A pulse shape processing method of the CsI (Na) scintillator under \(\alpha\) and \(\gamma\) excitation

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Abstract. In this paper, we investigated the pulse shape processing performance of the CsI (Na) scintillator by using the root mean square error (RMSE), because the CsI (Na) crystal presents different decay time characteristics when excited by \(\alpha\) (239Pu, \(\sim 15\)ns and \(\sim 460\)ns) and \(\gamma\) (137Cs, \(\sim 574\)ns) particles. First, we diagnosed this by using the frequency pulse processing with MATLAB software. Then, the origin software was used to fit the pulse waveforms. The peak position of the pulse waveforms was located and then the fitting curves were used to calculate RMSE between the waveforms and the fitting curves. After these two steps, we preliminarily divided the threshold range of the RMSE. While using \(\alpha\) fitting curve, the events with 0.02<RMSE<0.2 were due to \(\alpha\) particles while the events with 0.4<RMSE<0.6 were due to \(\gamma\) particles. While using \(\gamma\) fitting curve, the events with 0.4<RMSE<0.6 were due to \(\gamma\) particles, the events with 0.7<RMSE<0.85 were due to \(\gamma\) particles.

1. Introduction

There are \(\alpha\) and \(\gamma\) particles exist in many places around the nuclear facilities, which is called \(\alpha\) and \(\gamma\) mixed radiation field. In order to take the most reasonable protective measurement in that field, we must grasp the distribution rules of the two particles respectively. However, a detector commonly used for measuring a particle will respond to another particle that is the measurement of two particles will interfere with each other [1]. Two times measurements method (\(\alpha\) and \(\gamma\) superposition were measured first, then the shielding plate was placed in front window of the detector to block \(\alpha\) radiations so that we could obtain \(\gamma\) spectrum) was used in \(\alpha\) and \(\gamma\) mixed radiation field. However, the introduction of shielding plate changed the original radiation field due to which an error in results was large. In order to measure two particles in \(\alpha\) and \(\gamma\) mixed radiation field more accurately, we have to discriminate these particles [1].

Bollinger and Tomas [2] studied the pulse shapes of \(\alpha\) particles, fast neutron and \(\gamma\) particles entering the organic scintillators. The stilbene scintillator emits photons with slow and fast components having a different decay time constants. The ionization density is larger, the proportion of slow components are larger. The ionization density for three kinds of particles varies in the stilbene results in different pulses along the shape. Three types of particles can be identified by comparing the shape of pulse along the shape. The plastic scintillators [3-4], liquid scintillators [5], CsI (Tl), CsI (Na), LaBr\(_3\) (Ce) and LaCl\(_3\) (Ce), and other inorganic scintillators [6-8] have properties similar to the stilbene detector. These detectors were widely used in the study of \(\alpha\) / \(\gamma\) and \(n\) / \(\gamma\) particle discrimination. Besides this, the shapes of pulse generated by some semiconductor detectors were related to ionization density, so they can also be used for particle discrimination [9-10].
The pulse shape for different types of particles are different, we can use these pulse shape discrimination algorithm to determine the type of particles. The pulse shape discrimination algorithm extracts the characteristic parameters of the pulse shape and then compares the feature parameters with thresholds to achieve particle discrimination. Rising time discrimination (RTD), zero crossing discrimination (ZCM), constant discrimination method (CFD), charge comparison (CC), constant time discrimination (CTD), pulse gradient analysis (PGA) and principal component analysis (PCA) were commonly used pulse shape discrimination algorithm [11-14].

In this paper, we presented a pulse shape processing method of the CsI (Na) scintillator under $\alpha$($^{239}$Pu) and $\gamma$($^{137}$Cs) excitation, which use the fitting curves of the pulse waveforms and calculate the RMSE between the fitting curves and the pulse waveforms. After the analysis of the calculated RMSE, we divided the threshold range of RMSE between the fitting curves and the pulse waveforms.

2. $\alpha$ / $\gamma$ processing method

2.1. Data acquisition and processing method

We processed the pulse shape of the CsI(Na) crystal when excited by the $^{137}$Cs ($\gamma$, 2000 Bq) and $^{239}$Pu ($\alpha$, 1000 Bq) sources. We used the single photon pulse waveform, which was obtained from the previous work [15]. The sample interval was 0.2 ns, and recorded length was $10^5$. After de-noising process of the original pulse signal, the back edge of the signal was fitted mathematically and expressed in the form of exponential function. Then, the RMSE between the fitting curves and the pulse waveforms of two particles are been calculated.

2.2. Waveform processing

Through the FFT function in MATLAB, a signal in the time domain was transformed into the signal in frequency domain. After that, high frequency part of the signal was removed to achieve de-noising process. After that, IFFT function was used to transform the signal from frequency domain to time domain. Pulse signal of $\alpha$ / $\gamma$ particle is shown below.

![Figure 1](image1.png)  

**Figure 1.** Pulse waveform of $\gamma$ particle.

![Figure 2](image2.png)  

**Figure 2.** Pulse waveform of $\alpha$ particle.

Then pulse signal was fitted by Origin software. Fitting results are as follows:

Pulse curve of $\gamma$ photon is fitted along the following fitting:

$$y_{\gamma}(t) = 2.8681e^{-t(5.8071 \times 10^{-7})} + 0.12769$$  \hspace{1cm} (1)
When the CsI(Na) scintillator under $\alpha$ particle excitation, it emits photons with slow and fast components having a different decay time constants. It was necessary to fit two parts to get the fitting curve of $\alpha$ particle.

Pulse curve of $\alpha$ particle was fitted along the following fitting:

$$y_{\beta_{\text{fast}}} (t) = 14.35022e^{(9.87929\times10^{-7}t)^{-1}} + 1.24085$$  \hspace{1cm} (2)

$$y_{\beta_{\text{slow}}} (t) = 2.15349e^{(-t(1.5913\times10^{-6})^{-1})} + 0.90996$$ \hspace{1cm} (3)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{fitting curve from pulse waveform of $\gamma$ particle.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{fitting curve from pulse waveform of $\alpha$ particle.}
\end{figure}

At the same time, the RMSE was used to represent the deviation between the pulse waveform and the fitting curve, and we used it to represent the similarity between the pulse waveform and the fitting curve. And the RMSE in table 1 is a benchmark for dividing threshold.

\begin{table}[h]
\centering
\caption{The RMSE between the fitting curve and de-noising pulse signal.}
\begin{tabular}{|c|c|}
\hline
Particle & RMSE \\
\hline
$\gamma$ & 0.5246 \\
$\alpha$ & 0.04472 \\
\hline
\end{tabular}
\end{table}

We locate the peak position of the pulse waveform with Matlab software. This position is the starting position we calculated by using the RMSE between fitting curves and pulse waveform.

2.3. Position division of waveform appearance

According to the actual situation, we divided the pulse waveform into three cases:

- 1. The Pulse waveform of $\gamma$ particle was preceded by the pulse waveform of $\alpha$ particle.
- 2. The Pulse waveform of two kinds of particles appears simultaneously.
- 3. The Pulse waveform of $\alpha$ particle prior to the pulse waveform of $\gamma$ particle.

The following are superimposed pulse waveforms.
By comparing the amplitude value in figure 5, figure 6 and figure 7, we found that peaks of the pulse waveforms is clear. So we can locate the position of peak with MATLAB software correctly. Then calculate the RMSE between fitting curves and pulse waveforms.

Fitted curves of pulse waveforms from equation (1) (2) (3) were used to calculate the RMSE between the fitting curves and pulse waveforms. The RMSE and relative error were used to evaluate similarity between the pulse waveforms and fitting curves of known particles.

**Figure 5.** Pulse waveform in situation 1.

**Figure 6.** Pulse waveform in situation 2.
3. $\alpha / \gamma$ pulse shape processing results and discussion

3.1. Pulse shape processing results
Due to the RMSE in table 1 is between fitting curve and single photon pulse waveform. When the pulse waveform was superimposed, an error was introduced. So, the RMSE value changed. The RMSE data and relative error is given below:

Table 2. RMSE between $\gamma$ fitting curve and pulse waveforms.

| Particle | Time         | RMSE  | Relative error (%) |
|----------|--------------|-------|--------------------|
| $\gamma$ |              | 0.5246|                    |
| $\alpha$ |              | 0.8097| 54.35              |
| $\gamma + \alpha$ | $\gamma$ preceded | 0.5275| 0.55               |
|          | $\alpha$    | 0.7561| 44.13              |
| $\alpha + \gamma$ | $\gamma$    | 0.4965| -5.36              |
|          | $\alpha$ preceded | 0.8095| 54.31              |
| $\gamma + \alpha$ | $\gamma$ and $\alpha$ appeared at the same time | 0.4732| -9.80              |

3.2. Discussion
From table 2 and table 3, it is seen that the RMSE between the two fitting curves and the pulse waveform are quite different. From table 2, the RMSE value is in the range from 0.4732 to 0.8097, and the relative error from -9.80 to 54.35 %. From table 3, the RMSE value is in the range from 0.04472 to 1.1013, and the relative from 0 to 2362.66 %. We find that the RMSE between different waveforms different fitting curves are quite different. And, from table 2, we find the RMSE is divided.

Figure 7. Pulse waveform in situation 3.
into two parts and the same phenomenon can be found in table 3. The reason is the difference of two types of particles. From figure 5, figure 6 and figure 7, it is clear that waveforms excited by $\gamma$ particle are different from the waveforms excited by $\alpha$ particle. This difference provides a possibility for us to divide the threshold interval of RMSE.

Table 3. RMSE between $\alpha$ fitting curve and pulse waveforms.

| Particle | Time          | RMSE  | Relative error (%) |
|----------|---------------|-------|--------------------|
| $\gamma$ | -             | 0.5162| 1054.29            |
| $\alpha$ | -             | 0.04472| -                 |
| $\gamma+\alpha$ | $\gamma$ preceded | 0.5115| 1043.78           |
|          | $\alpha$     | 0.1030| 130.32            |
| $\alpha+\gamma$ | $\gamma$ preceded | 0.5278| 1080.23           |
|          | $\alpha$     | 0.04472| 0                 |
| $\gamma+\alpha$ | $\gamma$ and $\alpha$ appeared at the same time | 1.1013| 2362.66           |

Especially in table 3, there is a great difference in the numerical value of the RMSE between the pulse shapes of different particles and the fitting curves of $\alpha$ particle. Hence, using the fitting curves of $\alpha$ particle can more clearly divide the threshold range than use that of $\gamma$ particle. Reference to the work of the predecessors, Skulski W and Momayezi M [16] used digital pulse shape analysis, value of sample by the pulse height (PH) was the particle identification (PID), the events with 0.8>PID>0.6 were result of $\alpha$ particles, and events 0.55>PID>0.45 were result of $\gamma$-rays. The RMSE threshold range is preliminarily divided. While using the fitting curves of $\alpha$ particle, the events with 0.02<RMSE<0.2 are due to $\alpha$ particles and the events with 0.4<RMSE<0.6 are due to $\gamma$ particles. While using the fitting curves of $\gamma$ particle, the events with 0.4<RMSE<0.6 are due to $\gamma$ particles and the events with 0.7<RMSE<0.85 are due to $\gamma$ particles. Compared with the PID index, the threshold division of the RMSE was clearer. For example, the dividing line between the two parts of the PID index is 0.55 and 0.6, and the difference is 0.05. While using the fitting curves of $\alpha$ particle, the dividing line between the two parts of the RMSE is 0.2 and 0.4, the difference is 0.2. That’s means, RMSE can provide a more clear division. From the threshold interval of RMSE, this method performs well in the three situations.

4. Conclusions
In this paper, single photon pulse waveform generated by CsI (Na) scintillator when excited by 137Cs $\gamma$ particle and 239Pu $\alpha$ particle was studied. Back edge of the pulse waveform was fitted, and the RMSE between the fitting curves and superimposed pulse waveforms was calculated. By using the exponential function of different fitting curves, there was a big difference in the results. Because of these differences, RMSE is divided into two parts. By analyzing the RMSE of different waveforms and different fitting curves, and reference to the work of the predecessors. We have divided the threshold of RMSE. Because of the large difference of RMSE of different particles, the threshold of RMSE is clearer than that of PH. Especially when using alpha particle fitted curve to calculate RMSE, compared with the fitted curves of gamma particles, the RMSE thresholds of different particles can be more clearly distinguished. Therefore, this method has a good performance in dividing the threshold interval of different particles. Then the next work will optimize the processing of the pulse waveform and apply it to the actual particle discrimination.
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References

[1] Gale G Simons and Jack F Higginbotham 1990 Beta-particle spectroscopy with active gammaray discrimination Nuclear Instruments & Methods in Physics Research 293(3) 551-554
[2] Bollinger L M and G E Thomas 1961 Measurement of the Time Dependence of Scintillation Intensity by a Delayed-Coincidence Method Review of Scientific Instruments 32(9) 1044-1050
[3] Normand S, Mouanda B, Haan S and Louvel M 2002 Discrimination methods between neutron and gamma rays for boron loaded plastic scintillators Nuclear Instruments & Methods in Physics Research 484(1–3) 342-350
[4] Zaitseva N, Glenn A, Mabe A, Carman L, Hurlbut C and Inman J and et al 2018 Recent developments in plastic scintillators with pulse shape discrimination Nuclear Instruments & Methods in Physics Research A 889 97-104
[5] D’Mellow B, Aspinall M D, Mackin R O, Joyce M J and Peyton A J 2007 Digital discrimination of neutrons and γ-rays in liquid scintillators using pulse gradient analysis Nuclear Inst & Methods in Physics Research A 578(1) 191-197
[6] Crespi F C L, Camera F, Blas, N, Bracco A, Brambilla S, Million B and et al 2009 Alpha–gamma discrimination by pulse shape in labr 3 :ce and lacl 3 :ce Nuclear Instruments & Methods in Physics Research 602(2) 520-524
[7] Dinca L E, Dorenbos P, Haas J T, Bom V R and Eijk C W 2002 Alpha–gamma pulse shape discrimination in csitl, csitna and baf 2, scintillators Nuclear Instruments & Methods in Physics Research 486(1–2) 141-145
[8] Qin Z J, Chen C, Luo J S, Xie X H, Ge L Q and Wu Q F 2018 A pulse-shape discrimination method for improving gamma-ray spectrometry based on a new digital shaping filter Radiation Physics & Chemistry 145 193-201
[9] Ammerlaan C A J, Rumphorst R F and Koerts L A C 1963 Particle identification by pulse shape discrimination in the p-i-n type semiconductor detector Nuclear Instruments & Methods 22(2) 189-200
[10] Pausch G, Ortlepp H G, Bohne W and Grawe H 1996 Identification of light charged particles and heavy ions in silicon detectors by means of pulse-shape discrimination. IEEE Transactions on Nuclear Science 43(3) 1097-1101
[11] Usuda S, Abe H and Mihara A 1994 Phoswich detectors combining doubly or triply zn(s)ag, ne102a, bgo and/or naitl scintillators for simultaneous counting of α, β and γ rays Nuclear Instruments & Methods in Physics Research 340(3) 540-545
[12] Chandrikamohan P and Devol T A 2007 Comparison of pulse shape discrimination methods for phoswich and csitl detectors IEEE Transactions on Nuclear Science 54(2) 398-403
[13] Ramesh S, Bijan D, Ni P and Channel C D 2007 Verification of the digital discrimination of neutrons and γ rays using pulse gradient analysis by digital measurement of time of flight Nuclear Instruments & Methods in Physics Research 583(2–3) 432-438
[14] Alharbi T 2016 Principal Component Analysis for pulse-shape discrimination of scintillation radiation detectors Nuclear Instruments & Methods in Physics Research 806 240-243
[15] Liu J, Liu F, Ouyang X, Liu B, Chen L and Ruan J, et al 2013 The luminescence characteristics of CsI(Na) crystal under α and X/γ excitation Journal of Applied Physics 113(2) 185
[16] Skulski W and Momayez M 2001 Particle identification in csitl using digital pulse shape analysis Nuclear Instruments & Methods in Physics Research 458(3) 759-771