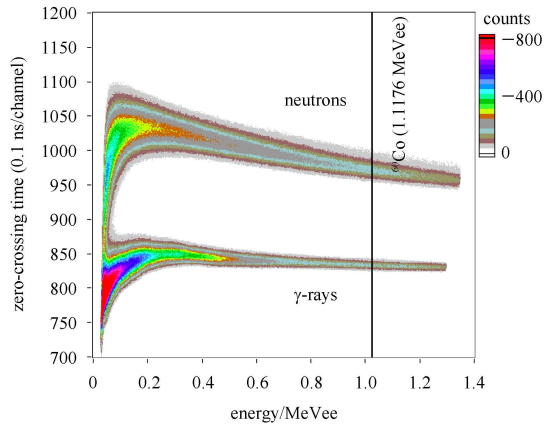


Fig. 3. 2D plot of energy versus zero-crossing time for the higher energy range.

The FOMs at 10 different energies are shown in Fig. 4, with the comparison with M. Nakhostin’s results [8]. The FOMs in this work were improved from 0.99 to 4.27 when the energy is increased from 50 keVee to 950 keVee, and the quality of n-γ discrimination was better than M. Nakhostin’s results because the FOM was comparatively higher at each energy.

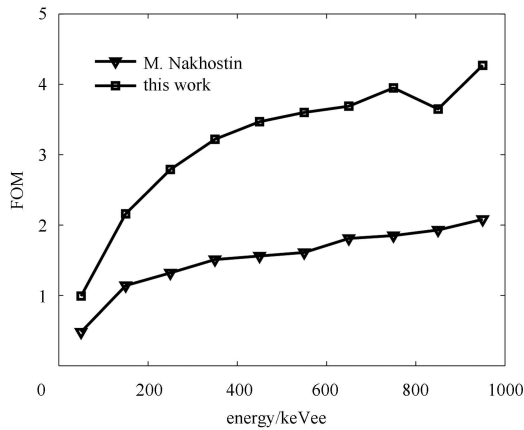


Fig. 4. Comparison of FOM at 10 energy thresholds with M. Nakhostin’s results.

In order to check the performance of n-γ discrimination in different neutron energy regions, the electron energy was converted into neutron energy according to the light output function [12]. The 1D plots of n-γ discrimination for three neutron regions (0.25–0.5 MeV, 0.5–0.75 MeV, 0.75–1 MeV) are shown in Fig. 5. The com-

parison of FOM with J. Yan’s results is shown in Table 1. Our results show an improvement in terms of the FOM.

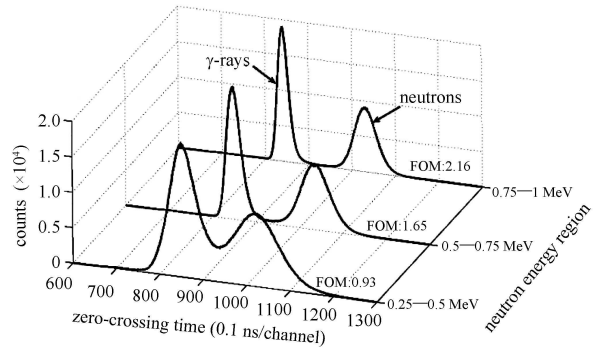


Fig. 5. 1D n-γ discrimination plots in three energy ranges.

Table 1. A comparison of FOM with J. Yan’s result in three neutron energy regions [9].

neutron energy region/MeV	FOM	
	J. Yan’s work	this work
0.25–0.5	0.9	0.93
0.5–0.75	1.3	1.65
0.75–1.0	1.7	2.16

The 1D n-γ discrimination in four neutron energy regions (0.3–0.4 MeV, 0.4–0.5 MeV, 0.5–0.6 MeV, 0.6–0.7 MeV) can be used to estimate the energy threshold of n-γ separation by the FOM, peak-to-valley ratio for neutrons, and lost neutron proportion. The FOM has been described before. It indicates the separation quality of neutrons and γ-rays, whereas the peak-to-valley ratio was defined by the ratio of neutron peaks over the valley between the neutron and γ-ray peak. The lost neutron proportion is the proportion of neutrons which leaked into the γ-ray region over all neutron events. As can be seen in Fig. 6, when the γ-rays were cut off, the lost neutrons were also cut off simultaneously.

The FOM, peak-to-valley ratio, and lost neutron proportion for four neutron energy regions are shown in Table 2.

For the neutron energy regions above 0.4 MeV, the FOMs are above 1, the peak-to-valley ratio for neutrons is more than 5, and the lost neutron proportion is less than 2%, so this indicates that the neutron energy threshold for n-γ discrimination was extended down to 0.4 MeV neutron energy in this work.

Table 2. The quality of n-γ discrimination in four neutron energy regions.

neutron energy region/MeV	FOM	peak-to-valley ratio for neutrons	leaked neutron proportion(%)
0.3–0.4	0.89	2.68	6.4
0.4–0.5	1.26	8.61	1.7
0.5–0.6	1.55	17.35	0.5
0.6–0.7	1.71	23.82	0.2

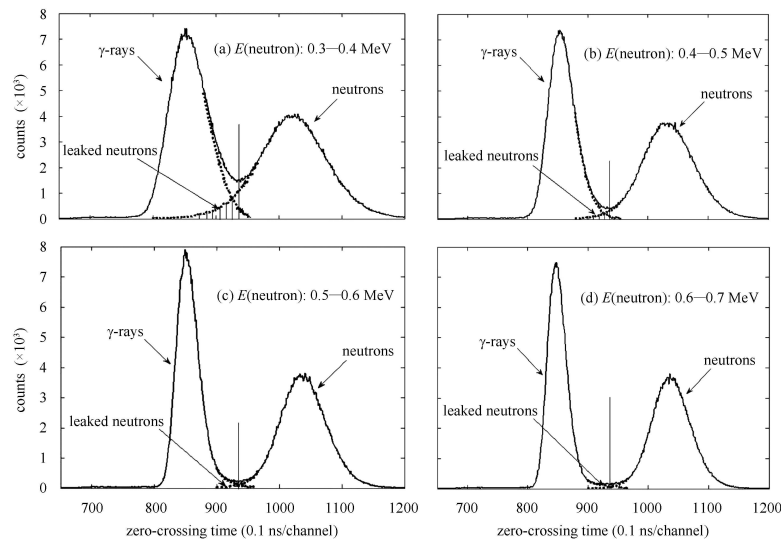


Fig. 6. 1D n- γ discrimination plots in four neutron energy regions.

The key points for extending the n- γ discrimination to 0.4 MeV were mainly based on the following. 1. The optimal liquid scintillator size (3" in diameter and 2" in height) for n- γ discrimination was used [13]. 2. The zero-crossing method was better than the rise-time method and charge comparison method for n- γ discrimination. 3. Thorough offline data analysis for 2D plots of energy versus zero-crossing time can discriminate the neutrons against γ -rays to the maximum extent compared with 1D analysis.

4 Conclusions

An experimental system for n- γ discrimination and energy measurement using a BC501A liquid scintillation detector was established and tested with an Am-Be neutron source.

Two-dimensional plots of energy versus zero-crossing time in two energy ranges were obtained by this system and showed excellent n- γ separation quality. The FOMs at 10 different energy thresholds (from 50 keVee

to 950 keVee with a 100 keVee interval) were calculated and compared with the previous results given by M. Nakhostin. The FOM was found to have increased to 0.99 (this work) from 0.48 (M. Nakhostin, et al.) at an energy threshold of 50 keVee, and the FOMs of the other nine energy thresholds were also improved. The FOMs of three neutron energy regions (0.25–0.5 MeV, 0.5–0.75 MeV, 0.75–1 MeV) were compared with J. Yan's results, and they were improved from 0.9, 1.3, 1.7 to 0.93, 1.65, 2.16, respectively.

The 1D plots of n- γ discrimination in four neutron energy regions were also presented. By comparing the FOM, peak-to-valley ratio, and lost neutron proportion for neutrons, it is concluded that the neutron energy threshold of n- γ discrimination has been extended to 0.4 MeV. The key points for extending the n- γ discrimination threshold to such a low level is that the optimal scintillator was used, the better zero-crossing method was carried out, and 2D plots of energy versus zero-crossing time were achieved for thorough offline analysis.

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