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Determination of the response function of the NaI detector for γ-quanta with an energy of 4.43 MeV, formed during inelastic scattering of neutrons with an energy of 14.1 MeV on carbon nuclei

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The work is devoted to determining the response function of the detector NaI(Tl) for γ-quanta with energy of 4.43 MeV, formed during inelastic scattering of neutrons with energy of 14.1 MeV on the nuclei ^{12}C. In gamma spectrometry, output pulses are recorded, the amplitudes of which are proportional to the energy lost in the detection medium by incident photons. One of the main tasks of radiation detection is to restore radiation characteristics from signals measured at the outputs of detectors. For this, it is necessary to know, first of all, the general characteristics of detectors as converters of radiation into signals. The main characteristic of the detector is its response function, which can be defined as the probability that a particle with given properties generates a certain signal in the detector that will be registered by the device. The article presents the results of modeling the response function of a scintillation detector based on a NaI(Tl) crystal for gamma radiation from inelastic fast neutron scattering in order to study the mechanism of its formation.

Keywords: response function, γ-quanta, scintillation detectors.

Introduction

Information about the response function of the detector and the possibility of calculating it are necessary to understand the formation of the analytical signal and background. They are important for decoding energy spectra, as well as for choosing the optimal recording conditions.

The response function of the detector characterizes the probability of transmitting energy E to the sensitive volume of the detector when a γ-quantum with energy E_γ enters it. Experimental acquisition of the response function requires a significant number of sources of monoenergetic gamma radiation and takes a long time. Therefore, in recent years, the Monte Carlo method has become widespread for calculating the response function of detectors [1-5]. Determination of the detector response function in a wide range of gamma-radiation energies is necessary for the correct interpretation of experimental data and for calculating the characteristics of the devices being developed for recording nuclear radiation [6].

In the present work, calculations of the response function are also made by the Monte Carlo method, which allows taking into account both the possibility of multiple interactions of photons with matter and the geometric features of the detector.

Defining the response function of the detector

In our case, to analyze the data on the angular correlations of γ-quanta in the reaction $^{12}C(n,n')^{12}C^* \xrightarrow{\gamma} {}^{12}C$, it is enough to determine the detector response function for one gamma line - 4438 MeV, since the gamma spectrum of carbon formed in this reaction consists of this single line corresponding to the first excited state of ^{12}C [1]. In detectors, the energies and intensities of γ-quanta are determined not directly, but with the help of secondary charged particles (electrons and positrons), which arise as a result of the interaction of the detected gamma quanta with the substance of the detector. When a γ-quantum enters the detector, charged particles are formed as a result of three processes: the photoelectric effect, the Compton effect, and the formation of electron-positron pairs.

To determine the response function of the detector, the energy spectrum was modeled, recorded by the NaI(Tl) detector when a γ-quantum with an energy of 4.43 MeV hits it. The simulation was carried out by the Monte Carlo method using the GEANT4 software package [7].

During the simulation process, seven main components of the response function were identified, which have different forms of energy dependence and which were described by the corresponding mathematical functions:

1. The peak of total absorption - corresponds to the complete transfer of the energy of the incident gamma quantum to the detector due to the photoelectric effect or multiple processes.

2. Peak single leakage - total absorption except single annihilation photon

(511keV).

3. Peak double leakage - total absorption except for two annihilation photons (1022keV).

4. Continuum from a single Compton scattering.

5. Continuum from multiple Compton scattering.

6. Continuum from Compton leakage of one or two annihilation photons.

It should be noted that the capabilities of the GEANT4 code allow each of these components to be selected programmatically, unlike in an experiment in which only the complete energy response of the detector can be observed. Figure 1 shows the calculated response function and its decomposition into the above components.

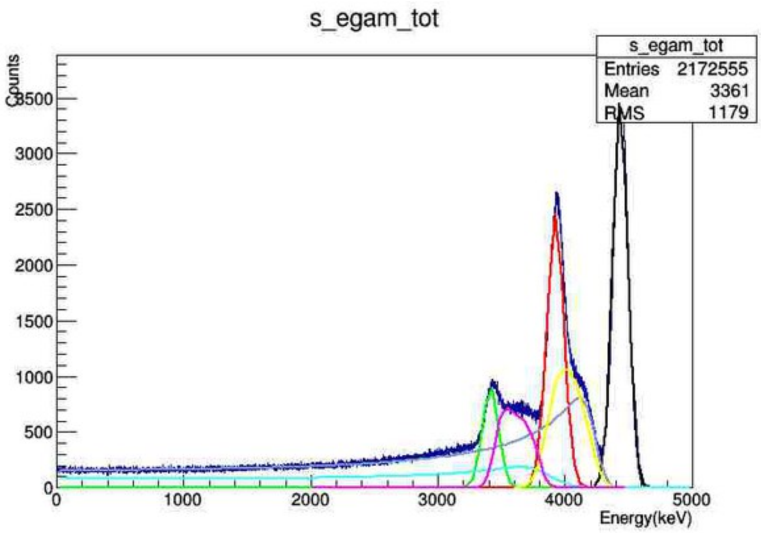

Figure 1. Model response function and its components.

In this histogram, the black line describes the total absorption peak, red is a single departure, green is a double departure, dark blue is a single Compton continuum, blue is a multiple Compton continuum, yellow and pink are Compton components accompanying a single and double leakage peaks.

The response function describing the interaction of a photon with energy E_γ is defined as

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

where E is the energy detected in the detector. It is assumed that the energy calibration of the detector has been carried out accordingly and the energies of the incident gamma-quantum, as well as the registered secondary particles in the detector, are measured in the same units (keV).

The seven parts, f_i , of the detector response function, which depend on the photon energy, as well as their parameters and fitting methods, are described in detail below.

1. Peak of total absorption

The first part of the histogram is the peak of total absorption. The fitting of this histogram was carried out by the Gauss function, which has the following form

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

where A – area under peak, $B_1 = \sigma$ – variance of the function (defines the width of the peak), E_0 – energy equal to 4438 keV (peak position). The result of fitting this component is shown in Figure 2.

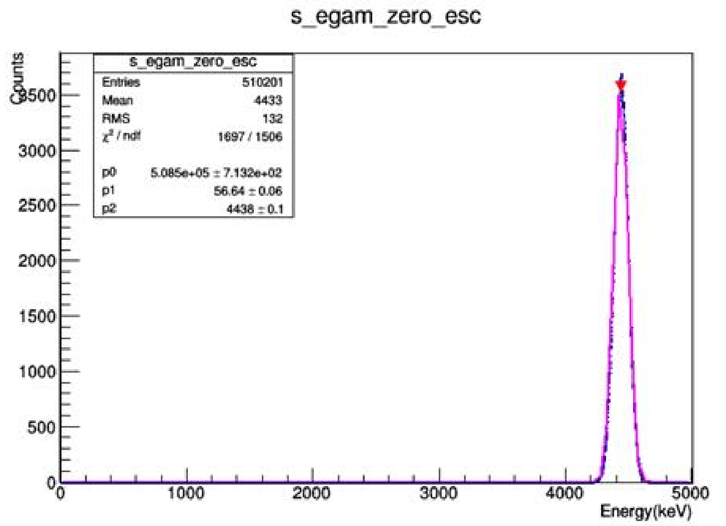

Figure 2. Peak of total absorption.

The total absorption of the photon is represented by a Gauss distribution with amplitude of A(p0), a dispersion of a (p1) and a centroid of E_0 (p2).

If the energy of the γ-quant is higher than 1022 keV in the detection volume, electron-positron pairs can be formed. In this case, all the energy of the γ-quant is transferred to the electron and positron. If both the electron and the positron are absorbed in the detector substance, then the total pulse will be proportional to the energy of the γ-quantum and the event will be recorded in the peak of total absorption. However, when the positron is annihilated, two γ-quanta are formed, each with energy of 511 keV, which can leave the detector.

2. Peak of single departure

If one of these annihilation γ-quanta, without interacting, leaves the detector, then the total absorbed energy in the detector will be E_0-511 keV. Such events will contribute to the so-called peak of single departure. And the result of fitting this peak is shown in Figure 3.

The fitting of this histogram was carried out by the Gauss function:

$$f(x) = \frac{A \cdot R_0}{\left(\sqrt{2\pi} \cdot B_2\right)} \exp\left(\frac{-(E - (E_0 - 511)^2}{2 \cdot B_2^2}\right) \tag{3}$$

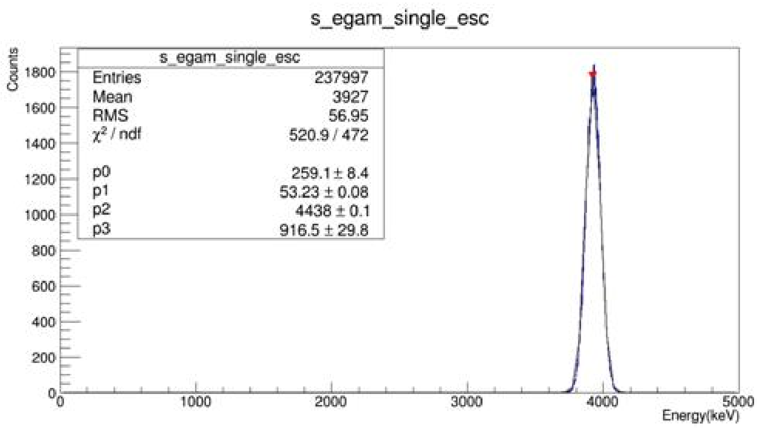

Figure 3. Peak of single departure.

$$B_2 = \sigma \cdot \left(\frac{\sqrt{E_0}}{\sqrt{E_0 - 511}} \right) \tag{4}$$

where A(p0) is the area under the peak, R_0 (p3) is the parameter determining the ratio of the amplitudes of the photo peak and single departure, E_0 (p2) is the energy equal to 4438 keV. It should be noted here that for this function, the free parameter is only the peak area, while its width (dispersion) and position are related to the width and position of the peak of total absorption by the ratios (3) and (4).

3. Peak of double departure

If both annihilation γ-quanta fly out of the detector, then this event will be recorded in the peak of double departure (E_0 - 1022 keV). This peak is shown in Figure 4. The peak of the double departure is also described by the Gauss function

$$f(x) = \frac{A}{\left(\sqrt{2\pi} \cdot B_3\right)} \exp\left(\frac{-(E - (E_0 - 1022)^2}{2 \cdot {B_3}^2} \right) \tag{5}$$

$$B_3 = \sigma \cdot \left(\frac{\sqrt{E_0}}{\sqrt{E_0 - 1022}} \right) \tag{6}$$

Here also, the free parameter is only the peak area, while its width (dispersion) and position are related to the width and position of the peak of total absorption by the ratios (5) and (6).

4. Compton continuum from a single Compton scattering

Compton scattering is the main cause of radiation from the detector and is most difficult to eliminate, since it is observed at any quant energies, and its distribution is very sensitive to the geometry of the source, screen and detector.

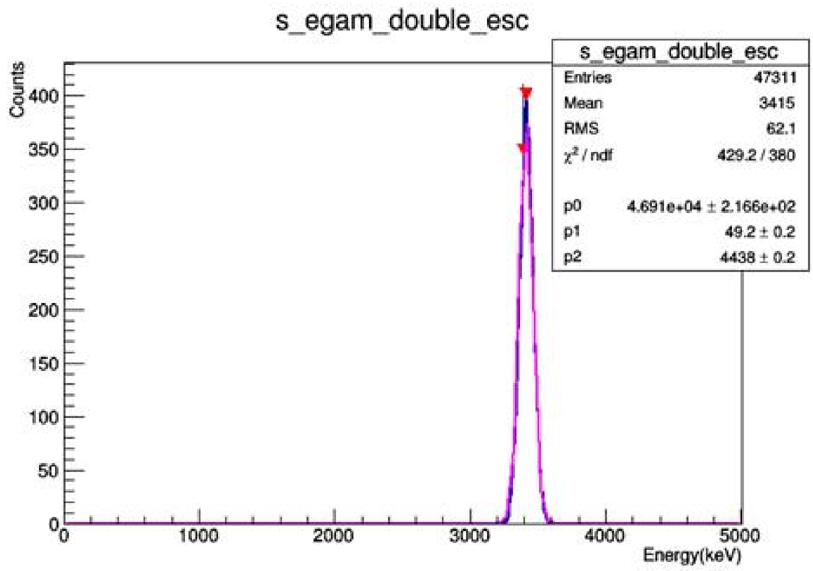

Figure 4. Peak of double departure.

A single Compton scattering of photons is usually described by the Klein-Nichina formula. In the experimental data, it is also necessary to take into account the widening of the right edge of the Compton spectrum in accordance with the energy resolution of the detector. The form of the Compton continuum is described by the Klein-Nishina formula, multiplied by an additional error function, which determines the broadening of the spectrum from the Compton boundary E_c due to the final resolution of the detector.

The complete formula for describing the Compton continuum looks like this:

$$f(x) = A \cdot \left[\left(\frac{E_0}{E_1} \right) + \left(\frac{E_1}{E_0} \right) - 1 + \cos^2\theta \right] erfc \left[\frac{(E - C_0)}{\sqrt{2} \cdot B_4} \right] \tag{7}$$

where $\cos\theta = 1 + \left(\frac{m_0 \cdot c^2}{E_0} \right) + \left(\frac{m_0 \cdot c^2}{E_1} \right)$, $E_1 = E_0 - E$, $B_4 = \sigma \cdot \frac{\sqrt{E_0}}{\sqrt{C_0}}$ and $C_0 = E_c = \frac{E_0}{\left[1 + \frac{m_0 \cdot c^2}{2 \cdot E_0}\right]}$ — this is the energy of the Compton edge and $m_0 \cdot c^2$ is the electron's resting energy. In this formula, the free parameter is only the amplitude A. The result of fitting the spectrum of single Compton scattering using function (7) is shown in Fig. 5.

In the formula (7) $A(p_0 \cdot p_2)$ is the relative amplitude and σ (p4) – variance in error function.

5. Compton continuum from multiple Compton scattering

The entire Compton continuum cannot be described by a relatively single simple Klein-Nichina formula, which correctly reflects only a single Compton scattering. Therefore, the complete Compton spectrum was divided into several components, each of which has its own meaning. The fifth part of the histogram is the Compton continuum from multiple Compton scattering, as well as from electron, positron leaks, that is, everything that is not described by components 4 and 6. To describe this component, formula (7) can also be used with three free

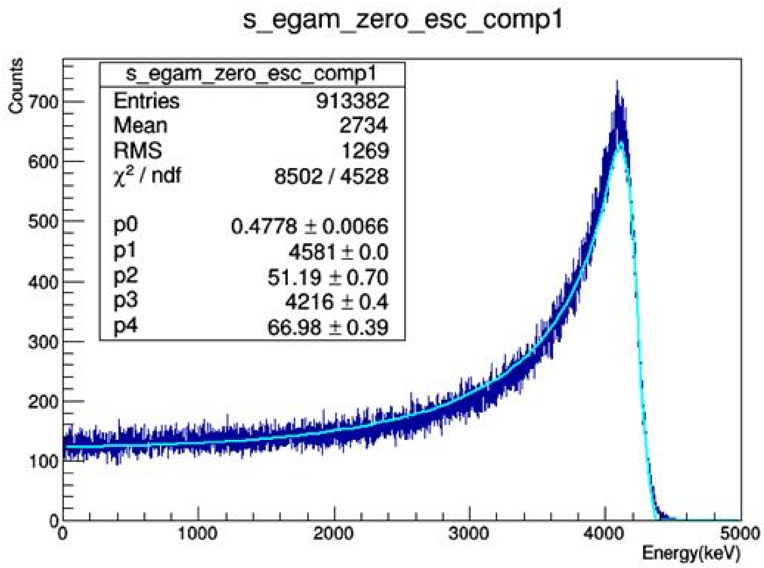

Figure 5. Compton Single Continuum.

parameters: amplitude A, variance γ and the position of the right edge of the spectrum C_0. The fitting result is shown in Figure 6. Since this component, conventionally designated as a Compton continuum from multiple Compton scattering, is composed of several components having a different physical nature, its description using formula (7) is not ideal. Nevertheless, we believe that the accuracy of the description of this component is sufficient for practical applications, since its contribution to the full spectrum of the response function is insignificant.

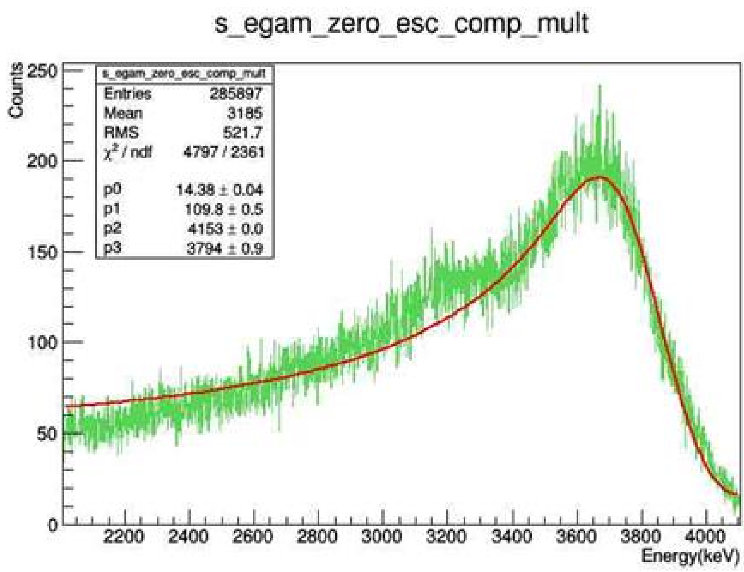

Figure 6. Compton continuum for annihilation photon.

6. Compton continuum from annihilation photons

The sixth and seventh parts are important components of the response function. These components are visible in Figure 1 as bumps to the right of the single and double-departure peaks. The physical meaning of these components is the incomplete leakage of annihilation γ-quanta, that is, one or both photons with energy of 511 keV experience Compton scattering, leave part of the energy in the detector, and part is carried outside the detector. Since the carried away part of the energy is less than 511 and 1022 keV, respectively, the absorbed energy in the detector is greater than E_0 - 511 and E0 - 1022, so these components are located to the right of the corresponding leakage peaks.

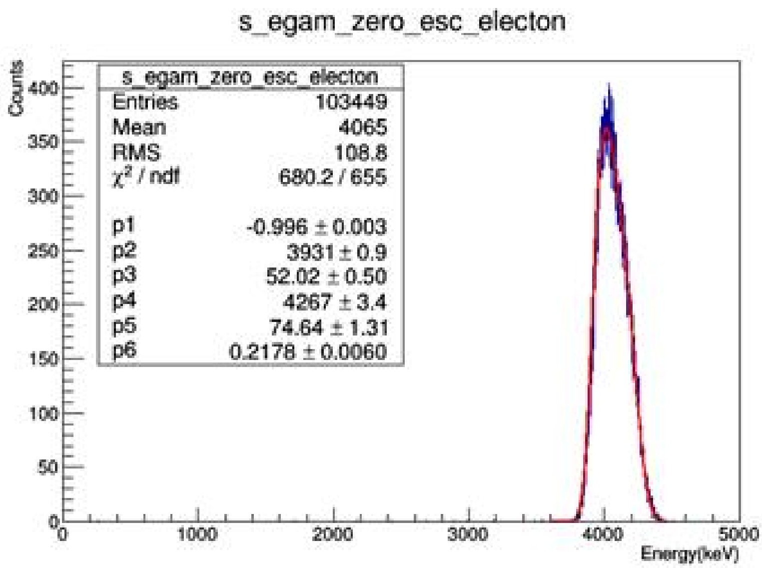

Figure 7. Electron departure.

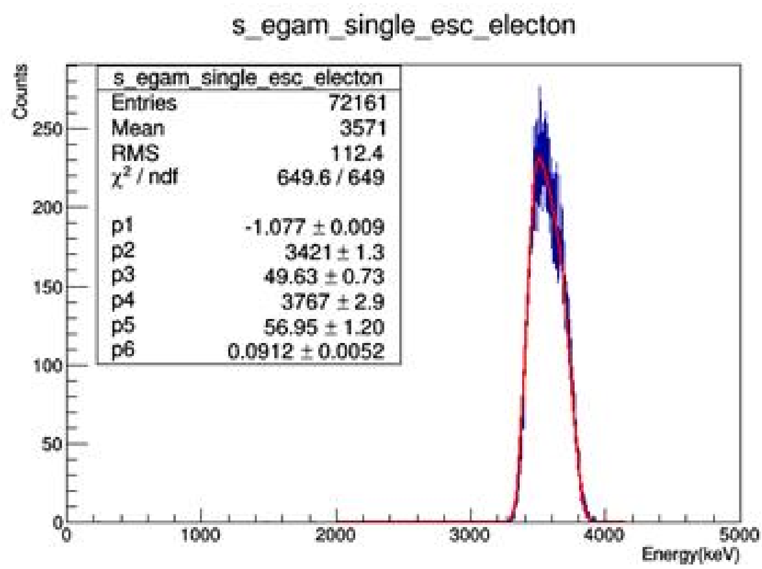

Figure 8. Electron departure.

These histograms (Fig. 7 and Fig. 8) were described by the following function:

$$f(x) = A \cdot (E_0 + k_1 x) \cdot erf\left(\frac{E - C_1}{\sqrt{2}B_5}\right) \cdot erfc\left(\frac{E - C_2}{\sqrt{2}B_6}\right) \quad (8)$$

where $B_5 = \sigma \cdot \left(\frac{\sqrt{E_0}}{\sqrt{C_1}}\right)$, $B_6 = \sigma\left(\frac{E_0}{C_2}\right)$ are the width-dependent parameters.

Figure 9 shows a summary description of the model response function based on the above components. A total of 14 independent fitting parameters were used in this description. As you can see, the response function correctly reflects all these components, as well as their energy dependence [8].

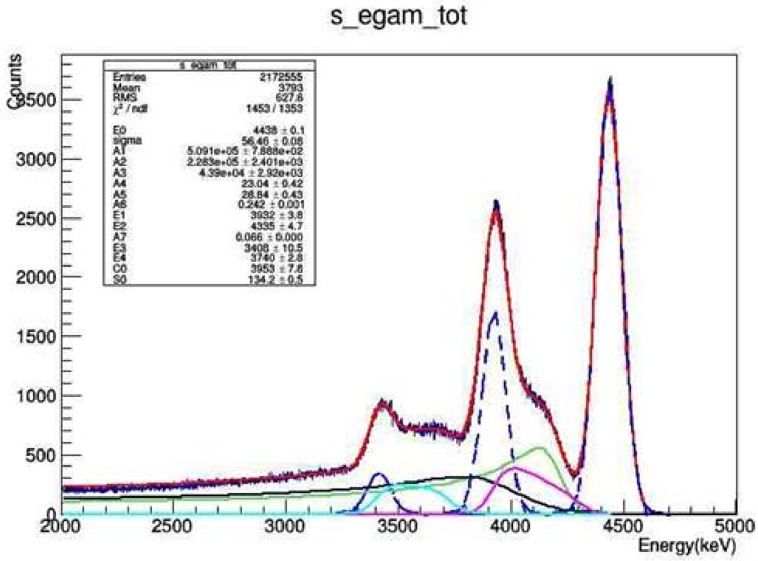

Figure 9. Electron departure.

Conclusion

Work was carried out to determine the parameters of the response function of scintillation detectors based on NaI[Tl] using model spectra obtained with the GEANT4 package. This work was carried out to determine the parameters of the "ROMASHKA" installation, with the aim of further using the installation in the "TANGRA" project [9]. The resulting response function can be used in the future to more accurately determine the angular correlations in this reaction, as well as for further work on gamma spectroscopy using scintillation detectors based on NaI(Tl) [10].

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