

Manufacture of a fast neutron detector using EJ-301 liquid scintillator

Phan Van Chuan, Nguyen Duc Hoa, Nguyen Xuan Hai, Nguyen Duy Tan

Abstract—A fast neutron detector using the EJ-301 scintillator was manufactured for study on detecting fast neutrons and gamma-rays. Detector characteristics include the energy linearity, the efficiency response and the neutron/gamma discrimination were guaranteed for neutron detection in the energy range from 50 to 3000 keV. The ability discrimination of neutrons/gamma-rays of the detector was evaluated by the charge comparison (CC) method using an ^{252}Cf source. The total efficiencies when measured on ^{22}Na , ^{137}Cs , ^{60}Co and ^{252}Cf sources were obtained 17.8%, 3.9%, 9.8% and 14.8%, respectively. The Figure of Merit (FoM) values of CC method were 0.4–1.55 for the range of energy 50–1000 keV (keV electron equivalent).

Keywords—EJ-301 liquid scintillator, fast neutron detector, pulse shape discrimination

1 INTRODUCTION

Neutron detection is very important in research about the field of neutron, such as radiation safety, research material, scattering particles, particle physics, etc. The slow neutrons are commonly detected based on the nuclear reaction mechanism, while the fast-neutrons are detected based on elastic scattering mechanism with light nuclei such as hydrogenous, ^4He or organic scintillators [1, 2]. Organic scintillator detectors are widely employed in studies with fast neutrons and gamma-rays by many good properties: the fast decay time, the relatively high light-output and a reasonably good efficiency for fast neutrons [1, 3]. EJ-301 organic scintillator was manufactured by EJen Technology (or its equivalent, NE213, BC501A), the yield curve consists of two exponential decays – the fast and

slow components of the scintillator light that depends on different kinds of radiation [1, 4, 5]. By coupling a photo multiplier tube (PMT) – to the scintillator, the light can be collected and converted into a voltage pulse, allowing for data acquisition/processing [1, 6]. Those properties are commonly used to identify neutrons and gamma-rays by using pulse shape discrimination (PSD) techniques.

Many PSD algorithms have been evaluated and reported, such as zero-crossing (ZC) [6-8], PGA [9], CC [6-8, 9-11], frequency gradient analysis (FGA) [5], TCT [12], discrete Fourier transform (DFT) [13], CPR [14], etc. Among them, the CC and ZC algorithms are commonly implemented, therefore they have become the industrial standards which are used to compare with new discrimination algorithms [5, 6].

In the present study, a fast neutron detector was designed and manufactured using the EJ-301 liquid scintillator for neutron monitoring and training purposes. A preamplifier was also manufactured in order to make the suitable shaping pulse for data acquisition and processing. The qualities of the detector were assessed by the total efficiency, sensitivity and linearity with gamma-rays. The ability to distinguish between neutrons and gamma-rays was assessed through digital CC method. The CC method was implemented by a program in MATLAB software using the data that are digitized from the pulses of detector by a digital oscilloscope.

2 MATERIALS AND METHODS

Detector manufacture

The designed layout of the detector is shown in Fig.1, which consist of a liquid scintillator container (cell), a photo-multiplier tube (PMT), a voltage divider, a shield cover and a preamplifier. The cell is a right cylinder made of aluminum with 34mm diameter 60mm length in size. The

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inner surface of the cell was polished and matched PMT through ultra violet glass window with 2 mm thickness. The PMT Hamamatsu R9420 has 1.6 ns and 550 ps rise time and transit time spread (FWHM), respectively [15]. The cell, PMT and preamplifier are housed inside the cover shield which is made of aluminum in the form of cylindrical, with 49mm in diameter 200mm in length. This cover prevents light from outside and magnetic interference. The high voltage, signal and power supply connectors are mounted at the tail of the detector.

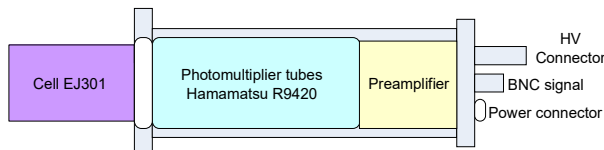


Fig. 1. Layout of neutron detector

The signals produced by the PMT have a very short rise time (less than 5 ns) because the fast decays component of EJ-301 is 3.2 ns [4], so that the signal is distorted when it is transmitted to the digitized block, which is usually placed away from the detector [1]. The preamplifier consists of four main stages because the anode pulses produced by the PMT are current pulses, the first stage converts the current pulses to the voltage pulses using the load resistance 50 Ohms. The second stage amplifies the signal voltage from the first stage (gain of 30 times). The third stage is a filter using the second-order low-pass Sallen-key filter ($f_{-3dB}=33.8\text{MHz}$, Butterworth=0.6). The final stage has matched impedance to match cable impedance 50 Ohms. The Preamp would shape the pulses which had the rise time of approximately 12 ns and fall time of approximately 31 ns for the pulse of gamma-rays. The total amplifier voltage gain of the Preamp is -17.85 V/V and the output amplitude at the Compton edge of the ^{137}Cs source is 344.7mV and the ^{60}Co source is 806.8mV, respectively. The total noise of preamplifier contribution to signal was $797.9\pm 0.34\mu\text{V}$, which is equivalent to 1.13keVee calculated a calibration energy scale of the detector.

Examined main characteristics of neutron detector

The preamplifier was designed for linear output voltages in the 0 to + 2.2V range, corresponds to range from 0 to 3100keVee. A

test setup is shown in Fig. 2 which the Preamplifier was tested in unconnected mode to PMT. The input of the Preamplifier was provided pulses from pulse generator (ORTEC Model 419), which was installed the rise time of 5 ns and fall time of 20 us. The amplitude and noise of both input and output pulses of the Preamplifier were measured by two channels of the digital Textronix Model DPO7254C (DPO7254C) that was installed in at 1 Giga samples per second (GSPS) and 2.5GHz bandwidth. For each input pulse amplitude, input/output amplitude values and the standard deviation σ_{In}/σ_{Out} of the pulses were measured by the DPO7254C. The amplitude of the input pulse was adjusted from 2.8 to 417mV by manual with 55 steps examined. The noise generated by preamplifier was calculated by the equation (1) [16].

$$\sigma_{Pre} = \sqrt{\sigma_{Out}^2 - \sigma_{In}^2} \tag{1}$$

The results of the signal-to-noise ratio (SNR), the gains, sensitivity and linearity of preamplifier were shown in Table 1 and Fig.3.

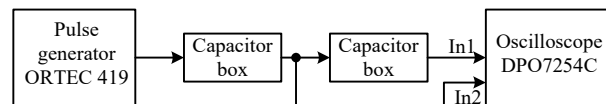


Fig. 2. The configuration of linearity, gain, noise and sensitivity evaluation for preamplifier

Table 1. The preamplifier parameters

Parameters	Values
Measuring range	0 ÷ 3000keVee
Total noise	$797.9 \pm 0.34\mu\text{V}$
Baseline	$35.8 \pm 0.288\text{mV}$
Sensitivity	$707\text{mV} / \text{MeV}$

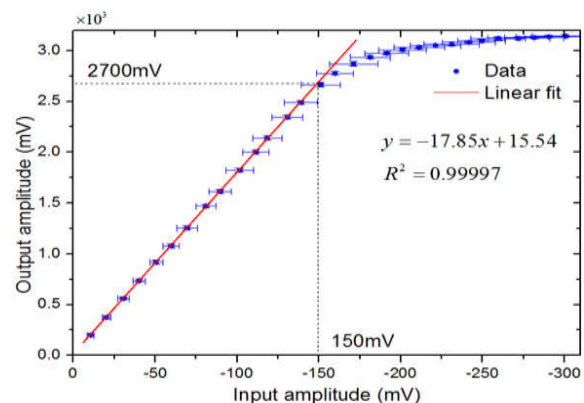


Fig. 3. The output versus input amplitude of preamplifier

Because the light intensity of the EJ-301 liquid scintillator is good linearity on gamma sources [1, 4], this study uses three ^{22}Na , ^{137}Cs and ^{60}Co standard sources to evaluate the linearity of the detector. The relation the height of pulse with energy at the Compton edge of the gamma sources was used that evaluate the linearity of the detector with energy. The maximum backscatter energy (E_c) was counted by equation (2) [1].

$$E_c = E_\gamma \left(1 - \frac{1}{1 + \frac{2E_\gamma}{m_e c^2}} \right) \quad (2)$$

Where, E_c , E_γ , m_e and c are maximum backscatter energy, the energy of gamma-ray, electron rest mass, and speed of light in vacuum, respectively.

Table 2. Gamma energies from different nuclides corresponding to their calculated energies of Compton edge as a function of experimental channels measured by the MCA

Sources	E_γ (MeV)	E_c (MeV)	The channel number
Cs-137	0.662	0.477	107
Co-60	1.332	1.12	141
Na-22	0.511	0.341	330
	1.27	1.06	313

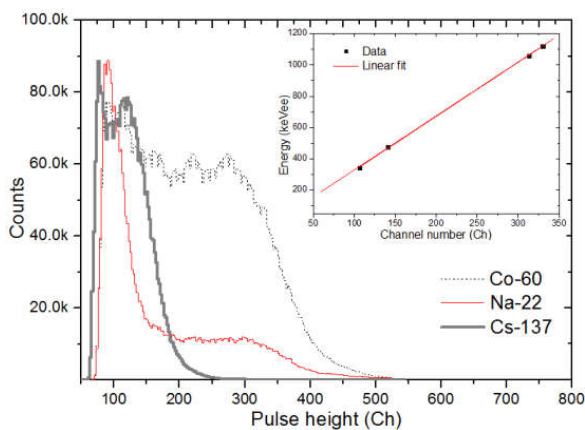


Fig. 4. Pulse height distribution from sources of ^{60}Co , ^{22}Na and ^{137}Cs . The upper inset shows the calibration data using the Compton edges of the gamma-ray spectra

The Table 2 showed that measurements were performed with gamma-ray sources of ^{22}Na , ^{137}Cs and ^{60}Co , and each the measurement of those gamma sources were placed beside the monitor scintillation. Each the measurement of the pulse amplitude histogram was measured by

the DPO7254C as the amplitude spectrum of the gamma source, respectively. The number of channels of the Compton edge corresponded to the E_c of the gamma source, respectively. Because the Compton edge of the 1137.2keV peak of ^{60}Co was obscured by the that of 1332keV peak, only the Compton edge of the 1137.2keV peak was not used in the calibration. The energy spectra of ^{60}Co , ^{22}Na and ^{137}Cs sources are shown in Fig. 4, that used the oscilloscope DPO7254C which was operated in spectrum mode.

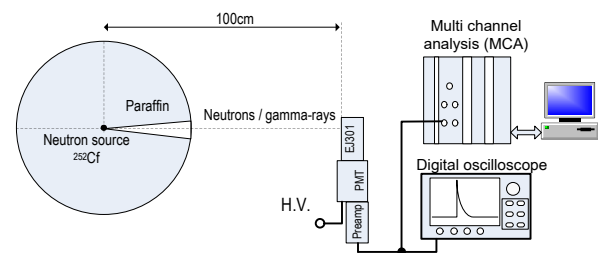


Fig. 5. Schematic view of assessing total efficiency and data acquisition system for EJ-301 detector

The total efficiency of the detector was evaluated by the schematic on Fig. 5. The total efficiency is defined as the ratio of the total number of events which are detected to the total number of gamma-ray incident on the detector. The total efficiencies of the detector were identified by ^{22}Na (activity on 12/2000 was $9\mu\text{Ci}$), ^{137}Cs (activity in 12/2001 was $11\mu\text{Ci}$), ^{60}Co (activity in 12/2000 was $11\mu\text{Ci}$), and ^{252}Cf (activity in 05/2011 was 11.6mCi) sources. The gamma sources are placed near the cell scintillator and placed 100cm from the ^{252}Cf source to the detector (see Fig. 5). The pulses in these processes include gamma source, ^{252}Cf and background were counted by the Multi-Channel-Analyzer (MCA) and spectrum analyzer software on a computer. The cross section of the liquid scintillator cell when decrease 5% by the air bubble was 19.4cm^2 .

Examined the ability of neutron-gamma discrimination

In order to assess the ability to discriminate of the detector, this study used the ^{252}Cf source, which was placed at 100cm from the detector (Fig. 5). The detector was biased high voltage of -

1200 V by the High Power Supply (Canberra 3002D); the detector's pulses were acquired by the DPO7254C which was set at 12bit resolution, the bandwidth of 2.5GHz and at a sampling rate of 1 GSPS. The pulses were transferred to the PC for offline analysis by the PSD CC method. The program of PSD CC method was performed on MATLAB software and the results of the graph and FoMs were calculated by the Originlab 8.5 software.

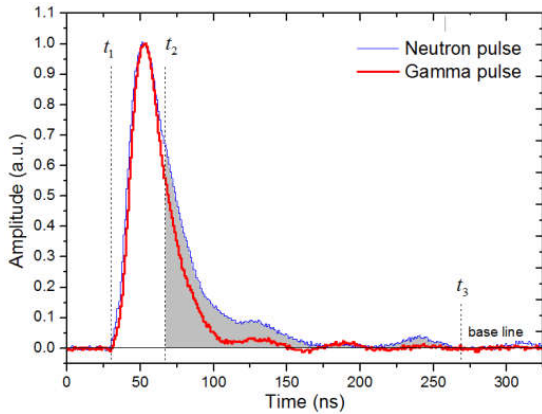


Fig. 6. Typical neutron and gamma-ray pulses in one sampling

The typical neutron and gamma – ray pulses with the same amplitude of the EJ-301 detector were shown in Fig. 6. The neutron pulses exhibited a larger decay time to the baseline, so with the same amplitude neutron/gamma pulses the area of the tail of the neutron pulse was greater than that of the gamma pulse. The digital PSD method chosen for comparison consists of integration techniques were applied to digitized

pulses, where each pulse was integrated twice, using two different ranges [7-10, 14]. The total integral was calculated for full pulse that began is at the start point (t_1) to an optimal point at the tail pulse (t_3). The tail integral was calculated in range begins at a fixed position after the pulse maximum (t_2) and also extended to the last data point chosen in the total integral range (t_3). The survey data indicate that the separation was the best where t_2 was 20ns and t_3 was 210ns after the pulse maximum. The PSD parameters could be created using the ratio values between the tail and total integrals. The PSD parameter of neutron pulses was larger than that of gamma pulses.

3 RESULTS AND DISCUSSION

The measured data with a neutron source ^{252}Cf and ^{60}Co were analyzed by the PSD CC method. The scatter plots of the neutron-gamma separation with an energy threshold of 50keVee by the CC method are shown in Fig. 7 (a) and (b), respectively. In the region of the energy survey shown that the threshold over 200keVee the ability to distinguish between neutrons and gamma-rays very well. While below the 200keVee threshold the ability to distinguish between neutrons and gamma-rays was not good and at the threshold 50keVee the discrimination was not clear for neutron and gamma. The statistical chart of the CC method at energy threshold 300keVee was shown that the ability to distinguish between neutrons and gamma-rays was very clear (FoM = 1.22).

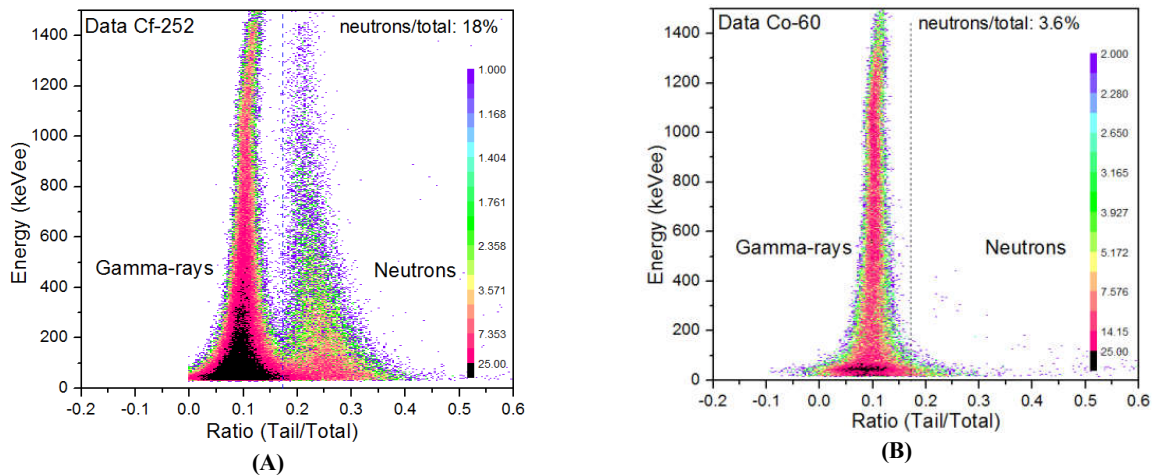


Fig. 7. The scatter plot of charge comparison: (A) the scatter plot of ^{252}Cf , (B) the scatter plot of ^{60}Co

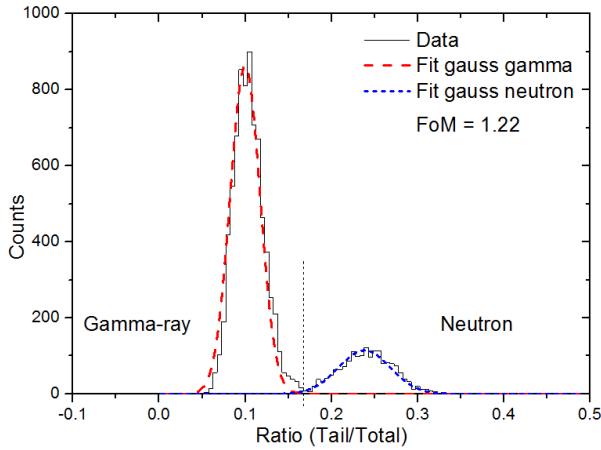


Fig. 8. Histogram of charge comparison at threshold 300 keVee

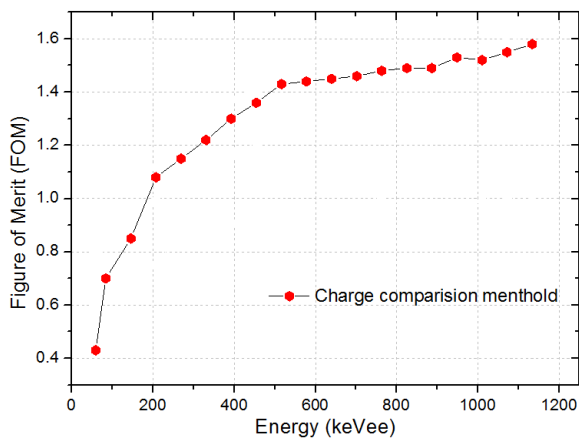


Fig. 9. The FoM values as a function of energy threshold corresponding of CC method in the range of energy from 50 to 1100 keVee

Fig. 9 showed the FoM values as a function of threshold in a range of energy from 50 to 1100keVee. The FoMs were approximately 0.43 at 50keVee and greater than 1.0 at 200keVee energy threshold. At the 83keVee energy threshold, the FoM was measured 0.7 and its reached the value 1.15 at the 200keVee energy threshold. At the 1000keVee energy threshold, the FoM increased of 1.55. These results were similar as the presented in Ref. [7, 8, 11].

Table 3. The total efficiency value determined by ²⁵²Cf, ¹³⁷Cs, ²²Na and ⁶⁰Co sources

Sources	Activity (Bq)	Count rate (cps)	Total efficiency (%)
²⁵² Cf	1,052 x 10 ⁷	88,906	14.8
⁶⁰ Co	47,962	1,732	9.8
¹³⁷ Cs	94,474	3,869	3.9
²² Na	4,397	440	17.8
Background*		182	

Note: * neutron source was closed

The results of the total efficiency of the detector were surveyed by ²²Na, ¹³⁷Cs, ⁶⁰Co and ²⁵²Cf sources (Table 3). The survey values showed that the total efficiency was maximum for the ²²Na source. The events of both 511 and 1274.5keV peaks were used for calculated total efficiency. The total efficiency on the ²⁵²Cf reached 14.8% that was measured with both neutron and gamma events. Determining exactly the efficiency of the EJ-301 was quite complex by the inadequate standard sources and the bad resolution of the EJ-301 liquid scintillator. This issue is still being studied by the authors and will be published in another time.

4 CONCLUSION

A scintillation detector using the EJ-301 liquid scintillator has been designed and built for fast-neutron measurements. The detector is designed to measure in the 50 to 3000keVee energy range corresponding to an output voltage of 35.8mV to 2200mV, which was compatible with the input voltage range of the high speed ADCs that it could directly interconnect. The sensitivity of the detector was 707mV/MeV. The most important characteristic of the neutron detector was the ability to discriminate between neutrons and gamma-rays to eliminate gamma-rays noise in fast-neutron measurements that have been evaluated by the PSD CC method. Those results showed that the EJ-301 detector could be used in system fast-neutron measurements by digital technology.

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Chế tạo đầu đo neutron nhanh sử dụng nhấp nháy lỏng EJ-301

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Tóm tắt—Một detector neutron nhanh sử dụng nhấp nháy EJ-301 đã được chế tạo phục vụ cho nghiên cứu neutron nhanh và tia gamma. Các thuộc tính chính của detector bao gồm độ tuyến tính năng lượng, hiệu suất ghi và khả năng phân biệt neutron – gamma đã được kiểm tra trong vùng năng lượng khảo sát từ 50÷3000keVee (keV tương đương). Khả năng phân biệt neutron – gamma của detector được

đánh giá thông qua phương pháp so sánh diện tích xung sử dụng nguồn ²⁵²Cf. Các hiệu suất tổng đo được trên các nguồn ²²Na, ¹³⁷Cs, ⁶⁰Co và ²⁵²Cf đạt các giá trị tương ứng 17,8%, 3,9%, 9,8% và 14,8%. Hệ số phẩm chất (Figure of Merit: FoM) đánh giá cho phương pháp so sánh diện tích xung của detector đạt 0,4÷1,55 trong vùng năng lượng khảo sát (50 ÷1000keVee).

Từ khóa—detector neutron nhanh, nhấp nháy lỏng EJ-301, phân biệt dạng xung