ALPHA EMISSION IN FAST NEUTRONS REACTION ON NEODYMIUM NUCLEUS

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Cross section, angular correlations and asymmetry effects in ^{143}Nd$(n,\alpha)^{140}$Ce process induced by fast neutrons with incident energies starting from 0.5 MeV up 25 MeV were investigated. Theoretical evaluations and modeling of (n,α) observables were realized with Talys combined with computer codes realized by authors. Contribution in the cross section and angular correlation of nuclear reaction mechanism were also determined. Cross section experimental data and theoretical evaluations are in a good agreement but similar comparison of forward – backward asymmetry effect results for few MeV neutrons energy revealed large discrepancy. The done calculations and computer modeling have demonstrated that the large asymmetry effect observed in the experiment cannot be explained by direct mechanism, rather the difference is coming from the presence of other open channels with participation of alpha particles. The results of present work were obtained in the frame of the fast neutrons scientific program of FLNP JINR Dubna.

INTRODUCTION

Nuclear reactions induced by the fast neutrons are for many years investigated at FLNP JINR Dubna. The fast neutron processes are of a great importance in fundamental and applicative researches. For theoretical investigations they represent an efficient tool in the investigation of nuclear reaction mechanism and structure of atomic nuclei. In the field of applicative researches the fast neutrons reactions offer precise nuclear data for fission and fusion reactors, reprocessing of Thorium and Uranium for nuclear transmutation, Accelerated Driven Systems projects and for Fast Neutrons Activation as a complementary method of Instrumental Neutron Activation Analysis with thermal and epithermal neutrons [1,2].

Neodymium is a chemical element with number of protons, $Z = 60$. This nucleus has five stable isotopes with atomic mass A= 142, 143, 145, 146, 148 and two long-lived isotopes with A= 144, 150. Isotopes of Neodymium are used in many applications such as manufacturing of powerful permanent magnets or in the Samarium–Neodymium dating as geochemical tracers and others [3,4].

In the present work nuclear process induced by fast neutrons with energies starting from 0.5 MeV up to 25 MeV on ^{143}Nd stable nucleus followed by the emission of charged alpha particles will be investigated (^{143}Nd$(n,\alpha)^{140}$Ce reaction).

ELEMENTS OF THEORY

Analysis of fast neutrons induced process on ^{143}Nd nucleus starts with the cross sections evaluations. In the theoretical calculations direct, compound and pre-equilibrium nuclear reactions mechanisms are considered. The direct processes are described by the Distorted Wave Born Approximations (DWBA), the compound processes are described in the frame of the statistical model of nuclear reactions and pre-equilibrium by the two exciton approach

[5–7]. The cross section of the (n,α) process with fast neutrons can be described in the frame of Hauser-Feshbach approach and has the following expression [6]:

$$\sigma_{n\alpha}\left(E_n\right)=g\pi\lambda\!\!\!^{-}{}_n^2 T_n T_\alpha W_{n\alpha}\left[\sum_c T_c\right]^{-1} \tag{1}$$

where $T_{n,\alpha}$ are the transmission coefficients in the incident and emergent channels respectively; g is the statistical factor; $\lambda\!\!\!^{-}{}_n =$neutron reduced wave number; $W_{n\alpha}$ is the width fluctuation correction factor. In the sum of relation (1) are considered all open channels (c).

Width fluctuation correction factor, $W_{n\alpha}$, represents the correlation between incident and emergent channels. At low incident energies this coefficient is equal with one indicating no correlation between neutron and alpha channels (Bohr hypothesis of compound nucleus is working). With the increasing of the incident energy width fluctuation correction factor is slowly decreasing. There are few way for the calculation of fluctuation factor but in this work is used the method described in [8].

Transmission (or penetration) coefficient represents the probability of particles to pass a potential barrier. Usual transmission coefficient is lower than one, is increasing with incident energy and is constant at high energies. There are some methods in the evaluation of transmission coefficient and for this work the quantum mechanical approach (based on reflection factor) described in reference [9] was used.

In the case of (n,α) reaction with fast neutrons of few MeV, Hauser-Feshbach formalism was implemented by authors, considering a rectangular nuclear potential and ten levels of residual nucleus. Also, in the given incident neutrons energy intervals, the all open channels such as elastic, inelastic, protons and gamma were considered in the realized computer code [10].

For the cross sections and angular correlations from 0.5 MeV up to 25 MeV evaluation, Talys code was used [11]. A very useful database including parameters like levels energy, spin, parity, time of life, levels density for more than 2000 of stable nuclei and isotopes are implemented in the software database. The parameters of Woods-Saxon potential (with components volume, central and spin-orbit with real and imaginary part), extracted mainly from experimental data for many nuclei and channels are also included [11].

RESULTS AND DISCUSSIONS

Target nucleus ^{143}Nd is stable and has the spin and parity J^{Π} = $(7/2)^-$. In the software created by authors, in ^{143}Nd$(n,\alpha)^{140}$Ce reaction, is considered that fast neutrons have the orbital momentum l_n = 0,1. Residual nucleus ^{140}Ce has the spin and parity J^{Π} = 0^+. Heat of reaction for ^{143}Nd$(n,\alpha)^{140}$Ce process is Q = 9.72 MeV [3]. In the frame of quantum mechanical approach neutrons and alpha transmission coefficients were calculated by our soft. Results are shown in Fig. 1. Transmission coefficients have values lower than one and with the increasing of the incident energy they are also increasing tending to a constant value. With the increasing of orbital momentum the transmission coefficient are decreasing mainly due to centrifugal potential [7].

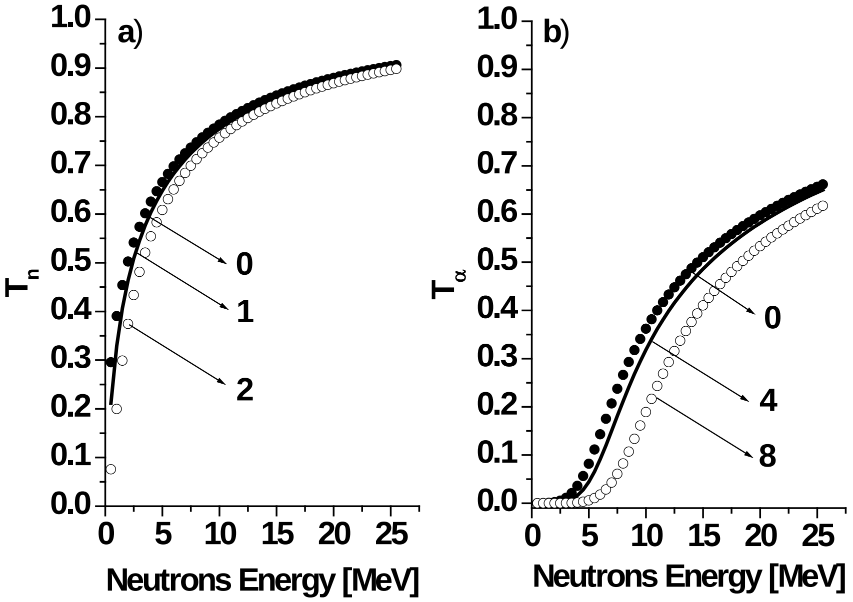

Figure 1. Transmission coefficients: a) neutrons (orbital momentum $l_n = 0, 1, 2$); b) alphas (orbital momentum $l_\alpha = 0, 4, 8$).

Neutron transmission coefficients have higher values than for alpha particles for the all incident energy interval (see Fig 1.a) and Fig 1.b)). This fact results from the presence of the Coulomb potential term in the case of alpha particles which acts like a barrier [7].

Transmission coefficients are an important term of Hauser-Feshbach cross section from relation (1). In the Fig. 2 cross section was evaluated using the author soft, considering neutrons with orbital momentum, $l_n = 0,1$, ten levels of ^{140}Ce residual nucleus, rectangular optical potential, with real and imaginary part in the incident and emergent channels ($U = V + iW = (172 + i0.1)$ MeV). Also, in the calculations, the elastic, inelastic, proton and gamma emergent channels were taken into account.

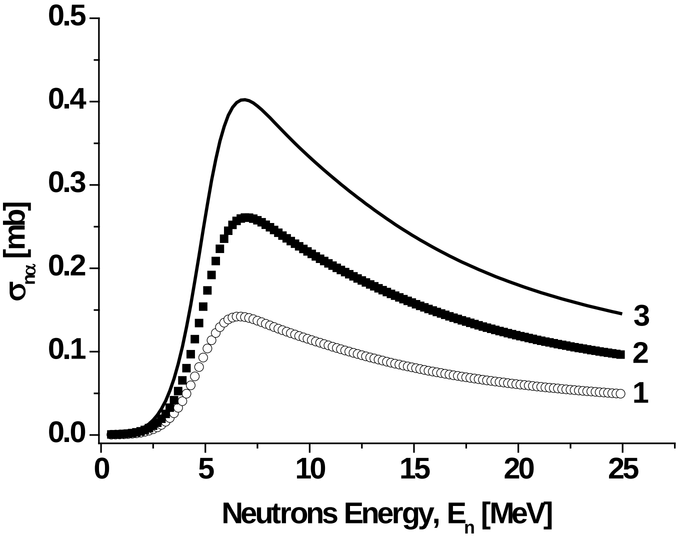

Figure 2. ^{143}Nd$(n,\alpha)^{140}$Ce cross section (XS) : 1 – neutron orbital momentum $l_n = 0$; 2 – neutron orbital momentum $l_n = 1$; 3 – XS as sum of curves 1, 2.

In Fig. 2 cross sections of ^{143}Nd(n,α)^{140}Ce fast neutrons reactions are represented. Contribution of neutrons with *0* and *1* orbital momentum are given by the curves 1 and 2, respectively. For analyzed process, cross section of orbital momentum, l_n = 1 is larger than for neutrons with l_n = 0 results which differ from the similar case of other investigated fast neutrons reactions [10]. Total (n,α) cross section is shown by the curve 3. Cross sections from Fig. 2 are increasing with energies, reach a maximum value followed by a slowly decreasing, which are the usual dependences in fast neutron reactions. Cross section of ^{143}Nd(n,α)^{140}Ce process has small values which make the experimental measurements very difficult.

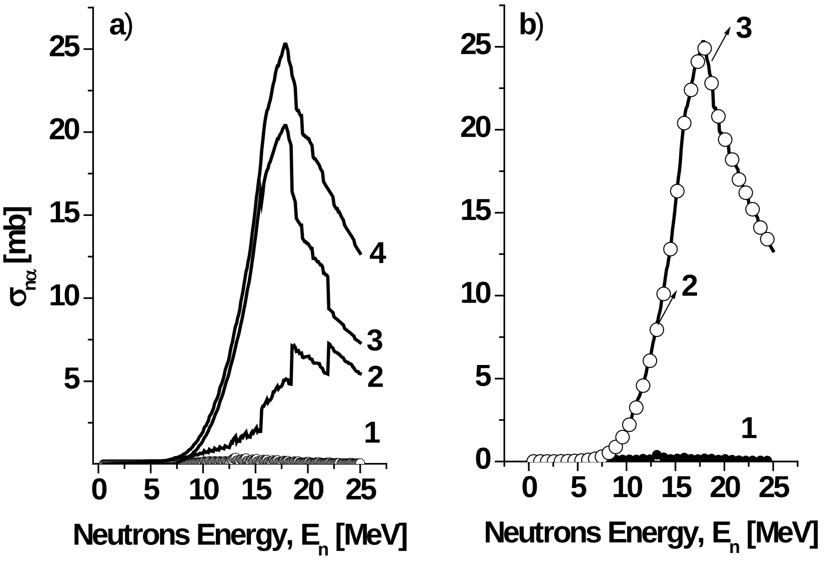

Figure 3. ^{143}Nd(n,α)^{140}Ce cross section (XS). Contribution to XS: 1 – of direct mechanism; 2– of compound mechanism; 3– of pre-equilibrium one; 4 – XS as sum of (1+2+3).

In Fig. 3 (n,α) the cross section calculated with Talys is shown. In Fig. 3.a contribution of nuclear reaction mechanisms to the cross section was obtained. Direct processes (dependence 1) have very low values and they are important at low energies. Compound processes are present in the whole energy interval (curve 2) with a consistent contribution to the cross section but pre - equilibrium multistep mechanism is the dominant one. In Fig. 3.b the (n,α) cross section is separated in contribution of discrete and continuum state of residual nucleus. Ten discrete levels of residual nucleus were taken into account (similar as in Fig. 2). At low energies the cross section is coming mainly from discrete levels (up to 7–8 MeV). At higher incident energies cross section is given by continuum states of residual nucleus. Contribution of discrete states from Fig. 2, evaluated with authors code is in good agreement with Talys calculations (Fig. 3.b – curve 1).

The evaluation of the (n,α) cross section with fast neutrons has small values, fact confirmed also in the experiment. The experimental cross section for the neutrons with the energy E_n = (4±0.23) MeV is $\sigma_{n\alpha}$ = (0.12±0.01) *mb* [12]. The cross section value obtained with author soft (Fig. 2) is $\sigma_{n\alpha}[E_n$= 4 MeV] = 0.14 *mb* and with Talys $\sigma_{n\alpha}[E_n$= 4 MeV]=0.11 *mb*. Both theoretical calculations are in a fair agreement with experimental data. The contribution of direct component cross section is $\sigma_{dir}[E_n$= 4 MeV]=0.002 *mb* and of compound one $\sigma_{n\alpha}[E_n$= 4 MeV]=0.108 *mb*. The cross section coming from discrete and continuum states of residual nucleus are $\sigma_{discr}[E_n$= 4 MeV]= 0.105 *mb* and $\sigma_{cont}[E_n$= 4 MeV]= 0.005 *mb*. At 4 MeV the main contribution to the cross section comes from the discrete states combined with the compound processes. The direct component is very low. The above results were used in the analysis of forward–backward (FB) asymmetry effects measured in the experiment. For the neutron incident energy E_n = 4 MeV, FB effect is $A_{FB}[(E_n = (4\pm0.23)] = (1.25\pm0.12)$ [12]. In the reference (12), experimental FB effect is the ratio between all forward and backward events registered by a gridded ionization chamber. Theoretical evaluation of FB effects, as defined in [12], necessitates the knowledge of the angular correlations. The differential cross section obtained using Talys is represented in the Fig. 4.

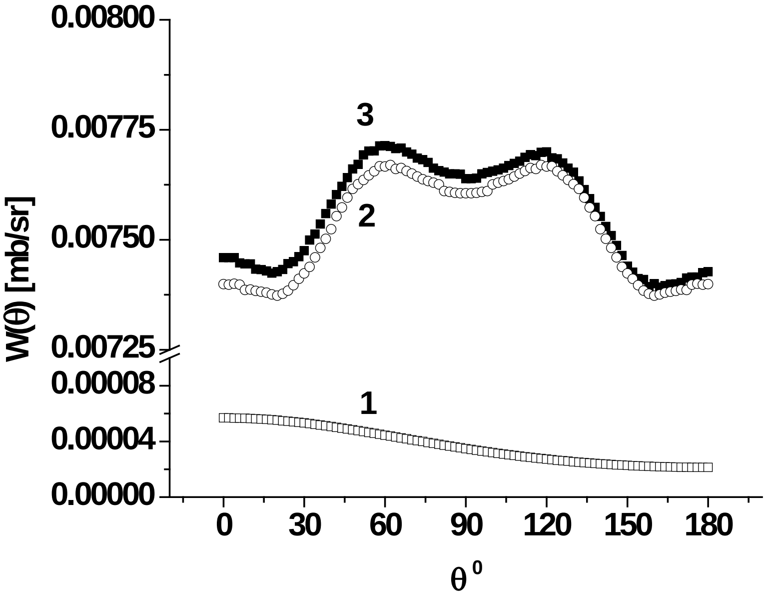

Figure 4. The differential XS of ^{143}Nd(n,α)^{140}Ce. Nuclear reaction mechanism: 1 – direct; 2 – compound one; 3 – sum of (1+2).

Using the results from Fig. 4, the FB effect was evaluated in the case of a point like target. From differential cross sections, the angular correlations were extracted. Further, the angular distribution was modeled by direct Monte-Carlo method [13]. Simulated FB effect, for 4 MeV incident neutrons is $A_{FB}^{sim} = 1.0076$. The difference between experimental FB effect theoretical and experimental data is large. The calculated direct component is very low (see Fig. 4) and in consequence the measured FB effect is also small. The discrepancy can be explained qualitatively by the influence of the other open channel with participation of alpha particles. In the investigated reaction, formed compound nucleus is an even-even one which in principle favors alpha particles emission.

In our evaluations using Talys 30 levels for residual nucleus, in the case of elastic and inelastic scattering and 10 levels in the case of reaction channels were took into account. For the density levels, Fermi gas model was chosen. In the description of experimental data a large number of the parameters of the Wood-Saxon optical potential were tested. Theoretical results are the most sensible to the variation of central volume parameter and for emergent alpha channels they are $U = V + iW = (172+0.11)$ MeV (results are practically the same obtained by authors code).

RESULTS AND CONCLUSIONS

The cross sections, angular correlations and forward – backward asymmetry effects were analyzed in the ^{143}Nd(n,α)^{140}Nd nuclear reaction induced by fast neutrons with energies starting from 0.5 MeV up to 25 MeV. The theoretical results were obtained with programs realized by authors and with Talys code. The cross section for the investigated reaction has very low values and therefore the experimental data are poor. The experimental and theoretical cross section data are in good agreement. In the case of forward – backward asymmetry effects a large differences were observed which cannot be explained by the presence of direct mechanism. The large experimental forward–backward effect in comparison with theoretical evaluations and computer modeling can be the results of the influence of other open emergent channels with participation of alpha particles but this discrepancy remains an open issue for the future. The well description of cross sections experimental data allowed to extracting new parameters of Woods-Saxon optical potential for incident neutron channels and emergent alpha channel.

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