ASSOCIATED PARTICLE IMAGING APPLIED TO UNDERWATER DETECTION OF HAZARDOUS SUBSTANCES

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Abstract
A possible use of the Associated Particle Imaging (API) for detection of hazardous substances masked in the underwater objects is investigated. The API application for the above purpose is theoretically justified. The principal design of the detector mock-up to detect the explosives under water is described.

Introduction

The detection of masked matters in possibly hazardous underwater objects has basically several purposes such as antiterrorist activity and search for hazardous matters (explosives, radioactive and highly toxic substances) contaminating oceans, seas and rivers.

As for the search for the matters hidden in different medium the most reliable results are given by the systems based on in-situ detection technique. It primarily relates to various devices where a chemical analysis of a matter is used. Besides nowadays there are the developments based on nuclear quadruple resonance (NQR). However these techniques are impossible to use if the explosives are in the sealed and waterproof metal enclosure. Such cases require the detection techniques relied on high penetration radiation that specifically reacts with the chemical elements.

A detection system for explosives, toxic and radioactive substances in underwater objects called Варяг-ЧС (Varyag-CHS) (Krylov Shipbuilding Research Institute) [1-4] is based on the penetrating radiation. The system functions using a thermal neutron analysis (TNA) that lacks the data on the spatial location of the hidden object and good background environment.

The API as we think is one of the most effective for search of masked substances in different medium. The thorough investigation of the technique and a line of stationary and portable API-based equipment [5, 6] prove this statement. These activities contribute to achieving a considerable progress such as development of portable fast neutron generator up to $\sim10^8$ s^{-1} yield with embedded alpha-detector, detection of gammas and neutrons, production of multi-channel high speed special-purpose data acquisition systems, development of data processing and simulation techniques. The API is mainly relied on the following laws. The investigated object is exposed to 14.1 MeV neutron emissions from $d + t \rightarrow \alpha + n$ reaction. The neutrons penetrating the object generate the gamma-photons in $A(n,n\gamma)A$ nuclei as a result of inelastic neutron scattering. The fast neutron scattering in matter nuclei transfers a part of neutron kinetic energy to excite a nucleus. The neutron can loose up to 90% of its energy. One or several gamma-photons emitted remove the nucleus excitation and the state of the target nucleus is restored. An energy spectrum of gamma-rays has the characteristic lines of chemical elements – constituents of the irradiated matter.

The measured characteristic spectra of gamma-rays allow getting the data on elements of the matter and a quantitative ratio of the chemical elements. For explosives N/O and C/O are different as compared with other matters.

Apart from detection of gamma-spectra a detection time between alpha-particle and gamma-photon is measured in experiment. This time defines a birth of gamma-photon. The data obtained enable to distinguish the voxels in the irradiated object. The gamma-spectrum is analyzed in each voxel.

As compared with other detection techniques (X-rays, infrared radiation, activation analysis, thermal neutron analysis, nuclear quadruple resonance) the API has a lot of merits:

- Data on 3-d location of the object;
- Sensitivity to the elemental composition of the matter;
- High penetration of fast neutrons up to 1-1.5 m;
- Effect/background ratio is 200 times better than without 'tagging';
- The object imaging for a measurement.

The API used for investigation of underwater hazardous objects was tried under UnCoSS [2, 7, 8] that was performed by a consortium of research and industrial partners from Europe and USA.

The API Background

To evaluate the possible application of the API to detection of explosives in underwater objects the properties of detectors for gamma-rays and neutron yield are calculated.

The calculations are made by means of GEANT4 [9] intended for simulating the penetration of elementary particles through the matter using Monte-Carlo. This software describes the interactions of <20 MeV neutrons to high precision with Neutron-VT module engaged [10]. ENDF libraries (Evaluated Nuclear Data Library) [11] converted into the GEANT 4 format, are used to calculate the probabilities and types of neutron-matter interactions (elastic scattering, inelastic scattering, nuclear decay, radiation capture and others).

Fast neutron absorption and a 'tagged' neutron path under water are calculated with respect to the scattering.

The calculations are relied on the simulation geometry from Fig. 1. Here a neutron source is inside an air-filled metallic tank (1) 5 mm thick. The planes (2) used for calculation of the neutron flow, are 5, 10 and 20 cm distant from the tank enclosure as showed at Fig. 1.

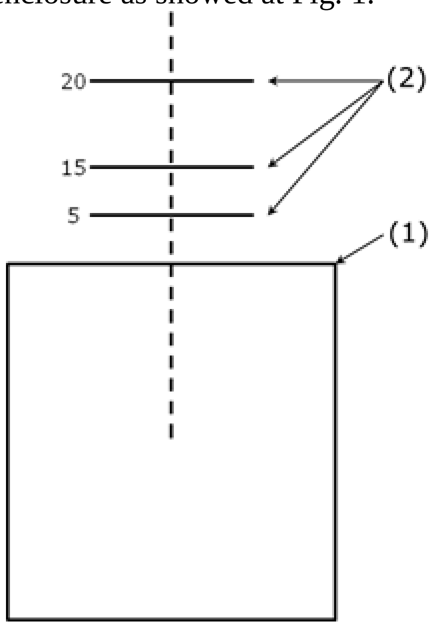


Fig. 1. Simulation geometry to calculate a fast neutron asbsorbtion in water medium

Fast neutron absorption and a 'tagged' neutron path under water are calculated with respect to the scattering.

Table 1 presents the calculations of the neutron flow that reaches the estimated planes and is not exposed to reaction or saves a major part of energy in water. The results demonstrate that the neutron flow at 5 cm distance from the detection module is two times lower and at 20 cm - five times lower.

Table 1

A fraction of neutron flow that reaches the estimated planes 5, 10 and 20 cm distant from the tank with the >13 and 14.1 MeV fast neutron source

Energy n (MeV)	5 cm	10 cm	20 cm
>13	0.64	0.44	0.20
14.1	0.59	0.39	0.15

The results prove a need to extend a statistics time for detection of gamma-rays induced by fast neutron irradiation of the underwater objects at respective distance from the neutron source. In addition the calculations show that the fast neutrons pass through the water layer as thick as indicated with a slight deviation from the flight path.

A mock-up of spectrometer was made in order to estimate a detector load through detection of characteristic gamma-rays from the fast neutron inelastic scattering (A(n,nγ)A) reaction in the light elements (^{12}C, ^{14}N и ^{16}O) of the investigated object and water background. A design of spectrometer prototype was identical to that of detectors ДВиН-1 (DViN-1) [12] for explosives and drugs. Fig. 2 illustrates a spectrometer prototype, the simulation was made for.

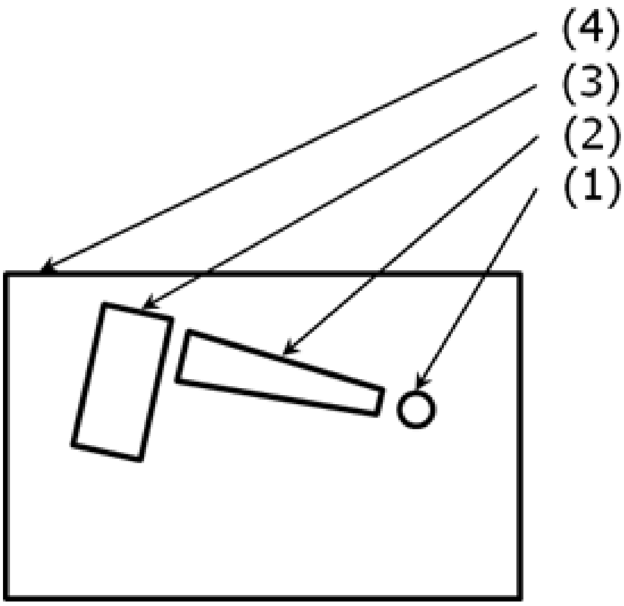


Fig. 2. Installation chart: 1 – Fast neutron generator, 2 – Gamma-ray shield, 3 – Gamma-detectors, 4 – Detector enclosure

A model of spectrometer system contains the next units: the fast neutron source (1), gamma-ray shield (2) made as a polyethylene or metal plug; BGO-detector (3) 76 mm in diameter and 65 mm thick; detector enclosure (4) 5 mm thick. The simulation is made with the detector put in water- or-air-filled tank with neutron yield 5×10^7 neutron/s.

The background load of gamma-detector with and without water is compared. Table 2 gives the comparison results and proves the use of BGO-detector for characteristic nuclear emission of C, N and O. The gamma-detector load is 3 times increased in water and due to it the gamma-detector resolution is getting worse. Thus a shielding of scintillation gamma-detectors from the background (of gamma-photons and neutrons) should be taken into account in order to construct a prototype for explosives detection.

Table 2

Compared loads of gamma-detectors for water and air

Energy Release (MeV)	Air	Water
>0	5.8×10^4	2.1×10^5
>0.1	4.6×10^4	1.35×10^5
>1.5	9.4×10^3	2.9×10^4

To construct a spectrometer (Fig. 2) the spectra of characteristic gamma-rays from irradiation of melamine sample with fast neutrons were obtained. This substance contains a high percentage of N and is used as simulator of explosives. The melamine sample taken was 10×10×10 cm. The calculations were made with sample put in water and air medium. Fig. 3 demonstrates the spectra compared. The spectra have the full absorption peaks of characteristic gamma-rays equal to E_γ = 4.43 MeV for C and E_γ = 5.1 MeV for N that constitute the melamine sample. The spectrum drawn for water medium has a full absorption peak equivalent to characteristic gamma-ray energy from oxygen - E_γ = 6.13 MeV. This peak is in the picture because of inelastic neutron reaction with oxygen nuclei that exists in water. The results prove that in-spite of need to extend the statistics time it is possible to single out a component equivalent to characteristic gamma-rays from C and N with energies E_γ = 4,43 MeV and E_γ = 5,1 MeV respectively. It means that there is a chance to use the API for identification of explosives under water using C/N/O ratio in it by respective criteria selected.

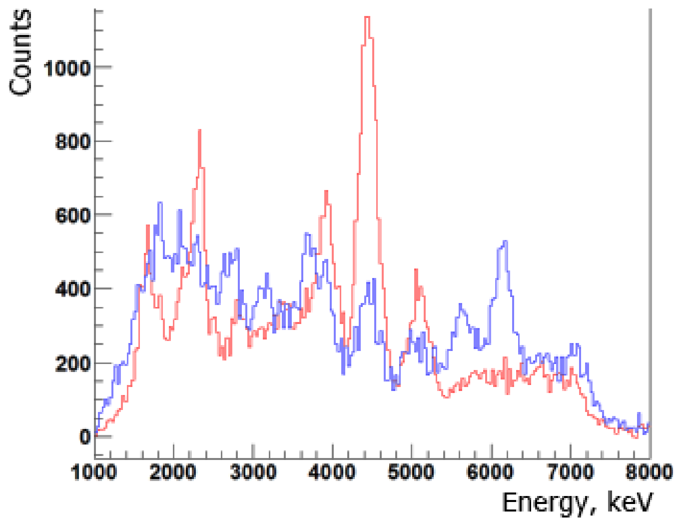


Fig. 3. Calculations of gamma-spectra drawn with irradiation of melimine sample with fast neutrons when the object is in water (in blue) and air (in red)

Experiment Results and Analysis

For the experiment a test bench was constructed. The portable API-detector for explosives ДВиН-1 [12] (Fig. 4) was taken as a core. The inspected unit was put in the sealed shockproof ABS enclosure. A corrugated hose was used to connect the inspected unit to the control module and power line. The inspected module was deployed on a platform with rails for the inspected object. As the design had a positive buyonance, the bottom of the platform was loaded with lead bricks of required quantity. The host was used to submerge the construction in the water pool.

View of the test bench is shown at Fig. 5.

Fig. 4. Inspected unit of the portable detection system for explosives ДВиН-1

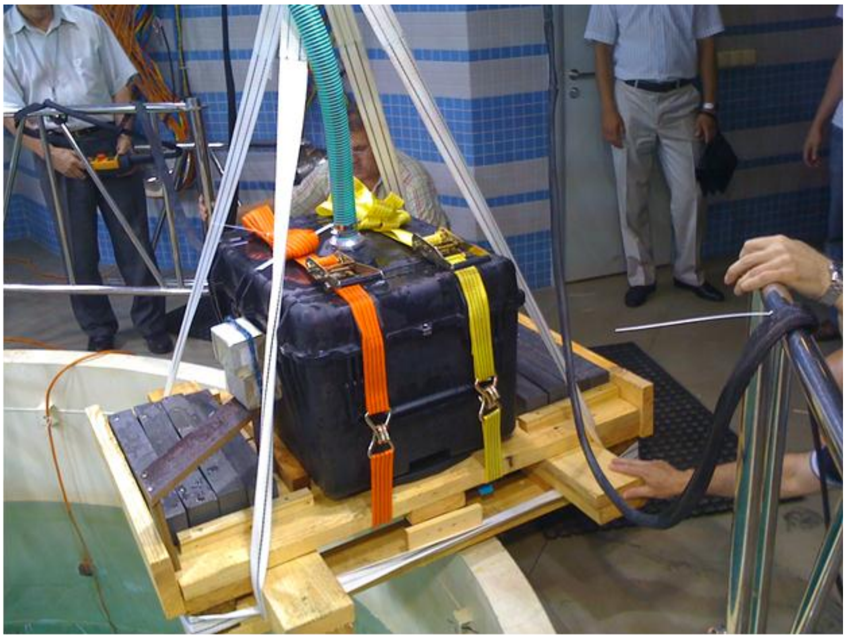


Fig. 5. Test banch based on ДВиН-1

The main features of ДВиН-1 are presented in Table 3. ДВиН-1 is designed for automatic detection and localization of explosives inside the inspected object without being opened. The explosives detection lies in processing of gamma-spectra drawn with irradiation of the inspected object with fast 'tagged' neutrons.

Table 3

ДВиН-1 Chief Characteristics

Quantity of 'Tagged' Neutron Beams (pcs.)	9
NG-27 Neutron Yield	$5 \times 10^7\ s^{-1}$
Neutron Energy (MeV)	14
Dimensions of Inspected Unit (L×W×H), mm	740×510×410
Dimensions of Control Module (L×W×H), mm	400×200×40
Dimensions of Wire Coil (L×W×H), mm	600×600×400
Net Weight of Inspected, kg	40
Net Weight of Control Module kg	3
Net Weight of Wire Coil, kg	17
Consumed Power, W	300

The system consists of the inspected unit, control module and wire coil. The inspected unit where the object is exposed to the neutron emission contains the neutron generator with Si alpha-detector embedded, BGO gamma-detector, detection electronics and power supply units. The control module encloses the operator PC.

A run of experiments was performed and gamma-spectra for melamine (1400 g in mass) as an explosive simulator and SPM-mine (the mine charge mass is 1 kg, the charge is composed of 17% TNT, 54% RDX, 17% Al, 7% deterrent) were drawn for air and water medium. The melamine sample and mine sample were put on the test bench (Fig. 6).

The water measurements demonstrated that the load of gamma-detector was four times higher at neutron yield $5 \times 10^7\ s^{-1}$ against that in the air medium (gamma-detector count is ~80 kHz in water and ~20 kHz in air). With the neutron yield going down to $1 \times 10^7\ s^{-1}$ the load of gamma-detector was decreased to 17 kHz in water.

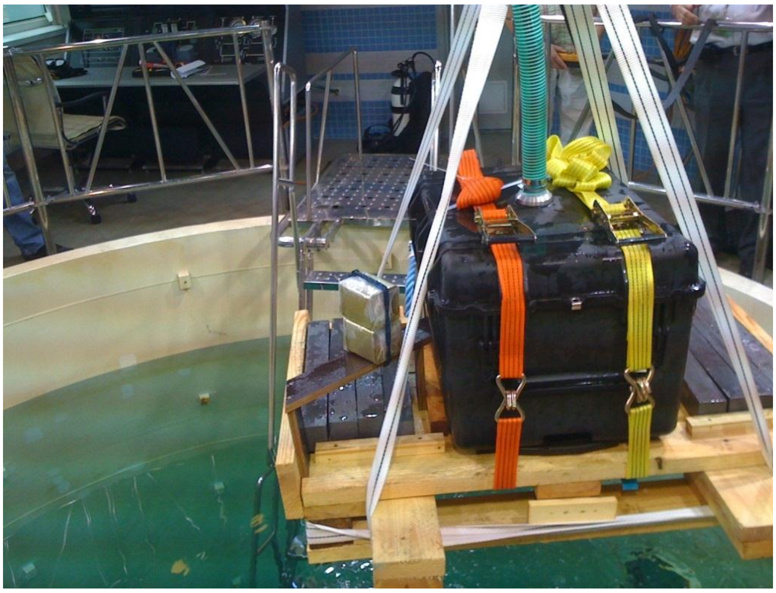
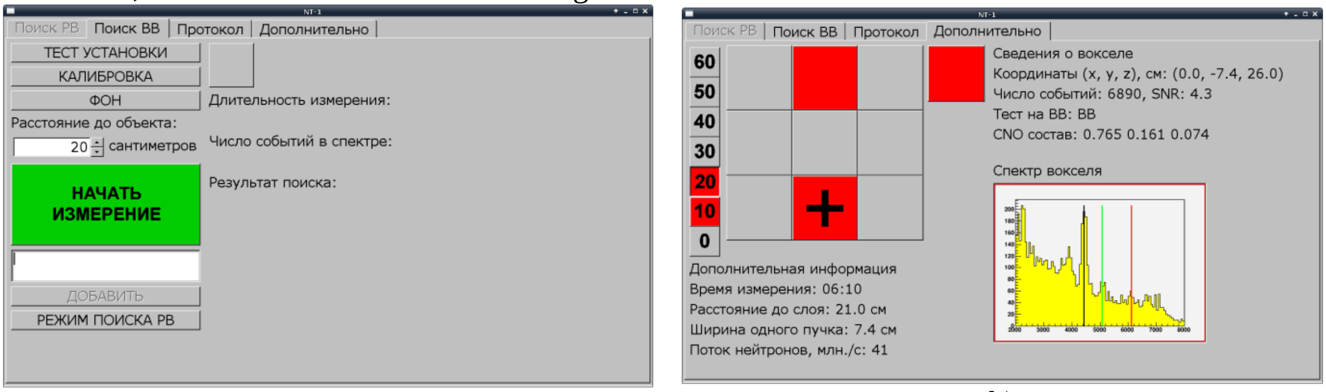


Fig. 6. Inspacted melamine sample on the test bench

Software of ДВиН-1 was used to process the data. Fig. 7 illustrates the software interface. The detectors transfer data to software that divides it into elementary domains relevant to the spatial cells (voxels) of the irradiated object. The voxels are formed by ‘tagged’ neutrons and a time span between signals coming from alha- and gamma-detectors. An index of ‘tagged’ beam is counted starting from the upper left corner (Fig. 7b). A distance to the elementary region along the selected ‘tagged’ beam is indicated in the left bar. A gamma-spectrum is drawn for each selected region. The spectrum is identified and its parameters are determined. If the selected voxel contains the matters identified as hazardous, the software marks it in red. It is green if the matters are unhazardous.



a) b)

Fig. 7. Interface of ДВиН-1 software: a) identification of explosives; b) measurement processing

Time and energy spectra of characteristic gamma-lines measured in water and air medium for two ‘tagged’ neutron beams are compared at Fig. 8 and 9. One beam (4) covers a hazardous substance (melamine), the second one (6) is free of explosives.

The observed differences of time gamma-spectra for beam 6 in water and air medium reveal a considerable contribution of water characteristic emission detected by gamma-detector. The energy spectra (Fig. 9) compared for two beams allow identifying the full energy absorption peaks of gamma-rays with energy E_γ = 4,43 MeV for C, E_γ = 5,1 MeV for N, E_γ = 6,13 MeV for O.

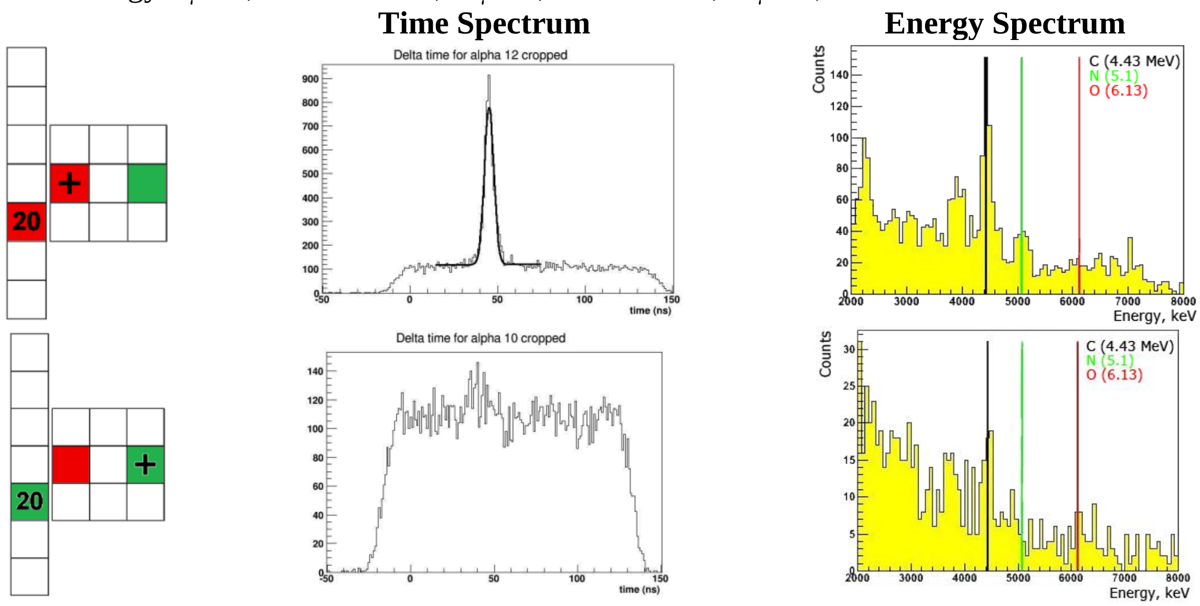


Fig. 8. Time and energy spectra of gamma-rays for beams 4 and 6 (air medium). Rightward “+” indicates a ‘tagged’ beam, the energy spectrum is drawn for, and a distance from the inspection unit along the selected beam is specified. The energy spectra have the lines that show the full energy absorbtion peaks of gamma-rays with enetry E_γ = 4.43 MeV for C, E_γ = 5.1 MeV for N and E_γ = 6.13 MeV for O

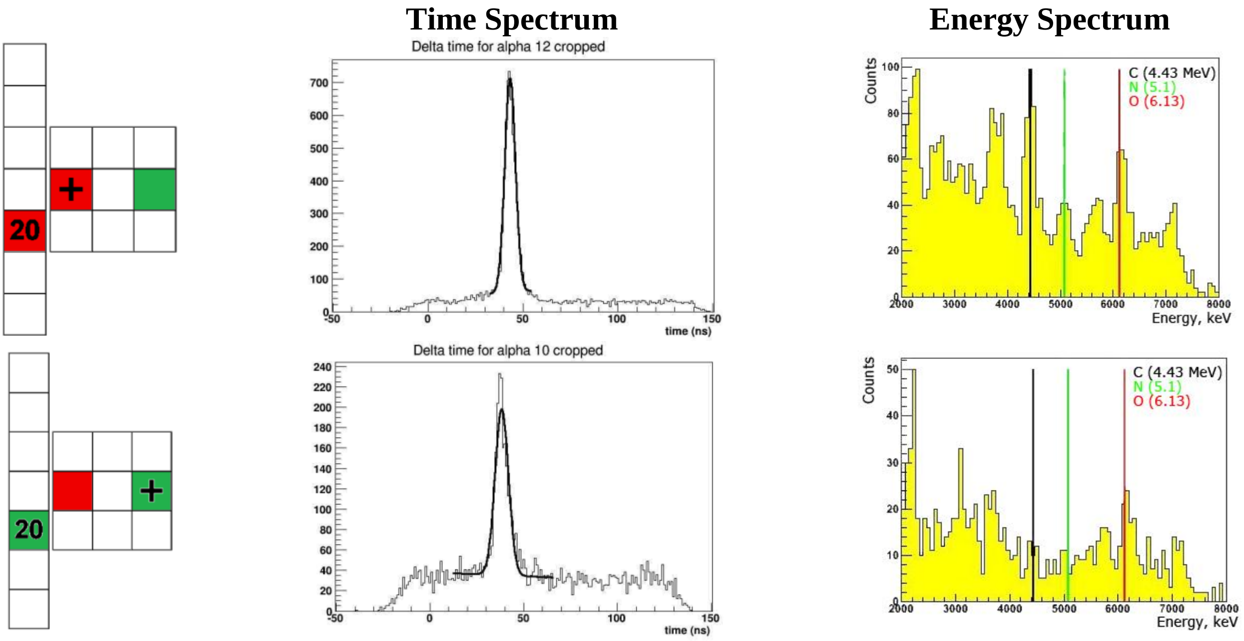


Fig. 9. Time and energy spectra of gamma-rays for beams 4 and 6 (water medium). Rightward "+" indicates a 'tagged' beam, the energy spectrum is drawn for, and a distance from the inspection unit along the selected beam is specified. The energy spectra have the lines that show the full energy absorbtion peaks of gamma-rays with energy E_γ = 4.43 MeV for C, E_γ = 5.1 MeV for N and E_γ = 6.13 MeV for O

A comparison of time and energy spectra in air and water medium reveals that the measurements of explosives in the same quantity are quite different subject to the medium. Hence the processing of data obtained in different medium (algorithms and selection criteria for the detected events) should be different.

In order to try the possible measurements of objects water-fenced from the inspected unit, a gamma-spectrum of melamine 20 cm distant was measured in water. Fig. 10 illustrates an energy spectrum of voxel. The spectrum has also a peak of N energy and an increased contribution in oxygen line. Thus it is possible to detect objects at 20 cm distance but with statistics time extended.

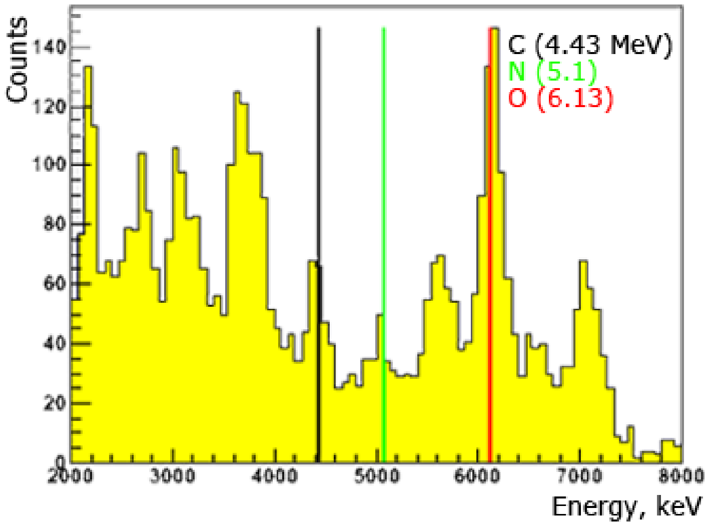


Fig. 10. Energy spectrum for melamine drawn in water at 20 cm distance from the inspected unit. The lines indicate the full energy absorbtion peaks of gamma-rays with energy E_γ = 4.43 MeV for C, E_γ = 5.1 MeV for N and E_γ = 6.13 MeV for O

As seen from the energy spectra when melamine and SPM mine are exposed to ‘tagged’ neutron radiation in water, peaks of C, N and O radiation become visual. As it becomes possible to single out the peaks of C, N and O among that of oxygen from H_2O, it allows detecting explosives under water.

The results obtained are well correlated with calculations made in GEANT4. Thus the defined criteria for ratio between the radiation rates of C, N and O enable to detect explosives submerged in water with high accuracy.

Conclusion

The API detectors for explosives were experimentally checked as to underwater operation. The results obtained revealed that its is feasible to single out the lines of characteristic radiation of C, N and O. It is shown that the effective detection of explosives under water is real provided that the water layer between the ‘tagged’ neutron source and the inspected object is less 20 cm thick. The experimental results are well correlated with calculations made in GEANT4.

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