JOINT INSTITUTE FOR NUCLEAR RESEARCH
Frank laboratory of Neutron Physics

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

Determination of the response function of the detector for y-quanta in the reaction of inelastic neutron scattering.

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Participation period:
July 01 – August 12

Dubna, 2018

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Abstract

Due to smearing of gamma-quantum energies in energy spectra, processing data from gamma-detectors with insufficient high resolution becomes non-trivial problem. To solve this problem, it is necessary to determine the response function of the gamma quantum detector, taking into account the most significant processes occurring in the interaction of detectors and particles.

The purpose of this work is to determine this function for the spectra, obtained in the simulation of the experiment in GEANT-4. This function has 7 components and takes into account the Compton scattering of gamma quanta in the detector, as well as the effect of the formation of electron-positron pairs with the possibility of subsequent escape of annihilation photons, and their scattering on the electrons of the scintillator.

Introduction

The TANGRA project (**TA**gged **N**eutrons and **G**amma **RA**ys), created in the Frank Laboratory of Neutron Physics considers the possibility of determining elemental composition of substance by angular distributions of neutrons and gamma quanta, emitted by irradiation of substance with a monochromatic neutron beam. Such a technique could be used to register explosives and drugs, and also to identify the contents of containers that could not be opened, and even to search for particularly valuable chemical elements in minerals.

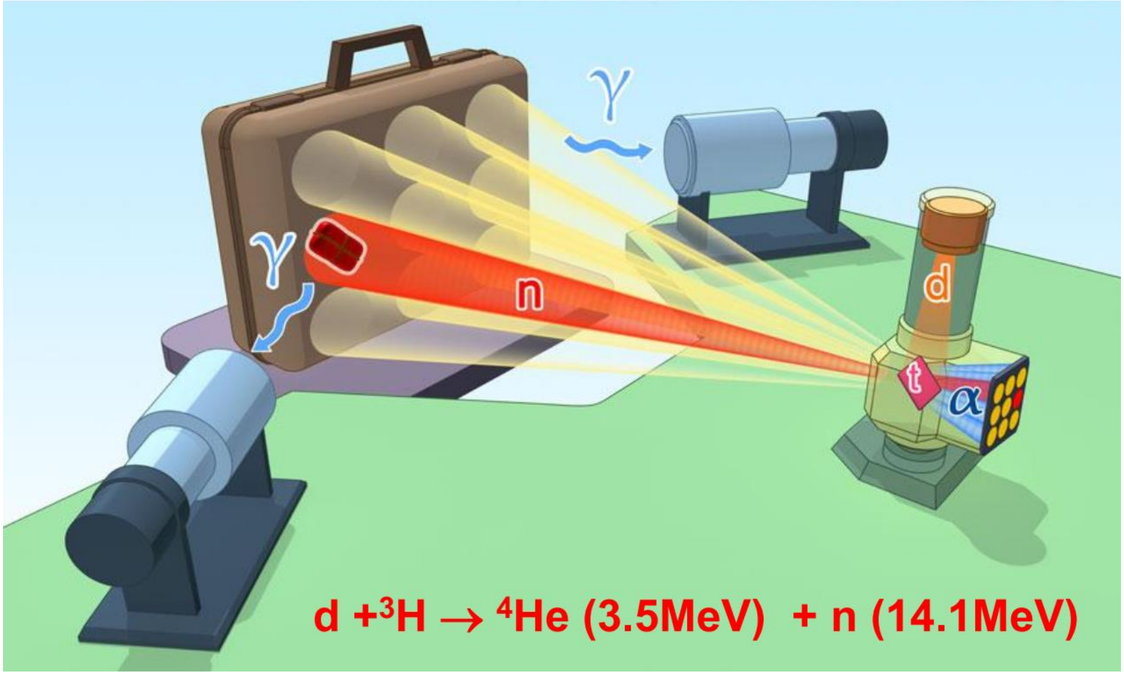


Fig. 1. *General scheme of detection of substances in closed containers using the tagged neutron method.*

The project is based on the method of tagged neutrons (MTN). This technique allows to identify neutrons, arising in the reaction

$$\mathrm{d} + \mathrm{t} \rightarrow \alpha(3.5\,\mathrm{MeV}) + \mathrm{n}\,(14.1\,\mathrm{MeV})$$

by alpha particles which correspond to them. The use of MTN compared to other identification methods, such as optical spectrometry, chromatography and others, has a list of advantages, including:

- Ability to determine precisely the intensity of the neutron beam and its angular distribution.

- Determination of the exact position of neutrons in space-time coordinate system by coincidence with the registered alpha particle.

- Reduction of background effect emerging because of long-term measurements.

- Ability to determine the composition and structure of unknown samples by the angular distribution of gamma lines, resulting from high-energy reactions between the observing sample and fast neutrons.

However, the current data on the angular distributions of gamma rays have insufficient accuracy. That’s why the method of tagged neutrons is still at the stage of development and improvement for now.

One important thing should also be mentioned. In addition to all that areas of practical application, the MTN is also applicable for the study of rare nuclear processes under the action of fast neutrons. This fact allows us to use this method in nuclear astrophysics, as well as for a more detailed description of the energy production and nuclear waste disposal.

Tagged neutron method

With the advent of reliable portable generators capable of creating monochromatic fast neutron beams, the method of labeled neutrons has gained wide popularity. The TANGRA project uses a neutron generator ING-27 based on the reaction

$$d + t \rightarrow \alpha(3.5\,\mathrm{MeV}) + n\,(14.1\,\mathrm{MeV})$$

Deuterons, accelerated by the potential difference to 100 KeV energy, collide with a tritium target. As a result of the reaction, alpha particles and neutrons appear, and the energy of the latter takes a certain value: 14.1 MeV.

Because of the α-particle and the neutron scattering occurs by 173° angle, it is easy to determine the direction of flight of the neutron by the corresponding α-particle. To do this, it is necessary to calculate the time between the collision between α-particles and pixel alpha-detector and the interaction of γ-quantum from the object of study with the corresponding gamma-detector. By measuring the time of flight, it is possible to determine the distance from the place of neutron arising to the point of its interaction with the nucleus, from which the γ-quantum flew. (The speed of a neutron with an energy of 14.1 MeV is known (5.2 cm/ns) and is considered to be constant.)

In the MTN, the substance is identified by its elemental composition, not by the density contrast, as in x-ray scanners. Fast neutrons excite the nuclei a of the substance in inelastic scattering reaction A (n,n' γ)A. this excitation is removed by emitting γ-quantum. The energy spectrum of γ-radiation contains the characteristic lines of the chemical elements of the object. This information allows us to build a three-dimensional image of the object and determine its elemental composition (C, N, O,...). The identification of explosives and drugs is based on the fact that the elemental composition of perilous substances is different from that of conventional substances.

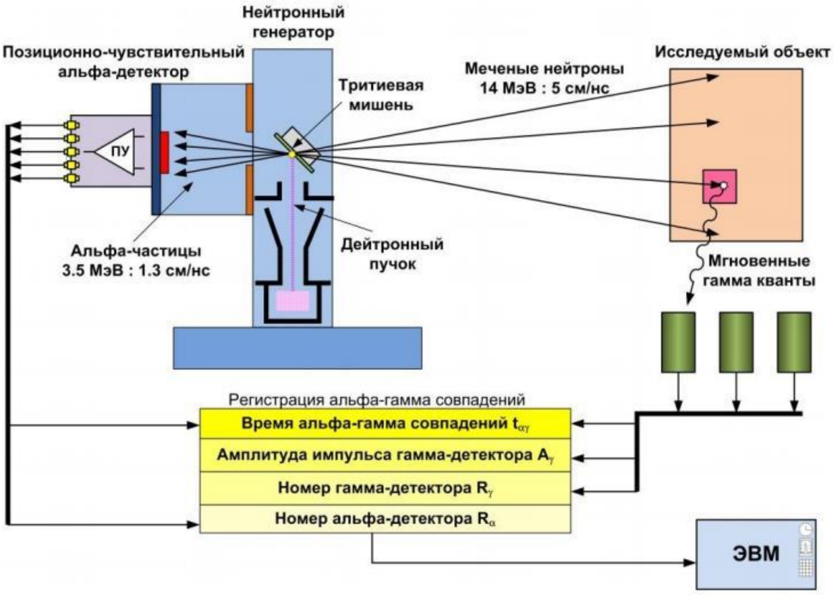


Fig. 2. *The TANRA measurement technique*.

The MTN’s ability to detect various elements allows it to be used not only for the detection of explosives and drugs, but also for quality control of coal, cement, oil (neutron logging), diamonds in kimberlite ores, etc.

Using the MTN for detection of dangerous substances in comparison with other methods of identification (the use of x-ray and infrared radiation, activation analysis on thermal and resonance neutrons) has a number of advantages, including:

- Obtaining information about the spatial location of the search object in one dimension;

- High sensitivity of the studied substances to the elemental and isotopic composition;

– High penetration of fast neutrons up to 1-1. 5 m;

- Almost complete absence of residual activation of the object under study;

- Improved effect/background ratio (> 200 times).

Experimental setup

A system of neutron generator and gamma detectors, called “ROMASHA” was created to implement the experimental work on the basis of the MTN. It consists of 18 scintillation BGO detectors and a neutron generator with a positionally sensitive alpha-detector.

The portable neutron generator ING-27 (NG) is used as a neutron source with a built-in silicon alpha detector, which forms 64 beams of labeled neutrons with an energy of 14.1 MeV. The neutron tube in its main modification creates a neutron flux into the solid 4π angle with a maximum intensity of 5·107 n/s, which is achieved at a maximum accelerating voltage of 80 kV and an ion beam current of 90 µa.

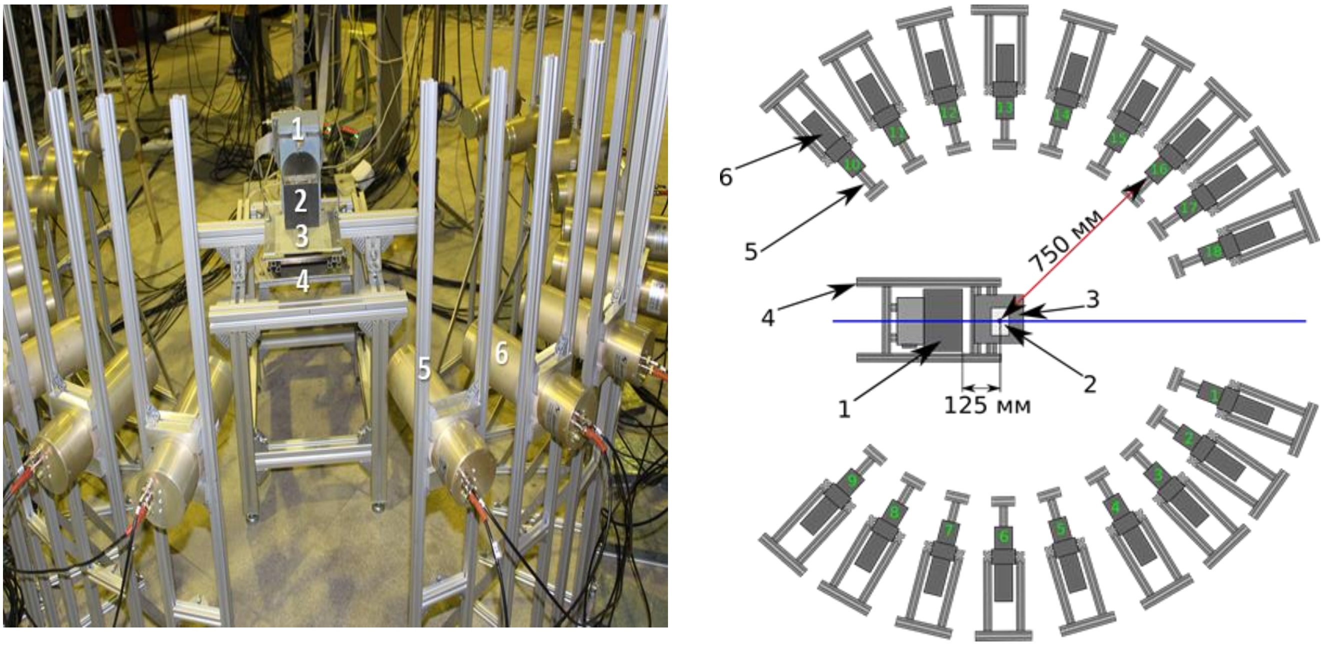


Fig. 3. *Photo of the experimental setup (left) and its schematic diagram(right): 1 neutron generator ING-27, 2 – tritium target, 3 – table with the irradiated object, 4 – table for ING-27, 5 –holder for gamma detector,6 – gamma detector (BGO), included in the array of 18 detectors «Romasha»*

The main configuration of the "ROMASHA" detector system consists of 18 scintillation BGO detectors, which are arranged in the form of two cylindrical assemblies of 9 detectors each. The diameter of each assembly and the distance between assemblies can be varied. It is possible to place the detectors in a compact configuration to achieve maximum geometric efficiency of the installation, or in an extended configuration to ensure sufficient span between the sample and the detectors to separate neutrons and gamma quanta registration events by time of flight, as well as to use an intermediate configurations to find the optimal relations between the efficiency of registration and resolution of the detector. The energy resolution of the detectors for gamma quanta energies of 662 Kev and 4-5 MeV is ~ 12% and 4%, respectively. The time resolution of the detectors in line with the fast scintillation counter is about 3 NS. The mechanical construction of the detector system allows the installation of additional detectors (HPGe, neutron counters, etc.).

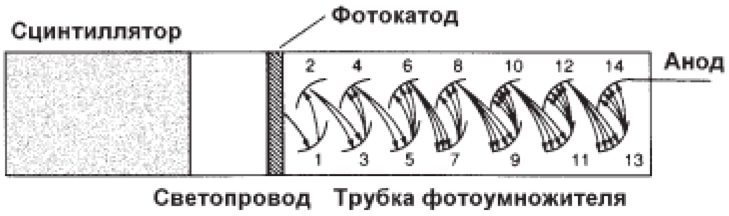


Fig. 4. *The typical location of components in a scintillation detector.*

The electronics used for both alpha-particle detection and gamma-quantum and neutron detection was made in the form of several boards with 16(32;48) inputs, which have the size of a standard PCI-card with the possibility of installing them in the PCI-E slot of a personal computer (PC). All information is exchanged with PC via PCI-e bus. The basis of the system of signal registration from alpha-and gamma-detectors relies on the principle of their digitization with restoration of time and amplitude characteristics of pulses.

Interaction of gamma-rays with matter

Insufficient high resolution of NaI and BGO detectors does not allow to identify precisely the energy spectra, obtained as a result of the experiment. To solve this problem, the TANGRA project develops a universal response function of gamma-ray photon detector of scintillation type.

This function should take into account the processes occurring with gamma rays in the scintillator.

The primary processes resulting from the interaction of gamma rays with the substance include the photoelectric effect, Compton scattering, and the formation of proton-electron pairs.

- Photoelectric effect:

A photoeffect is a process in which an atom absorbs a photon and emits an electron. In the internal photoelectric effect, the electron is emitted outside the atom with kinetic energy

$$T_e = E_\gamma - I_i$$

where, E_γ – energy of γ – quanta, I_i – potential of ionization of I atom shell.

Photovoltaic absorption is an important process for the registration of γ radiation, because γ-rays are losing all their energy, and therefore, all the energy of the gamma-ray will be absorbed by the detector.

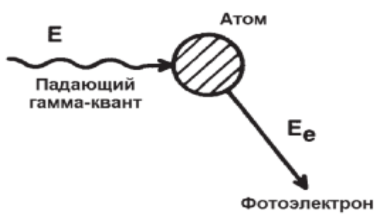


Fig. 5: *Photoelectric effect scheme.*

As the energy of the incoming photons increases, the reaction cross section begins to fall, as the electrons become more and more like free ones, for which the photoelectric effect is no longer possible. In descending order E_γ the cross section increases because of enlarged coupling of the electrons. Therefore, the photoelectric effect comes mainly from the K – shell (more than 80% of interactions occur with the participation of electrons to this shell).

- Compton effect:

Compton scattering is an elastic scattering process in which a γ - quantum interacts with a free or weakly bound electron and shares its energy with the electron.

The electron becomes non-coupled particle with kinetic energy equal to the difference between the energy lost by the γ - quantum and the binding energy of the electron. Since the binding energy of the electron is very small compared to the energy of the γ-quantum, the kinetic energy of the electron is very close to the energy lost by the γ-quantum:

$$E_e = E_\gamma - E'$$

where E_e — energy of emitted electron, E_γ — primary γ-quantum energy, E' — scattered γ – quantum energy.

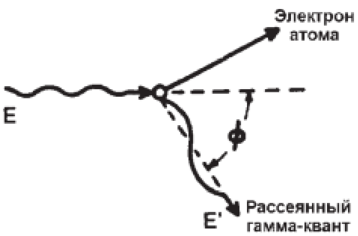


Fig. 6. *Compton scattering scheme.*

Two particles leave the interaction point: an emitted electron and the scattered γ - quantum. Trajectory of the electron and the scattered γ-quantum depends on the amount of energy shared with the electron during the interaction.

The formula for computing the Compton scattering differential cross section was derived by Klein and Nishina in 1928. It has the following form:

$$\frac{d\sigma_k}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'_\gamma}{E_\gamma}\right)^2 \cdot \left(\frac{E_\gamma}{E'_\gamma} + \frac{E'_\gamma}{E_\gamma} - \sin^2\theta\right) \cdot Z$$

where $r_e = \dfrac{e^2}{m_e c^2}$, - classical electron radius, Z - atomic charge.

The complete cross section of the Compton scattering can be obtained by integrating the previous formula over the entire solid angle:

$$\sigma_{комптон} = \pi r_e^2 \left\{ \left[1 - 2\frac{(\gamma+1)}{\gamma^2} \right] \ln(1+2\gamma) + \frac{1}{2} + \frac{4}{\gamma} - \frac{1}{2}(2\gamma+1)^2 \right\} \frac{Z}{\gamma}$$

- Electron-positron pairs formation:

The process of formation of electron-positron pairы is that as a result of the absorption of a quantum of light in the nucleus field. In this interaction, the nucleus acquires a small amount of energy to preserve the momentum. Another part of the energy (1022 MeV) goes to the formation of the electron and positron, and the excess energy is converted into the kinetic energy of the proton and electron.

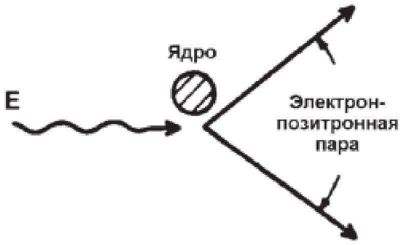


Fig. 7. *Electron-positron pairs scheme.*

After the deceleration of the decay products, the positron and electron annihilate, resulting in two gamma quanta with energies of 0.511 MeV. In this case, both photons or one of them can leave the detector and carry a part of the energy. If the quantum of light does not experience Compton scattering, then two peaks with energies separated from the peak of total absorption by 0.511 and 1.022 MeV will be allocated in the spectrum.

The response function of gamma detector

In this work, the response function of BGO and NaI detectors for different energies of γ-quanta is determined. The simulation of processes was carried out by the Monte Carlo method, using the GEANT 4 software package. In the simulation process, seven main components of the response function were identified. Each of them has a unique form of energy dependence. All of the components are described by different mathematical functions:

1. The total absorption peak - corresponds to the total energy of photon left in detector.
2. The single escape peak – is quite similar to the total absorption peak except the escape of one annihilated photon (511 KeV).
3. The double escape peak – is quite similar to the total absorption peak except the escape of two annihilated photons (1022 KeV).
4. The Compton continuum of single Compton scattering.
5. The Compton continuum of multiple Compton scattering.
6. 7. The Compton continuum after the single and double escape of annihilated photons.

GEANT4's capabilities allow us to distinguish each of these components programmatically, in contrast to an experiment in which only the full energy response of the detector can be observed.
The response function describing the interaction of a photon with the energy of the E_γ is defined as

$$R(E, E_\gamma) = \sum_{i=1}^{7} f_i(E, E_\gamma)$$

where E - energy, obtained by detector.

1. Total absorption peak

The processing of this histogram was carried out by the Gauss function, which has the following form:

$$f(x) = \frac{A}{\left(\sqrt{2\pi} \cdot B_1\right)} \exp\left(\frac{-\left(E - E_0\right)^2}{2 \cdot B_1{}^2}\right)$$

where A is the area under the peak, B1=σ is the dispersion of the function (determines the width of the peak), E_0 is the photon energy (peak position).

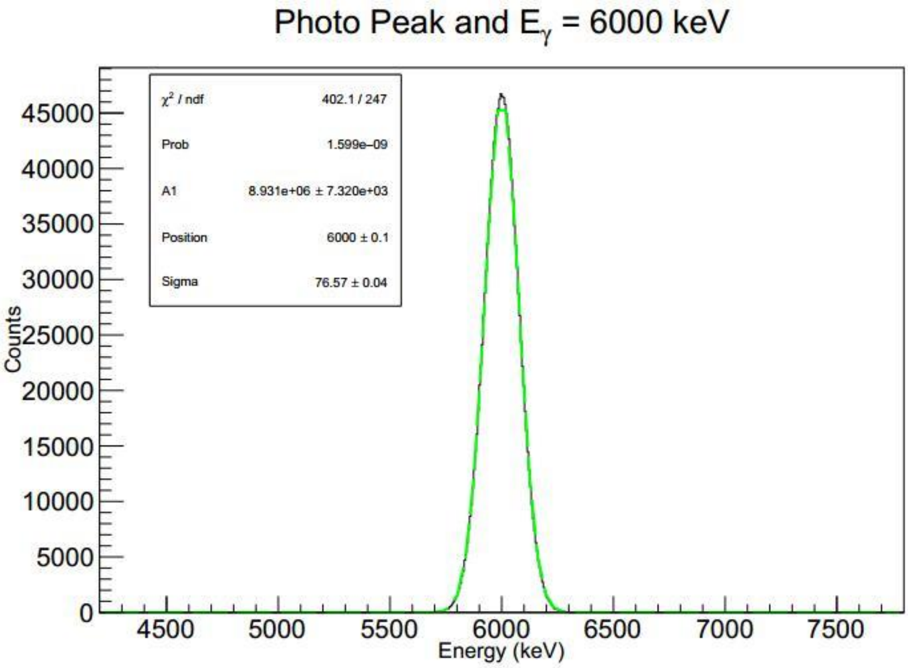


Fig. 8. *Total absorption peak.*

2. Single escape peak

If one of the annihilation gamma quanta, which appeared as a result of the formation of photon pairs, will escape from the detector without entering into interaction, the energy, registered in the detector, will be equal to E_0 – 511 KeV. Such events will contribute to the peak of a single flight.

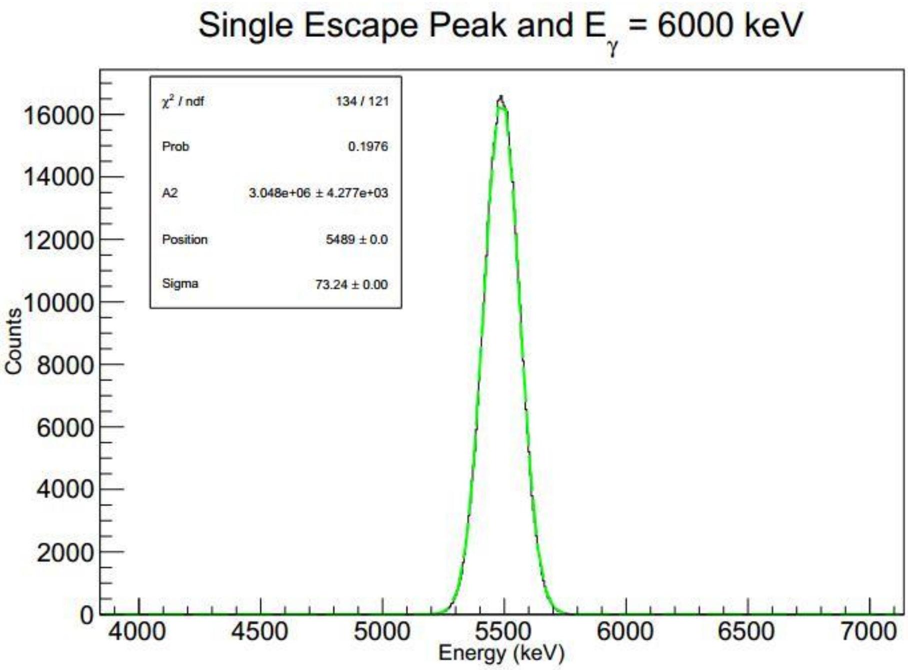


Fig. 9. *Single escape peak.*

This peak is also described by the Gauss function:

$$f(x) = \frac{A}{\left(\sqrt{2\pi} \cdot B_2\right)} \exp\left(\frac{-(E-(E_0-511)^2}{2 \cdot B_2^2}\right)$$

$$B_2 = \sigma \cdot \left(\frac{\sqrt{E_0}}{\sqrt{E_0 - 511}}\right)$$

where A is the area under the peak, E_0 is the energy of the gamma quantum. However, unlike the peak of total absorption, for this function the free parameter is only the peak area, while its dispersion and position are related to the width and position of the peak of total absorption by the mentioned ratios.

3. Double escape peak

If both annihilation γ - quanta are emitted from the detector, this event will be recorded in the double departure peak (E_0 - 1022 Kev). The peak of the double departure is also described by the Gauss function:

$$f(x) = \frac{A}{\left(\sqrt{2\pi} \cdot B_3\right)} \exp\left(\frac{-(E-(E_0-1022)^2}{2 \cdot B_3{}^2}\right)$$

$$B_3 = \sigma \cdot \left(\frac{\sqrt{E_0}}{\sqrt{E_0 - 1022}}\right)$$

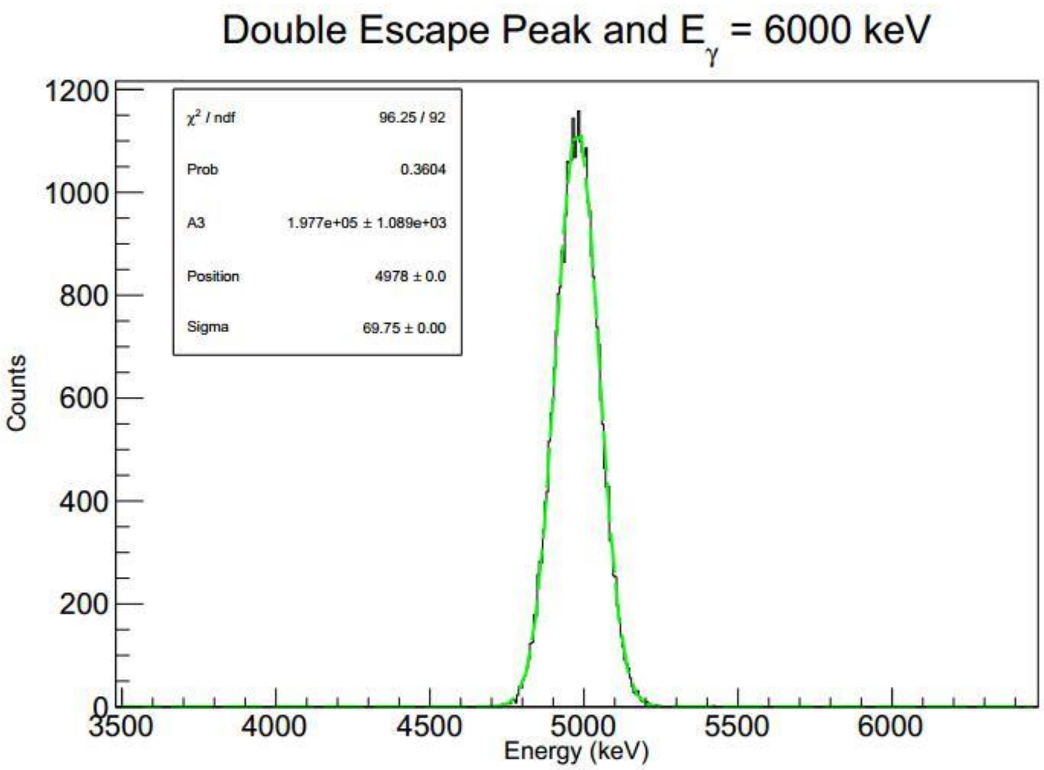


Fig. 10. *Double escape peak.*

4. The Compton continuum of single Compton scattering

The structure of the Compton effect is described by the Klein-Nishina formula multiplied by the exponential function and the error function, which determines the broadening of the spectrum to the edge of the Compton energy E_c.

The full formula for describing the Compton continuum is

$$f(x) = A \cdot \left[\left(\frac{E_0}{E_1} \right) + \left(\frac{E_1}{E_0} \right) - 1 + \cos^2 \theta \right] erfc \left[\frac{(E - E_c)}{\sqrt{2} \cdot B_4} \right] \exp \left[\frac{E - E_2}{C_0} \right]$$

where $\cos\theta = 1 + \left(\frac{m_0 \cdot c^2}{E_0} \right) + \left(\frac{m_0 \cdot c^2}{E_1} \right)$, $E_1 = E_0 - E$, $B_4 = \sigma \cdot \frac{\sqrt{E_0}}{\sqrt{E_c}}$

and $E_c = \frac{E_0}{\left[1 + \frac{m_0 \cdot c^2}{2 \cdot E_0} \right]}$ - Compton border energy, E_2 - maximum energy for which the exponent is defined (over that energy it equals 1) , C_0 - parameter that determines the slope of the exponent, and $m_0 \cdot c^2$ is the rest energy of the electron.

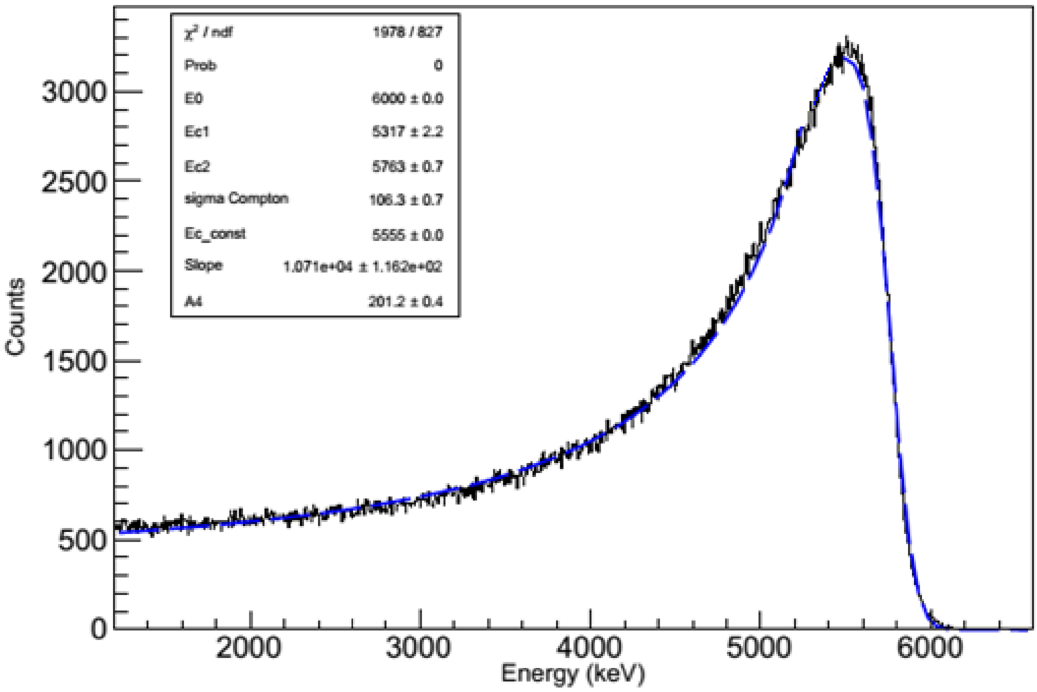


Fig. 11. *The Compton continuum of single Compton scattering.*

5. The Compton continuum of multiple Compton scattering

The entire Compton continuum cannot be described by one relatively simple formula. For multiple Compton effect, photon polarization as well as some other effects must be taken into account. Therefore, at this work only a single photon scattering by an electron is theoretically described. All other processes are included in the histogram of multiple Compton continuum except of the electron and positron leaks, (everything that is not described by components 4, 6 and 7).

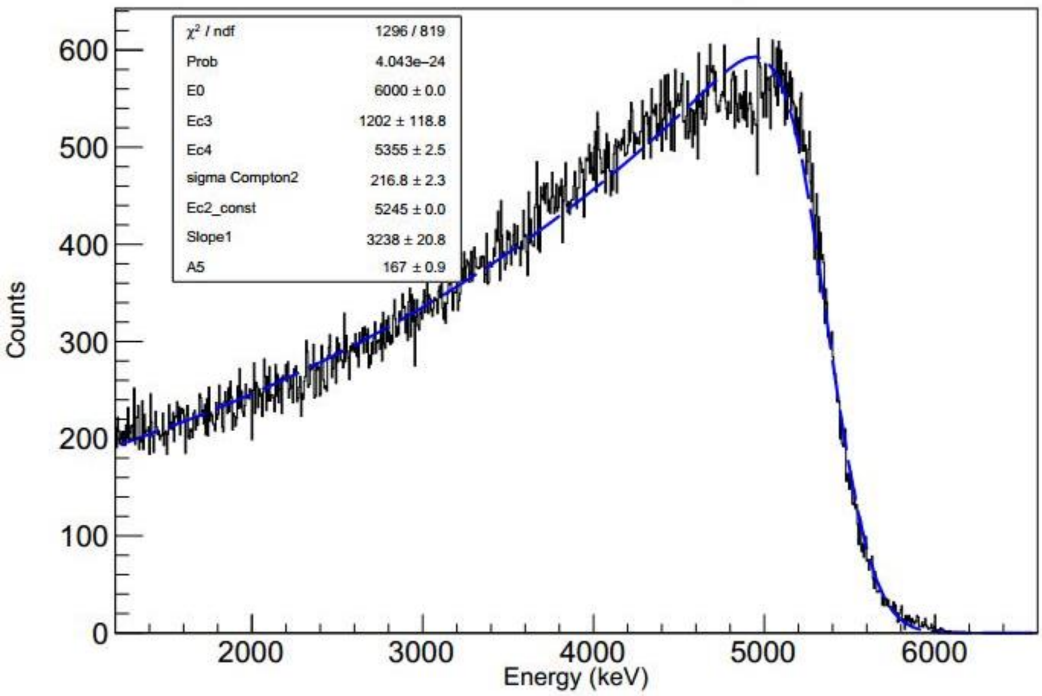
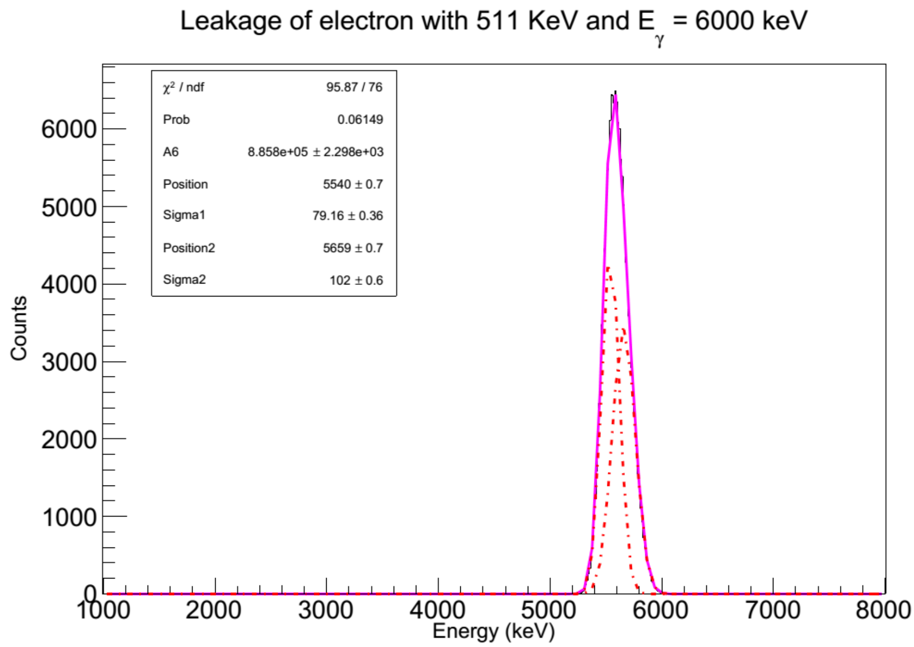


Fig. 12. *The Compton continuum of multiple Compton scattering.*

The formula for the Compton continuum of single Compton scattering can also be used to describe this component, but with other parameters.

6. Compton continuum from annihilation photons (6-7)

The sixth and seventh parts are important components of the response function. The physical meaning of these components is the leakage of annihilation γ - quanta that have experienced Compton scattering. Since the energy carried away is less than 511 and 1022 Kev, respectively, the absorbed energy in the detector is greater than E_0-511 and E_0-1022, so these components are to the right of the corresponding leakage peaks.



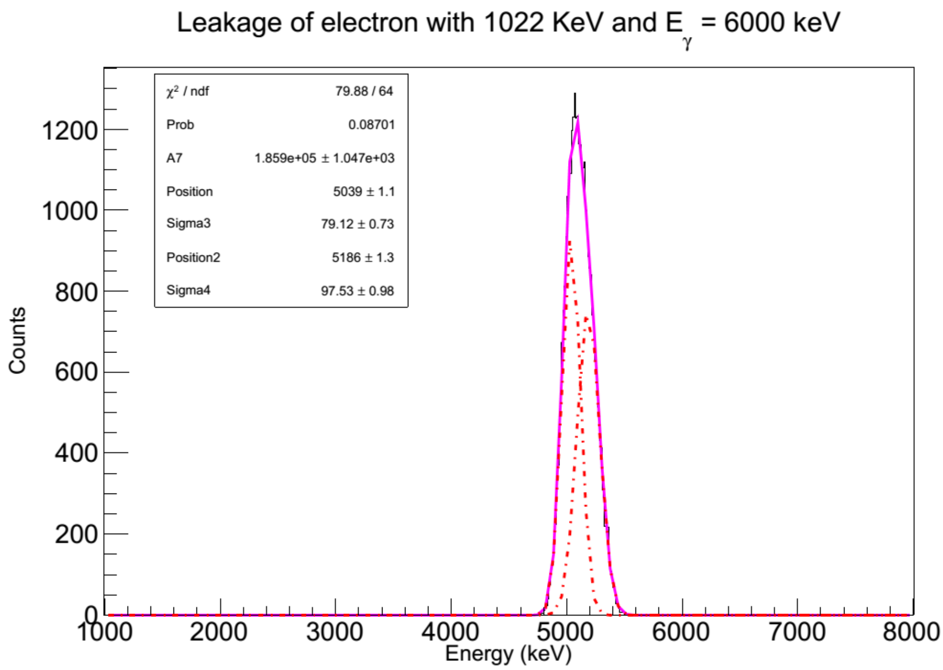


Fig. 13. *Leakage of electrons with* E_γ = *6 MeV*

These histograms were described by the following function:

$$f(x) = \frac{A}{\left(\sqrt{2\pi} \cdot B_5\right)} \exp\left(\frac{-(E - E_1)^2}{2 \cdot B_5^{\ 2}}\right) + \frac{A}{\left(\sqrt{2\pi} \cdot B_6\right)} \exp\left(\frac{-(E - E_2)^2}{2 \cdot B_6^{\ 2}}\right) \tag{36}$$

This histogram was processed by summing two Gauss functions, where A is the area under the peak, B_5 and B_6 are the dispersion functions, and E_1, E_2 determine the position of each peak.

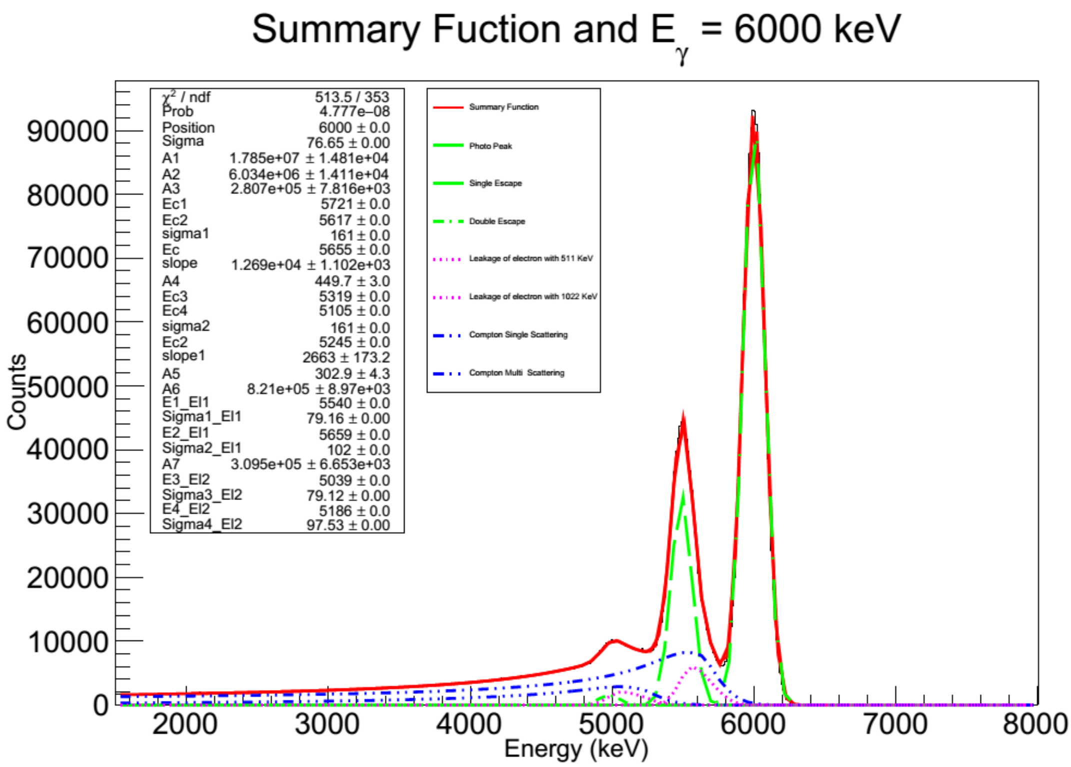


Fig. 14. *BGO detector response function (6 MeV).*

The total description of the model response function of the BGO detector in case of ingress of γ - quanta with energy of 6 MeV, based on the above components, is shown in the fig. 14.

Conclusion

Thus, in this work, a response function describing the energy spectrum from the monochromatic beam of gamma quanta of different energies, detected by the NaI and BGO detectors, was constructed.

The response function is the sum of seven major components contributing to the spectrum: the peak of total absorption, the escape peaks of one and two annihilation photons, the Compton continuums, and the Compton scattering of photons, formed as a result of the annihilation of positrons from primary gamma quanta.

The ROOT and GEANT4 software environments were used to solve the problem.

The response function, obtained as a result of the Summer Student Practice, can be used in the TANGRA project in the analysis of the elemental composition of various substances.

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