EXCITATION OF ISOMERIC STATES IN THE (γ, n) AND $(n, 2n)$ REACTIONS ON ^{86,88}Sr NUCLEI*

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In the present work, the induced activity method in measurements of the cross sections for isomeric state formations in the (γ, n) and $(n, 2n)$ reactions on nuclei of ^{86,88}Sr are used. The energy dependence of the isomeric ratio in reactions of $^{86}\mathrm{Sr}(\gamma, n)^{85m}\mathrm{Sr}$ at the energy range of 12–35 MeV with the energy intervals of 1 MeV have been obtained. In all calculations, we have used the TALYS-1.6 software package. Finally, we have compared our obtained experimental results with the results of previous works.

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1. Introduction

Investigations of the cross sections for the excitation of isomeric states in nuclear reactions allow for obtaining valuable information on the distribution of levels over spins, the parameters of the density of nuclear energetic levels, the parameters of the spin constraint of the statistical model, and the contribution of direct processes to the mechanism of nuclear reactions [1–6]. Data on the isomeric ratios of the yields of (γ, n) reactions are necessary to replenish nuclear data in this area and to optimize experiments in analytical studies using the methods of gamma and neutron activation analysis [2, 3]. In this work, we investigated the cross sections for the formation of isomeric states in the (γ, n) and $(n, 2n)$ reactions on ^{86,88}Sr nuclei. The energy dependence of the isomeric ratio of the yields of the $^{86}\mathrm{Sr}(\gamma, n)^{85m}\mathrm{Sr}$ reactions were obtained in the energy range of 12–35 MeV with a step of 1 MeV. The cross section for the excitation of the ^{85m,g}Sr and ^{87m}Sr isomeric states in

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the $(n,2n)$ reaction at a neutron energy of 14.1 MeV was also measured. At this energy, the isomeric ratios of the cross sections for the $(n,2n)$ reaction are determined. The cross sections and isomeric ratios in reactions of the (γ,n)-type on ^{86,88}Sr nuclei are poorly studied. There is only one work on the determination of the cross sections for the formation of isomeric states ^{85m,g}Sr and ^{87m}Sr in the energy range of 12–18 MeV [1]. In this work, the isomeric ratios of the yields and cross sections of this reaction are also determined. Isomeric ratios of the yields of photonuclear (γ,n) reactions were also studied in Refs. [6–9] at fixed energy. The energy dependence of the isomeric ratio of the yields of the reaction of the (γ,n)-type on the ^{86}Sr nucleus in the energy range of 26–35 MeV has not also been studied in detail.

2. Experimental technique

The studies have been carried out by the method of induced activity on the high-current betatron SB-50 in the National University of Uzbekistan and the neutron generator NG-150 in the Institute of Nuclear Physics of the Academy of Sciences of the Republic of Uzbekistan. Experiments on the (γ,n) photoreaction have also been carried out on the bremsstrahlung γ-beam of the SB-50 betatron in the energy range of 12–35 MeV with a step of 1 MeV. $SrCO_3$ of high purity ($> 99.9\%$) in a natural mixture of strontium isotopes pressed in the form of a disk with a diameter of 20 mm was used as a target. Each $SrCO_3$ sample was placed between two copper foils (in the case of neutron irradiation of an aluminium foil). The mass of the samples was 3–4 g. To increase the dose rate, the irradiation was carried out inside the accelerating chamber of the high-current betatron SB-50 at a distance of 12 cm from the tungsten inhibitory target, where the sample, in a special container, was delivered using a pneumatic transport unit of the K5-2A-type. The time of delivery of the sample to the place of irradiation by a pneumatic transport unit was ~ 4 s. The neutron source was the NG-150 neutron generator, which generates fast neutron fluxes at the energy of 14 MeV. The irradiation time with the neutron flux with an energy of 14.1 MeV is about 30–60 minutes. The gamma activity of the targets was measured on a γ-spectrometer consisting of a germanium detector, HPGe. The gamma spectra of the targets began to be measured after a pause of 5–60 min and were measured for 30–120 min. The population of the isomeric and ground levels was identified by the lines: 231.4 keV (^{85m}Sr: $J^\pi = 1/2^-, T_{1/2} =$ 68 min); 513.9 keV (^{85g}Sr: $J^\pi = 9/2^+, T_{1/2} = 64$ days) and 388.4 keV (^{87m}Sr: $J^\pi = 1/2^-, T_{1/2} = 2.8$ hours). The data on the decay scheme required for processing the measurement results were taken from [10]. The calculation of the isomeric ratios of the yields was carried out according to the ratios taken from [11].

3. Results and discussion

3.1. Reaction (γ, n)

The obtained experimental results on the isomeric ratios of the yields and cross sections of the (γ, n) and $(n, 2n)$ reactions on ^{86,88}Sr nuclei are given in Tables I, II, and III. In determining the experimental errors, statistical errors, the error in determining the detector efficiency, self-absorption of gamma rays and coincidence as well as the geometry of the target measurement have also been taken into account. Table I shows the experimental values of the isomeric ratios of the yields of the ^{86}Sr$(\gamma, n)^{85}$Sr reactions in the energy range of 14.5–35 MeV. Depending on the isomeric ratio of the yields, there is no steep rise in the values of the isomeric ratios of the yield, which is observed in most isomeric ratios.

TABLE I

Isomeric ratios of the yields of the ^{86}Sr$(\gamma, n)^{85}$Sr reactions.

$(E_\gamma)_{\max}$ [MeV]	Y_m/Y_g	Ref.	$(E_\gamma)_{\max}$ [MeV]	Y_m/Y_g	Ref.
14.5	0.7 ± 0.07	[7]	28	0.56 ± 0.03	this work
15	0.4 ± 0.04	[8]	29	0.57 ± 0.03	this work
25	0.7 ± 0.07	[9]	30	0.56 ± 0.04	this work
25	0.64 ± 0.02	[6]	31	0.56 ± 0.03	this work
30	0.54 ± 0.03	[6]	32	0.60 ± 0.03	this work
25	0.57 ± 0.03	this work	33	0.60 ± 0.03	this work
26	0.60 ± 0.03	this work	34	0.56 ± 0.03	this work
27	0.56 ± 0.03	this work	35	0.57 ± 0.03	this work

In addition to article [7], all other results are consistent within the measurement error. The isomeric ratios of the reaction yield in the excitation energy range are higher than the giant dipole resonance, *i.e.* in the range of 26–35 MeV, and were determined for the first time.

The excitation functions of the (γ, n) reaction were obtained from the experimental isomeric ratios, the relative yield, and the total cross section of the photoneutron reaction [12]. The cross section was calculated with the Penfold–Liss method with a step of 1 MeV [13].

The experimental dependence of the ^{86}Sr$(\gamma, n)^{85m}$Sr reaction cross sections on the boundary energy of the stopping quanta was approximated by the Lorentz function, the parameters of which (the position of the cross-section maximum E_m, the cross-section value at the maximum σ_m, and the distribution width at half its height Γ) were determined by the least-squares method using a set of experimental values. The approximation parameters are given in Table II. The errors were estimated on the basis of the statistics of the registered reports.

TABLE II

Cross section of the (γ, n) reaction on ^{86,88}Sr nuclei.

Nucleus	Reaction	E_m [MeV]	Γ [MeV]	σ_m [mb]	Ref.
^{86}Sr	$^{86}\mathrm{Sr}(\gamma,n)^{85}\mathrm{Sr}$	16.93 ± 0.04	5	1743	[14]
^{86}Sr	$^{86}\mathrm{Sr}(\gamma,n)^{85m}\mathrm{Sr}$	16.5	6	114	[1]
^{86}Sr	$^{86}\mathrm{Sr}(\gamma,n)^{85}\mathrm{Sr}^*$	17.01 ± 0.04	7.18 ± 0.42	162	this work
^{86}Sr	$^{86}\mathrm{Sr}(\gamma,n)^{85m}\mathrm{Sr}^*$	16.94 ± 0.05	6.18 ± 0.47	98	this work
^{88}Sr	$^{88}\mathrm{Sr}(\gamma,n)^{87}\mathrm{Sr}^*$	16.94 ± 0.11	3.8 ± 0.5	207	[14]
^{88}Sr	$^{88}\mathrm{Sr}(\gamma,n)^{87m}\mathrm{Sr}^*$	16.86 ± 0.05	4.4 ± 0.2	158	this work
^{88}Sr	$^{88}\mathrm{Sr}(\gamma,n)^{87m}\mathrm{Sr}^*$	16.75 ± 0.05	4.1 ± 0.2	148	this work

Note: * The cross sections were calculated using the TALYS-1.6 program.

In order to evaluate and compare these experimental results, we have calculated the reaction cross section using the TALYS-1.6 software package [15, 16]. The results of theoretical calculations are also given in Table II. As can be seen in the table, the value of the cross section at the maximum σ and the distribution width at half of its height Γ in all works agree with each other within the measurement error. The energy position of the maximum of the $^{86}\mathrm{Sr}(\gamma,n)^{85m}\mathrm{Sr}$ reaction cross section coincides within the error with the energy of the ^{86}Sr giant dipole resonance determined by the empirical relation $E_m = 75A^{-1/3}$, obtained at the energy of 16.99 MeV, and it is consistent within the measurement errors with the data given in Table II. At this energy, the experimental values of the isomeric ratios of the cross sections have also obtained and they are: 0.56 ± 0.09. The isomeric ratio of the reaction yields have also been calculated using the TALYS-1.6 software package for the ratio value of 0.56 at 25 MeV. For the $^{88}\mathrm{Sr}(\gamma,n)^{87m}\mathrm{Sr}$ reaction, the values of the giant dipole resonance parameters, within the measurement errors, agree with theoretical calculations obtained using the TALYS-1.6 software package. The position of the maximum in the reaction cross section coincides with the value obtained by the expression of $E_m = 75A^{-1/3}$ which is equal to 16.85 MeV. The isomeric ratios of the cross sections of reactions have been determined as $r = \sigma_m/\sigma_{\mathrm{tot}}$, where σ_{tot} is the total cross section of reactions. Note that the ground states in ^{87}Sr nucleus are stable and isomeric ratios were determined at an energy of 17 MeV, *i.e.*, at the maximum of the cross section σ_m. At these energies, the errors in the obtained data on the photoneutron cross sections are minimal. The obtained value of $r = \sigma_m/\sigma_{\mathrm{tot}} = 0.58$. As can be seen from Table III, the information on the parameters of the giant dipole resonance is insufficient for a detailed analysis of these reactions. In Ref. [1], the cross sections for the $^{86}\mathrm{Sr}(\gamma,n)^{85m}\mathrm{Sr}$ and $^{88}\mathrm{Sr}(\gamma,n)^{87m}\mathrm{Sr}$ reactions were determined in the energy range of 12–18 MeV. This does not completely cover the area of giant resonance. Our results on the width and position of the resonance coincide in the region of experimental errors with the data and the results of calculations of Ref. [1]. However, the values of the maximum cross sections differ from each other.

3.2. $(n, 2n)$ reaction

In the case of the $(n, 2n)$ reaction, the experimental results on the cross sections for the formation of isomeric states and their ratios are given in Table III. To obtain the absolute values of the cross sections for the ground and isomeric states, we used the methods of comparing the yields of the studied and monitor reactions. As a monitor reaction, we used ^{27}Al$(n, \alpha)^{24}$Na ($T_{1/2} = 15$ h, $E_\gamma = 1368$ keV), the cross section of which is: $\sigma = 121.57 \pm 0.57$ mb at $E_n = 14.1$ MeV [17]. One can see from Table III, at 14.1 MeV, that the values of the cross sections of the isomeric states of all experimental works agree within the measurement errors. In the case of cross sections of ground-state formations, the values of the measurement errors are consistent with each other, except for those in [18]. The absolute error of the isomeric ratios of the reaction cross sections is determined by the statistical error of counting in the photopeak of the measured γ-line, the efficiency of registration of γ-radiation, and the error in the values of the monitor cross sections.

TABLE III

Cross section of the ^{86}Sr$(n, 2n)^{85m,g}$Sr and ^{88}Sr$(n, 2n)^{87m}$Sr reactions.

Reaction	E_n [MeV]	σ_m [mb]	σ_g [mb]	σ_m/σ_g	Ref.
^{86}Sr$(n, 2n)^{85m,g}$Sr	14.1	227 ± 8	892 ± 53	0.25	[19]
^{86}Sr$(n, 2n)^{85m,g}$Sr	14.6	227 ± 8	665 ± 65	0.34	[19]
^{86}Sr$(n, 2n)^{85m,g}$Sr	14.1	253 ± 8	995 ± 53	0.26	[18]
^{86}Sr$(n, 2n)^{85m,g}$Sr	14.6	253 ± 8	702 ± 79	0.36	[18]
^{86}Sr$(n, 2n)^{85m,g}$Sr	14.1	221 ± 7	884 ± 62	0.25 ± 0.02	this work
^{86}Sr$(n, 2n)^{85m,g}$Sr	14.0*	189	585	0.32	this work
^{86}Sr$(n, 2n)^{85m,g}$Sr	13.99	221 ± 12	—	—	[20]
^{86}Sr$(n, 2n)^{85m,g}$Sr	14.1	226 ± 10	—	—	[20]
^{88}Sr$(n, 2n)^{85m,g}$Sr	14.1	218 ± 10	—	—	this work
^{88}Sr$(n, 2n)^{85m,g}$Sr	14.0*	199	—	—	this work

Note: * The cross sections were calculated using the TALYS-1.6 program.

Table III shows the experimental data for the ^{86}Sr$(n, 2n)^{85m,g}$Sr reaction. The results obtained in recent years are in agreement with each other within experimental errors.

4. Conclusion

The analysis of the data discussed in this work concentrates on experimental studies of the excitations of isomeric states in the (γ, n)-type photonuclear reactions. In particular, the energy range of 10–25 MeV in the region of giant dipole resonance has been discussed in detail. In the energy region above the giant resonance, the energy dependence of isomeric ratios has also been briefly studied. Using the results of these analyses, it has been possible to obtain information on the density levels of nuclear matter and the contribution of direct processes to the mechanism of photonuclear reactions in the above mentioned energy range.

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REFERENCES

[1] V.M. Mazur, *Phys. Part. Nuclei* **31**, 188 (2000).
[2] Yu.P. Gangrsky *et al.*, *Phys. Part. Nuclei* **27**, 428 (1996).
[3] S.A. Karamian, *Phys. Atom. Nuclei* **76**, 1437 (2013).
[4] D.T. Tran *et al.*, *J. Radioanal. Nucl. Chem.* **286**, 161 (2010).
[5] D.T. Tran *et al.*, *J. Radioanal. Nucl. Chem.* **299**, 477 (2014).
[6] S.R. Palvanov *et al.*, *At. Energy* **87**, 533 (1999).
[7] Fam Zui Hien, Ngo Kuang Zui, Nguen Tak An, *Yad. Fiz.* **35**, 257 (1982).
[8] D.T. Tran, *J. Radioanal. Nucl. Chem.* **289**, 161 (2011).
[9] Yu.P. Gangrsky *et al.*, *Izv. Akad. Nauk Ser. Fiz.* **65**, 111 (2001).
[10] R.B. Firestone *et al.*, «Table of Isotopes, 8^{th} ed.», New York, Toronto 1996.
[11] R. Vänska *et al.*, *Nucl. Instrum. Methods* **179**, 525 (1981).
[12] A.V. Varlamov *et al.*, «Atlas of Giant Dipole Resonances, INDS (NDS)-394», *IAEA*, Vienna 1999.
[13] A.S. Penfold *et al.*, *Phys. Rev.* **114**, 1332 (1959).
[14] A.M. Goryachev *et al.*, *Voprosy Teoreticheskoy i Yadernoy Fiziki* **1982**, 121 (1982), http://cdfe.sinp.msu.ru/cgi-bin/exf2htm?LINK=M0070019
[15] http://www.talys.eu
[16] A.J. Koning *et al.*, «TALYS-1.4 User is Manual, A Nuclear Reaction Program NRG», NL-1755 ZG Petten, The Netherlands, 2011, http://www.talys.eu
[17] H. Vonach, «The ^{27}Al$(n, \alpha)^{24}$Na», *Nuclear Energy Agency Organization for Economic Co-operation and Development*, 1992, pp. 75–77, http://www.oecd-nea.org
[18] Junhua Luo *et al.*, *J. Radioanal. Nucl. Chem.* **279**, 443 (2009).
[19] Guozhu He *et al.*, *Ann. Nucl. Energy* **33**, 37 (2006).
[20] A.A. Filatenkov, «Neutron Activation Cross Sections Measured at KRI in Neutron Energy Region 13.4–14.9 MeV», *IAEA*, 2016.