

NEUTRON AND GAMMA-RAY PULSE SHAPE DISCRIMINATION METHODOLOGY

 I. Yakymenko^{1*},  A. Dobrozhan¹,  G. Onyshchenko¹,  O. Kuzin¹,  V. Trusova²,  P. Kuznietsov¹

¹*O.I. Akhiezer Department for Nuclear Physics and High Energy Physics, V.N. Karazin Kharkiv National University, Kharkiv, Ukraine*

²*Department of Medical Physics and Biomedical Nanotechnologies, V.N. Karazin Kharkiv National University, Kharkiv, Ukraine*

*Corresponding Author e-mail: ivan.yakymenko@karazin.ua

Received April 2, 2026; revised May 5, 2026; accepted May 19, 2026

In this research, we proposed a new neutron gamma discrimination methodology in comparison with the classical charge integration. To record an experimental dataset, a high sampling rate oscilloscope, Keysight DSOX 6004a (20 Gs/s), was used. The reference experiment was recorded with the desktop digitizer CAEN DT 5720e with DPP PSD firmware installed. A stilbene scintillator size of 50 mm x 50 mm coupled with the PMT R1307 Hamamatsu was selected as a detector. The scintillation pulse decay has an exponential tail depending on the particle nature. The proposed technique aims to classify the geometrical peak asymmetry of the scintillation pulse detected by the detector, where the discrimination factor is a ratio of the calculated pulse weight (centroid) related to the pulse maximum amplitude position in time. The centroid of the faster gamma pulse is closer to the pulse maximum amplitude and significantly shifted for the delayed neutron pulses. The discussed approach allows us to classify events with comparable accuracy to the charge integration technique.

Keywords: Charge integration; Scintillators; Neutron gamma discrimination; Stilbene; PMT; Pulse Shape Discrimination; Charge Comparison; Zero-Crossing; Figure of Merit; CAEN DT5720e

PACS: 29; 29.40.Mc; 29.40.-n

1. INTRODUCTION

Analyzing recent publications and the experimental equipment, it is possible to draw a reasonable conclusion that the problem of neutron-gamma separation has today transformed from a highly specialized issue of nuclear physics into a fundamental interdisciplinary challenge. The relevance of developing reliable methods for discriminating particles by pulse shape is rapidly growing not only in traditional research applications, but also in strategically important applied areas, for example discussed in [1] land mine detection applications. In particular, in modern medicine, it is critical for the accuracy of hadron therapy; in research of new type of neutron detectors [2, 3], for conducting non-destructive elemental analysis; and in the security sector, for solving humanitarian problems, such as high-precision demining of territories and detection of hidden threats. However, despite the high demand, the practical implementation of these methods faces serious technological barriers related to the hardware base. The analysis shows that the vast majority of existing solutions capable of providing an acceptable quality factor figure of merit (FOM) are stationary and bulky complexes. The critical aspect remains the speed of signal processing and sampling rate. Thus, there is a clear scientific demand for the creation of high-speed data acquisition systems with open-source algorithms. In the article [4], a direct comparison of digital versions of the zero-crossing ZC and charge comparison CC methods was carried out using a NE213 liquid scintillator and an 8-bit digitizer with a frequency of 1 GS/s. Experimental results showed that the ZC method provides a higher quality of separation with an FOM = 1.05 at an energy of 100 keVee, while the CC method under the same conditions demonstrated FOM = 0.88. The authors found that the Z/C method is much more stable to changes in signal amplitude: when changing the energy from 100 keVee to 1 MeVee, the shift in the discrimination parameter for Z/C was only 2 %, while for CC it reached 12%. This confirms the advantage of Z/C for experiments with a wide dynamic range, where it is important to avoid energy dependence of the separation threshold. It was also shown that when using digital ZC, the threshold for effective neutron detection can be reduced to 40 keVee without a significant increase in gamma-ray leakage. The data obtained indicate that the high sampling frequency (1 GHz) allows the ZC method to better compensate for the influence of the low bit depth of the ADC (8 bits). It is also important to mention the work [5], which proposed and investigated in detail the pulse gradient analysis (PGA) method, which is based on comparing the current amplitude of the digitized signal with its value after a certain delay time. The experiment was carried out with a liquid scintillator NE213 (diameter and height 50 mm) and a digitizer with a frequency of 250 MS/s and a bit depth of 12 bits. The author established the optimal delay time for the gradient at 28–32 ns after the pulse peak, which allowed maximizing the difference between the fast and slow components of the illumination. The results showed that the PGA method provides FOM = 1.07 at a very low energy of 40 keVee, which significantly exceeds the capabilities of the standard CC charge comparison method in this range. At an energy of 100 keVee, the method achieved FOM = 1.63, demonstrating high resistance to electronic noise and statistical fluctuations. An important technical advantage of PGA is its computational efficiency: the algorithm requires only one compare and divide operation per event, which makes it 3–4 times faster than curve approximation methods

Cite as: I. Yakymenko, A. Dobrozhan, G. Onyshchenko, O. Kuzin, V. Trusova, P. Kuznietsov, East Eur. J. Phys. 2, 101 (2025), <https://doi.org/10.26565/2312-4334-2026-2-09>

© I. Yakymenko, A. Dobrozhan, G. Onyshchenko, O. Kuzin, V. Trusova, P. Kuznietsov, 2026; CC BY 4.0 license

when implemented in MATLAB or FPGA. The development of a PSD system based on FPGA (Xilinx Kintex-7 array) using a 12-bit ADC and a sampling rate of 500 MS/s is described in [6]. The authors implemented a charge comparison (CC) method optimized for operation under extremely high loads — up to 1.08 million samples per second (Mcps). In an experiment with a ^{252}Cf source and a BC501A liquid scintillator, the system demonstrated a stable $\text{FOM} = 1.15$ at an energy threshold of 100 keVee. Thanks to the parallel processing architecture in the FPGA, the system dead time per event was reduced to 200 ns, which allowed avoiding significant data loss at high radiation intensity. Comparison with offline processing on a PC showed the identity of the results with a significant gain in speed (real-time processing). The study confirmed that the 500 MHz configuration is sufficient for accurate separation of the “fast” component (10–30 ns duration) and the “tail” of the pulse. In [7], a digital implementation of the zero-crossing method ZC is presented, where the anode signal from the EJ-276 and EJ-309 scintillators was digitized with a frequency of 500 MS/s and a bit depth of 14 bits. The authors implemented a recursive digital filter to form a bipolar signal, which allowed achieving a value of $\text{FOM} = 1.32$ for the plastic scintillator EJ-276 at an energy of 100 keVee. For the liquid scintillator EJ-309, the quality indicator was $\text{FOM} = 1.83$ in the same energy range. It has been experimentally proven that the method provides stable particle separation at energies from 40 keVee, which is critical for the registration of low-energy fast neutrons. It is also noted that the baseline error was minimized to $< 1\%$, which allowed avoiding the drift of the discrimination peak. According to the test results, this digital ZC algorithm outperformed classical analog methods in terms of neutron event purity by 15%. In [8], the possibility of using a 64-channel TOFPET2 ASIC for particle identification in pixel detectors based on organic scintillators was investigated. The experimental setup consisted of an array of 4×4 trans-stilbene crystals ($6 \times 6 \times 30$ mm each) connected to an array of SensL J-series silicon photomultipliers (SiPM). Since TOFPET2 was originally developed for medical PET imaging, the authors adapted it for PSD using the Time-over-Threshold (ToT) method for charge estimation. At the SiPM operating overvoltage of 3V, the system demonstrated a maximum quality factor FOM of ≈ 1.2 at an energy of 478 keVee (Compton edge for the 662 keV line). The study highlights that despite the compactness and low cost per channel, the use of the ToT method instead of direct pulse shape digitization limits the quality of the separation at low energies. However, the results obtained confirm the suitability of TOFPET2 for creating portable systems with a large number of channels, where it is important to combine energy resolution, temporal characteristics, and basic $n - \gamma$ discrimination capabilities.

2. MATERIALS AND METHODS

The assembled experimental setup is shown in Fig.1 in details discussed at [9]. The data was obtained using a $^{239}\text{Pu-Be}$ neutron source 10^5 , which produces neutrons and instant gamma-rays. The $^{239}\text{Pu-Be}$ source is placed directly on the stilbene scintillator housing (5 mm housing wall) with dimensions of 50×50 mm. The scintillator is in optical contact with R1307 Hamamatsu photomultiplier (PMT, 76 mm window). The high-voltage power supply is configured taking into account the total gain of the path, the operating voltage is selected as 550 V. The signal from the PMT is fed to a custom amplifier with a gain of $G = 10$ and a bandwidth of at least 100 MHz. The CAEN DT5720e digitizer has a 50 Ohm built-in input. It was used a custom CFD module (constant fraction discrimination module) with a cable delay of 2.2 m (10.6 ns). The signal is additionally connected through a 1 MOhm probe to Keysight DSOX6004a oscilloscope.

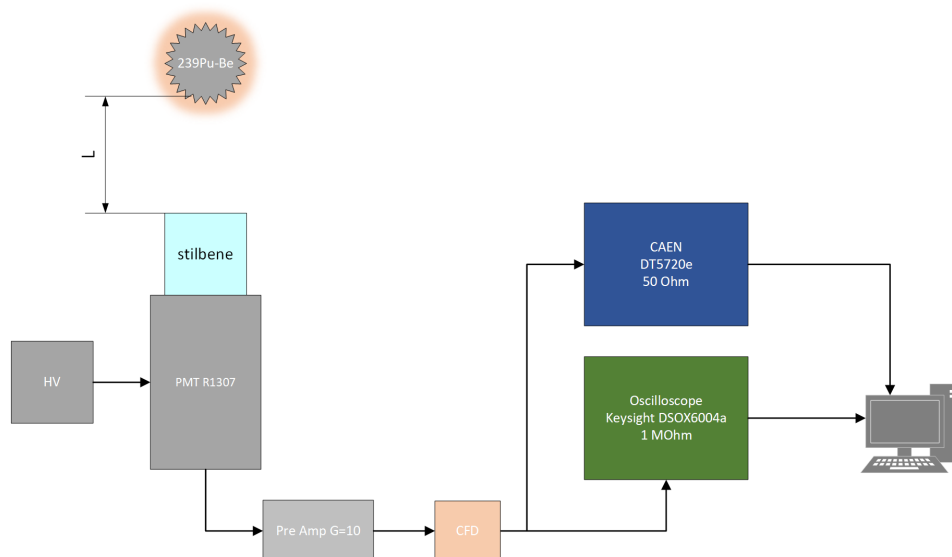


Figure 1. Experimental setup.

Typical scintillation signal is shown in Fig.2.

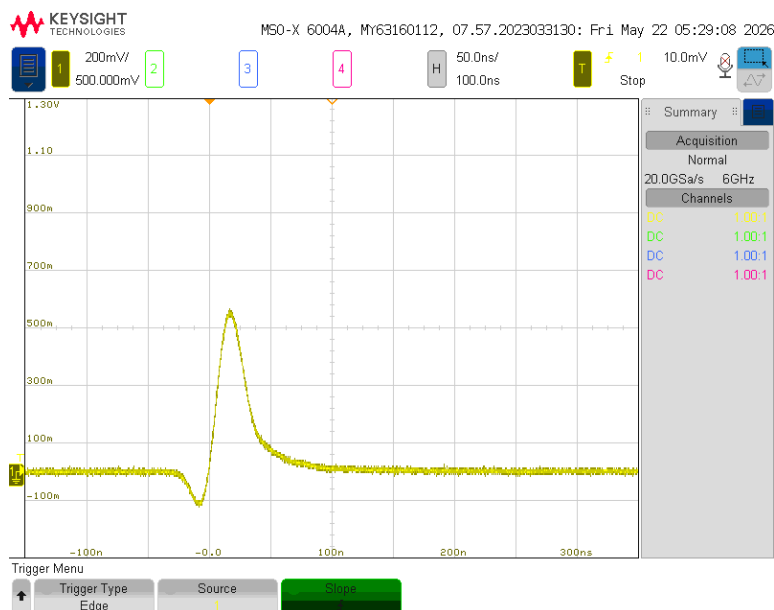


Figure 2. The scintillation signals captured with the oscilloscope. A visible pulse undershoot after analog CFD

The signals from the oscilloscope were automatically accumulated on the computer using a prepared script. The signal from the CAEN DT5720 was processed online in the Compass program. Figure Fig.3 shows the waveform triggered in the Compass program, the pulse duration is approximately 90-110 ns with a delayed trailing edge. The signals are in principle identical in shape both on the oscilloscope and on the CAEN digitizer.

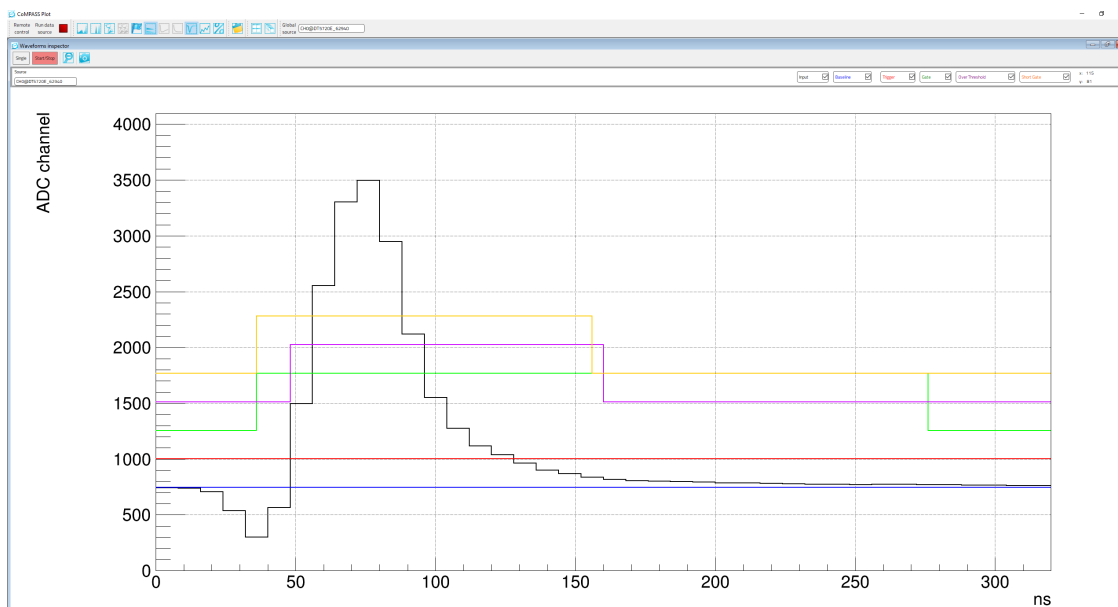


Figure 3. The triggered pulses in COMPASS software.

The settings for the CAEN digitizer were selected as follow: Energy coarse gain 40 fC/LBS, Gate 240 ns, Short gate 120 ns, Pre-gate 12 ns, Threshold 100 LBS (48 mV), Trigger holdoff 320 ns, Record length 320 ns, Pre-trigger 52 ns, N samples baseline 128.

The Short gate parameter was selected during the scanning process from the maximum pulse amplitude along the falling edge. The criteria of the setup tuning were the best PSD ratio Q_s/Q_t (integral in the short gate Q_s and Q_t integral in the gate). Also, the visual quality of PSD histogram Fig.4, straight gamma and neutron tails, and the resulting FOM value Fig.5 were controlled.

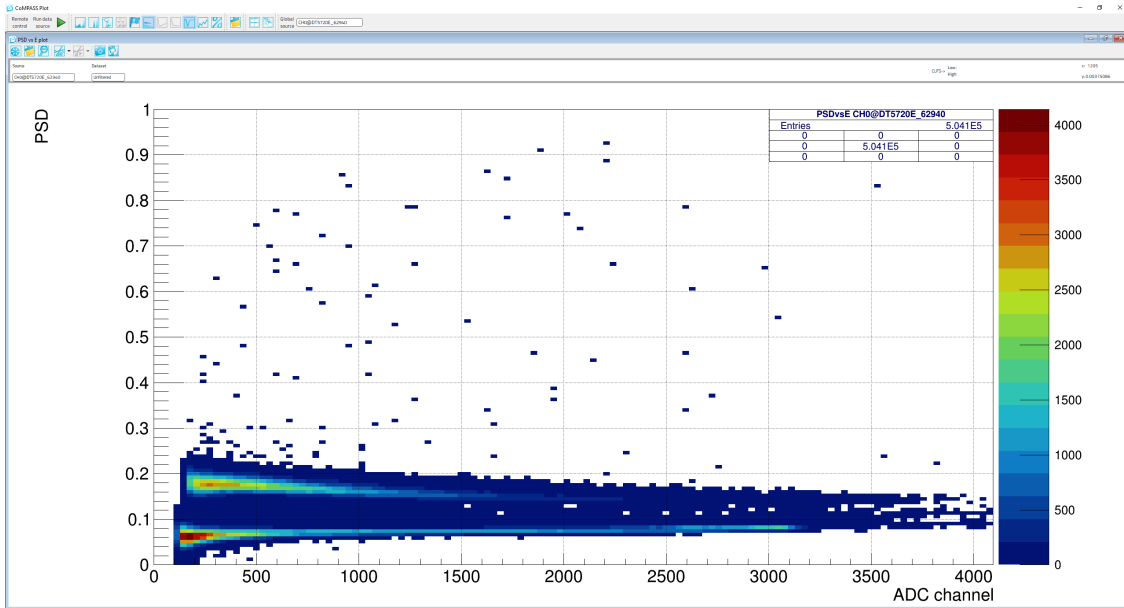


Figure 4. The PSD plot accumulated with the COMPASS software. Neutron and gamma events. Neutron (above 0.1 PSD) and gamma events (below 0.1 PSD)

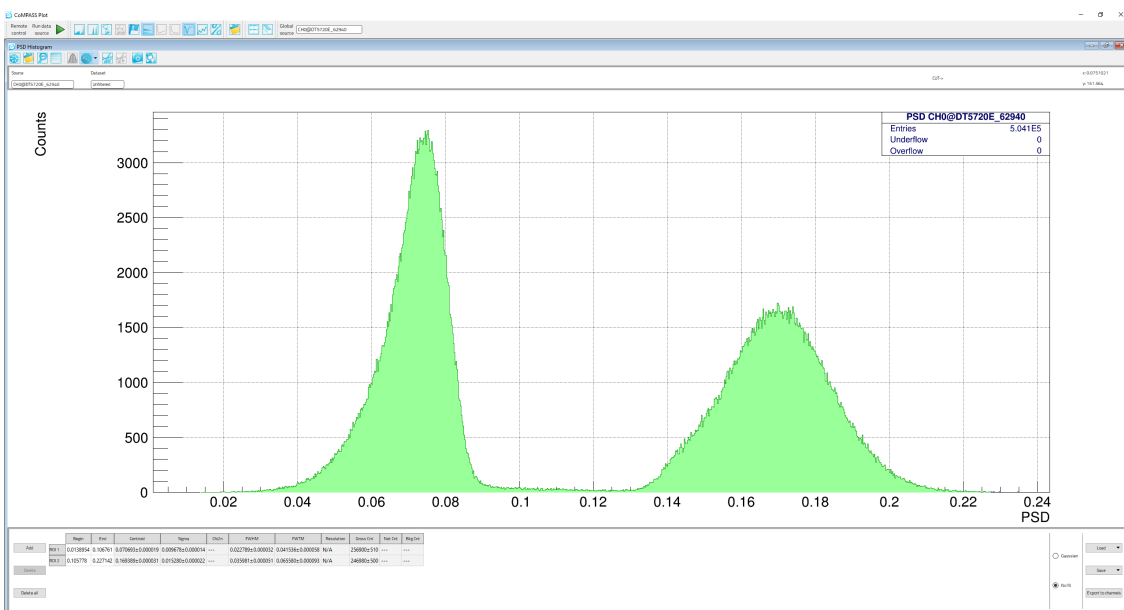


Figure 5. The PSD histogram accumulated with the COMPASS software. FOM = 1.871.

3. ALGORITHM AND EXPERIMENTAL RESULTS

For the working data set it was accumulated a 10000 events using the oscilloscope. To have a stable starting point, it was used a CFD module, to eliminate the pulses jitter caused by varying amplitudes [10]. To validate the quality of discrimination of designed method we were used two methods: charge comparison (CC) practically implemented in [11] and the results obtained with the CAEN software (basically the charge comparison). The CC method is the most famous pulse shape discrimination (PSD) technique with the comparable quality to the analog techniques of discrimination.

The discrimination ratio (1) could be recalculated using the charge comparison of the entire signal charge Q_{total} and the charge of the slow part of the signal tail Q_{slow} .

$$R = Q_s/Q_t \tag{1}$$

Typical neutron and gamma-ray pulse signals are shown in Fig.6.

Finally, to calculate the quality of neutron/gamma discrimination of the stilbene scintillator used the figure of merit

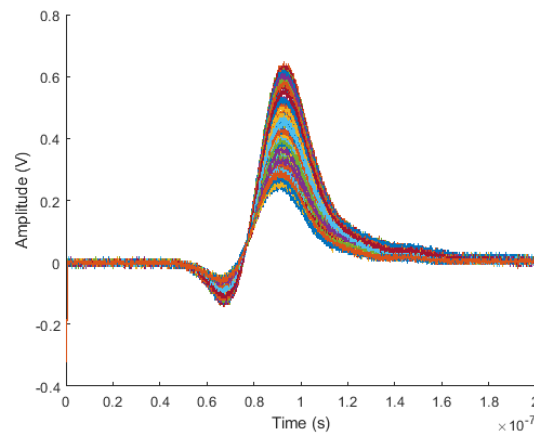


Figure 6. The typical signal recorded with the oscilloscope. Visible a CFD pulse undershoot.

(FOM), which is:

$$FOM = D/(FWHM_{\gamma}) + FWHM_n \quad (2)$$

Using the test bench Fig.1 it was obtained FOM 1.871 on CAEN digitizer. By variation of slow gate width with the fixed long gate, it was found the best ratio (1) for the FOM.

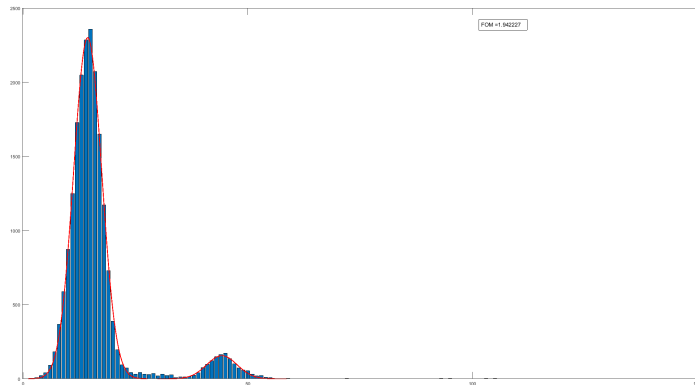


Figure 7. The calculated FOM using the CC method. FOM = 1.942

Using the custom CC code it was calculated FOM = 1.942 for the data set accumulated with the oscilloscope. Finally it was tested a new approach of neutron gamma discrimination on the obtained dataset.

The main hypothesis of the proposed Peak Asymmetry method (PA) is that the time distribution of photon emission, which forms a scintillation pulse, has a different level of tail asymmetry with respect to the position of the amplitude maximum for gamma quanta and fast neutrons. When a particle interacts with the scintillator, two key fluorescence components arise. The fast component which decays within a few nanoseconds and is practically identical for both types of radiation (neutron and gamma). In contrast, the slow or delayed fluorescence caused by the annihilation of triplet excitations is much more intense when neutrons are detected. From a Peak Asymmetry method approach, the pulse registered by the detector is a statistical distribution of photons in time, and the centroid of this distribution reflects the mathematical expectation or average time of photon emission during a single scintillation event. The practical implementation of the PA method uses the concept of the "center of gravity" to quantify the asymmetry of the pulse. The time centroid is defined as the weighted average over the entire scintillation pulse shape, where the signal amplitude acts as a statistical weight Fig.8. Since the pulse shape is perceived as a probability density function, the calculated time centroid becomes an analogue of the first moment of the distribution (normalized by total pulse "mass"). The main discriminating factor in this case is the parameter, which is equal to the ratio between the centroid time and the moment of reaching the peak amplitude. To quantify asymmetry within the PA method, the concept of the "center of gravity" (centroid) of the peak is used. Mathematically, the time centroid $t_{centroid}$ is defined as the first moment of the signal amplitude distribution:

$$t_{centroid} = \frac{\sum (t_i A_i)}{\sum A_i} \quad (3)$$

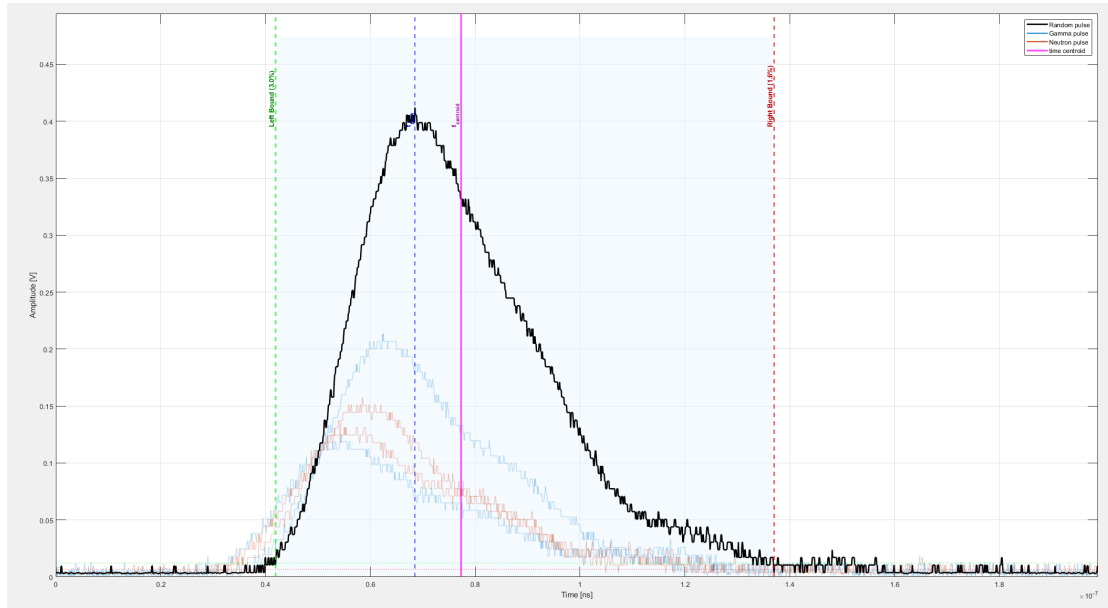


Figure 8. The Peak Asymmetry (PA) key parameters.

where A_i — the amplitude of the signal at time t_i , which acts as a statistical weight. The main discriminating factor is the time offset parameter Δt :

$$\Delta t = t_{centroid}/t_{peak} \tag{4}$$

Gamma rays: generate relatively symmetrical pulses, where the centroid almost coincides with the time of the amplitude maximum, leading to values of δt near 0. Neutrons: due to the intense slow fluorescence, the “center of gravity” of the pulse is shifted to the right of the peak, providing a positive value of $\Delta t > 0$. Gamma-ray events are characterized by a high degree of signal symmetry, as a result of which the calculated center of gravity practically coincides with the time of the amplitude maximum. In such cases, the value of the discriminating factor approaches zero. On the contrary, the intense “tail” of the neutron pulse creates additional weight to the right of the peak, leading to a physical shift of the centroid to a longer time region. The higher the specific gravity of the slow fluorescence, the more the time centroid deviates from the peak of the pulse, which provides a clear separation of particles. The resulting PSD plot and histogram presented on Fig.9, the obtained FOM with the PA method was 0.72.

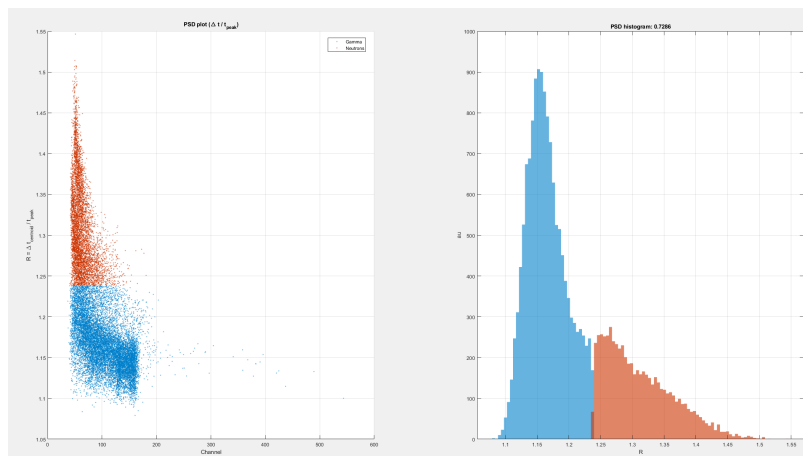


Figure 9. The calculated PSD distribution for the PA method.

4. DISCUSSION AND CONCLUSION

The pulse shape discrimination could be done with modern oscilloscope equipment with the high sampling rate along with the ultimate bandwidth. Summarizing the obtained results: $FOM_{CC} = 1.942$, $FOM_{CAEN} = 1.871$, $FOM_{PA} = 0.728$, the PA method provides a lower quality of pulse shape discrimination comparing to charge integration methods. An important advantage of the PA method over classical integral approaches, such as the CC method, is its positional nature.

While traditional methods require a careful fitting of time windows (gates) for the best separation, the peak asymmetry method focuses on the morphology of the entire pulse. This makes the algorithm less sensitive to baseline noise and allows for the consideration of the smallest changes in the shape of the decay that can be lost when simply integrating the area under the curve. Thus, the PA method is a more robust and adaptive tool for particle identification in conditions of high background noise.







5. DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6. ACKNOWLEDGMENTS

This work was supported by the Ministry of Education and Science of Ukraine (the projects: № 0124U000837, № Д3/174-2025, 0125U001050, 0124U000837, 0126U003796, 0126U001129).

ORCID

 **I. Yakymenko**, <https://orcid.org/0000-0002-0194-8376>;  **A. Dobrozhan**, <https://orcid.org/0000-0002-8830-0942>;
 **G. Onyshchenko**, <https://orcid.org/0000-0001-6945-8413>;  **O. Kuzin**, <https://orcid.org/0009-0004-3159-1680>; 
V. Trusova, <https://orcid.org/0000-0002-7087-071X>;  **P. Kuznietsov**, <https://orcid.org/0000-0001-8477-1395>

REFERENCES

- [1] G. Onyshchenko, I. Yakymenko, O. Sidletskiy, P. Kuznietsov, O. Tarasenko, O. Shchus, I. Tolkunov, *et al.*, "Analysis of radiation methods for explosive materials detection," *East European Journal of Physics*, (4), 682–695 (2025). <https://doi.org/10.26565/2312-4334-2025-4-74>
- [2] G. Onyshchenko, V. Ryzhikov, I. Yakymenko, V. Khodusov, S. Naydenov, A. Opolonin, and S. Makhota, "The Investigation of Mechanisms of Fast Neutron Registration in Oxide Scintillators," *East Eur. J. Phys.* (3), 54–62 (2019). <https://doi.org/10.26565/2312-4334-2019-3-07>
- [3] G.M. Onyshchenko, V.D. Ryzhikov, I.I. Yakymenko, and O.P. Shchus', "The Threshold of Detection of Fission Materials by ZnWO₄ and Bi₄Ge₃O₁₂ Scintillation Detectors," *East Eur. J. Phys.* (4), 91–94 (2019). <https://doi.org/10.26565/2312-4334-2019-4-10>
- [4] M. Nakhostin, and P. M. Walker, "A comparison of digital zero-crossing and charge-comparison methods for neutron-gamma pulse shape discrimination," *Nuclear Instruments and Methods in Physics Research Section A*, **621**(1-3), 498–501 (2010). <https://doi.org/10.1016/j.nima.2010.06.252>
- [5] M. Nakhostin, "A comparison of digital zero-crossing and charge-comparison methods for neutron/ γ -ray discrimination with liquid scintillation detectors," *Nuclear Instruments & Methods in Physics Research Section A-accelerators Spectrometers Detectors and Associated Equipment*, **797**, 77–82 (2015). <https://doi.org/10.1016/j.nima.2015.06.041>
- [6] X. Zhu, C. Feng, Q. Li, Z. Shen, S. Liu, and Q. An, "FPGA-Based Real-Time n/γ Discrimination With Liquid Scintillator," *IEEE Transactions on Nuclear Science*, **65**(12), 2877–2882 (2018). <https://doi.org/10.1109/TNS.2018.2877598>
- [7] S. Korolczuk, M. Linczuk, R. Romaniuk, & I. Zychor, "Development of a digital method for neutron/gamma-ray discrimination based on matched filtering," *Journal of Instrumentation*, **11**(09), C09013, (2016). <https://doi.org/10.1088/1748-0221/11/09/c09013>
- [8] K. J. Weinfurther, P. Marleau, and M. Sweany, "Pulse shape measurements for neutron/gamma discrimination using the TOFPET2 ASIC," *Journal of Instrumentation (JINST)*, **18**(07), P07015 (2023). <https://doi.org/10.1088/1748-0221/18/07/P07015>
- [9] I. Yakymenko, G. Onyshchenko, O. Sidletskiy, V. Trusova, O. Tarasenko, P. Kuznietsov, S. Lytovchenko, *et al.*, "Fast neutron discrimination using the Stilbene scintillator," *East European Journal of Physics*, **4**, 555–559 (2025). <https://doi.org/10.26565/2312-4334-2025-4-58>
- [10] I. Yakymenko, T. Szczesniak, O. Sidletskiy, P. Kuznietsov, A. Syntfeld-Kazuch, M. Grodzicka-Kobylka, V. Trusova, *et al.*, "Experiment details in time resolution measurements of LYSO scintillator," *East European Journal of Physics*, (4), 661–666 (2025). <https://doi.org/10.26565/2312-4334-2025-4-71>
- [11] P. Li, and H. Liu, "Dataset for neutron and gamma-ray pulse shape discrimination," arXiv (Cornell University). (2023). <https://doi.org/10.48550/arxiv.2305.18242>

МЕТОДОЛОГІЯ РОЗДІЛЕННЯ НЕЙТРОННИХ ТА ГАММА-ІМПУЛЬСІВ

І. Якименко¹, А. Доброжан¹, Г. Онищенко¹, О. Кузін¹, В. Трусова², П. Кузнецов¹

¹Кафедра фізики ядра та високих енергій імені О.І. Ахієзера, Харківський національний університет імені В.Н. Каразіна, Харків, Україна

²Кафедра медичної фізики та біомедичних нанотехнологій, Харківський національний університет імені В.Н. Каразіна, Харків, Україна

У цьому дослідженні ми запропонували нову методологію дискримінації гамма-нейтронних сигналів у порівнянні з класичним методом інтегрування заряду. Для запису експериментального набору даних використовувався осцилограф з високою частотою дискретизації Keysight DSOX 6004a (20 ГС/с). Еталонний експеримент було записано за допомогою настільного діджитайзера CAEN DT5720e з встановленою прошивкою DPP PSD. Як детектор було обрано сцинтилятор стильбен розміром 50 мм x 50 мм, з фотопомножувачем R1307 Hamamatsu. Згасання сцинтиляційного імпульсу має експоненціальний хвіст залежно від природи частинок. Запропонований метод спрямований на класифікацію геометричної пікової асиметрії сцинтиляційного імпульсу, виявленого детектором, де коефіцієнт дискримінації – це відношення розрахованої ваги імпульсу (центроїда) до положення максимальної амплітуди імпульсу в часі. Центроїд швидшого гамма-імпульсу ближче до максимальної амплітуди імпульсу та значно зміщений для затриманих нейтронних імпульсів. Обговорюваний підхід дозволяє класифікувати події з порівнянною точністю до методу інтегрування заряду.

Ключові слова: *Інтегрування заряду; сцинтилятори; гамма-нейтрон розділення; стильбен; розділення за формою імпульсу; метод порівняння зарядів; перетин нуля; показник якості розділення; CAEN DT5720e*