Isomers Production of Sn Nucleus in Nuclear Reactions Induced by Photons and Fast Protons

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Abstract. The isotopes of Sn can be obtained in the nuclear reactions of type (p,n) on Indium nucleus and in photoneutron processes on Sn nucleus. The cross sections of (p,n) and (γ, xn) processes were evaluated and compared with experimental data. For each reaction was evaluated the contribution of compound, direct and pre – equilibrium processes. Further, the parameters of nuclear potentials and other data were extracted. It was obtained a quite good agreement between existing experimental data and present evaluations and therefore we have calculated the isomer ratios using different models of incident gamma and protons sources. It is a new proposal for corresponding experiments at LNF JINR Dubna basic facilities.

INTRODUCTION

Nuclear reactions induced by fast protons and gamma particles with neutrons emission are of interest for fundamental and applied researches. These reactions provide for fundamental studies, data in the investigation of reactions mechanism and nuclear structure and represent a source of new isotopes for applications in medicine, electronics and other industry domains and human activities.

Indium is a chemical element with order number Z = 49 (protons number) which has two natural isotopes, ^{113}In, ^{115}In with abundances 4.29% and 95.71%, respectively. Stannum is a nucleus with magical number of protons (Z = 50) and therefore it has many natural isotopes which are the followings (atomic mass A– abundance %): 112– 0.96% 114– 0.66%, 115– 0.35%, 116– 14.30%, 117– 7.61%, 118– 24.03%, 119– 8.58%, 120– 32.85%, 122– 4.72%, 124– 5.94%). The Sn isotopes can be obtained in the (p,n) reactions with fast protons on In or in photons induced reactions (γ,xn) (x= 1,2,…) with energy higher than neutrons threshold on Sn isotopes[1,2].

The ^{113}In(p,n)^{113m,g}Sn (Q= –1.82 MeV) and ^{114}Sn(γ,n)^{113m,g}Sn (Q= –10.302 MeV) reactions are analyzed. In these nuclear reactions it is obtained the same Sn isotope in the ground (g) and isomer (metastable, m) states. The spin, parity and time of life of the isomer state ^{113m}Sn are $J^{\Pi} = (7/2)^{+}$ and τ = 21.4 m. For the ground state of ^{113g}Sn these values are: $J^{\Pi} = (1/2)^{+}$ and τ = 115.09 d [3]. For both reactions the production cross sections of ^{113m,g}Sn isotopes starting from neutron threshold and up to 25–35 MeV were evaluated. Theoretical evaluations were compared with experimental values from literature. Further the isomer ratios using different model of incident particle sources and nuclear data were extracted.

THEORETICAL BACKGROUND

Cross sections for ^{113}In(p,n)^{113m,g}Sn and ^{114}Sn(γ,n)^{113m,g}Sn reactions were evaluated with Talys computer code, a free software, working under Linux, dedicated to nuclear reactions and atomic nuclei structure calculations [4].

With the help of Talys it is possible to calculate inclusive and exclusive cross sections. In the case of a binary reaction of type A(a,b)B, inclusive processes are defined those reactions in which in the final stage are considered emergent b particles coming from other open channels with participation of particle b. If the final stage is well defined and the emergent particle b is considered only from the channel b+B then the cross section in this case is defined as exclusive. These notions, inclusive and exclusive cross sections are very useful in the processing of experimental data [4].

In the cross sections evaluations, the compound, direct and pre-equilibrium nuclear reaction mechanisms were considered for incident energies starting from the neutron threshold up to 25–35 MeV. Compound processes, including the multiple emission, are described by Hauser–Feshbach formalism [5], direct processes by Distorted Wave Born Approximation (DWBA) [6] and pre-equilibrium by two-component exciton model [7]. In the evaluations, discrete and continuum states of the residual nuclei were considered using corresponding nuclear states density based on Fermi gas model [8].

Isomer ratios measured in the experiment give us new data on cross section, nuclear structure like, states density, nuclear density parameters, deformations and other. Using the cross section obtained with Talys, the isomer ratios can be calculated according with the expression [9]:

$$R = \frac{Y_m}{Y_g} = \frac{\int_{E_{thr}}^{E_{max}} N_0 \Phi_{inc}(E_{inc}) \sigma_m(E_{inc}) dE_{inc}}{\int_{E_{thr}}^{E_{max}} N_0 \Phi_{inc}(E_{inc}) \sigma_g(E_{inc}) dE_{inc}} \quad (1)$$

Here $Y_{m,g}$ is yields of isomer and ground state; E_{thr} is neutron threshold energy; E_{max} is maximal energy of incident particles given by the source; E_{inc} is energy of incident particles; N_0 is number of particles in the target; Φ_{inc} is flux of incident particles; $\sigma_{m,g}$ is production cross section of isomer and ground states, respectively.

Relations (1) will be used in the both (p,n) and (γ,n) reaction considering different type of source of incident particles. In the case of photoneutron reaction a flux of incident photons close to real case, has a form according to Kramer expression [10,11]:

$$\Phi(E_\gamma) \sim I_\gamma = i_b Z(E_0 - E_\gamma) E_\gamma^{-1} \quad (2)$$

Here I_γ is intensity of gamma quanta; Z is a charge of stopping element; i_b is electron beam current; E_0 is energy of accelerated electrons; E_γ is energy of gamma quanta.

For cross sections evaluations the nuclear potentials, in the incident and emergent channels are necessary. Potentials are of Woods–Saxon type, including volume, surface, spin - orbit and other contributions. A large data base, of local optical potentials, extracted mainly from experimental data for many nuclei in different channels, are implemented in Talys. There is also a possibility to introduce the optical parameters considered by user. For those nuclei for which the potentials are not defined it is possible to enable the, so-called, global optical parameters defined by Konig and Delaroche [4,12].

RESULTS AND DISCUSSION

In the Figure 1 the inclusive cross sections (CS) for ^{113}In(p,n) reaction with the contribution of different nuclear reaction mechanisms and type of residual nucleus states are shown.

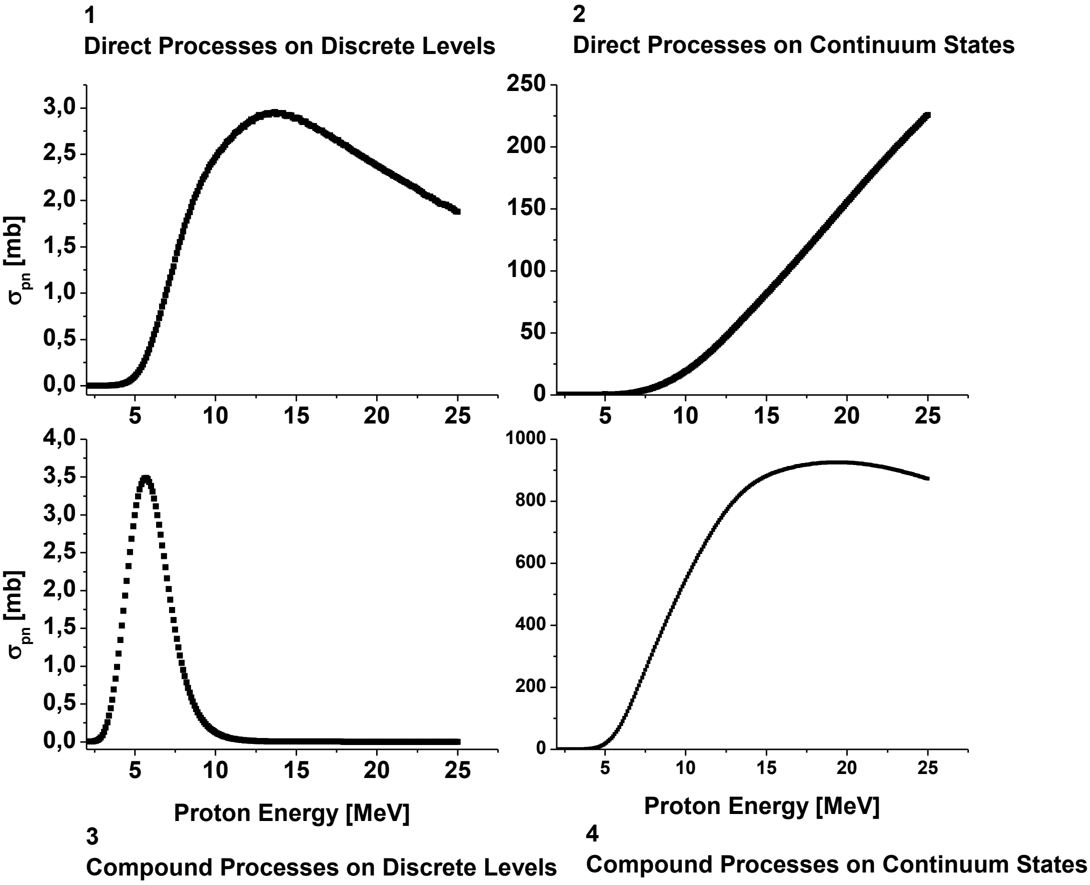

Figure 1. Inclusive CS in ^{113}In(p,n) process.

From Figure 1 results that the compound processes on continuum states of residual nucleus are dominant followed by direct processes. Compound and direct processes on discrete states can be neglected and for ^{113}In(p,n) reaction can be explained by the presence of Coulomb barrier. With the increasing of the protons energy, the origin of compound and direct processes are due to pre-equilibrium ones.

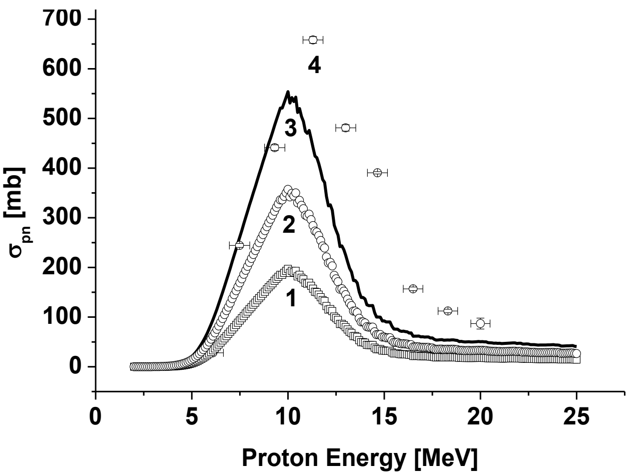

Figure 2. Exclusive CS in ^{113}In(p,n)^{113m,g}Sn. 1. – ground; 2 – isomer ; 3 – total (m+g); 4 – experimental data.

In the Figure 2 the exclusive cross sections in the $^{113}In(p,n)^{113m,g}Sn$ reaction are represented. Because for exclusive processes the final states are well defined, the production of ^{113}Sn isotope in the ground (Fig. 2 curve 1) and isomer states (Fig. 2 curve 2) respectively can be evaluated. The curve 3 from Fig. 2 is the total production of ^{113}Sn isotope which is compared after with experimental data (Fig. 2 curve 4). The contribution of other levels of ^{113}Sn can be neglected. In the low energy part the experimental data are very well described. After the maximum, the shape of the dependences is maintained but some differences appear. The differences can be explained by the fact that after 10 MeV are opened other channels including neutrons which could not be separated from those neutrons coming from "n+^{113}Sn" channel of interest. Experimental data are taken from [13].

The results are obtained with standard Talys input parameters and therefore the agreement between theory and experiment can be considered as good. Further, using relations (1) with different model of protons flux, the isomer ratios can be evaluated. In the more simple case, for proton flux equal with unity (Φ_{inc}= 1), starting from the neutron threshold E_p= 1.83 MeV, up to E_{max}= 25 MeV, the isomer ratio R is:

$$R = 1.82 \pm 0.26 \qquad (3)$$

The absolute error in the result from relation (3) comes from the transformation of integrals from relations (1) in sums due to numerical calculations. The proton energy step in relation (3) was equal to 0.1 MeV.

The isotope ^{113}Sn can be obtained in $^{114}Sn(\gamma,n)$ photoneutron reaction also. The main cross sections results are shown in Figure 3.

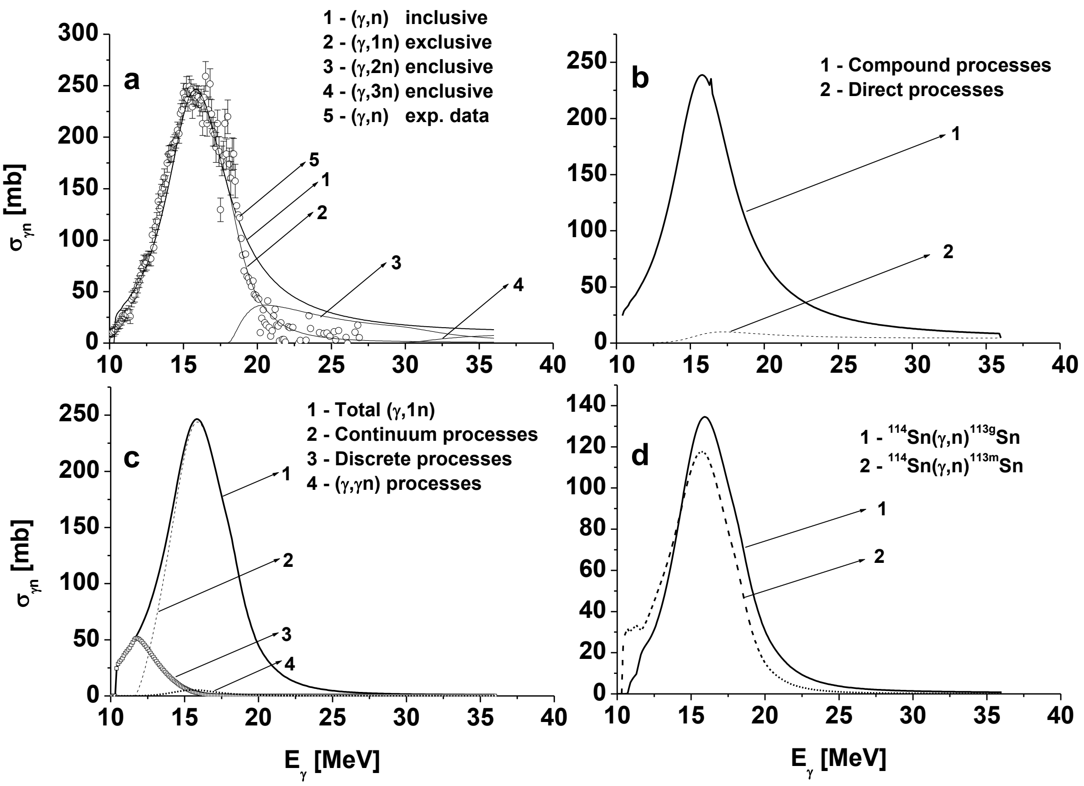

Figure 3.CS of $^{114}Sn(\gamma,n)^{113m,g}Sn$ reaction.

In the Figure 3.a are represented the exclusive (γ,xn) (x,1,2,3,…) reactions. The inclusive (γ,n) reaction, as is possible to observe, is a superposition of the other exclusive processes. Experimental data from literature [13] are very well described by the (γ,1n) process. In the Figure 3.b, the contribution of compound and direct processes, to the cross sections were obtained. By far, compound processes are dominant. Further, in Figure 3.c, the (γ,1n) reaction is separated in continuum and discrete processes. In Figure 3.d, the production cross section of ^{113}Sn isotope in isomer and ground states are represented. These results are necessary for the isomer ratio calculations. It is easy to observe that the sum of the isomer and ground states contribution, coincides practically with the (γ,1n) cross section. The contributions of other levels and channels including neutrons are small in comparison with (γ,1n) cross section and therefore were neglected.

The isomer ratios (IR) were evaluated, considering relation (1), energy of incident photons from neutron threshold up to 25–35 MeV (E_{max}) with flux (Φ_{inc}) equal with unity in one case, and in according with Kramers law from relation (2) in the other case. In the Table 1 are given the results for ^{114}Sn(γ,n)^{113m,g}Sn reaction (with bold), including also other photoneutron reactions on Sn isotopes analyzed by the authors.

	Reaction	(Case 1) R_1	(Case 2) R_2	(Case 3) R_3
1	**^{114}Sn(γ,n)^{113m,g}Sn**	**1.142±0.203**	**1.121±0.173**	**0.995±0.159**
2	^{118}Sn(γ,n)^{117m,g}Sn	0.081±0.015	0.077±0.012	0.062±0.010
3	^{120}Sn(γ,n)^{119m,g}Sn	0.131±0.025	0.126±0.022	0.104±0.018
4	^{122}Sn(γ,n)^{121m,g}Sn	0.258±0.052	0.243±0.045	0.170±0.030
5	^{124}Sn(γ,n)^{123m,g}Sn	4.075±0.532	4.187±0.785	5.078±0.954

Table 1. IR. 1) Φ_{inc}=1; E_{max}=35 MeV; 2) Φ_{inc}=1; E_{max}=25 MeV; Φ_{inc}=from (1); E_{max}=35 MeV; E_0=30 MeV.

In reactions 2,3,4,5 from Tabel 1, isomer ratios in photoneutrons reactions are also obtained. For all five reactions Talys evaluations show that compound processes are dominant, in comparison with others nuclear reactions mechanisms. The isomer ratios become constants with the increasing of maximal energy (E_{max}), but are more sensitive to the energetic dependence of incident flux (Φ_{inc}).

CONCLUSIONS

The protons and gamma induced reactions with neutrons emission for obtaining isotopes and isomer of Sn were analyzed. For both type of reactions, (p,n) and (γ,n), the inclusive and exclusive cross sections were evaluated. The dominant nuclear reaction mechanisms was determined with a separation between the contributions of discrete and continuum states. Obtained cross section results are compared with existing experimental data and in both cases the agreement between theory and experiment can be considered as good. Further the isomer ratios, in a few cases were calculated, using different maximal energy and different model of incident particle fluxes.

Cross sections evaluations were done with Talys computer code. It was demonstrated that Talys software represents and efficient tool for experimental data analysis.

As it is possible to observe, experimental data on cross sections exist for some energy regions, but for isomer ratios we have not found yet. In conclusions, for both processes would be of interest, cross sections and isomer rations experimental measurements which in principle are possible to run at the LNF JINR Dubna basic facilities.

Acknowledgement. The work was supported by Cooperation Program between JINR Dubna and Romanian Research Institutes coordinated by JINR Dubna Romanian Plenipotentiary Representative on 2016 – 2017 years and FLNP Thematic Plan.

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