Angular Distribution of Gamma Rays from the Inelastic Scattering of 14 MeV Neutrons on Light Nuclei

N.A. Fedorov[1,2], T.Yu. Tretyakova[1,3], Yu.N. Kopatch[1], V.M. Bystritsky[1], D.N. Grozdanov[1,4], F.A. Aliyev[1,5], I.N. Ruskov[1,4], V.R. Skoy[1], C. Hramco[1,6] and TANGRA collaboration

[1]*Joint Institute for Nuclear Research (JINR), Dubna, Russia*
[2]*Faculty of Physics, Lomonosov Moscow State University (MSU), Moscow, Russia*
[3]*Skobeltsyn Institute of Nuclear Physics (SINP MSU), Moscow, Russia*
[4]*Institute for Nuclear Research and Nuclear Energy (INRNE) of Bulgarian Academy of Sciences (BAS), Sofia, Bulgaria*
[5]*Institute of Geology and Geophysics, Baku, Azerbaijan*
[6]*Institute of Chemistry, Academy of Science of Moldova, Chisinau, Republic of Moldova*

Abstract

An investigation of the angular and energy distributions of γ-rays from the inelastic scattering of ~14 MeV neutrons on a number of light nuclei was performed in the frame of the project TANGRA (TAgged Neutron & Gamma RAys). Using an experimental setup, which consists of an ING-27 portable generator producing ~14 MeV "tagged" neutrons and a Fe-shielded ring of 22 NaI(Tl) gamma-ray detectors, we have accomplished the measurements with C, O, Si and Al samples.

1. Introduction

The main purpose of the TANGRA project (TAgged Neutron & Gamma RAys) in JINR [1, 2] is the detailed studying the ~14 MeV neutron inelastic scattering on atomic nuclei using the tagged neutron method (TNM). The measurement of *n*-γ angular correlations in the 14.1 MeV neutron inelastic scattering is important from the point of view of understanding the mechanisms of interaction of the nucleus with the incident nucleon. In the literature, information on processes of this type involving neutrons is presented substantially less, compared to the results of experiments on inelastic scattering of charged particles by atomic nuclei. A comparison between the neutron and proton inelastic scattering is very important for theoretical nuclear physics and nuclear astrophysics, because it provides a possibility to investigate the isospin symmetry of the nucleon-nucleon interactions. Interest in the reactions ($n, n'\gamma$) on light and medium-weight elements is also dictated by the need to refine the previously obtained experimental data, since such reactions have wide practical applications in geology, in nuclear power engineering, in the detection of hidden dangerous substances [3].

The tagged neutron method is based on the registration of the α-particle with energy of 3.5 MeV from the reaction:

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

The α-particle has practically the opposite direction of flight with respect to the direction of neutron emission. The energy of the neutron is 14.1 MeV. The α-particles are registered in coincidence with the pulses from the characteristic nuclear γ-radiation, emitted during the neutron inelastic scattering reaction on the nuclei A in the sample.

$$A(n,n')A^* \xrightarrow{\gamma} A. \qquad (2)$$

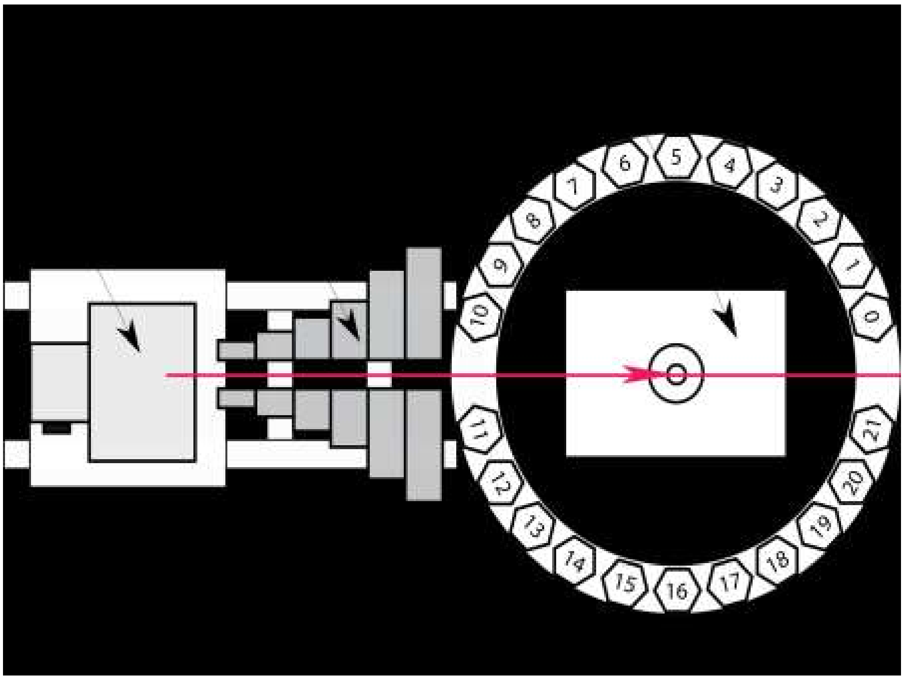

Fig. 1. Scheme of the TANGRA setup in the reaction plane: 1 – portable neutron generator ING-27, 2 – iron shielding, 3 – "Romashka" γ-ray registration system, 4 – sample holder, 5 – setup frame. Arrow of the longitudinal line shows the neutron beam direction.

So, it is possible to reconstruct the neutron flight direction by fixation of the alpha-particle emission angle, i.e. to "tag" each emitted neutron. Practically using a position-sensitive α-detector, embedded in the neutron generator, the "tagging" of the neutrons is achieved.

The information about the number of the emitted neutrons, the number of the n-γ coincidences and the efficiency of the γ-quanta registration, allows one to determine correctly the differential cross sections of inelastic scattering of neutrons by the nuclei of the investigated isotopes with the selected excitation states.

In our previous article [4] the γ-quanta angular distribution measurements of the 14.1 MeV neutron inelastic scattering on ^{12}C was considered. The use of tagged neutron method has made it possible to improve the accuracy of measurements, which is of fundamental importance, since the data available in the literature vary considerably. The chosen geometry of the experiment made it possible to carry out measurements with the emission of γ quanta at angles less than 10 ° for the first time. In this paper the results of γ-quanta angular distribution in reaction (n, n'γ) on ^{16}O, ^{27}Al и ^{28}Si are presented.

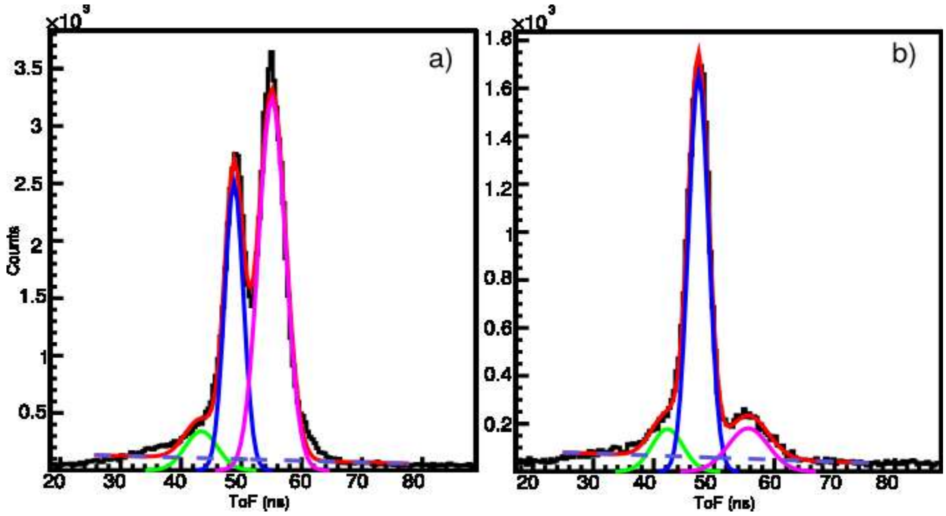

Fig. 2. Time-of-flight spectra and their approximations for γ-detectors placed at ~15° (a) and ~90° (b). The left peak corresponds to γ-quanta emitted from the neutron inelastic scattering in shielding, the central peak corresponds to the γ-quanta emitted from sample and the right peak is from the neutrons, which are elastically or inelastically scattered by the target.

2. Experimental setup

The detailed scheme of TANGRA-setup for studying the fast neutron scattering reactions is presented in [5] (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 80–100 keV focusing on a tritium target. The products of this reaction are 14.1 MeV neutrons and 3.5 MeV α-particles. The maximal intensity of the “tagged” neutron flux in 4π–geometry is 5×10^{7} c^{-1}. The α-particles are registered by a 64-pixel α-detector with a pixel dimensions or 6 × 6 mm^2. The detector is located at a distance of 100 mm from the tritium-enriched target.

The γ-quanta emitted after the neutron inelastic scattering by a target are registered by a system of 22 NaI(Tl) scintillator γ-detectors placed around the sample with ~15° step. To protect the detectors nearest to the generator from direct neutrons a compact steel collimator is used. The background events are separated using the Time-of-Flight (ToF) method. The “start” of the measurement time interval is given by the signal from the alpha-detector and the “stop” – by the signal from the γ-detector. The difference in speed between the neutron and the photon provides the possibility to separate the γ-rays from the neutrons. For data acquisition a personal computer with two ADCM-16 boards is used [6].

As targets in experiments on inelastic scattering of fast neutrons by oxygen and silicon, plastic containers filled with the test substances (water and chemically pure SiO_2 dust) with dimensions 10×10×10 cm^3 were used. For experiment with aluminum a block with dimensions 10×10×5 cm^3 was used. The optimal dimensions of the samples were determined by model simulations [4].

3. Experimental data analysis

The signals from the α- and γ-detectors, digitized by the ADCM, are written on the computer hard disk for creating the time and amplitude TOF neutron-gamma separated spectra. The examples of time-spectra from the detectors at angles ~15° and ~90° relative to the neutron beam are presented in Fig. 2. There are three peaks visualized in each spectrum. The left peak corresponds to the γ-quanta emitted from neutron inelastic scattering in the shielding-collimator, the central peak corresponds to the γ-quanta emitted from the sample

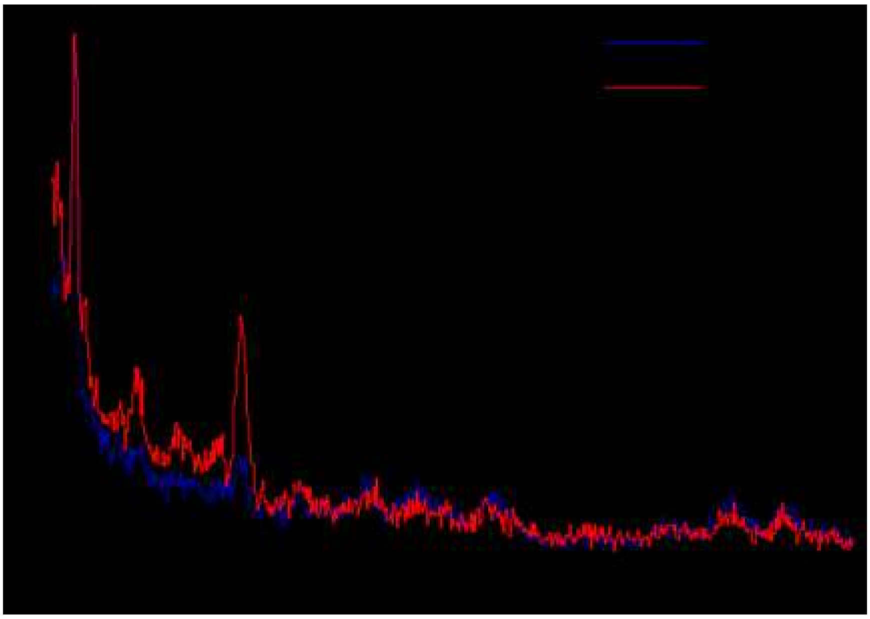

Fig. 3. Gamma-ray energy spectra emitted by SiO_2 and water from the 14.1 MeV neutron irradiation.

and the right peak is formed by neutrons that hit the γ-detector. Further, using the energy calibration of γ detectors, the energy spectra of the events occurring in a time window corresponding to γ-quanta are constructed.

The data from only one central pixel of the α-detector were taken into account in this experimental setup, which made it possible to substantially reduce the number of background events and simplify the algorithms for processing the experimental data. However, this technique leads to a reduction in the collected statistics and significantly increases the irradiation time.

The information on the number of events corresponding to the emission of the γ-quanta from the nucleus transition from a definite excited state to a lower state is extracted from the energy γ-spectra by evaluating the corresponding gamma-peak. This information is obtained from the events in the full energy absorption peak and/or single escape peak. The final angular distribution is normalized and fitted by a Legendre polynomial expansion. For quantitative description of γ-quanta emission angular distribution, an anisotropy parameter $W(\theta)$ is introduced:

$$\frac{d\sigma_j}{d\Omega} = AW(\theta) \tag{3}$$

$$W(\theta) = 1 + \sum_{i=2}^{2J} a_i P_i(\cos\theta), \tag{4}$$

where a_i are decomposition coefficients, J is the γ-transition multipolarity, the summation index i has only even values.

4. Results

In the inelastic scattering of 14 MeV neutrons by ^{12}C, the excitation of only one state that decays with the emission of a γ-ray with the energy of 4.43 MeV and the multipolarity of

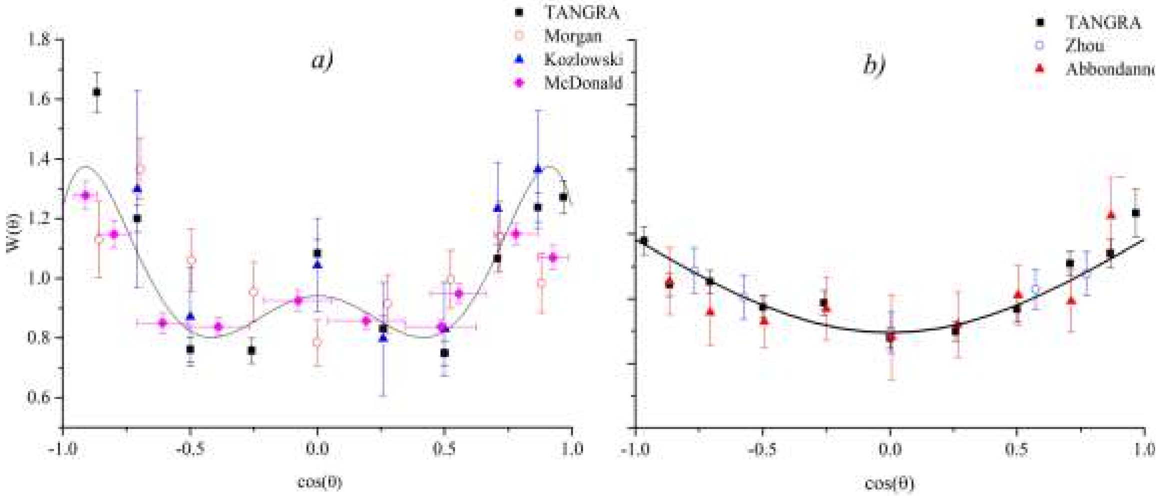

Fig. 4. The experimental angular distribution of γ-quanta with energy E_{γ}= 6.13 MeV, emitted during the neutron inelastic scattering on ^{16}O (a), and γ-quanta with energy E_{γ}= 1.78 MэB, emitted by ^{28}Si (b). Solid lines are approximations by Legendre polynomials.

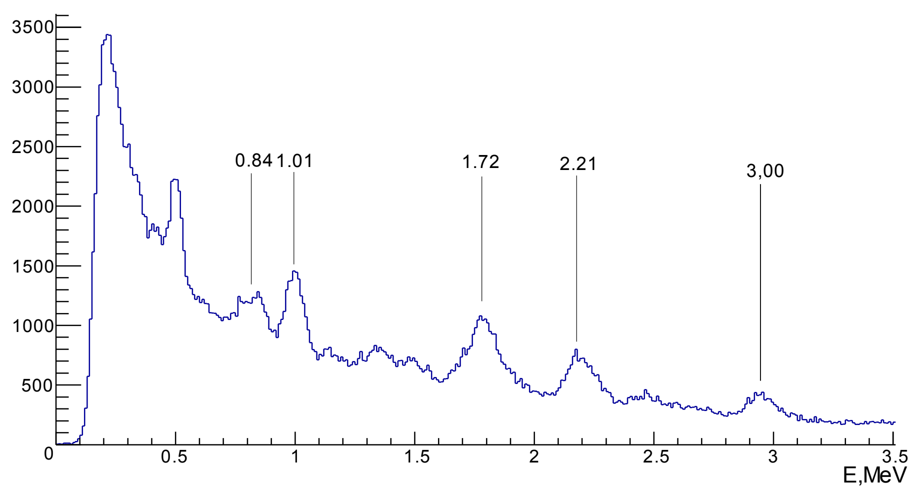

Fig.5. Gamma-ray energy spectrum emitted by ^{27}Al during 14.1 MeV neutron irradiation.

E2 is most pronounced. Many papers have been devoted to the study of this reaction and the angular distribution data are known with good accuracy [4]. With an increase in the number of nucleons, the spectra of the excited states of the nuclei become more complicated, which is reflected in the experimental data. In Fig. 3 the energy spectra from (*n*, *n*'γ) reaction on water and SiO_2 are presented. In both spectra, the peak is most clearly distinguished at 6.1 MeV, corresponding to *E*3 transition from the state with spin and parity $J^{\pi}= 3^{-}$ to the ground state 0^{+} ($3^{-}\rightarrow 0^{+}$) in ^{16}O. The structure of the energy spectra with E^{*} below ~ 6 MeV is more complex for interpretation. In case of neutron inelastic scattering on SiO_2 γ-quanta emitted in (*n*, *n*'γ) reaction make significant contribution to the photopeak at ~1.7 MeV, which also corresponds to the transition from state 2^- (8.87 MeV) to 1^-(7.12 MeV) in ^{16}O. The peaks near 2.7 and 3.8 MeV probably correspond to γ-transitions 2^- (8.87 MeV) → 3^-(6.13 MeV) and 2^+(9.84 MeV) → 0^+ (6.05 MeV) in oxygen. Also, the peak near 3.8 MeV could be formatted by the γ-quanta from deexcitation of ^{13}C, which could be produced in the reaction ^{16}O(*n*,α)^{13}C [8]. A definite contribution to the structure of the spectrum in this energy range is also provided by annihilation γ-quanta, which arise from the pair production in the target.

Table 1. The Legendre coefficients fitted to the γ-quanta angular distributions from (*n*, *n*'γ) reaction on ^{16}O and ^{28}Si

Experiment	a_2	a_4	a_6
^{16}O, 3^- (6.13 MэВ)			
Kozlowski (1965) [7]	0.2 ± 0.3	– 0.3 ± 0.5	– 0.7 ± 0.5
Morgan (1964) [7]	0.34 ± 0.04	0.01 ± 0.06	– 0.04 ± 0.06
McDonald (1966) [8]	0.22 ± 0.08	– 0,05 ± 0.10	– 0.32 ± 0.08
This work	0.39 ± 0.03	0.13 ± 0.04	– 0.28 ± 0.05
^{28}Si, 2^+ (1.78 MэВ)			
Zhou [9]	0.21 ± 0.02		
Abbondanno [10]	0.20 ± 0.09	0.11 ± 0.14	
This work	0.19 ± 0.02	0.02 ± 0.03	

As a result of an analysis of the events corresponding to the full absorption peak of γ rays with an energy of 6.13 MeV, the dependence of the anisotropy parameter *W*(θ) was obtained. The experimental values and the analytical approximation with formula (4) are shown in Fig.4. The Legendre coefficients are presented in Table 1 in comparison with the coefficients from our approximation of the results from [8] and the data from the CDFE SINP MSU database [7]. It should be noted that, in comparison with the number of experiments on inelastic neutron scattering by carbon, the data on the angular distribution of γ-radiation in the inelastic scattering of 14.1 MeV neutrons by ^{16}O nuclei are extremely poor. The data of our experiment are in accordance with the results of previous measurements, and they have a significantly higher accuracy. The contribution of the polynomials with higher degrees is very interesting because the behavior of the anisotropy is important not only for modeling or any practical application, but also needed for the theoretical description of the neutron inelastic scattering. In this case, a high multipolarity of the transition leads to a more complex angular dependence, which has not yet been qualitatively reproduced in theoretical approaches.

In 14.1 MeV neutron inelastic scattering by ^{28}Si a large number of states are excited, which can decay by emitting the γ-rays. The results of an experiment on scattering of neutrons with the energy of 14.9 MeV on natural silicon are presented in [9], and the structure of the formed γ–spectrum is considered in detail. According to ref. [9], the five of fifty identified γ-transitions occur during the ^{28}Si(*n*, *n*'γ)^{28}Si* reaction. The most intensive γ-transition is the transition from the first excited state 2^+ (1.778 MeV) to the ground state. For this γ transition, the parameters of the anisotropy were determined (see Table 1).

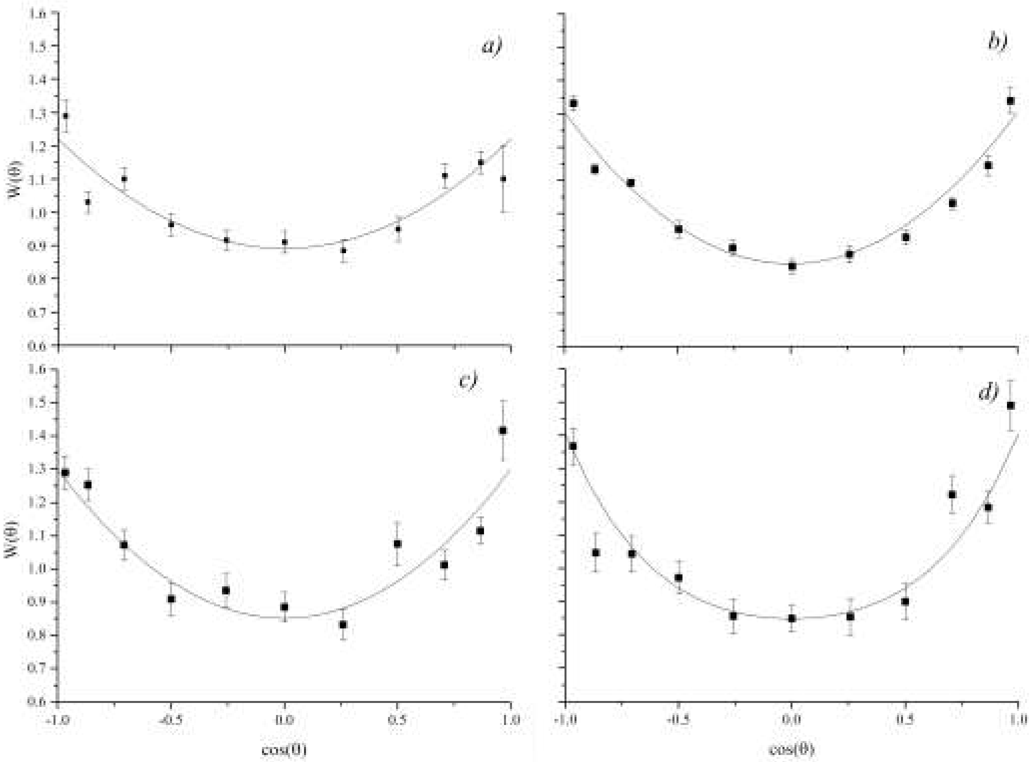

Fig. 6. The experimental angular distributions of γ-rays with energy E_γ= 1.014 MeV (a), E_γ= 1.72 MeV (b), E_γ= 2.21 MeV (c) and E_γ= 3,004 MeV (d) from inelastic scattering of 14.1 MeV neutrons by ^{27}Al. Solid lines are approximations by Legendre polynomials.

The data obtained in our experiment on the scattering of 14.1 MeV neutrons on a sample of SiO_2 make it possible to isolate γ–radiation for the transition from the first excited state 2^+ (1.778 MeV) to the ground state. Our results and their approximation are presented in Fig. 4 b). The Legendre coefficients, determined from our results in comparison with the coefficients from [9, 10] are presented in Table 1. The results of the approximation of the obtained angular distribution of γ-radiation agree with the data obtained in the previous experiments, within the limits of errors.

Interest in the inelastic neutron scattering reaction on ^{27}Al nuclei is explained by the fact that aluminum has only one stable isotope, and thus the experimental results must be in a good agreement with model calculations. An important factor is also the widespread use of aluminum as a constructing material.

However, ^{27}Al nucleus is even-odd, therefore the spectrum of the low-lying excited states is more complicated than that of the even-even nuclei. This feature makes the identification of the γ transitions more difficult. An additional uncertainty comes from mixing of γ-quanta with close energies from different reactions, for example, the γ-quanta from ^{27}Al(*n*, *n*'γ)^{27}Al and ^{27}Al(*n*, *p*γ)^{27}Mg* with consecutive β^- decay to ^{27}Al*. As a result, the accuracy of the obtained data is about 10% and only eight γ-transitions were identified. The most precisely the differential cross-section data for reaction ^{27}Al(*n*,*x*γ)^{27}Al were obtained in [11] at neutron energy of 14.9 MeV, 26 discrete γ-transitions were identified and ten of them in the energy range from 0.7921 to 3.004 MeV are related to the (*n*, *n*'γ) reaction. A lot of references for experimental works considered (*n*, *n*'γ) reaction cross-sections with neutron energies near 14 MeV were collected in [11, 12]. It should be noted that the obtained experimental data fluctuate over a wide range and, despite the presence of γ-emission differential cross-section measurements at different angles, the angular dependences of the anisotropy are not presented.

Table 2. The Legendre coefficients fitted by γ-quanta angular distribution from ^{27}Al(*n*, *n*'γ)^{27}Al reaction. The energies and the multipolarities of the γ–transitions are also shown.

E_γ, MeV (Mult.)	1.01 (*M*1+*E*2)	1.72 (*M*1+*E*2)	2.21 (*M*1+*E*2)	3.00 (*E*2)
a_2	0.22 ± 0.02	0.30 ± 0.01	0.30 ± 0.03	0.35 ± 0.03
a_4				0.06 ± 0.04

The γ-spectrum of the photons, emitted during the neutron inelastic scattering on aluminum, obtained in our experiment is presented in Fig. 5. The γ-transitions with energies 0.84 MeV (transition from $1/2^+$(0.844 MeV) to the ground state $5/2^+$), 1.01 MeV ($3/2^+$(1.014 MeV) → $5/2^+$, g.s.), 1.72 MeV ($5/2^+$(2.735 MeV) → $3/2^+$(1.014 MeV)), 2.21 MeV ($7/2^+$(2.212 MeV) → $5/2^+$, g.s.) and 3.00 MeV ($9/2^+$(3.004 MeV) → $5/2^+$, g.s.) were identified with the highest reliability. The angular distributions of the gamma-quanta emitted during these transitions and their approximations are showed in Fig. 6. The coefficients of Legendre series approximation are written in Table 2. It is interesting to notice that for *E*2-transition 3.00 MeV ($9/2^+$(3.004 MeV) → $5/2^+$, g.s.) a_4 is insignificant. In our experiment the parameters of anisotropy are quite similar for all observed transitions and it is completely different from the situation described in [13], where the γ-quanta angular distributions were investigated for ^{27}Al(*n*, *n*'γ)^{27}Al reaction with 3.5 MeV neutrons and a comparison with Hauser-Feshbach model was presented. For $J \leq 5/2$ the calculations predict $a_2 < 0.04$ and the experimental angular distributions for the gamma-transitions $E_\gamma = 1.01$ and 1.72 MeV are isotropic. The anisotropy coefficients for $E_\gamma = 2.21$ and 3.00 MeV have quite similar values, $a_2 = 0.22 \pm 0.04$. This value is comparable with our result for $E_\gamma = 3.00$ MeV transition. Such a discrepancy between the results of experiments at different neutron energies can indicate both the need for further refinement of the experimental data and a fundamental change in the dynamics of the reaction with increasing neutron energy.

Conclusion

At the TANGRA facility using the tagged neutron method on the beam of the ING-27 neutron generator, a study of the inelastic scattering of neutrons with the energy of 14.1 MeV on the nuclei of oxygen, silicon and aluminum was made. An important advantage of the experiment is a wide range of angles and a large number of points in which the registration of γ-quanta was simultaneously carried out.

The angular distributions of γ-quanta from the excited state of 6.13 MeV (3^-) in ^{16}O and from the first excited state of 1.78 MeV (2^+) in ^{28}Si were obtained with high accuracy. The values of the coefficients of the expansion of the anisotropy function in Legendre polynomials are in accordance with the results of the previous measurements. The angular distribution of γ-rays from the inelastic scattering of 14.1 MeV neutrons on ^{27}Al was measured for the first time.

This work was carried out with RFFR partial financial support (Grant 16-52-45056).

REFERENCES

1. Ruskov I.N., et al. // Phys. Procedia. 2015. **64**. 163.
2. Bystritsky V.M., et al. // Phys. Part. Nucl. Lett. 2015. **12**. 325.
3. Valković V. 14 MeV Neutrons. Physics and Applications. USA. CRC Press, 2016.
4. Bystritsky V.M., et al. // Phys. Part. Nucl. Lett. 2016. **13**. 504.
5. Ruskov I.N., et al.// EPJ Web of Conferences. 2017. **146**. 03024
6. ADCM – An universal Digital Pulse Processing System for nuclear physics experiments: http://afi.jinr.ru/ADCM16-LTC.
7. SINP MSU CDFE Data Base, http://cdfe.sinp.msu.ru/.
8. McDonald W.J., Robson J. M., Malcolm R. // Nucl. Phys. A. 1966. **75**. 353.
9. Hong-Yu Zhou, et al. // Nucl. Instr. and Meth. A. 2011. **648**. 192.
10. Abbondanno U., et al. // J. Nucl. Energy. 1973. **27**. 227.
11. Zhou H., Huang G. // Nucl. Sci. and Engineering. 1997. **125**. 61-74.
12. Hlaváč S., et al // Nucl. Sci. and Engineering. 1997. **125**. 196-204.
13. Chung K.C., et al // Nucl. Phys. 1968. **A115**. 476-480.