15

A new method for separation of signals from charged particles and gamma quanta by the shape of the rising edge of the scintillation pulse

© E.A. Borisevich, A.G. Bondarau, M.V. Korzhik, V.A. Mechinsky, K.E. Okhotnikova, A.A. Fedorov

Institute for Nuclear Problems, Belarusian State University, Minsk, Belarus
E-mail: gapovaknopka@mail.ru

Received December 11, 2024
Revised March 21, 2025
Accepted April 3, 2025

We described a discrimination method for separating of signals from charged particles and gammaγ-quanta by the shape of the scintillation pulse's rising edge. This method is based on the fact that the scintillation kinetics at the build-up stage in an activated scintillator depends on the ionization density nonlinearly. This approach became realizable with the development of fast waveform digitizers with the high sampling rate, providing the more precise form of the increasing part of the scintillation pulses detection. The method's efficiency is demonstrated by the example of a thallium-activated CsI crystal. The utilization of the method will essentially increase the performance of the charged particle scintillation pulses selection.

Keywords: scintillator, CsI(Tl), pulse shape discrimination, waveform digitizer.

DOI: 10.61011/TPL.2025.07.61423.20220

The method of separation of scintillation signals from particles with different specific ionization values is used widely in nuclear physics measurements [1]. This method relies on the fact that the scintillation decay time corresponding to strongly ionizing particles, such as α-particles or tritons, is effectively longer than the one for γ-quanta and electrons in a fairly large number of inorganic and organic scintillators.

Pulse shape discrimination (PSD) of signals of neutrons and γ-quanta has been proven efficient in experiments with both plastic-based and liquid scintillators [2] when the charge integration method with fast digitizers was used. The author of [3] has established that light pulses of different shapes are formed in a scintillator based on lithium glass under excitation by the products of reaction $^6\mathrm{Li}(n, \alpha)\mathrm{T}$ or Compton electrons. This is used to reduce the efficiency of detection of γ-radiation relative to thermal neutrons.

Two approaches to pulse shape discrimination are used at present. The first one is based on integration of the photodetector signal, which is induced by a scintillation light pulse, with subsequent determination of the time interval within which this integral reaches a certain fraction of its maximum. The second approach relies on comparison of the charges induced in a photodetector by a scintillation pulse over two different time intervals, one of which normally covers the rising edge of a pulse and a part of the falling edge, while the other is shifted toward the late stage of scintillation decay. A general methodology for calculating the performance of these PSD techniques was presented in [4]. The authors of [5] have demonstrated that the performance of digital PSD utilizing signal integration with a digitizer is significantly higher than the one of an analog system using zero crossing.

All of the above methods are based on the empirically established fact that a scintillation pulse decays differently at different ionization densities [6], which was extended to all types of scintillation materials. Modern concepts of scintillation formation in an inorganic medium establish a dependence of the shape of scintillation kinetics on the mechanism of its occurrence [7]. Specifically, scintillation build-up in inorganic activated scintillators, wherein activating impurity ions act as luminescent centers, also depends on the ionization density. This is attributable to the fact that the scintillation mechanism includes a chain of processes of transfer of electronic excitations from excitons formed by thermalized carriers to impurity centers. The higher the ionization density, the higher the concentration of excitons in an ionization track and, consequently, the rate of energy transfer to activator centers, since the average distance between excitons and luminescence centers decreases and volume interaction becomes more significant. Note that an increase in concentration of excitons in a track also promotes their mutual concentration quenching, reducing the scintillation yield at a higher ionization density in the medium. The use of only the rising edge of a scintillation pulse for PSD allows one to reduce the processing time (digitizers with a shorter time scale may be used) and to obtain a better discrimination figure of merit (FoM), which is calculated in the following way:

$$\mathrm{FoM} = |M_p - M_\gamma| / |\mathrm{FWHM}_p + \mathrm{FWHM}_\gamma|,$$

where subscripts γ and p correspond to γ-quanta and other particles, respectively; M_p, M_γ and FWHM_p, FWHM_γ — average PSD parameters and full width at half maximum values for particles and γ-quanta [8]. The CsI(Tl) scintillation material was used to verify the possibility of discrimination of signals from γ-quanta and α-particles by the shape of the rising edge of pulses. The rate of transfer of electronic excitations from the exciton subsystem to the

activator subsystem in alkali halide materials activated by thallium, NaI(Tl) and CsI(Tl), is low, which translates into scintillation build-up times on the order of nanoseconds. This allows one to use digitizers with relatively short sampling times (on the order of fractions of a nanosecond).

The examined CsI(Tl) scintillation crystal sample $9 \times 9 \times 6$ mm in size with a scintillation kinetics duration of approximately 1.3 μs was wrapped in a Teflon reflector and placed with its face on the surface of the input window of a Hamamatsu R329-02 photomultiplier tube (PMT). Optical contact was established using optical grease. A window 2 mm in diameter was made in the upper part of the reflector to introduce α-particles into the sample. The sample was irradiated both separately by α-particles with energy $E_\alpha \approx 5.5$ MeV from a ^{238}Pu source and γ-quanta from a ^{137}Cs (0.662 MeV) source and by both sources simultaneously. To obtain a PSD distribution, the output signal from the PMT anode was transmitted via a coaxial cable through a 10 dB attenuator to the input of a DRS4 Board digitizer (input impedance, 50 Ω; maximum input signal amplitude, ±500 mV; maximum resolution, $5.12 \cdot 10^9$ samples per second) [9]. The PMT supply voltage was 1800 V, and the output signal amplitude did not exceed 500 mV at the DRS4 input. The sampling rate of the digitizer was $3 \cdot 10^9$ samples per second; 10^5 events were recorded in each case. The spectra of ^{137}Cs and ^{238}Pu sources, which were measured by the same PMT with an ORTEC TRUMP 2k multichannel amplitude analyzer and a CAMAC spectrometric amplifier with a shaping time constant of 7.75 μs, were used to determine the α/γ-ratio.

A α/γ-ratio of 0.54 for the CsI(Tl) crystal was found by approximating the total absorption peaks and photopeaks in the spectra with Gaussian distributions. This result matches the previously reported value [10]. With a limit set on the signal amplitude, the measured α/γ-ratio allowed us to use only those signals for PSD that correspond to the peak of total absorption of γ-quanta and the photopeak of α-particles.

A specific criterion for signal separation was formulated in order to form a PSD distribution by the rising edge of the signal in the CsI(Tl) crystal. Averaged pulse profiles corresponding to γ- and α-radiation detection were obtained for this purpose (Fig. 1). It can be seen from Fig. 1 that the signal for γ-quanta has a rising edge that is more extended in time relative to the rising edge of the α-particle signal.

The averaged pulse profile was used to optimize the width of the time gate for determining the parameter of the criterion for signal separation by shape. This was done in the following way: in the first case, the initial time stamp (i) was set at a level of 0.1 of the signal amplitude, while the final one (f) was varied from 0.3 to 0.7 of the maximum value (Fig. 1). In the second case, the final time stamp was set at a level of 0.9, while the initial one was varied from 0.3 to 0.7 of the maximum signal value. With each time gate option, the criterion for separation by the rising edge was calculated as the charge in the rising part of the

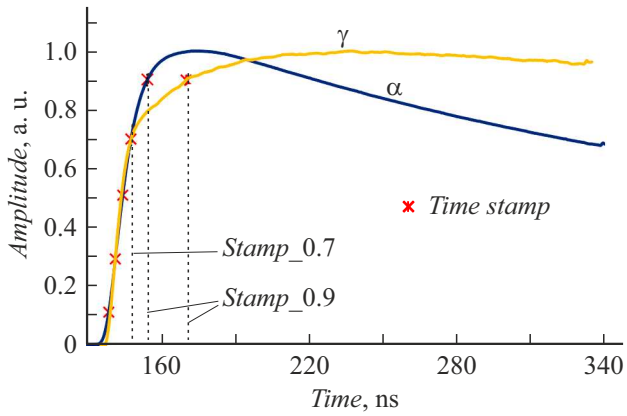

Figure 1. Averaged profiles of α-particle and γ-quanta pulses in the CsI(Tl) crystal normalized in amplitude. Time stamps with a step of 0.2 in relative amplitude (axis Y) are also added to the pulse profiles.

pulse (the rising part area) extending from time stamp i to time stamp f:

$$Q = \sum_{i}^{f} q_{i-f}.$$

Two distributions by the PSD parameter were then obtained for each of the time gate options with additional selection of events based on the boundaries of the peaks of total absorption of γ-quanta and α-particles. The obtained distributions were approximated by a normal one, and the separation figure of merit was calculated for each time gate option (see the table). A PSD spectrogram of α-particles from ^{238}Pu and γ-quanta from ^{137}Cs (Fig. 2) was obtained for the case with the highest figure of merit (~ 0.99): the amplitude of signals was plotted along the horizontal axis, and the charge in the rising part of the signal with the time gates set at 0.9–0.7 of the signal level maximum (Fig. 1) was plotted along the vertical axis.

The signals with a larger PSD value in Fig. 2 correspond to α-particles, while the signals with a small PSD value correspond to γ-quanta. Thus, the α- and γ-radiation signals in the CsI(Tl) crystal are separated by shape when just the rising edge of the signal is analyzed.

Results of FoM calculation for two distributions by the PSD parameter and different widths of the time gate for the rising part of the pulse in the case of α- and γ-radiation

Levels	Time gate width (alpha/gamma), ns	FoM
0.1–0.3	(3.0/2.0) ± 0.3	0.73
0.1–0.5	(6.0/4.3) ± 0.3	0.72
0.1–0.7	(9.6/8.7) ± 0.3	0.66
0.9–0.3	(13.0/28.7) ± 0.3	0.97
0.9–0.5	(10.0/26.4) ± 0.3	0.97
0.9–0.7	(6.7/22.0) ± 0.3	0.99

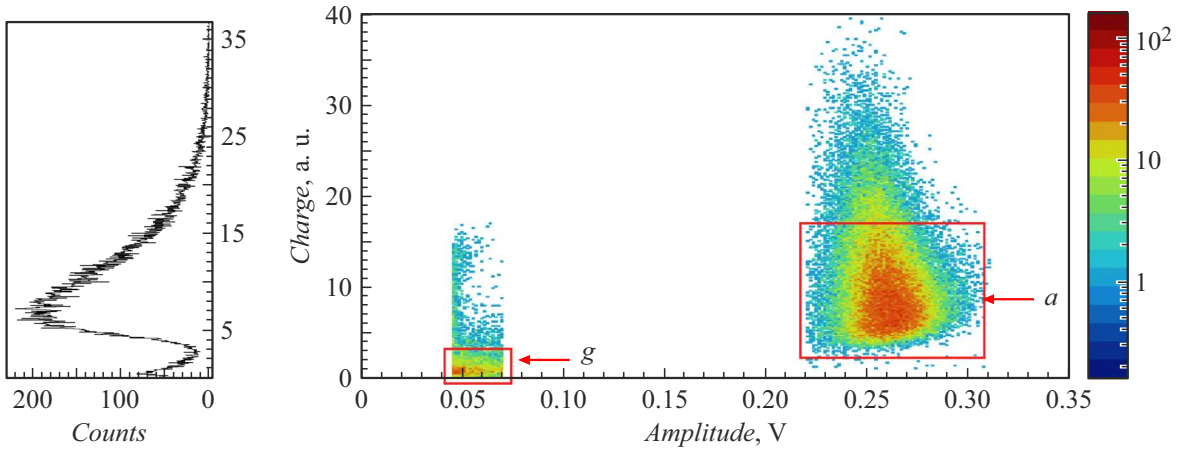

Figure 2. Distribution by the PSD parameter and PSD spectrogram with marked regions for signals of α-particles from ^{238}Pu (a) and γ-quanta from ^{137}Cs (g) for the CsI(Tl) sample in the case of separation by the rising edge (the sampling interval of the digitizer is 0.3 ns).

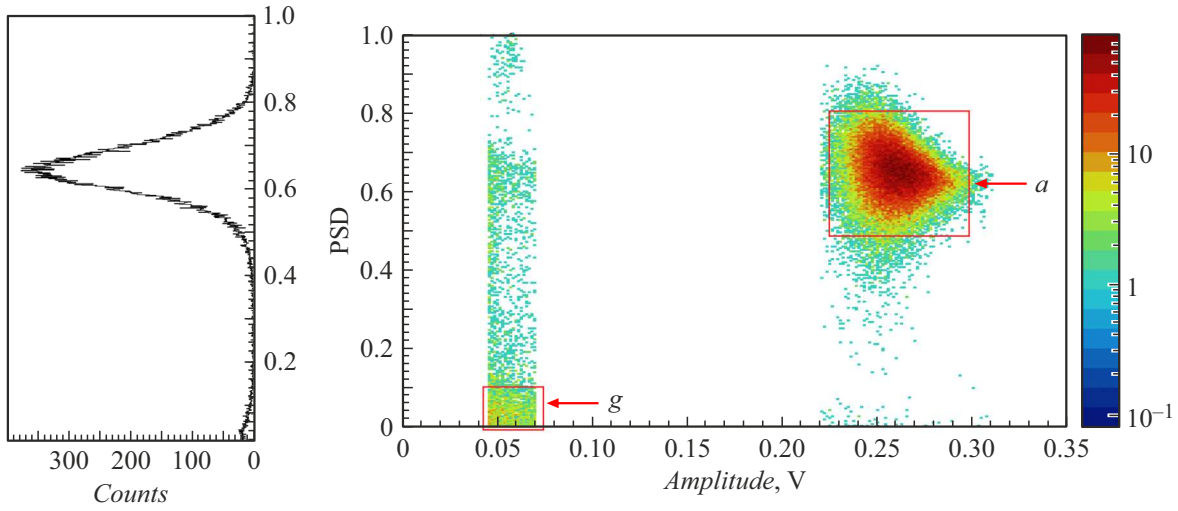

Figure 3. Distribution by the PSD parameter and PSD spectrogram with marked regions for signals of α-particles from ^{238}Pu (a) and γ-quanta from ^{137}Cs (g) for the CsI(Tl) sample in the case of separation by the falling edge of the scintillation signal (the sampling interval of the digitizer is 0.3 ns).

A PSD spectrogram with separation of the α- and γ-radiation signals by the falling part of the scintillation pulse was also obtained for comparison (Fig. 3). The PSD criterion is defined as follows in this case:

$$\mathrm{PSD} = 1 - Q_{fast}/Q_{total},$$

where Q_{fast} is the charge of the fast pulse component (measured from the maximum signal value to a certain specified position (PSD shift) beyond it) and Q_{total} is the total charge of the entire pulse (measured from the maximum signal value to the end of the digitized signal). To calculate the short component, the initial time stamp was set at the maximum signal level, and the final stamp was shifted by ~ 60 ns (PSD shift) to the right.

It is evident that discrimination exclusively by the vertical PSD scale in the case shown in Fig. 3 will be more efficient when the amplitudes of γ-quanta pulses increase and amplitude discrimination by the horizontal scale in Figs. 2 and 3 becomes infeasible. The FoM value was estimated at 2.45 from the data presented in Fig. 3, which is indicative of efficacy of the method.

The obtained results verified the feasibility of separation by the rising edge in experiments with the widely used CsI(Tl) scintillator. When one compares the shapes of signals from a charged particle and the γ-quanta background, the obtained FoM values for separation by the rising edge (~ 0.99) and the falling edge (~ 2.45) of a pulse indicate that the signals are indeed separated by shape.

Funding

This study was supported by the Belarusian Republican Foundation for Fundamental Research (agreement No. F23RNF-074 dated November 15, 2022).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] M.L. Roush, M.A. Wilson, W.F. Hornyak, Nucl. Instrum. Meth., **31** (1), 112 (1964). DOI: 10.1016/0029-554X(64)90333-7
[2] D. Cester, M. Lunardon, G. Nebbia, L. Stevanato, G. Viesti, S. Petrucci, C. Tintori, Nucl. Instrum. Meth. Phys. Res. A, **748**, 33 (2014). DOI: 10.1016/j.nima.2014.02.032
[3] C. Coceva, Nucl. Instrum. Meth., **21**, 93 (1963). DOI: 10.1016/0029-554X(63)90092-2
[4] G. Ranucci, Nucl. Instrum. Meth. Phys. Res. A, **354** (2-3), 389 (1995). DOI: 10.1016/0168-9002(94)00886-8
[5] C.S. Sosa, M. Flaska, S.A. Pozzi, Nucl. Instrum. Meth. Phys. Res. A, **826**, 72 (2016). DOI: 10.1016/j.nima.2016.03.088
[6] F.D. Brooks, Nucl. Instrum. Meth., **4** (3), 151 (1959). DOI: 10.1016/0029-554X(59)90067-9
[7] M. Korzhik, G. Tamulaitis, A.N. Vasil'ev, *Physics of fast processes in scintillators.* Ser. Particle Acceleration and Detection (Springer, Cham, 2020). DOI: 10.1007/978-3-030-21966-6
[8] M.J.I. Balmer, K.A.A. Gamage, G.C. Taylor, Nucl. Instrum. Meth. Phys. Res. A, **788**, 146 (2015). DOI: 10.1016/j.nima.2015.03.089
[9] *Paul Scherrer Institut (PSI). DRS4 Evaluation Board* [Electronic source]. https://www.psi.ch/en
[10] W. Wolszczak, P. Dorenbos, IEEE Trans. Nucl. Sci., **64** (6), 1580 (2017). DOI: 10.1109/TNS.2017.2699327

Translated by D.Safin