Non-Statistical and Asymmetry Effects in Fast Neutrons Reactions

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Abstract. Cross sections and strength functions in neutron reactions on ^{147}Sm were evaluated from slow and resonance neutrons up to MeV region. For their description the neutron resonance parameters, transmission coefficients for exit channels and the Hauser-Feshbach formalism were included. The theoretical evaluations are performed by using Talys free software and author's computer programs. The obtained cross sections and strength functions are compared with experimental data in order to explain possible non- statistical effects reported previously by some authors on the distributions of alpha widths.

INTRODUCTION

Fast neutrons reactions with emission of charged particles like protons and alpha particles are of interest for fundamental and applicative researches. For fundamental investigations, nuclear processes induced by fast neutrons provide new data on nuclear reactions mechanisms, structure of atomic nuclei, parameters of optical potential, levels density and spacing. Related to applicative studies fast neutrons processes are important for material sciences, nuclear technologies, neutrons activations analysis, tagged neutrons method, astrophysics, etc. [1, 2].

Fast neutrons reactions on medium and heavy nuclei are investigated for a long time in LNF JINR, Dubna, and became traditional due to accumulated experience, human resource and existence of necessary devices and facilities [3].

In the present work ^{147}Sm(n,α)^{144}Nd process induced by fast neutrons was investigated in a wide incident neutrons energy range starting from keV's region up to 20 MeV. Cross sections, asymmetry effects and alpha strength functions were evaluated using own and dedicated computer codes. Asymmetry effects and strength functions results are qualitatively explained considering changing of radius and parameters of potential in entrance and emergent channels respectively.

THEORETICAL BACKGROUND

The (n,α) reaction on ^{147}Sm nucleus with neutrons energy from keV up to 20 MeV can be described in the frame of statistical model of nuclear reactions and therefore cross sections are obtained applying the Hauser-Feshbach approach. In this case cross section has the form [4]:

$$\sigma_{n\alpha} = g\pi\lambda\!\!\!^{-}{}_n^2 \frac{T_n T_\alpha}{\sum_c T_c} W_{n\alpha}, \qquad (1)$$

where T is transmission coefficient; g is statistical factor; $\lambdabar_n$ is reduced neutron wavelength; $W_{n\alpha}$ is width fluctuation correction factor.

Transmission coefficients were evaluated using quantum mechanical approach based on reflection factor [5, 6]. Sum on the denominator is over all open energetic possible channels together with momentum and spin conservations. Width fluctuation correction factor, $W_{n\alpha}$, was evaluated using Moldauer approach [7, 8].

In the fast neutrons energy range direct and pre-equilibrium mechanisms give their contribution to the cross section also. For this reason Talys codes were used. This freeware soft, working mainly under Linux is dedicated to nuclear reactions and structure of atomic nuclei calculations. In Talys are implemented compound, direct and pre-equilibrium nuclear reaction mechanisms together with nuclear data of optical potential, nuclear density and levels spacing for a large number of nuclei and isotopes [9].

Another physical parameter of interest is the strength functions. Strength functions, as function of energy (E), momentum (J) and parity (Π), are related to transmission coefficients by a proportional factor and they are defined as [10]:

$$S(E,J,\Pi)=\frac{T(E,J,\Pi)}{2\pi}. \tag{2}$$

RESULTS AND DISCUSSIONS

For the evaluation of ^{147}Sm(n,α)^{144}Nd cross section starting from 0.5 keV up to 500 keV Hauser-Feshbach formalism were used. It was realized a computer program which calculates transmission coefficients using quantum mechanical approach and were considered all open channels. In this energy range were considered only compound processes. Experimental results from [10] were described very well. Results are shown in Fig. 1.

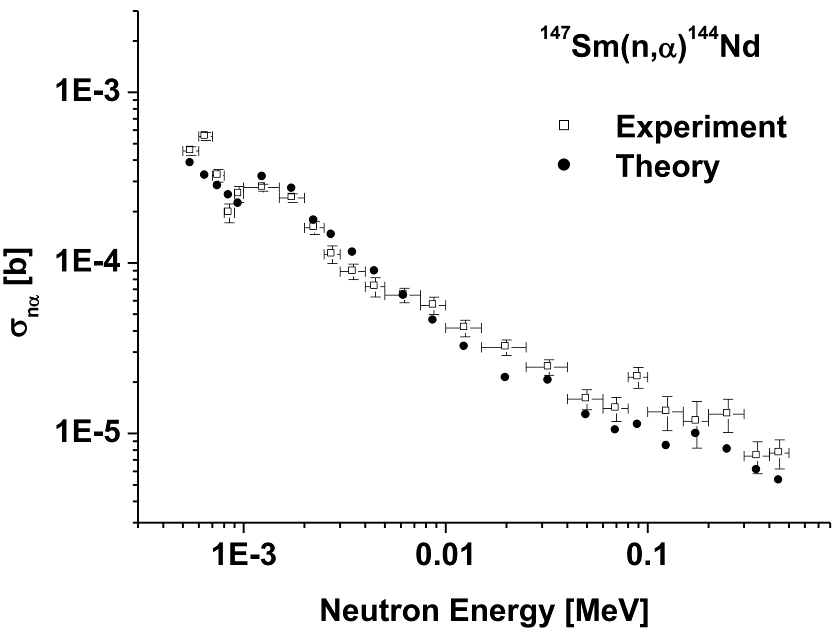

Fig. 1. Theoretical and experimental cross sections of ^{147}Sm(n,α)^{144}Nd reaction.

In the evaluation it was taken a rectangular optical potential, U = V + I·W, with real and imaginary part in the incident and emergent channels. Radius channel has the usual expression $R = R_0 \cdot A^{1/3}$ [fm] (R_0 = 1.45 fm, A is atomic mass). At 1 keV, in the alpha channel, real part of optical potential was V_α = 225 MeV and imaginary part, W_α = 0.15 MeV. With the increasing of the energy, up to 450 keV, in order to describe experimental data, V_α was also increased slowly with about 15%. Calculations result that the experimental data are not so sensible to parameters of optical potential and channel radius in entrance channel.

For neutrons energy interval from 0.45 MeV up to 20 MeV cross sections were calculated with the help of Talys. In comparison with our soft (results from Fig. 1) in Talys the optical potential is of Wood-Saxon form, with real and imaginary part, with the following components: volume, surface and spin-orbital [9]. Also, in the Talys calculations, compound, direct and pre-equilibrium mechanisms were enabled together with discrete and continuum states of residual nuclei. Results are shown in Fig. 2 a) and b).

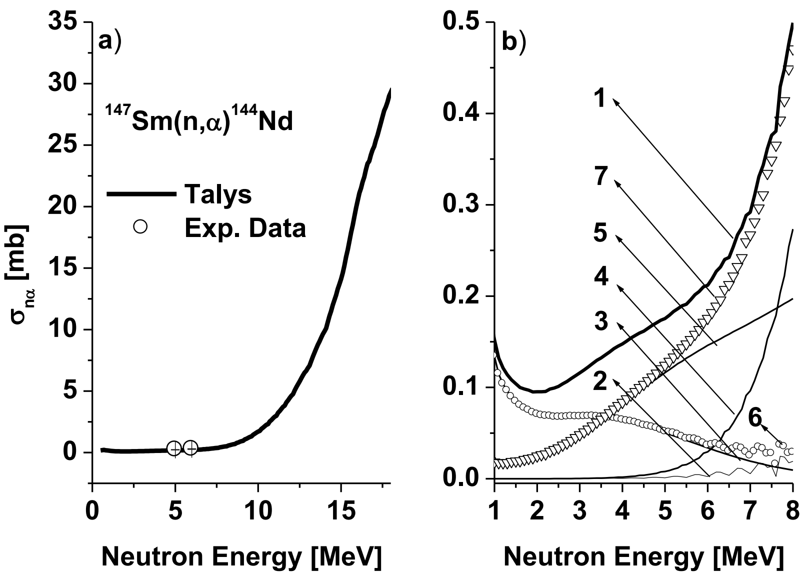

Fig. 2. Fast neutrons cross sections of $^{147}Sm(n,\alpha)^{144}Nd$ reaction. a) Comparison of Talys evaluations and experimental data (2 points – 5 and 6 MeV). b) Contribution to the cross section of direct and compound processes together with discrete and continuum states of residual nucleus. 1– total (n,α) cross section (1 = 2 + 3 + 4 + 5 = 6 + 7); 2 – Discrete states + Direct processes; 3– Discrete + Compound; 4 – Continuum + Direct; 5 – Continuum + Compound; 6 – Discrete + Direct + Compound; 7 – Continuum + Direct + Compound.

In Fig.2a theoretical evaluations are compared with experimental data obtained by us at 5 and 6 MeV respectively and a very good agreement was obtained. Up to 7–8 MeV compound processes are dominant. Lower than 1 MeV discrete states are dominant but with the increasing of incident energy continuum states become more important and higher than 8 MeV discrete states can be neglected (see Fig. 2b).

The above analysis it is important because at 5 and 6 MeV a forward–backward effect (FB) was observed [11]. FB effect is defined as the ratio of all registered forward and backward events, $S_{FB} = A_F/A_B$, where $A_{F,B}$ is:

$$A_F(E_n) = 2\pi \int_0^{\pi/2} \phi_n(E_n)\sigma_{n\alpha}(E_n,\theta)\sin(\theta)d\theta, \; A_B(E_n) = 2\pi \int_{\pi/2}^{\pi} \phi_n(E_n)\sigma_{n\alpha}(E_n,\theta)\sin(\theta)d\theta, \quad (3)$$

where θ is polar angle; $\sigma_{n\alpha}(E_n, \theta)$ is differential cross section of (n,α)-reaction; $\phi_v(E_n)$ is neutrons incident flux.

Using (n,α) differential cross sections, relation (3), neglecting the loss of alpha particles in the target (tin target) and a neutron flux proportional with $1/E_n^{0.9}$ the FB effect for 5 and 6 MeV was calculated. Results are given in Table 1.

Table 1. ^{147}Sm(n,α)^{144}Nd cross section with evaluated and experimental FB effect

E_n [MeV] [I]	Direct [mb] Talys		Compound [mb] Talys		Total Talys [mb] [VI]	S_{FB} Talys [VII]	S_{FB} Exp [VIII]
	Discr [II]	Cont [III]	Discr [IV]	Cont [V]			
5	0.00097	0.00787	0.05023	0.11627	0.1754	1.0122±0.0096	1.65±0.165
6	0.00248	0.02951	0.03379	0.14606	0.2118	1.0436±0.0127	2.54±0.254

In Table 1, columns II, III, IV and V are the cross sections for 5 and 6 MeV with the contribution of direct and compound processes related to discrete and continuum states of the residual nuclei calculated with Talys. Column VI is the sum of column II to V and these theoretical values are in good agreement with experimental data. From Table 1 results that the direct processes are not dominant at 5 and 6 MeV but they will become important at higher energies quite quickly. Considering these facts the experimental FB effects from column VIII are to large in comparison with theoretical evaluations (column VII) and they can not come from direct processes as suggested by authors of [11] naming them as non-statistical effects. This discrepancy can be explained taking into account that at fast neutrons energies many emergent channels with participation of alpha particles are open. Further the measurements were done with a double gridded ionization chamber and the resolution of registered alpha particles is of order of 200 keV which also could influence the final results of experiments.

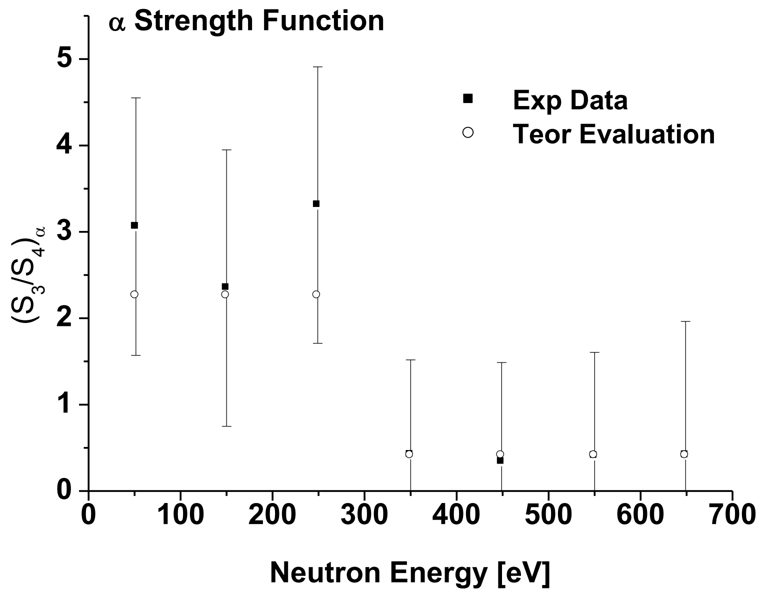

Fig. 3. Alpha strength function. Theory and experiment.

In the resonance region of ^{147}Sm(n,α) reaction, ratios of alpha strength functions, S_3/S_4, corresponding to the spin of compound nucleus $J = 3, 4$ where measured [10]. It was expected that alpha strength ratios to be constant with energy (as predicted by theory) but around 300 eV the ratio is abruptly decreasing. Experimental data on alpha strength ratios from [10] are compared with our theoretical evaluations (see Fig. 3). In [10] the decreasing was explained once again by the presence of non-statistical effects. In the given spin channel of the compound nucleus the averaged strength function was calculated as sum of transmission coefficients considering spin and momentum conservation. Calculations were realized with our soft, taking into account all possible channels and rectangular optical potential with real and imaginary part $U = V + I \cdot W = 225$ MeV $+ I \cdot 0.15$ MeV. The agreement between theoretical and experimental data was obtained by varying the radius of alpha channels with about +20%. According to theory a very low component of direct processes can exist in principle in the resonance region but this cannot explain the ratio decreasing. Another explanation can come also from the fact that in the hundreds of eV energy range there are present other channels including alpha particles. Furthermore experimental data have large errors which are coming from the low values of the cross sections (of order of 0.01 b) combined with high background.

CONCLUSIONS

Cross sections and angular distributions of ^{147}Sm(n,α)^{144}Nd reaction were calculated in a wide energy range, from 0.5 keV up to 20 MeV using own computer codes and Talys software. Also, FB effect for 5 and 6 MeV together with alpha strength ratios in the resonance region were evaluated. Cross sections, FB effect and alpha strength function ratios were compared with experimental data. In the case of (n,α) cross sections a good agreement between theory and experiment was obtained and the contribution of different nuclear reaction mechanisms given by discrete and continuum states of residual nuclei was also extracted. Differences between experimental and theoretical FB effect and alpha strength function ratios was explained mainly by the presence of other open channels involving alpha particles concurring with investigated (n,α) one because it was demonstrated that the direct component is low in comparison with compound processes for the mentioned incident neutrons energy values.

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