Isomeric States Produced in Nuclear Reactions on Indium

C. Oprea[1], A. Oprea[1], V. Macocian[2], S. Filip[2]

[1]*Frank Laboratory for Neutron Physics (FLNP),Joint Institute for Nuclear Research (JINR), 141980 Dubna, 6 Joliot Curie, Moscow Region, Russian Federation*

[2]*Faculty of Sciences, University of Oradea, 1 Universitatii, Oradea, Romania*

Abstract. In the nuclear reactions induced by fast protons the production of neutrons and isomer states are analyzed. Cross sections are an important part of the evaluations and they are evaluated with Talys. Present evaluations represent a starting point for proposal on isomer and isotopes productions at LNF JINR Dubna facilities.

INTRODUCTION

The Indium element has $Z=49$ and two natural isotopes, ^{113}In and ^{115}In nuclei with abundances *4.29%* and *95.71%* respectively [1, 2]. By interaction with fast protons of MeV's energy and emission of neutrons will be obtained the Sn nucleus which is an element with many isotopes because Sn has a magic number of protons, $Z=50$. The reaction of interest is $^{113}In(p,n)^{113}Sn$ reaction in which are produced the isomer state of ^{113m}Sn nucleus (m=meta – stable) and ^{113g}Sn in the ground state with $Q=-1.82\ MeV$. The main properties necessary in the evaluations are spin, parity and time life of the nuclei and the corresponding gamma transition. For ^{113m}Sn in the isomer state the spin and parity are: $J^{\Pi} = (7/2)^{+}$. For the ground state, ^{113g}Sn the spin and parity are, $J^{\Pi} = (1/2)^{+}$. The energy of gamma transitions is $E_{\gamma} = 77.389\ keV$. In the fundamental state the ^{113}In nucleus has the spin and parity, $J^{\Pi} = (9/2)^{+}$. It is necessary to note that the same states, $^{113m,g}Sn$ are obtained also in $^{115}In(p,3n)^{113}Sn$ reaction and these will be necessary to take into account in the case the experiments involving natural Indium.

For the evaluation of the production of neutrons and the isomer and ground states of ^{113}Sn where necessary to evaluate cross sections and they were evaluated with Talys. The computer codes Talys represents a software dedicated to nuclear reactions and nuclear structure calculations. This software is working under Linux, has an easy and friendly interfaces, it is freeware and is in a permanent development by contributions of many users [3]. In this software are implemented all nuclear reaction mechanism (compound, direct and pre – equilibrium) and the necessary nuclear data as energy and density levels, parameters of the potentials in the incident and emergent channels and others were mainly obtained in the processing of experimental data.

THEORETICAL BACKGROUND

The cross sections of $^{113}In(p,n)^{113}Sn$ reactions are evaluated with Talys for incident fast protons with energy from *0.5 MeV* up to *25 MeV* taking into account all type of reaction mechanisms (compound, direct and pre-equilibrium) which are implemented in Talys.

In the case of compound reaction mechanism it is used the statistical model of nuclear reactions described by Hauser – Feshbach formalism [3]. The main assumptions of statistical model of nuclear reactions consist in: by interaction of incident particle with target it is obtained a compound nucleus which "forgets" the way of its formation (Bohr hypothesis).

This compound nucleus has the same properties like an usual nucleus, characterized by mass, spin, parity, isotopic spins and others. Also is considered that the time of life of the compound nucleus is of order of $10^{-16} - 10^{-15}$ *s* is more higher than the time necessary for incident particle to pass the target nucleus. The passing time of the target nucleus by incident particle is of order of $10^{-19} - 10^{-20}$ *s* and this is a characteristic time of direct reactions.

In the case of direct reactions in the evaluations were used the Distorted Wave Born Approximation (DWBA). The characteristic time of direct processes is order of magnitude little than in the case of the compound processes and therefore the differential cross section of direct processes has a pronounced forward asymmetry [4].

The direct and compound processes are considered as limit cases of nuclear reaction mechanisms. Description of intermediate processes is given by pre – equilibrium mechanism and in the evaluations the two component exciton model was used [5].

For each cross section, in the incident and emergent channels are considered the following potentials: volume and surface Woods – Saxon potential with real and imaginary part, the spin – orbit interaction and other. In Talys, based on the processing of a wide base of experimental data, are introduced potential density levels parameters almost for all existent nuclei [3].

Cross sections are necessary for the evaluation of isomer and ground states production and after the isomer ratios. The expression of isomer ratio in the case of a *(p,n)* reaction is:

$$R = \frac{Y_m}{Y_g} = \frac{\int_{E_{th}}^{E_m} N_0 \phi_p(E_p) \sigma_{pn}^m(E_p) dE_p}{\int_{E_{th}}^{E_m} N_0 \phi_p(E_p) \sigma_{pn}^g(E_p) dE_p} \qquad (1)$$

The physical quantities in relation (1) are the following: $Y_{m,g}$ = yields of isomer and ground states; N_0 = number of target nuclei; ϕ_p = flux of incident protons; σ_{pn}^{mg} = cross sections of isomer and ground state production; E_{th} = threshold energy of neutron emission; E_m = maximal energy of incident protons usually given by the experimental setup.

Talys codes give the possibility to evaluate the inclusive and exclusive cross section. Lets consider the following binary nuclear reaction: *A(a,b)B*. Inclusive cross sections are defined those in which in the emergent channel *(a,b)* are registered *b* particles from other open channels like *(a,2b)*, *(a,3b)*, *(a, nb)* etc. Exclusive cross sections are those in which the final channel *(a,b)* is well defined and are not taken into account *b* emergent particle coming from other open channels.

RESULTS

The inclusive and exclusive cross sections of $^{113}In(p,n)^{113}Sn$ were evaluated in order to obtain the isomer ratios. Inclusive and exclusive cross sections, taking into account their definitions are in principle very useful in the analysis of experimental data. In was also obtained the separation of contributions of different reaction mechanisms and type of states of residual nuclei (discrete and continuum). Results on inclusive cross section are shown in the Figure 1. In Figure 1.a and 1.b. we have the contribution of discrete states given by direct and compound processes. Usual in Talys were considered in the calculation 10 discrete levels of residual nucleus.

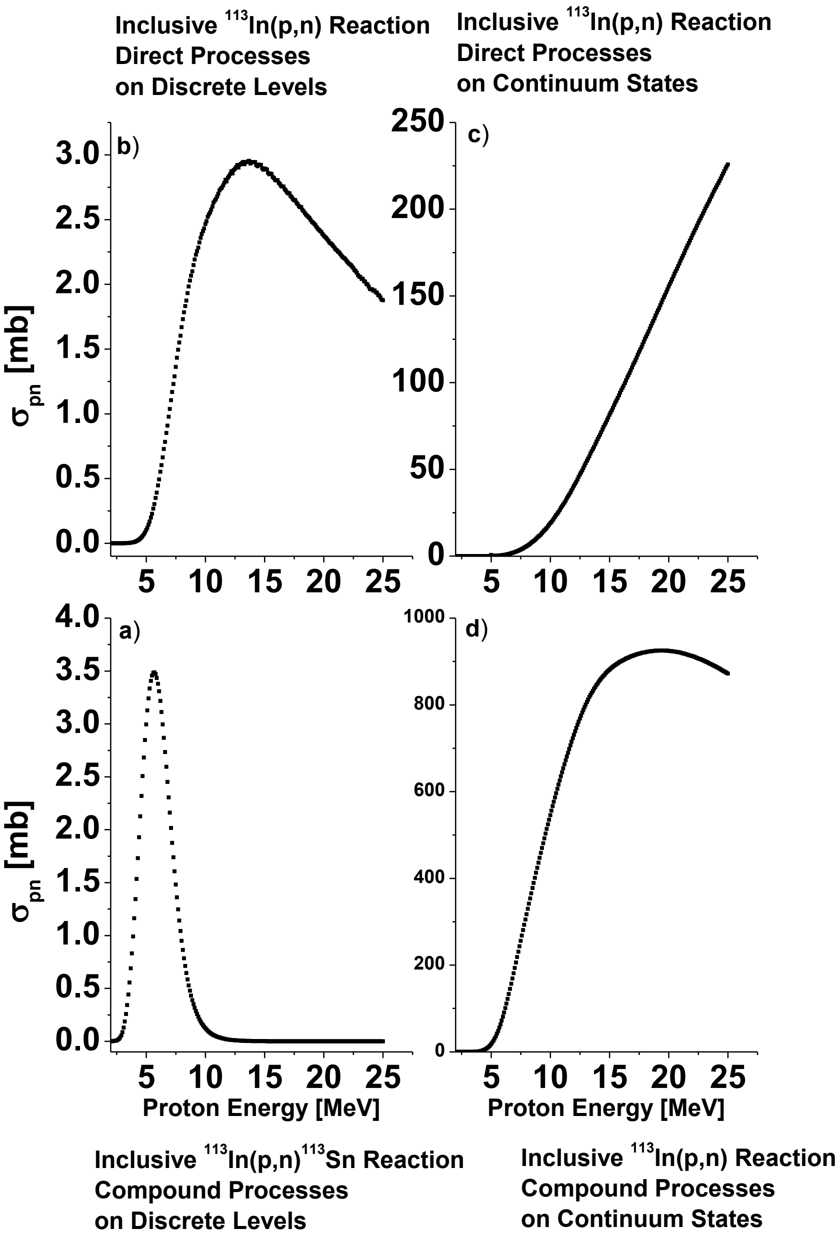

Figure 1. Inclusive Cross Section of ^{113}*In(p,n)* Reaction. Discrete States. Processes a) Compound b) Continuum States. Processes c) Direct d) Compound.

The contribution of discrete states are very low in comparison with those of continuum states but it is possible to observe the expected shape in which the cross section is increasing with energy, reaches a maximum, followed by a decreasing (Fig. 1.a and 1.b). The main contribution to the cross section is given by the direct and compound processes on continuum states (Fig. 1.c and 1.d). In Fig. 1.c the direct processes are increasing with energy and compound ones reaches some maximum followed by a slowly decreasing. For protons incident energy close to neutron threshold the compound processes are just simple compound ones as suggested by Talys. But with the increasing of the protons incident energy at some few MeV's the compound and direct processes are originated by pre – equilibrium mechanism.

Further we are interested in the production of isomer and isotopes and for these the exclusive cross sections are necessary. In the Figure 2 are represented the exclusive cross sections of production of *$^{113m,g}Sn$* in isomer and ground state respectively.

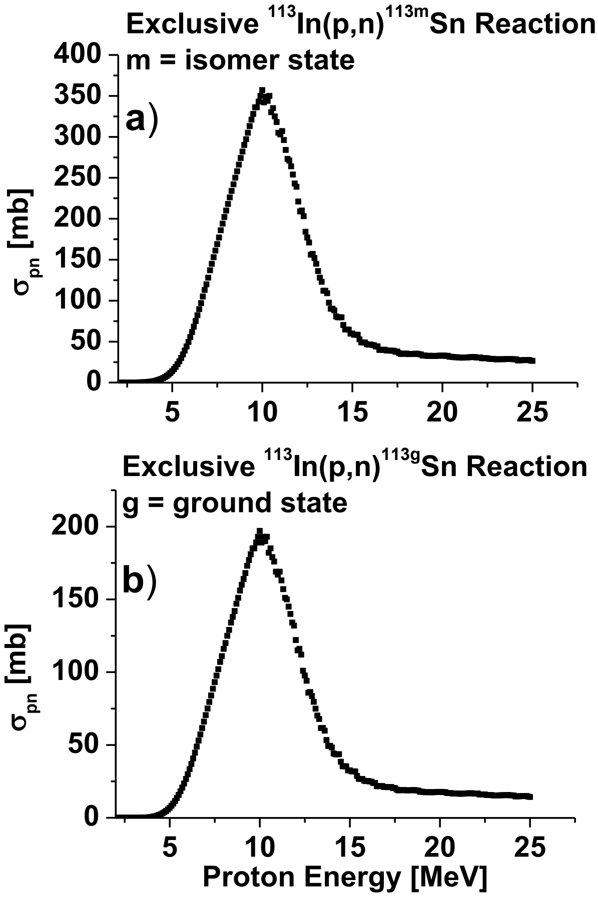

Figure 2. Exclusive Cross Section of ^{113}In(p,n)^{113m,g}Sn reaction.
a) Isomer b) Ground

The contributions in the cross sections from Figure 2 mainly are given by compound processes on continuum states like in the case of inclusive cross reactions. It is possible to observe that the cross section production of isomer state are higher than in the case of ground states in spite of the fact that spin of ground state is lower than the spin of isomer states. This can be explained by the fact that the *^{113}In* nucleus has the spin *9/2* and in this case the isomer state, *^{113m}Sn*, in principle can be easier populated in the *(p,n)*. In the Figure 3 we have the theoretical evaluation compared with existing experimental data from literature of the total production of *^{113g}Sn* nucleus in the ground states [6].

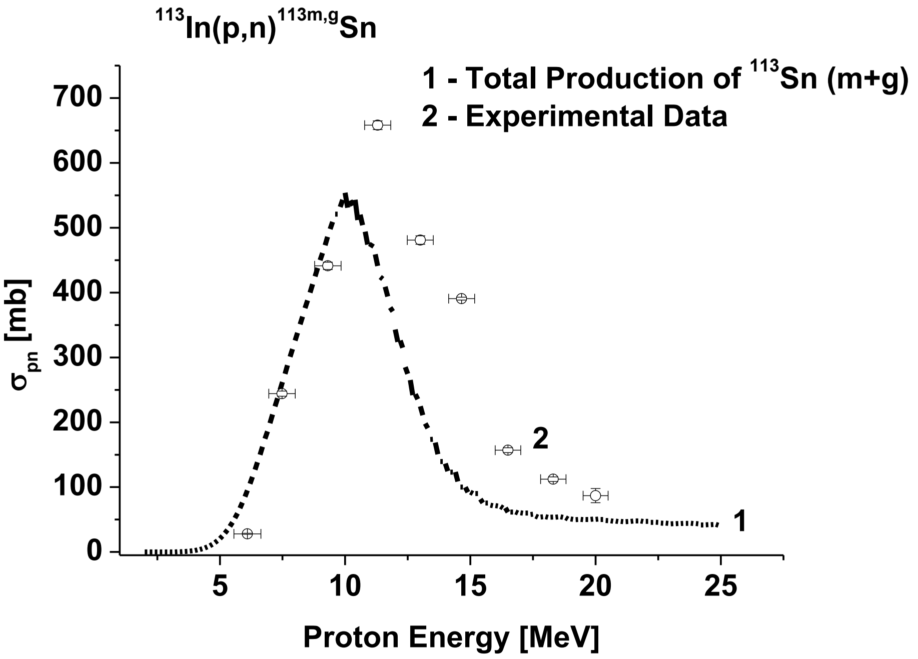

Figure 3. Production of ^{113g}Sn nucleus as sum of Fig. 2.a and Fig. 2.b compared with experimental data

In the Talys evaluation we used the standard Talys input of nuclear potential parameters, energies, density states and other. In this case can be considered that we have a quit good agreement between experiment and evaluation. As it is possible to observe up to 9 MeV the agreement between theory and experiment is very good. Higher the shape of theoretical and experimental curve is keeping but the values already, are not the same. After *10 MeV's* the number of open channels is increasing and in is very possible that in the experiment where measured neutron from other channels like *(p,2n)* with *Q=-9.46 MeV*, *(p,n2p)* with *Q=-15.47 MeV*, *(p,p2n)* with *Q=-17.11 MeV* and etc. It is obvious also, that it will be necessary to vary the input parameters of Talys.

Considering acceptable the agreement between theory and experiment we have evaluated the isomer ratio, based on relation (1) considering the simple case of an incident proton flux equal with 1 with energy varying from neutron threshold up to *25 MeV*. The step in energy is considered 0.1 MeV. In this case the isomer ratio, *R*, has the value:

$$R = 1.82 \pm 0.26 \tag{2}$$

The present results of cross sections and isomer ratio were obtained using in the incident and emergent channels, $(p+^{113}In)$ and $(n+^{113}Sn)$ respectively, the following parameters (real and imaginary part, V and W with radius r_V and diffuseness a_V) of volume Woods – Saxon potential $(U_{WS}=V+iW)$:

$$V=62\ MeV,\ W=0.11\ MeV,\ r_V=1.22\ fm,\ a_v=0.661\ fm \tag{3}$$

$$V=51\ MeV,\ W=0.14\ MeV,\ r_V=1.22\ fm,\ a_v=0.661\ fm \tag{4}$$

It is necessary to remind that in Talys are implemented all type of nuclear potential, including surface Wood – Saxon with real and imaginary part, spin – orbit interaction etc but they are not shown here.

DISCUSSIONS AND CONCLUSIONS

We have evaluated the inclusive and exclusive cross sections in the $^{113}In(p,n)^{113}Sn$ reaction and the isomer ratio with the help of Talys codes. Using standard input Talys parameters was obtained an acceptable agreement between theory and experiment of ^{113g}Sn production and therefore the isomer ratio also was evaluated. The effectuated research shown that Talys could be an effective tool of the analyzing of experimental and theoretical data.

Researches on $^{113}In(p,n)$ reaction are in the beginning. In future are planed a wide analysis of input parameters. In order to provide new measurements of cross sections and isomer ratios it is necessary also to study nuclear reactions given by other open channels like *(p,2n)*, *(p,pn)*, *(p,2np)*, *(p,n2p)* etc that could influence the measurements of $^{113}In(p,n)^{113}Sn$ reaction. In the case of natural Indium experiments there are necessary also to investigate the emergent channels of $(p+^{115}In)$ reactions.

The present evaluations are realized to propose new experiments on cross sections and isomer ratios measurements at LNF JINR Dubna facilities. In the studied reaction, it is possible to observe that there is a lack of experimental data and new measurements could be useful for fundamental and applicative researches by obtaining new nuclear data.

Acknowledgments. *The present researches are supported by JINR Dubna Annual Cooperation Program with Romanian Research Institutes coordinated by Romanian Plenipotentiary Representative and LNF JINR Scientific Plan on 2016.*

REFERENCES

[1] G. Audi, A.H. Wapstra, Nucl. Phys. A **565**, p. 1–65 (1993).
[2] G. Audi, A.H. Wapstra, Nucl. Phys. A **595**, p. 408–490 (1993).
[3] A.J. Koning, S. Hilaire and M.C. Duijvestijn, TALYS-1.0., Proceedings of the International Conference on Nuclear Data for Science and Technology, April 22–27, 2007, Nice, France, editors
O. Bersillon, F. Gunsing, E. Bauge, R. Jacqmin, S. Leray, EDP Sciences, p. 211 (2008).
[3] W. Hauser, H. Feshbach, Phys. Rev., **87**, 2, p. 366 (1952).
[4] G.R. Satchler, Direct Nuclear Reactions, Oxford University Press, New York (1983).
[5] A.J. Koning and M.C. Duijvestijn, Nucl. Phys. A **744**, p. 15 (2004).
[6] http://www-nds.iaea.org (Cross Section of $^{113}In(p,n)^{113}Sn$ reaction).