ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2013, Vol. 10, No. 7, pp. 860–867. © Pleiades Publishing, Ltd., 2013.
Original Russian Text © V.Yu. Aleksakhin, V.M. Bystritskii, N.I. Zamyatin, E.V. Zubarev, A.V. Krasnoperov, V.L. Rapatskii, A.V. Rogachev, Yu.N. Rogov, A.B. Sadovskii, A.V. Salamatin, M.G. Sapozhnikov, V.M. Slepnev, 2014, published in Pis'ma v Zhurnal Fizika Elementarnykh Chastits i Atomnogo Yadra, 2014, No. 1(185), pp. 221–232.

RADIOBIOLOGY, ECOLOGY AND NUCLEAR MEDICINE

Use of the Tagged Neutron Technique for Detecting Dangerous Underwater Substances

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Abstract—The tagged neutron technique (TNT) is analyzed in terms of its application for detecting dangerous substances hidden in underwater objects. The use of the technique for solving these problems is justified theoretically. The main characteristics of a prototype detector aimed at detecting explosives in a water environment are determined.

DOI: 10.1134/S154747711401004X

INTRODUCTION

The detection of hidden dangerous substances (explosive, radioactive, and highly toxic) in underwater objects is very topical in terms of both antiterrorism activity and searches for possible sources of pollution in oceans, seas, and rivers.

Systems based on direct detection techniques yield the most trustworthy results when searching for hidden substances in different media. These, first and foremost, are different devices that use, e.g., a chemical analysis of materials and a method based on the nuclear quadruple resonance phenomenon. However, the use of these methods is greatly limited, since the presence of a hermetically packed or impenetrable metallic envelope makes the detection of hidden dangerous substances impossible. In these cases, it is necessary to employ detection techniques based on the use of radiation, which is characterized by high penetrability and characteristic properties of interaction with chemical elements.

One of the detectors aimed at detecting toxic, explosive, and radioactive substances in underwater objects using penetrating neutron radiation is the Varyag-ChS system (the Krylov Central Scientific Research Institute) [1–4]. The operation of this system is based on the nuclear physical method of neutron activation analysis (the thermal neutron analysis, TNA) under the influence of thermal neutrons. The absence of information on the spatial location of a hidden object and a fairly high level of background radiation are disadvantages of this method.

In our opinion, the tagged neutron technique (TNT) [5, 6] is one of the most effective methods for searching for hidden substances in different media. This statement is based on the whole set of results that we obtained when studying the TNT in detail, as well as developing and producing a number of stationary and mobile devices that used TNT as a basis [5, 7–10]. The following physical principles underlie the tagged fast neutron technique. The object under investigation is irradiated by 14.1 MeV neutrons that are produced in the binary reaction $d + t \rightarrow \alpha + n$. The inelastic scattering of fast neutrons by nuclei in the substance of the irradiated object (the $A(n, n'\gamma)A$ reaction) yields γ quanta with energies specific for each chemical element that is part of this substance.

Spectra of detected characteristic gamma rays contain information on the elemental composition of the irradiated substance and its quantitative content. The concentration ratios of nitrogen, oxygen, and carbon nuclei (N/O, C/O, N/C) are different in explosive and most ordinary substances.

Apart from detecting the characteristic gamma radiation, the experiment measures a time interval between the moments of detection of an alpha particle and a gamma quantum. This interval determines a coordinate of the point where the gamma quantum arises inside the irradiated object along the direction of motion of a tagged neutron. Sensitive elements (pixels) of a silicon alpha detector will detect the alpha particle that accompanies a neutron released from a tritium target. The pixel number of the alpha detector, with allowance for the ratio between distances from the tritium target to the alpha detector and to the irradiated object, determines the coordinates of a point in which the tagged neutron interacts with the substance of the object in the plane that is perpendicular to its direction of motion. Thus, the 3D location of the hidden object in space is determined using the TNT. The use of a multipixel alpha detector makes it possible to single out independent beams of tagged neutrons whose quantity is equal to the number of the alpha-

detector pixels. Every tagged neutron beam irradiates a definite area of the analyzed object: a voxel. The voxel size in the plane perpendicular to the direction of neutron motion is determined by the size of the corresponding pixel of the alpha detector; in the direction of motion of the tagged neutron, it is determined by the temporal resolution of the system of alpha–gamma coincidences. The spectrum of gamma rays is analyzed at each volume element.

The use of TNT for detecting hidden explosives has a number of advantages when compared with other identification methods (using X-ray and IR radiation, activation analysis, thermal neutron analysis, and quasi-angular nuclear resonance):

—the acquisition of information about the 3D location of an object using only one measurement;

—sensitivity to the elemental composition of the substance;

—high penetrability of fast neutrons reaching 1–1.5 m;

—improvement of the effect–background ratio by a factor of greater than 200 in comparison with the absence of tagging.

The tagged-neutron technique for investigating dangerous underwater objects was tested in the UnCoSS project [11, 12]. The project was fulfilled by a consortium of academic and industry partners from Europe and the United States.

1. JUSTIFICATION FOR USING TNT

To estimate the possibility of using the TNT for detecting explosives in underwater objects, we calculated characteristics of the alpha–gamma coincidence system for specific values of the detection efficiency of the characteristic nuclear gamma radiation and the neutron flux intensity.

The calculations were performed using the GEANT4 software package [13] aimed at modeling the passage of elementary particles through the substance using the Monte Carlo method. In this software package, the interaction of neutrons with energies less than 20 MeV is very accurately described using the neutron-BT module [14]. To calculate the probability and the kind of interaction between neutrons and substance (elastic scattering, inelastic scattering, nucleus destruction, radiative capture, etc.), Evaluated Nuclear Data Library Files (ENDF) were used [15] that were reformatted for use in the GEANT4 software package.

The calculation of the fast-neutron flux absorption and the tagged neutron beam trajectory in water medium was performed considering the scattering effects.

Figure 1 illustrates a model used to perform the calculations. The source of fast neutrons is located inside an air container whose iron walls (*1*) are 5 mm thick. Figure 1 shows the estimation planes (*2*) for which the neutron flux was calculated. These estimation planes are located 5, 10, and 20 cm from the container housing.

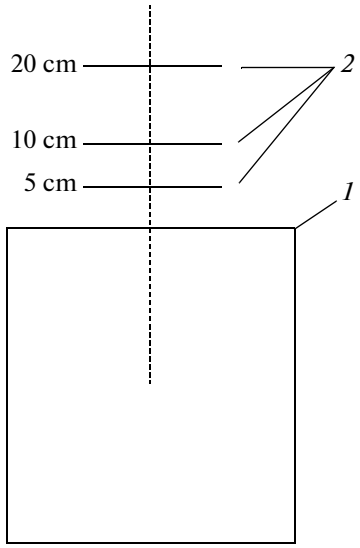

Fig. 1. Scheme of modeled conditions used in the calculation of fast-neutron flux absorption in the water medium. The estimation planes *2* are located at 5, 10, and 20 cm apart from the container housing *1*. The dashed line shows the symmetry axis of the central tagged beam.

The fast neutron beam absorption and the tagged neutron beam trajectory in water medium were calculated considering the scattering effects.

Table 1 shows the calculated results for neutron fluxes that reached the estimation planes and did not interact in the water medium or kept an appreciable fraction of energy when traveling across the medium. The presented results indicate that the neutron flux intensity at 5 cm from the inspection module is half as large as the initial one, decreasing by a factor of five at a distance of 20 cm.

This result suggests that it is necessary to properly increase (by a corresponding factor) the statistics-gathering time to detect gamma rays from underwater objects that are irradiated by the -neutron flux if these objects are located at large distances from the neutron source. Moreover, calculations indicate that the fast

Table 1. Fraction of the neutron flux that reached the estimation planes at 5, 10, and 20 cm from the metallic wall of the container with the fast neutron source for two neutron energies: >13 and 14.1 MeV

Energy n, MeV	5 cm	10 cm	20 cm
>13	0.64	0.44	0.20
14.1	0.59	0.39	0.15

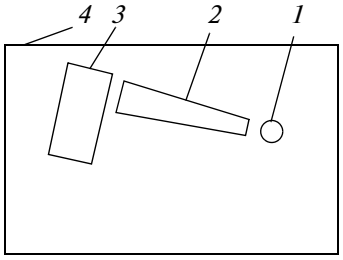

Fig. 2. Setup diagram: (*1*) fast-neutron generator, (*2*) protection of gamma detectors, (*3*) gamma-ray detectors, and (*4*) the detector housing.

neutron beam hardly deviates from the initial direction of propagation when traveling through the water layer of the abovementioned thickness.

To estimate the gamma detector loading due to detection of the characteristic gamma radiation that arises as a result of inelastic scattering of fast neutrons from light-element nuclei (^{12}C, ^{14}N, and ^{16}O), which are part of the analyzed object, as well as the external background radiation from the water medium, a prototype of the spectrometric system was modeled.

A scheme of the spectrometric system prototype was designed in accordance with the configuration of the DVIN-1 detector of explosive and narcotic substances [5]. The diagram of the modeled spectrometric system prototype is presented in Fig. 2.

The modeled spectrometric system includes the following modules: (*1*) the source of fast neutrons; (*2*) the gamma-detector protection in the form of a wedge made of polyethylene and iron; (*3*) the 76-mm-wide and 65-mm-thick scintillation gamma-ray detector with a bismuth-germanate crystal (BGO); and (*4*) the detector housing with 5-mm-thick aluminum walls. The modeling was performed for the detector being located in a cube filled with water and air. The neutron generator intensity was 5×10^7 s^{-1}.

The background loading of the gamma detector in the presence of water was compared with that in the absence of water. The comparison results are presented in Table 2. These suggest that scintillation gamma detectors with bismuth-germanate crystals (BGO) can be used to detect the characteristic nuclear radiation from carbon, nitrogen, and oxygen. The loading of the gamma-ray detector increases by a factor of three in the presence of water, deteriorating the energy resolution of the gamma detector. Therefore, when designing a pilot unit for detecting explosives, it is advisable to consider the problem of how the screening of gamma-detector scintillators can be strengthened against the lateral loading due to background radiation (gamma quanta and neutrons).

Table 2. Comparison between gamma detector loadings in air and in water

Energy release, MeV	Intensity, s^{-1}	
	Air	Water
>0	5.8×10^4	2.1×10^5
>0.1	4.6×10^4	1.4×10^5
>1.5	9.4×10^3	2.9×10^4

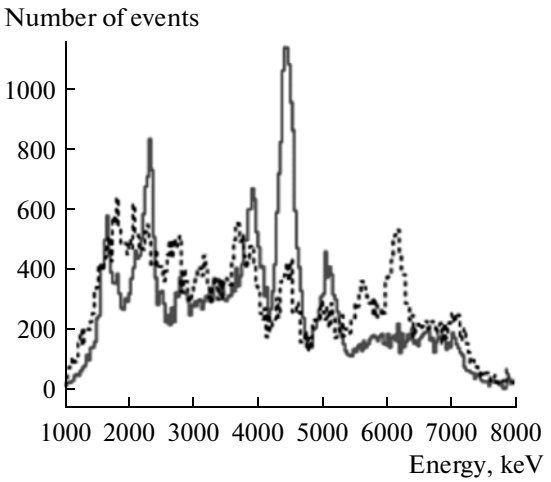

Fig. 3. Spectra of gamma radiation due to the irradiation of a melamine sample by fast neutrons when the sample is placed in water (dashed line) and in air (solid line).

For the modeled spectrometric system (Fig. 2), we obtained the spectra of the characteristic gamma radiation that arose when a melamine sample was irradiated by fast neutrons. This substance is used as an explosive imitator, since it has a high percentage of nitrogen. The size of the melamine sample was 10 × 10 × 10 cm (H × W × D). Calculations were performed when the sample was placed in both water and air media. Figure 3 shows a comparison of the model spectra. The peaks in these spectra correspond to the complete absorption of energy of the characteristic gamma radiation of carbon $E_\gamma = 4.43$ MeV and nitrogen $E_\gamma = 5.1$ MeV that are part of the melamine sample. The spectrum calculated for the water medium contains a complete-absorption peak that corresponds to the energy of characteristic gamma radiation of oxygen $E_\gamma = 6.13$ MeV. The presence of this peak is explained by inelastic interactions between neutrons and oxygen atoms that are present in water. The obtained results demonstrate that we can single out components that correspond to the detection of characteristic gamma radiation from carbon and nitrogen with energies of $E_\gamma = 4.43$ MeV and $E_\gamma = 5.1$ MeV, respectively, in the characteristic spectra of gamma rays, although it is necessary to increase the

Fig. 4. Inspection module of a portable DVIN-1 system for the detection of explosives [10].

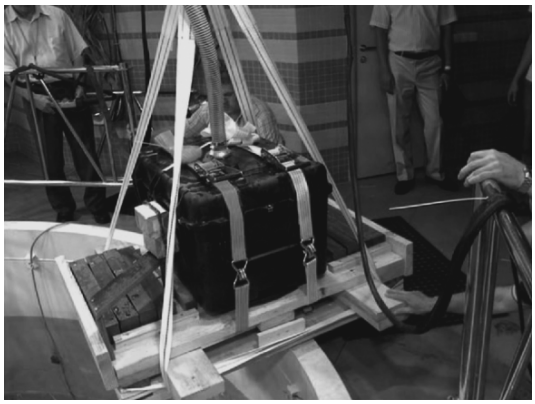

Fig. 5. Test bench based on a portable DVIN-1 detector for the detection of explosives.

statistics-gathering time. This suggests that the possibility still remains for analyzing explosives in water medium using the tagged fast-neutron technique by means of determining the carbon, nitrogen, and oxygen content ratios in the explosive, provided that relevant criteria are chosen.

2. EXPERIMENTAL RESULTS AND THEIR ANALYSIS

To carry out experimental studies, a test bench was designed for which a portable DVIN-1 detector for the detection of explosives using the TNT was taken as a basis (Fig. 4) [10]. The inspection module was placed in a hermetic impact-resistant box made of high-impact ABS resin. The inspection module was connected with a control module and a power network using a flexible tight joint. The inspection module was located on a platform supplied with rails for mounting analyzed objects. To compensate for the effect of module positive buoyancy, a ballast was set in the lower part of the platform. The module was immersed into a water basin using a winch.

A view of the test facility is shown in Fig. 5.

The main characteristics of a portable DVIN-1 detector are presented in Table 3. The DVIN-1 system is intended for the automatic detection and localization of explosives inside inspected objects without opening them.

The DVIN-1 system contains an inspection module, control module, and connector cables on a bobbin. The inspection module, which is used to irradiate an inspection object with a neutron beam, contains a neutron generator with a built-in silicon alpha detector, a scintillation gamma detector based on a BGO crystal, recording electronics, and power units. The control module contains an operator interface based on a PC with a program unit for analyzing the information that comes from the alpha and gamma detec-

Table 3. Main characteristics of a portable DVIN-1 detector

Number of tagged neutron beams	9
Intensity of the NG-27 generator, s^{-1}	5×10^7
Neutron energy, MeV	14
Overall size of the inspection module (L × W × H), mm, max	740 × 510 × 410
Overall size of the control module (L × W × H), mm, max	400 × 200 × 40
Overall size of the bobbin with connector wires (L × W × H), mm, max	600 × 600 × 400
Net weight of the inspection module, kg, max	40
Net weight of the control module, kg, max	3
Net weight of the bobbin with connector wires, kg, max	17
Consumed power, W, max	300

Fig. 6. Installation of the inspected melamine sample on the test bench.

tors in order to detect and identify hidden dangerous substances.

We carried out a series of experiments and obtained spectra of the characteristic gamma radiation of a 1400-g melamine sample and a medium sticky bomb (MSB) in air and water media (with an MSB charge mass of 1 kg; the charge contained 17% trotol, 54% hexogen, 17% aluminum, and 7% deterrent). The melamine samples and MSBs were installed on an external side of the hi-impact housing at a special platform of the measuring bench (Fig. 6).

The measurement results suggest that the gamma-ray detector loading increases by a factor of four in the water medium (with a neutron flux intensity of 5×10^7 s^{-1} from a neutron generator) in comparison with the detector loading in the air (the count rate of the gamma detector is ~80 kHz in the water and ~20 kHz in the air). When the neutron flux intensity decreased by a factor of five, the gamma-ray detector loading in the water was 17 kHz.

To analyze the information that came from the data received and tentative analysis units of the alpha and gamma detectors, we used the DVIN-1 system software. The outward appearance of the software structure is presented in Fig. 7.

Using the software, the data that come from the detecting facility are recorded in specific cells that correspond to 3D cells of an irradiated object (the so-called voxels); these are formed by the tagged neutron beams and given time intervals between the arrivals of signals from the alpha and gamma-ray detectors. The counting of tagged beam numbers starts from the top left corner (Fig. 7b). The distance along a chosen direction of the tagged neutron beam from the inspection module to the corresponding voxel of the object is identified using the ruler located in the left part of Fig. 7b. For each isolated area (voxel), the spectrum of the characteristic nuclear gamma radiation is constructed and its parameters are determined. If the material of the chosen voxel is identified as "dangerous," this voxel is marked in red in the software interface; otherwise it is marked in green ("not dangerous").

Figures 8 and 9 compare the time and energy spectra of the characteristic gamma radiation that were measured in the water and air media for two tagged neutron beams, one of which (no. 4) contained a dangerous-substance imitator (melamine) and the other (no. 6) was dangerous substance-free.

The observed difference in the time spectra of beam 6 measured in water and air demonstrates that the characteristic radiation detected by the gamma detector from the water contributes appreciably to the spectrum. The comparison of the energy spectra (Fig. 9) of the same two tagged neutron beams makes it possible to establish the presence of complete energy absorption peaks of the characteristic gamma radiation from carbon $E_\gamma = 4.43$ MeV, nitrogen $E_\gamma = 5.1$ MeV, and oxygen $E_\gamma = 6.13$ MeV in the melamine spectrum.

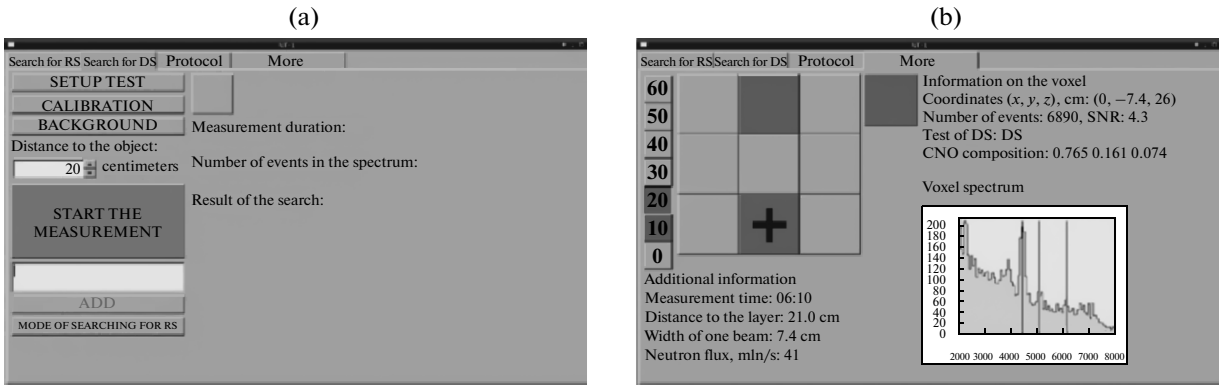

Fig. 7. Outward appearance of the software for analyzing the data from the DVIN-1 system: (a) operation in the mode of searching for explosives; (b) operation in the mode of analyzing the measurement results.

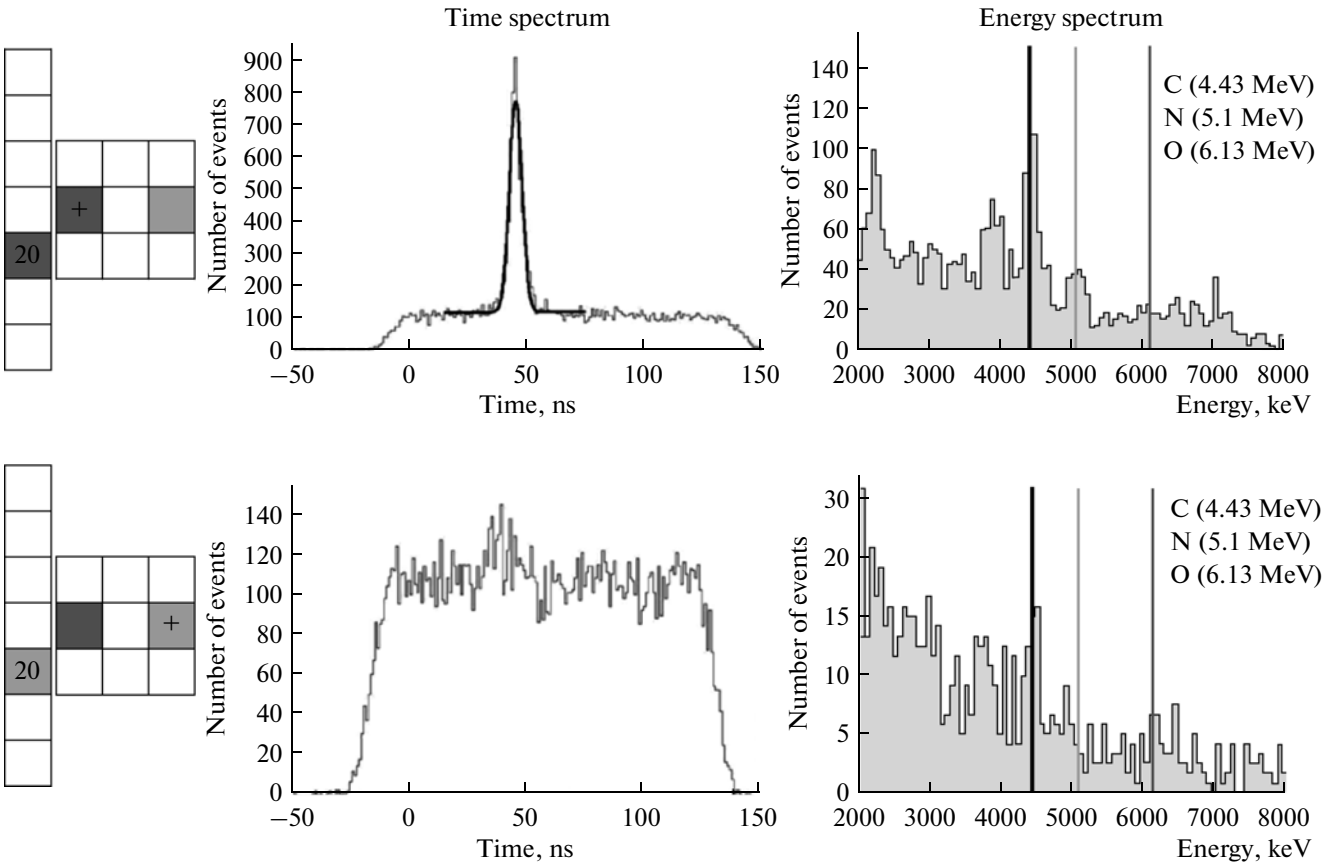

Fig. 8. Time and energy spectra of the gamma radiation for beams 4 and 6 in the air. The cross designates the tagged beam for which the time and energy spectra are presented; leftward, the distance (in cm) from the inspection module to the given separated voxel is given. The straight lines in the energy spectra indicate the complete energy absorption peaks of the characteristic gamma radiation from carbon $E_\gamma = 4.43$ MeV, nitrogen $E_\gamma = 5.1$ MeV, and oxygen $E_\gamma = 6.13$ MeV.

The comparison of the time and energy spectra obtained in the water and air media indicates that the measurements of the same amount of an explosive contained in these media yield essentially different results, suggesting that the methods for analyzing the data obtained in these media (the algorithm and selection criteria for detected events) should also differ.

To check the possibility of detecting dangerous objects that were located in a water medium, we measured the characteristic gamma radiation of the melamine that was 20 cm apart from the inspection module. The energy spectrum that corresponds to central voxel 5 is presented in Fig. 10. The peaks that correspond to the characteristic radiation of nitrogen and oxygen are clearly seen in the energy spectrum. Thus, dangerous substances (DSs) located in water within 20 cm from the inspection module can still be detected in principle. However, to reliably detect DSs in water, the statistics-gathering time should be increased, since the tagged neutron flux intensity weakens due to elastic and inelastic interactions of neutrons in this water layer.

The provided energy spectra indicate that fairly intense peaks of the characteristic radiation from carbon, nitrogen, and oxygen are clearly seen when a melamine sample and an MSB are irradiated in water with a tagged neutron beam. The possibility of isolating the carbon, nitrogen, and oxygen peaks against the background of oxygen peaks from water is an essential result that makes it possible to detect explosives located in water.

It should be noted that our experimental data correspond well to the results calculated using the GEANT4 software. Therefore, the introduction of specified criteria that establish relationships between the intensities of the C, N, and O characteristic radiation makes it possible to detect explosives immersed in water with high fidelity.

CONCLUSIONS

The characteristics of a detector intended to identify explosive substances were measured using the TNT in order to determine whether or not it can be used to spot dangerous objects underwater. Our find-

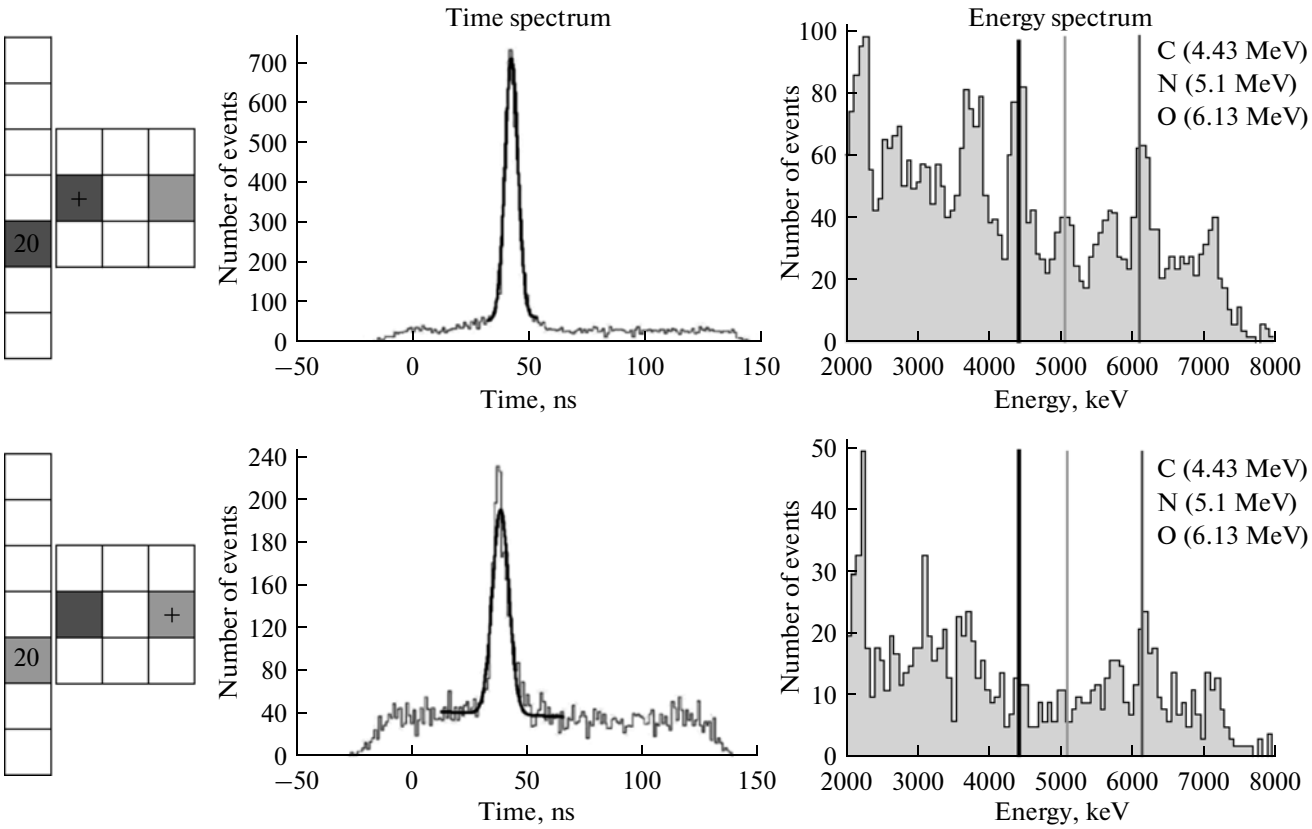

Fig. 9. Time and energy spectra of the gamma radiation for beams 4 and 6 in the water. The cross designates the tagged beam for which the energy spectrum is presented; the distance (in cm) to the inspection module along the direction of propagation of the chosen beam is given. The straight lines in the energy spectra indicate the complete energy absorption peaks of the characteristic gamma radiation from carbon $E_\gamma = 4.43$ MeV, nitrogen $E_\gamma = 5.1$ MeV, and oxygen $E_\gamma = 6.13$ MeV.

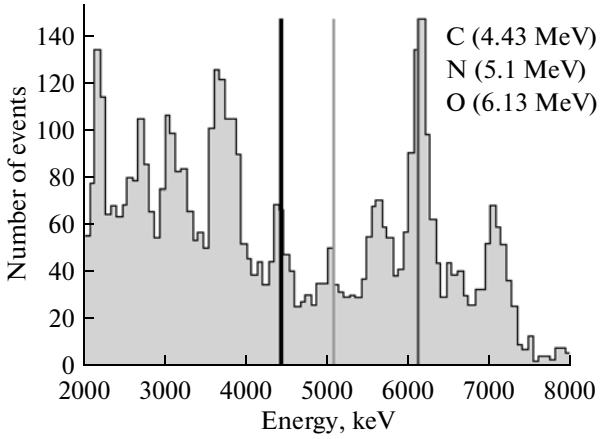

Fig. 10. Energy spectrum of melamine located 20 cm from the inspection module wall in water. The straight lines indicate the complete energy absorption peaks of the characteristic gamma radiation from carbon $E_\gamma = 4.43$ MeV, nitrogen $E_\gamma = 5.1$ MeV, and oxygen $E_\gamma = 6.13$ MeV.

ings suggest the possibility of DS identification using the detection of the characteristic gamma radiation from carbon, nitrogen, and oxygen nuclei. Effective sensing of an underwater explosive is possible under the condition that the water layer between the source of tagged neutrons and the object of inspection is

20 cm thick or thinner. The experimental results are in good agreement with the results calculated using the GEANT4 software package.

ACKNOWLEDGMENTS

We are grateful to B.P. Glazunov and S.V. Silant'ev for their interest in and support for these studies and to OAO Tetis-Pro for providing a basin for the experiments.

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Translated by N. Lipunova