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RADIOBIOLOGY, ECOLOGY, AND NUCLEAR MEDICINE

DViN-2 Stationary Inspection Complex

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Abstract—A DViN-2 stationary inspection complex has been designed and manufactured for identifying hidden explosives and drugs. The identification of hidden substances is based on the method of tagged neutrons. The source of the tagged neutron beam, which has an energy of 14.1 MeV produced in the reaction $d + t \longrightarrow \alpha + n$, is a portable neutron generator with a built-in 9-channel silicon α detector. The DViN-2 makes it possible to identify hidden explosives and drugs with a mass of from 100 g to 50 kg in objects with dimensions from 50 to 400 mm in all three directions. The results of 76 experiments testify to the high efficiency of the DViN-2 in regards to identifying hidden explosives and drugs and it has a rather low probability of false actuations: the probability of identifying explosives and drugs is 94%, and that of false alarms rate is 3%. The time it takes to identify hidden substances, depending on their mass and the thickness of the shielding material layer, is 3–7 min for an average neutron beam intensity into a solid angle of 4π of 2×10^7 s^{-1}.

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INTRODUCTION

The DViN-2 stationary inspection complex for the identification of explosives and drugs hidden in courier baggage and mail was designed and manufactured at the Joint Institute for Nuclear Research at the request of the State Courier Service of the Russian Federation.

The way DViN-2 identifies hidden substances is based on the method of tagged neutrons; this method consists of irradiating the inspected object by a beam of tagged neutrons with an energy of 14.1 MeV formed in the reaction $d + t \longrightarrow \alpha + n$. The source of the tagged neutrons is a portable neutron generator with a built-in multichannel α detector.

The registration of the α particle, in coincidences with the characteristic nuclear γ radiation produced in inelastic scattering $A(n, n'\gamma)A$ of the tagged neutron with the nuclei of the examined substance, makes it possible to identify the substances based on an analysis of the composition of elements of the substance. This is achieved by measuring the energy distributions of the characteristic γ radiation.

Data on the identification of a hidden substance was analyzed using the neural network method. The essence of this method is a comparison of the measured spectra of characteristic γ radiation with the standard spectra of the "hazardous" forbidden substance.

A more detailed description of the method of tagged neutrons can be found in [1–6].

1. DVIN-2 SETUP

The main elements of the DViN-2 are as follows:

(1) a portable neutron generator with a built-in α detector;

(2) γ detectors based on BGO crystals;

(3) data acquisition electronics;

(4) biological shielding from the neutron radiation created by the neutron generator;

(5) a sample stage with moving support for the studied object;

(6) power supply units for the neutron generator and α and γ detectors;

(7) a PC-based operator interface with a data processing program block.

Figure 1 shows a general view of the DViN-2.

1.1. Neutron generator. The portable neutron generator ING-27 (Fig. 2) with a built-in 9-element silicon α detector was developed at the All-Russia Research Institute of Automatics (Moscow) [7]. Unlike tagged neutron generators created earlier [3–6, 8] in which the tritium target was at a high voltage (~120 kV), a grounded target was implemented in this design. A Penning-type source is used as the ion source.

The α detector was designed and manufactured at the Joint Institute for Nuclear Research [4]. A matrix of α detectors consisting of 9 pixels is situated at a distance of 62 mm from the center of the tritium target. The presence of a 9-element α detector inside the neutron generator provides the formation of nine tagged neutron beams for irradiating the inspected object.

Fig. 1. Setup for the identification of hidden substances using tagged neutrons.

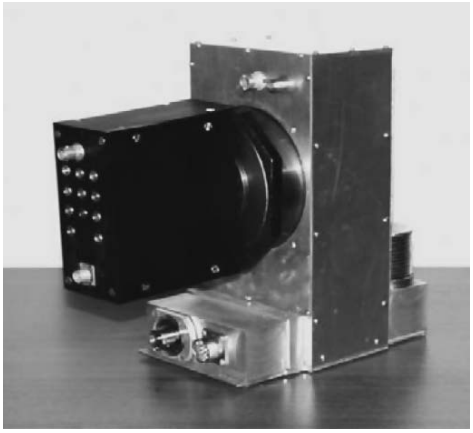

Fig. 2. ING-27 portable neutron generator.

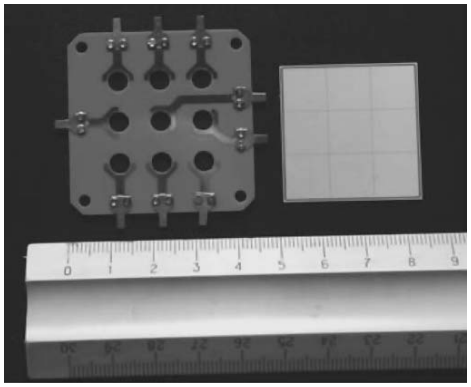

Fig. 3. Nine-pixels silicon α-detector.

The 9-pixel α-detector (Fig. 3) includes a planar silicon detector (crystal), a ceramic board–holder, and a stainless-steel frame.

The planar silicon detector consists of nine elements (pixels) forming a 3×3 matrix, the size of the sensitive area is 30×30 mm. The size of one element is $10 \times 10 \times 0.3$ mm.

The frame of the α detector is manufactured from stainless steel and is designated for mechanical protection, fixing the silicon detector position with respect to the target, and housing electric outputs from each element of the α detector. The ceramic printed-circuit board–holder is designated not only for mechanically protecting and fixing the silicon detector, but also for providing electric contacts with nine elements of the α detector.

The unit of detector electronics consists of nine independent amplifiers for signals received from nine pixels of the α detector. The board for detector electronics is mounted inside the metal frame–electromagnetic screen. The unit of electronics is fixed on the flange of the neutron generator and is connected with contacts of the α detector via the input connector.

The neutron generator possesses the following characteristics:

(i) a maximal neutron beam of 5×10^7 s^{-1};

(ii) a neutron energy of 14.1 MeV;

(iii) a continuous operation regime;

(iv) a maximal accelerating voltage of 120 kV;

(v) a power supply of (200 ± 10) V;

(vi) a mass of the neutron emission unit of no more than 6 kg;

(vii) a working temperature range of 10–45°C;

(viii) a limiting consumed power of 30 W.

The neutron generator is surrounded by a polyethylene biological shielding on all sides except for the output aperture of nine tagged neutron beams. The thickness of the biological shield is, on average, 300 mm.

Currently, the neutron generator has operated for 300 h at a neutron beam intensity of $\sim 2 \times 10^7$ s^{-1}.

1.2. γ Detector. The registration of characteristic γ radiation produced in the inelastic scattering ($A(n, n'\gamma)A$) of fast neutrons on the nuclei of light elements (^{12}C, ^{14}N, and ^{16}O) included in the studied object is performed using two scintillation detectors based on BGO crystals.

The γ detectors possess the following properties:

(1) good energy resolution ($(8 \pm 2.5)\%$) in the γ energy range 1–12 MeV;

(2) high γ registration efficiency in the above energy range, which provides the required statistics for identifying hidden substances in rather short amounts of time;

(3) low sensitivity to background neutron radiation.

The time resolution of the registration system of characteristic γ radiation in coincidences with signals

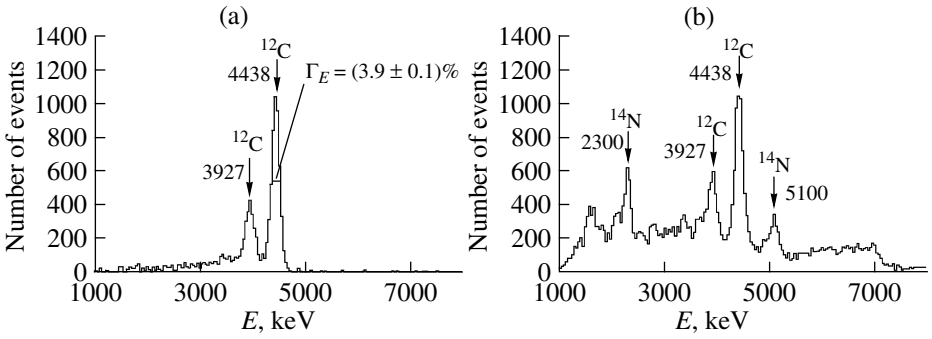

Fig. 4. Energy spectra of characteristic γ radiation of (a) carbon and (b) melamine.

from α detectors is 2.9 ns, which satisfies the requirements for this setup.

The γ detector consists of the 8-dynodes photomultiplier Hamamatsu R6233 with a photocathode diameter of 76 mm and BGO crystal (a diameter of 76 mm and a thickness of 70 mm). The BGO luminescence time is 300 ns, the density is 7.13 g/cm^3, and the light refractive index is 2.15.

Figures 4a and 4b show the characteristic γ spectra produced upon the irradiation of carbon (^{12}C) and melamine (simulating the explosive $C_3H_6N_3$) samples by the tagged neutron beam. The carbon and melamine sample thickness along the direction of the incident neutrons was 3 and 10 cm, respectively. It can be seen that the distribution in Fig. 4a is characterized by two peaks, the peak of total absorption of the energy of characteristic carbon γ radiation (E_γ = 4.43 MeV) and the peak of the single escape of 0.511 MeV γ radiation (E_γ = 3.92 MeV); the distribution in Fig. 4b is characterized by peaks of carbon and nitrogen γ radiation (E_γ = 5.1 MeV). The energy resolution of the γ detector for the E_γ = 4.43 MeV line is $\Gamma_E = (3.9 \pm 0.1)\%$.

1.3. Data acquisition. The recording electronics are manufactured as one board which is the same size as a standard PCI card with the possibility of being installed in the PCI slot of a PC and PC-controlled operation using a PCI bus for information exchange. The primary processing of information received from α and γ detectors, the formation of data files of which are transmitted via Ethernet into a PC for final processing and presentation of results, is performed using a PC.

The basis of the system of registration of signals from α and γ detectors is the principle of the pulse shape digitization with a subsequent calculation of their time and amplitude characteristics. The program package supporting the operation of the recording electronics includes drivers for PCI interface, a program for event selection and processing, a program of data file formation, and programs necessary for adjusting the operation regimes of the unit of electronics. For providing the required data transmission rate via the PCI bus, the interface operates in the regime of the direct memory access channel. This is the main requirement for the driver supporting the operation of this device. As the assigned data buffer is filled, the direct access channel is switched to a free memory domain and the filled part is processed by the selection and processing program. The processes of recording and processing happen in parallel.

All DAQ software operates on LINUX.

1.4. PC-based operator interface with the data processing program block. The program block for data processing and the visualization is designated for presenting the results of analysis in a form convenient for the user. The software operates under the operating system Linux and performs the following functions:

(i) total measurement cycle. The measurement cycle includes the initiation of the neutron generator, the accumulation and analysis of data, making decisions in the automatic regime, visualizing the results of analyses and decisions, switching off the neutron generator, logging the results of measurements, and archiving the data accumulated during the measurement;

(ii) diagnosting the operation of units and systems included in the complex;

(iii) archiving performed measurements.

The software was developed in the form of an applied program and a set of service files for storing the settings and logs. The code is written in C++ using the program package ROOT [9] based on the ROOT-set of classes for operation with neural networks. The interaction with the neutron generator is performed via RS 232 interface.

1.5. Parameters of tagged neutron beams of DViN-2 Setup. The spatial distribution of neutrons in nine tagged beams was measured using a specially designed and manufactured profilometer detector [6]. As an example, Figs. 5a and 5b show the spatial neutron distributions in the *XY* plane perpendicular to the direction of the emission of the tagged neutron beams from the target at a distance of 275 mm from the neutron generator. The distributions along the abscissa *X* and ordinate *Y* are given for tagged beams corresponding to the central rows of α pixels along the vertical (α_2, α_5, and α_8) and hori-

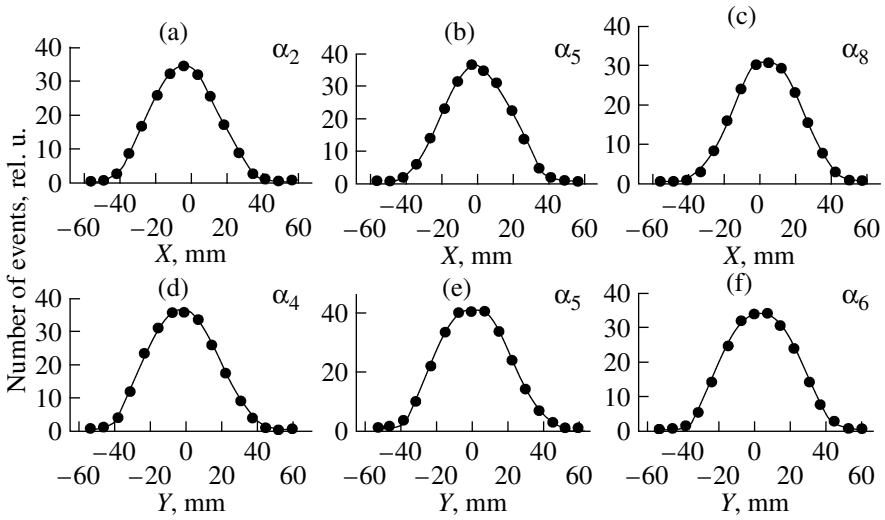

Fig. 5. Spatial distribution of tagged neutron beams along *X* and *Y* axes. The solid line is the result of fitting.

zontal (α_4, α_5, and α_6). The values of abscissa *X* and ordinate *Y* are counted from the point of intersection of the axis of the neutron generator passing through the center of the tritium target with the plane *XY*.

On average, the peak widths at a half maximum at a distance of 275 mm from the center of the tritium target to the plane *XY* in the *X* and *Y* directions are (41.1 ± 1.1) and (42.8 ± 1.4) mm, respectively.

Note that the shape of the measured spatial neutron distributions coincide with the calculated distributions for the point-like deuteron beam.

For the neutron beam intensity $I_n = 2 \times 10^7$ s^{-1}, the counting rate for the events recorded by one α pixel averaged over all nine pixels is ~4×10^4 s^{-1}.

1.6. Time resolution of DViN-2 detectors. The time resolution (Γ_t) of the system of tagged-neutron registration in coincidences with α particles from the *dt* reaction was determined in an experiment using a neutron detector based on the plastic scintillator that was installed directly into the tagged neutron beam corresponding to the central pixel. Figures 6a and 6b show the distributions of time intervals between signals from the central α pixel and γ detector measured at an irradiation of ^{12}C (10 × 10 × 3 cm) and melamine (10 × 10 × 10 cm) samples.

These distributions were approximated using the function which represents the sum of two Gaussians and a constant. The first peak corresponds to the registration of the characteristic γ radiation of carbon (E_γ = 4.43 MeV) and the second one to the detection of tagged neutrons scattered in the ^{12}C sample which hit the γ detector.

The measured time resolution of the system of registration of (α–*n*) coincidences were (1.6 ± 0.1) ns (Fig. 6c). The values of Γ_t for the system of registering characteristic γ radiation in coincidences with the accompanying α particles in experiments with ^{12}C and melamine samples were (2.6 ± 0.1) ns and (3.2 ± 0.1) ns, respectively (see Figs. 6a and 6b). The difference in the values of Γ_t is due to the different mean free times of the tagged neutron in the substances of these samples, which in turn are determined by the density of the matter and the thickness of the irradiated object.

2. RESULTS OF TESTING DVIN-2 SETUP

The main objective in testing this setup was determining the probability of identifying explosives and drugs in the presence of various screening materials and the probability of false alarms.

The reference energy distributions of the characteristic γ radiation produced during the irradiation of the following explosives and drugs by the tagged neutron beam were measured to learn the neuron network: hexogen ($C_7H_3N_3O_6$), ammonite (20% trinitrotoluene + 80% $H_4N_2O_3$), trinitrotoluene ($C_7H_3N_3O_6$), pentaerythritol tetranitrate ($C_5H_8N_4O_{12}$), tetryl ($C_3H_6N_6O_6$), elastite (cyclonite + plasticizer), PVV-5A (hexogen + plasticizer), heroin ($C_{21}H_{23}NO_5$), cocaine ($C_{17}H_{21}NO_4$), pseudoephedrine hydrochloride ($C_{10}H_{15}NO$ + various additions), and sodium oxibate ($C_4H_8O_3$). The γ spectra were measured in the regime of (α–γ) coincidences. The time spent on statistical accumulation for each of the above substances was, on average, ~1 h for an integral neutron beam intensity of ~4×10^7 s^{-1}. The mass of each sample was ~1 kg.

As an example for comparison, Fig. 7 shows the energy spectra of characteristic γ radiation obtained during the irradiation of trinitrotoluene, pentaerythritol tetranitrate, melamine (a simulator of explosive $C_3H_6N_6$), and ammonite by the tagged neutron beam.

It can be seen that the shape of these γ spectra differs even visually, which guarantees the clear identification

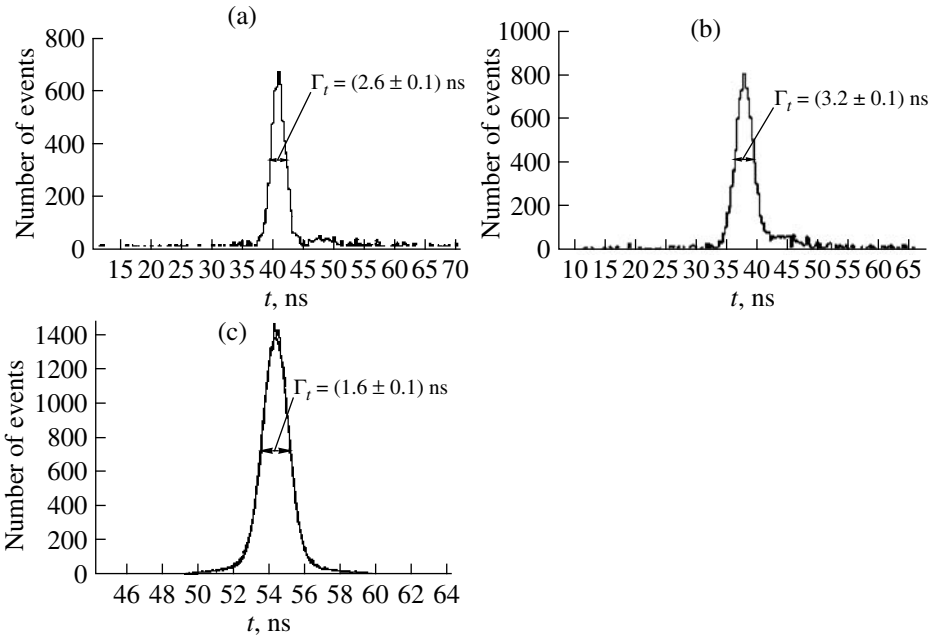

Fig. 6. Distribution of time intervals between signals from the central α pixel and γ detector measured during irradiation by a tagged neutron beam of (a) ^{12}C and (b) melamine samples; (c) distribution of time intervals between the signals from the central α pixel and the plastic detector.

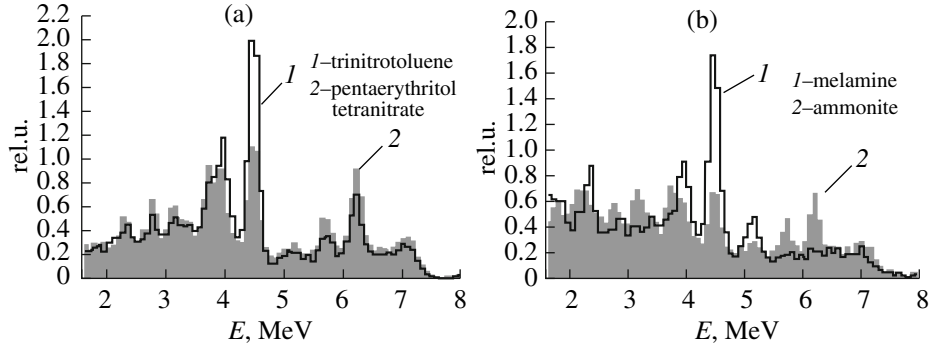

Fig. 7. Energy spectra of characteristic γ radiation obtained upon irradiation by a neutron beam of trinitrotoluene, pentaerythritol tetranitrate, melamine, and ammonite.

of these explosives using neural networks. This difference is related with the fact that the ratios of line intensities of characteristic ^{12}C, ^{14}N, and ^{16}O nuclei radiation for the above explosives are different.

A comparison of the spectra obtained for elastite and PVV-5A testify to the fact that they are almost completely similar; therefore, it is possible to identify these substances as explosives without indicating a particular explosive from the above set.

Figure 8 shows the energy spectra of γ radiation obtained upon irradiation by tagged neutrons of the following drugs: pseudoephedrine hydrochloride, sodium oxibutyrate, cocaine, and heroin.

It can be seen that the shape of spectra for heroin and cocaine—as well as for pseudoephedrine hydrochloride and sodium oxibutyrate—differ, which makes their identification reliable.

The results of 76 test experiments with explosives and drugs testify to the high efficiency of DViN-2 for identifying hidden explosives and drugs and the sufficiently low probability of false alarms. The explosive detection efficiency was 94%, and the probability of false alarms was 3%.

The minimal detectable explosive and drug mass in the presence of shielding substances was ~100 g.

All tests were performed for an average neutron beam intensity of $\approx 2 \times 10^7$ s^{-1}. In this case, the time it took to identify the hidden substance was 3–7 min, depending on the mass and thickness of the shielding material.

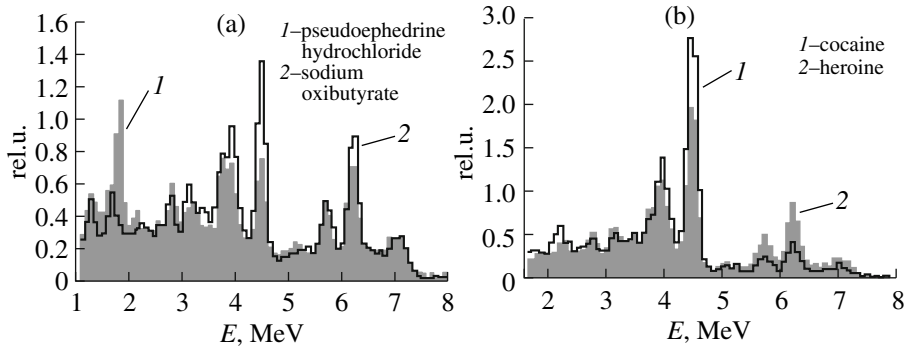

Fig. 8. Energy spectra of characteristic γ radiation obtained during the neutron-beam irradiation of pseudoephedrine hydrochloride, sodium oxibutyrate, cocaine, and heroin.

CONCLUSIONS

The following conclusions can be made based on the obtained results.

(1) The stationary inspection complex DViN-2, designated for identifying hidden explosives and drugs, was designed and manufactured at the Joint Institute for Nuclear Research. The nuclear physics method (tagged neutron method) was the basis for the creation of this setup.

(2) The DViN-2 setup makes it possible to identify explosives and drugs with a mass from 100 g to 50 kg in controlled objects with dimensions from 50 to 400 mm along all three axes without opening them. The inspection area of the controlled object situated at a distance of 600 mm from the neutron generator for single irradiation by the tagged neutron beam is 300×300 mm.

(3) The results of 76 test experiments with explosives and drugs testify to the high efficiency of DViN-2 and sufficiently low probability of false alarms. The probability of explosive identification is 94%; that of false alarms is 3%.

(4) The minimal detectable explosive and drug mass in the presence of shielding substances is ~100 g.

(5) The time it takes to identify hidden substances, depending on their mass and the thickness of the shielding material, is 3–7 min for an average neutron beam intensity of $\approx 2 \times 10^7$ s^{-1}.

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