Measurements of the gamma-quanta angular distributions emitted from neutron inelastic scattering on ^{28}Si

N.A. Fedorov[1,2,⋆], *D.N.* Grozdanov[1,3,⋆⋆], *V.M.* Bystritskiy[1], *Yu.N.* Kopach[1], *I.N.* Ruskov[1,3], *V.R.* Skoy[1], *T.Yu.* Tretyakova[4], *N.I.* Zamyatin[1], *D.* Wang[1,5], *F.A.* Aliev[1,6], *C.* Hramco[1,7], *A.* Gandhi[8], *A.* Kumar[8], *S.* Dabylova[1], *E.P.* Bogolubov[9], and *Yu.N.* Barmakov[9]

[1]*Joint Institute for Nuclear Research, Dubna, Russia*
[2]*Lomonosov Moscow State University, Moscow, Russia*
[3]*Institute for Nuclear Research and Nuclear Energy of the Bulgarian Academy of Sciences, Sofia, Bulgaria*
[4]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
[5]*Xi'an Jiao Tong University, Xi'an, China*
[6]*Institute of Geology and Geophysics of Azerbaijan National Academy of Sciences, Baku, Azerbaijan*
[7]*Institute of Chemistry of the Academy of Sciences of Moldova, Chisinau, Republic of Moldova*
[8]*Banaras Hindu University, Varanasi, India*
[9]*All-Russia Research Institute of Automatics (VNIIA), Moscow, Russia*

Abstract. The characteristic gamma radiation from the interaction of 14.1 MeV neutrons with a natural silicon sample is investigated with Tagged Neutron Method (TNM). The anisotropy of gamma-ray emission of 1.779 MeV was measured at 11 azimuth angles with a step of $\angle 15^\circ$. The present results are in good agreement with some recent experimental data.

1 Introduction

Natural silicon (Si) consists of three stable isotope ^{28}Si, ^{29}Si, and ^{30}Si, abundances of which are 92.2%, 4.7%, and 3.1%, respectively. Si and Si-based products have important scientific and industrial applications, for example, it is used in radiation detectors, computers and electronics (semiconductor integrated circuits), energy production (solar cells). Therefore, accurate knowledge of the behaviour of natural silicon materials in 14.1 MeV neutron field is very important for the nuclear electronics development.

From fundamental science viewpoint the chain of Si isotopes has attracted increased attention in recent years. New experimental possibilities for studying unstable nuclei with neutron excess made it possible to trace the changes in the shell structure with the neutron asymmetry growth up to the extremely neutron-rich double-magic ^{42}Si nucleus [1, 2], and to obtain the first experimental evidence of the formation of proton density bubble in the ^{34}Si [3]. New experimental results are a challenge to theoretical considerations and make it necessary to consider the chain of Si isotopes in general, including model calculations and experimental data for stable isotopes ^{28,29,30}Si [4].

⋆e-mail: na.fedorov@physics.msu.ru
⋆⋆e-mail: dgrozdanov@mail.ru

2 The Tagged Neutron Method

The method is based on the fact that the neutron and the α-particle formed in the reaction:

$$d + t \rightarrow \alpha(3.5\text{MeV}) + n(14.1\text{MeV}) \quad (1)$$

in the laboratory frame are scattered in almost opposite directions. Therefore, knowing the direction of emission of α-particle, it is possible to recover the direction of the neutron, i.e. to "tag" it. In practice, the "tagging" of a neutron is done by using a position-sensitive (pixelated) alpha detector embedded in the neutron generator.

Registration of α-particles permits to determine the intensity of tagged neutron flux and realize α-γ (detectors) coincidence scheme. The tagged neutrons irradiate the target and induce inelastic scattering reactions $(n, n'\gamma)$, resulting in the photon emission. The γ-quanta are detected with coincident α particle impulses. It has been shown [5] that using the $(\alpha - \gamma)$ coincidences helps reduce the signal-to-noise ratio by more than 200 times and significantly increase the accuracy of the experiment.

3 The experimental setup

For the investigation of neutron-induced reactions at En = 14.1 MeV, at the Joint Institute for Nuclear Research (JINR), Frank Laboratory of Neutron Physics (FLNP), the experimental setup called TANGRA (Tagged Neutrons & Gamma Rays) was created [6]. It consists of an ING-27 neutron generator, operating in continuous mode, in which the Deuteron and Triton ions are accelerate to energies of ~80-100 keV and focused on a Ti-target, forming this way a self-made Tritium enriched target. The maximum ‘tagged’ neutron flux from the reaction 1 in 4π-geometry, produced by the generator, is $\sim 5{*}10^7$n/s. The α-particles with energy of 3.5 MeV are registered with the built-in the generator 64-pixel Si-detector located at a distance of 100 mm from the TiT-target. The size of a pixel is 6×6 mm. Registration of the gamma rays is carried out by 22 scintillation detectors based on NaI(Tl)-crystal. The scheme of the TANGRA experimental setup is shown in Fig. 1.

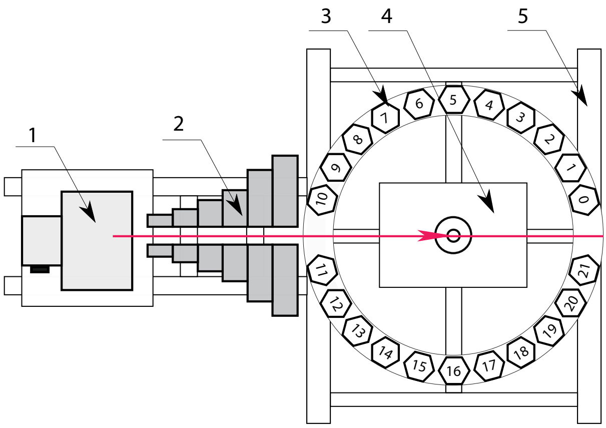


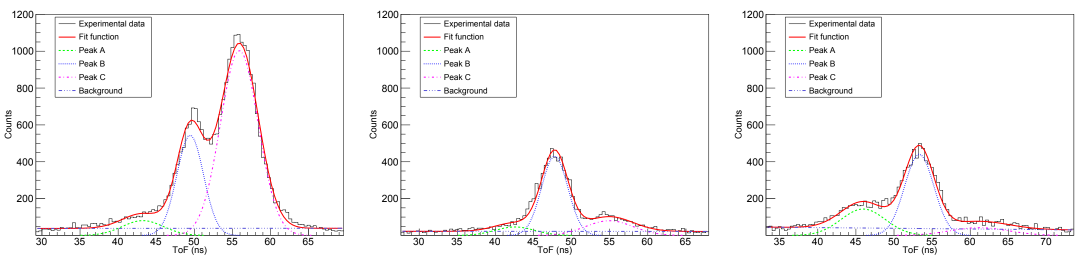
Figure 1. Scheme of TANGRA-setup: 1 – neutron generator ING-27, 2 – collapsible shielding-collimator made of iron (Fe), 3 – array of 22 NaI(Tl) gamma spectrometers, 4 – table with investigated samples, the 5 – frame. The direction of the neutron beam through the collimator and sample is shown by an arrow

Gamma-ray detectors are spaced by the angle of ∼15°. To protect the NaI(Tl) gamma-detectors from ING-27 direct radiation, we used a compact shielding-collimator made of iron plates with a total thickness of ∼40 cm. Separation of background events is done by the method of time-of-flight (ToF), using the known energy of the incident neutron (14.1 MeV), the distance from the n-generator's tritium target to the irradiated (Carbon, Oxygen) sample position, and that from the sample to the γ-ray detectors. Therefore, for further processing we selected the events lying within a narrow time interval, the beginning of which is given by α-particle of reaction 1. This allows to make an efficient separation of γ-rays from the neutrons, impinged the γ-detector, by the ToF-method. For the collection and prior analysis of the experimental data we used a PC with two ADCs ADCM-16 [7].

As targets in the experiments on inelastic scattering of fast neutrons with light nuclei, we used blocks (10×10×5 cm) from pure substances or plastic containers of the same size, filled with powder from element oxides.

4 Data processing

The signals from α- and γ- detectors of TANGRA-setup are digitized with ADCM and recorded on PC's hard-disk, after that there are off-line analyzed by plotting the time- and amplitude- spectra of the events caused by gamma-rays and neutrons separated by ToF-method, as shown in Fig. 2.



a) b) c)

Figure 2. (Color online) TOF-spectra and their approximation with Gaussian-functions for detector on ∠15° (a), ∠90° (b) and ∠165° (c). In each graph, Peak A (green dashed line) - is from neutron interactions with shielding-collimator, Peak B (blue dotted line) - is from neutron interactions with sample, Peak C (magenta dash-dotted line) - is from direct beam neutron interactions with detector. The total fit function is presented by solid red line.

Further, using the energy calibration of the gamma detectors, we obtained the energy spectrum of events that fall into the time-window corresponding to gamma-rays (Peak B in Fig. 2).

In this experimental setup configuration we used a single pixel of alpha-detector. This allowed us to reduce the number of background events significantly, to simplify and speed-up the data analysis, but in the same time, this method significantly increased the time required to get enough statistics. Registering γ-spectra, we obtain information about the number of events corresponding to the emission of gamma-rays during the transition of the nucleus from a certain excited state to a lower energy state. Typically, one counts only events in the gamma-ray full-energy absorption peak (FEAP) or in single annihilation gamma-quantum escape peak at a lower energy (FEAP minus 0.511 MeV).

5 Results

In inelastic scattering of neutrons with 14.1 MeV energy on ^{28}Si nuclei occurs excitation of a large number of states that can decay by emission of a gamma-ray, but in our experiment we succeed to get a 'correct' angular distribution of gamma-radiation only for the transition from the first excited state ($E^* = 1.779$ MeV, $J^\pi = 2^+$) to the ground state.

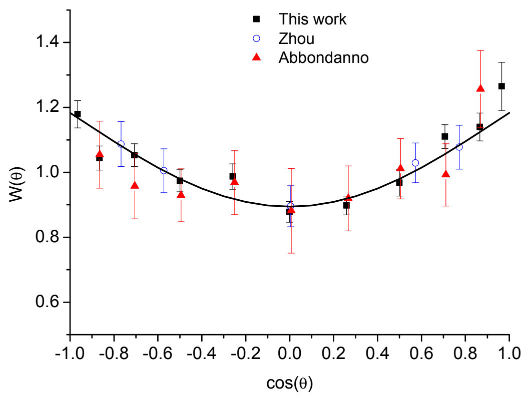


Figure 3. The experimental angular distribution of gamma-rays with $E_\gamma = 1.779$ MeV from the inelastic scattering of 14.1 MeV neutrons on ^{28}Si obtained with TANGRA-setup (square) together with the data from [8] (circle) and [9] (triangle). The black line is Legendre approximation of our data

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:

$$W(\theta) = A \sum_{i=0}^{2J} a_i P_i(\cos(\theta)) \tag{2}$$

where A-is a normalization constant, chosen so that $a_0 = 0$, a_i are the coefficients of the Legendre polynomials, and J – is the multi-polarity of the γ-transition. The summation index i takes only even values.

Fig. 3 presents the angular dependence of the parameter of anisotropy of the γ-quanta emission from the reaction $^{28}\mathrm{Si}(n, n')^{28}\mathrm{Si}^*$ was obtained from the analysis of the reported experimental data in comparison with the previous experimental results from [8, 9]. The Legendre polynomial coefficients are in agreement with those obtained from the experimental data of the other authors, within the frame of the achieved experimental uncertainties, as shown in the table 1. It is interesting to note the fact that the contribution of the components of the 4th degree Legendre polynomials is insignificant. To explain more research is needed.

Table 1. Legendre coefficients in $W(\theta)$ (2) for gamma rays from inelastic scattering of 14 MeV neutrons.

Experiment	a_2	a_4
14.9 MeV (Zhou [8])	0.21 ± 0.02	-
14.2 MeV (Abbondanno [9])	0.20 ± 0.09	0.11 ± 0.14
14.1 MeV (This work)	0.19 ± 0.02	0.02 ± 0.03

6 Conclusion

- The inelastic scattering of neutrons with an energy of 14.1 MeV on natural silicon sample was investigated by using the method of tagged neutrons. The angular distribution of the γ-rays with energy of 1.779 MeV from ^{28}Si$(n, n')^{28}$Si* was obtained.
- Within the limits of statistical errors, the calculated values of Legendre coefficient for the angular anisotropy is found to be in good agreement with the results published earlier [8, 9].
- Unlike the results for the angular distribution of gamma-rays from $^{12}C(n, n'\gamma)^{12}C$ with 14.1 MeV neutrons [10], it was confirmed that the contribution of the components of the 4th degree Legendre polynomials is insignificant for gamma-radiation from the first excited state $E^*(2^+) = 1.779$ MeV in ^{28}Si.

It is planned to do some model calculations of the angular distribution of gamma rays from the inelastic neutron scattering of 14.1 MeV on ^{28}Si nuclei in order to reveal the possible mechanism of this reaction.

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