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Digital Data Processing of Stilbene

Moslem Amiri, Frantisek Cvachovec, Zdenek Matej, Filip Mravec, Vaclav Prenosil

Abstract—**Stilbene is a proven spectrometric detector for mixed fields of neutrons and gamma rays. By digital processing of shape output pulses from the detector it is possible to obtain information about the energy of the interacting neutron / photon and distinguish which of these two particles interacts in the detector. Another numerical processing of digital data can finalize the energy spectrum of both components of the mixed field. The quality of the digitized data is highly dependent on the parameters of the hardware used for digitization and on the quality of software processing. Our results also show how the quality of the particle type identification depends on the sampling rate and as well as the method of processing of the sampled data.**

Index Terms—**Digitization, digitizer resolution, filtering, neutron/gamma discrimination, pulse length, sampling rate, stilbene, two-parameter spectrometer.**

I. INTRODUCTION

THIS article deals with dependence of quality digital processing on various factors in a radiation discrimination process. These factors are:

1) digitizer resolution (8-bits, 10-bits, 12-bits),
2) sampling frequency (0.2, 0.5, 1, 2, 4, 8 GS/s),
3) signal filtering,
4) number of samples for each pulse (pulse length),
5) pulse discrimination method.

Our focus is on the digitization phase, aiming to identify two characteristic parameters of the output pulses. The first parameter is usually the pulse amplitude that contains information about the transmitted particle energy to a detector. The other parameter can be the characteristic time constant of the leading or trailing edge of the pulse, whose value depends on the type of detected particles and allows distinguishing the components of mixed field made up of different types of particles. Most often we need to detect neutrons and photons. After this detection, the data are ready for the next stage of evaluation such as creating the energy spectrum. In the past, the above-mentioned tasks were solved using an apparatus consisting predominantly of analog electronics, whose weaknesses included high weight, the necessity of laboratory conditions, demands on the adjustment, and relatively low count rate of processed pulses. The development of digital electronics allows the researchers to reduce analog circuits of the two-parametric apparatus to a minimum and determine the necessary parameters of the output pulses by a fundamentally different approach. In principle, the voltage waveforms of the output pulses are expressed by certain values usually obtained as equidistant samples of its voltage waveform. Thus obtained discrete values (that replace the original continuous process) let us use a suitable mathematical process for acquiring the above-mentioned characteristic parameters.

In the rest of the paper, we first introduce the experimental equipment we have used in our measurements. Then a new separation quality function, which is employed to compare the effects of various factors on discrimination result, is explained. These factors including hardware features or settings, and mathematical evaluation methods are discussed and analyzed in the subsequent sections. Throughout this work, we used our digital spectrometer for measurements in the experimental reactor LR-0 in NRI Rez, Czech Republic.

This work also shows the possibility of extending the dynamic range of the detector for off-line and on-line data processing. A spectrometer based on a digital data processing of stilbene was used to successfully measure the spectrum of ^{252}Cf isotopic source and reaction $^{1}{}_{1}p(^{18}{}_{8}O^{18}{}_{9}F)^{1}{}_{0}n$ was realized on cyclotron.

II. EXPERIMENTAL EQUIPMENT

A. Detectors

The feasibility of distinguishing the detected particle types on the basis of output pulse digitization has been studied for stilbene organic scintillator.

The physics of the different time response of the neutron versus photon scintillation is known for many years, see, for example, [1]. We have investigated several specimens of stilbene, as well as various photomultiplier tubes, such as RCA and HAMAMATSU.

B. Digital Apparatus

The block diagram of the digital apparatus is shown in Fig. 1. Compared with the analogue solution, the digital apparatus is considerably simpler.

Three commercially available Agilent digitizers were used to digitize the output pulses. The main differences between them were the sampling rate and the output quantization level resolution. DP 210 type featured up to 2 GS/s and 8 bits

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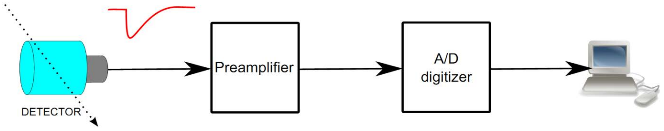

Fig. 1. Block diagram of a digital two-parameter analyzer.

resolution, whereas the maximum sampling frequency of the DC 222 type amounted to 8 GS/s at a 10-bit resolution, and DC 440 featured a resolution of 12 bits.

The preamplifiers were selected so as to match the detector output impedance. Two variants of the anode load resistance were tested in conjunction with the organic scintillation detectors. In the first variant, a load resistance of 40 kΩ was used. A preamplifier matched it to the coaxial cable whose characteristic impedance was 50 Ω. In this case, the different waveforms of the neutron and photon pulses can be detected in the voltage pulse leading edge (as shown in Fig. 10). If the magnitude of the load resistance is selected to be close to the characteristic impedance of the coaxial cable, which is 50 Ω, the different shapes of the neutron/photon pulses will appear to take effect during the decay time (as seen in Fig. 11). In this case, no preamplifier is necessary.

III. SEPARATION QUALITY FUNCTION

A novel separation quality function [2], *F(u),* is used in this article as a means for comparison of various discrimination methods. In a three dimensional coordinate system, with *x*, *y*, and *z* axes representing "particle type distinguishing parameter", "pulse amplitude *u*," and "number of pulses *n(u)*," respectively, for pulses with amplitudes higher than a specific level (called level 0), *F(u)* is calculated as follows:

$$F(u) = \frac{\Delta_{ab}}{\Delta_a + \Delta_b} \cdot \frac{N'(u)}{N(u)}. \qquad (1)$$

where *N(u)* is the number of pulses whose amplitudes are above the level 0, *N'(u)* is the number of pulses whose amplitudes are above the amplitude of the valley between the two fitted Gaussian plots to the two radiations, Δ_a and Δ_b are the distances between the first occurrence of the minimum value between peaks and the corresponding peak, and Δ_{ab} is the distance between the two peaks. *F(u)* can be defined for various level-0s. Diagram of Fig. 2 illustrates the application of this function on the fitted Gaussian plots of two radiations in the coordinate system (the third dimension, *n(u)*, is not shown here.) If *n(u)* = 0 in the minimum part between the peaks, the particles are separated perfectly; *n(u)* > 0 in a minimum between the peaks corresponds to the section with imperfect separation of the particle types.

It follows from the definition that the particles *a* and *b*, are separated from each other imperfectly for *F(u)* < 1. For *F(u)* > 1, they are separated from each other quite well. We are going to use this quantity to evaluate how the detectors are able to distinguish the certain radiation types under the conditions and evaluation methodology specified. We are only showing the behavior of *F(u)* for stilbene detectors, in the gamma radiation energy interval from about 200 to 1.200 keV, which corresponds to the neutron energy of about 1 to 4 MeV.

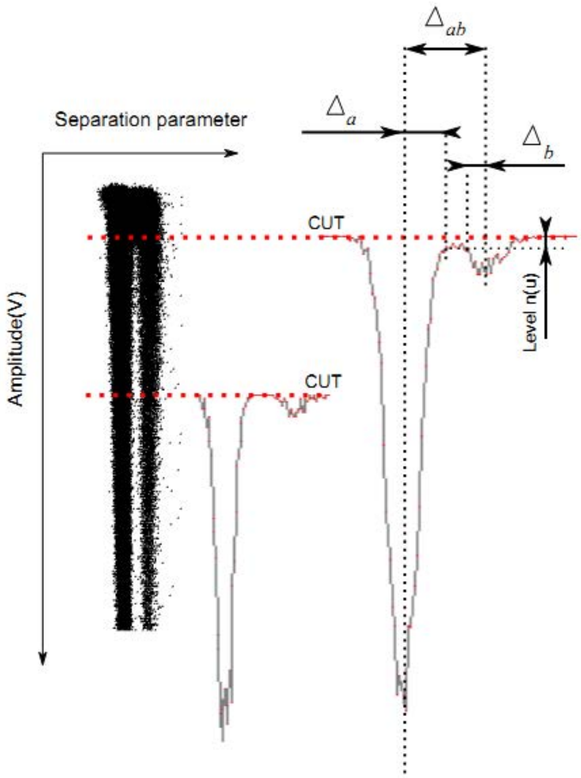

Fig. 2. On definition of the separation quality function.

IV. EFFECTS OF DIGITIZER'S TECHNICAL PARAMETERS ON QUALITY OF SEPARATION

It is experimentally verified [3,4] that the minimum necessary sampling frequency for digitizing the shape of the output signal from the detector in a mixed field of neutrons and gamma rays must exceed 200 MHz.

To verify the effect of sampling frequency and the number of bits of A/D converter, we used Cf source 5 cm away from the crystal detector. 20 mm Stilbene was used as the detector. The trigger level was set at 10% amplitude of the input analog signal. Data were analyzed using integration method (see section *V-A*) and using no pretreatment (see section *IV-D*).

A. The Separation Quality of the 8-bit Digitizer

Separation efficiency of the 8-bit digitizer for sampling rates of 2 GS/s, 1 GS/s, 500 MS/s, and 200 MS/s is shown in Fig. 3. The obtained results show that pulse discrimination is not efficient with an 8-bit digitizer, even at 2 GS/s. With sampling rate of 200 MS/s, the discrimination of neutrons and gamma rays is imperfect throughout the whole energy levels, up to 1 MeV gamma energy. With this sampling rate, it is no longer possible to separate neutrons and photons without fault even at higher energies.

With increasing sampling frequency, separation efficiency increases slightly.

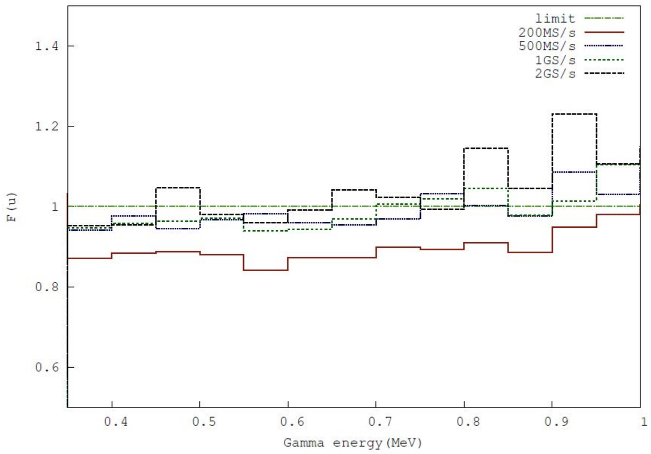

Fig. 3. Comparison of pulse discrimination quality for the 8-bit digitizer DP 210 with different sample rates using the separation quality function.

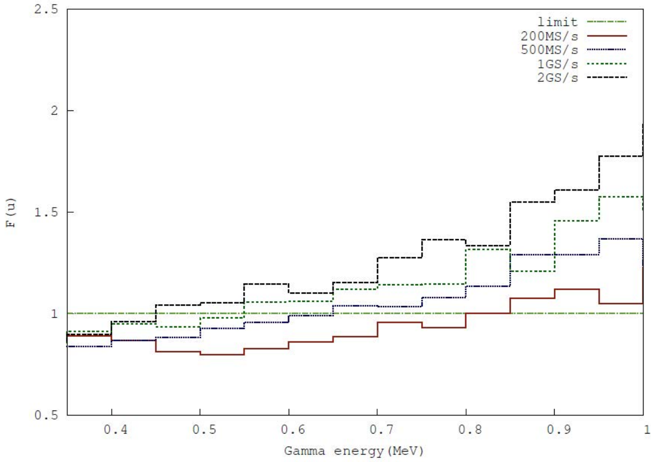

Fig. 4. Comparison of pulse discrimination quality for the 10-bit digitizer DC 222 with different sample rates (200 MS/s – 2 GS/s) using the separation quality function.

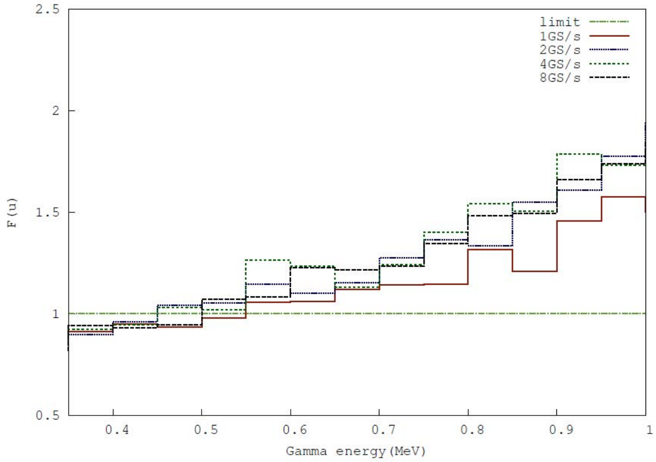

Fig. 5. Comparison of pulse discrimination quality for the 10-bit digitizer DC 222 with different sample rates (1GS/s – 8GS/s) using the separation quality function.

B. *The Separation Quality of the 10-bit Digitizer*

Fig. 4 shows the comparison of the separation quality function for various sampling rates from 200 MS /s to 2 GS /s and in Fig. 5 from 1 GS/s to 8 GS/s. Fig. 4 shows that increasing the sampling frequency reduces the energy threshold at which the efficient discrimination starts taking place (F(u) > 1). Fig. 5 shows that the sampling rates above 1 GS/s give almost the same discrimination quality; they result in F(u) > 1 after almost 0.5 MeV.

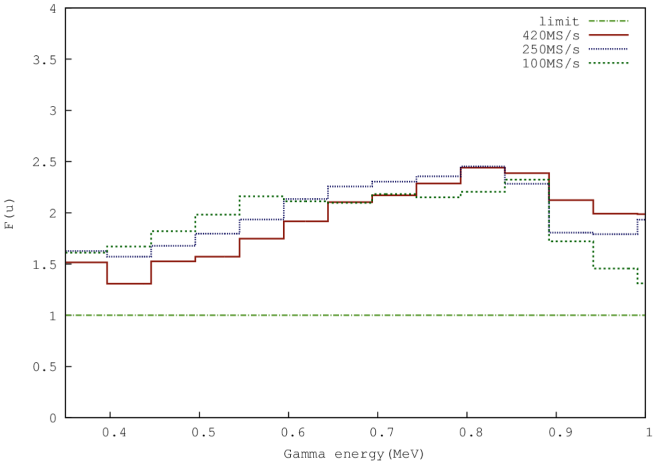

Fig. 6. Comparison of the effect of different sample rates on the separation quality function for the 12-bit digitizer DC 440.

C. *The Separation Quality of the 12-bit Digitizer*

DC 440 digitizer with a high resolution of 12-bit features the maximum usable sampling rate of 420 MS/s. The result of comparing different sampling frequencies using this digitizer is shown in Fig. 6.

From Fig. 6, it is evident that even at a sampling frequency of 100 MS/s, neutron and gamma pulses are well separated. However, a considerable reduction of discrimination quality occurs due to the insufficient sampling rate.

Our experiments show that the higher resolution of a digitizer improves separation quality of mixed pulses. The low sample rate of a digitizer, however, gives incorrect results. The top plot of Fig. 7 illustrates the faulty results due to down sampling of the signals from the detector. Low sampling rate causes the amplitude of some pulses to appear less than the trigger level, which is impossible. The bottom plot of Fig. 7 shows the correct discrimination resulting from the high sampling rate; all the amplitudes are over the specified trigger level.

As mentioned above, the low sampling rate of the digitizer causes aliasing problem in the output data which affects separation quality. However, the error introduced by aliasing does not cause substantial deterioration in the separation efficiency of the algorithms. The more important factor is the quantization error (the low resolution, i.e., the low number of bits of memory to save digitized data in A/D conversion process) which significantly influences the quality of the discrimination.

D. *Effect of Signal Filtering on Separation Quality*

To achieve a better separation quality, we can filter out the noise. Moving average filter is a very good option for our purposes. Application of a three or five point averaging results

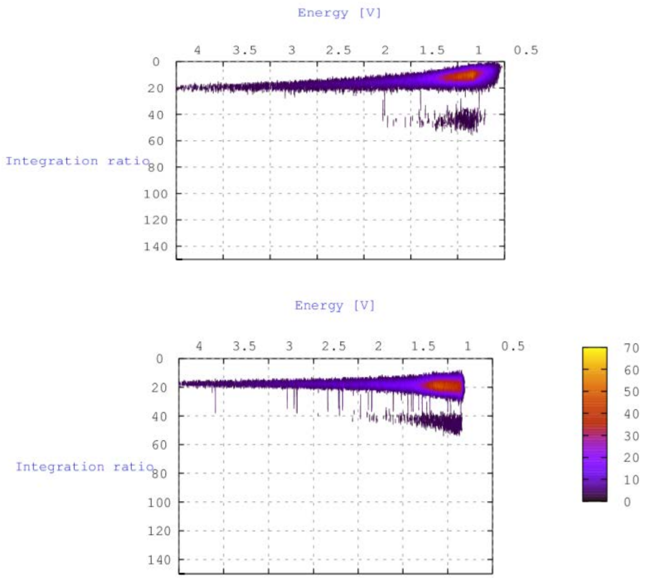

Fig. 7. Top histogram shows the results of processing data from a 12-bit digitizer with 100 MS/s sampling rate, and bottom histogram is the results from the same digitizer but at 420 MS/s.

in a satisfactory discrimination. This filter is very simple and fast, hence it can be used for on-line processing too.

Using this filter, however, has certain drawbacks. If this filter is used on data obtained with low sampling frequency (thus a small number of samples), it will cause a large deformation of the pulse shapes.

To demonstrate the benefits of using this filter, we use a 10-bit digitizer at a sampling frequency of 2 GS/s. The output data from this digitizer is once filtered (smoothed) and then processed for discrimination, and once is processed without filtering. Fig. 8 shows the noticeable difference between the separation qualities of these two cases where the integration method was used for evaluation (see section *V-A*).

As another verification of separation quality improvement using moving average filter, we applied integration evaluation method to discriminate a test data set of 1 million neutron and photon pulses obtained from a 12-bit digitizer. The results, once with a five point averaging of data and once without filtering, are compared in Fig. 9. This Figure approves the separation quality improvement when using a moving average filter.

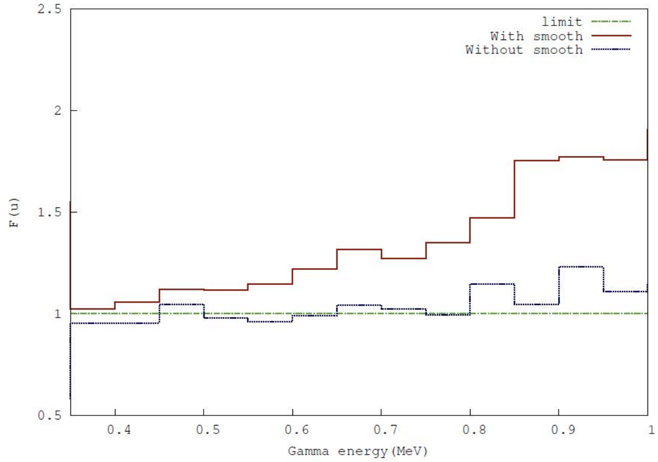

Fig. 8. Graph of the separation quality function for the output data from a 10-bit digitizer with and without application of a five point averaging filter.

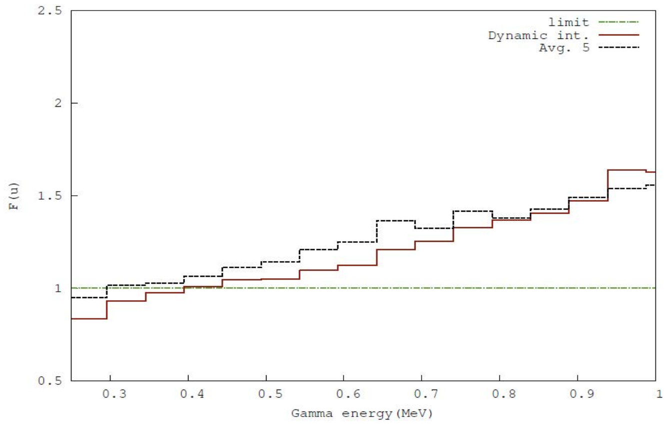

Fig. 9. Graph of the separation quality function for the data obtained from a 12-bit digitizer, once using a five point moving average filter and once with no filtering of data.

E. Effect of Pulse Length on Separation Quality

In order to discriminate the pulses properly, a required number of samples should be processed for every pulse. This length of pulse depends on the pulse discrimination method, as well as on the anode load resistance (i.e., whether we need to investigate the leading edge or the trailing edge of the pulse for discrimination.)

If a high anode load resistance is used in detector setup, the obtained pulses can be discriminated by investigating their leading edges, as shown in Fig. 10. Depending on the evaluation method, sufficient number of samples from the leading edge must be processed for proper discrimination.

If a low anode load resistance is used in detector setup, the obtained pulses can be discriminated by investigating their trailing edges, as shown in Fig. 11. The length of the pulse to be processed depends on the discrimination method. In the following, the required length for some methods is discussed.

1) *Integration Methods*

In general, integration methods require samples from the entire course of the pulse waveform for correct functioning. However, in some versions of this method, not

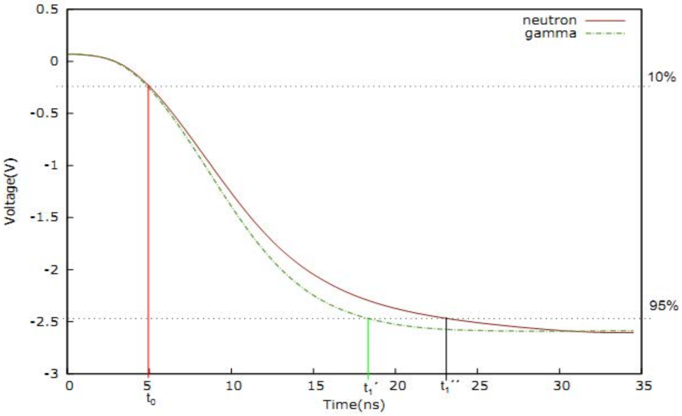

Fig. 10. For the pulses obtained from a detector with high anode load resistance, depending on the evaluation method, a sufficient number of samples from the leading edge needs to be processed.

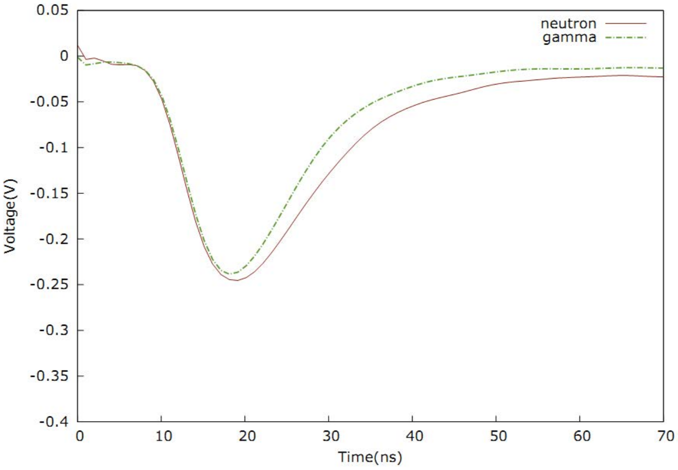

Fig. 11. For the pulses obtained from a detector with low anode load resistance, depending on the evaluation method, a sufficient number of samples from the trailing edge needs to be processed.

all the samples are used in calculations; the sections of the signal used to calculate the ratio of integrals are only a fraction of the whole signal. This method is discussed in section *V-A*.

2) *Mean vs. Variance*
This method discriminates very well when the entire samples of the pulse are processed. This method is explained in detail in section *V-B*.

3) *Support Vector Machines (SVM)*
Similar to "mean vs. variance", this method also requires a complete sequence of samples for discrimination. Section *V-C* summarizes this technique.

4) *Amplitude Difference*
This novel method, which is introduced in this article in section *V-D*, requires a low fraction of the entire pulse to be recorded and processed. First, the peak of the pulse or a certain level on the leading edge is marked. Then the amplitude of the pulse after a constant time from this marked point (which means a constant number of samples after this point) can identify the radiation type.

V. DATA EVALUATION

In order to discriminate different types of nuclear radiation particles (with no overlapping of the pulses) obtained in a mixed environment, some successful processing algorithms are available. In this section, we review several important ones, and also introduce a novel method with a high quality of separation.

A. *Integration Method*

When discriminating the interacting particle types, it is more convenient in some detectors to use a low load resistance which is matched to the detector output line impedance. With low load resistance, the output pulses become short, hence more pulses can be processed in a given period. It is seen in Fig. 12 that the neutron and photon pulses differ from each other in the pulse trailing edge shape; the leading edges are practically identical. One available processing algorithm is the pulse part integration method. This useful processing method compares the ratio *r* of integrals of the voltage pulse waveforms:

$$r = \frac{\int_{t_0}^{t_2} u(t).dt}{\int_{t_1}^{t_2} u(t).dt}. \qquad (2)$$

where t_0 is the voltage pulse start time, t_2 is the pulse end time, and t_1 is an empirically identified point between t_0 and t_2, at which the neutron pulse trailing edge starts to differ from that of the photon one ($t_0 < t_1 < t_2$). Fig. 13 shows the separation quality of this method. For a stilbene scintillator, the parameter *r* is equal to 110 and 70 for neutrons and photons, respectively.

B. *Mean vs. Variance Method*

This method [2] is used to process data obtained from the stilbene detector (low anode load resistance). Working on the features of the neutron and gamma signals reveals that the mean vs. square standard deviation (μ vs. σ^2) plot of the samples of each radiation type falls in a completely separate area in the coordination system. This method has the

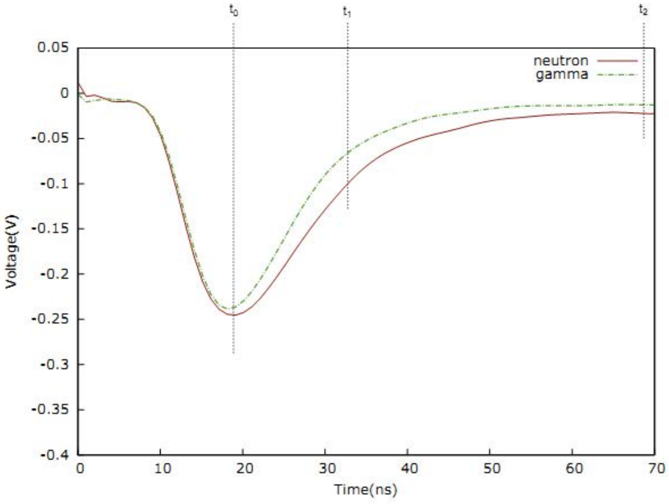

Fig. 12. Intervals [t_0, t_2] and [t_1, t_2] used in Eq. 2 applied on shapes of photon and neutron pulses from a stilbene detector with low load resistance.

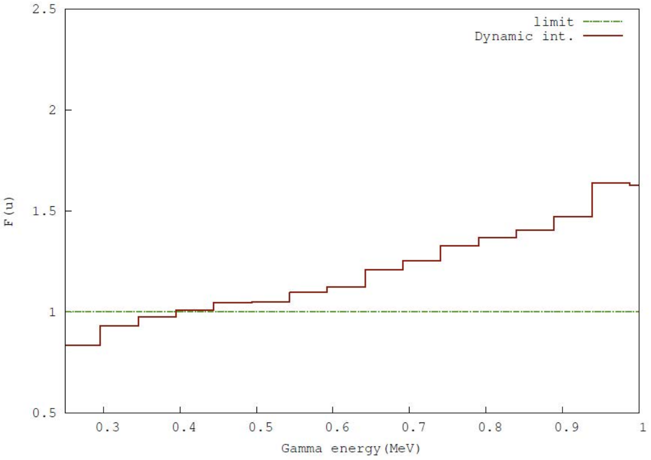

Fig. 13. Separation quality function of the integration method.

following advantages:

1) It does not need any noise filtering, since μ and σ^2 both contain average filtering properties;
2) It discriminates these two signals successfully with no overlapping;
3) μ and σ^2 can be processed extremely quickly using running statistics while receiving every new sample from the digitizer without requiring all the samples to be involved in each new calculation. This feature makes μ vs. σ^2 method ideal for real-time processing.

The mean of a signal contained in $x_0, x_1, \ldots, x_{N-1}$ is calculated as:

$$\mu = \frac{1}{N} \cdot \sum_{i=0}^{N-1} x_i \ . \tag{3}$$

and the variance as:

$$\sigma^2 = \frac{1}{N-1} \cdot \sum_{i=0}^{N-1} (x_i - \mu)^2 = \frac{1}{N-1} \cdot \left[\sum_{i=0}^{N-1} x_i^2 - \frac{1}{N} \left(\sum_{i=0}^{N-1} x_i \right)^2 \right] . \tag{4}$$

Since the number of samples for every signal is constant in an experiment of neutron and photon discrimination, on receiving every new sample of a signal, only two parameters need to be updated: 1) the sum of the samples received so far; 2) the sum of the square of the samples received so far. Upon receiving the last digitized sample of the signal, the values of these two parameters are used for the calculation of μ and σ^2 based on the Eqs. (3) and (4). The discrimination quality of this method is high, as Fig. 14 proves this.

C. *Support Vector Machines (SVM) Method*

This method belongs to the machine learning methods seeking an optimal distribution of data using a selected hyper plane. A model is created based on a set of training data, each marked as belonging to one radiation type. This model is a representation of the signals as points in space. SVM creates a hyper plane which is used for separation. To achieve a good separation results, the hyper plane should have the largest distance to the nearest training data point of the two signal types. This model assigns new pulses to one of the two radiation types. To describe the optimal hyper plane, simply the closest points are called support vectors [5]. To demonstrate the quality of the separation, we used the version by Byvatov et al. [6,7].

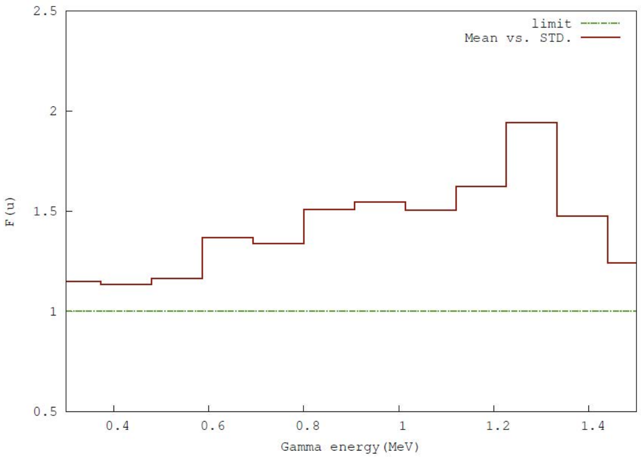

Fig. 14. The separation quality function for the Mean vs. Square Standard Deviation Method.

Fig. 15 shows the quality of the SVM method applied on the leading edge of pulses obtained from a detector with the high anode load resistance. It is apparent that the separability of the neutron and photon pulses throughout the entire energy level is very good.

D. *Amplitude Difference Method*

This method, introduced in this paper, takes advantage of the amplitude difference between neutron and gamma pulses at a certain fixed point of time within trailing edge of the pulse. To implement this method, a specific starting point should be assigned for every pulse, and some constant time after this starting point should be marked and the amplitude of the pulses at the marked point compared. While the peak of a pulse seems to be a good starting point, the problem is that matching peaks of the pulses does not necessarily mean that their leading edges also match each other. The best choice for starting point would be a specific level within leading edge. The constant time after this starting point should be set such that it falls on low 50% amplitude of the trailing edge of the pulse which makes the highest possible amplitude difference between the two pulses. The point on the trailing edge which makes the highest amplitude difference between the two radiations could be found by trial and error. This method

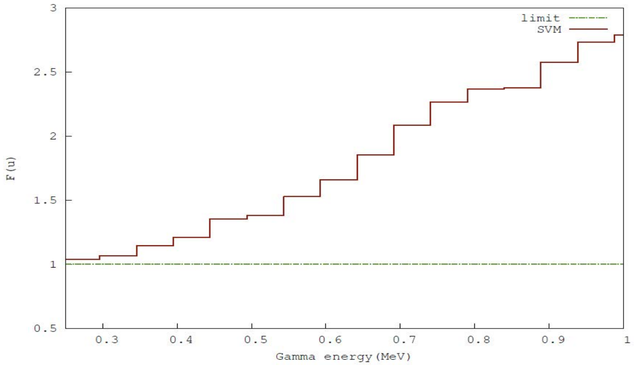

Fig. 15. The separation quality function of the SVM method.

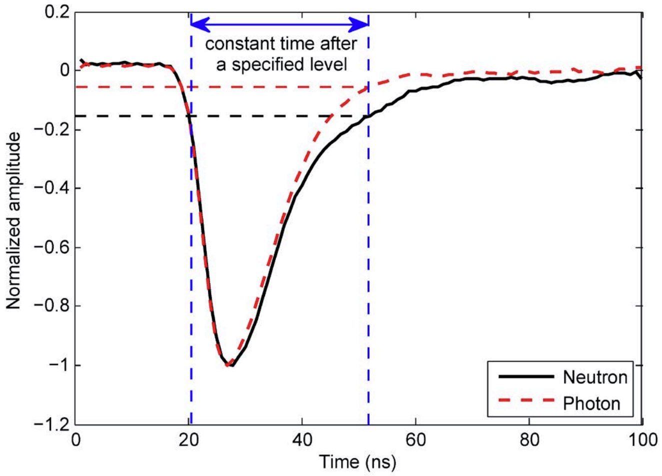

Fig. 16. Amplitude difference occurring within a predefined period of time starting from a specific level on leading edge of the pulse.

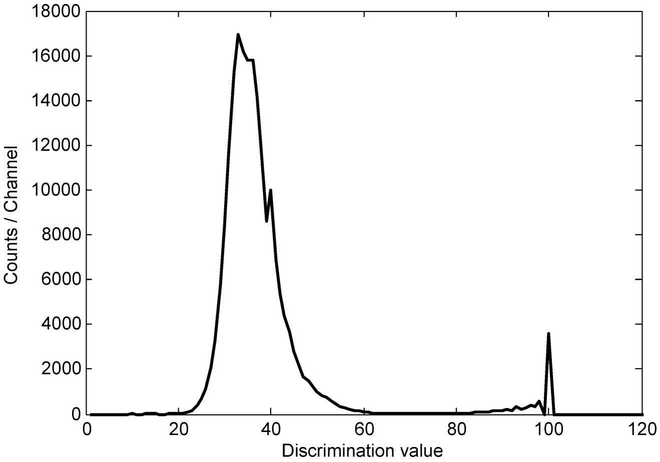

Fig. 17. The experimental distribution of the neutron and photon pulses when applying the Amplitude Difference method.

discriminates very well. Fig. 17 shows the experimental distribution for the mixed data of neutrons and photons.

VI. CONCLUSION

Our results show that the digital processing of the detector output data is a very useful and promising technique. Digital-technique-based apparatuses are considerably simpler than the analog ones and, chiefly thanks to their flexibility, are much more user-friendly. Experiments have proved that a sufficiently powerful digitizer is able to work in conjunction with pulse detectors of most diverse types. The sampling rate and the quantization level resolution make the decisive parameters. The selection of the most suitable sampling rate is closely related to the pulse length. Based on our experience, the sampling period should not exceed 5% of the pulse length. Better results can be achieved by its shortening, i.e., generally speaking, by using a higher sampling rate. The higher the energy resolution and the width of the required energy interval, the higher demands on the quantization level resolution.

Digital instruments prove to be most useful in the case of spectrometric apparatuses whose output signal depends on the interacting particle type. In addition, the digital processing is able to eliminate noise and interfering signals. The ability to handle the higher pulse rates is another valuable virtue of digital instrumentation.

ACKNOWLEDGMENT

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