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Digitized Two-Parameter Spectrometer for Neutron-Gamma Mixed Field

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Abstract:

This paper shows the results of digital processing of output pulses from combined photon-neutron detector using a commercially available ACQUIRIS DP 210 digitizer. The advantage of digital processing is reduction of the apparatus in weight and size, acceleration of measurement, and increased capability to handle pile-up of pulses. The neutron and photon spectrum of radionuclide source ^{252}*Cf is presented.*

Keywords:

Two-parameter spectrometer, digitization, stilbene, pulse shape discrimination

1. Introduction

The recent development in the area of digital data processing enables dramatic reduction of the spectrometric system; this is achieved by converting the time course of the detected pulse into numeric samples at the output of the digitizer. Further data transmission and processing can be done exclusively digitally. The above described procedure has a lot of advantages:

- Down-sizing of the spectrometric devices
- Increased measurement rate (i.e. a shorter and thus cheaper measurement is sufficient)
- Possibility of advanced pulse shape analysis – e.g. evaluation of superimposed impulses caused by fast sequence of particle detections.
- In certain cases, another characteristic of the output impulse can be determined – the characteristic duration (time constant) of the output pulses.

The last mentioned parameter sometimes carries very useful information about the nature of the detected particle. This applies e.g. to organic scintillator of stilbene or NE-213 type. The distinguishing of nature of the particles (in our case

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neutron / photon) is based on the different relation of the probability of triplet state excitation in the molecule of the scintillator (the de-excitation generates the slow part of the fluorescence) to the linear stopping power of the detected charged particles. The neutron scintillation (a neutron is detected by means of a scattered proton) has a longer decay than the photon impulse (a photon is detected by means of a scattered electron).

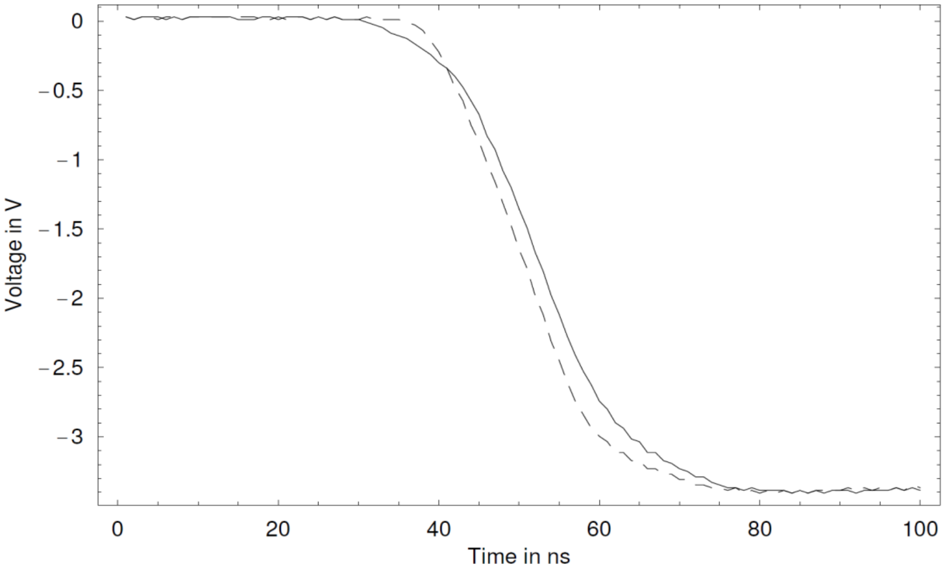

Fig. 1(a). Sample time courses of neutron (solid) and photon (dashed) negative anode pulses in case of a big load resistance

By setting a big load resistance at the output of the scintillation detector, we can achieve a state where the speed of the increasing part of the output voltage impulse (rise time) reflects the differences in the time course of the current impulses. This different information carried by the time courses can be utilized to distinguish the neutron impulse from the photon one. The time courses of a neutron and photon pulse are shown in Fig. 1(a). In this case, the scintillation time constant is significantly smaller than the time constant of the circuit consisting of a working resistance and parasitic capacitance. We can see that a neutron pulse rises 2-3 ns longer than a photon pulse.

In the other case, when the load resistance at the output of the scintillation detector is set to a small value (ca. 50 Ω), the decay of the output voltage pulse corresponds to scintillation time constants, i.e. the decay slightly longer for neutrons than for photons. The rise time is equal for both types of particles. The pulses are short (several tens of ns), which is favourable as it decreases the frequency of superimposed pulses. (The parameters of superimposed pulses are usually evaluated wrongly – both type of particle and amplitude / energy.) The whole pulse may be sampled, which is not possible in the previous case of a big load resistance when a pulse lasts a few μs. On the other hand, the signal-to-noise ratio is worse. The time course of a pulse in case of small load resistance is shown in Fig. 1(b).

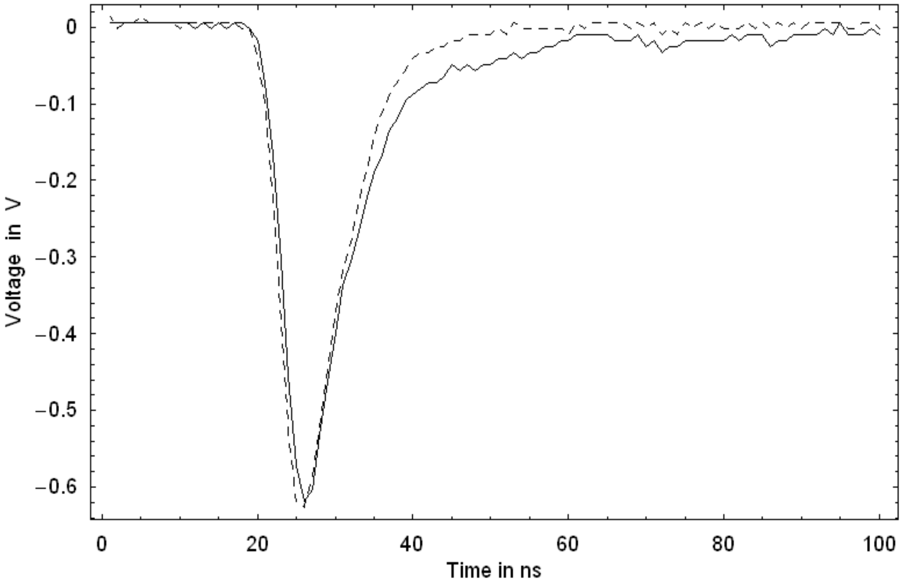

Fig. 1(b). Sample time courses of neutron (solid) and photon (dashed) negative anode pulses for load resistance 50 Ω

In the past, analog circuits were used to distinguish the courses. Since 2000, attempts have been made to evaluate both parameters (energy, type of particle) from the digitized output impulse. It is usual to arrange the measured data into a 3-D representation where one axis (e.g. x) represents the rise time (type of the detected particle), another (y) stands for amplitude (energy), and the last one (z) records counts of impulses of the same parameters. This distribution, which we measured with ACQUIRIS DP 210 digitizer, is shown in Fig. 2(a). We can clearly distinguish neutrons and gamma part in this distribution. Moreover, other types of charged particles, noise, disturbances can be identified. Further processing leads to spectral energetic distribution.

2. Experimental Data Processing

2.1. Big Load Resistance at the Output of the Scintillation Detector

The ACQUIRIS DP 210 digitizer converts the whole input pulse or its initial part (i.e. output signal from the detector) into 100 samples with a repetition frequency of 1 or 2 GHz. These 100 values (obtained as discrete data) represent the most important part of the pulse containing information on the amplitude (energy) and the timing of the rising part of the pulse (nature of the particle). The usually measured neutron spectra in the interval 0.5 to 10 MeV require the recording of about one million pulses. Since the neutron pulses are sampled simultaneously with the photon ones without knowing the nature of the particle and the ratio of neutrons to photons in the mixed fields being more than ten, we receive relatively large amounts of data. The data is transported to the memory where it is stored for off-line processing, since on-line processing cannot be performed quickly enough.

Further data processing is performed to find the largest number – amplitude for each pulse (100 numbers). Then we determine the parameter τ corresponding to the time interval between 5 and 95 percent of the amplitude in the initial part of the pulse.

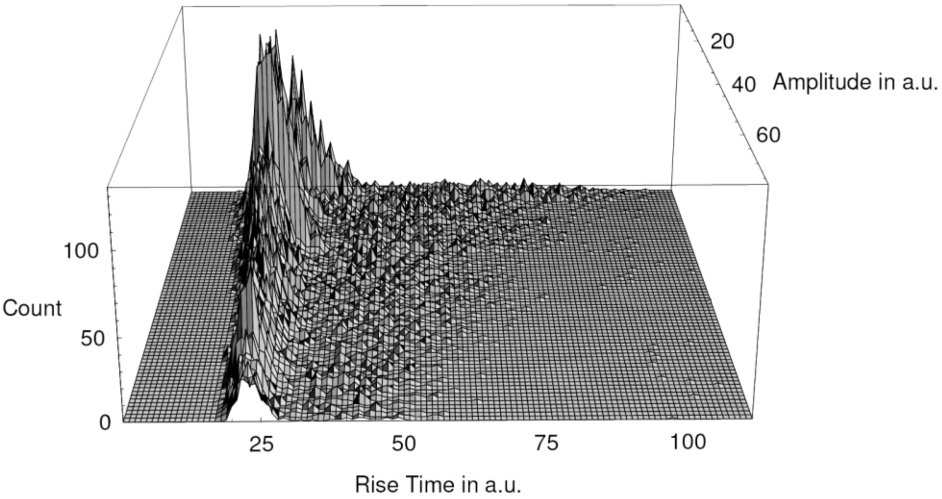

Fig. 2(a). 3-D distribution of output pulses from stilbene detector. The x-axis represents pulse rise time (parameter τ corresponding to the time interval between 5 and 95 percent of the amplitude), y-axis amplitude, and z-axis count of pulses of the same parameters. Gamma part on the left, neutron part on the right. (Top view of the same data is in Fig. 5 (c).)

According to that τ we should ideally be able to divide all pulses into two groups – neutrons and photons. However, reality is more complex and the result is a distribution as shown in Figs 2(a) and 5(c). It is obvious that the n/γ pulses can be easily distinguished for higher amplitudes; however, human interaction is still required for lower energies. This distribution is then split into neutron and photon parts; further, it is adjusted into a form required by the codes solving the Fredholm integral equation for the evaluation of the final product, i.e. the neutron and photon energy spectrum.

2.2. Small Load Resistance at the Output of the Scintillation Detector

In case of a small load resistance, neutron and photon pulses differ in decay. The preferred method of processing is then comparison of integrals from time courses $u(t)$ of the voltage pulses:

$$r = \frac{\int_1^3 u(t)\,\mathrm{d}t}{\int_2^3 u(t)\,\mathrm{d}t}$$

where 1 is the starting time of the voltage pulse, 3 corresponds to the end of the pulse and 2 is an empirically found time between 1 and 3 when the decay of a neutron pulse starts to differ from a photon pulse. Obviously $1 < 2 < 3$. The value of r is about 110 for neutrons and about 70 for photons – see Figs 2(b) and 5(d).

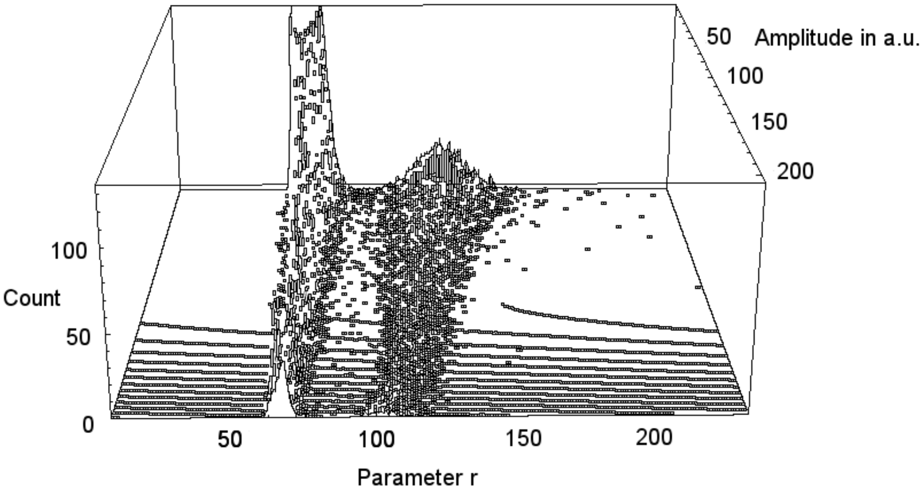

Fig. 2(b). Discrimination of output pulses from scintillation detector NE-213 using parameter r. (Top view of the same data is in Fig. 5 (d).)

3. Evaluation of Energy Spectrum

When evaluating experimental data from the detector, we face the *linear inverse problem* that can be formulated in case of neutron spectrum as follows: Let $g(E_p)$ and $A(E_n, E_p)$ be (continuous) functions. A (continuous) function $f(E_n)$ is to be found such that

$$g(E_p) = \int_{-\infty}^{+\infty} A(E_n, E_p) f(E_n) \mathrm{d}E_n \tag{1}$$

The above equation models the process of measurement using various devices or e.g. the output of a graphical device. It is a Fredholm integral equation of the first kind where

- $A(E_n, E_p)$ is the *kernel*, a characteristic of the measuring device, often called the *response function*. Its discrete approximation is determined by Monte Carlo modelling and measurement of monoenergetic neutron sources.
- $g(E_p)$ is the measured proton spectrum, i.e. experimental data. (Neutrons are detected by means of protons.)
- $f(E_n)$ is the result to be found, i.e. the neutron spectrum.

In general, equation (1) has no analytical solution and thus must be solved in a discrete form:

$$\mathbf{g} = \boldsymbol{A}\mathbf{f}, \tag{2}$$

where $\mathbf{g} = (g_1, \ldots, g_m)^T$, $\boldsymbol{A}$ is a $m \times n$ matrix, and $\mathbf{f} = (f_1, \ldots, f_n)^T$. (^{T} means transposition.) For stilbene and NE-213 detectors $m = n$. Our options for stilbene are $m \approx 60, 120, 240$. We solve (2) by the maximum likelihood method [1]. It is a standard statistical tool for point estimations. For the maximizing of the likelihood function, we use a general iterative algorithm called *Expectation Maximization*, originally developed for image reconstruction in astronomy, medicine etc.

4. Measurement Result and Energy Spectrum Evaluation for Neutrons and Photons from the ^{252}Cf Source

By the above described procedure we measured and evaluated neutron and photon spectrum of the ^{252}Cf source. The choice of this radiation source producing mixed field is not random. It is an artificial radionuclide and the neutrons originate from spontaneous fission of the Cf nuclei. Its neutron spectrum is widely regarded as standard and its shape can be used for testing correctness of the experimental method and accuracy of the evaluation process. It is very close to fission spectrum. Fig. 3 shows the neutron spectrum and Fig. 4 the photon spectrum of this source (measured with stilbene 45 × 45 mm).

5. Discussion

The first measurement results of energy spectra have shown prospects of the experimental methods used and a possibility of further improvement. The methodology of discrimination of impulses belonging to different types of radiation (in our case, neutrons and photons) requires more precise mathematical methods for finding the characteristics in which the pulses of the two types of radiation differ. These can be various, e.g. Fourier analysis, the use of neural networks, machine learning etc. We have recently used the Support Vector Machines (SVM) technique. It is a machine learning method which seeks optimum classification of the training data into two categories separated by a hyperplane. Simply said, this hyperplane maximizes the minimum distance between those two data sets. As SVM is a binary classifier, it can be used to distinguish neutron and proton pulses. Preliminary results, shown in Fig. 5, seem to be very promising. Fig. 5(a) depicts training data representing well separated neutron and photon pulses corresponding to higher energy values. Fig. 5(b) shows the result of the SVM classification / separation. You can compare these results with Fig. 5(c) that illustrates the classical separation according to pulse rise time (e.g. between 5 and 95 percent of the amplitude). Fig. 5(d) shows the result of neutron-gamma separation using parameter r – see Section 2.

The processing of pulses with the current digitizer is not ideal because of its low dynamic range of quantization (8 bits). For neutrons from energy interval 0.5 to 10 MeV, the ratio between the lowest and the highest pulse amplitudes is about 1:200. We solved this problem by taking measurements at three different voltage levels for the photomultiplier; the resulting amplitude distributions have been merged by a software routine.

Two-parameter measurements of neutron and gamma spectra were only possible in laboratory conditions until recently. The digitized spectrometer is perspective for in situ measurements e.g. in working environment next to nuclear reactors, accelerators, and also for monitoring unwanted transport of neutron sources through security frames.

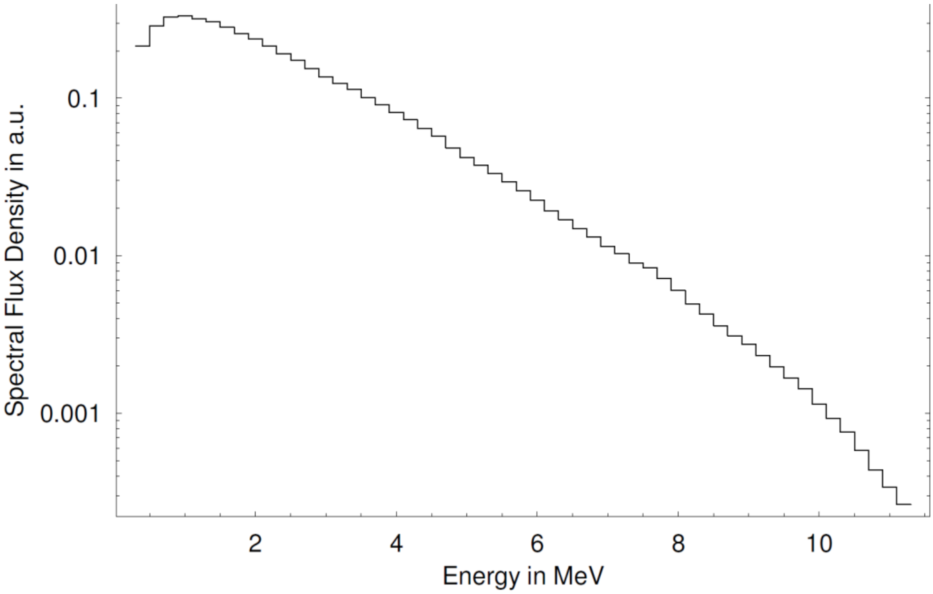

Fig. 3. Neutron spectrum $\varphi(E_n)$ *from spontaneous fission of* ^{252}Cf

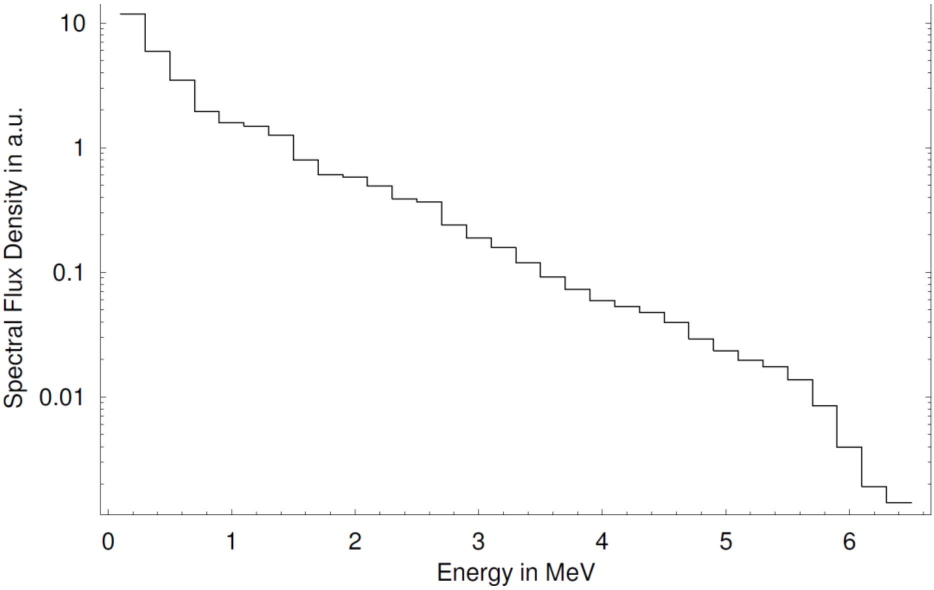

Fig. 4. Photon spectrum $\varphi(E_n)$ *from spontaneous fission of* ^{252}Cf

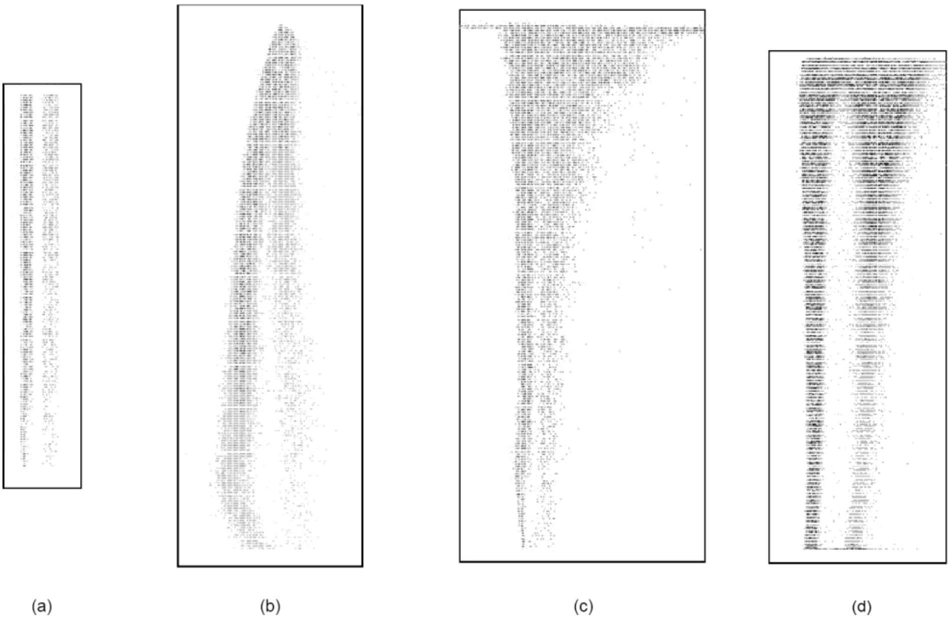

Fig. 5. (a) Training data, (b) Result of SVM separation, (c) n/γ discrimination based on pulse rise time, (d) n/γ discrimination based on parameter r

References

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