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Angular Distribution in Fast Neutrons Induced Reactions on ^{64}Zn Isotope

C. Oprea[1], A.I. Oprea[2]

[1]*County Center for Education, 11 Mihai Eminescu, 410019, Oradea, Bihor County Romania*

[2]*Frank Laboratory for Neutron Physics, Joint Institute for Nuclear Research,*
141980 Dubna, 6 Joliot Curie, Moscow Region, Russian Federation

Cross sections, angular distributions, forward-backward asymmetry effect and alpha spectra in fast neutrons induced processes on ^{64}Zn nucleus were investigated. Theoretical evaluations were realized using own authors codes and dedicated software for the investigation of the structure of atomic nuclei and nuclear reactions mechanisms. Contributions to the cross sections, angular correlations and alpha spectra of nuclear reactions mechanisms (direct, compound and pre-equilibrium ones) were obtained. Cross sections and angular distributions theoretical evaluations are in good agreement with existing experimental data from literature and those obtained in FLNP. Further, from the comparison of theoretical and experimental data, parameters of Woods-Saxon potential (volume, surface and spin-orbit each with real and imaginary part) were extracted.

For neutrons energy of few MeV's, experimental forward-backward effect was observed. For this incident energy of neutrons only compound mechanism is acting and therefore the measured asymmetry cannot be explained by the presence of direct processes. The possible explanations of measured forward-backward effect are also analyzed.

INTRODUCTION

Interaction of fast neutrons with light, medium and heavy nuclei are traditionally investigated for a long time at FLNP JINR, Dubna [1,2]. Fast neutrons processes are important for fundamental and applicative researches. For fundamental investigations, neutrons reactions allow to obtain new data on structure of atomic nuclei and nuclear reaction mechanisms. Neutrons represent an efficient tool for applicative studies necessary for fission and fusion projects, Accelerated Driven Systems researches (ADS), material sciences, reprocessing of nuclear waste, neutrons activation analysis and other [3,4].

Chemical element Zinc (Z = 30) has five natural isotopes. Their atomic mass A and natural occurrence (abundance) are (^{A}X(abundance[%])): ^{64}Zn(48.6%), ^{66}Zn(27.7%), ^{67}Zn(4%), ^{68}Zn(18.5%) and ^{70}Zn(0.6%) respectively [5,6].

Nuclear reaction, ^{64}Zn(n,α)^{61}Ni, with incident neutrons from 0.5 up to 25 MeV was investigated. Cross sections, angular distributions and alpha spectra were evaluated using dedicated software, authors programs and computer simulations. Theoretical evaluations were compared with experimental data obtained mainly at FLNP JINR, Dubna and in collaboration with Institute of Heavy Ions Physics from Pekin, China.

ELEMENTS OF THEORY

Authors has investigated previously the ^{64}Zn(n,α)^{61}Ni fast neutrons reactions and were established that compound nucleus mechanism is dominant [7,8]. In this case, cross sections and angular distributions can be obtained in the frame of statistical model of nuclear reactions and Hauser-Feshbach approach, according to relations [9]:

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

where T are the transmission coefficients; $W_{n\alpha}$ is the width fluctuation correction factor (WFC); c represents the open channels (sum is over all possible open channels)

Differential cross section (angular distribution) as function of solid angle (Ω) is:

$$d\sigma/d\Omega = \pi \lambda\!\!\!^{-}{}^2 (2l+1) T_l \sum_J \left(A_J\left(l, j \mid l', j' \mid \theta\right)\right) \cdot \left(1 + \sum_{p,q} T_p\left(E_q'\right) / T_{l'}\left(E'\right)\right)^{-1}, \tag{2}$$

$$A_J\left(l, j \mid l', j' \mid \theta\right) = \sum_{m,m'} \left|\left(l, j; 0m \mid l, j; Jm\right)\right|^2 \left|\left(l', j'; m'm-m' \mid l', j'; Jm\right)\right|^2 \left|Y_{l'm'}(\theta,\varphi)\right|^2, \tag{3}$$

where the sums are over quantum numbers (obeying conservation laws); Ω is the solid angle; θ is the polar angle; ϕ is the azimuth angle (is not appears in (2), (3) due to parity conservation).

Transmission coefficient represents the probability of a micro-particle to pass a potential barrier and therefore its value is lower than 1 and greater or equal with zero. There are many methods to evaluate transmission coefficients but the authors have chosen the quantum-mechanical approach based on reflection factor [7,10].

Width fluctuation correction factor indicates the correlation between incident and emergent channels. For neutrons reactions with energy around 0.5 MeV WFC factor is approximately 1 demonstrating no correlations between incident and emergent channels. By increasing the incident neutrons energy this factor is slowly decreasing and at 10–15 MeV WFC is about 0.7. From three methods of WFC factor evaluations, all with long and complicated calculations, the authors have chosen the approach from [11].

In order to take into account direct and pre-equilibrium processes in the evaluation of cross sections, angular distributions, yields and other observables, Talys code was used. Talys is a freeware soft, working under Linux, dedicated to structure of atomic nuclei and nuclear reactions mechanisms evaluations. In this code are implemented all nuclear reaction mechanisms and a large database including energy, spin and parity of the levels, parameters of optical potentials and levels density for more than 3000 natural and synthesized nuclei [12].

In the calculations direct mechanism was described by Distorted Wave Born Approximation (DWBA) [12,13] and pre-equilibrium one by two-components exciton model [12,14]. Interaction in incident and emergent channels is described by Woods-Saxon optical potential, with volume, surface and spin-orbit components, each with real and imaginary part. For charged particles it is necessary to include also Coulomb potential [12].

RESULTS AND DISCUSSIONS

Cross section of ^{64}Zn(n,α)^{61}Ni reaction (Q = 3.86 MeV – nuclear reaction heat) with neutrons with energies starting from 0.5 up to 25 MeV was calculated. Theoretical results are shown in Figs. 1a and 1b. In Fig. 1a, contribution of nuclear reaction mechanisms was obtained. Main contribution to the cross section is given by compound processes (curve 2). After 8 MeV multistep compound pre-equilibrium mechanism is enabled (curve 3), and around 18 MeV “pure” compound and pre-equilibrium compound are overlapped. Contribution of direct processes (curve 4) to the cross section can be neglected. Cross section of (n,α) reaction is given by curve 1 and is the sum of 1–3.

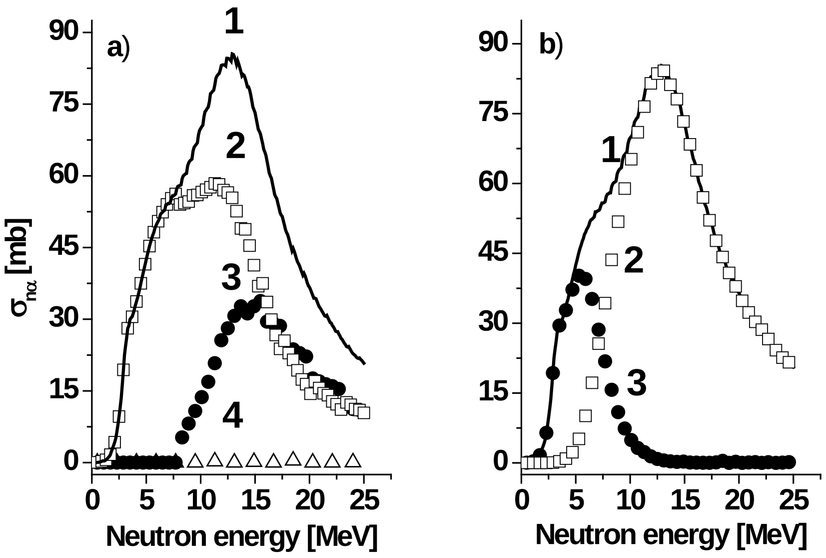

Fig. 1. Cross section evaluation of ^{64}Zn(n,α)^{61}Ni. a) Nuclear reaction mechanisms: 4 – direct; 3 – pre-equilibrium compound; 2 – compound; 1 – total (4+3+2). b) Contribution of residual nucleus states: 3 – discrete; 2 – continuum; 1– total (3+2).

In Fig. 1b the same cross section is separated in contribution of discrete and continuum states of residual nucleus ^{61}Ni. Cross section of discrete states is important up to 10 MeV and is much higher than in the other (n,α) processes investigated by authors. Continuum states (curve 2) are acting in whole neutrons energy interval but they become dominant after 12–13 MeV. Curves 1 in Figs. 1a and 1b are the same and both are the sum of extracted components.

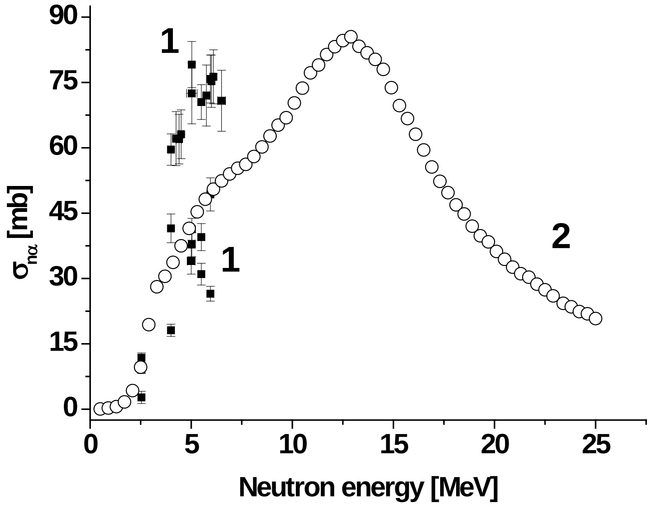

Fig. 2. ^{64}Zn(n,α)^{61}Ni cross section. Theory and experiment. 1 – Experimental data. 2 – Theoretical evaluation.

Comparison between theoretical and experimental cross section data are represented in Fig. 2. Experimental data were obtained mainly in international collaboration of FLNP JINR, Dubna with Chinese research institutes [16,17]. Two groups of data can be observed and can be described theoretically but with two different sets of input parameters. The authors have chosen an “average” set between both groups of measurements. Curve 2 in Fig. 2 is the same with curves 1 in Figs. 1a and 1b.

Angular distributions in a large neutrons energy interval were evaluated and compared with experimental data. In Fig. 3a theoretical and experimental differential cross section for E_n = 4 MeV are shown. In Fig. 3b alpha spectrum obtained in ^{64}Zn(n,α)^{61}Ni at 4 MeV neutrons incident energy is represented.

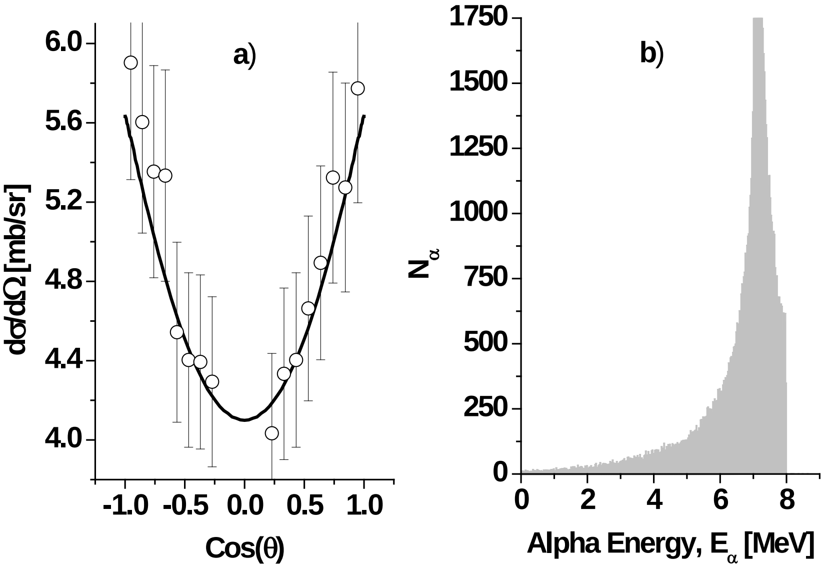

Fig. 3. Angular distribution and alpha spectra in ^{64}Zn(n,α)^{61}Ni for E_n = 4 MeV. a) Differential cross section. b) Modeled alpha spectrum.

Differential cross section from Fig. 1.a was considered as weighted sum of Legendre Polynomials:

$$\frac{d\sigma}{d\Omega} = \sum_{k=0,even} a_k P_k(Cos(\theta)). \tag{4}$$

Experimental data, taken from [16], are well described but with large errors. Like in the case of cross section, from Fig. 2, measurements are affected by the presence of other open channels with participation of alpha particles. At this energy, angular distribution is given only by compound processes.

Alpha spectra from Fig. 1.b were obtained using angular correlation which is calculated by norming differential cross section to cross section. Angular distribution of polar angle θ, was modeled by Direct Monte Method, according to the relation:

$$\frac{2\pi}{\sigma_{n\alpha}} \int_0^{\theta_c} W(\theta)\sin(\theta)d\theta = r \Rightarrow \theta_c, r \in [0,1), \theta \in [0,\pi). \tag{5}$$

In the simulations, target is considered with finite dimensions and it was taken into account energy loss of alpha particles in the target. Modeled alpha spectrum from Fig. 3b was obtained on a target with 263 μg/cm^2 thickness and 4 MeV neutrons energy.

Simulation of alpha spectra for different energy is of interest in the analysis of possible asymmetry effects in ^{64}Zn(n,α)^{61}Ni reaction. Authors from [16,17] revealed some forward-backward effects (FB) in (n,α) processes on other medium and heavy nuclei. Considering description of measurements from [16,17], FB effect has the following expression:

$$A_{FB} = A_{FW} / A_{BW} = \int_{0}^{\pi/2} W(\theta)\sin(\theta)d\theta \Bigg/ \int_{\pi/2}^{\pi} W(\theta)\sin(\theta)d\theta, \tag{6}$$

where A_{FB} is the number of forward events (azimuth and polar angle, $\phi\in[0,2\pi]$, $\theta\in[0,\pi/2]$); A_{BW} is the number of backward events ($\phi\in[0,2\pi]$, $\theta\in[\pi/2,\pi]$)

Taking into account procedure of generation of the events according with relations (4–6), modeled FB effect for 10^6 events, 263 μg/cm^2 thickness and 4 MeV neutrons energy, is:

$$A_{FB}^{SIM} = 1.001 \pm 0.0017. \tag{7}$$

Result from (7) is expected because angular distribution is given only by compound mechanism. There is no direct component, the mechanism responsible for asymmetries in differential cross section. Analysis of experimental data, at 4 MeV-energy [16], revealed the existence of an experimental FB effect of 1–2% affected by large error.

$$A_{FB}^{EXP} = 1.017 \pm 0.09. \tag{8}$$

Theoretical evaluations from the present work were obtained considering 30 levels of residual nuclei for elastic and inelastic scattering and 10 levels for reaction channels. In the calculations all nuclear reactions mechanisms possible open channels were enabled.

Table 1. Parameters of Woods-Saxon potential by components: volume, surface and spin-orbit with real and imaginary part

Channel	Volume WS – Real			Volume WS – Imaginary		
	V [MeV]	r_V [fm]	a_V [fm^{-1}]	W [MeV]	r_W [fm]	a_W [fm^{-1}]
n	52.69	1.203	0.668	0.19	1.279	0.668
α	169.37	1.184	0.676	25.70	1.340	0.500
	Spin – orbit – Real			Spin – orbit - Imaginary		
	V_{SO} [MeV]	r_{VSO} [fm]	a_{VSO} [fm^{-1}]	W_{SO} [MeV]	r_{WSO} [fm]	a_{WSO} [fm^{-1}]
n	5.08	1.024	0.590	0.01	1.024	0.590
α	0	0	0	0	0	0

Parameters of Woods-Saxon potential [12], for incident and emergent channels, obtained from analysis of cross section data are shown in Table 1.

CONCLUSIONS

Cross sections, angular distributions, alpha spectra and FB effect, for ^{64}Zn(n,α)^{61}Ni nuclear reaction induced by fast neutrons with energies from 0.5 up to 25 MeV were investigated. Using dedicated software and codes written by authors, cross sections, angular distributions were calculated and compared with experimental data from literature. The good agreement between experimental and theoretical cross sections and angular distributions data suggested the modeling of FB effect, applying Direct Monte-Carlo method. In the computer modeling, at 4 MeV neutrons energy, FB effect was not obtained, in comparison with existing experimental data. At 4 MeV incident energy only compound mechanism is acting and therefore no FB effect can be revealed. For full incident energy interval, contribution to the cross sections of nuclear reaction mechanisms and of discrete and continuum states of residual nuclei were extracted. Analyzing theoretical and experimental cross section data, parameters of nuclear potentials for incident and emergent channels was also obtained.

In the future it is necessary to extend and continue the analysis of angular distributions for energy higher than 4 MeV. In the same time, new cross section (n,α) measurements in a large energy interval are of interest in order to improve cross sections experimental data and computer modeling.

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