Cross Sections Evaluation in Nuclear Reactions with Fast Neutrons

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Abstract. For incident neutrons with energy about few MeV there are not so many cross section experimental data and between existing data there are differences from one group to another. For fast neutrons many channels are open and the cross sections usually are small (order of tens or hundred of milibarns) and their measurements are difficult and affected by high background. On the other hand in this incident neutrons energy region the mechanism of nuclear reaction is passing from compound to pre-equilibrium and direct processes.

In this work the cross sections for nuclear reactions induced by fast neutrons and emission of charged particles using the computer code Talys were evaluated and they are compared with experimental data obtained mainly at FLNP JINR. The theoretical and experimental cross section values obtained for nuclei as Sm, Zn, Nd and other nuclei can be used in many fields of sciences and one of great interest nowadays is the nuclear astrophysics for rates calculations.

INTRODUCTION

Nuclear reactions induced by fast neutrons are important for fundamental and applicative researches, respectively. For fundamental researches these reactions are a source for new data on: determination and refining of the parameters of different nuclear potentials in the input and output channels, nuclear structure, cross section evaluation for astrophysics and others. For many fast neutrons reactions on medium and heavy nuclei the cross section data differ from some authors to others and this fact leads to the necessity of its theoretical and experimental evaluations [1]. Concerning the applicative part of fast neutron reactions the cross section data are of a great interest in material researches for nuclear reactors construction and design. It is well known that the (n,p) and (n,α) reactions with fast neutrons lead to the accumulation of Hydrogen and Helium in the walls, facilities and devices of a nuclear complex which will affect in time the physical properties (like mechanical resistance) of the exposed surfaces.

The (n,α) cross sections induced by neutrons were determined using computer codes realized by authors based on the evaluation of reflection factor by a quantum mechanical approach and Talys codes.

The quantum mechanical approach of reflection factor calculation is very well described in [2]. The cross section of (n,α) reaction on ^{64}Zn and ^{147}Sm, using statistical model of nuclear reactions and the Hauser – Feshbach formalism, were calculated in [3]. In the reference [3] the necessary transmission (penetrability) coefficients were obtained with the help of reflection factor in the frame of quantum mechanical procedure described in [2].

With the increasing of incident neutrons energy there are opening other reaction channels and a competition is starting between different nuclear reaction mechanisms. In [3] we have considered only processes with formation of the compound nucleus and neglected the contribution of direct and pre-equilibrium processes. In the present work for the fast neutrons, considering some relative new experimental data on forward – backward (FB) measurements in (n,α) reactions [4], we have taken into account the direct and pre-equilibrium processes evaluating them with the help of Talys.

The Talys codes are dedicated to the structure of nucleus and nuclear reactions calculations and represent a set of freeware computer programs working under Linux in a friendly environment [5].

THEORETICAL BACKGROUND

The (n,α) processes with fast neutrons up to some MeV's are mainly the results of compound processes and therefore the cross sections will be obtained in the frame of statistical model for nuclear reactions [6] and the Hauser – Feshbach (HF) formalism [7]. The (n,α) cross section in the HF approach has the form:

$$\sigma_{n\alpha} = g\pi\lambda_n^2 \frac{T_n T_\alpha}{\sum_c T_c} W_{n\alpha} \quad (1)$$

$g =$ statistical factor; $\lambda_n =$ reduced neutron wave length; $T =$ penetrability coefficient; $W =$ fluctuation correction factor; $c =$ channels considered in the calculations.

One of the main elements of HF formula (1) are the penetrability coefficients. This coefficient has the following expression:

$$T_l(E) = 1 - |U_l(E)|^2 ,\ U_l(E) = \text{reflection factor};\ l = \text{orbital moment};\ E = \text{energy}; \quad (2)$$

The reflection factor is obtained using the quantum mechanical approach described in [2] and by considering the hypothesis of statistical model of nuclear reactions [6]. The fluctuation correction factor (*W*) has a few expressions but in our evaluations we used the relation proposed by Moldauer [8].

Contributions of the direct and pre-equilibrium processes were evaluated by Talys using the standard output data and corresponding relations for cross sections [5].

RESULTS

We have evaluated the cross sections of nuclear reactions induced by neutrons on ^{147}Sm nucleus. For incident neutrons from slow ones up to *500 keV* we have described well the ^{147}Sm(n,α)^{144}Nd experimental data cross sections from [9] using the software realized by us. In this energy interval the nuclear reactions are going by formation of compound nucleus. It was considered a simple rectangular nuclear well (with real and imaginary part respectively) and known nuclear radius.

$$U = V + iW ,\ R = R_0 A^{\frac{1}{3}} [fm] \quad (3)$$

Where was the case we have taken into account in the cross section the influence of the other open channels. The values of the real and imaginary part of nuclear potential initially had the values *V = 225 MeV* and *W = 0.15 MeV*. In order to have the good agreement the real part of nuclear potential was modified with about *15%* from *190 MeV* up to the initial value of *225 MeV*. The results are shown in the Figure 1.

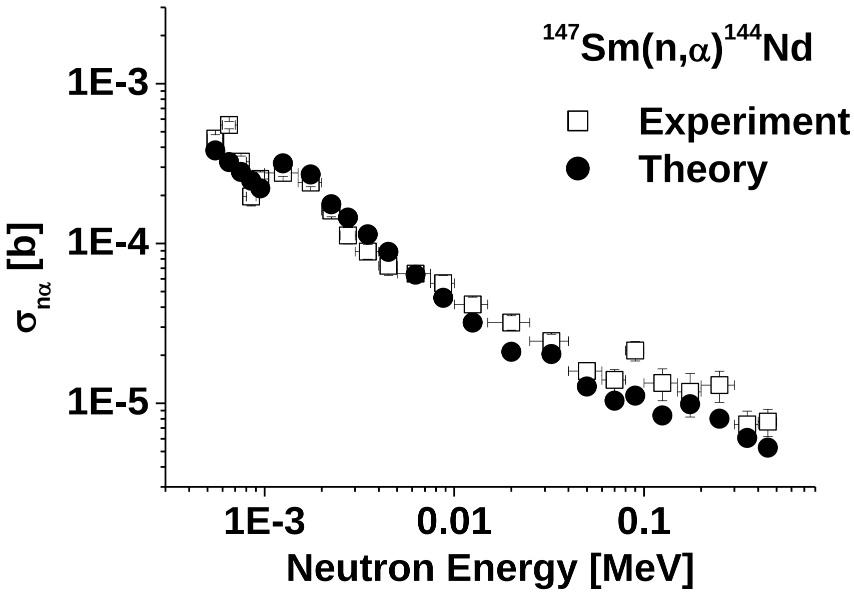

Figure 1. Comparison between theory and experiment of $^{147}Sm(n,\alpha)^{144}Nd$ cross section

For incident neutrons with energy higher than *500 keV* up to *20 MeV*, for the same reaction like in Figure 1, the cross sections have been evaluated using the Talys software. The results can be seen in Figure 2.

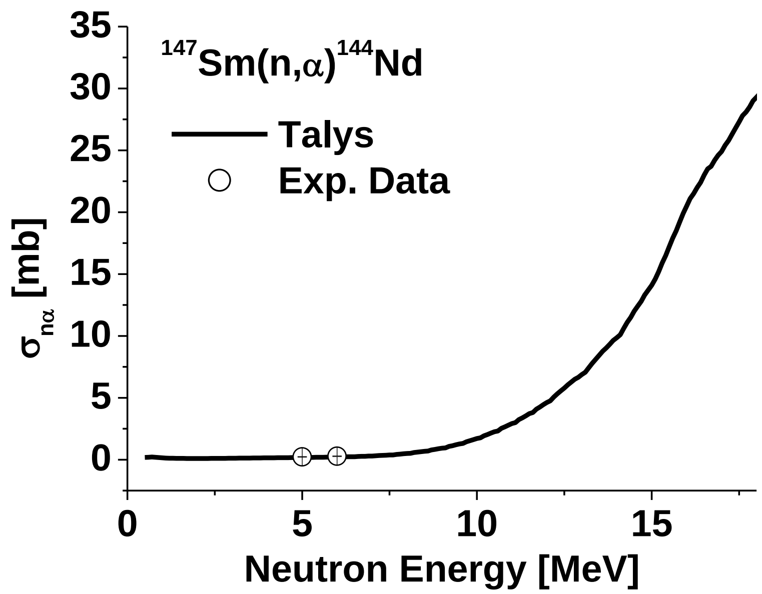

Figure 2. Talys evaluation of the cross section compared with existing experimental data

The experimental measurement of $^{147}Sm(n,\alpha)^{144}Nd$ cross section is difficult because its values are very low and in this way it should explain the small number of existent experimental data.

From Figure 2 we see that the experimental data are in a good agreement with theoretical evaluation. In the evaluation the Talys standard inputs with a nuclear potential with all components [5] were used. Also for Figure 2, the real and imaginary part of nuclear well have the values *V = 225 MeV* and *W = 0.15 MeV*, respectively. With Talys computer codes in a short time the cross section was decomposed into: 1) compound, direct and pre-equilibrium processes and 2) discrete and continuum processes. Pre-equilibrium processes can be neglected. Talys calculations are compared with existing experimental data from [4] (see Table 1). These decompositions were suggested by the following results on the measurements of the FB effect at 5 and 6 MeV, respectively [4].

Table 1. Talys evaluation of $^{147}Sm(n,\alpha)^{144}Nd$ cross section compared with experimental data

E_n [MeV]	Direct [mb] (Talys)		Compound [mb] (Talys)		Dir+Comp (Talys) [mb]	Experimental Data [10]
	Discr	Cont	Discr	Cont		Cross section [mb]
5	0.00097	0.00787	0.05023	0.11627	0.1754	0.023±0.0023
6	0.00248	0.02951	0.03379	0.14606	0.2118	0.029±0.0029

We have also evaluated the differential cross section of $^{147}Sm(n,\alpha)^{144}Nd$ reaction for 5 and 6 MeV, respectively. The differential cross section also was decomposed into compound and direct processes. The pre-equilibrium processes were neglected. The results are shown in Figures 3, 4 and are obtained with Talys standard input like in Figure 2.

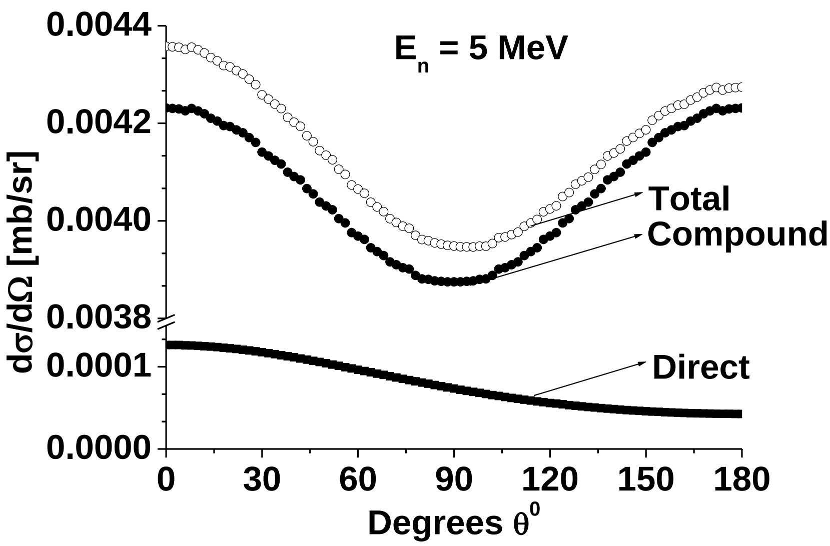

Figure 3. Differential cross section of $^{147}Sm(n,\alpha)^{144}Nd$ reaction with contribution of direct and compound processes for incident neutrons with 5 MeV.

From Figures 1, 3, 4 and Table 1 it results that the compound processes are dominant but their contribution is decreasing with energy as it is expected lefting place to the direct and pre-equilibrium processes.

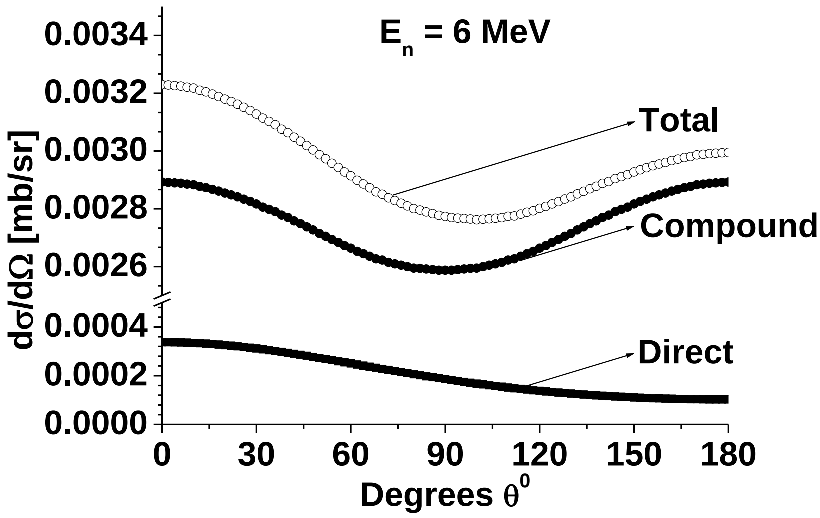

Figure 4. Differential cross section of $^{147}Sm(n,\alpha)^{144}Nd$ reaction with contribution of direct and compound processes for incident neutrons of 6 MeV.

In the reference [4] interesting results on the FB ratio for 5 and 6 MeV which are sensibly greater than 1 were obtained. The FB effect is the ratio between the number of all events in forward ($0<\theta<90^0$, $0<\phi<360^0$, θ, ϕ = polar, azimuth angle) and backward directions ($90<\theta<180^0$, $0<\phi<360^0$) relative to the direction of incident neutrons [4]. The results of FB ratios [4] are presented in Table 2 and they suggest a higher contribution of direct and pre-equilibrium processes compared with compound ones. In Table 2 there are as well our Talys evaluation of FB ratio for the same energies based on the results from Figures 3 and 4. Our results of FB ratios are much closer to 1 indicating at those energies that the cross sections is given almost entirely by the compound processes.

Table 2. The FB ratios for $^{147}Sm(n,\alpha)^{144}Nd$ reaction

E_n [MeV]	S_F/S_B (Talys)	$(S_F/S_B)_{exp}$
5	1.0122±0.0096	1.65±0.165
6	1.0436±0.0127	2.54±0.254

The cross sections of (n,p) and (n,γ) processes for the $^{147}Sm(n,\alpha)^{144}Nd$ reaction and the cross sections of (n,p), (n,γ), (n,α) reactions on ^{64}Zn, ^{143}Nd nuclei were evaluated with Talys too and these results will be presented in future works.

DISCUSSION AND CONCLUSIONS

The cross section of $^{147}Sm(n,\alpha)^{144}Nd$ reaction from slow neutrons up to 500 keV is well described by the computer programs realized by us and they showed that the compound processes are dominant. The compound processes remain dominant up to a few MeV but their effect is decreasing with energy being replaced mainly by the direct processes. In order to evaluate the contribution of other nuclear mechanism processes the cross sections with the help of Talys (with standard input) were calculated. We have separated the contributions of direct, pre-equilibrium and compound processes having a good agreement between theoretical and experimental data. The good description of the (n,α) cross section leads to the idea that the differential cross section is enough well described. This was in some degree not confirmed because a sensible difference between theoretical and experimental values of FB ratios. For the clarifying of the difference between theoretical and experimental FB ratios it is necessary: 1) to analyze more detailed the contribution of direct and pre-equilibrium processes and the experimental data on FB ratios; 2) to obtain new experimental data on FB ratios and cross sections for more energies of incident neutrons.

The present and future results obtained are of a great interest for fundamental and applicative researches and all these mean new data for nuclear structure, reaction mechanism, astrophysics, material sciences and others.

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