THE ALGORITHMS FOR NEUTRON PULSE DETECTION WITH SCINTILLATION DETECTOR

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ABSTRACT

The interference of gamma in neutron spectra reduces the accuracy of measurement results, especially when using the scintillation detector. The digital method can be used to identify either neutron or gamma pulses. In order to select the algorithm for NE213 scintillation detector, the Matlab Simulink tool was used to simulate neutron counting system. The results show that the figure of merits (FOM) of rise-time discrimination method, pulsed gradient analysis method, charge comparison method, and correlation pattern method are 1.09, 0.66, 2.21 and 1.97, respectively.

***Keywords**: FOM, neutron-gamma pulse shape discrimination, simulation of neutron and gamma pulse,correlation pattern method*

1. Introduction

The neutron - gamma pulse shape discrimination (PSD) technique is very important in neutron radiation measurements using the scintillation detector. NE-213 detectors can detect both neutron and photon, but their pulse shapes can be distinguished.

Various neutron - gamma discrimination techniques have been developed, including both analog and digital such as zero crossing, constant fraction discriminator[1,2], charge comparison[2,3], frequency gradient analysis[4], rise time discrimination, pattern recognition[5], etc.

High technology development has created a variety of techniques such as flash analog digital convertor (ADC), field programmable gate array (FPGA), and digital signal processing (DSP). That makes the PSD methods widely applied.In modern PSD systems, pulses from detector are digitized by flash ADC and the dataare stored in memory and analyzed by PSD method on computer[5-7], or on the board FPGA/DSP [4]. Almost all studies of neutron - gamma PSD were performed on different detectors in each way, therefore the evaluation of capacities of neutron-gamma PSDs have not carried out.

In the Dalat research reactor, we plan to setup a neutron counting system with NE213 detector, so the optimization of neutron-gamma PSD needs to be studied. A simulation model of signals of neutron-gamma with NE213 detector, photo multiplier tube (PMT), and preamplifier has been

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conducted. The sampling was digitized by behavioral modeling of pipelined ADC. All simulator models were executed by Matlab Simulinktools.

Based on the digitized sampling set, the four algorithms: rise-time discrimination, pulse gradient analysis, charge comparison method, and pattern recognition have been studied and evaluated through the FOM factor.

2. Experiment

The schematic of the neutron-gamma PSD algorithm simulation is shown in Fig 1. It consisted of a neutron-gamma pulse generator (NGPG), an electronic noise generator, an analog to digital converter, a filter, and a pulsesprocessor (PP). The neutron or gamma pulses were produced by block of NGPG, the amplitudes and start-time of pulses were generated randomly. Each pulse, after the sampling, would be filtered to reduce the noise, and then was taken to the PP block. The PP block included four parallel process modules corresponding to four PSD algorithms.

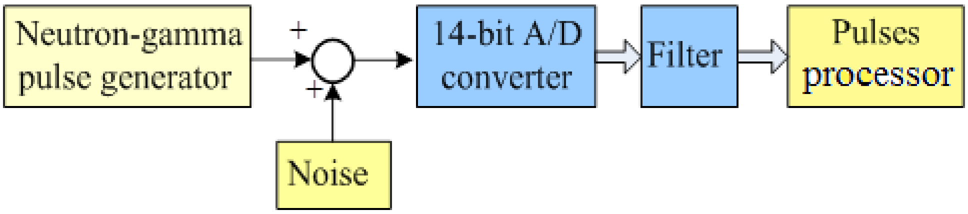

Fig. 1. *The simulation blocks of neutron - gamma PSD algorithms on Matlab Simulink.*

2.1. Simulation of neutron-gamma pulse for NE213 scintillation detector

The Marronne's model, including 6 parameters, was used to simulate neutron-gamma pulses of NE123 scintillation detector [4], [6]. The mathematical expression is given in equation (1).

$$y(t) = A\left[e^{-\frac{t-t_0}{\tau_1}} - e^{-\frac{t-t_0}{\tau_S}} + \frac{B}{A} e^{-\frac{t-t_0}{\tau_L}} \right] \quad (1)$$

Where, A and B are the amplitudes of the short (fast) and long(slow) life components at t = 0, respectively; τ_s and τ_L are decay timeconstants for the short and long life component, respectively; and τ_1 is the third decay constant and t_0 isthe time reference for the start of the signal. In this work, the parameters for the NE213 scintillator detector are shown intable 1. The data are assumed to have Gaussian distribution with a standard deviation of 10%.

Table 1.The parametersusedforsimulation of pulses of NE213 scintillator[6].

Parameters	B/A	τ_1 *(ns)*	τ_S *(ns)*	τ_L *(ns)*	t_0 *(ns)*
Gamma	1.658×10^{-2}	5.578	4.887	34.276	0.31
Neutron	4.151×10^{-2}	5.578	4.887	34.276	0.31

2.2. Simulation of electronic noises

*a) Thermionic emission:*The typical spontaneous emission rate at room temperature is in the range of $10^2 \div 10^4$ electrons/cm^2.s [8]. In most cases, these pulses originating from one single electronare often of small amplitude. Fig.2. is the equivalent circuit for noise analysis.

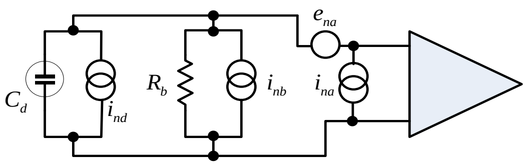

Fig.2. *Equivalent circuit for noise analysis.*

*b) Noise by dark current fluctuations in the photomultiplier tube (PMT):*A small amount of current flows in a PMT even when operated in a completely dark state. The fluctuations of dark current generatethe noise signals with Gaussian standard deviation, calculated according to equation (2) [8].

$$\sigma_Q = \sqrt{6\times10^{18}}\sqrt{U\tau / R} \qquad (2)$$

Where, U is the value high voltage, τ is the time constant of the electronic circuit, and R is the bias resistor of PMT.

c) The fluctuation of electrons going to the anode: The number of electrons flowing to the anode fluctuates statistically. The fluctuations are noise white and calculated according to equation (3) [9].

$$e_{nd}^2 = i_{nd}^2 \frac{1}{(\omega C_D)^2} = 2q_e I_D \frac{1}{(\omega C_D)^2} \quad (3)$$

Where, I_D is the bias current of detector, q_e is the electron charge, $\omega = 2\pi / \tau$ is the cutoff frequency of electronic circuit, and C_D is the capacitance of the detector.

d) Thermal noise in resistors: It is caused by resistors connected in parallel with PMT and calculated according to the equation(4)[9].

$$e_{np}^2 = 4kTR_p \frac{1}{1+(\omega R_p C_D)^2} \qquad (4)$$

Where, T is absolute temperature, R_b is the parallel resistor PMT, and k is the Boltzmann constant.

e) Noisefrompreamplifier: The noise ofpreamplifier consists of the input noise and the thermal noise of the feedback resistors. Therefore, the total noise of the preamplifier is expressed as follows:

$$e_{nt}^2(j\omega) = e_{n1}^2\left(1+\frac{C_{in}}{C_f}\right)+\frac{1}{j\omega C_f}\left[i_n^2+\left(\frac{e_{n2}}{R_f}\right)^2\right] \quad (5)$$

Where, e_{n1} is thermal noise of first-stage FET, e_{n2} is thermal noise caused by feedback resistance, i_n is shot noise caused by the input current of preamplifier, C_{in} is the input capacitance, C_f is the feedback capacitance, and R_f is the feedback resistance.

2.3. Simulation of signal sampling

The sampling of signal was performed by behavioral modeling of pipeline ADC with 14-bit resolution, 500 mega sample per second (MSPS), and three stages (4+4+6). The behavioral modeling of 14-bit pipeline ADC was based on reference [10]. The after sampling, signal interference was filtered by infinite impulse response (IIR) filter. The mathematical expression is given in equation (6).

$$y(n) = \left(y(n-2)+y(n-1)+y(n)+y(n+1)+y(n+2)\right)/5 \quad (6)$$

Where $y(n)$ is the value of amplitude at the n^{th}sampling period.

2.4. PSD algorithms

Rise time discrimination (RTD): It generally measures the difference between the integrated charge in the entire pulse and the integrated charge over the rising or the falling portion of the pulses. The slope of gamma pulse tail is greater than that of the neutron pulse tails (time for pulse amplitude increases from 10% to 90% of its height)[7].

Pulse gradient analysis (PGA): PGA method uses gradient analysis to discriminate neutron radiation. PGA is based on the comparison of the relative heights of the samples at the tail of the pulses. It is determined by equation (7)[11].

$$\delta = \left|\frac{dV(t)}{dt}\right| = \left|\frac{V(k+nT)-V(k)}{nT}\right| \quad (7)$$

Where V(k) is a variable voltage level of the k^{th} sampling period, T is sampling period of the signal, and n is the number of sampling periods. In approximation, if n is a constant, then $\delta \sim \left|V(k+nT)-V(k)\right|$.

Charge comparison method (CCM): CCM is based on area comparison of the rising or the falling portions of the pulse. Because the gradient of neutrons is different from that of gamma; therefore, the ratios of the area pulse are also changed. The area of the pulse can be calculated by equation (8)[5].

$$S = \int_{t_1}^{t_2} v(t)dt = \sum_{k=1}^{n} v(k).\Delta t \quad (8)$$

Where $\Delta t = T$ is sampling period, v(k) is a variable voltage level of the k[th] sampling period, t_1 and t_2 are timing of begging and ending of sampling period.

Pattern recognition method (PRM): In this method, a signal is considered as an object vector X whose components are the digitized amplitude x_n of the signal at sampling time t_n. PSD is performed by taking a scalar product of this vector with the reference vector Y which describes a gamma ray or neutron signal[5].

$$\vec{X} = (x_1, x_2, ..., x_n); \qquad \vec{Y} = (y_1, y_2, ..., y_n) \quad (9)$$

$$r = \frac{\vec{X}.\vec{Y}}{|\vec{X}|.|\vec{Y}|} \quad (10)$$

Where, r is the correlation coefficient between vector $\vec{X}$ and vector $\vec{Y}$, $\vec{X}.\vec{Y}$ is scalar product, $|X|$ and $|Y|$ are the norm of the vectors X and Y respectively.

$$\theta = Acr\cos\frac{\sum_{i=1}^{n} x_i.y_i}{\sqrt{\sum_{i=1}^{n} x_i^2}\sqrt{\sum_{i=1}^{n} y_i^2}} \quad (11)$$

Where, $\theta(rad)$ is the angle between the vectors; the θ value indicates the similarity of the object vector with the reference vector.

2.5. Evaluation of pulse shape discrimination methods

To evaluate the quantitative results of neutron-gamma discrimination, the FOM is used and defined as follows:

$$FOM = \frac{Ch_n - Ch_\gamma}{FWHM_n + FWHM_\gamma} \quad (12)$$

Where, Ch_n, Ch_γ are the values of neutron and gamma peaks respectively; $FWHM_n, FWHM_\gamma$ are the full-width-half-maximum of neutron and gamma peaks respectively,in the histogram.

3. Results and discussion

3.1. The results of pulse simulation for NE213 detector

The results of gamma and neutron pulse simulation at the same amplitude for NE213 detector with the parameters in Table 1 are presented in Fig.3. It shows that the front of the neutron and gamma pulses is the same, while the pulse tails of gamma decreases faster than those of neutron.

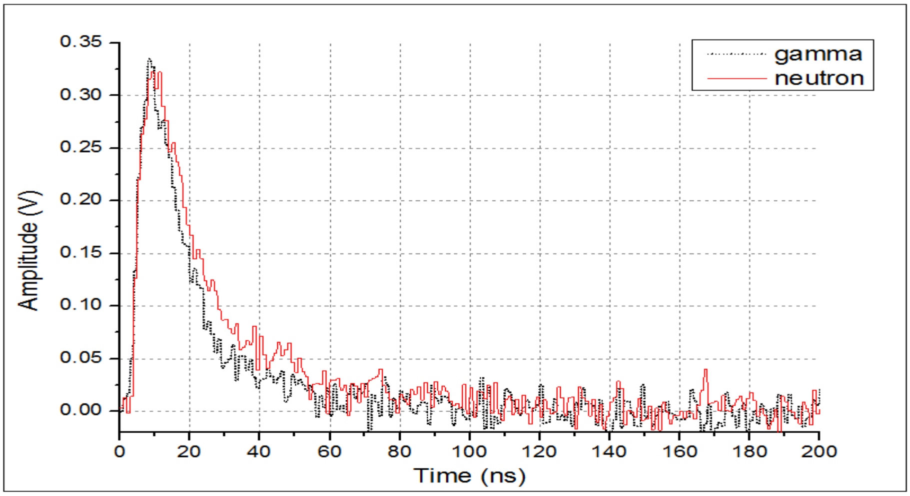

Fig.3. *The simulated pulse for NE213 detector.*

3.2. Sampling the neutron - gamma pulses by pipeline ADC model

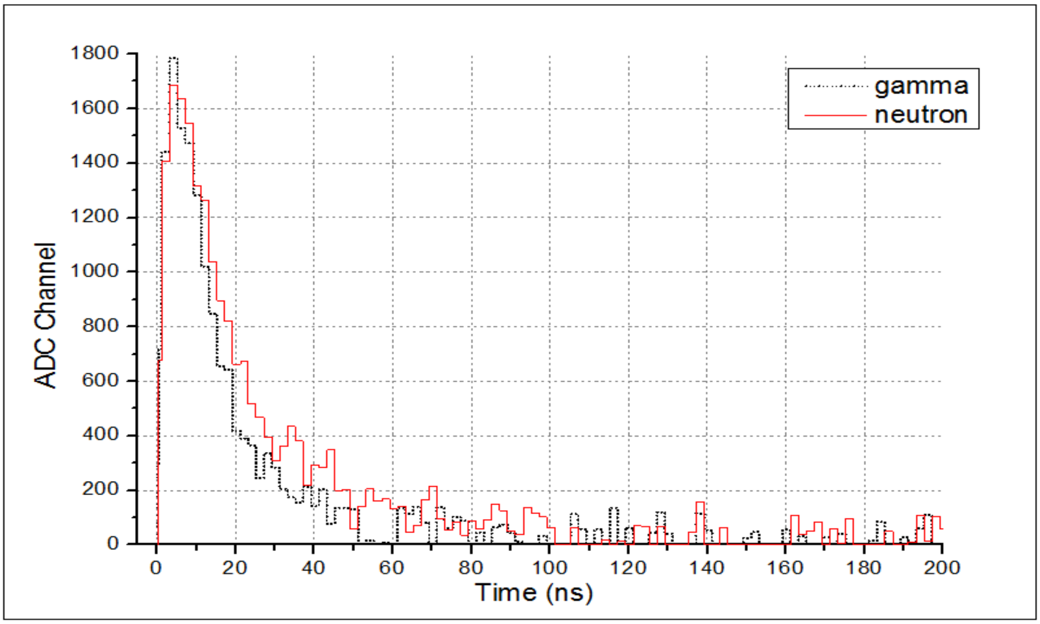

Fig.4. *The neutron – gamma pulses after being sampled by pipeline ADC model.*

The simulation results of neutron - gamma pulses after pulse sampling by pipeline ADC model with 14-bit resolution and sampling rate of 500MSPS are presented in Fig.4.It indicates that the pulses are added noise, but the differences in the pulse tails still exist.

3.3. The results of PSD algorithms

The survey results of approximately 100.000 neutron-gamma pulses with different algorithms: rise time discrimination, pulse gradient analysis, charge comparison, and correlation pattern methods are given in the Fig. 5, 6, 7 and 8. Fig.5 shows a scatter plot of the threshold crossing time versus the pulse heights for each waveform. Fig.6 shows a scatter plot of the calculated gradient to amplitude ratios versus the pulse heights for each waveform. Fig.7 shows a scatter plot of the charge of tail to amplitude ratios versus the pulse heights for each waveform. Fig.8 shows a scatter plot of the angle ratios versus the pulse heights for each waveform.

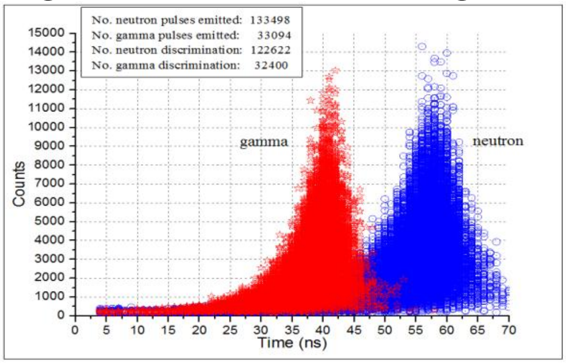

Fig. 5. *Threshold crossing time versus pulse heights.*

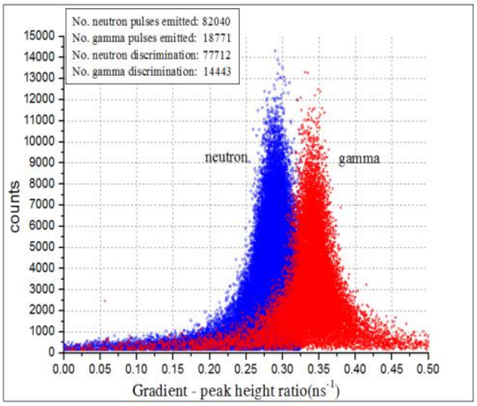

Fig. 6. *Gradient to amplitude ratios versus pulse heights.*

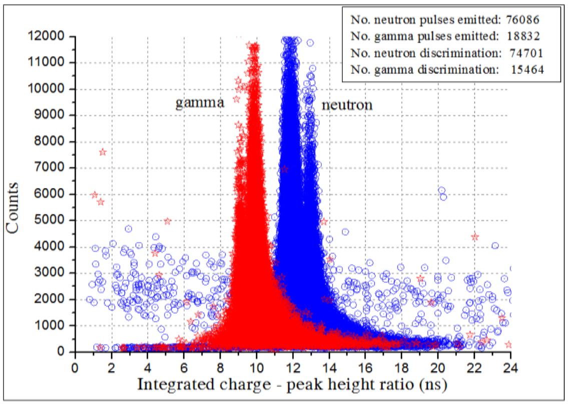

Fig. 7. *Charge of tail to amplitude ratios versus pulse heights.*

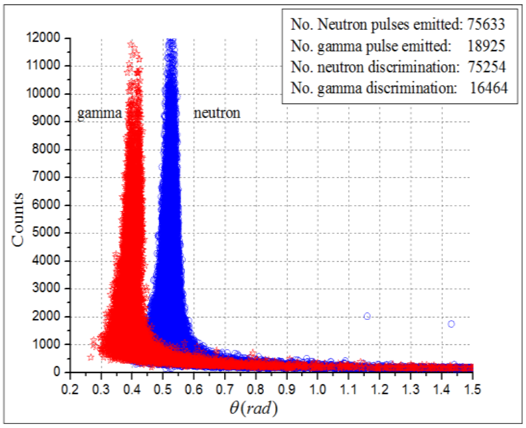

Fig. 8. *Angle ratios versus pulse heights.*

Fig. 9, 10, 11 and 12 are the statistical charts of PSD algorithms of rise time discrimination, pulse gradient analysis, charge comparison, and correlation pattern method respectively. The FOMs of these methods are shown in table 2.

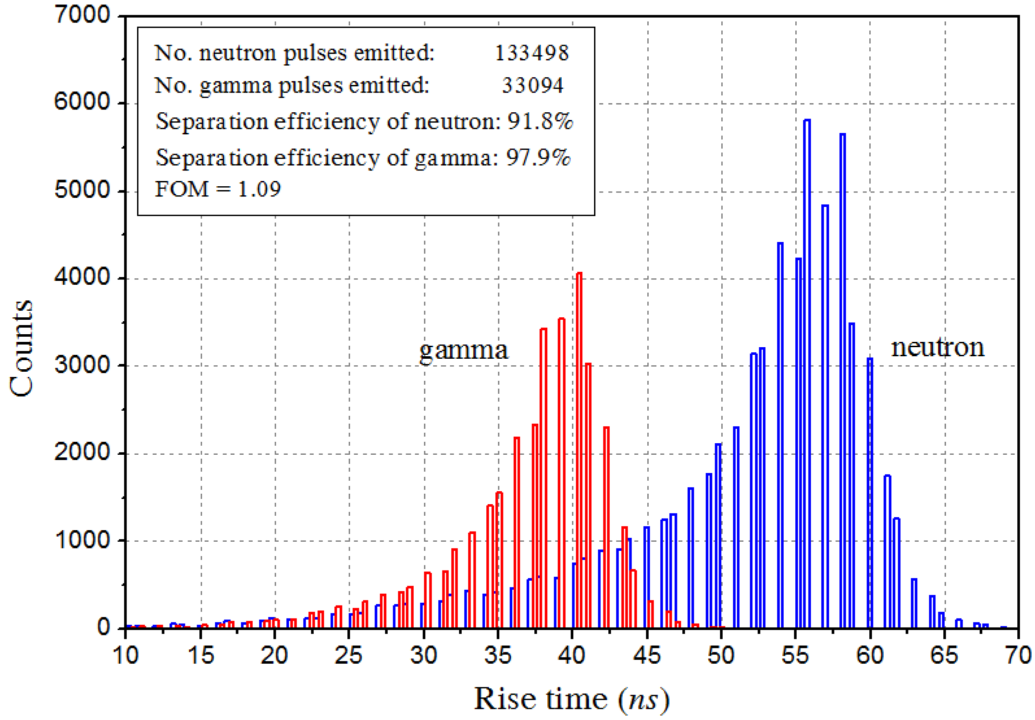

Fig. 9. *Histogram of rise-time discrimination.*

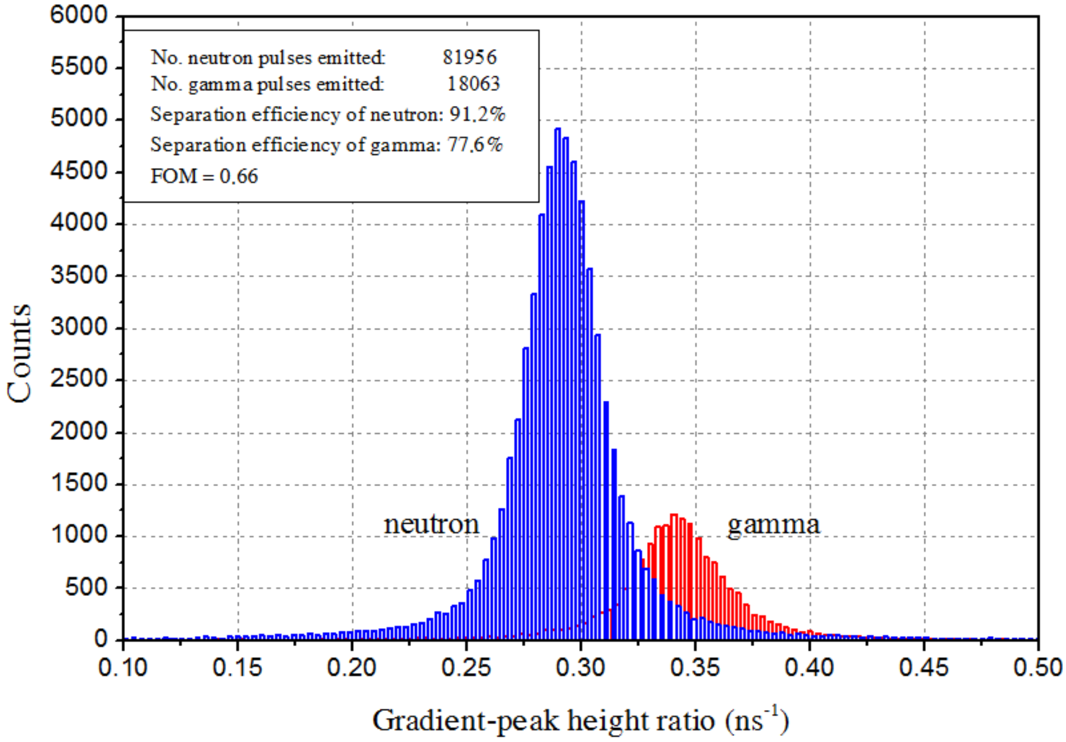

***Fig. 10.** Histogram of pulse gradient analysis.*

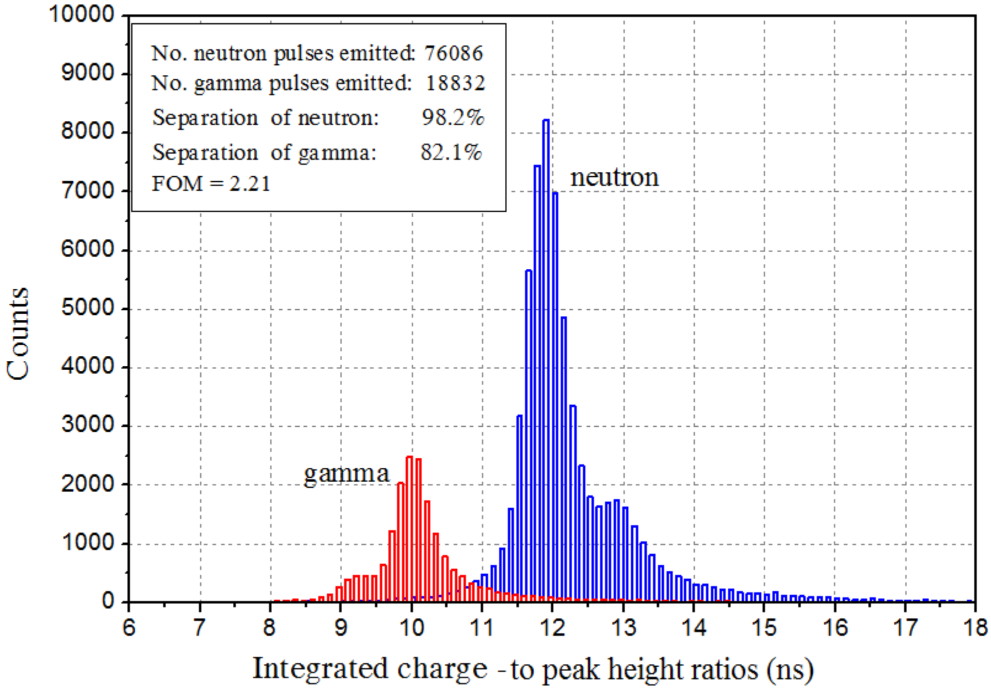

***Fig. 11.** Histogram of charge comparison.*

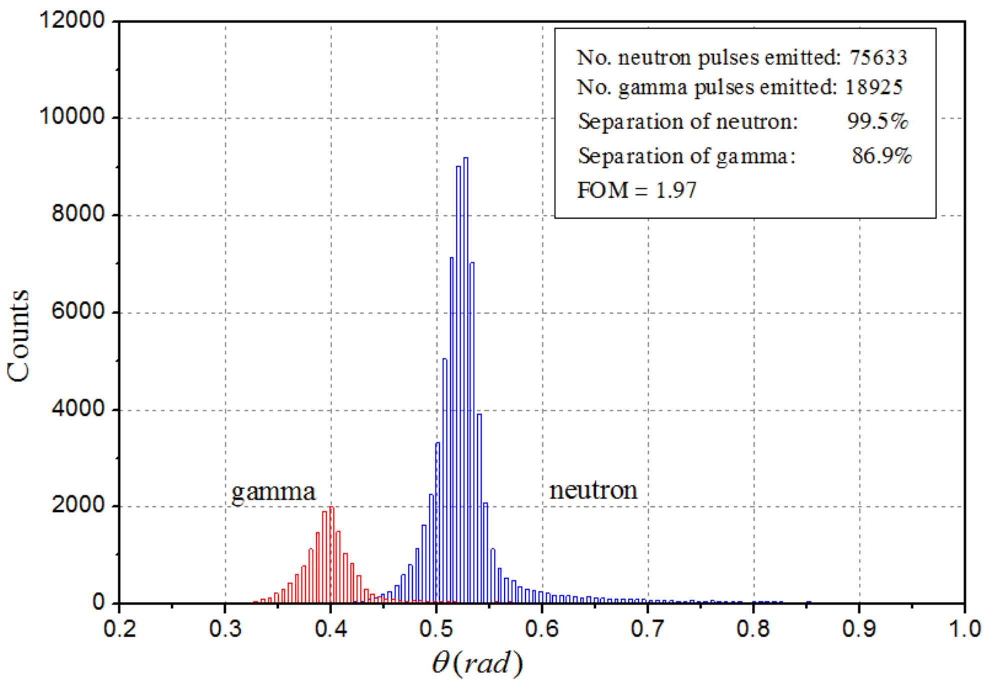

***Fig. 12.**Histogram of correlation pattern.*

Table 2.Comparison of four PSD methods.

Methods	FOM	Neutron recognizing capacity (%)	Gamma recognizing capacity (%)	Processing time/pulse (ns)
Rise time discrimination	1.09	91.8 ± 0.3	97.9 ± 0.5	34.0 ± 4.1
Pulse gradient analysis	0.66	91.2 ± 0.3	77.6 ± 0.6	38.0 ± 4.4
Charge comparison	2.21	98.2 ± 0.3	82.1 ± 0.6	54.0 ± 5.2
Correlation pattern	1.97	99.5 ± 0.3	86.9 ± 0.6	420.0 ± 14.5

3.4. Discussion

Based on the obtained values of the FOM, recognizing capacity, and processing time, the approximately capacity of the correlation pattern method is the biggest; its processing time is too long, approximately more than eight times in comparison with others. The charge comparison has a good FOM and is fast enough to analyze pulses. It can be applied for manufacturing neutron spectrometers, which enables to measure high count rates.

4. Conclusion

This study simulated the signals of neutron - gamma pulses produced from NE213 scintillator detector on Simulink software - Matlab. From the simulated pulses, the four PSD neutron-gamma algorithms have been studied with digital methods. Research results show that the FOMs of the charge comparison method and the correlation pattern method are higher than those of the rise time discrimination and pulse gradient analysis methods. In that, charge comparison method has the ability distinguishing neutron-gamma pulses well in low amplitude regions. The research results are the basis for building the neutron detection systems using NE213 scintillator detectors in combination with DSP and FPGA techniques.

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CÁC THUẬT TOÁN PHÂN BIỆT XUNG NEUTRON CHO DETECTOR NHẤP NHÁY

TÓM TẮT

Can nhiễu gây ra bởi gamma làm giảm độ chính xác trong kết quả đo lường phổ nơtron, đặc biệt khi sử dụng các detector nhấp nháy. Các phương pháp kỹ thuật số có thể sử dụng để nhận biết xung nơtron và gamma sinh ra trong detector nhấp nháy. Để lựa chọn các thuật toán tối ưu cho detector NE213, phần mềm Matlab/Simulink được sử dụng để mô phỏng hệ thống đếm nơtron. Kết quả thu được cho thấy phương thức phân biệt theo thời gian tăng có hệ số phẩm chất (Figure-of-Merits: FOM = 1,09), phương pháp phân tích độ dốc xung (FOM = 0,66), phương thức so sánh diện tích xung (FOM = 2,21) và phương thức tương quan mẫu (FOM = 1,97).

Từ khóa: *FOM, mô phỏng xung nơtron và gamma, phân biệt dạng xung nơtron-gamma, phương thức tương quan mẫu*