PROBLEMS OF REMOTE DETECTION OF CHEMICAL EXPLOSIVES AND FISSILE MATERIALS USING NEUTRON-ACTIVATION DIAGNOSTICS METHOD

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This paper presents results of computer simulation of nuclear processes (using Geant4 9.0 package) for neutrons passing through a shell-free explosive model and through a model of military load containing some fissile material. Spectral distributions of γ-quanta were calculated for the neutron with fixed energy at different points of time after irradiation. The programs were designed using $C++$ and function under execution control of OS Red Hat LINUX 6.2 FEDORA.

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1. INTRODUCTION

Detection of secretly transported explosives is one of the major components of terrorism control. In connection with growth of the number of countries possessing nuclear weapon, there is a threat of nuclear terrorism and, naturally, a problem of inspecting possible secret transportation of nuclear weapon fissile materials. Experts in many laboratories over the world have been working for the period of more than two dozen years already on development of engineering tools for detection of standard chemical explosives, as well as fissile materials transported in the luggage of passengers travelling by various types of transport, especially by air. In spite of certain progress in development of the detection engineering tools it is still early to state that the problem of quick and faultless detection of explosives has been solved. At first, this problem is caused by a large amount of luggage transported all over the world; the airline traffic industry alone services more than billion passengers a year. Hence, to prevent getting an explosive aboard a plane, the detection system should function quickly, automatically, with high probability of identification and very low level of false operations. Secondly, the explosive may be masked with any materials containing the same set of chemical elements, for example, various types of plastics, as well as with some special kinds of masking. Therefore, the detection system should be capable to detect and unmistakably recognize the unique characteristics inherent only in the explosive. Similar problems might also occur when detecting fissile materials. Chemical explosive consists, generally, of atoms of nitrogen and oxygen in the condensed state. Detection of nitrogen high concentration would signal about possible presence of explosives, and high concentration of nitrogen and oxygen with a high level of probability points to the presence of a bomb [1]. More than a dozen of various nuclear-physical techniques have been offered for scanning luggage with the purpose of detecting any hidden explosives by measuring distribution of these elements. These techniques are based on physical principles, well-known since the 50th - 60th of the last century, however to implement these principles the most advanced technological achievements are required today. The purpose of this work is to further research feasibilities of remote detection of fissile materials and chemical explosives using method of sounding them with high power pulses of neutrons having different energies, initiated by authors in [2]. As it was stated in *http://www.jurnal.org/articles/2008/enerj4.html*, passive methods show rather unreliable result, in particular, because of possible usage of some kind of protection (this article is also devoted to this case); as to conventional explosives, just none of any other effective possibilities to detect them is available now. Pulsed ion sources would enable creating rather powerful neutron sources for irradiation of remote objects. Preliminary calculations [3] showed a number of essential advantages in usage of sub-MeV neutrons for reliable detection of fissile substance at rather long distances. However, simulation of actual military loads having shell structure, showed essential problems in the process of implementation of such projects. In the process of the universal activation method development [9] the possibilities to detect fissile materials as well as chemical explosives, using neutrons from $T(d,n)^4He$-type reaction were analyzed. Energies of about $14\,MeV$ allow researching

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a substance gamma response in a broad range of energies what is especially important for obtaining reliable information about presence of explosives generally used during acts of terror. Taking into account that the technique of nuclear radiation detection has been continually improved (spectral selectivity, time resolution, sensitivity, etc.), special attention in this paper is given to progress of the object response in time after irradiation it by a short neutron impulse. In combination with quickly developing computer possibilities as to the information flow processing, the obtained data, according to the authors' opinion, would allow creating more perfect recognition algorithms in systems designed for detection of explosives and fissile materials.

2. NEUTRON SOUNDING OF A MILITARY LOAD FILLED WITH A FISSILE MATERIAL

Usage of sub-MeV neutrons for irradiation of ^{235}U and ^{239}Pu nuclides that are principal components of nuclear weapon, allows detecting them against the background of other masking materials, such as ^{238}U or W which also might be used as elements for military load construction. As far as ^{238}U and tungsten could not undergo fission by sub-MeV neutrons, so, occurrence of the fission neutron response in a signal would signalize about presence of true weapons grade uranium or plutonium. Up-to-date technologies of high power pulsed beams of light ions allowed to create compact accelerators generating ion flows of more than $3.12 \cdot 10^{16}$ ions per pulse whose duration is several tens of nanoseconds what allows generating neutron flows of 10^{12} per pulse. When using a low-threshold nuclear reaction $^{12}C(d,n)^{13}N$ with energy threshold of neutron generation $E_d = 324\,keV$, or more effective reactions $T(p,n)^3He$, $^7Li(p,n)^7Be$ with energy thresholds of $E_p = 1.018\,MeV$, $E_p = 2.25\,MeV$ accordingly, it is possible to develop sub-MeV-neutron generators with variable energy. High-efficiency $T(d,n)^4He$ reaction is used to generate mono-energetic neutrons with energy of $14\,MeV$.

High-energy gamma rays of bremsstrahlung (more than $6\,MeV$, photofission threshold $(\gamma,\, f)$) generated by electron beams, are also capable to cause fission and to get a stable signal from a spherical object with radius of $23\,cm$ at a distance of up to $50\,m$. However reaction $(\gamma,\, f)$ deals with large cross-sections not only for ^{235}U, but for other transuranic elements too, including ^{238}U. I.e., adding of a signal from ^{235}U at big enough mass ratios of $^{238}U/^{235}U$, just as for fast neutrons, could be insignificant. An advantage of gamma radiation as compared to the neutrons is its high coefficient of passage through the shell surrounding the fissile material, for example, the hydrogenous layer of the explosive.

To calculate the warhead response signal to the probing neutron pulse the hypothetical warhead model from [5] was used (Fig.1).

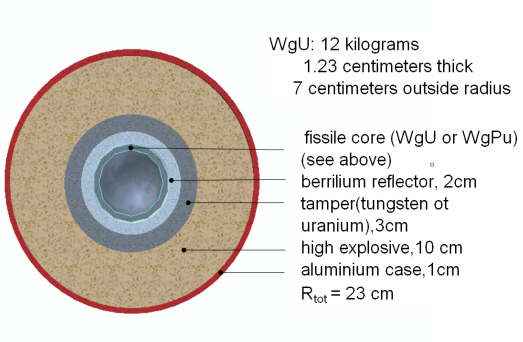

Fig.1. *Warhead model. The model mass is of about* $182\,kg$. *WgU or WgPu – weapons grade* ^{235}U *or* ^{239}Pu *(with the degree of enrichment more than* $93,3\%$*)*

The model is presented by a series of concentric spherical shells with some fissile material inside surrounded by Beryllium reflector, a large case (tamper) of depleted uranium or tungsten, a layer of high-efficiency explosive and an outer case of aluminum. Neutron beams with energy of $0.5\,MeV$ and $14\,MeV$ were used in calculations; beam diameters were accepted to be equal to the exterior diameter of the warhead model. At the same time the composition of radiation emitted to the front and back hemispheres after interaction between the incident neutrons and the irradiated object were analyzed.

When the fissile substance enclosed in $10\,cm$ hydrogenous explosive ($H_2CN_2O_2$) is irradiated by neutrons, a significant portion of the irradiating neutron flow (Figs.3, 4) is moderated to the energy lower than $1\,keV$ at which the ^{235}U fission cross-section increases to more than 10 barn. Gamma-radiation accompanying neutron fission and capture by a fissile material is essentially absorbed by the fissile material itself and by surrounding heavy cases. The greatest yield of gamma radiation is along the channel $(n,\, f)$.

Fig.2,a. presents absorption of gamma signal $(n,\, f)$, mainly by the fissile ^{235}U itself and the shells of ^{238}U or W. The peak in the energy range of $94\,keV$ within the emitted radiation spectrum corresponds to the uranium K-line generated in the process of absorption of higher energy gamma rays. Gamma radiation yield is less by the factor of ten along the channel $(n,\, \gamma)$. Fig.2,b presents this signal self-absorption in ^{235}U.

When the war head model is irradiated the neutron flow spectrum undergoes essential transformation, which, first of all, is due to neutrons penetration of the explosive material (up to $20\,cm$). Fig.3a presents spectral distribution of neutrons emitted from the model to the front hemisphere after the model was irradiated by $14\,MeV$ neutrons.

The model neutron yield forward makes 27% of the incident flow, while 8% of neutrons passes without interaction which may be accounted for by tangential passage of these neutrons in regard to the spherical object), 5% of neutrons reduce their energy to the value below $1\,keV$ due to their elastic scattering.

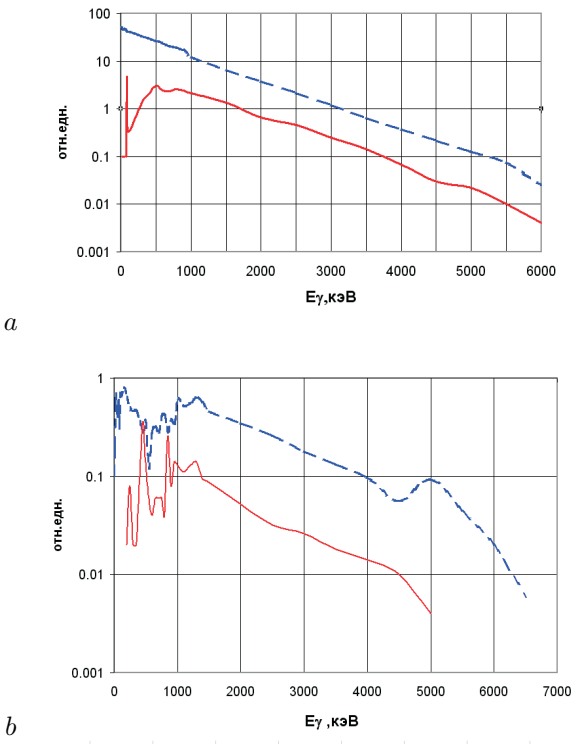

Fig.2. *Absorption of fission gamma rays (a) and capture gamma rays (b) by elements of the war head structure. The dotted line here is for the generated radiation, and solid line for the radiation emitted from the model*

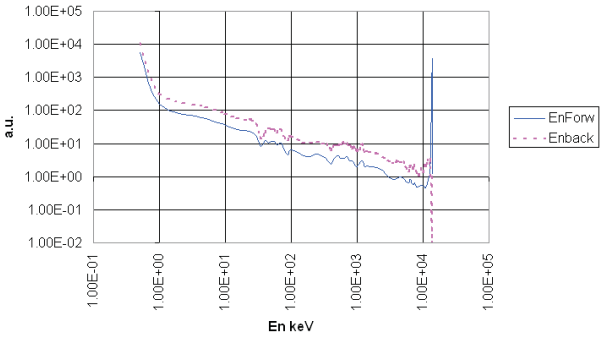

Fig.3. *Spectral distribution of the neutrons emitted forward after passing through the test specimen (dotted line) and the neutron reflected signal (solid line) at irradiation energy* $E_n = 14\,MeV$

In the diagram maximal and minimal energies show approximately identical marked peaks, in the middle of the energy range the neutrons are distributed evenly enough what points to deceleration occurring in the hydrogenous medium. The most promising as to the detection problem, is the analysis of the neutron reflected signal. The neutron spectrum directed to the background hemisphere when the model is irradiated by 14 MeV neutrons is also shown in Fig.3. The figure shows that 14 MeV neutrons are virtually not reflected by the model, and neutrons, strongly decelerated in the explosive, as well as fission neutrons emit backward. If the reflected signal makes 50% of the incident flow (together with the fission neutrons emitted backward), then about 20% of neutrons in this signal have energy less than 1 keV. Rather a different pattern is watched when the model is irradiated by sub-MeV neutrons (500 keV). The reflected signal for the sub-MeV neutrons is shown in Fig.4.

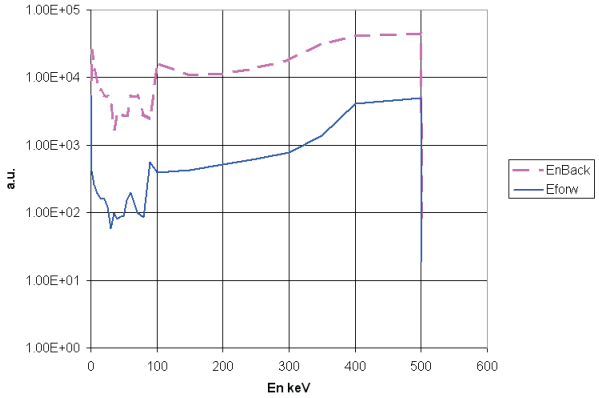

Fig.4. *Spectral distribution of sub-MeV neutrons (500 keV), emitted through the model (solid line). The reflected signal of sub-MeV neutrons (dotted line)*

About 20% of neutrons are reflected practically without interaction with the model. The number of neutrons moderated to the energy of less than 1 keV, is also about 20%. Distribution of the neutrons which have passed through the model, is similar to that of the reflected neutrons (Fig.4). Nearly 50% of the signal are the neutrons that passed through the model practically without interaction (elastic scattering). Most likely, major portion of them passed over periphery of the spherical model, 25% of them are neutrons moderated to the energy of less than 1 keV. However, the total amount of the neutrons emitted forward is not more than 3% of the incident flow. To detect the military load on the basis of fission neutrons for certain it is required that the primary neutrons not only effectively hit the area under research (the area containing ^{235}U), but also that fast ("super-MeV") fission neutrons of ^{235}U effectively emitted from the model. Special calculations showed the following effectiveness of fast neutrons passage through 10 cm of a shell containing some hydrogenous substance.

Penetration effectiveness of neutrons with various energies through a 10-cm explosive target

En	100 keV	1 MeV	2 MeV	14 MeV
K = N/N0	0.15	0.29 (>700 keV)	0.37 (>1 MeV)	0.66 (>1 MeV)

Only 15.4% of the sub-MeV neutrons passes through the explosive and 30% of them are moderated to thermal ones (see Table). 30% of neutrons with primary energy of 1 MeV would conserve energy in the range of over 700 keV; accordingly 37%

of the $2\,MeV$ neutrons leave the moderator with energy of over $1\,MeV$. The Table shows as well high penetration efficiency of $14\,MeV$ neutrons with low reflection coefficient (see Fig.3).

Calculations for the warhead model were carried out by comparison of algorithm of signals in the presence of ^{235}U and at in its absence. Both gamma response signals and the reflected neutron signal in the energy range of more than $100\,keV$ were analyzed. When the model with tamper of ^{238}U was irradiated by $14\,MeV$ neutrons, the signal increased by 16%, and by 8% when the model was with tamper of W. Relative amplification of the signal is accounted for the fact that in the spectrum of ^{235}U fission the neutrons with energy higher than $106\,eV$ are present which cause additional fission in ^{238}U. In case of irradiation by sub-MeV neutrons the signal increased by 7% when the model with ^{238}U shell was irradiated, and by 1.3% when the model with a tungsten shell was irradiated. The relative effect of the signal amplification caused by fast neutrons fission in the ^{238}U shell is more evident. However in case with a tungsten shell it is more difficult to note change of the output. Nevertheless, the signal of fast neutrons (above $1\,MeV$) even in case with a tungsten shell which makes only 0.5% of general signal of the reflected neutrons can be fixed at a distance of up to 10 m using a $100\times100\,cm$ detector when the model is irradiated by a pulsed source of neutrons with a flow of $10^{11}/pulse$.

When a variety of materials with big $(n,\,\gamma)$ cross-section, are present in an object, in particular, such as tungsten, to analyze the gamma signal spectrum is rather difficult since the value of gamma signal is determined by the value of the object under irradiation area and mass. Research of the active detection technique for the fissile material placed in the shell simulating a nuclear warhead, indicates that analysis of the integral signal of the reflected neutrons (the signal containing fission neutrons whose amount could essentially exceed the flow of incident neutrons due to their multiplication) is most preferable. But for this purpose it is necessary to know precisely enough the value of the expected reflected signal. As a rule, it does not always work. Irradiation of an object by fast neutrons or gamma rays excludes any possibility to identify the object through spectral analysis of the neutron reflected signal. But irradiation of an object by sub-MeV neutrons allows to explicitly identify presence of a threshold-free fissile material, for that it would be quite enough to register at least one fast neutron. This is feasible for the up-to-date diagnostics.

3. USE OF $14\,MeV$ NEUTRON PULSED SOURCES FOR DETECTION OF CHEMICAL EXPLOSIVES

Passive detection methods are absolutely unsuitable for detection of chemical explosives unlike of the fissile materials, therefore, a wide range of nuclear-activation methods for detection of appropriate components of explosives are developed. On the other hand, activation methods allow defining chemical composition of materials, including both fissile materials, and the radiation-passive ones. For example, some general-purpose portals for detection of explosive and fissile materials were developed on the basis of usage of a source of neutrons generated during irradiation of a beryllium target by a deyton beam [10] and they are widely used nowadays. The activation methods utilize not only neutrons, but also high-energy (up to $50\,MeV$) gamma-ray beams produced on electron accelerators with appropriate energy [11]. However, for the purpose of detection the neutrons of wide energy range are mostly used, and, accordingly, with using different channels of nuclear reactions [1]. Usage of the high-energy neutron sources allows essential increase of the detection depth of the hidden explosives. For diagnostics aims this method allows both using threshold gamma radiation of inelastically scattered neutrons (reaction $(n,\,n')$), and effective using capture gamma-rays of the moderated (to thermal energies) neutrons (reaction $(n,\,\gamma)$). Usage of the high-energy neutrons for explosive detection allows generating gamma-quantum lines specific for each component of the explosive. Simulation by applying Geant4 9.0 package [4] allowed to identify the following characteristic lines generated along the channel $(n,\,n')$ within the first moments of irradiation: for nitrogen – $2.30\,MeV$, for carbon – $4.43\,MeV$, for oxygen – $6.14\,MeV$, $6.92\,MeV$, $7.128\,MeV$ [6] (Fig.5).

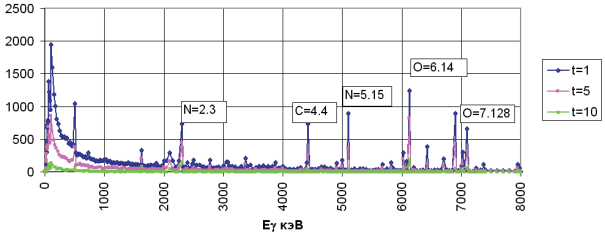

Fig.5. *Characteristic lines of the explosive basic elements in t=1.5 and 10 nanoseconds after irradiation*

As is evident from Fig.5, all main lines necessary for identification of explosives can be simulated by the program quite adequately. The maximum signal would be registered within the first 5 nanoseconds after irradiation due to elastic scattering of the incident neutrons in the material, especially on the hydrogen atoms which are inherent chemical components of explosives as well as of many types of plastics (see Figs.5,6).

Further moderation of neutrons in the explosives results in increase of $(n,\,\gamma)$ reaction cross-sections, but at the same time one may observe neutrons escaping the explosive volume which results in very slow decrease of γ-quanta radiation intensity lasting about $100\,\mu s$ after beginning of the irradiation when large masses of explosives are irradiated (Fig.7, curve 2).

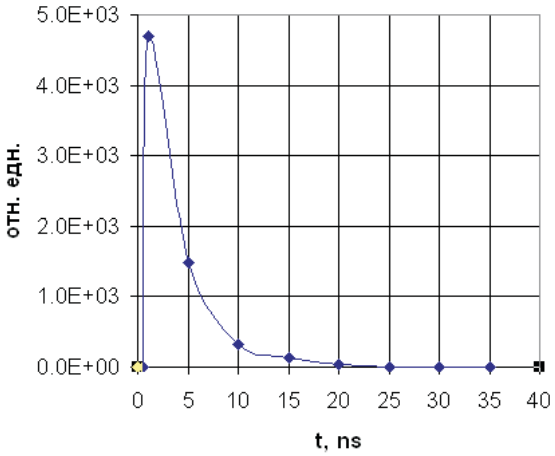

Fig.6. *Dependence of the carbon characteristic line on time in* (n, n') *reaction,* $E_\gamma = 4.43\,MeV$

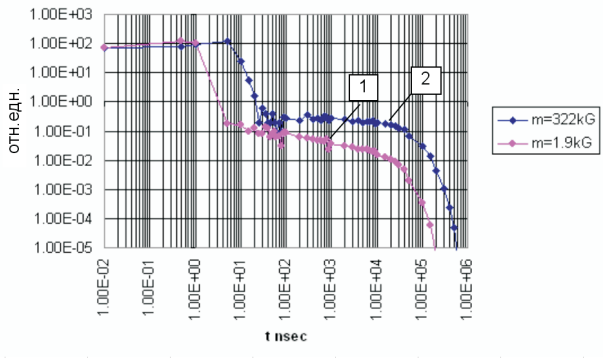

Fig.7. *Dependence of generation of gamma rays with energy of* $2.23\,MeV$ *(* $^1H(n,\gamma)^2H$ *reaction) on the moderation time in an explosive with* $m = 1.9\,kg$ *(1),* $m = 322\,kg$ *(2)*

In case when smaller masses are irradiated the time of gamma release virtually does not change, but intensity would drop more quickly because of faster escape of neutrons from the explosive volume (see Fig.7, curve 1).

Calculations of distribution of the capture gamma ray characteristic lines in time showed conservation of the hydrogen line during all the points of time under consideration (Fig.9,a) what is accounted for by effective moderation of neutrons in hydrogenous materials to $1\,keV$ during $100\,ns$ [7]. Fig.8 presents time dependence of fluorescence intensity of nitrogen capture lines $E_\gamma = 5.269\,MeV$ and $10.829\,MeV$. These curves show a pronounced peak during the first $10\,ns$ which is determined by the time of fast neutrons escape from the volume under consideration. During interaction of a neutron along the channel (n, n'), the neutron loses most of its energy, comparable with energy of the generated γ-ray, which results in more probable reaction of neutron capture (n, γ) and less probable reaction of elastic scattering. Further dip of the curve during $10...100\,ns$ is connected with escape of slow neutrons from the volume due to their elastic scattering. And only after the period of time of about $100\,ns$, when the neutrons energy drops to the value of the order less than unities of keV and still less, the explosives capture lines become more clearly observed (see Fig.9). However the peak value of these lines is much less than that of gamma radiation induced by (n, n') reaction. In the process of simulation the value of radiation emitted from the cylinder with dimensions $R = 30\,cm$, $h = 60\,cm$, $m = 322\,kg$ was calculated, (such dimensions were chosen in order to obtain reliable resolution of characteristic lines due to the great statistics). The signal induced by the thermal neutrons capture the period of time from $100\,ns$ to $500\,\mu s$ after irradiation) was of the order of 10% of the total yield of gamma rays emitted from a target. But when a target with $m = 1.9\,kg$ was irradiated the contribution of the gamma quanta from the slow neutrons was already less than 1%. However even at sharp decrease of the capture radiation component all the characteristic lines (see Fig.9) were clearly identified.

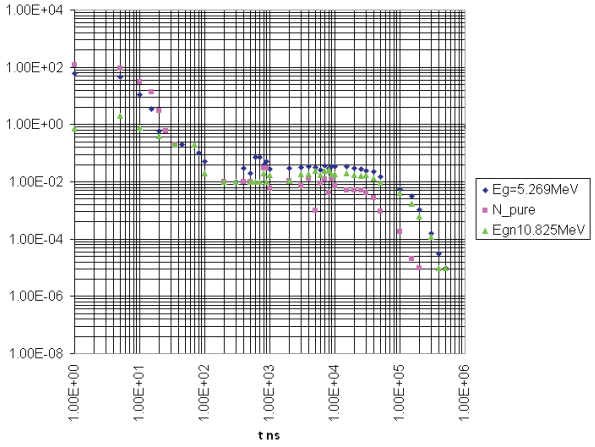

Fig.8. *Dependence of generation of nitrogen lines gamma radiation with energy of* 5.269 *and* $10.829\,MeV$ *((*n, γ*) reaction) on the neutron moderation time in an explosive with* $m = 322\,kg$*, and in nitrogen substance having the same mass*

As it was mentioned above a characteristic feature in the spectrum of the capture gamma ray in any of the hydrogenous materials including explosives, is a high peak value of the hydrogen line $E_\gamma = 2.23\,MeV$, the peak value of all the rest lines is essentially smaller (see Fig.9). Presence of a hydrogen line, at essentially smaller peak values of other lines in spectrum of the explosives capture radiation and at small intensities of characteristic capture radiation could be used as the reference signal when adjusting some kind of diagnostic equipment and, accordingly, might increase reliability of the capture lines detection within certain ranges of spectral distribution. Besides the hydrogen line also nitrogen capture lines are clearly observed in the capture spectrum of the explosive gamma radiation (compare Fig.9,a and Fig.9,b). Simulation with usage of Geant4 9.0 package allowed to identify the following nitrogen capture lines: $1.678\,MeV$,

1.884 MeV, 3.677 MeV, 4.509 MeV, 5.269 MeV, 5.298 MeV, 5.533 MeV, 5.562 MeV, 6.322 MeV, 7.299 MeV, 8.310 MeV, 9.149 MeV and 10.829 MeV [6]. It was expected to find out also characteristic lines of oxygen: 1.087 MeV, 2.184 MeV, and 3.271 MeV. However because of negligibly small cross-sections of (n, γ) reaction for carbon and oxygen against cross-sections of nitrogen [8] these lines could not be detected. Thus, for 1 keV neutron energy the capture cross-section for nitrogen is 20 times larger than that for carbon (that is the reason for carbon to be a good moderating material) and more than 300 times larger than cross-section for oxygen [7,8]. Therefore, lines of nitrogen and hydrogen dominate in the capture radiation of explosives. As a rule, the presence of nitrogen in the process of irradiation by thermal neutrons is identified by the 10.8 MeV line of γ-radiation [1] (see Fig.9).

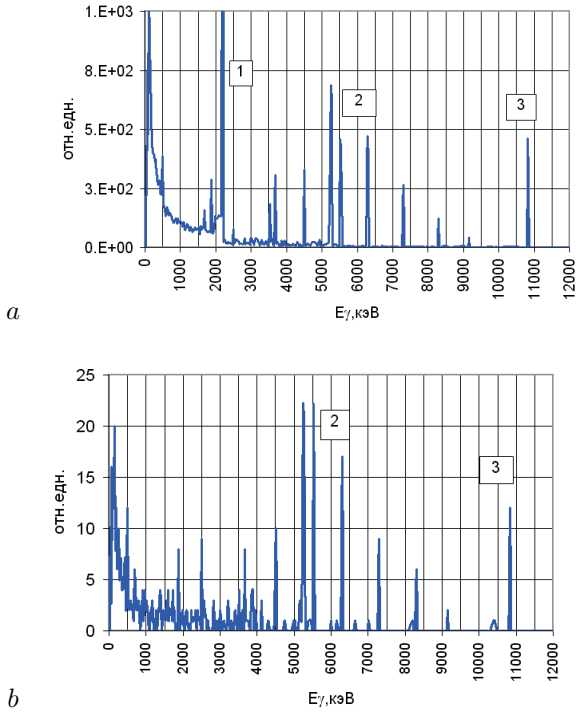

Fig.9. *Spectral distribution of the capture radiation gamma-rays after the period of time of* 10 μs*: a - explosives, b - pure nitrogen under irradiation by* 14 MeV *neutrons. 1 - a hydrogen line of* 2.28 MeV*, 2 - a nitrogen line of* 5.269 MeV*, 3 - a nitrogen line of* 10.84 MeV

The luminescence time in materials with high content of nitrogen (pure nitrogen with density inherent to explosives was calculated) would not exceed 200 μs after a pulse of irradiation (see Fig.8). In the carbonaceous substances (including explosives) the nitrogen lines fluorescence time essentially increases and reaches 500 μs (see Fig.8) which is accounted for by low capture cross-section of carbon (lifetime of a neutron in graphite is known to be 12.9 ms [6]).When interacting with carbon, the neutron is elastically scattered, and remains in volume for a longer time. Thus, time characteristics of the nitrogen lines capture radiation allow obtaining information on the nature of the material containing nitrogen.

4. CONCLUSIONS

When using sub-MeV neutrons for detection of fissile material by active method, in spite of such obvious advantages as: possibility to diagnose neutrons with energy higher than that of neutrons from the irradiation source; possibility to diagnose increase of gamma response in comparison with that of non-fissile materials [3], it is required to solve a number of problems connected with primary irradiation. Among them are the reflected signal, and irradiation by a "wide-angle beam" when the background signal is a strong noise due to the large volume under irradiation in comparison with the volume of a potentially dangerous object. To solve these problems it is necessary to conduct very serious computer analysis, to provide shielding of the diagnostic equipment, etc. The presented comparative data on irradiation by a 14 MeV neutron source show such advantages as: more expressed signal of gamma response, greater neutron multiplication factor, and possibility to draw a single-valued conclusion by the number of the reflected neutrons. A further advantage of using a high-energy irradiation source is the possibility to obtain information from the potentially dangerous object that is "placed deeper", and it is easier to break a conventional shielding against neutrons, usually it is a hydrogenous shell. However in the process of fissile substance detection the capture radiation of the materials surrounding the fissile substance presents some difficulties in gamma response estimation. Fissile material identification by the neutron flow, when large area is irradiated, also makes some difficulties for analyzing increase of the neutron flow due to the neutron multiplication. Presence in the neutron response of the whole range of neutron energies, that is, from thermal energies to the energies of probing neutrons, impedes detecting a fission material by neutron response spectrum. Unlike the fissile material, the capture gamma radiation allows definitely to identify presence of a conventional explosive. As it was mentioned above, in this case only the source of high-energy neutrons allows to definitely identify presence of the main characteristic components of a conventional explosive. The task to reduce the number of false operations is the main problem here. Therefore, undoubtedly, nitrogen diagnostics alone is insufficient. A definite ratio of carbon and oxygen lines would allow appreciable reduction of the number of false operations. The pulsed irradiation by high-energy neutrons would allow measuring spectral distribution of characteristic lines of the explosive basic elements (see Fig.5.) during the first points of time (before deceleration of the total neutron flow), and tracing in time characteristic lines of the capture gamma radiation by a signal from the moderated neutrons (see Figs.7,8). The multiple-detector detection system with a short-pulse source of neutrons would allow to distinguish between the cap-

ture radiation and the radiation induced by neutron inelastic scattering (system with time resolution of spectra). When analyzing the capture radiation, it is possible to obtain the hydrogen/nitrogen ratio by weight, and analyzing the deceleration time of the capture radiation fluorescence it is possible to obtain information concerning the amount of carbon or the hydrogen/nitrogen ratio by weight. These problems require further researches. Comparison of the results concerning the material weight composition obtained when analyzing the gamma radiation fast component with the results obtained when analyzing the capture radiation, would allow considerable improvement of reliability and validity of the explosives detection.

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ПРОБЛЕМЫ ДИСТАНЦИОННОГО ОБНАРУЖЕНИЯ ХИМИЧЕСКОЙ ВЗРЫВЧАТКИ И ДЕЛЯЩИХСЯ МАТЕРИАЛОВ МЕТОДОМ НЕЙТРОННО-АКТИВАЦИОННОЙ ДИАГНОСТИКИ

В. Н. Дубина, А. В. Чёрный, В. В. Чёрный

Представлены результаты компьютерного моделирования с использованием пакета Geant4-09 – ядерно-физических процессов прохождения нейтронов через безоболочечную модель взрывчатого вещества, а также через модель боезаряда с делящимся веществом. Рассчитаны спектральные распределения γ-квантов для фиксированной энергии нейтронов в различные моменты времени после облучения.. Программы разработаны на языке $C++$ и работают под управлением OS Red Hat LINUX 6.2 FEDORA

ПРОБЛЕМИ ДИСТАНЦІЙНОГО ВИЯВЛЕННЯ ХІМІЧНОЇ ВИБУХІВКІ ТА ПОДІЛЬЧИХ МАТЕРІАЛІВ МЕТОДОМ НЕЙТРОННО-АКТИВАЦІЙНОЇ ДІАГНОСТИКИ

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Представлено результати комп'ютерного моделювання з використанням пакету Geant4-09 – ядерно-фізичних процесів проходження нейтронів через модель вибухової речовини без оболонки, а також через модель боєзаряду з подільчим матеріалом. Розраховані спектральні розподіли γ-квантів для фіксованої енергії нейтронів у різні моменти часу після опромінення. Програми розроблені на мові $C++$ і працюють під управлінням OS Red Hat LINUX 6.2 FEDORA.