Alpha emission from fast neutron interactions with $^{64}$Zn nuclei

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Abstract. In this study, the nuclear process $^{64}$Zn($n$, $\alpha$)$^{61}$Ni induced by fast neutrons in the $^{64}$Zn nucleus was investigated. With the authors' computer programs and Talys codes, cross-sections, angular correlations, and forward-backward asymmetry effects were investigated for incident neutrons with energies ranging from 0.5 MeV to 25 MeV. $^{61}$Ni cross-sections were determined through an investigation of nuclear reaction mechanisms (direct, compound, pre-equilibrium) and discrete and continuum states within the $^{61}$Ni residual nucleus. Our analysis of the neutron incident and alpha emergent channels included the extraction of optical potential parameters (with real and imaginary parts) with volume, surface, and spin-orbit components. The cross-sections calculated theoretically and found in our experiments confirm earlier published data. For neutrons with energies of a few MeV, the $^{64}$Zn($n$, $\alpha$)$^{61}$Ni reaction produced by fast neutrons exhibits an unusual forward-backward asymmetry. At this energy, the observed effect cannot be explained by direct mechanisms with orders of magnitude lower; compound processes that predominate must be used. To understand the observed forward-backward asymmetry effect, the spectra of emitted alpha particles were modelled by the direct Monte Carlo method while taking into consideration the energy loss of alpha particles on Zn targets with finite dimensions.

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1. Introduction

Nuclear reactions caused by fast neutrons that are followed by the emission of charged particles (protons and alphas) are traditionally studied [1-5]. Fast neutrons processes are of interest for basic and applied researches. In the field of fundamental physics fast neutrons reactions give new data on the structure of atomic nuclei and the mechanisms of nuclear reactions. Accurate information is provided by these processes for nuclear fission and future fusion reactors, handling long-life nuclear waste, transmutation, energy, and accelerated driven systems (ADS) programs [6,7].

There are five naturally occurring isotopes of the chemical element zinc: $^{64}$Zn, $^{66}$Zn, $^{67}$Zn, $^{68}$Zn, and $^{70}$Zn, with abundances of 49.2%, 27.7%, 4%, 18.5%, and 0.6%, respectively [8]. Nuclear reaction $^{64}$Zn(n, D)$^{61}$Ni induced fast neutrons with energies starting from 0.5 MeV up to 25 MeV was investigated. Using programs written by the authors and also using Talys code, cross-sections, angle distributions, alpha spectra, and parameters of Wood-Saxon potential in incident and emergent channels were produced [9]. Theoretical evaluations and conclusions are in good agreement with the available experimental data.

2. Elements of theory

Cross-sections, angular distributions and alpha spectra were obtained using Talys code [9]. All nuclear reaction mechanisms are taken into account in the analyses. Distorted Wave Born Approximation (DWBA) [9,10] is used to explain direct processes, a statistical model of nuclear reaction using Hauser-Feshbach formalism [9,11] is used to describe compound processes, and a two-component exciton model is used to characterize pre-equilibrium processes [9,12]. In the framework of the Fermi gas model with constant temperature, the nuclear states density was determined [9].

3. Results and discussions

Cross-section of $^{64}$Zn(n, α)$^{61}$Ni reaction (heat of reaction $Q = 3.86$ MeV) was evaluated with Talys. Contributions to the cross-section of nuclear reaction mechanisms as well as the discrete and continuum states of residual nuclei were obtained. Results are shown in Fig. 1. Compound processes are dominant in the whole energy interval (Fig. 1.a curve 2). Pre-equilibrium mechanisms are activated after 7-8 MeV (Fig. 1.a curve 3). Direct mechanisms can be neglected (Fig. 1.a curve 4). Compound processes for neutrons with energies more than 15 MeV originate from a pre-equilibrium mechanism.

Fig. 1. Cross-section of $^{64}$Zn(n, α)$^{61}$Ni reaction. Contribution of: a) Nuclear reaction mechanisms; 1) Total (1 -> 2 + 3 + 4) 2) Compound 3) Pre-equilibrium 4) Direct. b) States of residual nuclei; 1) Total (1 -> 2 + 3) 2) Continuum 3) Discrete

Contributions to the cross-section of the discrete and continuum states of the residual nucleus are shown in Fig. 1.b. Cross-section is primarily provided by discrete states for neutron energies up to 7 - 8 MeV (Fig. 1.b curve 3). There is a rising contribution of continuum states to the cross-section at incident energy higher than 8 MeV. After 10 MeV neutron energy, the cross-section can only be produced by continuum states (Fig. 1.b curve 2). The theoretical assessment of the $^{64}$Zn(n,α)$^{61}$Ni cross-section for incident neutron energies ranging from 0.5 MeV to 25 MeV is shown in Fig. 1.ab curve 1. Figure 2 compares estimated cross-sections to experimental data from [13–16]. There are two sets of experimental data that can be seen. Two alternative sets of parameters can be obtained primarily by adjusting the optical potential's characteristics. In Fig. 2 a set of parameters which is passing between both groups of data is represented. Because different cross-section values were measured in the experiment for the same incident neutron energy, the authors decided to choose the above approach.

For example, the experimental cross-section had three distinct values at 4 MeV incident energies: 18, 41, and 60 mb, respectively [13–15]. At the same energy, theoretical cross-section is 33 mb. Taking into account the above considerations, experimental data are in good agreement with theoretical evaluations.
Differential cross-section was evaluated for a large incident neutrons energy range. For incident neutron energies $E_n = 4$ and $5.5$ MeV, respectively, theoretical calculations and experimental results of $^{64}$Zn(n, $\alpha$$)^{61}$Ni differential cross-section as a function of polar angle $\theta$ are shown in Fig. 3. Experimental information is sourced from [14].

The computed cross-sections from Fig. 1 are $\sigma_{\text{ex}}(E_n = 4 \text{ MeV}) = (59.6\pm3.3)$ mb and $\sigma_{\text{ex}}(E_n = 5.5 \text{ MeV}) = (70.5\pm4.0)$ mb, respectively [14]. Therefore, a new set of Wood-Saxon potential parameters had to be discovered in order to have the same cross-section value in both theory and experiment. If this assumption is fulfilled then the measured differential cross-section is described very well by theoretical evaluation for neutron energy $E_n = 4$ MeV, and satisfactorily for $E_n = 5.5$ MeV. Theoretical analysis reveals that there is only a compound mechanism present for neutron energy of 4 and 5.5 MeV and no direct process. Computer simulations were carried out using the results of the differential cross-section from Fig. 3. Starting from differential cross section, angular correlations were calculated and applying direct Monte-Carlo method, it was possible to determine the angular distribution of the polar angle $\theta$ [17].

The forward-backward effect was evaluated using simulated angular distribution for targets with different dimensions. In any event, simulations have not identified any forward-backward effect for either a point-like target or a target with a thickness of 266.3 g/cm$^3$ [14]. In the simulations, the forward-backward asymmetry effect is defined as the ratio between all forward events (polar angle $\theta$ from 0 to $\pi/2$) and all backward events (polar angle $\theta$ from $\pi/2$ to $\pi$) [2, 14]. The alpha particle loss in the target was assessed for targets with finite dimensions [18].
= 5.5 MeV (see Fig. 3b) and some higher energies [13-16], although the observed asymmetry is not brought on by the target thickness. If this effect does indeed exist, it can be accounted for by the presence of other open channels with the participation of alpha particles. All open exit channels were taken into account during the analyses. 30 distinct states of the residual nucleus were considered for both elastic and inelastic channels, but only 10 levels were considered for reactions. Table 1 lists the optical potential parameters for the incident and emerging channels according to [9].

4. Conclusions

The nuclear reaction $^{64}$Zn(n, $\alpha$)$^{61}$Ni, with neutron energy ranging from 0.5 to 25 MeV, was under investigation. Using Talys code and the author's programs, cross-sections, angle distributions, and alpha spectra were examined. Theoretical assessments and available experimental data are in good agreement. The largest contribution to the cross-sections is given by compound processes. Practically, direct processes can be neglected. Up to 7-8 MeV contribution of the discrete states of the residual nucleus in the cross-sections are dominant but as input neutron energy increases, continuum states become important and gradually replace the discrete ones. Contrary to what differential cross-sections for neutrons with energy higher than 5 MeV anticipated, forward-backward effects were not visible in the modelled alpha spectra starting from angular distribution. In the absence of direct mechanisms, the observed forward-backward asymmetry effect can be explained by the existence of additional open emergent channels with the participation of alpha particles.

References