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Response function of a BGO detector for γ-rays with energies in the range from 0.2 MeV to 8 MeV

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This work is devoted to determination of the response function of a BGO detector of γ-rays, which is used in experiments aimed at investigation of inelastic scattering of neutrons with energies of 14.1 MeV on various nuclei. A function is constructed to describe the Monte-Carlo simulated response of a gamma-detector, which allows taking into account all possible mechanisms of interaction of γ-rays with matter, as well as the geometric parameters of the detector. For all components of the function, an analytical form of their energy dependencies is selected and its parameters are determined in the case of registration of γ-quanta with energies in the range from 0.2 MeV to 8 MeV.

Keywords: TANGRA, 14 MeV Neutrons, BGO, GEANT4, Monte-Carlo simulation

1 Introduction

At Joint Institute for Nuclear Research (JINR, Dubna, Russia), in the framework of the project TANGRA (TAgged Neutrons and Gamma RAys), we continued the experiments for studying the inelastic scattering of fast neutrons on some important for nuclear science and technology isotopes[1]. The design of the experimental setup that includes a ring of γ-detectors and a neutron generator, allows measuring the angular distribution of gamma quanta with good accuracy[2,3]. The information about these distributions makes it possible to test different models, describing neutron-nuclear reactions, and to improve the accuracy of the fast neutron elemental analysis.

When processing data from γ-ray detectors with insufficient high resolution, the task is to accurately determine the number of events corresponding to registration of γ-quanta with certain energy. Due to the variety of physical processes that occur during the interaction of gamma quanta with the detector material, both the broadening of the peak of total absorption of gamma quanta energy (photo-peak) and the formation of various components in the energy spectrum take place. To solve this problem, it is necessary to determine the response function of the γ-ray detector, taking into account the most significant processes that occur during the interaction of the detected particles with the detector material. The experimental obtaining of the response function requires a significant number of sources of monochromatic γ-radiation and takes a lot of time, therefore, in recent years, the Monte-Carlo method[4,5] has been widely used to calculate the response function.

The aim of this work is to construct a response function that allows us to approximate the energy spectra of gamma rays, obtained in experiments with the TANGRA setup. Such a function has seven components and takes into account the Compton scattering of γ-quanta in the detector, as well as the effect of the formation of electron-positron pairs with

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the possibility of subsequent emission of annihilation photons. For each component, the dependences of the fitting functions on the energy of incident γ-quanta are established.

2 TANGRA Setup

The scheme of TANGRA-setup for studying the fast neutron scattering reactions is shown in Fig. 1. The neutron generator ING-27 is used as a neutron source. The neutrons are produced in the reaction (1), induced by the continuous deuteron beam with kinetic energy of about 100keV, focused on a tritium-enriched target.

$$d + t \rightarrow n + \alpha \quad \dots (1)$$

The products of this reaction are a 14.1 MeV neutron and a 3.52 MeV α-particle. The maximal intensity of the "tagged" neutron flux in 4π-geometry is $5{*}10^7 c^{-1}$. The α-particles are registered with a 64−pixel α-detector with pixel dimensions of 6×6 mm^2. The α-detector is located at a distance of 10cm from the tritium-enriched target.

The γ-quanta emitted in the neutron inelastic scattering are registered by a "Romasha" system, consisted of 18 BGO-scintillator γ-detectors placed around the sample with step of ∼14°. The energy resolution of these detectors for 662keV and 4-5MeV γ-ray energies is 12% and 4%, respectively. The time resolution for gamma detection is about 3ns.

3 Determination of the Response Function

The energy spectrum of gamma quanta can be decomposed into separate components, and their

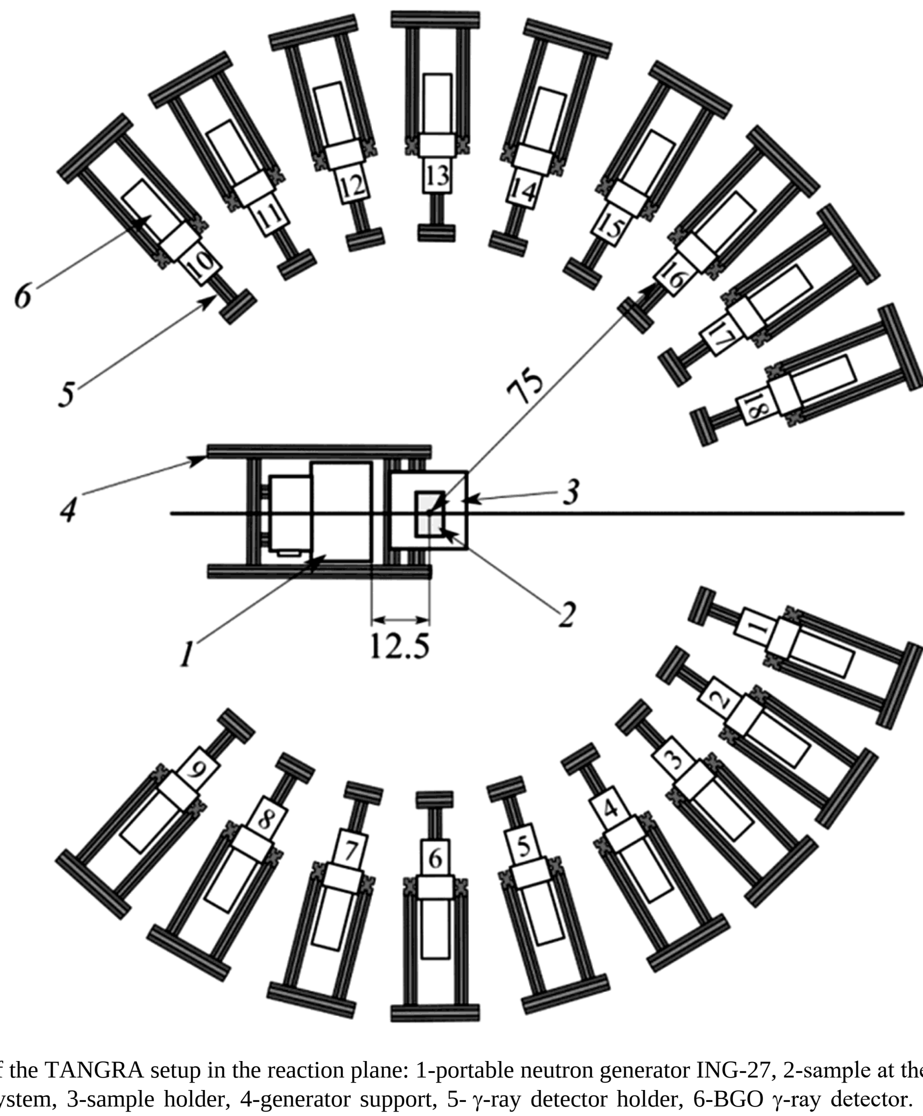

Fig. 1 — Scheme of the TANGRA setup in the reaction plane: 1-portable neutron generator ING-27, 2-sample at the center of "Romasha" γ-ray registration system, 3-sample holder, 4-generator support, 5- γ-ray detector holder, 6-BGO γ-ray detector. The "tagged" neutron beam direction is indicated by vertical plane line.

correct accounting will improve the determination of the number of registered gamma quanta due to a qualitative description of the "substrates" under the photo-peaks Fig. 2.

Each component of the spectrum is approximated by its corresponding function. The detector response function defined in this work is the sum of these components and describes the spectrum of recorded photons.

The response function $R(E,E_\gamma)$ of the detector to monochromatic radiation characterizes the probability of the transfer of energy E to the sensitive volume of the detector when a gamma quantum with energy E_γ hits it. Since the experimental determination of the response function is a costly process, numerical modeling is currently widely used. In this work, the modeling was carried out using the Monte-Carlo method implemented in GEANT4[6]. The capabilities of GEANT4 make it possible to distinguish the physical component of the response function in a programmatic manner, in contrast to an experiment in which only the total response function of the detector can be observed. The response function describing the interaction of a photon with energy E_γ is defined as:

$$R\left(E, E_\gamma\right) = \sum_{i=1}^{n} f_i\left(E, E_\gamma\right) \quad \dots (2)$$

where $f_i(E, E_\gamma)$ are functions of the individual component and E is the energy deposited in the detector. During the modeling process, six main components of the response function were identified, which are described by various mathematical functions:

a) **Full energy peak** – full absorption of gamma-quantum energy in the detector crystal. To approximate the peak, we used a Gauss function with parameters A_0 , σ_0 and E_0:

$$f_1(E) = \frac{A_0}{\sqrt{2\pi}.\sigma_0} \exp\left(\frac{-(E-E_0)^2}{2\sigma_0^2}\right) \quad \dots (3)$$

b) **Single Escape Peak** – when gamma-quantum with $E_\gamma \geq 1022\text{keV}$ interacts with a crystal substance, an electron-positron pair is created, followed by a further positron annihilation and one of the two 511keV annihilation gamma-quanta escapes the crystal (energy released in the crystal is ($E_\gamma - 511$ keV)). The parameters of the function describing this contribution are related to the parameters of the peak absorption function:

$$f_2(E) = \frac{A_1}{\sqrt{2\pi}.\sigma_1} \exp\left(\frac{-(E-E_0-511)^2}{2\,\sigma_1^2}\right) \quad \dots (4)$$

Where $\sigma_1 = \sigma_0 * \sqrt{\frac{E_0-511}{E_0}}$

c) **Double Escape Peak** – when a gamma-quantum with $E_\gamma \geq 1022\text{keV}$ interacts with a crystal substance, an electron-positron pair is created, followed by a further positron annihilation and both 511 keV annihilation gamma-quanta escape the crystal (energy released in a crystal is (E_γ–1022 keV)). In this case, the parameterization is also related to the parameters of the peak absorption function:

$$f_3(E) = \frac{A_2}{\sqrt{2\pi}.\sigma_2} \exp\left(\frac{-(E-E_0-1022)^2}{2\sigma_2^2}\right) \quad \dots (5)$$

where $\sigma_2 = \sigma_0 * \sqrt{\frac{E_0-1022}{E_0}}$

d) **Compton of the Single Escape Gamma**– one of the annihilation gamma-quanta with energy of 511 keV experiences Compton scattering (single or multiple) and escapes the detector, the other is fully absorbed. This energy distribution has the form of a continuum located to the right of the single escape peak. This component can be approximated by the sum of two Gaussians:

$$f_4(E) = \frac{A_3}{\sqrt{2\pi}*\sigma_4} \exp\left(\frac{-(E-E_4)^2}{2\sigma_4}\right) + \frac{A_3}{\sqrt{2\pi}*\sigma_5} \exp\left(\frac{-(E-E_5)^2}{2\sigma_5}\right) \quad \dots (6)$$

e) **Compton of the Double Escape Gamma**–both annihilation gamma-quanta with energy of 511 keV experience Compton scattering (single or multiple) and escape the detector. This energy distribution has the form of a continuum located

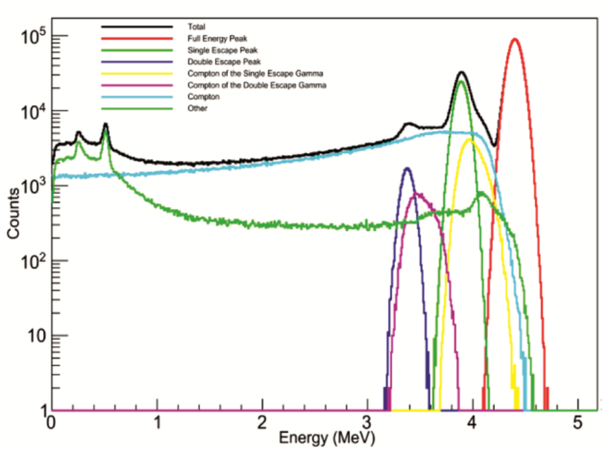

Fig. 2 — Simulation of response to mono energetic γ-rays with energy 4.4MeV.

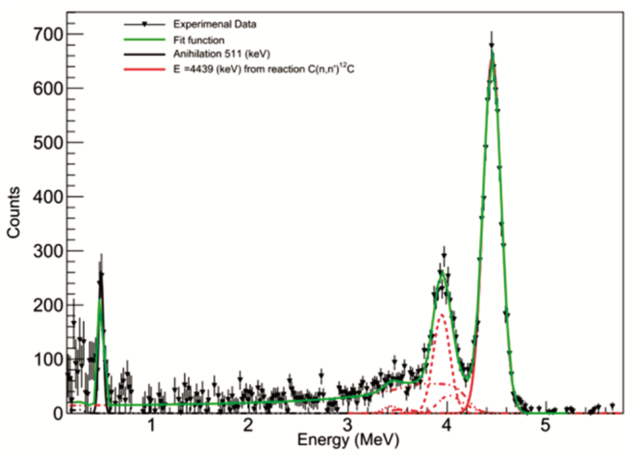

Fig. 3 — Use the response function to fit experimental data from reaction $^{12}C(n,n'\gamma)^{12}C$ and γ-rays with energy 4.39 MeV[7].

to the right of the double escape peak and can also be approximated by the sum of two Gaussians:

$$f_5(E) = \frac{A_4}{\sqrt{2\pi}*\sigma_6}\exp\left(\frac{-(E-E_6)^2}{2\sigma_6}\right) + \frac{A_4}{\sqrt{2\pi}*\sigma_7}\exp\left(\frac{-(E-E_7)^2}{2\sigma_7}\right) \quad \dots (7)$$

f) **Compton** - scattering is usually described by the Klein-Nishina formula, but this formula is valid only for the scattering of a photon on a single free electron. In real detectors the Compton scattering processes are more complicated, including multiple scattering, influence of the detector resolution etc. We approximated the Compton scattering processes by two components: one is approximately accounting for the single Compton scattering, and the second – all multiple processes. Both components have similar shape, but different parameters.

$$f_6(E) = A_5 * \left[\left(\frac{E_0}{E_0-E_8}\right) + \left(\frac{E_0-E_8}{E_0}\right) - 1 + cos^2\theta_1\right] * \mathrm{erfc}\left[\frac{E-E_c}{\sigma_8}\right] * \exp\left(\frac{E-E_c}{C_0}\right) + A_6 * \left[\left(\frac{E_9}{E_9-E_{10}}\right) + \left(\frac{E_9-E_{10}}{E_9}\right) - 1 + cos2\theta 2 * \mathrm{erfc} E - Ec\sigma 9 * \exp E - EcC1\right. \quad \dots (8)$$

where $cos\theta_1 = 1 + \left(\frac{m_0e^2}{E_0}\right) + \left(\frac{m_0e^2}{E_0-E_8}\right)$,

$$cos\theta_2 = 1 + \left(\frac{m_0e^2}{E_0}\right) + \left(\frac{m_0e^2}{E_9-E_{10}}\right)$$

and $E_c = \frac{E_0}{1+\frac{m_0e^2}{2*E_0}}$.

The total function includes all previous components. Using this way constructed response function we successfully fitted the energy spectra of γ-rays from $^{12}C(n,n'\gamma)^{12}C$-reaction which consists of a single 4.44MeV line (Fig. 3).

4 Conclusions

Based on different interactions of gamma-rays with detecting media atoms, we constructed a semi-empirical detector response function, describing main components of these processes. After the successful fitting of GEANT4-generated energy spectra with the constructed combined analytical function, we applied this approach for deconvolution of gamma-spectra from neutron-induced radioactive nuclear reactions on Carbon investigated by TANGRA BGO crystal-based gamma-ray spectrometers.

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