ANGULAR CORRELATION OF GAMMA-RAYS IN THE INELASTIC SCATTERING OF 14.1 MEV NEUTRONS ON CARBON

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Abstract

The work is dedicated to the measurement of the angular distribution of γ-rays with energy of 4.438 MeV produced in inelastic scattering of neutrons with energy of 14.1 MeV on ^{12}C. As a source of "tagged" neutrons a portable neutron generator ING-27 (designed and manufactured by VNIIA in Moscow) with built-in 64-pixel silicon α-detector was used. The registration of the characteristic γ-rays from the reaction ^{12}C(n,n'γ)^{12}C was done by a γ-spectrometer consisting of 22 γ-detectors based on NaI(Tl) crystals, located around the target. The analysis and comparison of the measured angular distribution of γ-rays with energy of 4.438 MeV with the results from other experimental studies available in the literature are reported.

Introduction

One of the first experiments, which we have planned to do with the frame of the project TANGRA (TAgged Neutrons and Gamma RAys) [1], is the measurement of the angular correlations of γ-rays and neutrons produced in the reaction of inelastic scattering of neutrons with energy of 14.1MeV on carbon nuclei:

$$^{12}C(n,n')^{12}C^{*} \xrightarrow{\gamma} {}^{12}C \qquad (1)$$

The result of this experiment will not only allow to make a correct comparison with the experimental data, which were obtained earlier in experiments [2-11] dedicated to study the characteristics of the reaction (1) and significantly differ each other, but also to obtain information on the mechanism of the inelastic scattering of fast neutrons from carbon nuclei.

As a neutron source, in this case, is used a binary Deuterium-Tritium fusion reaction:

$$d + t \to \alpha(3.5\ MeV) + n(14.1\ MeV) \qquad (2)$$

The method of tagged neutrons is based on the detection of α-particles, produced in the reaction (2) and practically having an opposite direction of irradiation comparing to that of the neutron, in coincidence with the characteristic γ-rays resulting from the inelastic scattering of neutrons with energies of 14.1 MeV from the nuclei of the irradiated sample.

Knowing the number of neutrons incident on the irradiated sample-target, by registering of the α-particles accompanying the formation of neutrons in reaction (2), the number of the (n-γ)-coincidences, the dimensions of the target, as well as, the characteristic γ-rays detection efficiency, allows correctly to determine the differential cross-sections of the inelastic neutron scattering from the nuclei of the investigated elements by exciting them to a certain levels (the de-excitation transition to the ground state occurs by a subsequent emission of γ-quanta of corresponding energy).

As follows from the above, an important advantage of the tagged neutron method (TNM) is the possibility of monitoring the tagged neutron fluxes with almost 100% efficiency. Moreover, by introducing (α-γ)-, (α-n')-, (α-n'γ)- coincidences the background radiation level can be lowered by more than 200 times. These properties of the TNM allow to use it for precision studies of nuclear processes of the type (n, n'γ) and (n, 2n), which are extremely important not only in terms of nuclear physics and astrophysics, but also in terms of a more detailed description of the neutron multiplication chains, energy production and utilization of nuclear waste disposals.

The experimental setup

The scheme and a photo of the experimental setup is shown in Fig. 1.

As a source of neutrons with energy of 14.1 MeV we used a portable neutron generator (NG) ING-27 [12-14] developed and manufactured by Dukhov All-Russia Research Institute of Automatics (VNIIA). To form a tagged neutron flux by registering the complementary 3.5 MeV α-particle from the reaction (2), a double-sided silicon strip α-detector [13] is mounted inside the generator vacuum tube. The two sets of eight strips perpendicular to each other form an 8 x 8 matrix with a size of each element (pixel) of 4 x 4 mm. The whole sensitive area of the 64-pixel α-detector is 32 x 32 mm^2. It is positioned at a distance of 62 mm from the neutron producing tritium target.

The signals from the 8 horizontal and 8 vertical stripes of the α-detector are fed to the corresponding preamplifiers via a16-pin connector.

The spatial characteristics (the profiles) of the 64 tagged neutron beams were measured with a one-dimensional profile-meter [13], consisting of 16 plastic scintillation strips, the dimensions of each strip are 150 x 7.5 x 5 mm.

As an example, the distribution of a “tagged” neutron beam along the X-axis (in the plane, perpendicular to the direction of the neutron beam propagation), obtained in coincidence between the signals from the profile-meter vertical strips and those from a single α-particle detector pixel, is shown in Fig. 2.

As a detector-spectrometer of the characteristic γ-radiation with energy of 4.438 MeV from the inelastic scattering of 14.1 MeV neutrons from^{12}C nuclei, 22 regular hexagonal prisms (with apothem of 42.5 mm and height of 200 mm) made from NaI(Tl) crystal were used. The γ-ray detectors were placed vertically in the form of a horizontal circular ring with a radius of 370 mm, in which the geometrical center the carbon sample was positioned. The angle between the central axes of adjacent NaI(Tl) γ-detectors in the horizontal plane is 15^{o}. On average, the energy resolution of the γ-ray detectors is at the level of 8.5% FWHM for 662 keV γ-line of ^{137}Cs, the time resolution of the α-γ coincidences is about 3.3 ns FWHM.

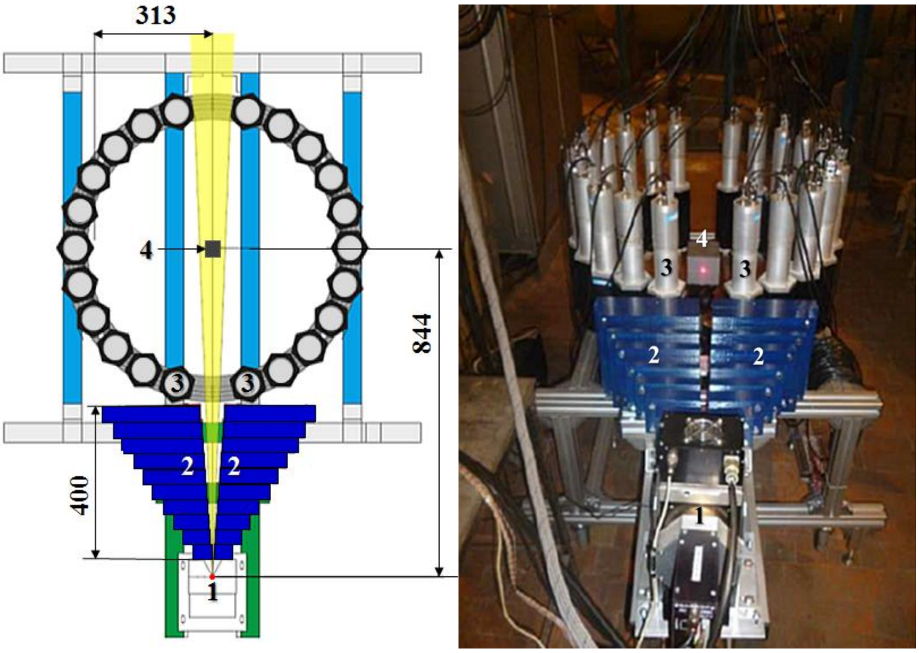

Fig. 1. The scheme (left) and photo (right) of the “source-detector” part of the experimental setup: 1 - neutron source (ING-27), 2 - iron shield-collimator of neutrons and γ-rays, 3 - NaI(Tl) scintillation detectors of γ-rays and neutrons, 4 - carbon (^{12}C) target-sample. The main dimensions in the scheme are shown in millimeters.

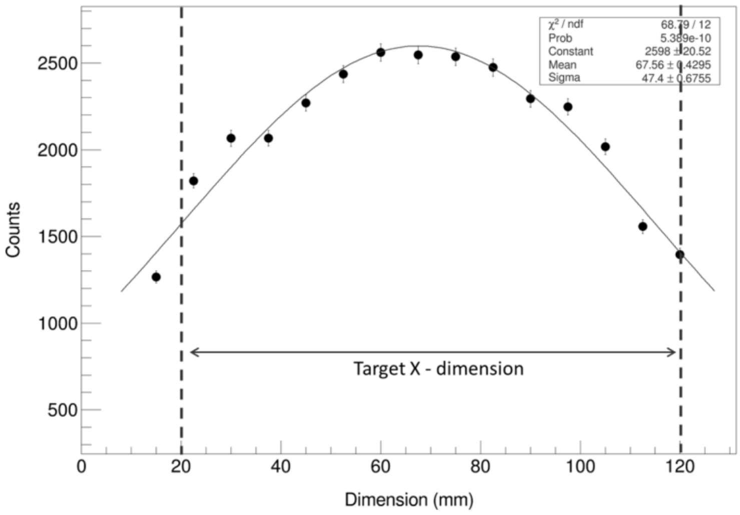

Fig. 2. Distribution of a single “tagged” neutron beam along the X (horizontal) axis in the plane perpendicular to the neutron beam direction.

The recording electronics is a 32-channel signal digitizer constructively designed as two boards, with the size of a standard PCI card, giving the possibility to install it in a PCI slot of a personal computer and to work under its control, exchanging the information via its PCI bus [1].

The main principle of operation of the digitizer is recording of the waveforms from the α- and γ-detectors with subsequent calculation of their time and amplitude characteristics.

The software package, supporting the work of the recording electronics, includes drivers for the PCI-interface, a program of events selection and analysis, a program for creating a data file, as well as the software needed for configuration of the electronics operation mode. All the software that supports the work of the electronics is running in Linux operating system.

In the experiment on the measurement of the angular distribution of the γ-rays generated in the inelastic neutron scattering on carbon nuclei, a target of pure carbon in the form of a parallelepiped with dimensions 10x10x5 cm (the thickness of the target along the beam of tagged neutrons was 5 cm) was used.

To select an optimal size of the target, in terms of getting the best angular resolution and high count-rate for each of the 22 γ-ray detectors installed at different polar angles with respect to the initial direction of the neutrons, we carried out a modeling of the experimental conditions for investigating the reaction (1) on carbon samples of dimensions 5 x 5 cm and 10 x 10 cm and variable thickness (from 1 to 10 cm). As a result, the target of pure carbon in the form of a parallelepiped with dimensions 10 x 10 x 5 cm (the thickness of the target along the beam of tagged neutrons was 5 cm) was chosen as an optimal one for these measurements.

Before the start of data-acquisition an alignment of the central tagged neutron beam and the center of the carbon target was made.

Data analysis and results

The analysis of the spectra from the characteristic γ-rays with an energy of 4.438 MeV was based on the statistics obtained in coincidence with the signals from the central pixel of the α-detector for a pure carbon target of dimensions 10 x 10 x 5 cm.

Figure 3 shows the energy distribution of events from the γ-detector, placed at an angle of 30^0 in comparison with the background spectrum, which was measured without the target. The α-γ coincidence window was rather large and included events from the neutron scattering on the shielding (neutrons and γ-rays), γ-rays from the inelastic scattering of neutrons on the target, as well as the neutrons, scattered on the target (elastically and inelastically), hitting the gamma-ray detector.

As can be seen from Fig. 3, the ‘effect-to-background’-ratio is still rather high, mainly due to the contribution of the scattered neutron events. In order to reduce the background, it is necessary to analyze the time-of-flight distributions carefully.

In Fig. 4, as an example, the time distributions of the events recorded by the γ-detectors in coincidence with the signals from the central pixel of the α-detector are shown (for a better visualization of the ‘effect-to-background’-ratio, the scale of the abscissas in the Fig. 4 is stretched). On the abscissas of the above figures is denoted the time interval between the moments of registration of the α-particles from the binary reaction (2) and the γ-quantum from the reaction (1). As can be seen from Fig. 4, in the time distributions three peaks are visible – **a**, **b** and **c**.

The left peak (**a**) corresponds to the γ-rays, emitted after the interaction of the tagged neutron beam with the media of the shielding-collimator, the central peak (**b**) is due to the registration of the characteristic γ-emission from carbon, and the right peak (**c**) corresponds to the registration of the scattered (on the carbon-target) neutrons by the γ-detectors.

To suppress the background, for further evaluation we selected the events which were registered by each of the 22 γ-detectors in coincidence with the signal from the central pixel of the α-detector, (α-γ)-detector coincide system (*i*), lying in the time interval ΔT_i equal to the same number (*K*) of standard deviations $\sigma_t^{(i)}$ for every (*i*):

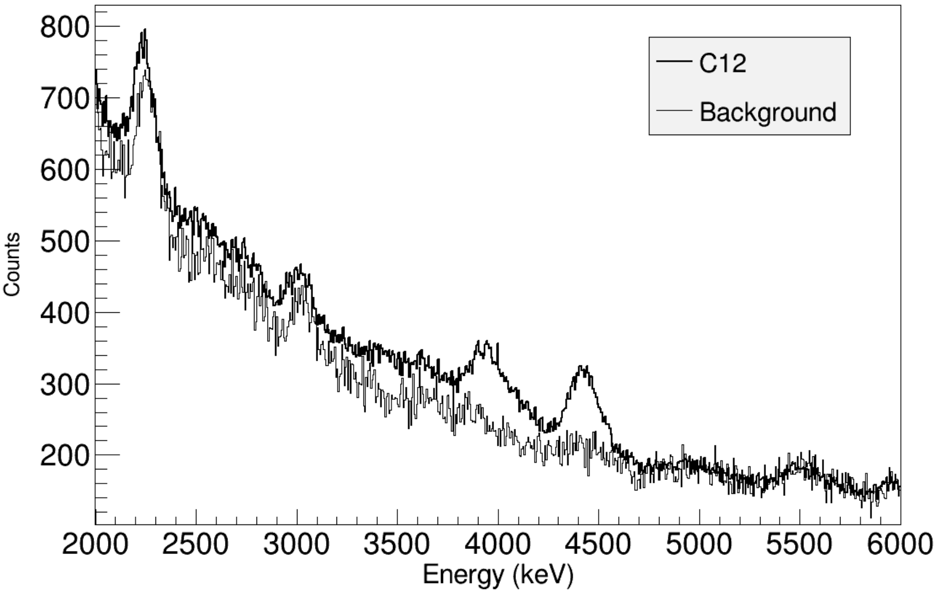

Fig. 3. The energy distribution of the reaction (1) and background events (the upper and lower curve, respectively) as recorded by NaI(Tl) γ-ray detector located at an angle of 30°.

$$\bar{T}_i - K\sigma_t^{(i)} \le T_i \le \bar{T}_i + K\sigma_t^{(i)}, T_i = T_\alpha^{(i)} - T_\gamma^{(i)}, \Delta T_i = 2K\sigma_t^{(i)} , \qquad (3)$$

where $\bar{T}_i$ – the average time interval between the registration of the α-particle (by α-detector) and the γ-quantum with an energy of 4.438 MeV (by the *i*-th NaI(Tl) γ-detector);

$T_\alpha^{(i)}$ and $T_\gamma^{(i)}$ are the time of occurrence of the signals from the *i*-th α- and γ- detectors;

$\sigma_t^{(i)}$ – the standard deviation characterizing the time distribution of the events recorded by γ-detector (*i*) in coincidence with the signal from the α-detector;

$FWHM_t^{(i)} = 2.35\sigma_t^{(i)}$ – the time-resolution of the (α-γ) coincide systems, corresponding to the *i*-th γ-detector;

K – the number of standard deviations is equal to 3 and is the same for all 22 systems (α-γ) coincide systems.

After defining the boundaries of the time intervals for registration of the γ-rays in coincidence with the α-detector for each of the 22 γ-detectors, the energy spectra of γ-events corresponding to the selected time intervals were built.

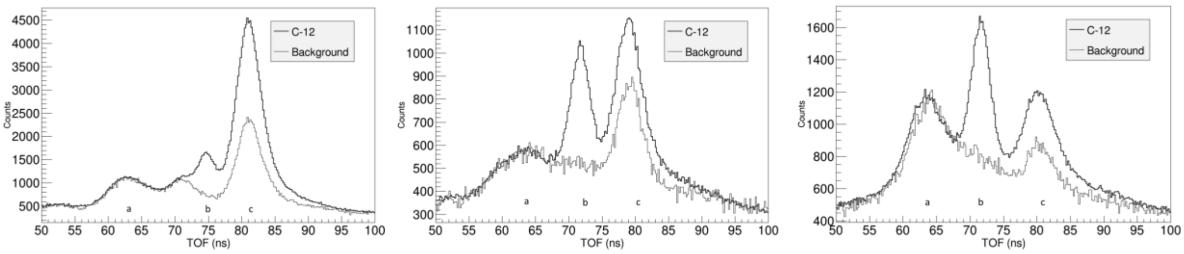

Fig. 4. Time distributions of the reaction (1) and background events (the upper and lower curves, respectively) as recorded by NaI(Tl) γ-ray detector positioned at an angle of 30˚, 90˚ and 150˚.

These spectra for the same three detectors (at 0^0, 90^0 and 150^0) are shown in Fig. 5.

Thus, as a result from the analysis of the experimental data we obtain 22 amplitude (energy) distributions of γ-rays from the reaction (1).

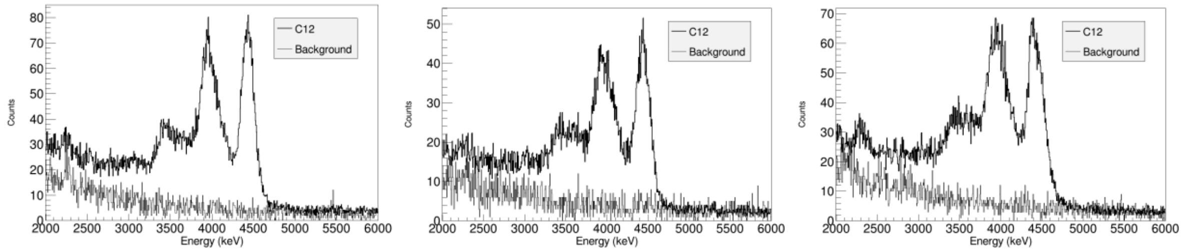

Fig. 5. The energy distributions of the reaction (1) and background events (the upper and lower curve, respectively) as recorded by the γ-detector positioned at an angle of 30º.

The next step in the analysis of the γ-ray energy distributions data was to determine the number of events registered by each of the 22 γ-detectors in coincidence with the signal from the α-detector and formed the total absorption (photo) peaks, the time boundaries of which were defined according to the equations (3).

To do this, the experimental distribution of γ-rays for each γ-detector was fitted by an energy E dependent function $F(E)$ of the following form:

$$F(E) = Peak(E) + Compton(E) + Background(E)\ , \tag{4}$$

where $Peak(E)$ – a Gaussian function, describing the peak of total absorption of γ-rays with an energy of 4.438 MeV and taking into account the energy resolution of the detector:

$$Peak(E) = \frac{A}{\sigma\sqrt{2\pi}} \times \left(-\frac{(E-E_0)^2}{2\sigma^2}\right) \tag{5}$$

E_0 – the energy related to the center of gravity of the total energy absorption peak (4.438 MeV);
σ – the standard deviation of Gaussian distribution;
A – the area under the peak (number of events).
$Compton(E)$ – a function describing the contribution to the distribution of Compton scattered in NaI(Tl) detector γ-rays.

An analytical expression for this function was obtained by using Monte Carlo based model calculations taking into account the geometry of the experimental setup and characteristics of the detectors. In the energy range that corresponds to the total absorption peak it can be written as (5) with fixed parameters, taken from the model calculations;

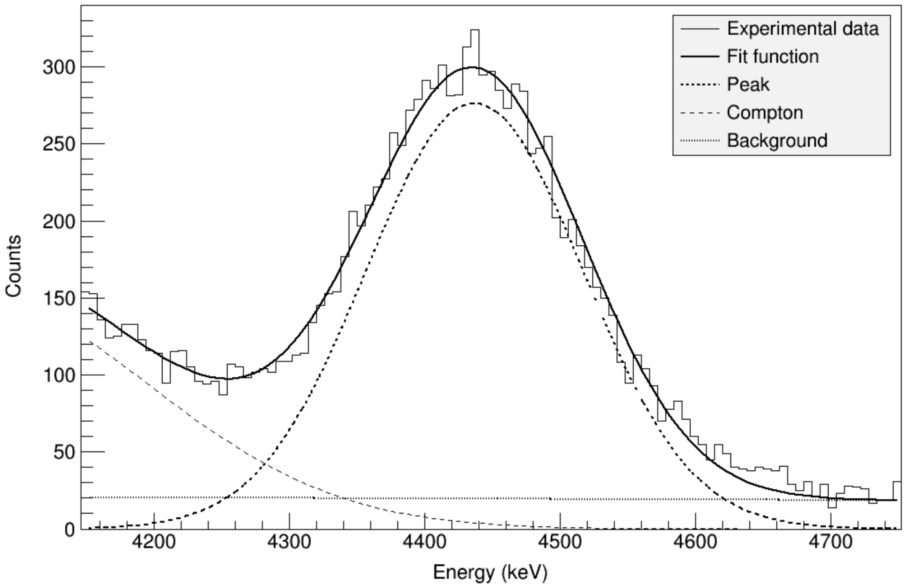

Fig. 6. The decomposition of the amplitude (energy) spectrum in the region of the total absorption peak from γ-rays with an energy of 4.438 MeV into components, for a detector located at an angle of 30˚.

$Background(E) = aE + b$ – energy dependent background from random coincide events. The constants a and b were determined, for each γ-detector, based on of the results from the analysis of the amplitude (energy) spectra of the recorded events in the energy range from 4.8 MeV up to 6.0 MeV.

Figure 6 shows the decomposition of the energy spectrum, in the region of the total absorption peak at 4.438 MeV, into the above described components, for a detector located at angle of 30°.

As a result of fitting the model function (4) to the experimental amplitude (energy) distributions of the events registered by each of the 22 γ-detectors, we determined the number of registered events corresponding to the peaks of total absorption of the γ-rays with energy of 4.438 MeV. Then, the obtained number of events was averaged for each pair of γ-detectors located symmetrically with respect to the tagged neutron beam direction.

The angular dependent parameter of the anisotropy of the irradiation of the γ-rays from the inelastic scattering of neutrons $W(\theta)$ which is defined as the ratio of the number of events recorded by the detector located at an angle θ to the number of events recorded by a detector at the angle of 90°, can be well described by the following expression:

$$W(\theta) = 1 + a\,cos^2(\theta) - b\,cos^4(\theta) \tag{6}$$

Figure 7 demonstrates the dependence of the parameter of anisotropy of the γ-quanta emission from the reaction (1) on the polar angle θ as obtained from the analysis of the reported experimental data. The angular resolution of a single detector $\Delta\theta$ was obtained by Monte Carlo method using the Geant4 software toolkit [15].

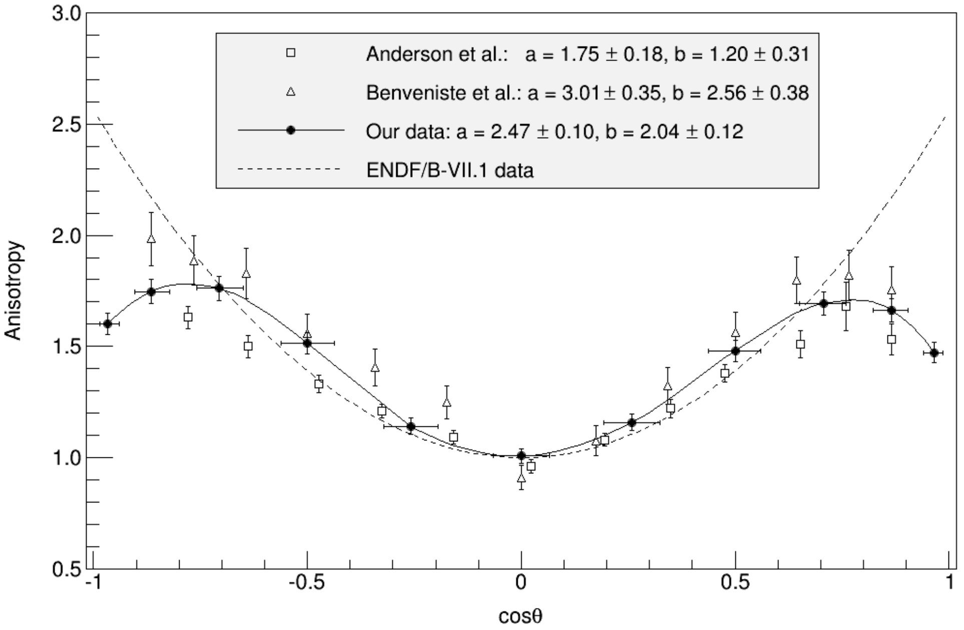

Fig. 7. The angular dependence of the anisotropy obtained in this work (plain line with dots), compared with the data of Anderson et al. (hollow squares), Benveniste et al. (hollow triangles) and the evaluated data from the ENDF/B-VII.1 library (dashed line).

The obtained angular dependence can be analytically described by the equation (6) with parameters $a = 2.47 \pm 0.10$ and $= 2.04 \pm 0.12$. The errors in a and b include both, statistical errors and systematic ones, arising from the Monte Carlo simulations. With regards to the possible additional systematic errors, we are currently investigating the nature of their possible sources.

Conclusions

1,. Using the method of tagged neutrons allowed accurately to measure the angular distribution of the γ-rays with energy of 4.438 MeV produced in the inelastic scattering of neutrons with an energy of 14.1 MeV on ^{12}C nuclei by exciting its first level.

2. Within the limits of statistical errors, the calculated values for the anisotropy is found to be in good agreement with the most accurate results published earlier in refs. 2 and 10.

3. The evaluated anisotropy parameters for nuclei ^{12}C in the ENDF B-VII.1 do not consider the using 4th order Legendre polynomial expansion, which leads to significant discrepancies between the model and experimentally obtained angular distributions of γ-quanta with an energy of 4.438 MeV irradiated at polar angles smaller than 45° and larger than 135°.

The next step in the planned scientific research program is to measure the angular correlation between the directions of the neutrons and γ-rays from the reaction (1).

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