Numerical Evaluation of Sn Isotope Cross Sections by Photoneutron Activation Method

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Abstract. Photoneutron cross section reactions on natural Sn were evaluated using Talys code for incident neutron energy up to some ten's of MeV's. For each Sn isotope the contribution of compound, direct and preequilibrium mechanism were extracted. The isomer cross sections and isomer ratios were calculated. The results are compared with existing experimental data obtained by bremsstrahlung source and activation methods.

INTRODUCTION

Nuclear reactions induced by gamma quanta with emission of neutrons are efficient in fundamental and applied researches. In fundamental researches with the help of the photoneutron reactions new data on atomic nuclei structure and states as well as on nuclear reaction mechanism are obtained. In applied researches these reactions are used in nuclear safeguard, nucleosynthesis, radiation transport, isotopes productions and many others [1,2].

In the present report the photoneutron reactions on Sn nucleus will be analyzed. This nucleus has ten natural isotopes with the following atomic mass abundances, respectively: 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 % [3-5].

For all isotopes the (γ,xn) cross section (x=1,2,3,4) and the isomeric ratio in the (γ,n) reaction for incident photon energy from the neutron threshold (8÷9 MeV) up to 36 MeV were evaluated. Also analyses of the contribution of compound, direct and preequlibrium processes to the cross section as well as of discrete and continuum states were perfomed. With the help of Talys the cross sections were evaluated. Talys is a freeware software working under Linux operating system and is dedicated to nuclear reactions calculations [6,7].

Isomer states are of a great interest from a long time in nuclear physics and they can be considered excited states of atomic nuclei with high spins value and consequently very large time of life compared with other excited nuclear states.

For some isotopes of Sn the isomeric ratios in (γ,n) reactions were not measured in the Great Dipole Resonance (GDR) region. Because the related cross sections are known as calculated by using Talys then it is possible to estimate the isomeric ratio starting from the threshold up to some maximal energy of the Brehmsstrahlung X-ray source.

THEORETICAL BACKGROUND

Isomer ratio *R*, is defined as the ratio between the cross sections of metastable (m) and ground state (g) isotope production:

$$R = \sigma_m \cdot \sigma_g^{-1} \tag{1}$$

$\sigma_m, \sigma_g =$ cross sections of isotope production in metastable and ground states, respectively.

In Talys the isomer ratio is defined slightly different [7]:

$$R = \sigma_m \cdot \left(\sigma_m + \sigma_g\right)^{-1} \tag{2}$$

Relations (1,2) are theoretically because in the experiment the isomeric ratios are measured using other expression. Experimental isomeric ration in the case of Brehmsstrahlung source of incident gammas is [8,9]:

$$R^{\exp} = \left[\int_{E_{th}}^{E_m} N_0 \phi\left(E_\gamma\right) \sigma_m\left(E_\gamma\right) dE_\gamma\right] \cdot \left[\int_{E_{th}}^{E_m} N_0 \phi\left(E_\gamma\right) \sigma_g\left(E_\gamma\right) dE_\gamma\right]^{-1} \tag{3}$$

where E_{th} = neutron threshold energy of incident gammas, E_m = maximum energy of gammas, N_0= concentration of investigated isotope, ϕ = incident gamma flux.

The analysis of isomeric ratios is starting from neutron threshold (≈ 8MeV) up to 36 MeV. In this large energy interval, including the GDR region, it is possible to act the known compound, direct and preequilibrium [10] nuclear reaction mechanisms. As it will be demonstrated below in the analyzed cases the compound processes are dominant so the Hauser-Feshbach formalism can be applied. In this case the cross section has the form [11]:

$$\sigma_{\alpha\beta} = \pi \bar{\lambda}_\alpha^2 T_\alpha T_\beta \left(\sum_c T_c\right)^{-1} W_{\alpha\beta} \tag{4}$$

where T = penetrability coefficients, $W_{\alpha\beta}$ = width fluctuation correction factor, λ_α = reduced wavelength of incident particle, α, β, c = incident, emergent and possible outgoing channels respectively. Sum is taken over all possible open channels c. Our case $\alpha = \gamma$, $\beta = xn$, $x = 1,2,3,\ldots$

The main elements in the Hauser-Feshbach cross section formula (4) are the penetrability coefficients. The penetrability coefficient represents the probability of a particle to pass a potential barrier. The transmission coefficients are increasing with energy but their values are always lower than one.

The width fluctuation correction factor W represents a correlation between incident channel (α) and outgoing channels (β,c). At low incident energies this factor is equal with one indicating no correlation between ingoing and outgoing channels (Bohr hypothesis) and it is decreasing slow with the energy showing some dependencies between ingoing and outgoing channels. There are a few ways for the calculation of the correction factor W and they are described very detailed in [7].

The cross sections and isomer ratios are evaluated using Talys codes. Talys provides very precise nuclear reaction evaluations starting with 1 keV up to 200 MeV, that is very useful for describing of experimental data or nuclear data generation. By free contributions of many authors the nuclear reactions mechanisms (compound, direct, pre-equilibrium), nuclear data like energy levels, nuclear data density, nuclear models and many others in a unitary friendly easy to use interface were implemented [6,7].

In the next paragraph some of definitions implemented in Talys like exclusive and inclusive cross sections will be used. The cross section is defined exclusive when the outgoing channel is exactly specified by the number of emergent particles (plus any number of photons). For example (γ,2n) exclusive cross section is considered as in the outgoing channel exists two neutrons and only two neutrons (plus any number of photons). By comparison inclusive cross sections can be understood when in outgoing channel the emergent particle is coming from other type of reaction. We have a (γ,n) inclusive cross section when the registered neutrons come from other photonuclear reactions involving neutrons like (γ,xn), (γ,np), (γ,2np), (γ,n2p), (γ,nα) etc [7].

RESULTS AND DISCUSSION

The photoneutron cross sections for all natural isotopes of Sn nucleus were calculated For each nucleus the inclusive (γ,n) cross sections have been obtained and later they were decomposed in the corresponding exclusive (γ,xn) (*x = 1,2,3,4*). The contribution of compound, direct and pre-equilibrium processes were obtained. Also a separation into discrete and continuum processes was effectuated. For isotopes where it was possible we have extracted the isomer and ground state production cross sections (σ_m, σ_g) in the exclusive (γ,1n) reactions. In multiple emission processes of type (γ,np), (γ,2np), (γ,n2p), (γ,3np), (γ,n3p) and others with the participation of charged particles a lot of isomer states are produced but they were not considered as their cross section usually are very low since they are partially suppressed by the presence of nuclear Coulomb field. Further only the results on (γ,n) reaction on ^{114}Sn and ^{120}Sn are presented (Figures 1 and 2).

In the Figures 1 and 2 the photoneutron cross sections for the ^{114}Sn(γ,n)^{113}Sn and ^{120}Sn(γ,n)^{119}Sn have been represented. In the Figures 1.a and 2.a the (γ,n) inclusive reactions are shown. The inclusive (γ,n) reactions is a superposition of (γ,1n), (γ,2n), (γ,3n) exclusive processes. The experimental data are described very well by (γ,1n) exclusive reactions [12]. In the Figures 1.b and 2.b the inclusive (γ,n) cross section is separated in compound and direct processes. The pre-equilibrium processes were neglected as resulted from the evaluations. In the Figures 1.c and 2.c the exclusive (γ,n) cross section is represented as sum between discrete and continuum processes. At low energies the processes on discrete levels are predominant but with the increasing of energy the role of continuum processes become more important. In the Figures 1.d and 2.d the cross sections of ^{114}Sn(γ,n)^{m,g113}Sn and ^{120}Sn(γ,n)^{m,g119}Sn reactions are represented. Some models of Brehmsstrahlung sources were used together with the cross sections of isomer and ground state production for the isomer ratios evaluations. The isomer ratios can be easy calculated by using relation (1) and cross sections from Figures 1.d and 2.d. In order to be closer to the experiment it is necessary to use the expression (3).

The evaluation of the incident X-ray flux is a quite complex question for which many papers in the literature are dedicated. In the present evaluation of isomer ratios the simplest two cases have been used. In the first case the incident flux is considered unity with gamma energy from neutron threshold up to 36 Mev. In the second case a continuous X-ray source with a flux based on Kramers formula was considered [13].

$$\phi(E_\gamma) \sim I_c = i_b Z(E_0 - E_\gamma)E_\gamma^{-1} \tag{5}$$

I_c = intensity of gamma quanta; i_b = electron beam current; E_0 = energy of accelerated electrons; Z = charge of stopping element.

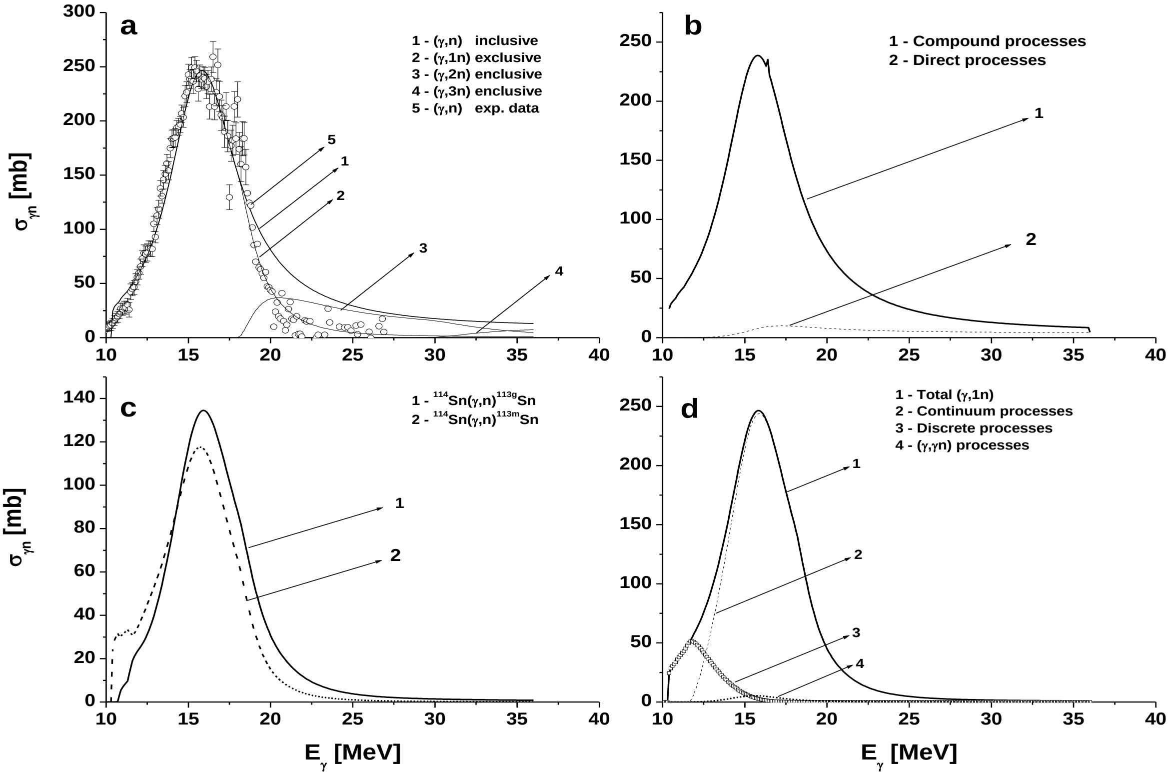

Figure 1. Cross section of $^{114}Sn(\gamma,n)^{113}Sn$ reaction. a) Inclusive (γ,n) cross section and contribution of (γ,xn) (x=1,2,3) processes. Results are compared with experimental data. b) Decomposition into direct and compound processes (pre-equilibrium states are neglected) c) Decomposition into discrete and continuum processes d) Isotopes production $^{113m,g}Sn$ of isomer and ground states, respectively.

The incident gamma flux (5) is decreasing with energy and therefore the maximum energy E_m from (3) must be taken up to 25 MeV in order to have enough statistics in the experiment. The incident flux can be calculated using other more complicated models like Schiff model [14] or by Monte Carlo simulation. In the Table 1 are shown the main properties of isotopes considered in the calculation of isomeric ratios [15].

Table 1. Main properties of isomer (m) and ground (g) states of Sn isotopes used for isomer ratios calculation

	Isotope	Isomer (m)		Ground (g)	
		J^π	τ_m	J^π	τ_m
1	^{113}Sn	$(7/2)^+$	21.40 m	$(1/2)^+$	115.9d
2	^{117}Sn	$(11/2)^-$	13.60 d	$(1/2)^+$	stable
3	^{119}Sn	$(11/2)^-$	293.1 d	$(1/2)^+$	stable
4	^{121}Sn	$(11/2)^-$	55.00 y	$(3/2)^+$	27.06 h
5	^{123}Sn	$(3/2)^+$	40.60 m	$(11/2)^-$	129.2 d

In Table 2 are represented the isomer ratios for the Sn isotopes (1) if the flux of incident gammas is equal with one and (2) if the flux is calculated by Kramers formula (5) with different maxim energy E_m.

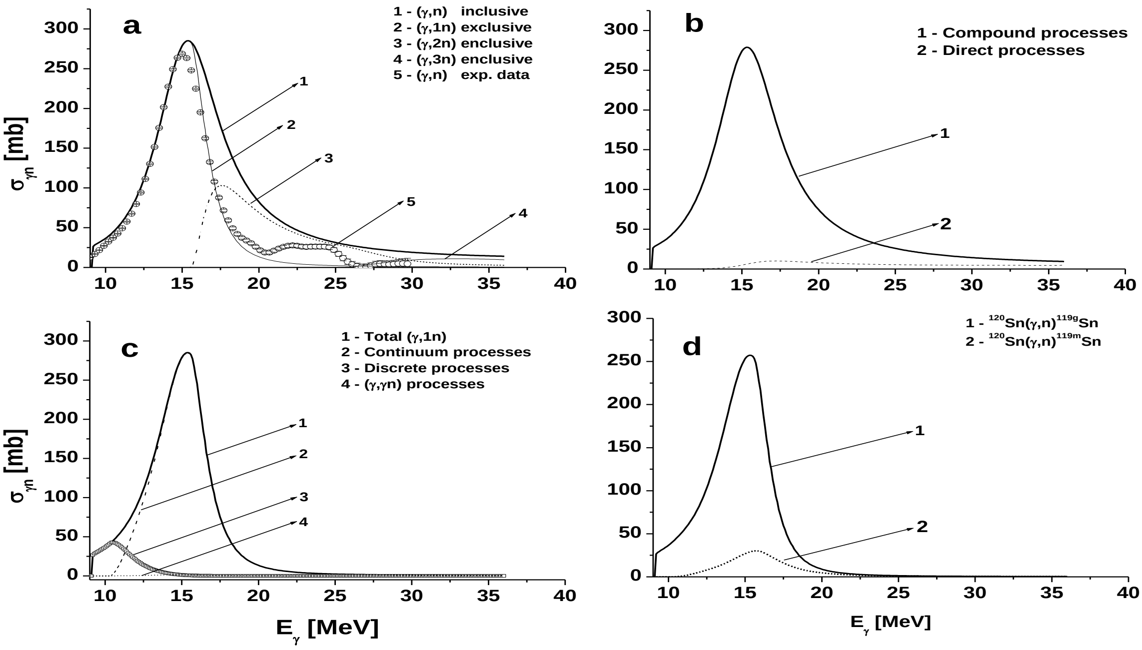

Figure 2. Cross section of ^{120}Sn(γ,n)^{119}Sn reaction. a) Inclusive (γ,n) cross and contribution of (γ,xn) (x=1,2,3) processes. Results are compared with experimental data. b) Decomposition into direct and compound processes (pre-equilibrium states are neglected) c) Decomposition into discrete and continuum processes d) Isotopes production: ^{119m,g}Sn of isomer and ground states respectively.

Table 2. Isomer ratios calculated for Sn isotopes obtained in (γ,n) reaction. 1) $\phi = 1; E_m = 35$ MeV; $\phi = 1; E_m = 25$ MeV; $\phi \sim (E_0 - E_\gamma)/E_\gamma$ (6); $E_m = 25$ MeV; $E_0 = 30$ MeV

	Reaction	R_1	R_2	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	0.0768±0.012	0.0616±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

The results in Table 2 were evaluated numerically based on relations (1-5) implemented in Talys, starting from neutron threshold up to 25 and 35 MeV, respectively, with step 0.1 MeV (which is the source of showed errors).

In the first and second case of Table 2 (R_1, R_2) the incident flux was taken unity just for simplicity. The maximum gamma energy first was considered 35 MeV because the maximum energy in the Figures 1 and 2 is also up to 35 MeV. From relation (5) it results that an experiment is limited by the energy of stopped electrons E_0. If electron energy (E_0) is taken

30 MeV than the maximum energy of gamma quanta (E_γ) should be up to 25 MeV for a suitable incident intensity and statistics of events. This is the situation of the second and third cases of Table 2 where for useful comparisons the intensity was taken unity (R_2) and after in accordance with (5) (R_3). The R_3 case is more close to reality and therefore these evaluations are needed in new measurements on isomer ratios of Sn isotopes.

From Table 2 it is shown that if the spin of isomer states is greater than the spin of the ground state then the isomer ratio is less then unity and greater than one if vice versa. This has the following explanation: due to the selection rules, the levels with high spin values are less populated than those with lower spin values. Exception seems to be the first case of ^{114}Sn(γ,n)^{113m,g}Sn reaction but in this case a) the isomer state has a not so great value and b) the difference between spins values of isomer and ground states is not so high too.

CONCLUSIONS

The cross sections and isomer ratios of photoneutron reactions on Sn isotopes in the region of GDR were evaluated. The cross sections were obtained with Talys and for isomer ratios some models of incident gamma were used. The Talys code allowed to extract the contributions of different processes to the cross section (compound - direct - preequilibrium or discrete - continuum). A very good agreement between theoretical cross section evaluations and experimental data from literature has been obtained.

The agreement between theoretical and experimental cross sections evaluations has given a serious base for isomer ratios calculations. Then the isomer ratios were calculated using Talys cross sections, different incident gamma flux and maximum values of gamma incident energies. One of future tasks is to measure experimentally the isomer ratios from Table 2 which is possible to the basic installations of JINR Dubna.

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