ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2008, Vol. 5, No. 5, pp. 441–446. © Pleiades Publishing, Ltd., 2008.

METHODS OF PHYSICAL EXPERIMENT

DViN—Stationary Setup for Identification of Explosives[1]

V. M. Bystritsky[a], V. V. Gerasimov[a], V. G. Kadyshevsky[a], A. P. Kobzev[a], A. A. Nozdrin[a], Yu. N. Rogov[a], V. L. Rapatsky[a], A. B. Sadovsky[a], A. V. Salamatin[a], M. G. Sapozhnikov[a], A. N. Sissakian[a], I. V. Slepnev[a], V. M. Slepnev[a], V. A. Utkin[a], N. I. Zamyatin[a], A. N. Peredery[b], N. P. Likhachev[b], I. V. Romanov[b], M. V. Safonov[b], A. N. Sedin[b], and A. G. Scherbakov[b]

[a] *Joint Institute for Nuclear Research, Dubna, Russia*

[b] *Federal Security Service, Russia*

Received September 26, 2007

Abstract—A stationary system for the identification of hidden explosives was developed and constructed at the Joint Institute for Nuclear Research (JINR). The results of the examination of the system, as well as the operation principle of the system and design of the main elements are presented.

PACS numbers: 28.20.-v; 25.40.-h

DOI: 10.1134/S1547477108050075

INTRODUCTION

A stationary system to identify explosives was constructed at JINR (Dubna) and tested at the laboratory of the Federal Security Service (FSS) of the Russian Federation. The system is based on a portable neutron generator with a built-in 9-pixel α detector, which tagged 14 MeV neutrons that were produced in the binary nuclear reaction $d + t \longrightarrow \alpha + n$. The 14 MeV neutrons hit the inspected object and induced an inelastic scattering reaction of the $A(n, n'\gamma)A$ type, and nuclear γ radiation with energies characteristic of each chemical element in the interrogated object were emitted. The characteristic γ radiation was recorded in coincidence with the signal from the α detector. The measurement of the time interval between the signals from α and γ detectors allows the possibility of reconstructing the three-dimensional position of the hidden object.

This approach is called the Tagged Neutron Method (TNM), which is also sometimes named the Associated Particle Imaging Method [1–5].

The main advantage of the TNM is the sensitivity of the hidden substances to the elemental content rather than to its density contrast as many X- and γ-ray introscopes can define.

The tagging of the neutrons provides the time information, which can be used to select the events from a particular time interval and the results in the drastic decrease of the background. It is shown [6–9] that the use of (α–γ) coincidences reduces the background-to-signal ratio by a factor of more than 200, which allows one to identify small quantities of explosives.

The fast 14 MeV neutrons are suitable for the interrogation of the hidden objects because of their high penetration into the bulk material. They are especially convenient for the inspection of medium (luggage) and large (cargo containers) scale objects.

The development of this system is being successfully performed in a collaborative project between the Joint Institute for Nuclear Research (Dubna) and FSS of the Russian Federation. The project is called DViN, which is named after the Russian acronym for the Detector of Explosives and Drugs. This paper presents the results obtained in the tests on the detection of explosives hidden in luggage.

1. DESCRIPTION OF THE APPARATUS

The system was installed in a specialized box of the FSS laboratory for tests with explosives. The overall view of the system is shown in Fig. 1.

It consists of a portable neutron generator (NG) with a built-in silicon alpha detector, which provides nine beams of tagged neutrons. The gamma quanta, which were excited by tagged neutrons in the inspected object, were detected by two BGO γ detectors. The α and γ signals, being in coincidence, were processed by the data acquisition (DAQ) system and sent to the main PC. The decision-making software (DMS) identified the hidden substance by using the Neural Net (NN) method. The results were displayed on the user interface (UI).

[1] The text was submitted by the authors in English.

Fig. 1. General view of the DViN setup.

The neutron generator is ING-27, which was produced by the All-Russia Institute of Automatics (Moscow). It has the following characteristics:

Maximum neutron intensity, s^{-1}	5×10^7
Neutron energy, MeV	14.1
Operation mode	DC
Power supply, V	200 ± 10 DC
Maximum power consumption, W	30
Neutron generator dimensions, mm	$145 \times 215 \times 300$
Weight, kg	~6

The tritium target is electrically isolated from the ground and has a potential of –80 kV, which can be varied. The neutron generator is controlled by the PC. Up to now, the NG has operated for 350 h.We have developed and constructed a silicon α detector that was implemented in the neutron generator. It consisted of 3×3 elements which formed a matrix with the size of each pixel being 10×10 mm. All nine pixels of the alpha detector were manufactured on a single wafer. Figure 2 shows the α detector before it was installed in the NG. The front-end electronics were developed and constructed for the alpha detector. It was mounted to the rear side of the neutron generator, as shown in Fig. 3.

Figure 4 shows the amplitude spectrum of the signals that were recorded by one pixel of the α detector. Line *1* corresponds to the spectrum at the beginning of the work using the neutron generator. Line *2* shows the spectrum of the same pixel after 100 h of its operation.

One could see that the amplitude spectrum was changing in a nontrivial manner with time: more energetic α particles began to appear. These α particles were formed in the $d + t \longrightarrow \alpha + n$ reaction on the surface of the alpha detector, which was covered by the tritium that evaporated from the target.

Curiously, not all of the pixels exhibited a change in the α-particle energy spectrum with time. The spectra from the upper row of pixels did not change and demonstrated spatial nonuniformity to the effect.

The alpha detector allows one to form nine beams of the tagged neutrons. For fast measurement of their spatial distributions, we constructed a specialized device called a profilometer, as shown in Fig. 5.

It consists of 16 plastic scintillator strips with fibers, which were embedded into the scintillator. The profilometer aperture is 120×150 mm. The fibers are coupled to the 16-channel photomultiplier tube readout by a dedicated electronic plate, providing an adjustable threshold to each channel. The profilometer significantly facilitates measurements of the spatial characteristics of the tagged beam.

We used two gamma detectors based on the BGO scintillators to register γ rays that were excited by tagged neutrons in the inspected objects. The crystals were produced by the Institute of Inorganic Chemistry at the Siberian Branch of RAS. Each crystal was 100 mm in diameter and 70 mm thick. The light decay time of the BGO scintillators was 300 ns. Figure 6 pre-

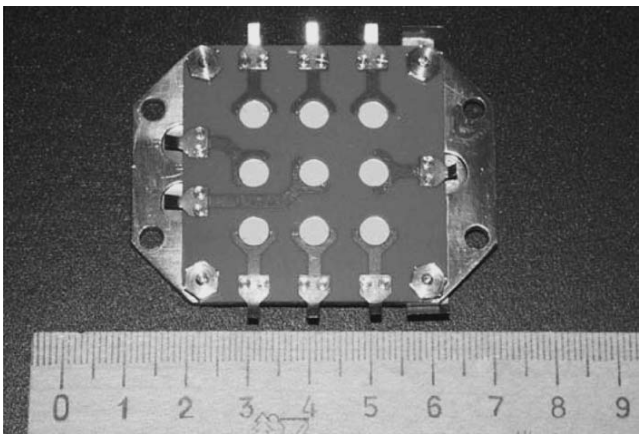

Fig. 2. Nine-pixel alpha detector viewed from the back.

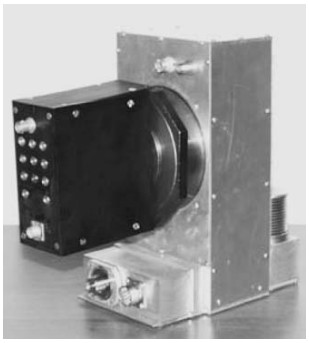

Fig. 3. The box of the front-end electronics of the alpha detector mounted on a neutron generator with a ground target.

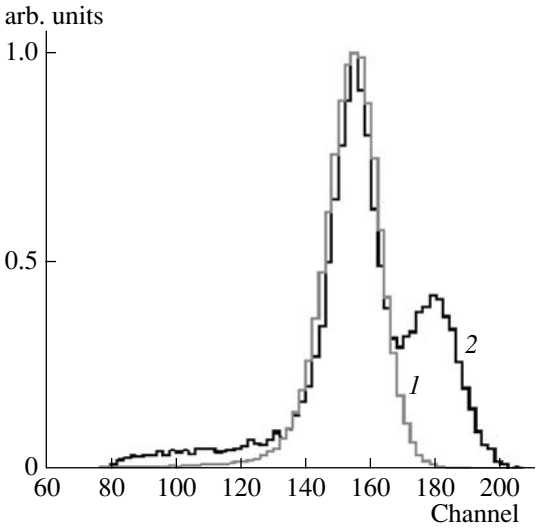

Fig. 4. Amplitude spectrum of the signals recorded by an α pixel without coincidence with the signal from the gamma detector.

sents the energy spectrum of characteristical γ rays that were detected by the γ detector in coincidence with the signal from an alpha channel. The spectrum was obtained in the irradiation of a ^{12}C sample $10 \times 10 \times 10$ cm with a tagged neutron beam.

As seen in Fig. 6, the energy distribution was characterized by two peaks in the spectrum: a peak in the total gamma energy absorption from the line E_γ = 4438 keV and a single escape peak with $E_\gamma = 3927$ keV, which correspond to the leakage of the 0.511 MeV γ quantum that was formed in the electron–positron annihilation. The energy resolution of the gamma detector for the $E_\gamma = 4438$ keV line was $\Gamma = (5.1 \pm 0.2)\%$.

Fig. 5. The profilometer used to measure spatial distributions of the neutron tagged beams. The working area is marked by the white sheet with the cross.

The data acquisition system (DAQ) was also developed and constructed. It consists of a data acquisition board with 16 channels for alpha and gamma detector signals (see Fig. 7) and the software package, which includes a kernel module (driver), a control program, and a reconstruction program.

The board was designed for the direct digitizing of signal pulses coming from the alpha and gamma detectors. It has a built-in trigger circuitry for three modes of operation: time-driven, single-channel, and alpha–gamma coincidence events. By using the software, it is possible to accurately reconstruct the amplitude and time mark of the signal.

The power supply system for gamma detectors, for front-end electronics of the alpha detectors, as well as for some systems of the neutron generator, was developed and constructed. Together with the PC of the DAQ system, it occupies a rack at the bottom of the setup (see Fig. 8).

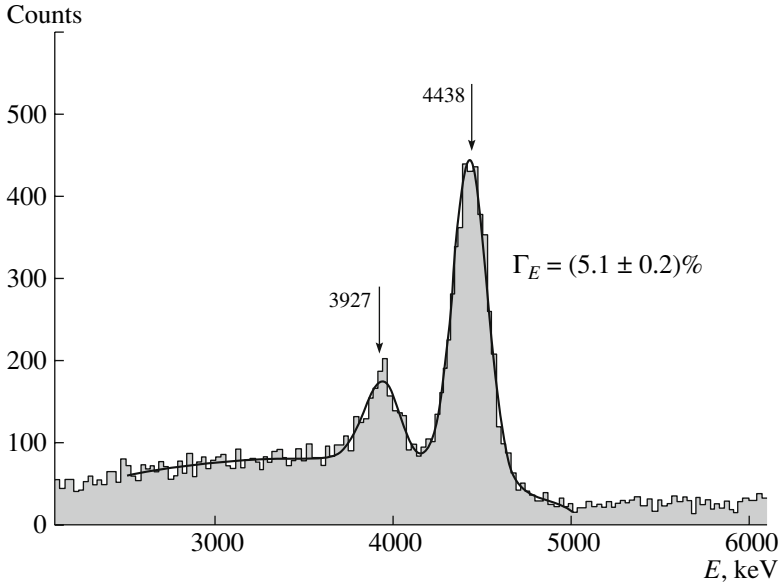

Fig. 6. Energy spectrum of γ rays recorded by the gamma detector in irradiation of a ^{12}C sample with a tagged neutron flux.

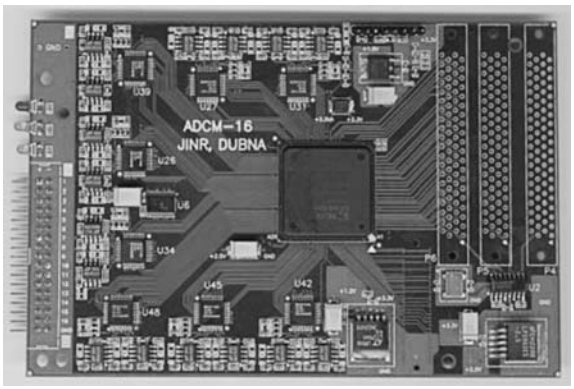

Fig. 7. The data acquisition board with 16 channels for alpha and gamma detector signals.

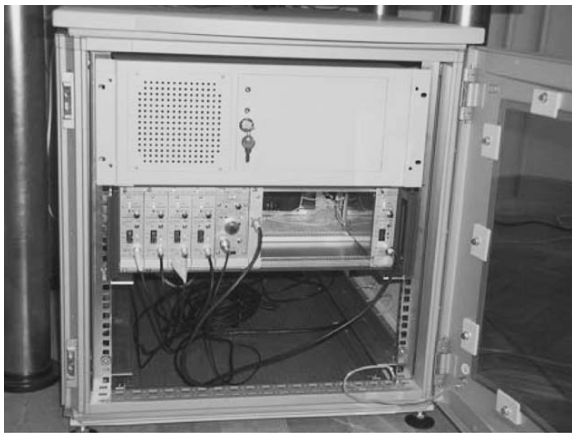

Fig. 8. The DAQ system and the detector power supply.

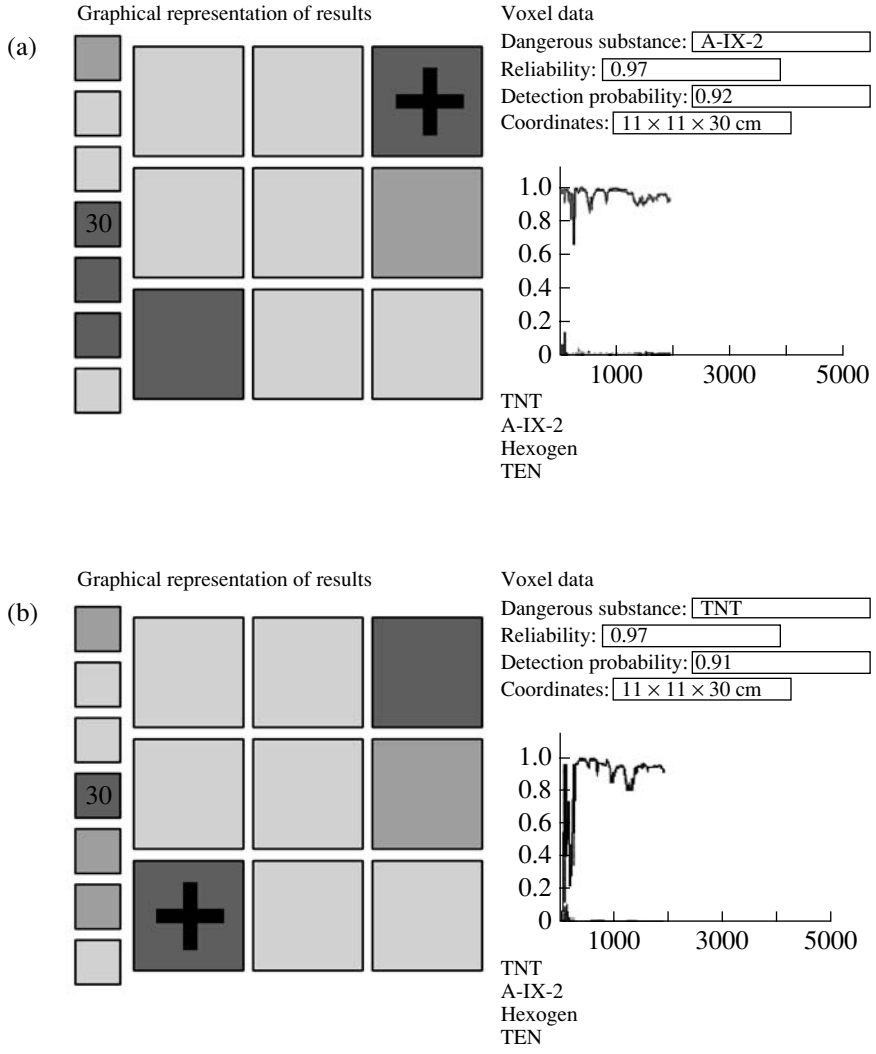

Fig. 9. General view of the user interface for a test with two explosives: A-IX-2 (a) and TNT (b).

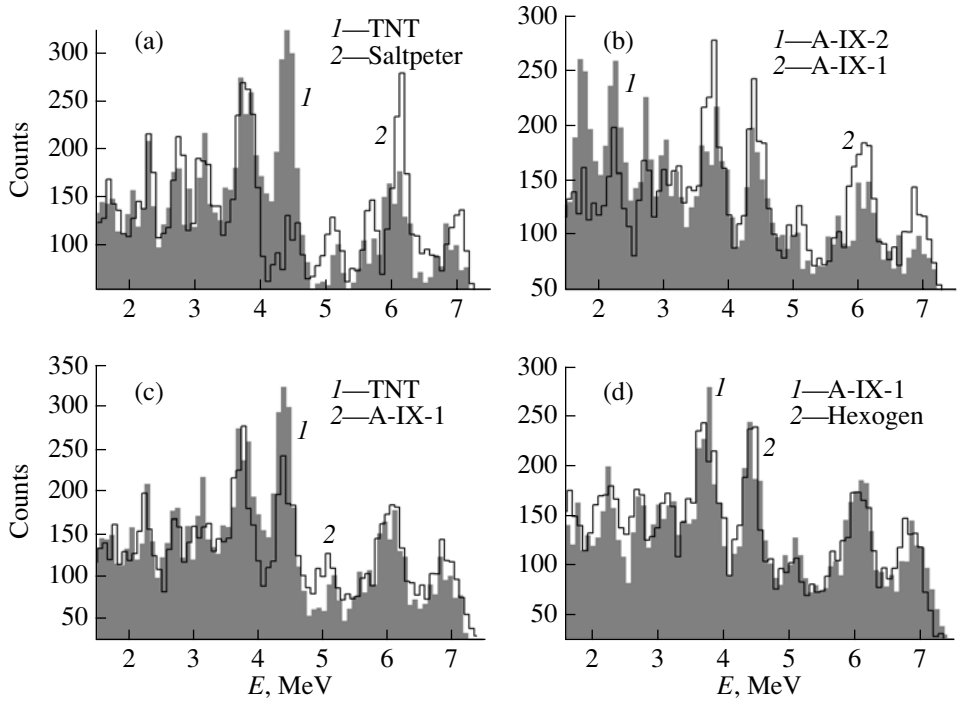

Fig. 10. The energy spectra of γ quanta for different explosives: (a) TNT (*1*) and saltpeter (*2*); (b) A-IX-2 (*1*) and A-IX-1 (*2*); (c) TNT (*1*) and A-IX-1 (*2*); (d) A-IX-1 (*1*) and hexogen (*2*).

To identify the explosives, the decision-making software (DMS) based on the NN method was developed. To train the NN, one should measure the spectra of typical explosives. The present version of DMS is able to distinguish some explosives and innocuous substances.

2. RESULTS OF THE TESTS

The user interface (UI) with the results of a typical test is shown in Fig. 9. The surface of the inspected object was divided into nine regions. In this particular test, a sample of TNT was positioned in the bottom left corner of the case, whereas a sample of A-IX-2 explosives was placed in the upper right corner. Each of the nine regions of the case was irradiated with the corresponding tagged neutron beam and independently analyzed. Moreover, the volume inspected by each tagged beam was divided along its direction into seven regions, corresponding to 10 cm each. These seven regions are shown on the left-hand side in Fig. 9. Therefore, the inspection of the 63 space volumes (called voxels) proceeded independently during the test. The size of the inspected volume depends on the distance between the neutron source and the investigated object. Typically, the inspected volume varied from 50 to 600 mm in all three dimensions.

If the decision-making software (DMS) finds that the spectrum from some voxel is similar to that of one from the database of dangerous substances, the corresponding image in the UI is marked in red. For unambiguous identification, it is required that the similarity of the investigated spectrum to the one from the database be higher than a certain limit, and at the same time, the similarity to every other spectrum from the database be less than a certain limit. The control window on the right side of the UI shows the results of the DMS work in real time. It shows the probability of the identification of each substance from the database with the acquired statistics.

The tests were performed with nine explosives. Figure 10 shows the energy spectra of γ quanta for some explosives. The energy spectra of TNT ($C_7N_3O_6$) and saltpeter (N_2O_3) are compared in Fig. 10a. The TNT spectrum is dominated by the carbon line at 4.4 MeV. This prominent peak corresponds to the characteristic line of carbon, which is absent in the saltpeter spectrum. The characteristic line of carbon provides a clear distinguishing pattern for identification.

The spectra in Fig. 10 illustrate the sensitivity of the tagged neutron method to the elemental content of the explosive. The distinction between different substances depends on the difference in their elemental content. Thus, A-IX-1 comprises 95% of hexogen ($C_7N_3O_6$) and 5% of a bounded material. Therefore, one may expect that the spectra of hexogen and A-IX-1 should be similar, and the spectra shown in Fig. 10d confirm that. The TNT explosive contains more carbon than hexogen and A-IX-1. The spectrum in Fig. 10c confirms that in the region where the carbon line is at 4.3 MeV, more TNT events are observed. The A-IX-2 explosive contains 80% of hexogen and 20% of aluminum powder. Its spectrum differs from the A-IX-1 (Fig. 10b).

Finally, the hexogen and A-IX-1 explosive are not distinguishable, but the hexogen and A-IX-2 are.

The identification time depends on the intensity of NG, total acceptance of the gamma detectors, mass of the illicit substance, and shielding conditions. Usually, for the intensity of NG $I = 3 \times 10^7$ s^{-1}, one gamma detector and 200 *g* of explosives hidden in a case can be identified in a few minutes.

We have tested the influence of the shielding material on the identification. The explosives were placed into a container made from different materials such as cardboard, wood, plastic, steel, and leather. The thickness of the shielding varied from 4 mm (for leather) to 20 mm (for steel) and 50 mm (for the other substances). The identification was performed in all cases where the mass of the explosive in the voxel was larger than the mass of the shielding material in the voxel. Therefore, to identify a small amount of the hidden substances, one should decrease the dimensions of the tagged neutron beam and improve the time resolution of the system.

In total, we carried out 102 tests to identify different explosives under various shielding conditions. The correct identification was performed in 98% of the cases.

An important problem for reliable identification is false alarms. We define false alarms as a positive signal on an innocuous substance in the DMS, or a positive signal on the explosive in the wrong cell of the inspected volume. Thus, 776 tests were performed to determine the rate of the false alarms. The probability of false alarms turned out to be less than 2%.

CONCLUSIONS

The main conclusions of the work could be formulated as follows:

• The Tagged Neutron Method, its advantages and limits have been tested.

• The stationary system to identify explosives has been constructed at JINR and tested at the FSS laboratory.

• The system has demonstrated a high efficiency in identifying explosives hidden in a suitcase, and a low probability of false alarms.

At present, the system is under experimental exploitation at the FSS laboratory.

Any up-to-date information about the project can be found at http://nf-100-056.jinr.ru/dvin.

ACKNOWLEDGMENTS

The authors would like to thank A.P. Dergunov and I.M. Melnichenko for their help during the construction of the system. We are grateful to E.P. Bogolyubov, T.O. Khasaev, Yu.K. Presnyakov, and V.I. Ryzhkov for the construction of the neutron generator and numerous consultations. We thank L.G. Ignatova, E.V. Zemlyanichkina, and E.A. Perevalova for help in the data analysis.

REFERENCES

1. P. O. Hawkins and R. W. Sutton, "Compact Pulsed Generator of Fast Neutrons," Rev. Sci. Instrum. **31**, 241–248 (1960).
2. L. I. Ussery et al., "Fast Neutron Interrogation Systems for Detection of Hazardous Materials," Los Alamos Nat. Lab. Report LA12847-MS (1994).
3. E. Rhodes, C. E. Dickerman, and C. W. Peters, "Associated—Particle Sealed—Tube Neutron Probe for Characterization of Materials," SPIE Proc. **2092**, 288–300 (1993).
4. A. Beyerle, J. P. Hurley, and L. Tunnell, "Design of an Associated Particle Imaging System," Nucl. Instrum. Methods Phys. Res. A **299**, 458 (1990).
5. S. Pesente et al., "Detection of Hidden Explosives by Using Tagged Neutron Beams with Sub-Nanosecond Time Resolution," Nucl. Instrum. Methods Phys. Res. A **531**, 657–667 (2004).
6. V. M. Bystritsky et al., "Experiments on Hidden Substances Identification with Neutron Probing Via Associated Particle Registration," in *Proc. of the 4th Intern. Symp. on Technology and the Mine Problem, Naval Postgraduate School, Monterey, California, March 13–16, 2000*.
7. V. M. Bystritsky et al., "Study of the Associated Particle Imaging Technique for the Hidden Explosives Identification," in *Proc. of the Intern. Conf. on Requirements and Technologies for the Detection, Removal and Neutralization of Landmines and UXO, EUDEM2-SCOT-2003, Vrije Universiteit Brussel, Sept. 15–18, 2003* (Brussels, 2003), Vols. 1, 2.
8. V. M. Bystritsky et al., "Study of Nuclear Physics Methods for Identification of Hidden Materials in JINR," in *Proc. of Conf. on Portable Neutron Generators and Technologies on Their Basis* (Moscow, 2004), p. 283.
9. V. M. Bystritsky et al., "Portable Neutron Generator with 9-Section Silicon α Detector," JINR Commun. E13-2006-36 (Dubna, 2006).