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MULTIDETECTOR SYSTEM FOR NANOSECOND TAGGED NEUTRON TECHNOLOGY BASED ON HARDWARE SELECTION OF EVENTS

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At the $T(d,n)^4$He reaction a neutron is accompanied by an associated alpha particle emitted in the opposite direction. A time and direction of the neutron escape can be determined by measuring a time and coordinates of the alpha particle at the position-sensitive alpha detector. The nanosecond tagged neutron technology (NTNT) based on this principle has great potentialities for various applications, e.g., for remote detection of explosives. A spectrum of gamma rays emitted at the interaction of tagged neutrons with nuclei of chemical elements allows one to identify a chemical composition of an irradiated object. For practical realization of NTNT, a time resolution of recording the alpha–gamma coincidences should be close to 1 ns. The total intensity of signals can exceed $1 \cdot 10^6$ s^{-1} from all gamma detectors and $7 \cdot 10^6$ s^{-1} from the alpha detector. The processing of such a stream of data without losses and distortion of information is one of the challenging problems of NTNT. Several models of analog DAQ system based on hardware selection of events were devised and their characteristics are examined. The comparison with the digital DAQ systems demonstrated that the analog DAQ provides better timing parameters, lower power consumption, and higher maximum rate of useful events.

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INTRODUCTION

Neutron technologies are widely used in elemental analysis of organic materials — in particular, for detection of explosives [1]. When an interrogated object is probed with fast neutrons, gamma rays of discrete energy (informative radiation) are generated and recorded by gamma detectors. The spectral composition of gamma radiation reveals quantitative information on the presence of the main chemical elements in the object.

One of the main problems of using neutron technologies is a high background mostly caused by gamma rays emitted during interaction of neutrons with elements of the setup or surrounding objects, the decay of produced isotopes, etc. In recent years, the Nanosecond Tagged Neutron Technology (NTNT) has been rapidly developed, which, owing to spatial and time selection of events, allows a substantial decrease in the level of background radiation [2].

Figure 1 shows a typical device with tagged neutrons. Fast neutrons and alpha particles (^{4}He) are produced in the T$(d,n)^4$He reaction. Initial energies and the directions of the neutron

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and alpha particle are unambiguously interrelated (see Fig. 2, which presents the neutron and alpha-particle energies and the angle of neutron emission as a function of the exit angle of the alpha particle in the T$(d, n)^4$He reaction at a deuteron energy of 100 keV). A position-sensitive (multipixel) alpha detector generates a time stamp t_α and measures coordinates of recorded alpha-particle, thereby allowing the determination of the vector of its motion direction and exit time (via correction for the alpha particle velocity). With these data one can evaluate the neutron exit time, movement direction, and energy in the direction of the interrogated object, i.e., to "tag" the neutron by the associated recorded alpha particle.

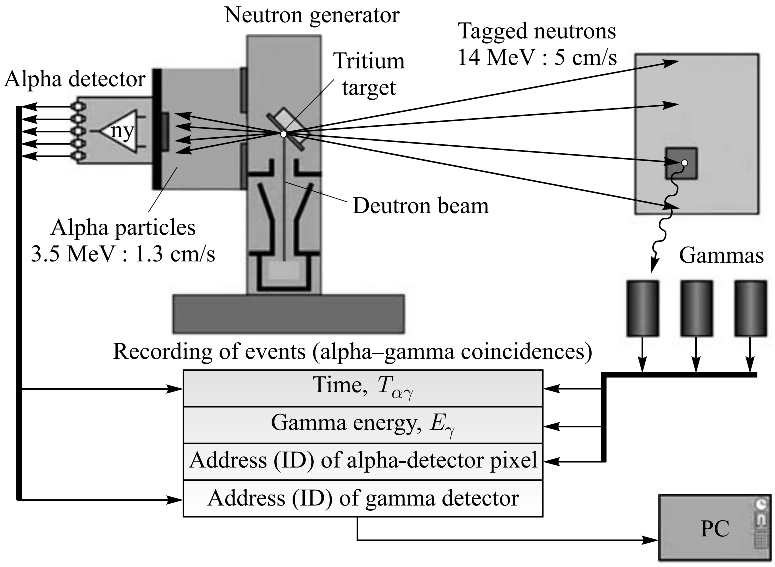

Fig. 1. Tagged neutrons device

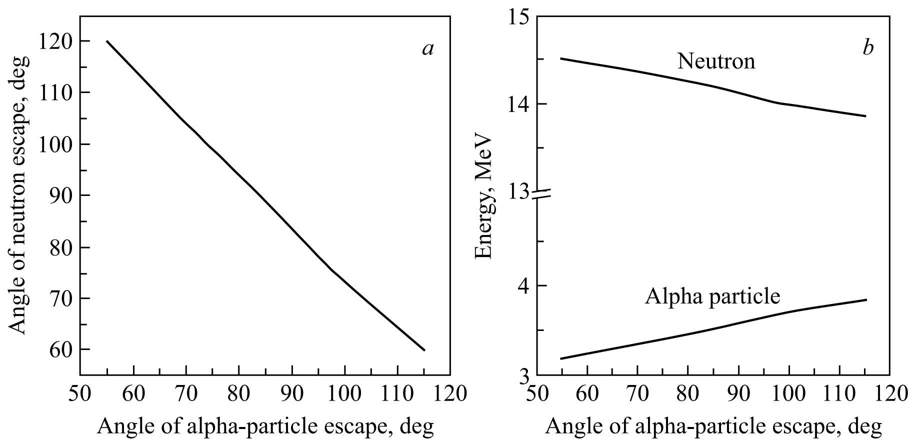

Fig. 2. Angle of neutron emission (*a*) and energies of a neutron and alpha particle (*b*) as functions of the exit angle of the alpha particle

A distance from the target of the neutron generator to the point of emission of a gamma quantum resulting from inelastic scattering of a tagged neutron in the interrogated object can be determined via a time interval between the recording of the gamma quantum and the alpha particle accompanying the tagged neutron. In inelastic scattering of the neutron by nitrogen, oxygen, and carbon nuclei, the energy of gamma rays has pronounced signatures and substantially exceeds the energy of gamma rays emitted during neutron scattering by nuclei of other elements, e.g., iron.

The maximum intensity of neutron generators for NTNT is about 10^8 s^{-1}. The total counting rate of alpha detector can be as high as $7 \cdot 10^6$ s^{-1}, and the total intensity of signals from all gamma detectors can exceed $1 \cdot 10^6$ s^{-1}. The processing of such a stream of data without losses and distortion of information is one of the challenging problems of NTNT. At present, two approaches to the solution of the problem of processing signals from devices based on the tagged-neutron technology are used: (1) preliminary online selection of pulses by hardware and transmission of only useful events to a PC [2] and (2) complete digitization of signals from all detectors and data-stream transmission to the intermediate computer for subsequent processing [3, 4]. In this study, we used the first approach based on the selection of useful events according to specified criteria and data storage by the buffer-memory unit with the subsequent transfer of data arrays to a remote computer for processing and visualization.

DATA ACQUISITION SYSTEM FOR THE TAGGED-NEUTRON TECHNOLOGY

The main selection criterion is the presence of signals from alpha and gamma detectors within the preset time window and amplitude ranges in the absence of overlapped events. These principles were assumed as a basis for the specialized data acquisition system of MATA (multichannel amplitude–time analyzer) series for the tagged-neutron technology. The basic features of this system are as follows.

1. Timing is executed by a constant fraction discriminator (CFD) the parameters of which (fraction, delay) are adjusted for the specific parameters of signals. The time interval $T_{\alpha\gamma}$ between the recording times of a gamma quantum and an alpha particle is measured by a time-digital converter (TDC).

2. The TDC is initiated by the gamma-detector signal, though in real life an alpha particle is recorded prior to the gamma quantum. For that the signal of alpha particle is transmitted through a delay line and used as a STOP signal for TDC. It sufficiently reduces a triggering rate of TDC.

3. The useful events (alpha–gamma coincidences) are represented by 5 bytes containing the amplitude of gamma-detector signal, $T_{\alpha\gamma}$ time interval, number of actuated pixel of alpha detector, and number of actuated gamma detector. They are transmitted to the computer as a buffered data flow as well as the spectra of gamma-detector signals accumulated simultaneously regardless of coincidences. It allows one to calibrate the gamma detectors on-line by specific peaks of the gamma spectra.

The tagged neutron devices based on the digitization of signals from all detectors have a sampling period as low as 7–10 ns. Very short signals from detectors should be extended in time up to several dozens of nanoseconds to provide meaningful number of samples for time and amplitude measurements. It may lead to the restriction in the maximum signal rate.

Comparison of digital and analog electronics for signal processing

<table>
<tr><td>Digital signal processing</td><td>Analog front-end electronics</td></tr>
<tr><td colspan="2">Advantages</td></tr>
<tr><td rowspan="2">Versatility, can be used for processing of signals from various detectors. No need in hardware tuning for specific detectors</td><td>Higher rate of events processing (up to 200000 s^{-1})</td></tr>
<tr><td>Operation with any reasonable number of detectors without decrease of rate of events processing</td></tr>
<tr><td rowspan="2">Application of complex algorithms for off-line and on-line processing of signals, zero-line correction, recovery of superimposed pulses</td><td>Low power consumption (< 50 W)</td></tr>
<tr><td>More accurate and stable timing</td></tr>
<tr><td colspan="2">Disadvantages</td></tr>
<tr><td>High power consumption (> 150 W)</td><td rowspan="2">Necessity of tuning of CFD and charge-sensitive amplifier parameters to meet signal falling and rising edges</td></tr>
<tr><td>Necessity for extension of short signals for meaningful number of samples</td></tr>
</table>

A comparison with these devices demonstrates that MATA provides more accurate and stable timing, higher maximum rate of processed event, lower power consumption (see table).

It was reported [5] that while using the digital signal processing, a time stamp of alpha–gamma coincidences drifts up to several ns during neutron generator operation and restores its initial position during 4–5 hour standstill. However, the statistical analysis did not reveal the alteration of signal rising edge. As far as front-end analog electronics of MATA provides timing by the rising edge of signal, this effect is practically absent in this system. Moreover, the time stamp of alpha–gamma coincidences is invariable during all lifetime of neutron generator.

EXPERIMENTAL STUDIES OF THE DATA ACQUISITION SYSTEM FOR THE TAGGED-NEUTRON TECHNOLOGY

Experimental studies were performed on a setup including a neutron generator ING-27 with a peak intensity 10^8 s^{-1}, and a gamma detector. A nine-pixel silicon alpha detector was built into a sealed tube of the neutron generator. The pixel size was 1×1 cm; the distance from the alpha detector to the tritium target was 6.2 cm. As far as the signal amplitude from one pixel of the alpha detector in a 50-Ω load is < 1 mV, signals were amplified by a preamplifier with a gain of 800 and a bandwidth of 80 MHz. Gamma quanta were recorded by the gamma detector with a 5×5 cm LYSO crystal.

To measure the time resolution, we used two graphite bars with a cross-sectional size of 7×7 cm and a thickness of 1.5 cm. The bars were placed along the axis of the flow of tagged neutrons corresponding to the 5th pixel of the alpha detector. The distance between the bars was varied from 5 to 10 cm. The time peaks corresponding to the positions of the graphite bars were well separated even at a distance of 5 cm between the bars. The evaluated time resolution of alpha–gamma coincidences (FWHM) was as low as (1.0 ± 0.1) ns.

To confirm the capability of the tagged-neutron technology of identifying the elemental composition of the substance in separate elementary volumes (voxels), two sets of experiments were ran. The object was represented by three 8-cm cubic containers filled with melamine ($C_3N_3(NH_2)_3$, a substance with a high concentration of nitrogen and carbon), water, and graphite powder. Net weight of each container was 500 g.

In the first version, the containers were placed along the axis of the tagged-neutron flow corresponding to the 5th (central) pixel of the alpha detector (Fig. 3). Figure 4 shows the time spectra of the coincidences of signals from gamma detectors and the gamma spectra

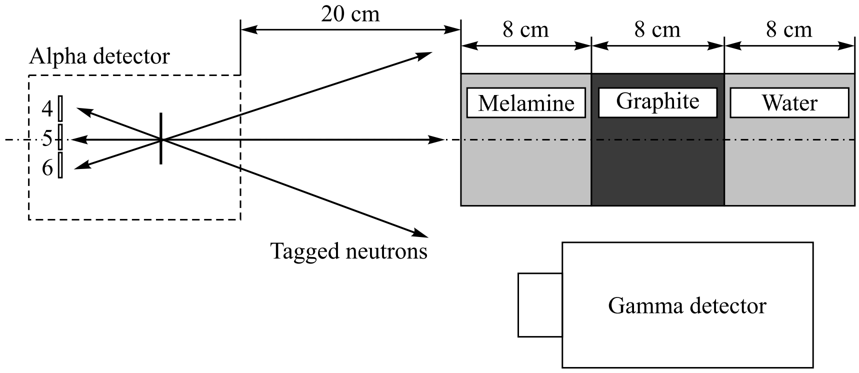

Fig. 3. Horizontal layout of containers

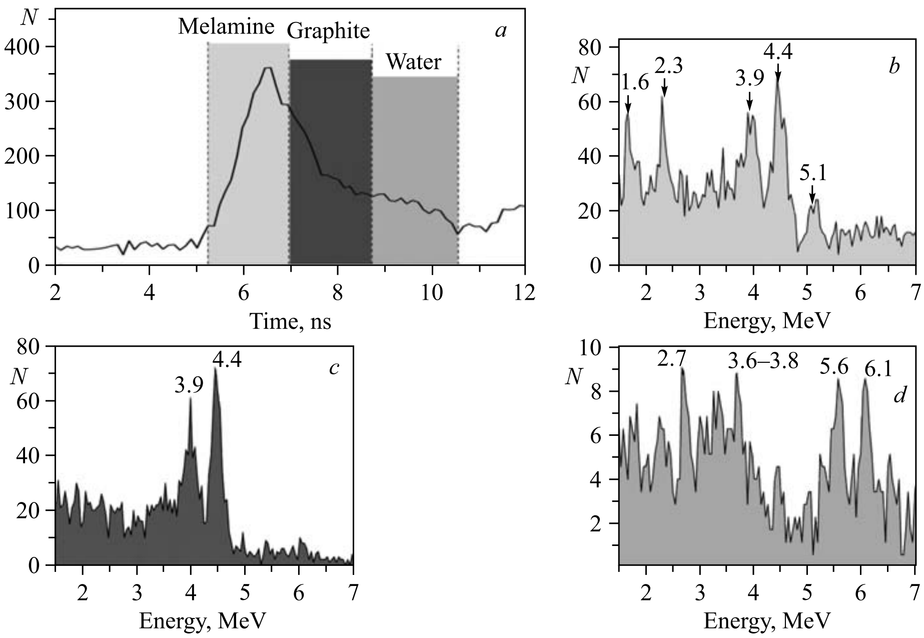

Fig. 4. Time spectrum (*a*) and gamma spectra corresponding to the time of passage of the containers with melamine (*b*), carbon (*c*), and water (*d*) by tagged neutrons for horizontal layout of containers

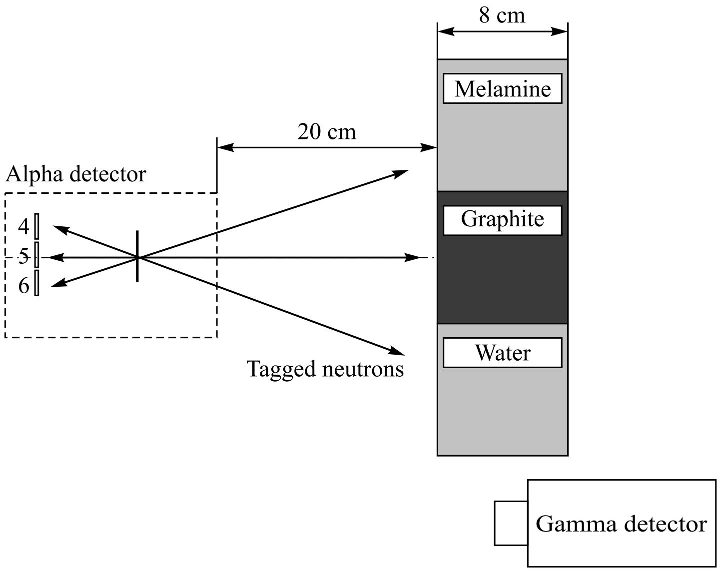

Fig. 5. Vertical layout of containers

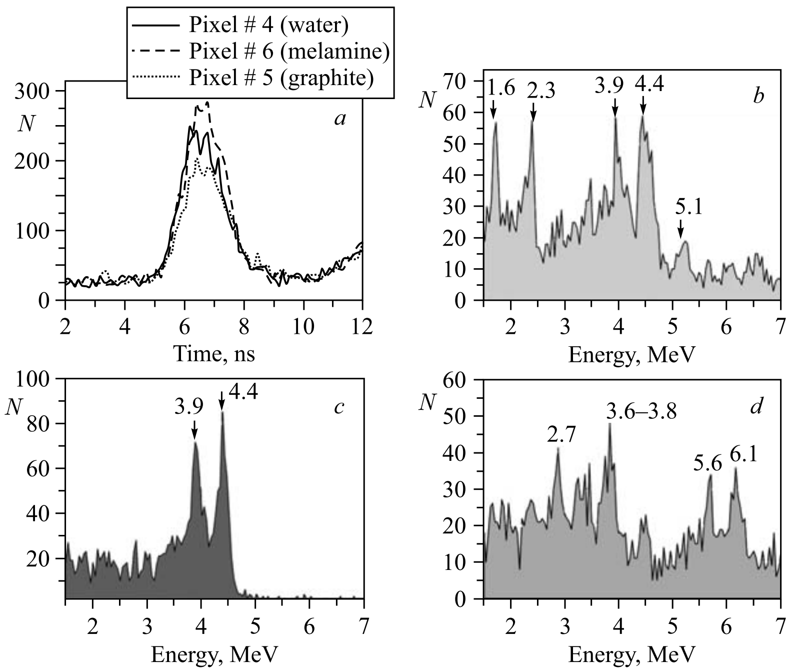

Fig. 6. Time spectrum (*a*), and gamma spectra corresponding to the time of passage of the containers with melamine (*b*), carbon (*c*), and water (*d*) by tagged neutrons for vertical layout of containers

corresponding to the time of passage of the containers with melamine, carbon, and water by tagged neutrons. In the second version (Fig. 5), the containers were arranged vertically at the same distance from the neutron generator. The gamma spectra corresponding to the time of passage of the containers and various pixels are displayed in Fig. 6. As is seen, all gamma spectra have pronounced signatures of characteristic elements (oxygen for water and carbon and nitrogen for melamine) that allow unambiguous identification of the contents of the container.

Note that there is no radiation shielding between the neutron generator and the gamma detector in the experiments, which is a necessary element in the implementation of other neutron-analysis technologies and is used for shielding the gamma detector against direct incidence of neutrons from the neutron generator. The background emission has decreased by several orders of magnitude. This is illustrated in Fig. 7, which shows the measured complete spectrum of gamma quanta produced under irradiation of 500 g of graphite with fast neutrons and a fragment of the spectrum selected via discrimination of the background by the tagged-neutron technology.

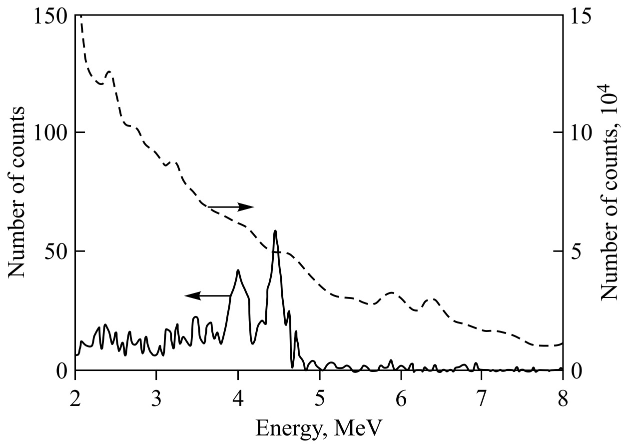

Fig. 7. Complete gamma spectrum (on the right) and a fragment of the spectrum (on the left) selected via discrimination of the background by the tagged-neutron technology

The intrinsic radiation of detectors (activation after neutron irradiation or presence of natural radioactive isotopes) also has a weak effect on the measured parameters. In particular, a characteristic feature of a LYSO crystal is an additional background caused by the β decay of the ^{176}Lu isotope. The maximum ^{176}Lu radiation energy is ~ 1.2 MeV and the specific activity is 2681 $s^{-1} \cdot cm^{-3}$; i.e., for a 5×5 cm crystal, the activity is close to 26500 s^{-1}. Nevertheless, this radiation has almost no effect on the event acquisition rate and the amplitude resolution because it is efficiently discriminated from useful events.

CONCLUSIONS

The detecting equipment developed for the tagged-neutron technology ensures precise and stable measurements of the event recording time. The time resolution reached in recording of alpha–gamma coincidences is (1.0 ± 0.1) ns at an amplitude resolution of the gamma detector of 3.6–3.8%, a value that meets the requirement for the practical realization of the tagged-neutron technology.

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