Neutron capture cross sections and strength functions on ^{147}Sm

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Abstract
Cross sections and strength functions in neutron induced reactions on ^{147}Sm nucleus from slow neutrons up to 15 - 20 MeV's were evaluated. The neutron resonance parameters, transmission coefficients and the Hauser – Feshbach formalism were included in the calculations. In the MeV's region 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 alpha widths distributions.

1 Introduction

Cross sections, asymmetry effects and strength functions at the EG-5 and IREN basic facilities of FLNP - JINR by using a double gridded ionization chamber were regularly measured in the last decade. By recent measurements cross sections for 5 and 6 MeV of ^{147}Sm (n,α) reaction were obtained. Because the values of the cross sections are very low (hundreds of microbarns) their measurements are very difficult. The cross sections experimental data are very well described by the theoretical model evaluations performed in this study [1,2].

Capture processes of neutrons with emission of charged particles, starting from thermal region up to 14 MeV, on ^{147}Sm, were analyzed. Cross sections for (n,α) reactions, from slow neutrons up to some MeV's, in the frame of Hauser – Feshbach formalism (HFF), were evaluated using computer codes realized by authors [3]. The main element of HFF is represented by the transmission coefficients for incident and emergent channels. Transmission coefficients were calculated by applying a quantum-mechanical approach based on reflection factor [3,4].

Starting from 0.5 MeV up to 14 MeV, a separation in the contribution of different nuclear reaction mechanisms related to discrete and continuum states were realized with the help of Talys computer codes. It was demonstrated that the main contribution to the cross sections is given by compound nucleus processes followed by direct processes. Also, nuclear data as parameters of optical potential, nuclear states densities and other were extracted.

The computed cross sections and strength functions are compared with experimental data in order to explain possible nonstatistical effects reported previously by some authors on the distributions of alpha widths.

2 Theory and codes

Compound processes can be described in the frame of the statistical model of nuclear reactions. Main assumptions of statistical approach are: a) by interaction of incident particle with target nucleus a compound nucleus (CN) is formed; b) CN time of life is much larger than the time necessary to incident particle to pass the target nucleus; c) CN decays on one possible channels and "forget" how it was formed (Bohr hypothesis); d) CN and residual nucleus are characterized by a great number of states; e) nuclear potential acts in a finite range and is zero outside. These assumptions lead to the following consequences: 1) no interference terms in the cross section; 2) differential cross section is symmetrical relative to 90^0 in the center mass system [5,6]. In this case, for a binary nuclear reaction, A(a,b)B, according to Hauser – Feshbach approach the cross section has the [7]:

$$\sigma_{ab} = g\pi \lambda\!\!\!^{-}{}_a^2 T_a T_b W_{ab} [\sum_c T_c]^{-1}, \quad (1)$$

where: g= statistical factor; ƛ= reduced wave length; T= transmission coefficient; W_{ab}= width fluctuation correction factor.

Transmission coefficients are defined as the probability of a particle to pass a potential barrier. This parameter can be calculated using the Gamow factor or applying a quantum mechanical approach based on the reflection factor [4].

Widths fluctuation correction factor, W_{ab}, represents the correlation between incident and emergent channels. When Bohr hypothesis is working, W_{ab}=1 and is slowly decreasing with the increasing energy of incident particle. There are a few ways to calculate $W_{ab,}$ but for evaluations, the authors have chosen the Moldauer expression [8].

For the evaluation of compound processes contribution to the cross section a computer code was created based on the Hauser – Feshbach formalism and quantum mechanical approach for transmission coefficients calculations. Previous results on (n,α) reactions are in [1,3].

The contributions of direct and pre-equilibrium processes to the cross sections, considering continuum and discrete states of residual nuclei, were evaluated with Talys, which is a dedicated software to nuclear reactions and structure of atomic nuclei calculations [9]. For strength function evaluation (S), the definitions from reference [2] are used. Then the strength function is:

$$S = \langle\Gamma\rangle / D = T / 2\pi, \quad (2)$$

where: <Γ>= averaged width; D= average level spacing.

Expression (2) demonstrated the relation between strength function and transmission coefficients. Furthermore, strength functions describe how widths are distributed in the nucleus.

Spectra of emitted alpha particles in $^{147}Sm(n,\alpha)^{144}Nd$ reaction from a target with a given thickness have been realized by Monte Carlo modeling. Angular correlation is simulated by using the direct method. Solving the following integral equation the current polar angle θ_c is extracted:

$$\frac{\int_0^{\theta c<\pi} [p_0 + p_1 \cos\theta + p_2 (\cos\theta)^2] \sin\theta d\theta}{\int_0^{\pi} [p_0 + p_1 \cos\theta + p_2 (\cos\theta)^2] \sin\theta d\theta} = r \in [0,1), \quad (3)$$

where: p_1, p_2, p_3= coefficients; θ= polar angle; θ_c= current polar angle; r= random number.

Stopping power of alpha particles in the Samarium target was determined using SRIM & TRIM free software [10].

3 Results and discussion

Nuclear reaction $^{147}Sm(n,\alpha)^{144}Nd$ (Q=10.128 MeV) induced by incident neutrons with energy starting from 0.5 keV up to 20 MeV had been analyzed. Using the soft created by authors the (n,α) cross sections, from 0.5 keV up to 0.5 MeV were calculated. Results are shown in the Fig. 1 and are compared with experimental data [11]. In the calculations, a nuclear potential, U = V + iW, with real and imaginary parts, is considered. Spin and parity of target and compound nucleus are: for ^{147}Sm - $(7/2)^+$ and for ^{148}Sm - 3^-, 4^-, respectively. Ten discrete levels of residual nucleus were taken into account. In the mentioned incident neutrons energy interval the compound nucleus mechanism was considered.

Real and imaginary parts of nuclear potential in the incident and emergent channels have the following values: V_n= 65 MeV, W_n= 0.15 MeV, V_α= 225 MeV, W_α= 0.15 MeV. The results are not very sensible to the imaginary part for neutrons and alphas. The real part of potential, V_α, is increasing with about 15% from 0.5 up to 500 keV neutron energies.

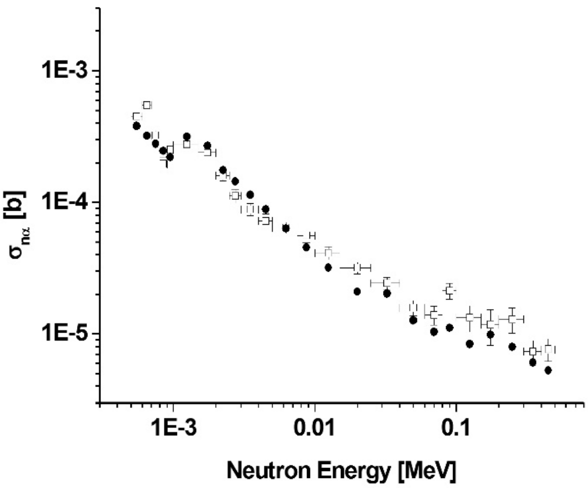

Fig. 1. ^{147}Sm(n,α)^{144}Nd cross section. □- Experiment. ●- Theory

For energies higher than 0.5 keV the cross sections were calculated with Talys because for fast neutrons the contributions of direct and pre-equilibrium processes become significant. In Fig. 2a a separation between nuclear reaction mechanisms correlated with discrete and continuum states of the residual nuclei was realized. They are compared with experimental data from Fig. 2b and a good agreement can be observed between them. In Table 1 the results for experimental data at 5, 6 MeV are shown [12].

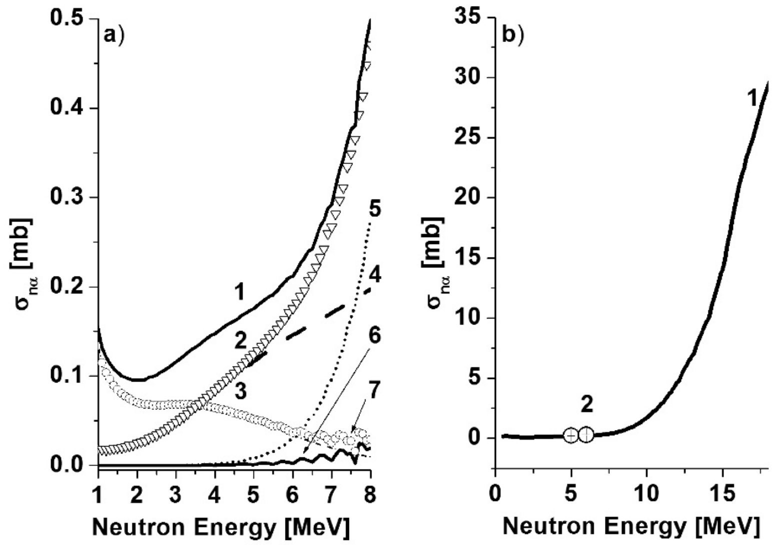

Fig. 2. ^{147}Sm(n,α)^{144}Nd cross section. Talys calculations: a) Separation between mechanisms related to discrete and continuum states. 1- All contributions from 2 to 7; 2- Continuum states & Direct + Compound processes; 3- Discrete states & Direct +Compound; 4- Continuum & Compound; 5- Continuum & Direct; 6- Discrete & Compound; 7- Discrete & Direct. b) 1- Talys evaluation; 2- Experimental data

Table 1. Contribution of reaction mechanisms and states of residual nucleus

E_n [MeV]	Direct [mb]		Compound [mb]		$\sigma_{n\alpha}$ [mb]	$(\sigma_{n\alpha})_{exp}$ [mb]
	Discrete	Continuum	Discrete	Continuum		
5±0.16	0.00097	0.00787	0.05023	0.11627	0.1754	0.23±0.023
6±0.12	0.00248	0.02951	0.03379	0.14606	0.2118	0.28±0.028
15	0.04970	1.57825	0.00156	0.26330	1.89201	-

From Table 1 and Fig. 2b it is shown that up to 8 - 10 MeV the compound processes are dominant, but higher than 10 MeV the direct mechanism becomes important. With the increasing of incident energy, the contribution to the cross section of the continuum states is also increasing in comparison with discrete ones. For 15 MeV there are no experimental data and it can be observed that direct processes and continuum states give the main contribution to the cross section.

The experimental data for $^{147}Sm(n,\alpha)^{144}Nd$ fast neutron process are poor because: a) cross section values are very small; b) low intensity of incident deuterons beam with energy of about 2 - 4 MeV, necessary to produce fast neutrons in $^{2}H(d,n)^{3}He$ reaction; c) high background due to the presence of open channels involving alphas in $^{147}Sm(n,\alpha)^{144}Nd$ reaction [12].

Differential cross sections in the fast neutron energy range were evaluated by Talys. In the Figs. 3a - c the contributions of direct and compound mechanisms for 5, 6, and 15 MeV are shown. In [12] a forward – backward asymmetry effect was measured. This effect was defined as the ratio between the number of forward and backward events. In the case of a point target the ratio is:

$$A_{FB} = N_F/N_B = \int_0^{\pi/2} \sigma(\theta) \sin\theta \, d\theta \Big/ \int_{\pi/2}^{\pi} \sigma(\theta) \sin\theta \, d\theta, \qquad (4)$$

where: $N_{F,B}$ = events in forward and backward directions; $\sigma(\theta)$= differential cross section.

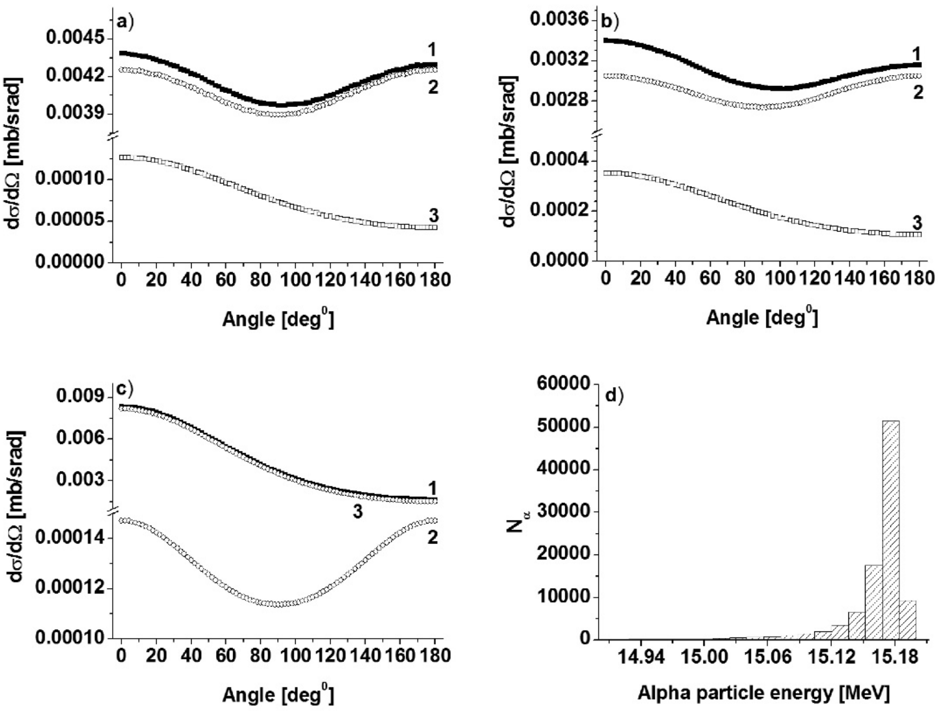

Fig. 3. Differential cross section a) 5 MeV; b) 6 MeV; c) 15 MeV d) alpha spectra for E_n = 5 MeV, 100000 events, 5 mg/cm^2 target thickness. Curves: 1 - sum of compound and direct processes; 2 - compound processes; 3 - direct processes

Using the obtained results on cross sections and angular distribution, considering a 5 mg/cm^2 thickness target and alpha particles stopping power, the forward – backward effect was calculated by two methods. In the first way, Talys results and relation (4) was applied. The alpha particles lose in the target was neglected. In the second way, a direct Monte Carlo simulation was realized, based on relation (3) and a finite dimensions target. Both theoretical results and experimental measurements on forward – backward effect are presented in Table 2 for 5, 6 and 15 MeV, respectively.

From Figs. 3a - c at 5 and 6 MeV, compound processes are dominant in comparison with the 15 MeV case. It is expected that the asymmetry generated by the direct component is small for 5 and 6 MeV and significant at 15 MeV.

Table 2. Forward – backward effect: 1) Talys; 2) Simulation; 3) Experimental

E_n[MeV]	$(A_{FB})_{Talys}$	$(A_{FB})_{MC}$	$(A_{FB})_{exp}$
5	1.0122 ± 0.0096	1.02 ± 0.007	1.65 ± 0.165
6	1.0436 ± 0.0127	1.04 ± 0.009	2.54 ± 0.254
15	2.342 ± 0.008	2.31 ± 0.017	-

Experimental data on asymmetry from Table 3 are much higher than the theoretical evaluations. At 15 MeV there are not experimental data on forward – backward effect. The authors from [12] tried to explain such an unexpected high asymmetry effect by the presence of the so-called non-statistical effects. Taking into account the present theoretical evaluations, the experimental results from Table 2 can be explained by the presence of other emergent channels involving alpha particles. Very low value of (n,α) cross section in fast neutrons energy range makes difficult the separation of "α+^{144}Nd" channel in the measurements.

Theoretical results evaluated with Talys were obtained in the frame of the constant temperature Fermi gas model for nuclear states density and optical potentials with real and imaginary parts (volume-central (V), surface-central (D), spin-orbit (SO)) for incident (n) and emergent (α) channels [9]. In Table 3 the nuclear potential parameters are shown.

Table 3. Parameters of optical potential. Parameters of surface-central potential are not shown

	Volume central Real			**Volume central Imaginary**			**Spin orbit Real**			**Spin orbit Imaginary**		
	V [MeV]	**r_v [fm]**	**a_v [fm^{-1}]**	**W [MeV]**	**r_W [fm]**	**a_w [fm^{-1}]**	**V_{so} [MeV]**	**r_{vso} [fm]**	**a_{vso} [fm^{-1}]**	**W_{so} [MeV]**	**r_{wso} [fm]**	**a_{wso} [fm^{-1}]**
n	49.81	1.227	0.656	0.11	1.227	0.656	6.18	1.063	0.59	-0.01	1.063	0.59
α	226.25	1.227	0.657	0.38	1.227	0.657	0	1.071	0.59	0	1.071	0.59

In reference [2] strength functions ratio (S_3/S_4) in ^{147}Sm(n,α)^{144}Nd reaction for incident neutrons from 3 eV up to 700 eV were measured. In the process the compound nucleus ^{148}Sm is formed characterized by spin and parity $J^{\Pi}=3^{-},4^{-}$, respectively. Experimental results from [2] and calculations realized by our program are presented in Fig. 4.

It is expected that strength functions have to be constant with energy [2]. At 300 eV an evident decreasing is observed (Fig. 4). The authors of [2] tried to explain the results of measurements like in [12], by the presence of non-statistical effects.

Using the relation (3), quantum mechanical approach for the calculation of transmission coefficients, optical potential U = V+iW, and radius channel $R = R_0A^{1/3}$ [fm] (R_0 = 1.45 fm, A = atomic mass number), we have described the experimental data, by increasing the alpha radius channel with about 20% higher 300 eV. The optical potential for alpha channel was U = (225+I 0.45) MeV. Other explanations for the above results could be the following: a) large errors in alpha strength functions ratio; b) the presence of alpha particles from other channels; c) compound nucleus ^{148}Sm is an even-even nucleus and therefore it is of interest to search emission of complex particles larger than alpha.

4 Conclusions

Cross sections, forward-backward effects, alpha spectra and strength functions were obtained using own codes and Talys software in ^{147}Sm(n,α)^{144}Nd reaction. Cross section experimental and theoretical data are in good agreement. The concurrence of reaction mechanisms related to residual nucleus states is reflected. For the forward - backward and strength functions ratios experimental data, new explanations were proposed. Further data (cross sections, angular distributions), in a wide energy range are necessary. Improvements of computer simulations, strength functions evaluations correlated with nuclear reaction mechanism analysis are planned. Present results on ^{147}Sm(n,α) process were realized in the frame of FLNP JINR Dubna thematic plan and are proposals for future measurements at FLNP basic facilities.

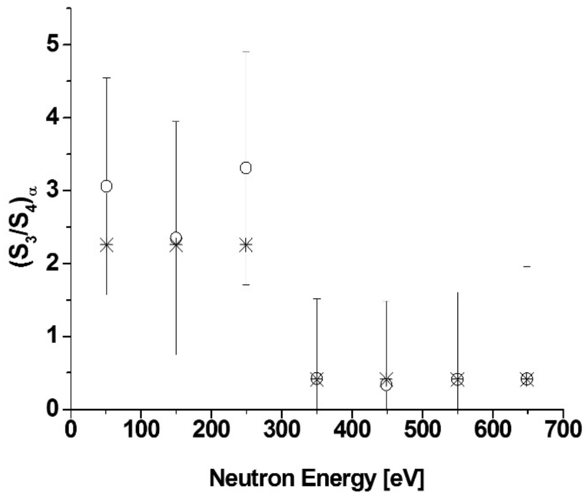

Fig. 4. Alpha strength functions ratio: Circle – measurements; Star – theoretical evaluations

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