DETECTOR FOR INSPECTION OF MINED CARS

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Consideration is being given to the design and characteristics of a detector for inspection of mined cars that is based on the tagged neutron method (TNM). The source of 14.1 MeV tagged neutrons produced in the reaction $d + t \rightarrow \alpha + n$ is ING-27 portable neutron generator (NG) of VNIIA production with a built-in 64-pixcel silicon α-detector developed in JNRI. This detector allows identifying explosives hidden in a car and designed for in-situ operation. The test results demonstrate high efficiency of the detector in identification of hidden explosives at sufficiently low probability of false alarms. The identification time of hidden explosives attains to 2-15 min at a neutron flux of 5×10^7 neutron/s depending on their weight and the thickness of a shielding material layer.

1. Introduction

The Joint Nuclear Research Institute (Dubna, Russia) developed and manufactured on demand of RF FSS a mobile inspection system for detection of explosives hidden in cars. The system is designed for detection of explosives in cars and explosive charges in car-bombs. Detection of explosives is based on spectrum analysis of characteristic nuclear gamma radiation resulted form irradiation of an investigated object by a flux of fast tagged neutrons.

The *Deuterium* system makes it possible to remotely detect hidden explosives and to determine the position of hazardous objects in the space using the tagged neutron method. Fig. 1 presents a flow chart of the method.

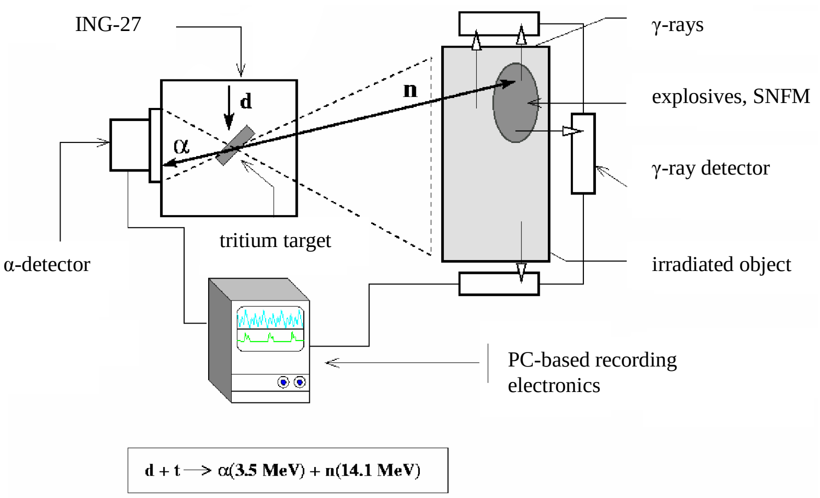


Fig. 1. Tagged neutron method

ING-27 portable neutron generator with a built-in 64-section strip silicon α-detector is used as a source of 14.1 MeV neutrons.

A deuterium ion beam is accelerated in the neutron generator to energies of the order of 100 keV and is focused on the tritium target. The $d + t \rightarrow \alpha + n$ reaction produces 14 MeV neutrons and 3.5 MeV α-particles that in the c.m. system scatter in the opposite directions. Detecting α-particles allows tagging a neutron and tracing the direction of its movement.

A tagged neutron interacts with the matter of an object under investigation, inelastic process A(n,n'γ)A* results in production of γ-rays with a definite energy that is characteristic of each chemical element. The γ-ray spectrum is recorded and analyzed to determine the elemental composition of the investigated object. Measuring the distribution of time intervals between signals from α- and γ-detectors, one can obtain information on the coordinate of interaction between a neutron and matter nuclei along the neutron trajectory and restore a 3-D image of the object. Selection of events based on the time criterion for (α-γ)-coincidences suppresses the background by more than 200 times, which is due to scattered neutrons, γ-rays and induced activity.

The use of 64-section α-detector positioned inside the neutron generator allows simultaneously producing 64 independent tagged neutron beams that irradiate the object under investigation.

Joint analysis of energy distribution of gamma-rays of characteristic nuclear radiation and time interval distribution between signals from α- and γ-detectors permits both detecting and identifying the type of an explosive in each of 64 regions (voxels) of the irradiated object that correspond to 64 beams of tagged neutrons. Detection and identification of explosives are based on the neural network method and the method of intensity ration of characteristic nuclear radiation peaks of carbon, nitrogen and oxygen.

For more detailed description of the tagged neutron method refer to [1-8].

2. *Deuterium* System

Fig. 2 shows the outward appearance of the Deuterium system inspection unit.

1.

Fig. 2. Outward appearance of the Deuterium system inspection unit

The *Deuterium* system comprises an inspection module and a monitoring module.
The inspection module consists of the following components:

1. ING-27 neutron generator with a built-in 64-element α-detector;
2. Six γ-detectors based on BGO crystal (diameter – 76 mm, thickness - 65 mm);

3. Electronics for data acquisition and analysis;
4. Power supply units of NG, α- and γ-detectors;
5. Inspection unit housing.

The monitoring module incorporates:
1. Personal computer;
2. PC-based interface with a data processing program unit.

The inspection and monitoring modules communicate via the 220 V supply cable, the computer network and control cables. Availability of a standard mobile robot makes it possible to use the system remotely at a distance of up to 150 m from the operator workstation.

3. Neutron Generator

ING-27 portable neutron generator (see Fig. 3) with a built-in 64-element silicon α-detector is developed in All-Russia Research Institute of Automatics (VNIIA, Moscow).

Figure 3. ING-27 portable neutron generator

A neutron generator is an accelerator of deuterons that produce 14.1 MeV fast neutrons in the reaction $d+t \rightarrow \alpha+n$. The important peculiarity of pulsed neutron generators is that they are completely tritium-sealed. It is very significant for convenience of operation and ensuring of radiation safety. The user receives a sealed accelerating tube with a built-in α-detector. The only thing he has to do is to feed it from a standard voltage source. The dimensions of an accelerating tube are $132\times204\times263.5$ mm^3 and the weight – 8 kg. The dimensions of a power supply unit are $351\times276.5\times98.5$ mm^3 and the weight – 4 kg.

The housing of the neutron generator is made of stainless steel in the form of a cylinder ~230 mm in length and 72 mm in diameter. The wall thickness of the housing is 1 mm. The tritium target is a layer of hydride-forming material applied on a metal substrate. The target is positioned in the centre of the end surface of the neutron tube at an angle of 45° to an accelerated ion beam at an angle of 90° to which is positioned α-detector array.

ING-27 neutron generator employed in the *Deuterium* system has the following characteristics:

- maximum neutron flux – 1×10^8 s^{-1};
- neutron energy – 14.1 MeV;
- operating mode – continuous;
- operating temperature range – 10÷45° C;
- ultimate power consumption – 70 W;
- power supply unit dimensions – 351×276.5×98.5 mm;
- life
  - neutron-emitting unit - 800 h;
  - power supply and control unit - 5000 h;
- time of preparation for work – no more than 10 min.

4. Alpha-detector

A silicon semiconductor detector is designed for detecting α-particles with typical energy of 3.5 MeV produced in the reaction d+t→α+n. The advantage of semiconductor detectors resides in the principle of operation – direct conversion of α-particle energy loss in the detector into an electric pulse at the output (signal amplitude at the detector output is proportional to α-particle energy loss in the detector). High mobility of charge carriers and small energy (2÷4 eV) spent on production of a single electorn-hole pair for materials like Ge, GaAs, CdTe, Si make the latter the main materials for manufacture of detectors with high energy resolution. Silicon is the most widespread and best suited semiconductor material for detection of α-radiation. The main advantages of silicon are as follows:

- operation at room temperature (Ge-detectors operate only if cooled);
- high mechanical strength as compared with GaAs, CdTe;
- high quality of present-day silicon monocrystals (homogeneity, large lifetime of charge carriers);
- high-resistant silicon (FZ-float zone Si) is currently commercially available, it costs no more than 2000 $/kg;
- diameter of wafers from manufacturing companies (Wacker, Topsil, Siltronix) is 100 through 150 mm, which makes it possible to manufacture large-area detectors;
- state-of-the-art level of silicon-based detector planar technology allows developing and manufacturing detectors with a thin input window, which ensures high energy resolution (more than 1% for 5.5 MeV α-particles);
- high time resolution of 0,5 ns; radiation resistance of modern planar silicon detectors permits their use without cooling to the fluence of fast neutrons and α-particles of 10^{13} neutron/cm^2 and 10^{12} α/cm^2, respectively.

Fig. 4 shows the outward appearance of 64-channel α-detector of JNRI production.

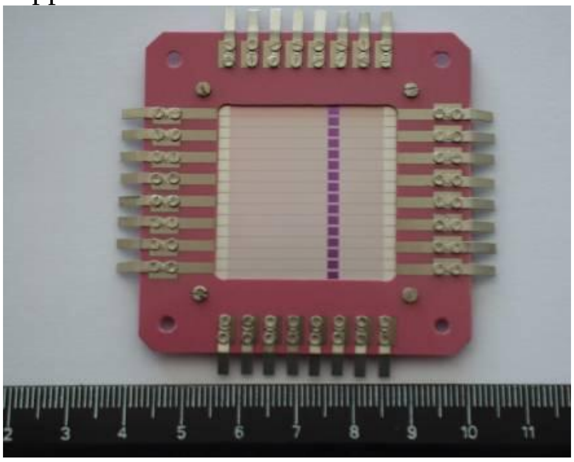


Fig. 4. Outward appearance of 64-channel α-detector

Alpha-detectors are designed as an array of 64 elements that is formed by intersection of two planes with eight strips on each. The total sensitive area of the detector is determined as the product of the element size by the number of strips and equals to 4×8=32 mm. The total sensitive area of 64-element detector is equal to (32×32) mm^2. Signals from 64 elements of the detector are output with the help of 16 contacts on a flange of the NG tube. The amplifier unit is connected to outputs on the NG flange through a 16-contact input connector and is fixed on the NG tube with the help of a ring.

5. Gamma-Quantum Detector

Six BGO scintillation detectors of JNRI production are used for detection of characteristic γ-radiation resulted from the reaction of inelastic scattering (A(n,n'γ)A).

Gamma-ray detectors must posses the following features:

1. Good energy resolution in the 1-12 MeV (8-2,5)% γ-ray energy range, which is critically important for correct determination of line intensities of characteristic γ-radiation of ^{12}C, ^{14}N and ^{16}O;
2. High efficiency of γ-ray detection in the specified energy range that makes it possible to acquire required statistics for identification of hidden substances within short periods of time (~5-10 min);
3. Low sensitivity in relation to background neutron radiation detection.

Time resolution of the system for detection of characteristic γ-radiation in coincidences with signals from α-detectors is 2.9 ns, which meets the requirements to this system.

The γ-detector consists of Hamamatsu R6233 8-diode photomultiplier with Ø76 mm photoelectric cathode and BGO crystal (diameter - 76 mm, thickness - 70 mm). BGO deexcitation time is 300 ns, density – 7.13 g/cm^3, light refraction factor – 2.15.

Climatic tests were carried out using a KTK3000 climatic chamber. The *Deuterium* inspection unit was placed inside the climatic chamber. Signals from the output of the recording electronics unit and NG control unit arrived at the personal computer positioned at the operator workstation.

The main results obtained during the tests: at temperature variation in a range from -20 C to +50°C energy resolution of the γ-detector on the carbon line (Eγ = 4.43 MeV) and time resolution of (α-γ)- coincidences did not vary and amounted on average to 4.7% and 2.9 ns, respectively.

6. Recording Electronics

The recording electronics is designed as a single circuit board the size of a standard PCI card, it can be installed in a PCI-slot of a personal computer and controlled by the latter using a PCI-bus for information exchange. PC enables preprocessing of data read from α- and γ-detectors, generation of data files for transfer via ETHERNET to PC for final processing and presentation of the results.

The system for recording signals from α- and γ-detectors is based on the principle of digitization of a pulse shape and following calculation of pulse time and amplitude characteristics. The program package supported the operation of the recording electronics consists of PCI-interface drivers, event selection and processing program, data file generation program and programs needed for mode adjustment of the electronics unit. To provide the required rate of data transfer via the PCI-bus, the interface operates as a direct memory access channel. This is the main requirement for the driver that supports the operation of this device. As the dedicated data buffer is filled up, the direct access channel is switched over to free storage area and the filled part is processed by the selection and processing program. Processes of recording and processing are carried out in parallel.

The software supported the operation of the electronics unit is controlled by the LINUX operating system.

7. Operator Interface Based on PC with Data Processing Program Unit

The unit for data reception and processing, as well as visualization of the analysis results of time and energy distributions obtained with the help of α- and γ-detectors is intended for displaying the analysis results in the convenient for the user form. The software is controlled by the LINUX operating system and fulfils the following functions:

- performance of a full measurement cycle. The measurement cycle comprises: neutron generator start-up, data acquisition and analysis, decision-making in the automatic mode, visualization of the analysis results and decisions made, neutron generator shutdown, logging of measurement results and archiving of data obtained for the measurement time;
- fault diagnostics of units and systems incorporated in the complex;
- archiving of the made measurements.

The program software is developed as an applied program and a set of service files for storage of settings and protocols. The program code is written in the C++ language with the use of the ROOT package created on the basis of ROOT class set for operation with neural networks. The MySQL package which interface is built in ROOT is used as a database for protocol storage. RS 232 interface is used for interaction with the neutron generator.

8. Power Supply Units of ING-27, Alpha- and Gamma-Detectors

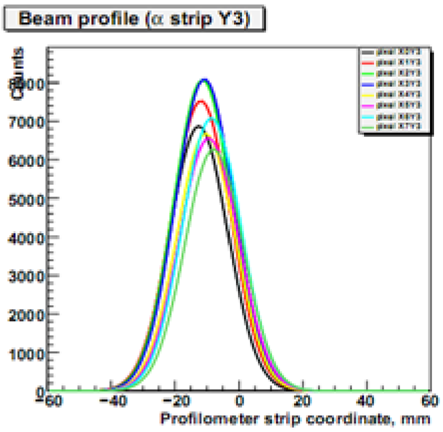
Power supply of α- and γ-detectors is installed in a common crate that is designed in the *Euromechanics-C19* standard. The crate accommodates six power supply units of БВН 2.5*2.5 scintillation detectors and a common power supply unit of БВН-0.5*0.1 16-element silicon detectors. The mentioned units are developed and fabricated at JNRI. High-stability reference signal generators and a detector power source output voltage control unit are also installed in the crate in order to ensure stable operation of the detectors in a wide variation range of their loads and climatic conditions. Correcting signals are delivered to the control unit connectors. ICOP6070LV embedded processing board can be installed for the purpose of specifying stabilization algorithm, logging of operating modes and communicating with the operator main workstation.

9. Neutron Beam Space Distribution

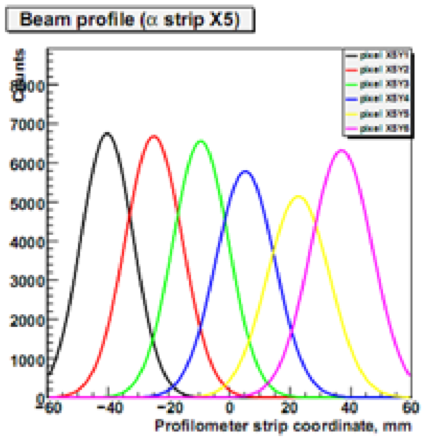
Measurement of space distribution of neutrons in 64 tagged neutron beams was made using a specially developed and fabricated for this purpose device – a profilometer. At a distance of 300 mm from the centre of the tritium target the widths of peaks, corresponding to strips X and Y, amount to 14.6±0.9 и 14.8±1.1 mm, respectively at a half-height in the direction of the X and Y axes.

It should be noted that the measured neutron space distributions coincide in the shape with the calculated distributions for a point deuteron beam.
At the intensity of a neutron flux (I = 4.5×10^{7} neutron/s) the count rate of events, detected by either X or Y strip of an α-detector, averaged by all X and T strips, amounts to ~ $6{,}5\times10^{4}$ s^{-1}.

Fig. 7a shows the distribution of tagged neutron beams detected by profilometer horizontal strips in the presence of coincidence of signals from an α-detector from strip Y3 in turn with signals X0-X7 (strip count from 0). As might be expected, for this combination of signals from an α-detector peak centers of gravity must coincide as this sampling of tagged beams correspond to one and the same strip Y3 of an α-detector.



a)



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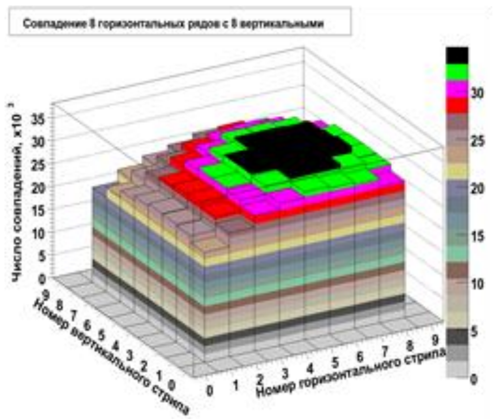

c)

Fig. 7. Distribution of: a) 8 tagged neutron beams along the profilometer vertical axis that correspond to coincidences of signals from an α-detector from strip Y3 in turn with signals X0 – X7; b) tagged neutron beams detected by profilometer vertical strips in the presence of coincidences of signals from an α-detector from strip X5 in turn with signals Y1-Y6 (strip count from 0); c) neutrons (two-dimensional) in the plane XY, perpendicular to the direction of a neutron flux, corresponding to 64 tagged neutron beams

Fig. 7b shows the distribution of tagged neutron beams detected by profilometer vertical strips in the presence of coincidence of signals from an α-detector from strip X5 in turn with signals Y1-Y6 (strip count from 0). For this combination of coincidence signals from an α-detector peak centers of gravity must be spaced along the vertical axis at a distance determined by X5 strip width (4 mm) and ratio of distances from the tritium target to α-detector and to an irradiated object. The measurement results coincide with the calculation results.

Fig. 7c shows two-dimensional neutron distribution corresponding to 64 tagged neutron beams.

10. Testing of the *Deuterium* System

To determine the probability of explosive detection in different places of a car and the probability of false alarms of the explosive identification system, we performed several tests with explosives of different types and different shielding materials.

Explosives were hidden in the trunk and on the back seat of a Land Cruiser. Explosives were irradiated through the trunk and the side door of the car, respectively. The intensity of NG was 4.7×10^{7} s^{-1}. We carried out 20 tests with inserts of hexogen and trinitrotoluene of various mass and in different places of the car: in the trunk and on the back seat. Besides, tests were performed with the use of non-hazardous substances – textile, paper, water, iron, etc. – in order to determine the probability of false alarms of the system for identification of "hazardous" objects.

Explosive mass varied in a range from 200 g to 3.2 kg and a distance from NG to the trunk or a sample on the back seat - from 10 to 50 cm. The identification time varied from 2 to 10 minutes, respectively. 20 tests were performed and during all the tests explosives were detected in the trunk and on the back seat of the car.

Melamine $C_3H_6N_6$ was used a dummy explosive. It was irradiated through a metal barrier that completely shielded a neutron source and γ-detectors. NG intensity was 4.5×10^{7} s^{-1}. A distance from NG to a melamine sample was 300 mm. A distance from HG to a metal barrier was 100 mm. Table 1 presents the thickness of a metal barrier, dummy explosive mass and detection time.

Table 1

Test number	Explosive weight, kg	Steel thickness, mm	Detection time, min
1	3	6	5.3
2	3	12	5.7
3	3	20	5.5
4	1	20	6.3
5	0,2	6	8.5
6	0,2	12	20.0

Conclusion

The Joint Nuclear Research Institute (Dubna) developed and manufactured on demand of RF FSS a *Deuterium* mobile inspection system designed for detection and identification of hidden explosives in mined cars. The system is designed for detection and explosives hidden in cars and explosive charges in cars-bombs. Availability of a standard mobile robot allows using the system at a distance of 150 m from the operator workstation.

The minimum detectable mass of explosives behind 20-mm metal barriers is 0.2 kg.

The operating temperature range of the *Deuterium* system is from -20°C to +50°C at relative humidity of 80%.

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