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Determination of the target parameters using the Monte Carlo method for an experiment on inelastic neutron scattering in different samples at the "TANGRA" installation

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Using the tagged neutron method at the "TANGRA" facility at Frank Laboratory of Neutron Physics of the Joint Institute for Nuclear Research based on the ING-27 standard neutron generator, a study of the 14.1 MeV inelastic neutron scattering reaction on different nuclei was carried out. The angular distributions of γ - quanta accompanying inelastic neutron scattering on atomic nuclei were measured. This article presents a GEANT4-based program that allows calculating the interaction of fast neutrons with matter and simulating the experiment and also presenting the results of the experiment in a convenient and visual form. Using the written program, optimal target parameters were determined. The algorithm used by the program is given in this work. The general description of the experimental installation, data collection and processing systems is given.

Keywords: GEANT4, γ -quanta, fast neutrons, angular distribution, method of tagged neutrons.

Introduction

Information about neutron-nuclear interaction is extremely important for both fundamental and applied physics. The study of neutron-nuclear processes also allows learning more about the properties of nuclear forces and the structure of nuclei, to verify the correctness of theoretical models. Accordingly, for the study of neutron-nuclear reactions in the Laboratory of Neutron Physics of the Joint Institute for Nuclear Research (Dubna), the "TANGRA" installation was created, and, after some time, the "TANGRA" collaboration was formed [1, 2]. The objectives of the collaboration are as follows:

1. Creation and development of a database on the cross-sections of reactions of neutrons with energy 14.1 MeV with the nuclei of various elements and characteristic γ-lines to expand the applicability of the tagged neutron method (TNM) for the identification of a wider range of complex chemicals;
2. Investigation of (n, n′γ) - reactions using the tagged neutron method;
3. Measurement of characteristics of reactions of the type (n, 2n′) and (n, n′);
4. Development and testing of gamma detectors with improved time and energy characteristics for use in intense neutron fields;
5. Development of algorithms and programs for the analysis of experimental information.

And one of the main directions of this project is the study of rare processes occurring as a result of the interaction of fast neutrons with an energy of 14.1 MeV with medium and heavy nuclei (n, n′), (n, n′γ), (n, 2n′) [3]. The implementation of such studies on the equipment declared in the project will require the selection of objects for study that are of interest today.

Experimental setup

In 2014, at the Frank Laboratory of Neutron Physics of the Joint Institute for Nuclear Research created the "TANGRA" (TAggedNeutrons&GammaRAys – Tagged Neutrons & GammaRays) facility to study nuclear reactions under the action of fast neutrons (with energy 14.1 MeV). Its scheme is shown in Figure 1.

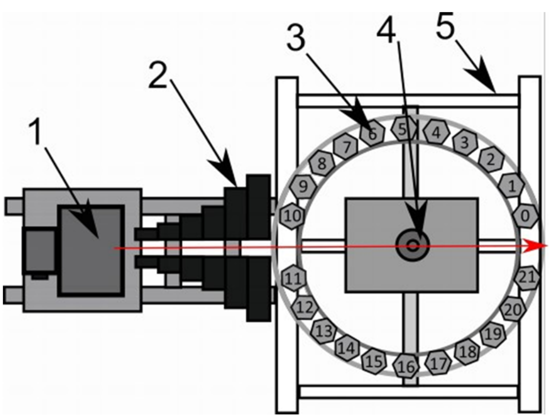

Figure 1. Scheme of installation "ROMASHKA".
1– neutron generator ING-27, 2 – iron protective collimator of neutrons and γ-rays, 3– gamma spectrometers NaI(Tl), 4– table with irradiated sample, 5– frame. The arrow shows the direction of the tagged neutron beam used.

The installation of the "TANGRA" project based on the "ROMASHKA" spectrometer consists of 22 gamma detectors using crystals NaI(Tl) and a neutron generator with an integrated alpha detector manufactured by FSUE VNIIA named after N.L. Dukhov [4].

Neutron generator ING – 27

The source of tagged neutrons is a new generation "neutron generator ING-27" based on a sealed gas-filled neutron tube with a built-in multipixel detector of associated alpha particles (Figure 2) [5]. The intensity of the neutron flux produced by this generator reaches a value of $5 \times 10^{7} \text{sec}^{-1}$.

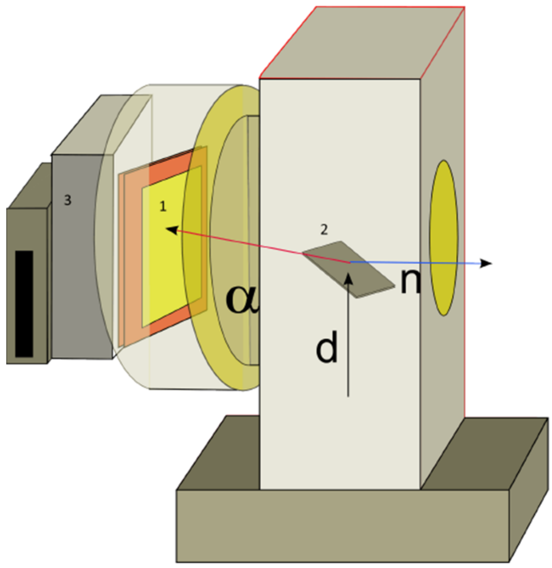

Figure 2. Neutron generator scheme: 1– pixel α -detector, 2–target enriched with tritium, 3–block reducer.

The neutron generator ING-27 was developed by VNIIA (Moscow) and it is a source of mono energy neutrons with the energy of 14.1 MeV formed in a binary nuclear reaction d + t $\rightarrow \alpha$ (3 .5 MeV)+ n(14.1 MeV).

Since the reaction products are only two particles, according to the law of pulse conservation, they scatter in opposite directions (in the system of the center of mass). Therefore, registering the direction of departure of one of the particles, information about the time and direction of departure of the second particle can be obtained. The main purpose of the alpha detector is to obtain so-called "tagged" beams of fast neutrons [6].

Setting up an experiment to measure the angular distributions of gamma quanta and determine the target parameters

In 2016-2017 the measurements of angular distributions of γ - quanta accompanying inelastic neutron scattering on atomic nuclei were carried out at "TANGRA" facility. Pure substances and chemical compounds containing nuclei in a wide range of mass and charge numbers, from carbon to bismuth, were used as targets. The list and parameters of used targets are given in Table 1.

Table 1.
Elements for which angular anisotropy of γ - quanta was measured.

Target	Density	Section	Energy γ-quanta	Thickness targets (cube)
^{12}C	2 g/sm^3	1.3205 barn	4.44 MeV	10×10×5 sm
^{27}Al	2.699g/sm^3	1.7460 barn	0.843 MeV 3 MeV	10×10×5 sm
^{56}Fe	7.874g/sm^3	2.5793 barn	0.847 MeV 1.810 MeV	10×10×5 sm
^{208}Pb	11.35 g/sm^3	5.3998 barn	0.510 MeV 0.771 MeV	10×10×5 sm

The experiment was set up in the following way. The targets were placed in the center of the "ROMASHKA" detector system (see Figure 1), after which the neutron generator was turned on and data were collected (usually within 8 hours), after which the installation was shut down and data were processed.

On the basis of the obtained amplitude spectra from each of the 22 detectors, the construction of angular distributions of γ - quanta was carried out. Results can be seen in [7].

From this setting of the experiment, the parameters of the target for the experiment were determined. First of all, for processing and modeling experimental data, a software module was created in the package GEANT4 [8], which allow calculating the interaction of fast neutrons with the substance of various materials and constructing probabilistic distributions.

A detector in the form of a "ring" was created in the program, and the beam fell at different angles on the target (Figure 3). The target was the samples shown in Table 1.

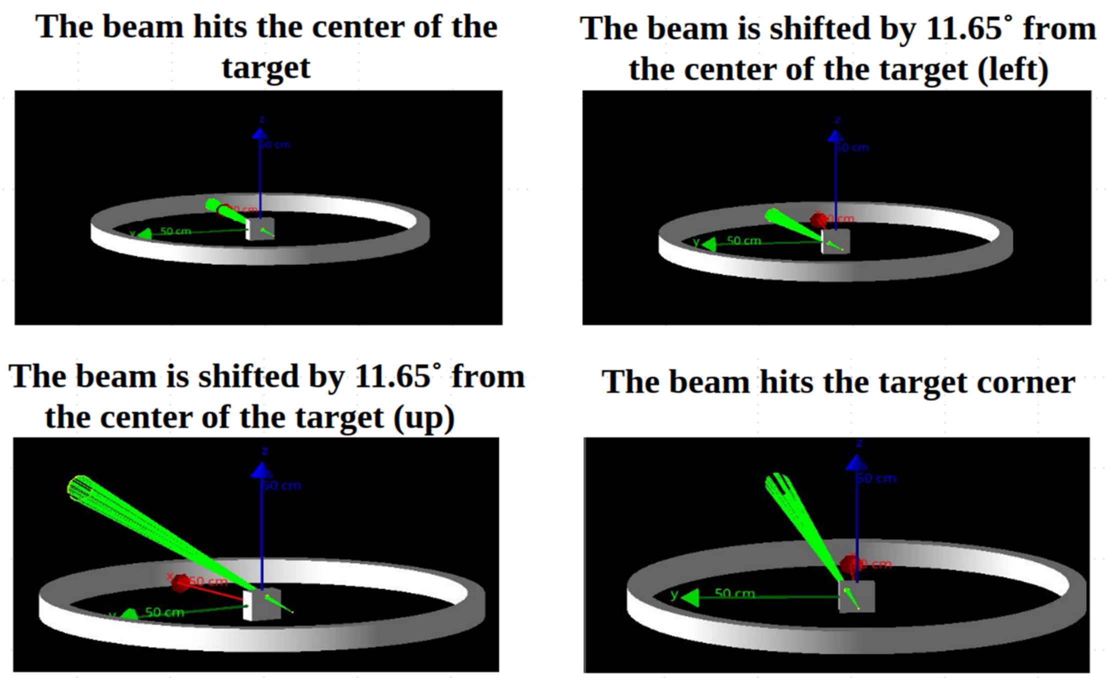

Figure 3. Model of experiment on Geant4 software package.

Using this program, modeling of angular distributions of γ-quanta from targets irradiated by a neutron beam with energy of 14.1 MeV was carried out, assuming isotropic radiation of γ-quanta from excited nuclei formed as a result of inelastic neutron scattering.

As can be seen from Figures 4 and 5, the observed angular distributions are anisotropic, which is a consequence of the absorption of γ- quanta in the sample thickness.

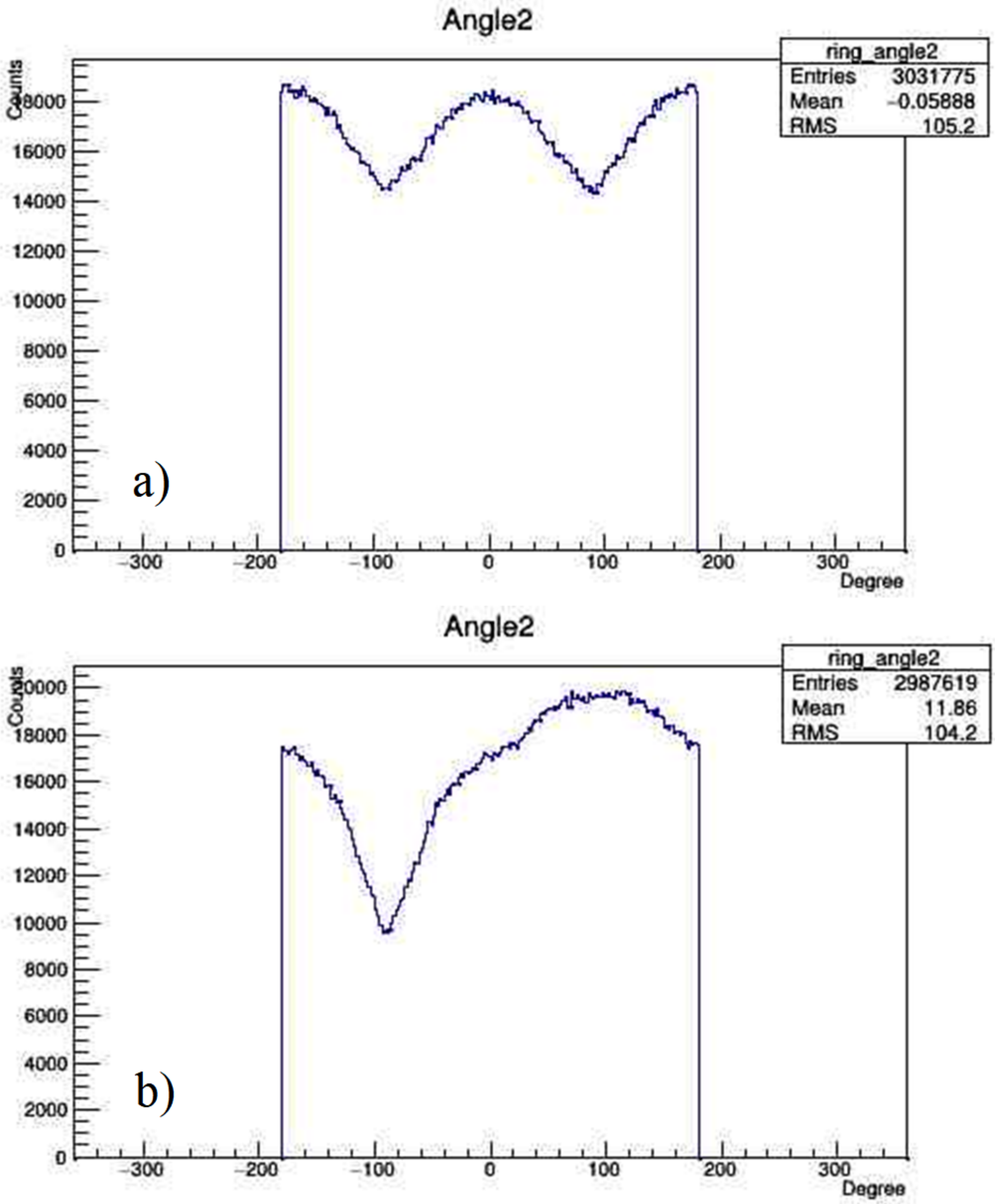

Figure 4. Angular distributions of γ-quantum (3 MeV) for ^{27}Al:
a) The beam hits the center of the target
b) The beam is shifted by 11.65 ^{o} from the center of the target (left).

Accordingly, from the figures it can be seen that the selected target size is too large for heavy nuclei (Fe) because the corrections to the angular distribution are too large. For light nuclei - carbon and aluminum, the corrections are at an acceptable level. To calculate the angular anisotropy of γ-quanta, based on the

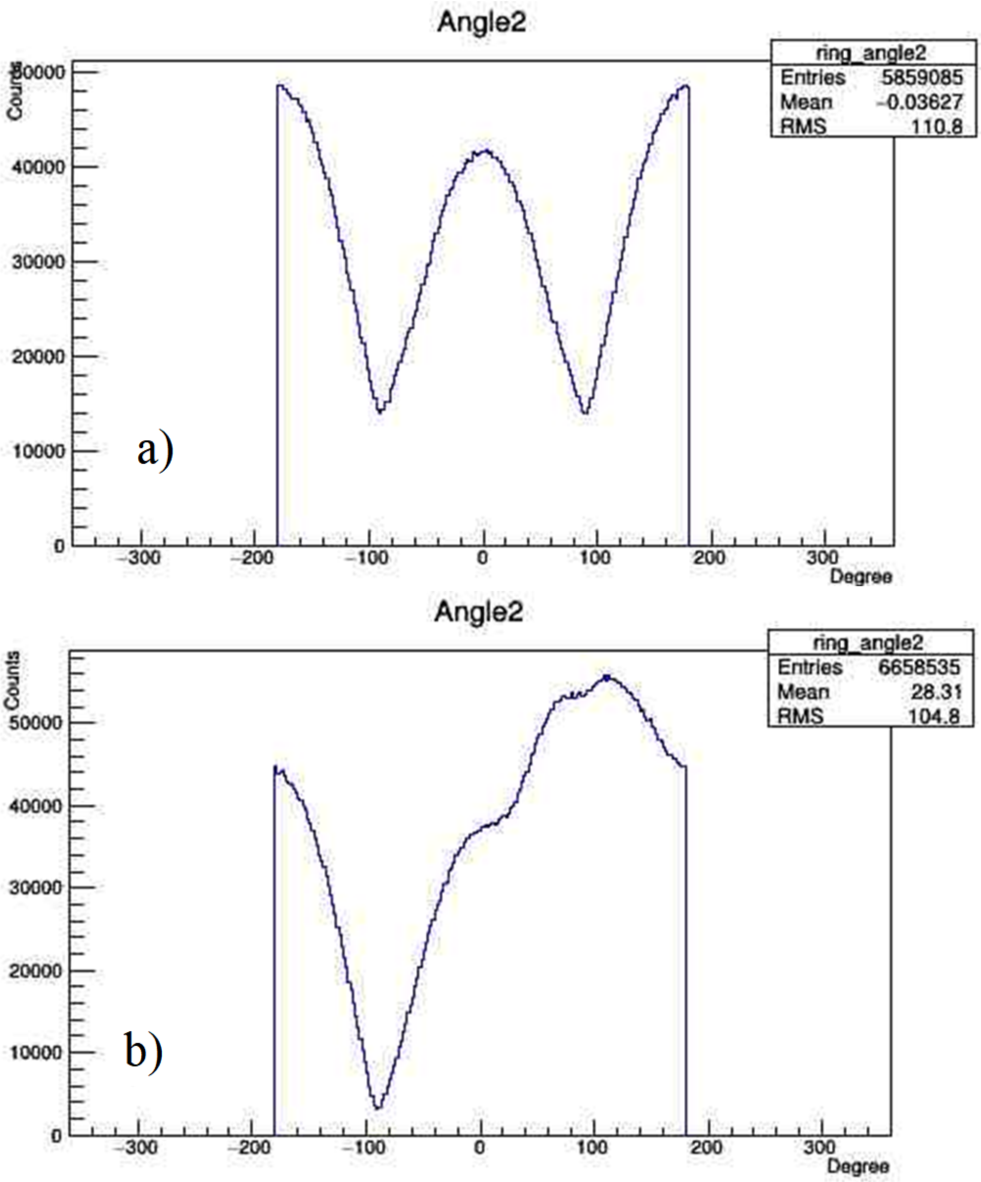

Figure 5. Angular distributions of γ -quantum (0.85 MeV) for ^{56} Fe:
a) The beam hits the center of the target
b) The beam is shifted by 11.65 ^{o} from the center of the target (left).

above, a computer program was written that allows calculating the anisotropy for any possible combination of the numbers of the incident neutron and the target nucleus. Due to this, the target parameters were optimized, that is, the final thickness and height of the target were selected so that all tagged neutrons fell into the sample. The optimization results are shown in Figures 6 and 7.

According to the result, the output of γ -quanta depends on the atomic number of the target material and the angle of bombardment. Investigation of angular distributions of γ -quanta for determination of correction to experimental data is connected with final thickness of sample and with absorption of γ -quanta. And the chosen parameters of the target (height at z = 14, see Figure 7 (a,b)) allow the tagged neutrons to completely hit the target.

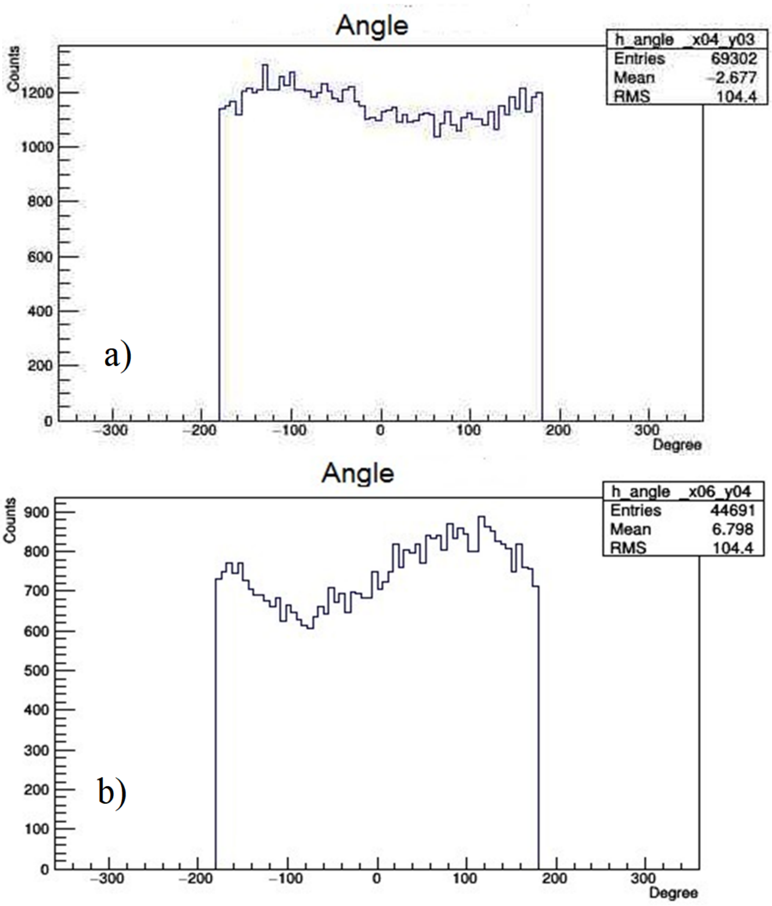

Figure 6. Angular distributions of γ -quantum (1.8 MeV) for ^{56}Fe:
a) The beam hits the center of the target
b) The beam is shifted by 11.65 ^{o} from the center of the target (left).

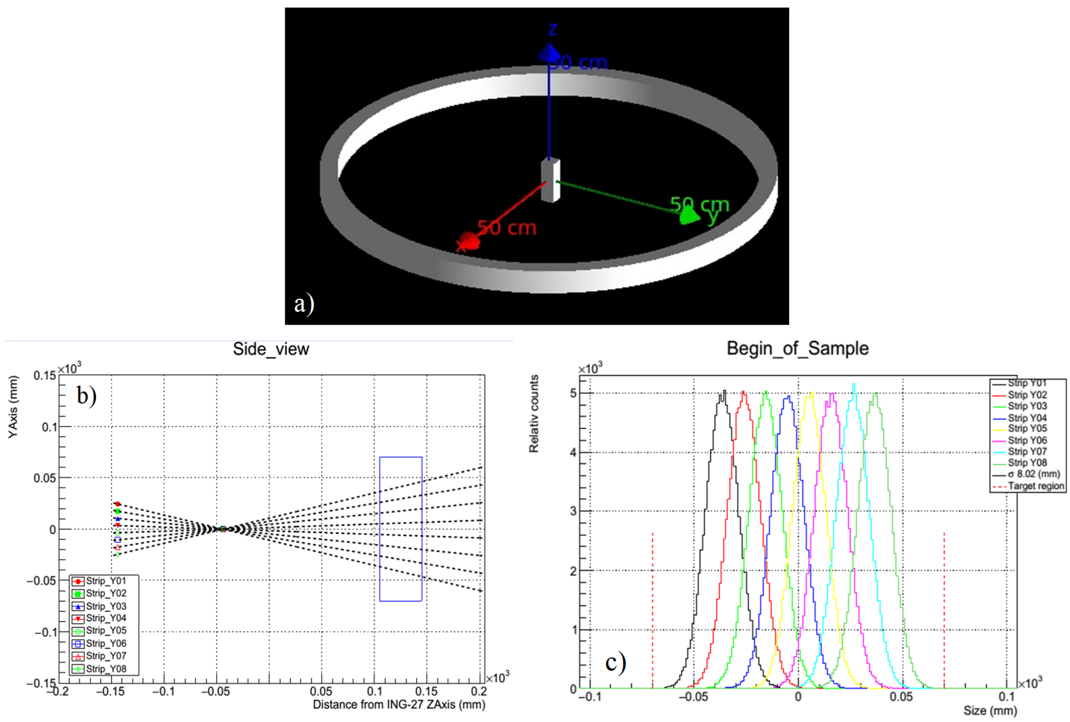

Figure 7. a,b) Target size: 4 × 4 × 14. c) Tagged neutrons in the target.

Conclusion

In order to perform a correct measurement of angular distributions of γ-quanta, it is necessary to estimate the effect of γ-quanta and neutron absorption and rescattering within the sample under study. For this purpose, a Monte Carlo simulation of our experiment with different-size samples was performed on the basis of the GEANT4 code package. For optimum target dimensions, we took those for which the change in the angular distribution of γ-quantum (originating from reactions induced by inelastic neutron scattering on nuclei of the substances under study) because of variations in the geometric parameters of the sample did not exceed 10%.

And taking all this into account, due to this simulation revealed that a sample $4 \times 4 \times 14\,\text{cm}^3$ in size makes a rather small contribution to the anisotropy.

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