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Photonuclear reactions in nuclear astrophysics

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At present, 35 neutron-deficient so-called bypassed p-nuclei from ^{74}Se to ^{196}Hg are known, which cannot be formed in s- and r-processes. Their formation is possible in photonuclear reactions of the (γ, n), (γ, p) or (γ, α) type. In this regard, data on photoneutron reactions play an important role in predicting and describing the processes of p-nucleus formation. In this work, the excitation cross-sections of isomeric states in the (γ, n) reactions on ^{80,82}Se in the energy range of 11–35 MeV are investigated by the induced activity method. The experimental results are compared with calculations performed using the TALYS-1.6 software package.

Keywords: Photonuclear reactions, isomeric ratios, bremsstrahlung, selenium isotopes, radioactivity, cross-section, spin, neutron, activity, isomer, nucleus, nuclear reaction

1 Introduction

At present, one of the main problems of nuclear astrophysics is understanding the nature of the synthesis of chemical elements. Most of the heavy elements existing in nature are formed in stars in the processes of radiative neutron capture, the so-called s- and r-processes, respectively slow and fast compared to the competing processes of beta decay. At the same time, 35 neutron-deficient so-called bypassed p-nuclei from ^{74}Se to ^{196}Hg are known, which cannot be formed in the s- and r-processes. Their formation is possible in photonuclear reactions of the type (γ, n), (γ, p) or (γ, α). In this regard, data on photoneutron reactions play an important role in predicting and describing the processes of formation of p-nuclei. Recently, interest in determining the cross-sections of photoneutron reactions in the energy region near the threshold, which is of particular interest from the point of view of astrophysics, has increased significantly (Varlamov 2014).

In this work, the cross-section of the reactions (γ,n) on ^{80,82}Se was studied. The excitation cross-sections of isomeric states in the reactions (γ,n) and (n,2n) on ^{80,82}Se were also studied.

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The study of excited isomeric states in a nuclear reaction allows one to obtain information on the reaction mechanism, in particular, on the moment of inertia of the nucleus, on the spin dependence of the level density and on the nature of transitions between highly excited nuclear states. The relative probability of excitation of isomeric states is defined as the isomeric ratio of yields or cross-sections. The magnitude of the isomeric ratios of yields and reaction cross-sections depends on the spin of the target nucleus, the introduced angular momentum, the reaction mechanism and the properties of the excited states (Palvanov et al. 2021, Egamova et al. 2021, Palvanov 2014). Of particular interest is the study of nuclear reactions of the (n,2n) and (γ,n) types, which result in the formation of the same nucleus.

2 Experiment

The studies were carried out on a high-current betatron SB-50 of the Research Institute of the National University of Uzbekistan in the energy range of 10–35 MeV with a step of 1 MeV (Babadzhanov et al. 1997). Selenium samples weighing 2–3 g in the form of tablets with a diameter of 15 mm were used as targets. Irradiation time, 20–40 min.

The induced γ-activity of the targets was measured on a gamma spectrometer from Canberra, consisting of a germanium HPGe detector (with a relative efficiency of 15%, resolution of 1.8 keV for the 1332-eV ^{60}Co line), a DSA 1000 digital analyzer and a personal computer with the Genie software package 2000 for collecting and processing gamma spectra. The energy gamma spectrometer was calibrated using a standard set of OSGI sources. The measurements were performed in standard geometry, in which the detector was calibrated according to efficiency. The time for measuring the induced γ-activity of targets is 30–60 min.

The occupancy of the isomeric and main levels was identified by γ-lines. Spectroscopic characteristics of reaction product nuclei (γ,n) and (n,2n), necessary for processing measurement results, are taken from Lederer and Shirley (2000), Firestone and Shirley (1996).

3 Result

The obtained experimental results of the cross-sections for excitation of isomeric states in reactions (γ,n) and (n,2n) are given in Tables 1 and 2. Also, using the TALYS 1.6 software package (Koning et al. 2015), the integral cross-sections for excitation of isomeric states in photonuclear reactions of the type (γ,n) are given. TALYS will provide accurate and complete simulations of nuclear reactions in the energy range from 1 keV to 200 MeV using the optimal combination of robust nuclear models, flexibility and ease of use. TALYS can be used to analyze basic scientific experiments or to obtain nuclear data for applications.

The excitation functions of the ^{80}Se(γ,n)^{79m,g}Se reaction were obtained from the experimental isomeric ratios and total cross-sections of the photoneutron reaction σ_{tot} (Varlamov et al. 1999). The bremsstrahlung photon spectrum was calculated

Table 1 Nuclear reaction data for selenium isotopes.

Reaction	E_m (MeV)	Γ (MeV)	σ_m (mb)	σ_{int} (MeV·mb)	E_b (MeV)	Refs
^{80}Se(γ,n)^{79}Se	16.43	4.9	141.6	748.3	28.08	1
^{80}Se(γ,n)^{79m}Se	16.09±0.04	5.42±0.4	78	–	–	2
^{80}Se(γ,n)^{79}Se*	16.30±0.06	4.94±0.29	72	594±40	25	3
^{80}Se(γ,n)^{79m}Se*	15.10±0.10	3.78±0.19	66	648±53	25	3
^{80}Se(γ,n)^{79m}Se	16.07±0.07	4.85±0.36	79±2.2	634±53	25	3

Note: 1, Carlos et al. 1976; 2, Mazur 2000; 3, this work.

Table 2 Nuclear reaction data for selenium-82 isotopes.

Reaction	E_m (MeV)	Γ (MeV)	σ_m (mb)	σ_{int} (MeV·mb)	E_h (MeV)	Refs
^{82}Se(γ,n)^{81}Se	15.89	4	142.7	727	26.5	1
^{82}Se(γ,n)^{81m}Se	16.00±0.11	4.76±0.24	51.1±2.2	–	–	2a
^{82}Se(γ,n)^{81}Se*	15.65±0.09	3.73±0.37	93.24	552±58	30	3
^{82}Se(γ,n)^{81m}Se*	16.01±0.05	3.78±0.19	47.19	286±13	30	3
^{82}Se(γ,n)^{81m}Se	16.01±0.06	4.07±0.36	48	302±33	21	3

Note: 1, Carlos et al. 1976; 2a, Mazur et al. 1991; 3, this work.

using the GEANT4 program (Agostinelli et al. 2003). The cross-section was calculated using the Penfold–Liss method with a step of 1 MeV (Penfold and Leiss 1959). The energy dependencies of the reaction cross-sections were approximated by Lorentz curves. The cross-sections have a single-hump shape with a maximum position of E_m = 16.1 MeV. At E_γ=16 MeV, we obtained the isomeric ratio of the cross-sections: $r = \sigma_m/\sigma_g = 0.52\pm0.09$.

The experimental dependence of the cross-sections of the ^{80}Se(γ,n)^{79m,g}Se reaction on the boundary energy of bremsstrahlung quanta was approximated by the Lorentz function, the parameters of which (the position of the cross-section maximum E_m, the value of the cross-section at the maximum σ_m and the width of the distribution at half its height Γ) were determined by the least squares method using a set of experimental values. The experimental value of the cross-sections was compared with theoretical calculations performed using the TALYS 1.0 code.

For comparison with the experiment, we calculated the isomeric ratios using the statistical model of the nucleus. By fixing the spin limitation parameter σ, we were able to improve the quantitative agreement between the calculations and the experiment. It was found that satisfactory agreement is achieved at $\sigma = 2.71\ \hbar$.

4 Conclusions

From the analysis of the data presented in Tables 1 and 2 it follows that the experimental studies of the excitation of isomeric states in a photonuclear reaction of the (γ,n) type were carried out mainly in the energy range of 10–25 MeV, i.e. in the region of giant dipole resonance. In the energy range above the giant resonance, the energy dependence of isomeric ratios has been little studied. Thanks to these studies, it is possible to obtain information on the density of nuclear levels and the contribution

of direct processes to the mechanism of photonuclear reactions in this energy range. The data obtained can be used to study the mechanism of photonuclear reactions and to develop methods for gamma and neutron activation analysis.

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