Comparison of Time Interval Statistic and Pulse Shape Discrimination in Fast Neutron Detection Method with Liquid Scintillation Detector Loaded Gd

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Abstract

Neutron usually appear with gamma, which is requiring the detector has the capability of n gamma discrimination. Pulse shape discrimination (PSD) is a common approach of n, gamma judgment, but required a complex process to select a suitable discrimination factor, and poor performance in the low energy range. A method based on the time interval of adjacent Signals was disrupted and adopted to compare to pulse shape discrimination in the fast neutron detection method. A good agreement between the adopted method and PSD method was achieved, including the total count ratio and neutron count ratio. The comparison proves the correctness of the theoretical derivation and validate the method in practice. The advantages and limitations of the method based on time Interval of adjacent signals were analyzed. The method provides an effective way to confirm the calibration of the neutron detection of a liquid scintillation detector. Also, as a simple way only requiring the time information about events, the described method has large application potential in some case of fast neutron flux or intensity measurement.

Keywords : Neutron detection, Gd-loaded liquid scintillation detector, Fast-slow signal, Time interval distribution, Pulse shape discrimination

1 INTRODUCTION

Liquid scintillation (LS) detectors are used widely in experiments related to neutron detection. Although they have high detection efficiency and the n/γ pulse-shape discrimination (PSD) properties, the accurate measurement of neutron events is still challenging because of the poor PSD capability for lower energy neutron[1-3]. And the calibration of detection efficiency usually needs a simulation of the detector, which is also probably causing an error due to the difference between the real detector and the simulated detector. The addition of Gd is helpful to identify neutron event by electron recoiling signal and Gd capturing event, which is also named fast-slow signal coincidence. But since the strong gamma background, occasional coincidence can also cause a detection error of neutron events.

The time interval between fast-slow signals of neutrons and the time interval between two gamma events (two occasional events) are different [4]. For fast-slow signals of neutron, the time constant is relatively small, while for gamma events, the time constant of any two adjacent events is large. On the case of neutron mixed gamma background, the time constant of any two adjacent events depends on the proportion of neutron and gamma. This also means, according to the time interval distribution of any two adjacent events, one can get the information about neutron count and gamma count.

According to the above, the time regulation among the neutron and gamma events, Liu and Yang propose new technique to measure the count or count ratio of neutron based on the distribution of time interval between any two adjacent signals and then compare it with simulation by MCNP5 [5]. But they did not compare their method to the classical neutron discrimination method PSD. On the other hand, their method also is lack of application in practice, and the potential use has not yet been discovered. In this work, we used Yang's method to measure a 252Cf source and compare the result to the PSD method with the same Gd-loaded LS detector.

2 FAST-SLOW NEUTRON MEASUREMENTS WITH A LIQUID SCINTILLATION

After entering the LS detector, the fast neutrons will gradually decrease by colliding with the nuclei in the detector and then their energy will move into the energy of the nuclei because neutrons will lose their energy. They will turn into slow neutrons while the nuclei are being nuclei excite or ionizing atoms will generate light pulses. The remaining thermal neutrons will pick up the Gd nuclei at the end of their path and generate excited nuclei which will ultimately generate several γ rays on the time-scale of nanoseconds with a total energy of approximately 8 MeV. The overall process is schematically shown in Fig. 1.

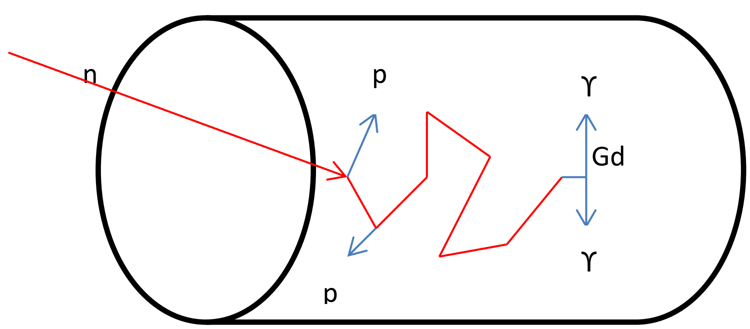

FIG. 1 The process of neutron when enter to detector

Firstly, we'll illustrate the temporal relationship between the signal of the concern neutron capture and the signal of its corresponding recoil proton according to Yang' work [5]. In terms of that look the first recoil proton event as 0 time moment, the time interval between a recoil proton signal and capture signal determined by the moment of neutron capture events. Since the fast neutron slowing down process entrance the absorption cross section that change with regular 1/v (v is speed), so that when the absorbent body (Gd atoms) and moderator (atoms in LS) are approximated mixed uniformly, for all neutron that was captured by a detector, the probability of being captured changes over time are determined by the following formula.

$$\mathrm{P(t)} = \tau^{-1}\exp(-t/\tau) \qquad (1)$$

$\mathrm{P(t)}$:is the probability that a neutron is captured at t time ,

τ: is the time constant and determined by the following formula,

$$\tau = (N\sigma\nu)^{-1} \qquad (2)$$

Among the formula N is the number of atoms of ^{113}Cd or ^{155}Gd or ^{157}Gd and other Neutron absorber; σ is absorption cross-section, ν is the speed of neutrons. When the absorption cross section that change with regular 1/v, $\sigma\nu = \sigma_0\nu_0$, is a constant and won't change when energy change, so for neutrons τ is a constant. So the temporal relationship between the signal of the concern neutron capture and the signal of its corresponding recoil proton follow an exponential decreased law. As for detector made up of ^{nat}Cd absorber in our experiment, calculate τ as 1.98 μs. Because we ignore the time that before neutrons enter the interval absorption cross section that change with regular 1/v (when simulation ,each captured neutron with energy under 5×10^{-5} MeV average need 0.247μs to be moderated to under 5×10^{-5} MeV interval), so calculated τ slightly smaller than the average capture time 2.15μs that got by simulation.

Based on the conclusions above, we can infer the temporal relationship between any two adjacent signals follow the following derivation:

First, we should define two variables p and m. all signals measured by the detector can be divided into two categories, one is the signals of neutron captured, another is signaled not from capture, include signals of recoil proton and signals of γ rays and signals of cosmic rays as well as signals of other background. Note counting rate of all the non-captured signal for m, the counting rate of captured signal will be$m \times$ p. p is the ratio of captured signal and non-captured signal. From m and p, we can learn that the probability for any signal to be a captured signal is $^{p}/_{1+p}$; the probability to be a recoil proton signal is also $^{p}/_{1+p}$; the probability to be a non-captured signal is $^{1}/_{1+p}$.

Because for two adjacent signals, the second signal can be divided into the following three categories.

1) The second signal is non-captured signal. In this case, the distribution of time intervals between two adjacent signals fully complies with the index decreased law.
2) The second signal is a captured signal, and is independent of the first signal. That is to say, the corresponding recoil proton signal of captured signal is before the first signal.
3) The second signal is a captured signal and the first signal is a neutron recoil proton signal produced by a

same neutron. This situation is the true coincidence events that we need to measure, and reflects a neutron moderated and absorbed in the detector.

According to the above classification, if $f(t)dt$ is used to represent the probability of a second signal come in $t\sim t+dt$ time slice when think the first signal as zero moment, then:

$$f(t)dt = f_1(t)dt \cdot \overline{F_2(0\sim t)} \cdot \overline{F_3(0\sim t)} + f_2(t)dt \cdot \overline{F_1(0\sim t)} \cdot \overline{F_3(0\sim t)} + f_3(t)dt \cdot \overline{F_1(0\sim t)} \cdot \overline{F_2(0\sim t)}$$

In above equation$f_1(t)dt$, $f_2(t)dt$ and $f_3(t)dt$ show the probability of a second signal come in $t\sim t+dt$ time slice when separately consider three kinds of the second signals respectively. $F_1(0\sim t)$, $\overline{F_2(0\sim t)}$ and $\overline{F_3(0\sim t)}$ show the probability of three kinds of signal absence during $0\sim t$ period.

$$f(t) = \frac{1}{1+p}.\exp\left[-mt + mp\tau(e^{\frac{-t}{\tau}} - 1)\right] \times \{(2m + \frac{1}{\tau}).p.\exp(-\frac{t}{\tau}) + mp^2 \exp(-\frac{2t}{\tau}) + m\} \ldots(3)$$

By integrating (t) , we can get the probability of the time t between two adjacent signals distributed between $t_1$and t_2 :

Where :

f(t): is the probability of the time t between two adjacent signals distributed between $t1$ and$t2$

P(t): is the probability that neutron captured at t time

τ: is the time constant and determined by the equation (2).

t :is the time interval between any two adjacent signals

$$F\left(t \in [t_1, t_2]\right) = -\frac{1}{\left(\frac{1}{1+p}\right)}.\exp\left[-mt + mp\tau\left(e^{\frac{-t}{\tau}} - 1\right)\right].\left[pe^{\frac{-t}{\tau}} + 1\right] \ldots(4)$$

It can be seen from the probability density function, when p=0, the function degenerated into the temporal relationship between two random signals, that is to say the decay time follow1/m index fell .When p≠0,where this much larger than the average neutron absorption time τ the downward trend of the curve approximates the temporal relationship between two random signals .where t is smaller the downward trend of the curve determined by τ and p and m[5].

4 STRUCTUURE OF DETECTOR

The detector used in the comparison experiment consists of high purity oxygen and free copper [6]. The dimension of this cylindrical vessel is 30 cm diameter and 40 cm length, this cylindrical vessel wrapped in a layer of Teflon, which acts as a reflective film. The cylindrical vessel is filled with organic liquid scintillation and loading with EJ-335(EJ-335 is a gadolinium loaded liquid scintillation produced by Eljen technology

Company). Delayed coincidence and pulse shape discrimination techniques are commonly used with this liquid scintillator. EJ-335 contains mineral oil replace for some of the aromatic solvent for goals of higher hydrogen content and higher flash point for use in very large containers. The utmost gadolinium content is 0.5%, and loadings down to 0.1% are used in very big volume detectors [7]. Two 20 cm diameter photomultiplier tubes (PMTs, HamamatsuR5912-02) are fixed on either side of the cylinder; tapered Plexiglas light guides are set between the cylindrical vessel and each PMT, and these parts are coupled by silicone grease at the interfaces to enhance the light collection efficiency. The entire detector is placed in a lead chamber with 5 cm thick walls to shield the gamma background environment. Figure 2 shows the structure in the experiment

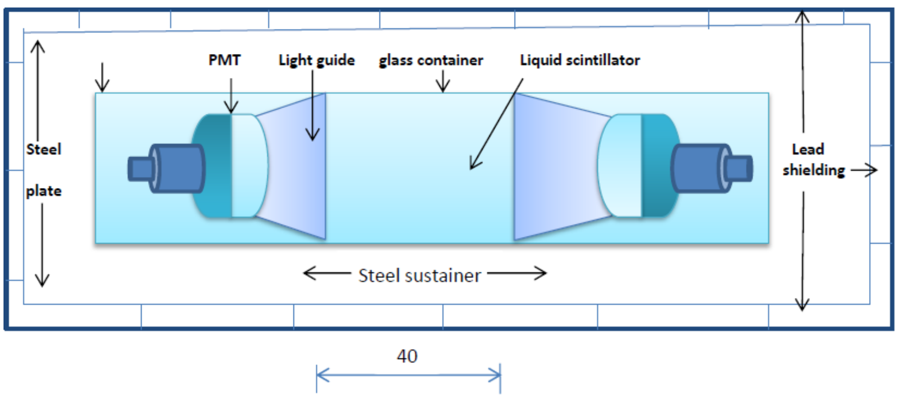

FIG. 2 The structure of liquid scintillator detector

5 DAQ STSTEM

The schematic diagram of the electronics and data acquisition (DAQ) system is shown in Fig.3. The scintillation light is read out by PMTs at both ends of the detector. The PMT signal is read out by a Fan In/Fan Out model to generate two outputs which are identical with the input signal. One output is fed into a 500 MHz, flash analog-to-digital convertor (FADC) where the signal is sampled and recorded. The other is fed into the discriminator to provide triggers. To reduce the accidental events from the noise of PMTs, the events are recorded only if both PMTs are triggered. Events provided by a random trigger with a pulse generator are recorded for DAQ dead time measurement. The 99.9% DAQ live time is achieved. The timing information about triggers is recorded by the FADC time tag with a resolution of 8 ns.

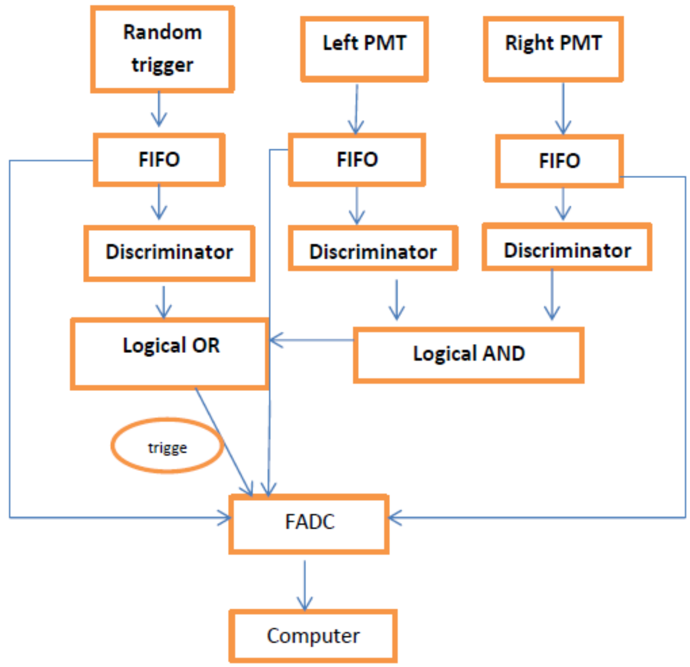

FIG.3 DAQ system

6 CALIBRATION

PSD method requires the signal has enough signal noise ratio, which also means the PSD can be applied on the evens over an energy threshold (1 MeV). Energy calibration was performed by two gamma sources ^{60}Co and ^{137}Cs We select three highest points in spectrum to fit the energy calibration. We put the sources in the lead shielding through the small hole. We used GEANT4 simulation to confirm energy calibration with experiment. The energy resolution of the detector was not interesting by GEANT4, wherefore the simulation spectrum should be expanded by a Gaussian function with the standard derivation of the form (σ/E)2= α+β/E according to compare with experiment . We can calculate the parameters α and β by the comparison with the spectrum.

7 PULSE SHAPE DISCRIMINAION AND RESULTS

The heavy charged particles lead various excitation degrees than lighter charged particles do. This makes the basis for neutron/γ-ray pulse shape discrimination (PSD) in scintillation. neutron collisions produce heavy recoil protons cause greater specific ionization therefore scintillation reaches higher excited states that take longer to de-excite. The pulse shape will depend on the specific ionization caused by the striking particle; this shape consists of a fast component (also called prompt component or rise time) with a few nanosecond decay times, and a slow component (also called delayed component or tail) with a few hundred nanoseconds decay time [3].

For the neutron whose equivalent electron energy is lower than 1 MeV, the number of them can be achieved by the proportion to the number of neutrons over 1 MeeV from the GEANT 4 simulation.

8 ANALYSIS DATA BY CERN ROOT

Root is a modular scientific program set used in high energy physics and particle physics. Its offer all functions wanted to process big data, such as statistical analysis, visualization and storage [8]. The experiment data were analyzed by root software. We analyzed time interval between any two adjacent signals to put them it in our method. The center of the bin was selected to get the time value for any two adjacent signals, where 200 bin was selected (in these bins, it shows clearly the neutron process from entering the detector until the loss of its energy begins to fade), the distance between any two bins is 10000ns as shown in Fig.4, and then we took these values and used for fitting. the total events in our experiment is 4260000.

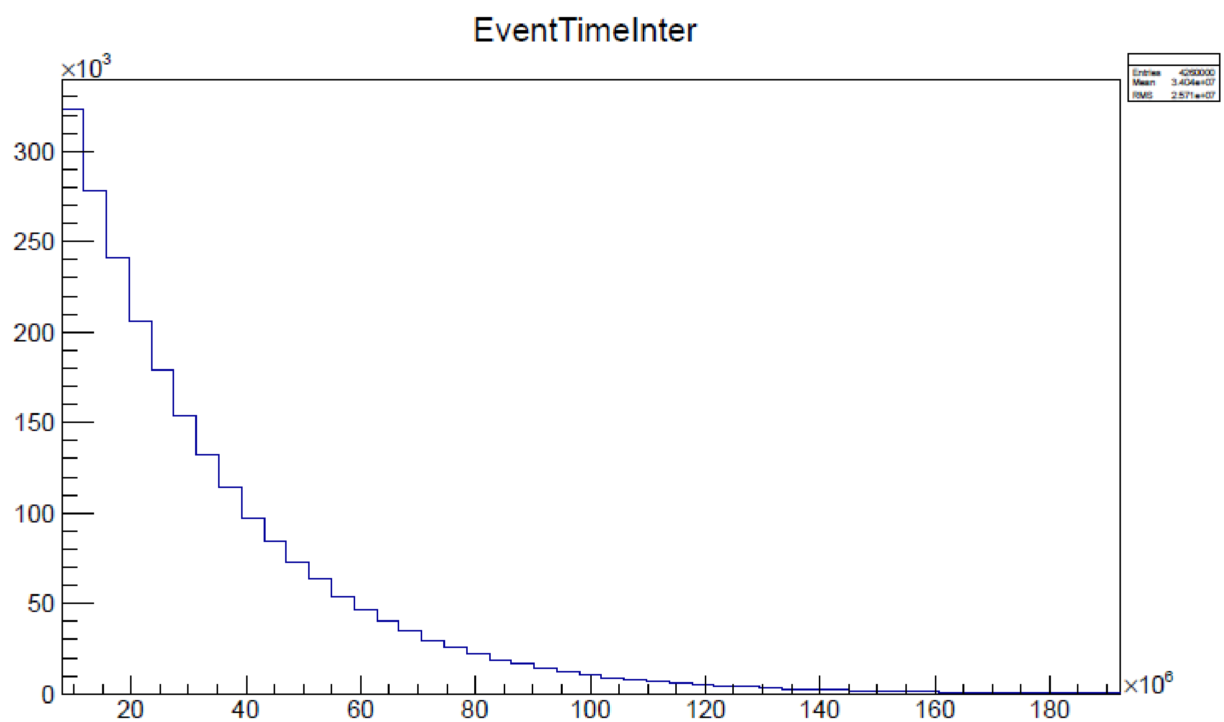

FIG. 4 the relationship between time interval and counts(y-axis is count ,x axis is time(ns)), achieved from Root

9 FITTING

We fitted the formula (3) with the same data set in Fig.4 by using the fitting tool in MATLAB (Mathworks, Inc.， Natick, MA). The fitting is executed with the function of lsqcurvefit(). The fitted value and experiment value are plotted in Fig.5. The resnorm of fitting is 6.3466×10^5.

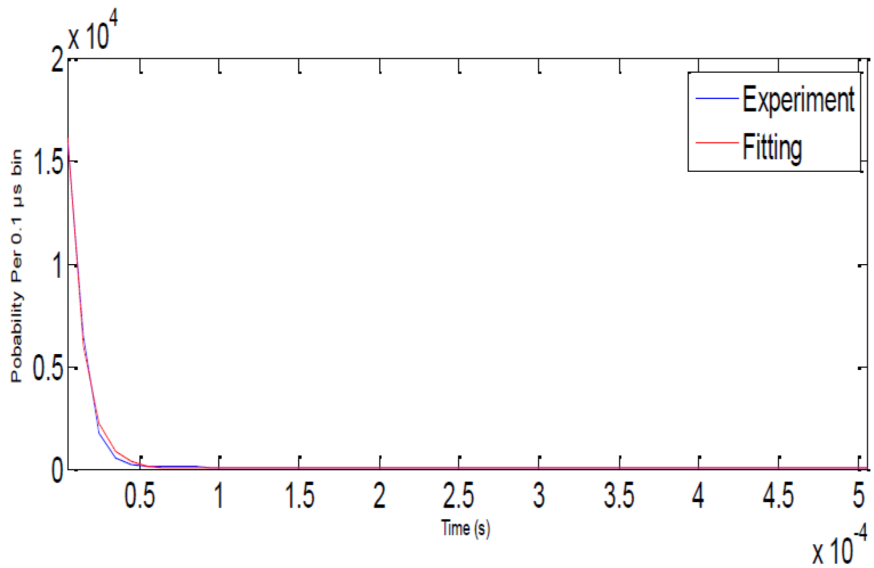

FIG. 5 The distribution of time interval

10 COMPARISION

From the above fitting, we can see there is a good agreement between experimental data and the formula (3). From the fitted formula, an event count ratio and total neutron number are calculated. The result is listed in Table 1. Also, the number of neutrons by PSD and the count ratio are presented as a control.

Table 1. the detected neutron number and count ratio from two methods

Method	Number of neutrons	Ration of counts
PSD method	930035	51.86
Mathematical method	1187400	54.39

11 DISCUSION AND CONCLUSION

This paper describes a new technique of measuring neutrons from the LS detector loaded Gd. Comparing to the typical PSD neutron discrimination method, the number of the measured neutron is a good agreement, and the difference between two methods less than 3%. The small difference between them can be explained by the statistical error. Both the total number of neutrons and total count rate obtained from the method also validate its theoretical formula as the fundament of the described method.

The described method has obvious advantages is that the number of neutrons measured can be achieved only from the recorded time of all events, no any necessary of the pulse shape, energy calibration, and complex proceed by selecting discrimination condition. For PSD, it is not accurate enough, especially in the low energy range due to the relative low signal/noise ratio. The described method performs robustly without the worry the SNR problem. The advantage also make the measurement of neutron easy and fast. A limitation of it is low precision of proceeding the case of rare neutron, such as some measure of background neutron whose number is few. This is a fixed default as a method based on statistics. Another limitation is the described method cannot provide any information about neutron energy spectrum, which is important in some applications, especially for science research. Anyway, as a simple way only requiring the time information about events, the described method has large application potential in some case of fast neutron flux or intensity measurement.

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