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THE FAST NEUTRON INDUCED (n, p) REACTION CROSS SECTIONS. Pre-equilibrium Reaction Mechanism

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Сечения (n,p)-реакции, вызываемой быстрыми нейтронами.
Предравновесный механизм

В рамках предравновесного механизма ядерных реакций с использованием экситонной модели Гриффина выведена формула для сечения индуцированных нейтронами реакций с вылетом заряженных частиц. С помощью выведенной формулы в широкой области энергии нейтронов проведен систематический анализ экспериментальных сечений (n,p)-реакции.

Показано, что в районе энергии нейтронов 14–16 МэВ теоретическая формула неплохо описывает экспериментальные сечения, хотя имеется значительное расхождение между экспериментальными и теоретическими сечениями в области энергии от 6 до 10 МэВ.

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Khuukhenkhuu G. et al. E3-2007-26

The Fast Neutron Induced (n,p) Reaction Cross Sections.
Pre-equilibrium Reaction Mechanism

In the framework of the pre-equilibrium mechanism using Griffin's exciton model a simple formula was deduced for the fast neutron induced charged particle emission reaction cross sections. Using the obtained formula in a wide energy range, the systematic analysis of the experimental (n,p) cross sections was carried out. It was shown that in the case of 14–16 MeV the theoretical formula satisfactorily describes the experimental data, however, in the energy region from 6 to 10 MeV there is a significant discrepancy between the theoretical and experimental cross sections.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

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1. INTRODUCTION

The investigation of fast neutron induced charged particle emission reactions is important for both nuclear energy application technology and the understanding of fundamental nuclear physics problems. In particular, the study of fast neutron induced reactions is necessary to clarify energy dependence of contributions from different reaction mechanisms to total cross section.

In last decade we carried out a systematic analysis of known (n,p) cross sections and observed the so-called isotopic effect in a wide energy range and for broad mass number of target nuclei [1]. However, up to now there is no consistent theoretical explanation on existence of the systematical regularity for the (n,p) cross sections. Several formulae have been suggested to describe the isotopic dependence of the (n,p) cross sections around the neutron energy of 14–15 MeV only (see references in [2]).

In this connection, for systematic analysis of the fast neutron induced (n,p) reaction cross sections in a wide energy range we considered compound, pre-equilibrium and direct reaction mechanisms and suggested some versions of the statistical [2] and exciton models [3] and plane-wave Born approximation (PWBA) [4].

In this paper for systematical analysis of the (n,p) cross sections the version of the simple exciton model is described.

2. THE EXCITON MODEL FORMULAE

2.1. (n,x) **Reaction Differential Cross Section.** According to Griffin's simple exciton model [5] the neutron induced charged particle emission reaction differential cross section is expressed as follows:

$$\frac{d\sigma(n,x)}{dE_x} = \sigma_r(E_n)\sum_{n=n_0}^{n_{\max}} \lambda_x(n,E_x)\tau(n,E). \qquad (1)$$

Here $\sigma_r(E_n)$ is the neutron induced reaction total cross section; n is the exciton number ($n = p + h$, p is the particle number, h is the hole number);

n_0 is the initial exciton number; $n_{\max}$ is the maximum number of excitons; $\lambda_x(n, E_x)$ is the decay rate (transition rate) of x particle from states with n excitons; $\tau(n, E)$ is the mean lifetime of an n-exciton state, E is the excitation energy ($E = E_n + B_n$; E_n is the kinetic energy of neutrons, B_n is the binding energy of neutrons); E_x is the kinetic energy of outgoing x particle.

The transition rates for the n-exciton states are expressed as follows [6–8]:

$$\lambda_x(n, E_x) = \frac{2S_x + 1}{\pi^2 \hbar^3} M_x E_x \sigma_i(E_x) R_x \frac{\rho(p - p_x, h, U)}{\rho(p, h, E)}, \tag{2}$$

where S_x and M_x are the spin and mass of the outgoing x particle, respectively; $\sigma_i(E_x)$ is the inverse reaction cross section; R_x is the charge-conserving correction coefficient; ρ is the state density; U is the excitation energy of the residual nucleus ($U = E_n + Q_{nx} - E_x$; $Q_{nx} = B_n - B_x$ is the reaction energy). In the case of semi-classical approximation the inverse cross section is determined as follows:

$$\sigma_i(E_x) = \pi R^2 \left(1 - \frac{V_x}{E_x}\right), \tag{3}$$

where R and V_x are the radius and potential energy of the residual nuclei, respectively.

The mean lifetime for the n-exciton states is determined as follows:

$$\tau(n, E) = \frac{1}{\lambda_n^+ + \lambda_n^- + \gamma_n} D_n, \tag{4}$$

where λ_n^+ is the $n \to (n+2)$ transition rate; λ_n^- is the $n \to (n-2)$ transition rate; γ_n is the total rate for emission of nucleon from n-exciton state; D_n is the depletion factor.

The state density is expressed by Ericson's formula [9]:

$$\rho(p, h, E) = \frac{g(gE)^{n-1}}{p!h!(n-1)!}. \tag{5}$$

Here g is the single-particle state density:

$$g = \frac{6}{\pi^2} a, \text{ where } a = \frac{A}{13.5} \ (\mathrm{MeV}^{-1}). \tag{6}$$

If we use the following approximation:

$$\lambda_n^+ \gg \lambda_n \gg \lambda_n^- \tag{7}$$

and assume $D_n \approx 1$ and $\gamma_n \approx 0$, from (4) we get

$$\tau(n, E) \approx \frac{1}{\lambda_n^+}. \tag{8}$$

The decay rates could be calculated in the first-order approximation in the framework of time-dependent perturbation theory using the golden rule:

$$\lambda_n^+ = \frac{2\pi}{\hbar} \left\langle |M|^2 \right\rangle \rho_f. \tag{9}$$

Here $\left\langle |M|^2 \right\rangle$ is the average squared matrix element for the two-body interaction, which is assumed to be energy-independent, ρ_f is the final states density, which for the $n \to n+2$ transition is determined as follows [6, 8]:

$$\rho_f = \frac{g^3 E^2}{2(n+1)}. \tag{10}$$

For the average squared matrix element the following approximation [7] is used:

$$\left\langle |M|^2 \right\rangle = K_0 A^{-3} E^{-1}, \text{ where } K_0 \approx 400 \text{ MeV}^{-3}. \tag{11}$$

From (1)–(11) we can obtain the following expression for the differential (n, x) cross section:

$$\frac{d\sigma(n,x)}{dE_x} = 352.6\pi^6 R^2 \sigma_r(E_n) \frac{2S_x+1}{\hbar^2} M_x E_x \left(1 - \frac{V_x}{E_x}\right) \frac{R_x}{K_0} \frac{U}{AE^3}. \tag{12}$$

Reaction total cross section is given by

$$\sigma_r(E_n) = \pi(R_0 + \lambda\!\!\!^{-})^2 \approx \pi r_0 (A^{1/3} + 1)^2, \tag{13}$$

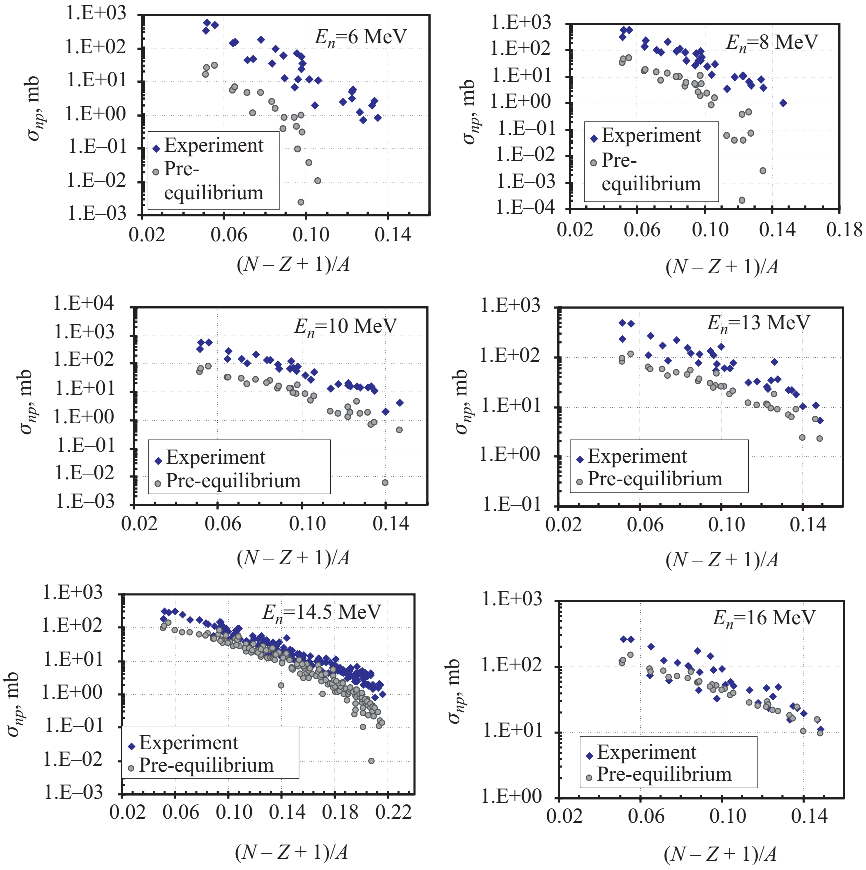
where $R_0 = r_0 A^{1/3}$ is the radius of target nucleus.

2.2. The (n, p) Reaction Total Cross Section. From equation (12) by integrating from V_x to $E_x^{\max} = E_x + Q_{nx}$ we get the following expression for the (n, p) cross section:

$$\sigma(n,p) = 68.3 \frac{\pi^6}{\hbar^2} R^2 \sigma_r(E_n) \frac{2M_p}{K_0 A} \frac{[(E_n + Q_{np}) - V_p]^3}{(E_n + B_n)^3}. \tag{14}$$

2.3. Analysis of (n, p) Reaction Cross Sections. The comparison of the calculated by (14) results with known experimental data is given in the Figure.

It is seen that in the region from 6 to 10 MeV there is a significant discrepancy between the experimental and theoretical cross sections. But in the case of 14–16 MeV the conformity between the experimental and theoretical cross sections is improved. This means that the contribution of the pre-equilibrium mechanism increases with growth of neutron energy.



The values and experimental data of (n, p) cross sections calculated by exciton model

3. CONCLUSIONS

1. In the framework of the pre-equilibrium nuclear reaction mechanism using Griffin's simple exciton model the formula for (n, p) reaction cross sections was deduced.

2. Using the exciton model the systematical analysis for the fast neutron induced (n, p) reaction experimental cross sections was carried out. It was shown that in the case of 14–16 MeV theoretical formula satisfactorily describes experimental data, however in the region from 6 to 10 MeV there are significant discrepancies between the experimental and theoretical cross sections.

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