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ANALYSIS OF RADIATION METHODS FOR EXPLOSIVE MATERIALS DETECTION

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The paper examines the physical aspects of some landmine detection methods based on fast neutron backscattering. An analysis of the reaction products of the interaction of fast, slow, and thermal neutrons with H, C, N, O nuclei, which are part of explosive substances, was carried out. Mainly, to make it clear how to use secondary instantaneous and delayed gamma quanta emitted by the nuclei of explosive substances to achieve an increased detection efficiency. Discussed the physical features of some well-known methods of detecting explosive materials, exploiting elastic and inelastic scattering of fast neutrons. The reaction products of the interaction of fast, slow, and thermal neutrons with H, C, N, O nuclei included in explosives were analyzed. The goal was to simultaneously use both scattered fast and intermediate-energy neutrons emitted by the nuclei of explosives from elastic and inelastic scattering reactions (backscattering), as well as secondary instantaneous and delayed gamma quanta. The most suitable candidate for this role may be gamma-neutron detectors based on oxide scintillators of the *ZWO* type, which are simultaneously sensitive to both fast, slowed, and resonant neutrons, as well as to gamma quanta in a wide range of energies from tens of MeV to hundreds of eV. The using of a low-threshold single-photoelectron mode of photon registration makes it possible to significantly increases the sensitivity of the detection systems.

Keywords: *Neutron backscattering; Landmine detection; Neutron detector; Detection efficiency*

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1. INTRODUCTION

Over the past decade, significant efforts have been made to develop neutron-based methods for the detection of hidden explosives (EXP), and other contraband materials. None of the well-known landmine detection technologies are capable of detecting mines in all applications. Therefore, a combination of several technologies is required. Among a large number of different instrumental analytical detection methods, some nuclear technologies have retained leading positions in solving special problems. For example, the high penetrating ability of fast neutrons and the characteristic gamma rays generated in reactions (n,γ), $(n,n'\gamma)$ and $(n,x\gamma)$ make it possible to carry out multi-element analysis of bulk samples [1]-[10], [37]. Currently, the requirements for technologies that could provide a successful solution to the task of search and identification (EXP) have been developed. Such requirements include: - permeability, i.e. the detection method must ensure the detection and identification of explosives at a great distance from the surface of the object or behind thick barriers; - sensitivity, i.e. the need to ensure the minimum volume and mass of detectable explosives, since modern explosives can be dangerous even in small quantities; - selectivity, since hidden explosives are often found in a large volume of harmless objects and substances; - reliability, as the level of false positives should not be high.

The chemical composition of the substance under investigation. Explosives consist mainly of elements of low and medium atomic mass: hydrogen H, carbon C, nitrogen N, oxygen O, they have a relatively high ratio of nitrogen and oxygen content to the total mass compared to carbon and hydrogen. Therefore, mine identification technology must detect the nitrogen content along with the oxygen content.

When developing explosive detection methods, the assumed chemical composition of both the explosive and the surrounding soil is taken into account. Chemical composition and density of some explosives: trinitrotoluene (TNT), $C_7H_5N_3O_6$, mol. mass = 227.132 g/mol, density up to 1.65 g/cm^3; hexogen (RDX), $C_3H_6N_6O_6$; minor mass = 222.117 g/mol, density up to 1.80 g/cm^3; C-4, composition: RDX, 91%; plasticizer $C_{26}H_{50}O_4$ 5.3%; binder C_4H_8 2.1%; oil $C_{20}H_{42}$ 1.6%, density up to 1.60 g/cm^3; octogen (HMX), $O_8N_8C_4H_8$, mol. mass = 296.156 g/mol, density up to 1.90 g/cm^3 [11].

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Table 1. Mass fractions (in %) of elements H, C, N, O in some substances [11]

	H	C	N	O	Si	N/H	N/C
TNT ($C_7H_5N_3O_6$)	2.22	37.02	18.05	42.26	-	8.34	0.50
RDX ($C_3H_6N_6O_6$)	2.72	16.22	37.84	43.22	-	13.90	2.33
C4 ($C_3H_6N_6O_6$)	3.64	21.75	34.43	40.13	-	9.46	1.58
Saltpeter ($N_2H_4O_3$)	5.04	-	35.00	59.97	-	6.94	-
Urea $(NH_2)_2CO$	6.71	20.00	46.65	26.65	-	6.95	2.33
Polyethylene (C_2H_4)	14	86	-	-	-	-	-
Sand (SiO_2)	-	-	-	53.3	46.7	-	-

When analyzing and developing explosive detection methods, it is also necessary to take into account the chemical composition and density of dry soil in which explosives can be found: O (51.4%), Na (0.614%), Mg (1.31%), Al (6.87%), Si (27.06%), K (1.43%), Ca (5.11%), Ti (0.46%), Mn (0.072%), Fe (5.64%), density up to 2.70 g/cm^3.

The composition of the soil may include the following components: Al_2O_3 - 20%, SiO_2 - 57.2%, K_2O -2.5%, CaO - 2.6%, TiO_2- 1.3%, Mn - 0.08%, Fe_2O_3 - 16.2%, Rb_2O - 0.04%, SrO - 0.05%, ZrO_2 - 0.07%. In addition, data on the composition of dry sand are required: SiO_2 - 90–98%, Al_2O_3 - 1–5%, Fe_2O_3 -0.2–2%, CaO - 0.1–1%, MgO -0.1–0.5%, K_2O -0.1–1%, Na_2O - 0.1–0.5%, grain density 2.60 – 2.65 g/cm^3, bulk density 1.60–1.85 g/cm^3.

When experimentally modeling the processes of interaction of neutrons with explosives, it is possible to use ammonium nitrate, $N_2H_4O_3$, mol. mass = 80.0434 g/mol, density 1.72 g/cm^3, urea $(NH_2)_2CO$, mol. mass = 60.056 g/mol. density 1.32 g/cm^3. To obtain experimental data on the response of fast neutrons, as close as possible to the response of neutrons from TNT, it is possible to use the above-mentioned substances with carbon additives (graphite) as a dummy explosive.

The technology of registering gamma radiation emitted during neutron activation was first described as a process for identifying useful materials in the 1970s.

Nuclear composition of the substance under investigation. The essence of neutron analysis methods is to probe the area of interest with a beam of fast or thermal neutrons, which, due to their neutrality, penetrate quite deeply into the volume of the substance, and then interact with the nuclei of certain atoms (for explosives, this is usually hydrogen (^1H), carbon (^{12}C), nitrogen (^{14}N), oxygen (^{16}O), some soil elements - silicon (^{28}Si), etc., and measure the response value - scattered fast and thermal neutrons, instantaneous and delayed gamma quanta that arise in the substance as a result of the interaction of neutrons with the nuclei of its atoms [12].

Neutron analysis methods. Neutron analysis methods differ:
- by the energy of neutrons in the beam (thermal or fast neutrons, mono energy neutrons or neutrons with a continuous spectrum);
- by type of response (scattered thermal neutrons, backscattered thermal neutrons (shadow method), scattered fast neutrons, gamma radiation from nuclear reactions (radiation capture), gamma radiation from inelastic scattering);
- by to the type of neutron source (impulsive or continuous flow of neutrons, continuous neutron spectrum or mono energy).

Interaction mechanisms. During the process of interaction of neutrons with matter, atomic nuclei are excited and emit gamma radiation and secondary neutrons. It should be noted that neutrons, both instantaneous scattered and delayed secondary ones, can also interact repeatedly both in the substance of the sample and in the substance of the detector and makes a useful contribution to the response of the detector in the form of gamma quanta with energy from approximately 8 - 10 MeV to hundreds of electron volts at the points of neutron scattering from the target nuclei due to inelastic collisions and reactions of resonance and radiation capture.

Registration of gamma radiation in the form of a spectrum or registration of the flow of gamma quanta as a whole, in the counting mode, allows you to detect either the corresponding element or the anomaly of the chemical composition, and the radiation intensity correlates with the amount of the substance present. The key components of this technique are a neutron source, a gamma detector, a spectrum analysis, and a decision-making algorithm.

Types of neutron sources. Neutrons can be obtained in synthesis reactions, for example (d,t), (d,d), reactions using radioisotope sources, for example $^{238.9}Pu-Be$, $^{241}Am-Be$ from $Pu(\alpha,n)^9Be$ reactions, in spontaneous fission reactions (^{252}Cf). In addition, by now, compact accelerators have been created that consume about 100 W of power and generate acceptable flows of fast neutrons.

Types of detectors. As detectors, sensitive gamma-quantum scintillation detectors such as $NaI(Tl)$, BGO, ZWO, $LaBr_3$, $NE-213$, $stilbene$ are used, which allows obtaining reliable results and unambiguously identifying target materials at distances of 0.5 m within 5 minutes. The use of methods of visualization of associated particles simultaneously with the method of labeled neutrons makes it possible to mark the time and direction of neutron movement, which significantly improves the signal/background ratio. If the neutron generator is located within 20-30 cm from the target, the materials can be identified in a few seconds [13, 14, 15].

Limitations of the neutron method. These include the fact that in many work scenarios, the number of sensors covering a small corner of the body is limited, so the speed of the identification process increases to several minutes [12]. It should also be noted that neutrons are emitted isotropically from neutron sources, and gamma quanta are emitted isotropically

from atomic nuclei. Consequently, useful signals (gamma quanta) decrease as $1/r^4$. So, if the neutron source and the gamma detector are moved to double the distance from the target, the signal will drop 16 times. Another characteristic that can increase the time of identification of materials is the mass of the object of interest. As the mass increases, the detection time decreases linearly.

Therefore, the limitations of the methods are the proximity of the target and the system, as well as the detection sensitivity. Despite certain shortcomings and limitations of neutron methods, this method proved to be useful for detecting organic materials hidden from the eyes. The fact is that the general approach to the search for hidden explosives (explosives) at the present time consists in the simultaneous use of several methods of identification, for example, $X - ray$ radiation, electromagnetic radiation, etc. Therefore, the neutron method, due to its high sensitivity, can provide significant help in clarifying both the localization of the object of interest and its chemical composition.

2. INTERACTION OF NEUTRONS WITH MATTER

Neutrons can be obtained in reactions using radioactive sources, for example $Pu(\alpha, n)^9Be$, $Am(\alpha, n)^9Be$, in reactions of spontaneous fission (^{252}Cf). Neutrons are also obtained in synthesis reactions, for example (d, t), (d, d), in electro-nuclear reactions (e, n) using electron accelerators. Neutrons interact with nuclides in different ways, depending on the neutron energy (E_n) and, to some extent, the atomic number (Z). The neutron's lack of charge distinguishes the way it interacts with matter compared to other particles. Scattering (elastic and inelastic), absorption, and neutron and proton emission reactions are important mechanisms that reduce the flow of neutrons when they pass through matter. Neutrons, having reached resonance and thermal energy, are usually absorbed by the nucleus, creating at the same time secondary radiation, which usually consists of gamma quanta and recoil nuclei. In addition, as a result of nuclear reactions caused by neutrons, instantaneous gamma quanta emitted by a composite (compound) nucleus, or delayed gamma quanta from beta decay by an excited finite nucleus, and also, as a rule, electrons of internal conversion appear. The interaction of neutrons with nuclei depends on the energy: slow ($E_n < 0.5eV$) and resonant neutrons ($E_n \sim 0.5eV$–$100keV$), fast neutrons ($E_n \sim 100keV$–$1 - 20MeV$ and higher) [16, 17]. The forms of interaction of neutrons with matter are as follows:
- elastic scattering (n, n). This reaction leads to the slowing down of fast neutrons;
- inelastic scattering $(n, n'\gamma)$. Threshold reaction, neutron energy is spent on the excitation of nuclei, leads to the appearance of "$sloweddown$" fast neutrons, instantaneous and delayed gamma quanta and electrons of internal conversion;
- absorption with emission of gamma radiation (n, γ) - radiation and resonance capture. The reaction is thresholdless. The neutron binding energy is spent on the excitation of compound nuclei and is released through gamma quanta and conversion electrons;
- absorption with proton emission (n, p);
- absorption with nuclear splitting, leaving various fragments (n, r).

In elastic scattering $X(n, n)X$, the loss of kinetic energy during a collision strongly depends on the mass of the target nucleus: if the nucleus is massive, then the incoming neutron practically does not lose energy. Therefore, a hydrogen-rich material such as polyethylene is often used to slow down fast neutrons. In the case of a head-on collision with a proton, the entire momentum of the neutron is transferred to the target nucleus, so the neutron cannot scatter back. Elastic scattering dominates for fast neutrons. Elastic scattering on light nuclei, such as hydrogen nuclei, which form ionization tracks, is usually used to detect fast neutrons. Elastic scattering on the light nuclei of the moderator leads to reactions on thermal neutrons. Heavy nuclei absorb only a small part of the neutron energy.

Inelastic scattering $X(n, n'\gamma)X$ dominates for fast neutrons when the incident (primary) neutron has sufficient kinetic energy (usually more than 100 keV for heavy nuclei and more than several MeV for light nuclei) to excite the target nucleus.

If the reaction proceeds through an intermediate (compound) nucleus ($E < 20 - 50MeV$), then in a very short time it can decay to the ground state ($\tau < 10 - 12s$), releasing all the excitation energy in the form of instantaneous ("$fast$") gamma quanta. But a more likely case is when the neutron energy, without taking into account the reaction threshold, goes to the partial excitation of the nucleus and the formation of a secondary neutron with reduced energy (up to 2-3 MeV).

Inelastic scattering on heavy nuclei leaves, as a rule, finite nuclei in an excited state. Its energy is released in the form of a cascade of instantaneous (fast) and, possibly, delayed gamma rays from final nuclei from the reaction (n, n'g) and electrons of internal conversion. It should be noted that the probability of emission of internal conversion electrons (EC) can be comparable to the probability of emission of gamma quanta, therefore, when modeling the energy response of the detector to fast neutrons, it is important to take EC into account. The secondary fast neutron with reduced kinetic energy continues to interact with the surrounding nuclei, generating additional gamma quanta in the capture reaction. Compound nuclei (intermediate) emit instantaneous gamma rays. The total energy of these instantaneous gamma quanta can be comparable to the excitation energy of the nucleus and, in the case of a slow detector path, can be recorded by hardware as one high-energy pulse. Final nuclei, in turn, also emit both instantaneous and delayed gamma rays, which have different energies and are useful in the identification process.

Radiation capture of neutrons by nuclei $A(n, \gamma)A + 1$, i.e. the formation of radionuclides (isotopes) mainly occurs when the neutron has resonant or sufficiently low energy. Neutron capture is an exponential process that indicates the inelastic nature of scattering as the dominant mechanism. When a neutron is captured, both instantaneous and delayed gamma quanta arise from the excited nucleus. It is also possible that, as a result of beta-decay of the final nucleus,

additional delayed and isomeric gamma quanta from excited compounds of the daughter final nucleus may occur.

The reaction of radiation capture of a neutron by a proton ($n + p- >^2 H + \gamma$), despite the absence of excited states in the deuteron, occurs with the emission of a high-energy photon with energy $E_\gamma = 2.225\ MeV$, equal to the binding energy of the deuteron and the formation of a bound neutron-proton system (deuteron) in the final state. It is also useful for identifying slow neutrons. That is, hydrogen acts as a moderator and absorber of neutrons. Note that the effect of neutron-proton momentum transfer during s-scattering is used in the shadow method of detecting explosives, when there is a complete absence of thermal neutron scattering at an angle of 180° [8].

Direct detection of neutrons is complicated by the fact that these interactions are most often measured in more complex environments (methods), which include reactions with the emission of gamma quanta and alpha particles.

3. NUCLEAR REACTIONS USED IN THE DETECTION OF EXPLOSIVES

The following reactions are used to detect slow (thermal) neutrons [3, 12, 13, 18, 19, 20, 21, 22]:

$$^1H(n,\gamma)^2H,\ Q = 2.225MeV; E_\gamma = 2.225MeV; \tag{1}$$

$$^3H(n,p)^3H, Q = 0.764MeV, \sigma_{tot} = 5.328kb; \tag{2}$$

$$^6Li(n,\alpha)^3H, Q = 4.783MeV, \sigma_{tot} = 0.9404kb; \tag{3}$$

$$^{10}B(n,\alpha)^7Li, Q = 2.789MeV; E_\gamma = 478keV; \sigma_{tot} = 3.837kb, Q = 2.31; \alpha - thread; \sigma(1eV) = 1kb; \sigma(10MeV) = 2b; \tag{4}$$

$$^{12}H(n,\gamma)^{13}C_*, E_\gamma = \ 1 - 5MeV; \tag{5}$$

$$^{14}H(n,\gamma)^{15}N_*, E_\gamma = \ 1 - 10MeV; \tag{6}$$

The following reactions are used to detect fast neutrons [3, 12, 13, 18, 19, 20, 21, 22]:

$$^1H(n,p)^1H, \sigma_{tot} = (4.5MeV) = 3.85b. \quad \sigma_{tot}(14MeV) = 3.9b; \tag{7}$$

$$^1H(n,\gamma)^2H, \sigma_\gamma = (4.5MeV) = 25ub. \quad \sigma_\gamma(4.5MeV) = 14ub; \tag{8}$$

$$^6Li(n,\alpha)^3H, Q = 4.783MeV; E_thr = 0MeV; \sigma_{tot}(4.5MeV)\ 0.0975b; \sigma_{tot}(14MeV) = \ 0.06–0.08b \tag{9}$$

$$^{12}C(n,n'\gamma)^{12}C^*, E_thr = 4.8130MeV; E_\gamma = 4.438MeV; \sigma_{tot}(4.5MeV)\ 0.1b; \sigma_{tot}(14MeV) = 0.421b \tag{10}$$

$$^{14}N(n,n'\gamma)^{14}N^*, E_\gamma = \ 5.1MeV; \sigma_\gamma = 0.103b; \sigma_{tot}(14MeV) = 0.3664b \tag{11}$$

$$^{16}O(n,n'\gamma)^{16}O^*, E_\gamma = 6.129MeV; \sigma_\gamma = 2.785b; \sigma_{tot}(14MeV) = 0.5084b \tag{12}$$

4. PARAMETERS OF NEUTRONS AND SECONDARY GAMMA QUANTA USED IN THE DETECTION OF EXPLOSIVES

The interaction of fast neutrons with hydrogen, oxygen, carbon and nitrogen, which are part of most explosives, creates gamma-neutron responses (signatures), which are registered with the help of separate gamma- and neutron detectors [19, 20, 21, 22, 23, 24]. The quality of identification depends on the intensity of the signal from the explosive substance compared to the background signal, that is, on the signal/background ratio. The signal/background ratio depends on such parameters as the distance, the mass of the explosive, as well as the sensitivity (efficiency and size) of the detector.

In addition to recording neutrons and gamma quanta with separate detectors, it is possible to use oxide scintillators as a universal gamma-neutron detecting device that combines the properties of a neutron detector and a gamma detector [15]. Neutrons in this approach are registered due to their conversion into secondary cascades of gamma quanta from the reactions of inelastic scattering and resonance capture. At the same time, the high efficiency of registration is achieved due to the absence of an intermediate moderator, which is used in traditional devices for registration of fast neutrons. The effectiveness of the deceleration, as a rule, does not exceed $\sim 5 - 6\%$.

A further significant increase in the calculated efficiency of fast neutron registration is possible when using the single-electron registration mode of the detecting photomultiplier (PMT). This PMT mode makes it possible to significantly reduce the threshold of registration of low-energy secondary gamma quanta, which arise during the interaction of secondary resonant and slowed down neutrons in the scintillator substance.

In Tab. 2 shows the parameters of nuclear reactions with neutrons on the most relevant elements of explosives hidden in the ground and of interest for the detection/identification of explosives [19, 20, 21, 22, 23, 24]. The energies of secondary gamma quanta arising in nuclear reactions with fast and thermal neutrons are also given.

Table 2. Parameters of the products of nuclear reactions with neutrons

Element	Reaction	E_γ, keV	σ_γ, b, [23, 24]	$\sigma_{\gamma,tot}$,b,[23]	σ_n,b,[22]	Neutron
H	1H(n, n)1H				0.6876	Elast(14 MeV)
	1H(n, γ)2H	2223.248	0.3326	0.3326	0.332	Thermal
					0.1495	Resonance
					2.956E-5	Fast (14MeV)
C	12C(n, n)12C				0.8192	Elast(14MeV)
	12C(n, γ)13C*			0.00351	0.00386	Thermal
	-//-				0.00177	Resonance
	-//-				1.1567E-4	Fast (14MeV)
	-//-	1261.765	0.00124			Thermal
	-//-	3683.920	0.00122			-
	-//-	4945.301	0.00261			-
	12C($n, n'\gamma$)12C*	4438.03	0.1847 (5MeV)			
0.31(10MeV)		0.4207	Fast (14MeV)			
	-//-	3214.83	0.0009			-
N	14N(n, n)14N				0.9697	Elast (14MeV)
	14N(n, γ)15N*			0.0795	0.0750	Thermal
	-//-				0.03368	Resonance
	-//-				1.7140E-5	Fast (14MeV)
	-//-	1884.821	0.0147			Thermal
	-//-	3531.981	0.0071			-
	-//-	3677.732	0.0115			-
	-//-	5269.159	0.0236			-
	-//-	5297.821	0,0168			-
	-//-	5533.395	0.0155			-
	-//-	5562.057	0.0084			-
	-//-	6322.428	0.0145			-
	-//-	8310.16	0.0033			-
	-//-	10318	-			-
	-//-	10829.12	0.0113			-
	14N(n,n'γ)14N*				0.3664	Fast (14MeV)
	-//-	729.6	0.0562			-
	-//-	1634.6	0.3136			-
	-//-	2312.8	0.468			-
	-//-	2792.5	0.02668			-
	-//-	3384	0.05148			-
	-//-	3949.9	0.01685			-
	-//-	5104.6	0.10296			-
O	16O(n, n)16O				0.9566	Elast(14MeV)
	16O(n, g)17O*			1.90E-4	1.6991E-4	Thermal
	-//-				1.5829E-4	Resonance
	-//-				2.8349E-5	Fast (14MeV)
	-//-	870.68	1.77E-4			Thermal
	-//-	1087.75	1.58E-4			-
	-//-	2184.42	1.64E-4			-
	16O($n, n'\gamma$)16O*				0.5084	Fast (14MeV)
	-//-	1983.0	0.468		-	-
	-//-	5618	-		-	-
	-//-	6129.3	2.785		-	-
	16O(n, p)16N*	7̃120	-		0.0421	-
Si	28Si(n, n)28Si				0.6619	Elast (14MeV)
	28Si(n, γ)29Si*			0.172	0.169	Thermal
	-//-				0.0818	Resonance
	-//-				6.631E-4	Fast (14MeV)
	-//-	1273.349	0.0289			Thermal
	-//-	2092.902	0.0331			-
	-//-	3538.966	0.1190			-
	-//-	4933.889	0.1120			-
	-//-	6379.801	0.0207			-
	-//-	7199.199	0.0125			-
	28Si($n, n'\gamma$)28Si*	1778.8	0.468		0.5224	Fast (14MeV)
	-//-	2837.9	0.01264			-
	-//-	3199.9	0.00468			-
	-//-	4496.3	0.00393			-

5. NEUTRON METHODS USED IN THE DETECTION OF EXPLOSIVES

To date, a significant number of techniques using neutron methods have been developed for the search and identification of explosives in the environment of bulk soil [1]-[10], [37]. These include the following:

- TNA - thermalized neutron analysis [1, 2, 5, 6, 7, 9, 10, 18, 26, 27, 28, 37, 38, 39];
- FNA, (NRA) - fast neutron analysis [1, 2, 4, 5, 7, 9, 10, 12, 18, 26, 37, 38, 39];
- PGNAA, (PGAA)- Prompt Gamma-Neutron Activation Analysis [3, 4, 7, 9, 10, 12, 18, 25, 31, 34, 39];

- PFTNA - Pulsed Fast-Thermal Neutron Analysis [1, 2, 3, 4, 6, 7, 12, 31, 38, 39];
- PFNTS - Pulsed Fast Neutron Transmission Spectroscopy [1, 3, 12, 38];
- PFNA- Pulsed Fast Neutron Analysis [1, 2, 3, 4, 6, 12, 29, 36, 37, 38];
- FNSA - fast neutron scattering analysis [4, 29, 32, 33, 35, 38];
- MNBRP - Monoenergetic Neutron Backscattering with Resonance Penetration [7, 8, 33, 39];
- API - Associated Particle Imaging [1, 2, 3, 4, 37];
- EBS – elastically backscattered spectrometry [31, 35];
- NBS (FNBS, FNB, FNS) - Neutron Back Scattering [32, 33, 34];
- NRA - Neutron Resonance Absorption [1, 2, 4, 7, 32, 37].

In Table 3 shows the characteristics of the main methods of material analysis using neutron radiation [1].

1. TNA - *Thermalized Neutron Analysis*. [1, 2, 5, 6, 7, 9, 10]. The main mechanism of interaction is the radiation capture reaction (n, γ), which uses instantaneous gamma quanta that arise when activated by slowed down $(< 0.025eV)$ neutrons. Thermal neutrons fall on the inspected object, and the gamma radiation obtained as a result of capture provides information for detection. The measured spectra of gamma rays are related to the number of incident neutrons and known capture cross sections (velocities) for the corresponding nuclides, which allows determining the concentration of elements in the irradiated sample. The use of TNA for the detection of explosives is mainly based on the identification of nitrogen (N) and hydrogen (H) contained in most explosives [1]. Two reactions of delight:

$$^{14}N + n_{thermal} \sim^{15} N + \gamma\,(5.27MeV, 10.83MeV) \tag{13}$$

$$^{1}H + n_{thermal} \sim^{2} H + \gamma\,(2.223MeV) \tag{14}$$

generate energetic (”fast”) γ-rays, which are registered by detectors and analyzed tomographically to obtain the spatial distribution of nitrogen (N) and hydrogen (H) density. A typical TNA spectrum of a metal land mine in sand is shown in Fig.1. The full energy peak, the first and second peaks of the 10.835 MeV nitrogen gamma radiation leakage (N) are not fully resolved, and an exponential slope due to the summation of events with lower energy is observed in the lower part of the region of interest (ROI) window [18, 26, 27, 28, 37, 38, 39].

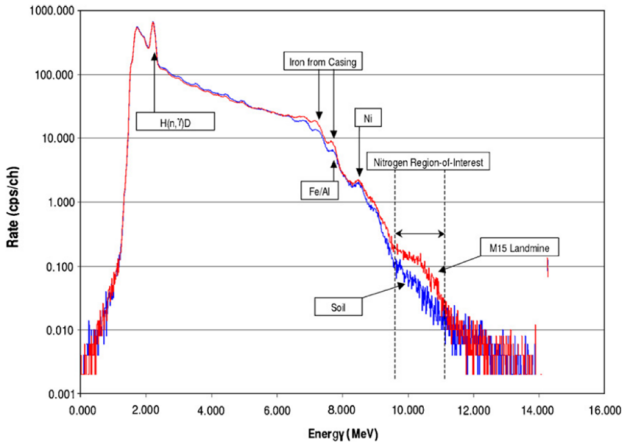

Figure 1. Gamma spectrum of an anti-tank mine in the soil (red upper curve). The mine has a steel case and contains approximately 3.6 kg of nitrogen equivalent. Also shown is the spectrum without the mine (blue lower curve) [27].

2. FNA - *Fast neutron analysis* [1, 2, 4, 5, 7, 9, 10]. The main mechanism of interaction is the reaction of inelastic scattering (n, n’γ). This method approach is very similar to TNA, but it involves bombarding the object under inspection with a collimated beam of continuous fast neutrons, usually from a neutron generator. Nuclei in the sample are excited as a result of inelastic collisions to certain low-level nuclear states, which decay with the emission of discrete gamma rays. Strong gamma transitions, which can be excited by fast neutrons $(E_n \sim 8MeV)$ in nuclides, are important for the detection of ^{1}H, ^{12}C, ^{14}N, ^{16}O nuclei. Particular attention should be paid to the absence of low-lying levels $(< 5MeV)$ in ^{16}O. The attenuation of fast neutrons inside the object is much less than the attenuation of thermal neutrons, which allows obtaining a better image reconstruction than when using the TNA method. Limitations of the fast neutron scattering (FNA) method include a high background and relatively low visualization capabilities of large objects [12, 18, 26, 37, 38, 39].

3. PFNA - *Pulsed Fast Neutron Analysis*. The method was developed with the aim of removing restrictions on the possibility of visualization of large objects. The main mechanism of interaction is the reaction of inelastic scattering $(n, n'\gamma)$. The nanosecond pulse generation method of incident neutrons and the neutron time-of-flight method are used. The deuteron accelerator with an energy of 5.5 MeV generates nanosecond $(\tau \sim 1-2\,ns, f\ 10MHz)$ neutron beams with an energy of about 8 MeV, which are collimated and directed to the scan. Neutrons produced in inelastic scattering processes

Table 3. The main characteristics of some methods of analysis of explosive materials using neutron radiation [1]
[1]ENG: Electronic Neutron Generator – can be based on neutron production processes such as $(d,D),(d,T),(d,Be),(p,Li)),(p,Be)$.
[2]SNM: Special Nuclear Materials – e.g., fissile isotopes ^{235}U, ^{239}Pu.
[3]TOF: Neutron Time of Flight method.

#	Technique Name	Probing Radiation	Main Nuclear Reaction	Detected Radiation	Sources	Primary and Secondary Detected Elements
1	TNA, Thermalized neutron analysis	Thermalized neutron	(n,γ)	Neutron capture γ-rays/promt and delayed neutrons, γ-rays for SNM^2	^{252}Cf, also accelerator based sources (ENG^1)	Cl, N, SNM^2, H, Metals, P, S
2	FNA, Fast neutron analysis	Fast (high energy, usually 14 MeV) neutrons	$(n,n'\gamma)$	γ-rays produced from inelastically scattered neutrons	ENG^1 based on (d,T)	O, C(N), (H)Cl, P
3	FNA/TNA	Pulsed neutron source, fast neutrons during the pulse, thermal neutrons between pulses	$(n,n'\gamma)$ + (n,γ)	During pulse (FNA), after pulse (TNA)	us pulsed ENG based on (d,T)	N, CL, SNM, H, C, O, P, S
4	PFNA (ns Pulsed fast neutron analysis)	Nanosecond pulses of fast neutrons	$(n,n'\gamma)$	Like FNA w / TOF^3 / prompt and delayed neutrons, γ-rays from SNM	ns pulsed (d,D) accelerator with E_d 6 MeV	O, C, N, Cl, Others, SNM
5	API (Associated particles inspection)	14 MeV neutrons in coincident with the associated α-particles	$(n,n'\gamma)$	Like FNA in delayed coincidence with α	(d,T)	H, Metals, Si, P, S, Others
6	NRA (Neutron resonance absorbtion)	Nanoseconds pulsed fast neutrons (0.5-4 MeV), broad energy spectrum	(n,n)	Elastically and resonantly scattered neutrons	Accelerator based ns pulsed (d,Be) or (d,D) w/angular correlation, with $E_d \geq 4$ MeV	O, C, N, Metals

are recorded in an array of $NaI(Tl)$ crystals and sorted by energy and time of registration relative to the neutron pulse, resulting in a spectrum of neutron energies. Gamma rays produced in the process of inelastic scattering are registered by an array of $NaI(Tl)$ crystals and sorted by energy and time of registration relative to the neutron pulse, resulting in a

three-dimensional image of the object under study, Fig.2.

The PFNA technique is used to detect explosives and drugs in passengers luggage, as well as to determine the characteristics of hazardous and nuclear materials transported in containers. On Fig.3 shows the gamma radiation spectrum of PFNA, measured with the NaI(Tl) detector for a sample of the $C-4$ type explosive simulator. Characteristic peaks associated with inelastic gamma rays such as ^{12}C, ^{14}N, ^{16}O are clearly visible. Intense lines of nitrogen and oxygen indicate the presence of an explosive substance. The content of hydrogen (H) in the object under study is not directly measured using this technique [1, 2, 3, 4, 6, 12, 29, 36, 37, 38].

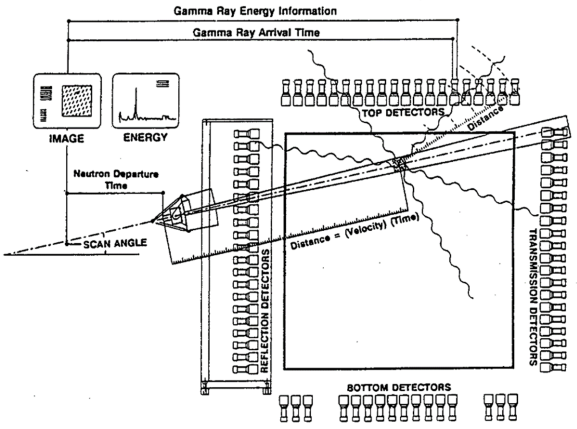

Figure 2. Schematic representation of cargo inspection system based on fast neutron pulse analysis (PFNA) [1].

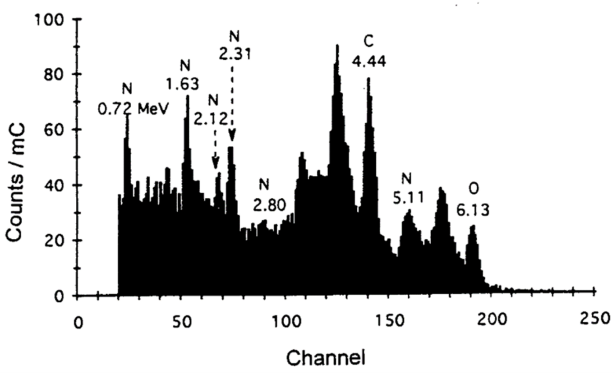

Figure 3. The energy spectrum of gamma radiation measured by the PFNA method with the help of a NaI(Tl) detector for a sample of a $C-4$ explosive simulator. The gamma lines indicated are ^{16}O (6.13 MeV), ^{12}C (4.44 MeV), and ^{14}N (0.72, 1.63, 212, and 2.31 MeV). A weak line of 2.80 MeV associated with ^{14}N is also indicated. The 5.11 MeV ^{14}N line merges with the second leakage peak of the 6.13 MeV ^{16}O line.

4. PGNAA - *Prompt Gamma-Neutron Activation Analysis*, often called thermal neutron analysis, is an isotopic or elemental radioanalytical method. PGNAA is based on the reaction of radiation capture of neutrons (n, γ) - a fundamental nuclear reaction that occurs on every isotope except ^4He. PGNAA is an effective method of non-destructive multi-element analysis of samples such as metals, coal (minerals), cement and radioactive materials, as well as explosives, chemical warfare agents, various drugs, land mines, etc. This method can be used in the laboratory or for on-site analysis of various samples. Thanks to this nuclear reaction, PGNAA stands out among other analytical methods due to several special advantages. This is not only a non-destructive multi-element analysis, which simultaneously analyzes all elements, but also allows for instant measurements, regardless of the state of the sample substance and without any sample preparation. In addition, it is possible to analyze entire arrays of samples, and the measurement results are not limited to the surface of the sample. The method has a wide dynamic range and is characterized by the ability to measure light elements, especially hydrogen (H). PGNAA is a unique method that allows you to determine even trace amounts of H [3, 4, 7, 9].

PGNAA, which has a wide range of applications, has shown great potential in detecting plastic mines. The detection of buried mines using the PGNAA method consists in irradiating the ground with neutrons to activate the elements. Then the sample emits gamma rays by means of (1) instantaneous emission of gamma rays as a result of de-excitation of nuclei, (2) emission of gamma rays as a result of short-lived beta decay, or (3) instantaneous emission of gamma rays as a result of exoenergetic nuclear reactions. On Fig. 4 The schematic diagram of the PGNAA system [Im] is presented.

The detection of instantaneous gamma rays produced in (n, γ) and ($n, n'\gamma$) reactions in hydrogen ^1H (E_γ=2.223 MeV), oxygen ^{16}O (E_γ=6.129 MeV), carbon ^{12}C (E_γ=4.438 MeV) and nitrogen ^{14}N, which is much greater in mines than in soil (E_γ=10.8 MeV), shows the probability of the presence of buried mines in this area. Since the neutron capture cross section (n, γ) on ^{14}N increases with decreasing neutron energy, the optimal geometry of the moderator, which leads to the maximum flow of thermal neutrons, certainly increases the efficiency of this method. In most cases, activation systems are not considered portable and are usually installed at customs terminals.

Several types of neutron sources can be used for PGNAA: nuclear reactors, radioisotope neutron sources such as ^{252}Cf or $^{241}Am-Be$, 14 MeV neutron generators, or accelerators. Pulsed neutron sources can be used in PGNAA systems. The development of small-sized neutron generators made it possible and expanded the scope of application, since a stationary nuclear reactor is no longer an indispensable element in PGNAA. However, the use of pulsed neutron generators without the advantages of a pulsed mechanism is ineffective. Since the nuclear reactor (including the moderator system) produces the highest flux among these sources, it provides the highest analytical sensitivity and is the preferred source.

The most noticeable advantages of using PGNAA methods are non-destructive and direct measurement, since neutrons and γ-rays have high penetrating properties. This radioanalytical method also allows for rapid and simultaneous

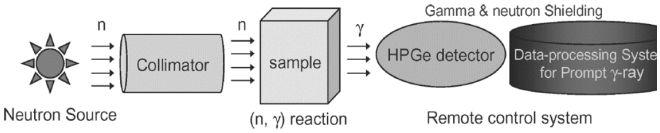

Figure 4. Schematic diagram of the PGNAA system [Im]

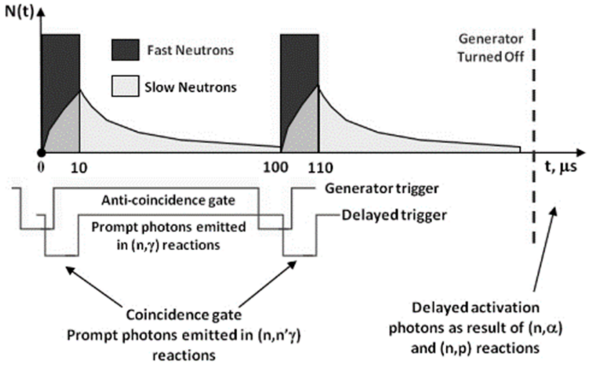

Figure 5. Schematic diagram of the PFTNA system[Im]

analysis of a large number of different elements. In addition, the entire detection system can be built as a mobile system due to the use of small neutron generators. In PGNAA, hydrogen has one fast gamma peak at 2.223 MeV. Therefore, determining the hydrogen content in various materials is quite simple [10, 12, 18, 25, 31, 34, 39].

5. PFTNA (TNA/FNA) - *Pulsed Fast-Thermal Neutron Analysis*. This is a combined method that combines the measurement of γ-radiation and the interaction of fast and thermal neutrons with substance nuclei [1, 2, 3, 4, 6, 7, 12, 31, 38, 39]. The main mechanisms of interaction are reactions of radiation capture and inelastic scattering (n, γ) + $(n, n'\gamma)$. PFTNA is used in conjunction with portable neutron generators. Unlike PFNA, which has a pulse duration of about 2 ns, PFTNA uses pulses with a minimum duration of $\tau_{min} \sim 5 - 10us$. Long pulse duration significantly reduces the cost of PFTNA systems. The PFNA system can be used in the "macropulse" mode, in which the neutron beam is turned off for a period of 100 us. This "macropulse" mode imitates the mode of the PFTNA system.

The advantage of PFTNA systems is the ability to separate the gamma radiation spectrum of inelastic scattering reactions $(n, n'\gamma)$ from the gamma radiation spectra of thermal neutron capture reactions (n, γ) and activation reactions (for example, (n, p)). The data acquisition system collects data during a neutron pulse at one memory address, and then switches to another memory address to collect data between pulses. The data collected during the pulse mainly refer to the $(n, n'\gamma)$ reactions, and the data collected between the pulses mainly refer to the (n, γ) reactions. PFTNA pulses usually have a duration of 10 us with a pulse frequency of 10 kHz. The scheme of the PFTNA with the temporal structure of the neutron pulse is shown in Fig.5.

6. PFNTS - *Pulsed Fast Neutron Transmission Spectroscopy* - (neutron spectroscopy), the same pulsed transmission spectroscopy with fast neutrons — a technique that examines the resulting spectrum of neutrons, not the spectrum of gamma radiation [1, 3, 38]. In this technique, a wide energy beam of neutrons is directed at the array neutron detectors. The investigated object passes through the beam, and the resulting the attenuated spectrum of neutrons is measured with the help of neutron detectors. This method is similar to the method that researchers use to measure cross sections of neutrons. The pulsed nature of PFTNS allows the system to perform time measurements a flight of neutrons. These time-of-flight measurements are used to determine energy of neutrons with a flight path from 4 to 10 m. The resulting spectrum of neutrons is used to estimate the attenuation of neutrons as a function of energy. Light elements such as H, C, N and O have high cross sections for attenuation of neutrons at these energies. Thus, it is possible to determine relative quantities of H, C, N and O, and it becomes possible to "visualize" elements Due to high neutron fluences and the need for accurate timing for PFTNS, this system requires an accelerator similar to that used in PFNA. PFTNS was proposed as a security inspection system airlines.

7. API - *Associated Particle Imaging*. Field analysis methods of neutrons scattered in certain directions, visualization of associated particles by the method of labeled neutrons are also being developed [1, 2, 3, 4, 37]. The main mechanism of interaction is the reaction of inelastic scattering $(n, n'\gamma)$. In associated particle imaging (API), the final nucleus, such as an alpha particle from a d-t reaction, is used to determine the time of flight and direction of the neutrons. In addition, the signal-to-noise ratio for gamma spectra from the $(n, n'\gamma)$ reaction can be significantly improved by measuring the gamma signals emitted only from the selected volume. However, the application of this technique will not affect the signal-to-noise ratio (SNR) of gamma radiation spectra (n, γ) or gamma radiation spectra with an activation delay. The scheme of the API technique is shown in Fig.6 The $d - t$ fusion reaction produces an alpha particle and a fast neutron of 14.1 MeV, which are emitted in opposite directions due to conservation of linear momentum.

A segmented alpha detector, installed inside the hermetic tube of the neutron generator, is used to detect the position and time of the alpha particle event to "mark" the direction of the 14.1 MeV neutron. The geometry of the segments of the alpha detector and the time of flight of neutrons determine the geometry of "voxels" for three-dimensional analysis. A $ZnO(Ga)$ detector was used as an alpha detector. Flashing time $\sim 3.3ns$. The data collection system is configured to generate a logic signal when both events (detection of an alpha particle and a photon) are registered within a short time interval - a "coincidence window". This logic signal is used to select those gamma radiation signals in the energy spectrum that come from the marked voxel. The width of the coincidence window and the neutron flux are interrelated:

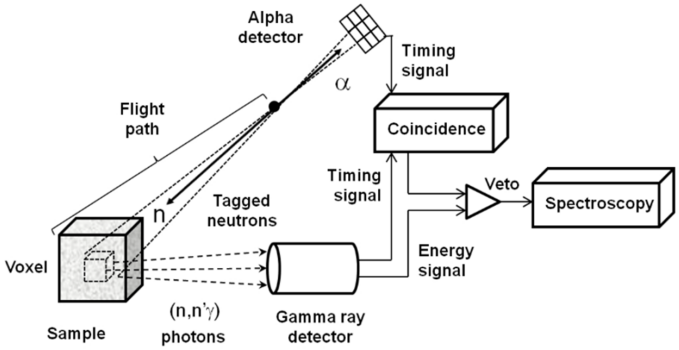

Figure 6. Method of visualization of bound particles [3]

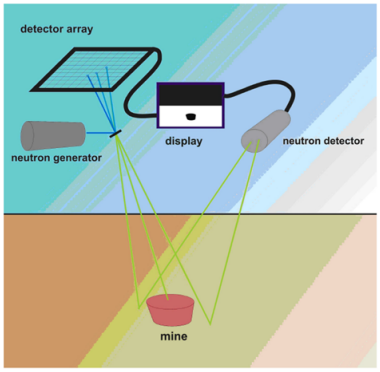

Figure 7. Schematic representation of the device for detecting mines using MNBRP

the frequency of random coincidences increases with the growth of the neutron flux, which limits the neutron output of the generator [3].

8. The MNBRP - *Monoenergetic Neutron Backscattering with Resonance Penetration* method is based on the kinematic property of ^1H not to scatter neutrons in the opposite direction [7, 8, 33, 39]. The method allows detection of hydrogen anomalies in the soil by irradiating the soil with a neutron beam and analyzing the quality of backscattered neutrons. The method uses monoenergetic neutrons. To obtain a shadow image of a buried object containing hydrogen, the following components are required: – monoenergetic neutrons; – backscattering; – the time-of-flight method (split by time) to suppress the background; – method of bound particles to facilitate the visualization of an object containing hydrogen; – resonant penetration for deeper scanning. Figure 7 shows the scheme of the proposed device for detecting mines. It consists of a neutron generator, an array of detectors for the detection of bound charged particles, detector shielding and collimation (not shown), a neutron detector and a visual display of the shadow image. The sensitivity of the method is due to the fact that neutrons are not backscattered from ^1H, an important component of all explosive substances. Thus, when hydrogen is present in an object surrounded by backscattering material, the backscattered monoenergetic neutron flux is suppressed. Thus, it is possible to obtain a shadow image of an object containing hydrogen.

The displacement of the soil by the mine leads to the formation of a volume that does not contain the components of the soil, but contains the components of the mine. The elastic backscattering of neutrons from the volume of a mine is very different from the scattering from a volume of soil of the same size, both in terms of neutron intensity and energy. The components of explosives have low mass numbers, which leads either to the complete absence of backscattering of neutrons (hydrogen), or to the backscattering of neutrons with very low energy (carbon, nitrogen, oxygen in a high energy range). The components of explosives have low mass numbers, which leads either to the complete absence of backscattering of neutrons (hydrogen), or to a noticeable weakening of the energy of backscattered neutrons (Table 4) [7, 39]. Thus, the number of backscattered neutrons with higher energy less in the presence of an explosive substance,

Table 4. Properties of neutrons with an energy of 2.35 MeV scattered at 150° from some isotopes [8]

Isotope	Energy fraction	Energy, MeV
1H	0	
12C	0.730	1.715
14N	0.764	1.795
16O	0.790	1.857
28Si	0.874	2.054
41Ca	0.912	2.143
56Fe	0.935	2.197
	1.00	2.350

which leads to the formation of a "shadow" for backscattered neutron radiation with higher energy. Since the shadow arises due to the difference in scattering from two spaces of the same volume (determined by the collimation of the source and selected in the time domain), the magnitude of the measured effect does not depend on the depth of the mine, i.e., on the thickness of the soil cover above this volume. The depth limitation lies only in the relative intensity of detected neutrons, which decreases exponentially with depth.

9. NRA - *Neutron Resonance Absorption method*. One of the obvious ways to use neutrons is to analyze their energy and scattering angles after interaction in the region of interest [1, 2, 4, 7, 32, 37]. The main mechanism of interaction is the reaction of elastic scattering (n, n). Neutron resonance analysis (NRA) is another method of analysis that requires neutrons of variable energy (white spectrum). Neutron energy is measured using short (ns) pulses to distinguish the time

between pulses. To carry out this analysis of the (n, n) reaction, a powerful source of neutrons is required.

To date, two methods of using neutron scattering to detect mines have been developed. Both methods are based on a sufficiently high content of hydrogen in almost all known explosives. Thermalization of neutrons with hydrogen is used in HYDAD (HYdrogen Density Anomaly Detection) systems, developed for the detection of small (less then 300 g) anti-personnel mines (APM) of plastic construction. Explosive substances contain low-mass elements for which neutrons have a high interaction cross section. The main component of explosives is hydrogen, ^1H. Therefore, the detection of a hydrogen anomaly in some soils is a reliable indicator of the presence of buried explosives. Examination of the soil with the help of a neutron beam and analysis of the quality of backscattered neutrons gives information about the anomalies of hydrogen in the soil. For this, two main properties of ^1H are used:
1. The energy loss of elastically scattered fast neutrons is maximal when neutrons are scattered by ^1H nuclei gives information about hydrogen anomalies in the ground;
2. At the same time, multiple scattering leads to the fact that neutrons acquire thermal energy, resulting in the formation of (backscattered) thermal neutrons that are easy to detect and identify. Using a "white" source of neutrons, thermalization of neutrons by multiple elastic scattering in hydrogen can be measured using a neutron detector, which is insensitive to fast neutrons, but very sensitive to low-energy neutrons (thermal neutrons). This method is usually called the neutron backscattering method.

Single elastic scattering from ^1H occurs with a maximum scattering angle of 87° [8], since the mass of a proton is less than the mass of a neutron. Thus, fewer fast neutrons are backscattered from the soil if an object containing hydrogen is buried in it. It is possible to measure the decrease in the flow of neutrons with the highest energy of backscattering, emanating from the soil components. In principle, backscattering from other light components of explosives, such as nitrogen and carbon, can also be measured. Oxygen is not suitable, since there is a lot of it in typical soil.

When the neutron energy is chosen in such a way that attenuation in the soil is minimal, this method is called MNBRP (monoenergy backscattering of neutrons with resonant penetration).

10. FNSA - *Fast neutron scattering analysis* is an approach that detects neutrons scattered from the material under study. The main mechanism of interaction is the reaction of elastic (n, n) and inelastic $(n, n'\gamma)$ scattering. The nuclides responsible for scattering are determined by measuring the dependence of the intensity and energy of the scattered neutrons on the scattering angle and energy of the incident neutrons. The FNSA method [4, 29, 32, 33, 35, 38], consists in the fact that the processed material sample is bombarded with a beam of monoenergetic neutrons, the energy of the incident neutrons alternates between two carefully selected values, and two detectors are used to observe the scattered neutrons: one detector is positioned at a forward angle (45°), and the other at a backward angle (150°). The pulse height resolution of neutron detectors should ideally, but not necessarily, be sufficient to resolve small energy differences (4%) between neutrons backscattered by elements C, N, and O. Time-of-flight can also be used to resolve large energy differences, for example, to separate elastically and inelastically scattered neutrons. Measurements obtained with the help of two detectors at two different energies of incident neutrons are combined to form a "scattering signature". The FNSA method is based on the assumption that the relative intensities of the H, C, N, and O signatures will be proportional to the atomic shares of the corresponding elements in the scatterer. It was shown that with the help of the FNSA method, atomic fates of elements in a small sample (0.2±0.8 kg) of $HCNO$ material can be measured with an accuracy of several percent and that explosive substances can be reliably identified based on these measurements. An important feature of the FNSA method is that it measures elements that are important for mine detection (H, C, N and O) with equal sensitivity. This guarantees that the atomic proportions of these different elements in the sample are determined with the same accuracy, which leads to a more reliable identification of the investigated material.

11. The EBS *Elastically Backscattered Spectrometry* method. The main components of drugs and explosives are H, C, N and O, which can be identified by various interactions with neutrons [31, 35]. For explosives, the atomic fates of these elements, in particular the C/O and C/N ratios, are significantly different from those present in other materials used for their concealment. The sensitivity and spatial resolution of the methods of neutron transmission, elastic scattering, inelastic scattering, and reactions depend on the size and composition of the sample being studied. Both neutron leakage spectrometry and neutron reaction analysis, used for the analysis of bulk media, require knowledge of the neutron flux density spectrum at a given point inside the sample or averaged over an extended area of the survey. Neutron leakage spectra depend on the interaction cross section, as well as on the integral density of elements between the neutron source and the detector. The energy of elastically backscattered neutrons depends on the mass of the scattering nucleus at a given source-sample-detector geometry. In experiments related to elastic backscattering spectrometry (EBS), the neutron spectrum of the Pu-Be source covers a large energy interval (1.5 - 10 MeV) of the elastic scattering cross sections of C, N and O, which allows the use of various methods for determining the energy of neutrons. In the work [35] the spectral outputs of elastically backscattered PuBe neutrons from C (graphite), H_2O, SiO_2, liquid nitrogen, polyethylene, paraffin oil, Al, Fe, and Pb were investigated the measured dependences of the outputs on the thickness. The net spectral yield was derived as the difference between the data measured with and without the samples. Some of the measured typical spectra of EBS neutrons together with the calculated energy dependence of the reaction rate $R(E_n)$ are shown in Fig.8.

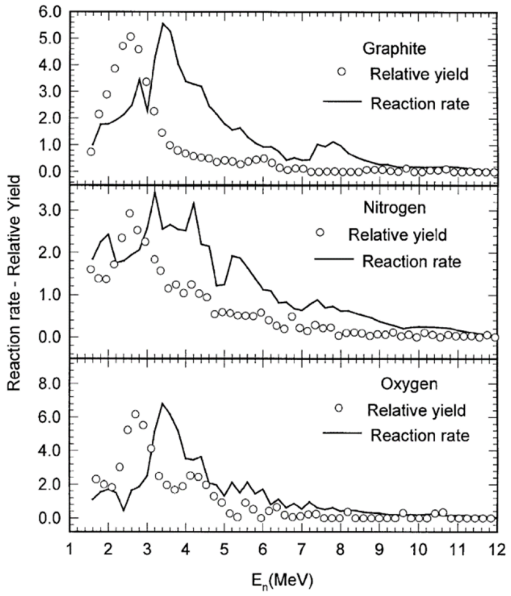

Figure 8. Backscattered spectra of PuBe neutrons for 4 cm slabs of graphite, water and 5.6 cm thick liquid nitrogen as compared to the calculated reaction rates.

6. CONCLUSIONS

The analysis of the products of the interaction of fast and thermal neutrons with nuclei of low atomic number, which are the primary components of explosives, combined with their ability to penetrate the soil, makes neutrons a preferable choice for detecting buried land mines that also have a plastic shell.

The composition of the reaction products of the interaction of fast, slowed, and thermal neutrons with H, C, N, O nuclei, which are part of explosive substances, indicates the presence of a significant number of secondary instantaneous and delayed multiple gamma quanta from both inelastic scattering reactions and resonance and radiation capture reactions. In addition, it is possible to note the high value of the flight cross section of secondary fast neutrons in the reactions of elastic scattering, "slowed down" secondary neutrons from the reaction of inelastic scattering from the investigated explosive samples.

As a rule, the existing neutron detection methods for explosives focus mainly on one type of secondary radiation, which occurs in the interaction of neutrons with matter - these are either secondary instantaneous gamma quanta flying out of target nuclei, or fast or thermal neutrons scattered in the matter of the target. The use of effective oxide scintillation gamma-neutron detectors, for example ZWO, which are simultaneously sensitive to the fast and slow resonance energies of neutrons arising in the samples, as well as gamma quanta in a wide range of energies from tens of MeV to hundreds of eV, in combination with the corresponding high-speed low-threshold single-electron photon detection methods, can contribute to increasing the detection efficiency of detection, and hence the sensitivity of explosives.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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НЕЙТРОННІ МЕТОДИ ДЕТЕКТУВАННЯ ВИБУХОВИХ РЕЧОВИН

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У статті розглядаються фізичні аспекти деяких методів виявлення наземних мін, заснованих на зворотному розсіюванні швидких нейтронів. Було проведено аналіз продуктів реакції взаємодії швидких, повільних та теплових нейтронів з ядрами H, C, N, O, що входять до складу вибухових речовин головним чином для того, щоб з'ясувати, як використовувати вторинні миттєві та затримані гамма-кванти, що випромінюються ядрами вибухових речовин, для досягнення підвищеної ефективності виявлення вибухових речовин. Обговорюються фізичні особливості деяких відомих методів виявлення вибухових матеріалів, що використовують пружне та непружне розсіювання швидких нейтронів. Метою було одночасне використання як розсіяних швидких, так і нейтронів середніх енергій, що випромінюються ядрами вибухових речовин в результаті реакцій пружного та непружного розсіювання (зворотного розсіювання), а також вторинних миттєвих та затриманих гамма-квантів. Найбільш підходящим кандидатом на роль таких детекторів можуть бути детектори гамма-нейтронів на основі оксидних сцинтиляторів типу ZWO, які одночасно чутливі як до швидких, теплових, і особливо, до резонансних нейтронів, а також до гамма-квантів у широкому інтервалі енергій від десятків МеВ до сотень еВ. Використання низькопорогового одноелектронного режиму реєстрації фотонів дозволяє значно підвищити чутливість систем детектування.

Ключові слова: *зворотне розсіювання нейтронів; виявлення наземних мін; детектор нейтронів; ефективність виявлення.*