STUDY OF 14.1 MeV NEUTRONS INELASTIC SCATTERING ON IRON

Fedorov N.A.[1,2*], Tretyakova T.Yu.[3], Kopatch Yu.N.[1], Bystritsky V.M.[1], Grozdanov D.N.[1,4], Aliyev F.A.[1,5], Ruskov I.N.[4], Skoy V.R.[1], Dabylova S.[1], Gorelikov A.V.[2], Hramco C.[1,6], Kumar A.[7], Gandhi A.[7], Wang D.[8], Bogolyubov E.P.[9], Yurkov D.I.[9], 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), Bulgarian Academy of Sciences (BAS), Sofia, Bulgaria*
[5]*Institute of Geology and Geophysics (IGG), Baku, Azerbaijan*
[6]*Institute of Chemistry, Academy of Science of Moldova, Chisinau, Republic of Moldova*
[7]*Banaras Hindu University, Varanasi, India*
[8]*Xi'an Jiao Tong University, Xi'an, China*
[9]*All-Russia Research Institute of Automatics (VNIIA), Moscow, Russia*

Abstract

The angular distributions of gamma-rays from the inelastic scattering (INS) of 14.1 MeV neutrons on iron (Fe) are investigated with Tagged Neutron Method (TNM). The anisotropy of γ-rays emitted during the INS-process was measured, using an improved TANGRA (TAgged Neutron and Gamma RAys) setup. The setup's configuration and the digital method of data processing provide a possibility to significantly improve the spatial resolution of gamma-ray detection system and, on the other hand, to increase the precision of obtained gamma-ray angular distributions data. Detailed γ-spectrum for *(n,n')* reaction was obtained and γ-ray angular distribution was measured for 847 keV and 1238 keV γ-transitions.

Keywords: Iron (Fe), Fast neutrons; Tagged neutrons and gamma rays; TANGRA

* Corresponding author: N.A. Fedorov
Tel. + 7-496-216-3131; Fax: +7-496-216-5085; Email: na.fedorov@physics.msu.ru.

1. Introduction

The present work was undertaken with the aim to study the angular distributions of gamma rays following inelastic scattering of 14.1 MeV neutrons with various nuclei. The precise measurement of the γ-ray yields and *n*-γ correlations at large (>165^o) and small (< 45^o) angles are very important for formulation of correct assumptions about the neutron inelastic scattering mechanism, because the theoretical description of the angular correlations in these areas is very sensitive to the neutron-nucleus interaction parameters and depends on the theoretical model features. Moreover, precise information about the γ-ray angular distributions is necessary for fast elemental analysis of compound chemical substances, because one has to take into account the dependence of the γ-ray intensity on the angle between the direction of the neutron beam and the γ-detector. The existing database on the angular distributions of γ-rays emitted during the neutron inelastic scattering process contains contradictory information and quite scattered values at large and small angles. The tagged neutron method is based on registration of the 3.5-MeV α-particle from the reaction:

$$d + t \rightarrow n + \alpha \quad (1)$$

The α-particle has practically the opposite direction of flight relative to the direction of the 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-induced reaction on the nuclei *A* in the sample.

$$A(n,x)B^* \xrightarrow{\gamma} B \quad (2)$$

So, it is possible to reconstruct the neutron flight direction by fixing the α-particle emission angle, i.e. to "tag" the neutron. Practically, the position-sensitive α-detector, embedded in the neutron generator, does the "tagging" of the neutrons. The α-γ coincidences allows one significantly decrease number of the background events in the γ–spectra.

This paper is dedicated to the investigation of the neutron inelastic scattering reaction on iron. The ^{56}Fe is an important structural material for nuclear engineering and nuclear physics research applications. There were a lot of experiments made on iron in the past with neutron energies from 1 up to 14 MeV to investigate inelastic scattering process, but most of them didn't consider γ-quanta angular distributions. Recently, a high-resolution measurement of the inelastic scattering cross-section was done at the nELBE neutron ToF-facility in the energy range from about 0.1 up to 10 MeV, It was shown that angular distribution coefficients have a strong energy dependence [10]. In this work we measured γ-quanta angular distributions with 14.1 MeV incident neutrons.

2. Experiment

The scheme of TANGRA-setup for studying the fast neutron scattering reactions is shown in 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, focused on a tritium-enriched target. The products of this reaction are a 14.1 MeV neutron and 3.52 MeV α-particle. 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 pixel dimensions of 6×6 mm^2. The α-detector is located at a distance of ~ 10 cm from the tritium-enriched target.

The γ-quanta emitted in the neutron inelastic scattering are registered by a "Romasha" system, consisted of 18 BGO-scintillator γ-detectors placed around the sample with ~14° step. The background events are separated by using the Time-of-Flight (ToF) method. The "start" of the measurement time duration is given by the signal from the αγ-detector and the "stop" – by the signal from the α -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 was used [2].

The profiles of the tagged neutron beams were measured prior to the experiment, using a position-sensitive silicon charged particle detector (profilometer) [3]. This information is used for adjusting the neutron generator beams and for sample's sizes optimization. The experimental data analysis procedure is discussed in detail in our previous paper [1].

The sample used was a 4×4×4 cm^3 Al-container filled with natural iron powder.

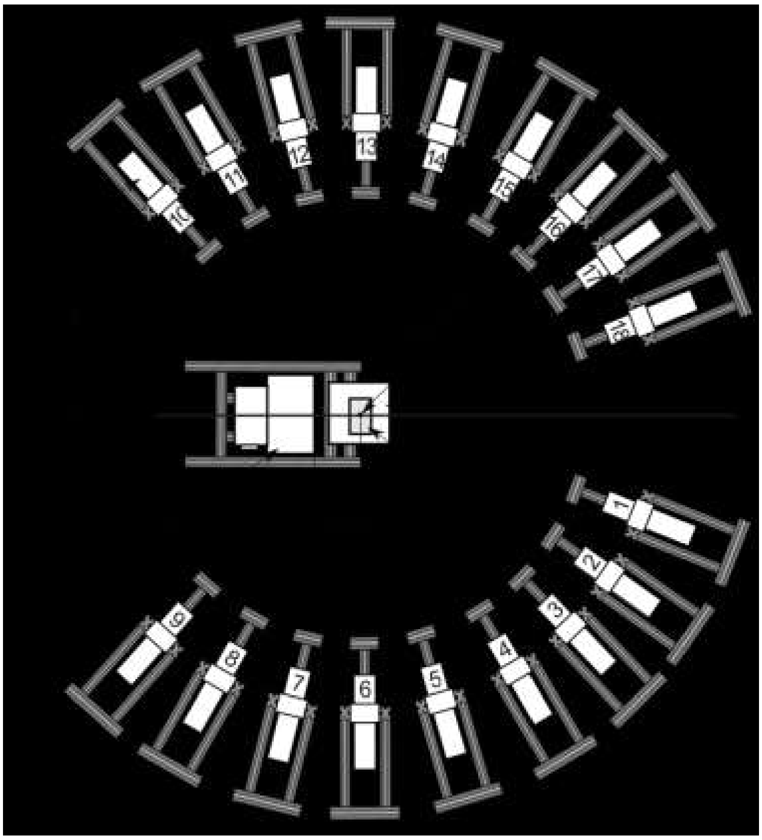

Fig. 1. Scheme of the TANGRA setup in the reaction plane: *1* – portable neutron generator ING-27, *2* – sample at the center of "Romasha" γ-ray registration system, *3* – sample holder, *4* – generator support , *5* – γ-ray detector holder, *6* – BGO γ-ray detector. The "tagged" neutron beam direction is indicated by horizontal plain line.

3. Optimization of sample's sizes and correction factor calculation

Sizes of the irradiated sample were chosen from two contradictory criteria: the sample's sizes must allow us to use as many tagged beams as possible, but, on the other hand, the self-absorption γ-quanta inside the sample must not significantly change the observed γ-quanta angular distribution.

We used Geant4 Monte-Carlo simulation to estimate the influence of the γ-quanta and neutrons absorption inside the sample. The simulation results showed that the optimal sample shape has a square section in the detector plane. To calculate the influence of the sample on the observed angular distribution, the predefined in Geant4 was changed to isotropic. The difference between the angular distributions for different pixels on the same vertical strip was found to be insignificant, so, we decided to use all 8 pixels on the vertical strip, and the height of all samples was set equal to 14 cm.

The example of Geant4-calculation based data correction procedure is illustrated in Fig. 2. The simulated areas of the full energy absorption peaks for each "strip-detector" combination were calculated and normalized per average photopeak area of each strip. In Fig. 2(*a*) the calculated correction factor C^i is presented. After that, the obtained experimental angular distribution W^i_{exp}, which is shown in Fig. 2(*b*), was divided by the correction factor:

$$W^i_{corrected} = \frac{W^i_{exp}}{C^i} \tag{3}$$

Here index *i* is the detector's number in Fig. 2. The example of corrected experimental data is presented in Fig. 2(*d*), with approximation by series of Legendre polynomials and renormalization per coefficient *A* (Eq. 3):

$$W(\theta) = A(1 + \sum_{k=2,4..}^{2J} a_k P_k(\cos\theta)), \tag{4}$$

where a_k are expansion coefficients, *J* is γ-transition multipolarity.

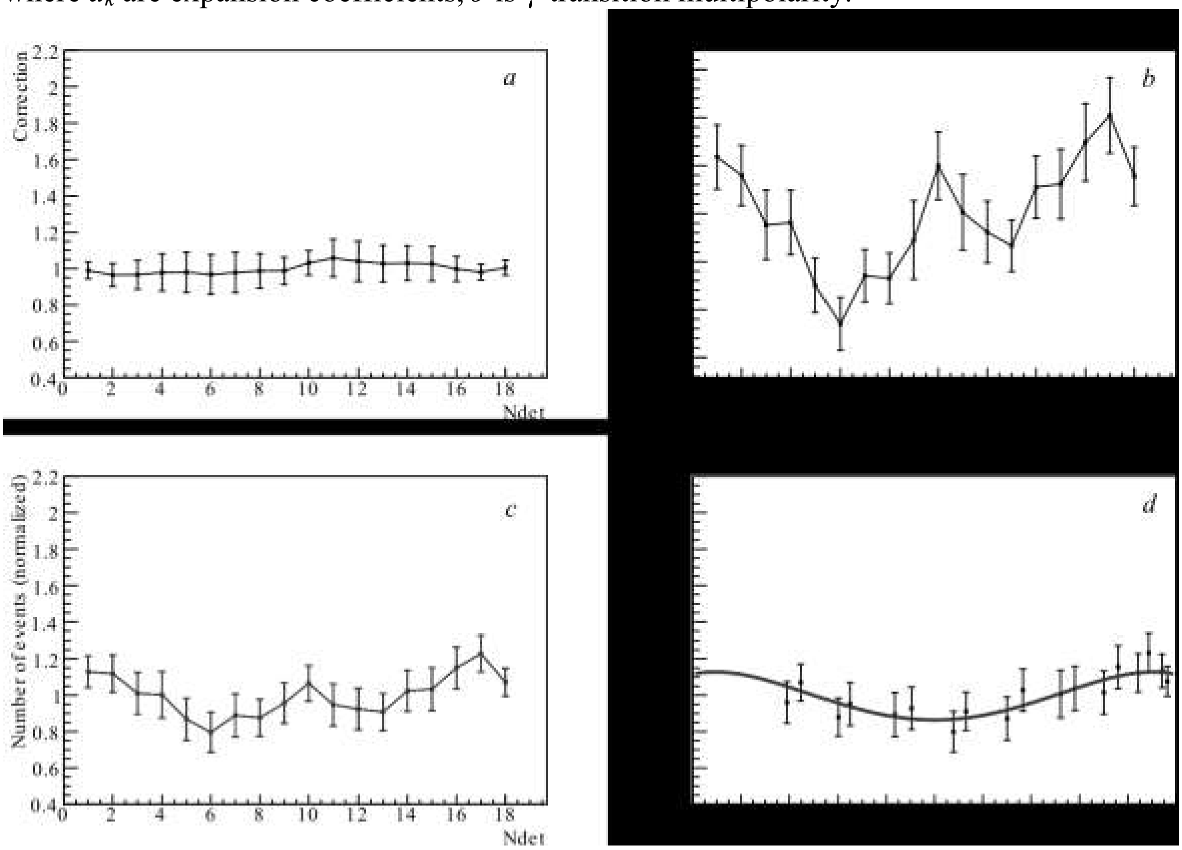

Fig. 2. Data processing example: calculated correction factor (*a*), experimental angular distribution (*b*), corrected experimental data (*c*), corrected angular distribution (*d*).

4. Results

In this experimental session we used HPGe γ-spectrometer to obtain high-resolution γ-spectrum. We can distinguish at least 46 γ-transitions generated from ^{56}Fe(n,n′), ^{56}Fe(n,2n′) reactions. Their parameters and references to other experiments in which the same γ-lines were observed are presented in the Table 1.

Table 1. Parameters of the γ-transitions observed in this work.

E_γ, keV[12]	Reaction	E_{in},keV	JP_{in}	E_{fin}, keV	JP_{fin}	Reference
477.2	*(n,2n')*	1408	7/2–	931.3	5/2–	[5]
846.8	*(n,n')*	846.8	2+	0	0+	[5],,[7],[9],[11]
931.3	*(n,2n')*	931.3	5/2–	0	3/2–	[5] ,[6]
955.8	*(n,n')*	4401.3	2+	3445.3	3+	[9]
1037.9	*(n,n')*	3123.0	4+	2085.1	4+	[5],[9],[11]
1175.2	*(n,n')*	4298.2	4+	3123	4+	[9]
1238.3	*(n,n')*	2085.1	4+	846.8	2+	[5],[7],[9],[11]
1303	*(n,n')*	3388.6	6+	2085.1	4+	[5],[11]
1312	*(n,n')*	4683.04	3+	3370	2+	[5]
1335.4	*(n,n')*	4458.4	4+	3123	4+	[9]
1360.3	*(n,n')*	3445.4	3+	2598.5	2+	[9]
1408.4	*(n,2n')*	1408.4	7/2–	0	3/2–	[5]
1579.5	*(n,n')*	4539.5	1+,2+	2960	2+	[9]
1669.9	*(n,n')*	3755.6	6+	2085.1	4+	[5],[9],[11]
1771.5	*(n,n')*	3856.5	3+	2085.1	4+	[9],[11]
1810.8	*(n,n')*	2657.6	2+	846.8	2+	[5],[9],[11]
1852.4	*(n,n')*	4509.6	3–	2657.6	2+	[9]
1881.9	*(n,n')*	4539.5	1+,2+	2657.6	2+	[9]
1918	*(n,n')*	4878	2+	2960	2+	[9]
1963.9	*(n,n')*	4048.9	3+	2085.1	4+	[9]
2015.2	*(n,n')*	4100.3	4+	2085.1	4+	[9]
2034.9	*(n,n')*	4119.9	3+	2085.1	4+	[5],[9]
2094.9	*(n,n')*	2941.7	0+	846.8	2+	[9],[11]
2113.2	*(n,n')*	2960.0	2+	846.8	2+	[5],[9],[11]
2212.9	*(n,n')*	4298.1	4+	2085.1	4+	[9]
2273.2	*(n,n')*	3120.1	1+	846.8	2+	[9],[11]
2373.2	*(n,n')*	4458.4	4+	2085.1	4+	[9]
2424.9	*(n,n')*	4509.6	3–	2085.1	4+	[9]
2460.3	*(n,n')*	5402.3		2491.5	0+	[9]
2468.9	*(n,n')*	4554.8	4+	2085.1	4+	[9]
2523.4	*(n,n')*	3370	2+	846.8	2+	[9],[11]
2573	*(n,n')*	4660.0	3+,4+	2085.1	4+	[9]
2598.6	*(n,n')*	3445.3	3+	846.8	2+	[9],[11]
2601	*(n,n')*	3448.4	1+	846.8	2+	[9],[11]
2657.6	*(n,n')*	2657.6	2+	0	0+	[9]
2753	*(n,n')*	3600	2+	846.8	2+	[9]
2759	*(n,n')*	3605	2+	846.8	2+	[9],[11]
2983	*(n,n')*	3829.8	2+	846.8	2+	[9],[11]
3009.7	*(n,n')*	3856.5	3+	846.8	2+	[9]
3064	*(n,n')*	5149.5	2+	2085.1	4+	[9]
3202.03	*(n,n')*	4048.8	3+	846.8	2+	[9]

3253.7	*(n,n')*	4100.4	3+	846.8	2+	[9]
3448	*(n,n')*	3448.4	1+	0	0+	[9]
3548	*(n,n')*	4395.0	3+	846.8	2+	[9]
3600	*(n,n')*	3600	2+	0	0+	[9]
3663.6	*(n,n')*	4509.6	3–	846.8	2+	[9]

The most detailed spectrum is obtained in paper [9]: 82 γ-transitions correlated with reaction ^{56}Fe(n,n′) are described and their intensities are measured. In our γ spectrum we can identify γ-lines with intensities higher than 0.4% only, due to the high background radiation level generated from the inelastic scattering of neutrons in the shielding and construction elements of the experimental setup. The registered γ-ray spectrum for Fe is shown in Fig. 3.

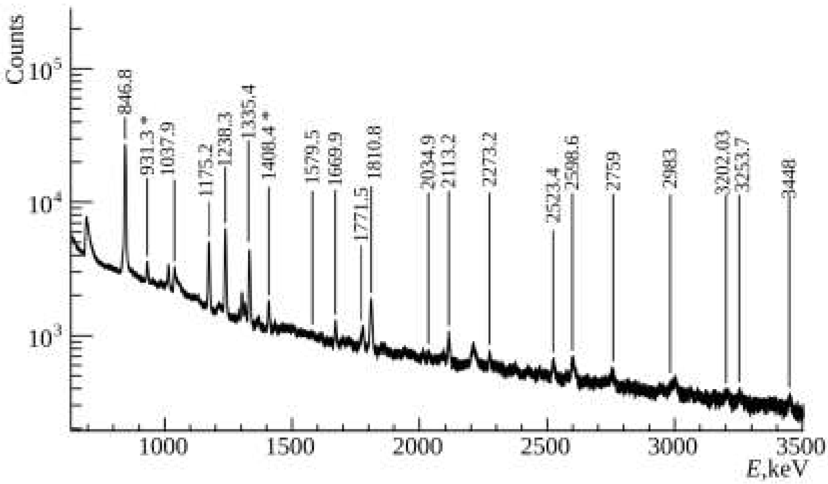

Fig. 3. Gamma-spectrum for Fe (HPGe). Energies of the most intensive γ-transitions E_γ (in keV) from reactions ^{56}Fe(n,n′),(n,2n′) are signed. Lines generated by reaction (n,2n′) are marked with an asterisk.

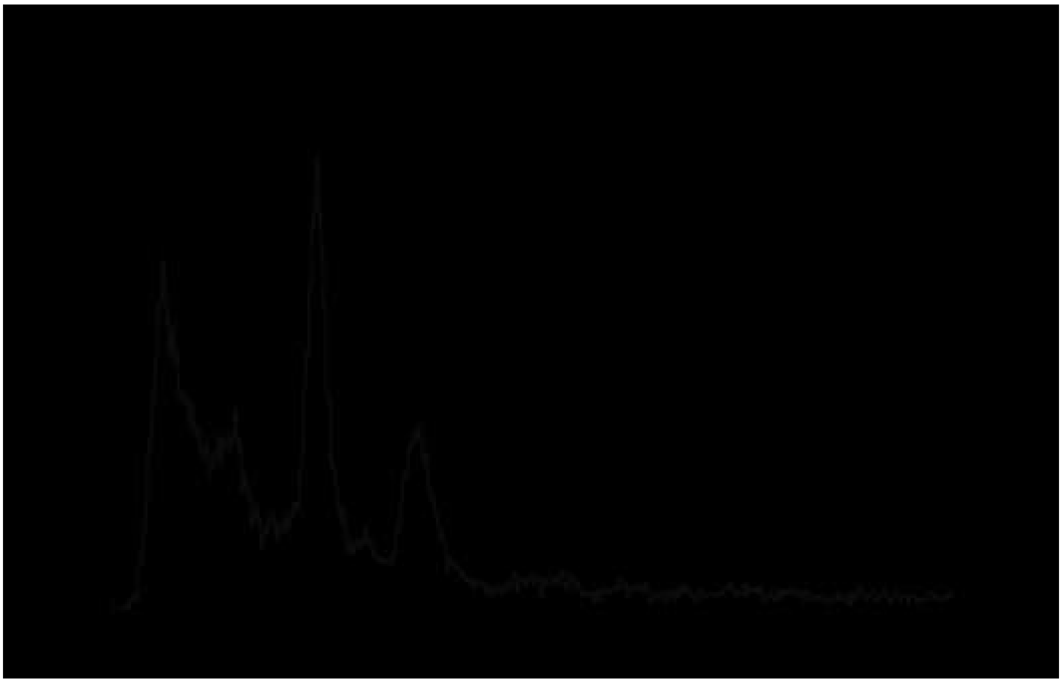

Fig. 4. Gamma-spectrum for iron, obtained by "Romasha" BGO γ-detector system.

During the last series of experiments with TANGRA setup, the γ-quanta angular distributions for Fe have been measured using the "Romasha" γ-spectrometer system. In Fig. 4 the γ-spectrum obtained by the BGO γ-detectors is presented.

We measured γ-quanta angular distributions for two the most intensive γ-transitions: 847 keV and 1238 keV that correspond to excitation of 847 keV(2^+) and 2085 keV(4^+) levels. Measured γ-quanta angular distributions and their approximations are shown in the Fig. 5. The coefficients of the Legendre polynomial approximation are presented in Table.2 in comparison with experimental results from papers [6–8].

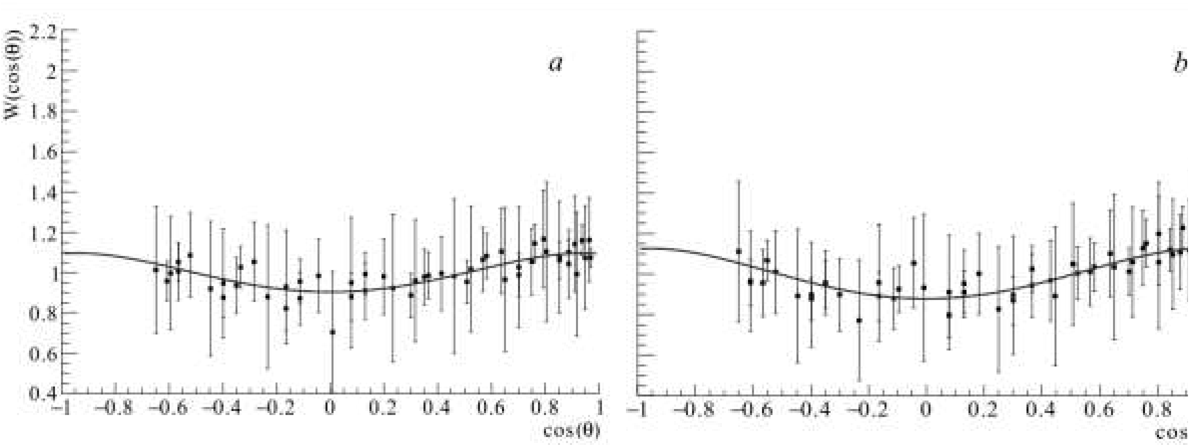

Fig. 5. The angular distributions of the γ-quanta from 14.1 MeV neutron inelastic scattering on ^{56}Fe: 847 keV (a), 1238 keV (b).

Table 2. Legendre polynomial approximation coefficients for the γ-quanta angular distributions obtained in this work in comparison with previous measurements.

E_γ, keV	a_2	a_4	Reference
846.8	0.15 ± 0.04	−0.06 ± 0.05	this work
	0.21 ± 0.05	0.07 ± 0.03	[6]
	0.36	0.38	[7]
	0.09	0.1	[8]
1238.3	0.19 ± 0.04	−0.07 ± 0.06	this work
	0.32 ± 0.08	0.16 ± 0.08	[6]
	0.37	−0.23	[7]
	0.14	−0.1	[8]

The discrepancy between results of different experiments is not significant, except the results from paper [7]. The obtained values correspond to the main trends of the energy dependences of the angular distribution coefficients obtained in the work [10]: for 846.8 keV γ-transition a_2-value is clearly positive and a_4 is mainly negative in the range of initial neutron energies between 0.1 and 7 MeV. Above 2 MeV the angular distribution flattens out. For the 1238.3 keV γ-ray angular distribution positive a_2 and negative a_4 in the same neutron energy range are observed.

Conclusion

Using TANGRA facility and the tagged neutron method we studied the inelastic scattering of 14.1 MeV neutrons on the iron. The most important advantage of the setup used in all the experiments is that we succeed to cover a wide range of angles with a big number of points, in which the registration of γ-quanta was simultaneously carried out.

References

1. D.N. Grozdanov, N.A. Fedorov, V.M. Bystritski, Yu.N. Kopach, I.N. Ruskov, V.R. Skoy, T.Yu. Tretyakova, N.I. Zamyatin, D. Wang, F.A. Aliev, C. Hramco, A. Gandhi, A. Kumar, S. Dabylova, E.P. Bogolubov, Yu.N. Barmakov, Measurement of Angular Distributions of Gamma Rays from the Inelastic Scattering of 14.1-MeV Neutrons by Carbon and Oxygen Nuclei, Phys. of At. Nucl., v. **5**, 588 (2018).
2. «AFI electronics,». Available: http://afi.jinr.ru.
3. N. Zamyatin, V. Bystritsky, Y. Kopach, F. Aliyev, D. Grozdanov, N. Fedorov, C. Hramko, I. Ruskov, V. Skoy, V. Slepnev, D. Wang и E. Zubarev, Neutron beam profilometer on the base of double-sided silicon strip detectors, Nucl. Instr. and Meth. A, v. **898** , 46 (2018).
4. N. Fedorov, T. Tretyakova, D. Grozdanov, V. Bystritsky, Y. Kopach, I. Ruskov, V. Skoy, I. Zamyatin, D. Wang, F. Aliev, C. Hramko, A. Kumar, A. Gandi, S. Dabylova, D. Yurkov, and Yu. Barmakov, Investigation of the neutron inelastic scattering on 27Al, Phys. of At. Nuclei, in press.
5. S. Simakov, A. Pavlik, A. Vonach и S. Hlavac, Status of experimental and evaluated discrete γ-ray production at En=14.5 MeV, INDC(CPP)-0413, Vienna: IAEA NUCLEAR DATA SECTION, 1998.
6. A.P. Dyagterev, Yu.E. Kozyr, G.A. Prokopec, Angular distribution of gamma-quanta from 14,6-MeV neutron interaction with 56Fe and 23Na nuclei, "Neutron Physics" (Proc. Of IV All-Union Conf. on Neutr. Physics, Kiev. 18–22 Apr. 1977), Moscow, CNIIautomatinform, v. **2**, p. 57, 1977.
7. U. Abbondanno, R. Giacomich, M. Lagonegro, G. Paul, Gamma Rays Resulting from Nonelastic Processes of 14.2 MeV Neutrons with Sodium, Magnesium, Silicon, Sulfur, Titanium, Chromium and Iron, J. Nucl. Energ., v. **27**, 227 (1973).
8. J. Lachkar, J. Sigaud, Y. Patin, G. Haouat., Nucl. Sci. Eng., v. **55**, 168 (1974).
9. J. Lachkar, J. Sigaud, Y. Patin, G. Haouat, Etude des niveaux de 56Fe excites par parles reactions (p, p'γ) et (n, n'γ), Nucl. Phys. A, v. **222**, 333 (1974).
10. R. Beyer , M. Dietz, D. Bemmerer et.al., Eur. Phys. J. A, v. **54**, 58 (2018).
11. R. Beyer, R. Schwengner, R. Hannaske, A.R. Junghans, Nucl. Phys. A, v. **927**, 41 (2014).
12. H. Junde, H. Su, Y. Dong., Nucl. Data Sheets, v. **112**, 1513 (2011).