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# Measuring the yields and angular distributions of $\gamma$ - quanta from the interaction between 14.1 MeV neutrons and sodium nuclei

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A study of the reaction of inelastic scattering of 14.1 MeV neutrons by $^{23}$Na nuclei was carried out at the TANGRA facility using the tagged neutron method. In this work, the energies of visible $\gamma$-transitions are determined, the yields of $\gamma$-quanta are obtained, the angular distributions of $\gamma$-quanta for $^{23}$Na are measured. The results obtained are in good agreement with the data of other published experimental works.

**Keywords:** gamma-quanta, detectors, neutron, neutron generator, angular distribution.

# Introduction

Investigations of reactions of inelastic scattering of fast neutrons by atomic nuclei are an important source of information on the process of interaction of neutrons with nuclei, including the properties of excited states of target nuclei [1]. From the point of view of theoretical research in nuclear physics, it is interesting to compare the processes of inelastic scattering of protons and neutrons, which is important for discussing isospin symmetry in nucleon interactions. On the other hand, reactions ($n, n' \gamma$) have wide practical application, which entails the task of expanding and clarifying the available amount of experimental information on this process. In particular, in recent years, interest in reactions of inelastic scattering of fast neutrons has grown significantly in connection with the development of new power plants - fast neutron reactors.

The present work is devoted to the study of the characteristics of $\gamma$-radiation generated in reactions of inelastic scattering with energy 14 MeV neutrons by Na nuclei. Sodium is important in the design of IV reactors because it can be used as a coolant. Accordingly, detailed information on the properties of the Na isotope is critical in assessing the physics and safety of many reactor systems. Earlier, the measurement of the characteristics of $\gamma$-radiation generated as a result of scattering of fast neutrons by $^{23}$Na, in particular, the measurement of the angular distribution of $\gamma$-quanta using detectors based on NaI (Tl) was carried out in [2]. In this work, the yield cross sections are measured and the angular distributions of $\gamma$-quanta are obtained for the four most intense $\gamma$-lines in the $^{23}$Na spectrum. The main purpose of our experiment was to refine the existing data, as well as to measure the angular anisotropy of $\gamma$-radiation from $^{23}$Na isotopes.

The TANGRA project (TAgged Neutrons and Gamma RAys), carried out at the Frank Laboratory of Neutron Physics of the Joint Institute for Nuclear Research (FLNP JINR, Dubna), is aimed at studying the inelastic interaction of 14.1 MeV neutrons with atomic nuclei using the tagged neutrons (TNM) [3, 4]. In this technique, the object under study is irradiated with neutrons with energy of 14.1 MeV, formed in the binary reaction

$$d + t \rightarrow \alpha + n \tag{1}$$

The energy of emitted alpha particles in this reaction is 3.5 MeV. Registration of $\alpha$-particles occurs when they coincide with the characteristic $\gamma$-radiation, arising mainly as a result of inelastic reactions of neutrons with target nuclei, for example:

$$A(n, n'\gamma)A \tag{2}$$

The products of reaction (1) in the center of mass system scatter in opposite directions. That is, by fixing the direction of emission of an $\alpha$-particle, it is possible to determine the direction of emission of a neutron. In practice, neutron “tagging” is carried out using a position-sensitive multipixel $\alpha$-detector built into the ING-27 neutron generator [5, 6].

Information about the number of neutrons incident on the sample obtained by recording $\alpha$-particles accompanying the formation of neutrons in the reaction

(1), the number of coincidences $n$ - $\gamma$, target dimensions, and detection efficiency $\gamma$-quanta can let correctly determine the differential cross section of inelastic neutron reactions with the nuclei of the isotopes under study, accompanied by the emission of $\gamma$-quanta of certain energies.

An important advantage of TNM is the monitoring of the flux of tagged neutrons incident on the sample under study and the possibility of highly efficient suppression of the contribution of background events to the resulting $\gamma$-spectra.

## Statement of the experiment

As part of the project TANGRA created several configurations of the experimental setup. The basic part of the TANGRA facility includes a portable ING-27 tagged neutron generator with energy of 14.1 MeV, a collimator and a fast neutron beam profilometer. Various options for detecting systems include a line of detectors with the ability to arrange them in a ring geometry (Romashka [7]), an HPGe-based detection system, and a data acquisition and analysis (DAQ) system. The study of the reaction of inelastic neutron scattering by $^{23}$Na was carried out with the detecting systems "Romasha" and "HPGe".

As a source of tagged neutrons, we use an ING-27 portable neutron generator operating in a continuous mode, in which deuterons are accelerated to energies of 80-100 keV and are focused on a tritium target. The portable neutron generator ING-27 manufactured by FSUE VNIIA has a built-in 64-channel silicon $\alpha$-detector, divided into 8 strips both horizontally and vertically, due to which 64 tagged neutron beams with an energy of 14.1 MeV are actually formed. The maximum intensity of the neutron flux in the $4\pi$-geometry created by the generator is $5 \times 10^7$ s$^{-1}$.

The installation of the TANGRA project based on the «Romasha» spectrometer (Figure 1) consists of 18 scintillation $\gamma$-detectors based on BGO crystals with a diameter of 76 mm and a thickness of 65 mm. The detectors of $\gamma$-quanta are located in the horizontal plane along a circle with a radius of 750 mm with an angle step of $14^\circ$.

In this configuration, there is no additional passive collimation of the neutron beam incident on the target, which makes it possible to reduce the distance from the neutron source to the sample under study to 125 mm.

Installation "HPGe" (Figure 2) is a $\gamma$-detector based crystal of high purity germanium (HPGe) diameter of 57.5 mm and a thickness of 66.6 mm. The detector is located at the minimum possible distance from the sample, which excludes the hit of direct tagged neutrons into the detector. A lead collimator is used to reduce the background from direct neutrons and protect the detector from damage by fast neutrons.

Powdered sodium chloride (NaCl) was used as a target sample, placed in a rectangular aluminum container $6 \times 6 \times 14$ cm$^3$ in size. Since the $\gamma$-quanta detectors were located in the horizontal plane, the corresponding sample dimensions were optimized in order to minimize the absorption of $\gamma$-quanta in the sample. In the GEANT4 (GEometry And Tracking) software package, simulation

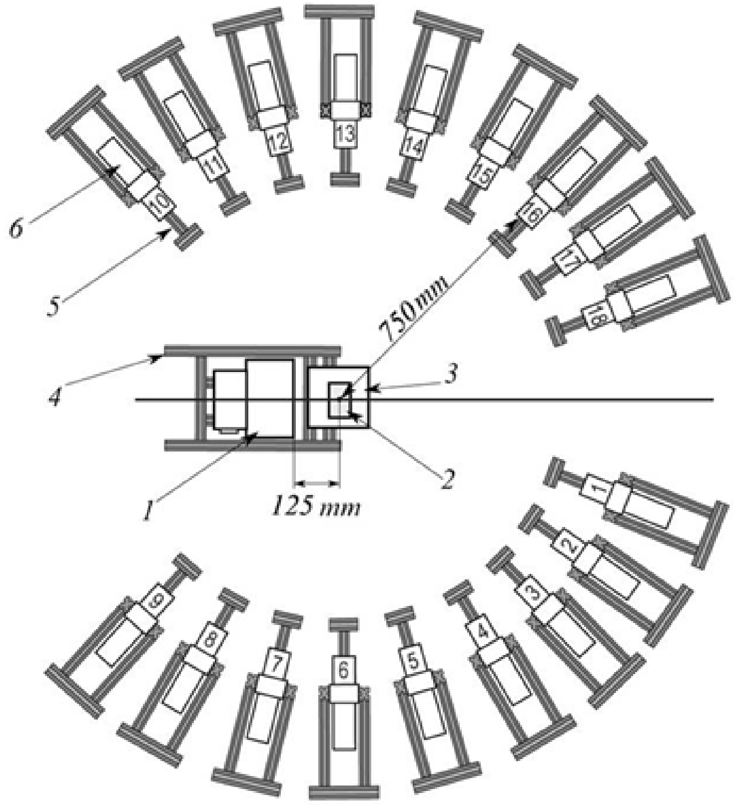


Figure 1. The experimental setup "Romasha": 1 - ING-27 neutron generator; 2 - target; 3 - target holder; 4 - aluminum frame of the setup; 5 - supports for $\gamma$ -radiation detectors; 6 - $\gamma$ -radiation detectors; numbered from 1 to 18.

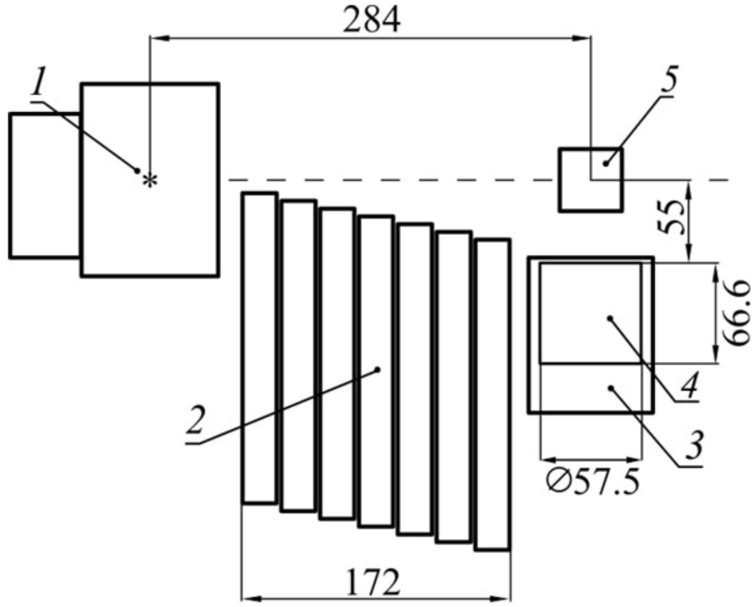


Figure 2. The experimental setup with HPGe: 1 - ING-27 neutron generator; 2 - lead shield; 3 - HPGe $\gamma$ -detector; 4 - sample.

of the experiment was carried out to evaluate the absorption and scattering of $\gamma$ -quanta and neutrons in the target, which showed that for all used tagged beams a sample with dimensions $6 \times 6 \times 14$ cm$^3$ contributes to the observed anisotropy $\gamma$ -radiation quanta distortion not exceeding 20% [8].

The sample was placed on a lightweight aluminum stand. To determine the background component in the $\gamma$ -spectra due to the interaction of neutrons with the support and other structural materials, a separate measurement was carried out without a sample.

All detectors were calibrated using standard $\gamma$-radiation sources. For BGO scintillation detectors, whose light output and, accordingly, energy calibration are not very stable and depend on temperature, load, and other external factors, additional real-time calibration was applied using known background lines recorded during measurements with the sample.

A computer with an ADCM-32 digitizer based on two 16-channel ADCM-16 boards is used for data collection and preliminary analysis [9].

## Analysis of experimental data

The experimental spectra of $\gamma$-quanta obtained in coincidence with tagged neutrons using the HPGe detector and one of the BGO detectors are shown in Figure 3.

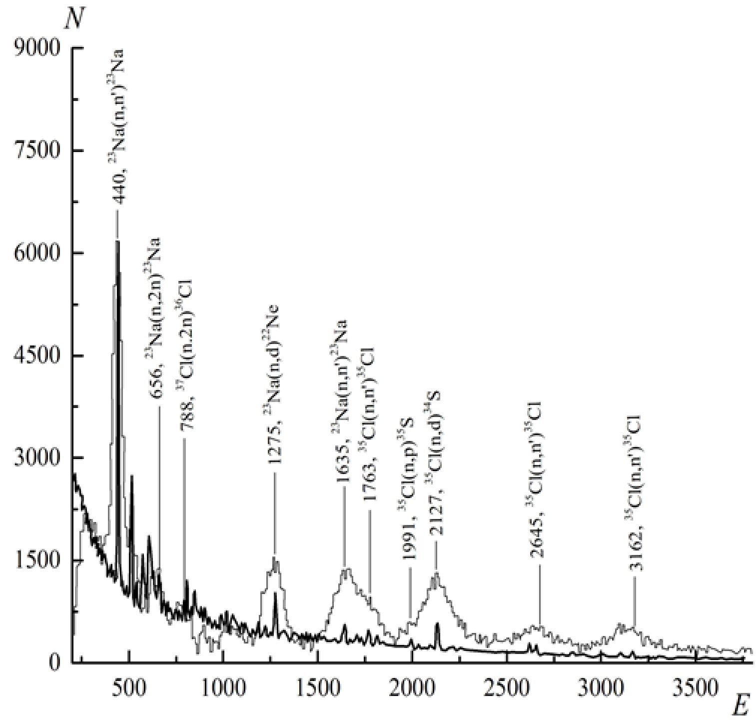


Figure 3. Spectra of $\gamma$-emission obtained by irradiation of a NaCl sample with neutrons with an energy of 14.1 MeV. The thin line shows the spectrum measured with the BGO scintillation detector, the bold line - with the HPGe detector. The energies of the revealed $\gamma$-transitions are indicated according to ENSDF [10].

The $\gamma$-ray yields were measured using a high purity germanium (HPGe) detector. The $\gamma$-quanta emitted by the sample were identified by comparing the-spectra in the coincidence window with tagged neutrons, where they were present as lines arising in the studied reaction to $^{23}$Na, with the $\gamma$-spectra outside the coincidence window, containing background lines from the interaction of neutrons with surrounding materials.

The determination of the parameters of the angular distributions of $\gamma$-quanta relative to the direction of the incident neutron beam was carried out in an experiment with the “Romasha” detector system based on BGO scintillators. Since the energy resolution of BGO detectors does not allow to effectively separating the peaks of total absorption of $\gamma$-quanta of close energies, the angular distributions were determined only for the strongest $\gamma$-transitions. The measured energy spectra for each angle were fitted using the least squares method with a function containing a substrate from random coincidences, a contribution from the interaction of scattered neutrons with the nearest environment of the sample, and a set of Gaussians corresponding to the observed peaks. The areas of the approximated peaks are proportional to the probability of emission of $\gamma$-quanta of a given energy for a given angle. The necessary corrections for the absorption of $\gamma$-quanta in the sample, as well as the effective solid angles for each detector were obtained using simulation in the GEANT4 environment [11].

To quantitatively describe the anisotropy of the angular distribution of $\gamma$-quanta, the anisotropy parameter $W(\theta)$ is introduced, which is defined as the ratio of events recorded at an angle $\theta$ to the number of recorded events averaged over all angles. The obtained angular distributions of $\gamma$-quanta are usually approximated by the expansion in Legendre polynomials:

$$W(\theta) = 1 + \sum_{i=2}^{2J} a_i P_i(cos(\theta)) \tag{3}$$

where $a_i$ - expansion coefficients, $J$ - multipolarity $\gamma$- transition, and the summation index $i$ takes only even values.

# Results

The spectra of $\gamma$-quanta formed in the interaction of 14.1 MeV neutrons with $^{23}$Na nuclei are shown in Figure 3 with the indication of the energy values of the most intense identified by us $\gamma$-transitions. In an experiment using an HPGe detector, 26 $\gamma$ transitions corresponding to reactions of the $(n, X\gamma)$ type, where $X = n', p, d$ or $\alpha$, on $^{23}$Na nuclei were isolated. The list of selected $\gamma$-lines with an indication of the reaction during which they were emitted are given in Table 1.

The characteristics of the initial and final states of the nucleus are also given for the corresponding transitions from the Evaluated Nuclear Structure Data File (ENSDF) nuclear database. In addition to comparison with other experimental data, the tables also show the results of model calculations using the TALYS 1.9 program. The main advantage of the TALYS software is its versatility: it includes modern descriptions of the main reaction mechanisms and covers a wide range of energies (up to 200 MeV) and target nuclei [12].

Angular distributions of $\gamma$-quanta obtained for the most intense lines in the spectrum of the $^{23}$Na nucleus with $\gamma$-quanta energies $E$=439.9 keV, 656.0 keV, 1274.5 keV and 1636 keV, related to reactions of the $(n, X\gamma)$ are shown in Figure 4.

The angular distributions were measured on the «Romasha» setup with the annular geometry of the BGO detectors (see Figure 1). To reduce the statistical error, the data obtained by a pair of detectors located at the same scattering angle, but from different sides of the sample, were averaged. The solid line corresponds

Table 1.
The energies of $\gamma$-transitions $E_\gamma$ (keV) observed upon irradiation with 14.1 MeV neutrons of $^{23}$Na nuclei. Gamma-producing reactions and the spins and parities of the initial $(J^\pi)^i$ and final $(J^\pi)^f$ states of the corresponding nucleus are indicated. The $Y_\gamma$ yields obtained at the TANGRA facility are compared with the literature values and with the calculations in TALYS 1.9. The asterisk "$*$" marks the $\gamma$-lines that could not be separated in this experiment. Transitions for which angular distributions are defined are in bold.

| $E_\gamma$ | Reaction | $E, (J^\pi)^i \to E, (J^\pi)^f$ | $Y_\gamma$,% | | |
|---|---|---|---|---|---|
| | | | TANGRA | TALYS | [13] |
| 166.7 | $^{23}$Na$(n,\alpha)^{20}$F | 823(4$^+$)→656(3$^+$) | 8.7±1.4 | 6.8 | |
| 439.9 | $^{23}$Na$(n,n')^{23}$Na | 440(5/2$^+$)→0(3/2$^+$) | 100 | 100 | 100 |
| 627.5 | $^{23}$Na$(n,n')^{23}$Na | 2704(9/2$^+$)→2076(7/2$^+$) | 5.3±0.8 | 7.4 | 4.7±0.8 |
| 656.0 | $^{23}$Na$(n,\alpha)^{20}$F | 656(3$^+$)→0(2$^+$) | 9.3±0.9 | 15.3 | 10.2±0.9 |
| 983.5* 1001.07* | $^{23}$Na$(n,\alpha)^{20}$F $^{23}$Na$(n,\alpha)^{20}$F | 983(1$^-$)→0(2$^+$) 1824(5$^+$)→823(4$^+$) | 4.3±1 | 6.5 | |
| 1274.5 | $^{23}$Na$(n,d)^{22}$Ne | 1275(2$^+$)→0(0$^+$) | 30.9±1 | 77.7 | 41.8±2.7 |
| 1636.0 | $^{23}$Na$(n,n')^{23}$Na | 2076(7/2$^+$)→440(5/2$^+$) | 17.2±1 | 37.8 | 32±3.4 |
| 2239.8 | $^{23}$Na$(n,n')^{23}$Na | 2639(1/2$^-$)→0(3/2$^+$) | 2.6±1.3 | 3.5 | |

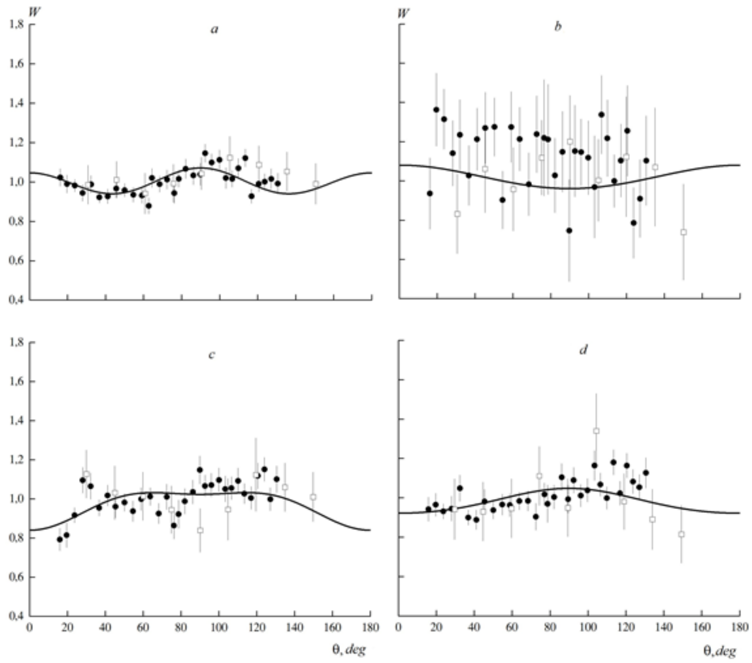


Figure 4. Angular distributions of $\gamma$ -quanta for transitions in the reaction $^{23}$Na ( $n$ , $n'$ $\gamma$ ) $^{23}$Na: $E_\gamma$ =439.9 (a) and 1636 (d) and also $\gamma$ -quanta $E$ =656.0 keV from the reaction $^{23}$Na ( $n$ , $\alpha$ ) $^{20}$F(b) and $E_\gamma$ =1274.5keV from the reaction $^{23}$Na ( $n$ , $d$ ) $^{22}$Ne (c). In Figure rectangles - data from work [2]. The solid line corresponds to the approximation of the data by Legendre polynomials according to formula (3).

to the approximation of the data by Legendre polynomials according to formula (3). The obtained angular correlation parameters for $^{23}$Na are presented in Table 2 in comparison with the results [2].

Table 2.
Coefficients Legendre polynomial expansion for the angular distribution $\gamma$ -rays emitted in the interaction of neutrons with the energy of 14.1 MeV and nuclei $^{23}$Na.

| $E_\gamma$(keV) | $a_2$ | $a_4$ |
|---|---|---|
| 439.9 | -0.05±0.01 -0.04$^{a)}$ | 0.132±0.02 0.01$^{a)}$ |
| 656.0 | -0.42±0.06 0.22$^{a)}$ | -0.78±0.07 -0.02$^{a)}$ |
| 1274.5 | -0.09±0.02 0.14$^{a)}$ | -0.06±0.03 -0.16$^{a)}$ |
| 1636 | -0.09±0.02 0.18$^{a)}$ | 0.01±0.03 0.13$^{a)}$ |

*a*) Data from work [2]

In general, the values of the angular coefficients are in good agreement with previously reported data.

# Conclusion

A study of the reaction of inelastic scattering of 14.1 MeV neutrons by $^{23}$Na nuclei was carried out at the TANGRA facility based on the ING-27 portable neutron generator using the tagged neutron method. The energies of the visible $\gamma$ -transitions formed in various reactions of neutrons with $^{23}$Na nuclei were determined. The data obtained are generally consistent with the known literature data. For the strongest lines, the parameters of the angular anisotropy of the emission of $\gamma$-quanta relative to the direction of the neutron beam are determined.

New experimental results were presented on the measurement of $\gamma$-ray yields for transitions in $^{23}$Na arising from the irradiation of $^{23}$Na nuclei with neutrons with an energy of 14.1 MeV. The calculated values of the $\gamma$-quanta arising from the irradiation of the sample from the TALYS 1.9 outputs are in good agreement with our experimental data.

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# References

[1] W. Hauser, H. Feshbach, Phys. Rev. **87** (1952) 366-373.
[2] U. Abbondanno et al., J. Nucl. Energy **27** (1973) 227-239.
[3] V.M. Bystritsky et al., Phys. Part. Nucl. Lett. **12** (2015) 325-335.
[4] D.N. Grozdanov et al., Phys. of Atom. Nucl. **81** (2018) 588-594.
[5] V.M. Bystritsky et al., Physics of Particles and Nuclei Letters **5** (2008) 441-446.
[6] V.Yu. Alexakhin et al., Nucl. Instrum. Meth. A **785** (2015) 9-13.
[7] N.A. Fedorov et al., EPJ Web Conf. **177** (2018) 02002.
[8] S. Dabylova et al., Eurasian Journal of Physics and Functional Materials **4**(3) (2020) 226-233.
[9] ADCM16-LTC (16-channel 14-bit 100MHz ADC board with signal processing core), http://afi.jinr.ru/ADCM16-LTC.
[10] R.B. Firestone, Nucl. Data Sheets **108** (2007) 2319-2392.
[11] Geant4 (Toolkit for the simulation of the passage of particles through matter), https://geant4.web.cern.ch.
[12] A.J. Koning et al., Nucl. Data Sheets **155** (2019) 1-55.
[13] S. Simakov et al., INDC(CPP)-0413 (1998) Vienna: IAEA NUCLEAR DATA SECTION.