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THE FAST NEUTRON INDUCED (n, p) REACTION CROSS SECTIONS. Direct Reaction Mechanism

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

В рамках прямого механизма ядерных реакций с использованием борновского приближения плоской волны выведена простая формула для индуцированных быстрыми нейтронами реакций с вылетом заряженных частиц. В широкой области энергии нейтронов от 6 до 16 МэВ проведен систематический анализ сечения (n,p)-реакции. Показано, что теоретические полные сечения, рассчитанные по статистической и экситонной моделям и борновскому приближению плоской волны, удовлетворительно согласуются с экспериментальными данными.

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The Fast Neutron Induced (n,p) Reaction Cross Sections.
Direct Reaction Mechanism

In the framework of the direct reaction mechanism using the plane-wave Born approximation (PWBA) a simple formula was deduced for the fast neutron induced charged particle emission reaction cross sections. In the wide energy range from 6 to 16 MeV the systematic analysis of the (n,p) reaction cross sections was carried out. It is shown that theoretical total cross sections calculated by statistical and exciton models and PWBA satisfactorily agree with the experimental data.

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

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1. INTRODUCTION

The investigation of the fast neutron induced (n, p) reaction is important for nuclear reaction mechanism study and reactor construction calculations. Because of these, it would be very useful to carry out a systematical analysis for known experimental (n, p) reaction cross sections.

In 1993 for a wide energy range we observed the so-called isotopic effect in the fast neutron induced (n, p) reaction cross sections [1]. To explain this effect some formulae based on the statistical [2] and exciton models [3] were deduced.

In this paper we report on the attempt to obtain a simple formula for the (n, p) reaction cross sections in the framework of the direct reaction mechanism using the plane-wave Born approximation (PWBA) [4].

2. DIRECT REACTION MECHANISM

2.1. The Reaction Cross Section. In the general case a simple direct nuclear reaction can be written as follows:

$$a + A \rightarrow B + b, \tag{1}$$

where a is the incident particle; A is the target nucleus; B and b are the reaction product nucleus and particle, respectively.

Reaction rate is determined in the form

$$\omega = \sigma(a, b) n \upsilon_a, \tag{2}$$

where $\sigma(a, b)$ is the reaction cross section; n is the density of a particles; υ_a is the velocity of a particles.

On the other hand, the probability of the transition of a system from the initial to the final state is given by [5]

$$\omega = \frac{2\pi}{\hbar} \left| M_{fi} \right|^2 \rho(E), \tag{3}$$

where M_{fi} is the matrix element; $\rho(E)$ is the density of the final states. According to the perturbation theory the matrix element can be written in the form

$$M_{fi} = \int \Psi_f^* H \Psi_i d\tau, \tag{4}$$

where H is the perturbation operator; $d\tau$ is the volume element; Ψ_i and Ψ_f are the wave functions for the initial and final states of system, respectively.

Neglecting the spins of the nucleus and particle, we get the number of final states as follows:

$$dn_b = \frac{4\pi P_b^2 dP_b V}{(2\pi\hbar)^3}, \tag{5}$$

where P_b is the momentum of the b particles; V is the interaction volume.

Taking into account the energy interval in the C system (center-of-mass)

$$dE = \upsilon_b dP_b \tag{6}$$

we can obtain from (5) and (6) the density of the final states as follows:

$$\rho(E) = \frac{dn_b}{dE} = \frac{4\pi P_b^2 V}{(2\pi\hbar)^3 \upsilon_b}. \tag{7}$$

Further, we assume that in the volume V there is only one a particle:

$$n = \frac{1}{V}. \tag{8}$$

Then, by substitution of (7) and (8) into (2) and (3), we get the (a, b) reaction cross section formula [4]

$$\sigma(a,b) = \frac{\omega}{n\upsilon_a} = \frac{|M_{fi}|^2 P_b^2 V^2}{\pi\hbar^4 \upsilon_b \upsilon_a}. \tag{9}$$

2.2. The (n, p) Reaction Cross Section. In the case of (n, p) reaction we use the following approximations for the initial and final states of system

$$\Psi_i = U_i U_n \tag{10}$$

and

$$\Psi_f = U_f U_p, \tag{11}$$

where U_i, U_f, U_n and U_p are the wave functions of the target nucleus, reaction product nucleus, neutron and proton, respectively.

In order to simplify, we shall assume that the perturbation operator is equal to a constant

$$H = C = \text{const}. \tag{12}$$

Then, the matrix element is expressed by

$$M_{fi} = C \int U_f^* U_p^* U_i U_n d\tau. \tag{13}$$

If we use localized interaction, then integration is simplified and instead of four-fold integral we have a single one. In the case of plane-wave approximation it can be written as

$$U_n = N_n \mathrm{e}^{\frac{i}{\hbar}(P_n r)}, \tag{14}$$

and

$$U_p = N_p \mathrm{e}^{\frac{i}{\hbar}(P_p r)}, \tag{15}$$

where N_n and N_p are the normalizing constants. So, from normalizing condition

$$\int\limits_{(V)} U_n^* U_n d\tau = \int\limits_{(V)} U_p^* U_p d\tau = 1 \tag{16}$$

the normalizing constants are found as follows:

$$N_n = N_p = \frac{1}{\sqrt{V}}. \tag{17}$$

In the case of $\upsilon \ll c$ the wave functions of neutron and proton are nearly constant and are equal to their values at the $r = 0$. Then from (14), (15) and (17) we get

$$U_p^*(r=0) = U_n(r=0) = \frac{1}{\sqrt{V}}, \tag{18}$$

and from (13) and (18) we find

$$M_{fi} = \frac{C}{V} \int U_f^* U_i d\tau. \tag{19}$$

If we neglect the effect of the Coulomb field of the nucleus, the following approximation can be written

$$U_f \approx U_i \equiv U. \tag{20}$$

So, from (19) and (20), taking into account the normalizing condition

$$\int\limits_{(V)} U^* U d\tau = 1, \tag{21}$$

we get

$$M_{fi} = \frac{C}{V}. \tag{22}$$

From (9) and (22) the following formula for the (n, p) reaction cross section can be written

$$\sigma(n,p) = \frac{P_p^2}{\pi \hbar^4 \upsilon_n \upsilon_p} \left| C \right|^2 . \tag{23}$$

In the case of $\upsilon \ll c$, using the formula for kinetic energy of neutrons $E_n = \dfrac{m_n \upsilon_n^2}{2}$, we can obtain formula for (n, p) reaction cross section as follows:

$$\sigma(n,p) = \frac{m_p \sqrt{m_n m_p}}{\pi \hbar^4} \sqrt{\frac{E_p}{E_n}} \left| C \right|^2 . \tag{24}$$

If we assume the following approximation:

$$E_p \approx E_p^{\max} = E_n + Q_{np} \tag{25}$$

the (n,p) cross section can be written as follows:

$$\sigma(n,p) = M\sqrt{1+\frac{Q_{np}}{E_n}}\,|C|^2\,, \tag{26}$$

where

$$M = \frac{m_p\sqrt{m_n m_p}}{\pi\hbar^4}. \tag{27}$$

We use for asymptotic total cross section the following approximation:

$$\sigma_{\max}^{\text{tot}} = \sigma_{np} + \sigma_{n\alpha} + \sigma_{nn'} + \sigma_{n\gamma} + \sigma_{n2n} + ... = \pi R^2. \tag{28}$$

In the case of $E_n \gg Q_{np}$ for (n,p) cross section the following formula can be written:

$$\sigma(n,p)_{\max} = C_0\pi R^2. \tag{29}$$

Here C_0 is the factor, which represents a probability of proton emission channel in the total cross section. So, the factor $C_0 \ll 1$ and we can determine it by fitting the experimental cross sections.

From (26) and (29) the perturbation constant can be evaluated as follows:

$$|C|^2 \approx \frac{C_0\pi R^2}{M}. \tag{30}$$

Then, from (26) and (30) we have the following formula for the (n,p) reaction cross section:

$$\sigma(n,p) = C_0\pi R^2\sqrt{1+\frac{Q_{np}}{E_n}}. \tag{31}$$

3. ANALYSIS OF THE (n,p) REACTION CROSS SECTIONS

3.1. The Plane-Wave Born Approximation Analysis. In the case of PWBA we have two possibilities to obtain the parameter C_0. First, we can choose the parameter C_0 as a best fit to experimental data for each nucleus. Second, it can be considered for all nuclei $C_0 = \text{const}$ at each energy point. In the second case, we should take into account the compound [2], pre-equilibrium [3] and direct [4] reaction mechanisms. Then (n,p) reaction theoretical total cross section is expressed as follows:

$$\sigma_{np}^{\text{tot}} = \sigma_{np}^{\text{com}} + \sigma_{np}^{\text{pre}} + \sigma_{np}^{\text{dir}}, \tag{32}$$

where $\sigma_{np}^{\mathrm{com}}, \sigma_{np}^{\mathrm{pre}}$ and $\sigma_{np}^{\mathrm{dir}}$ are the theoretical cross sections calculated by statistical and exciton models and PWBA, respectively. In this case we have only one fitting parameter C_0. So, from (32) we can determine fitted parameter C_0, which is shown in Fig. 1 for 6, 8, 10, 13, 14.5 and 16 MeV. Also, Fig. 1 shows theoretical cross sections calculated by PWBA, using only the fitted parameter C_0 in comparison with experimental data.

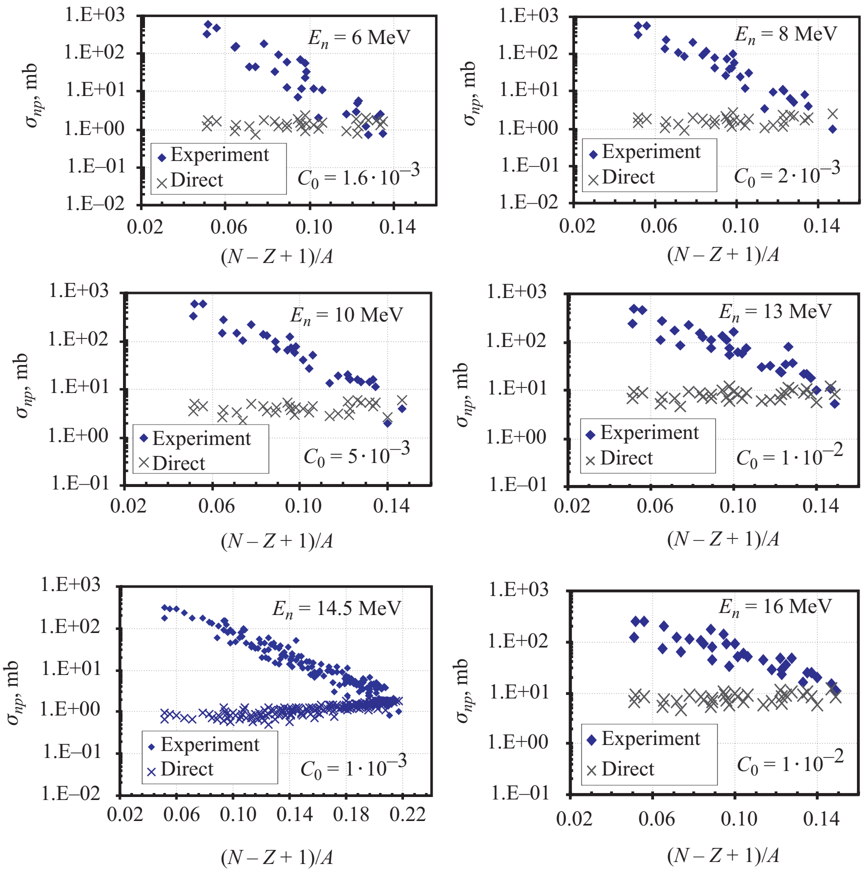

Fig. 1. Values and experimental data of (n, p) cross sections calculated by PWBA

3.2. The Total Cross Section Analysis. The theoretical total (n, p) cross sections determined by (32) in comparison with experimental data for 6, 8, 10, 13, 14.5 and 16 MeV are shown in Fig. 2. It is seen that theoretical total cross sections are in agreement with experimental data.

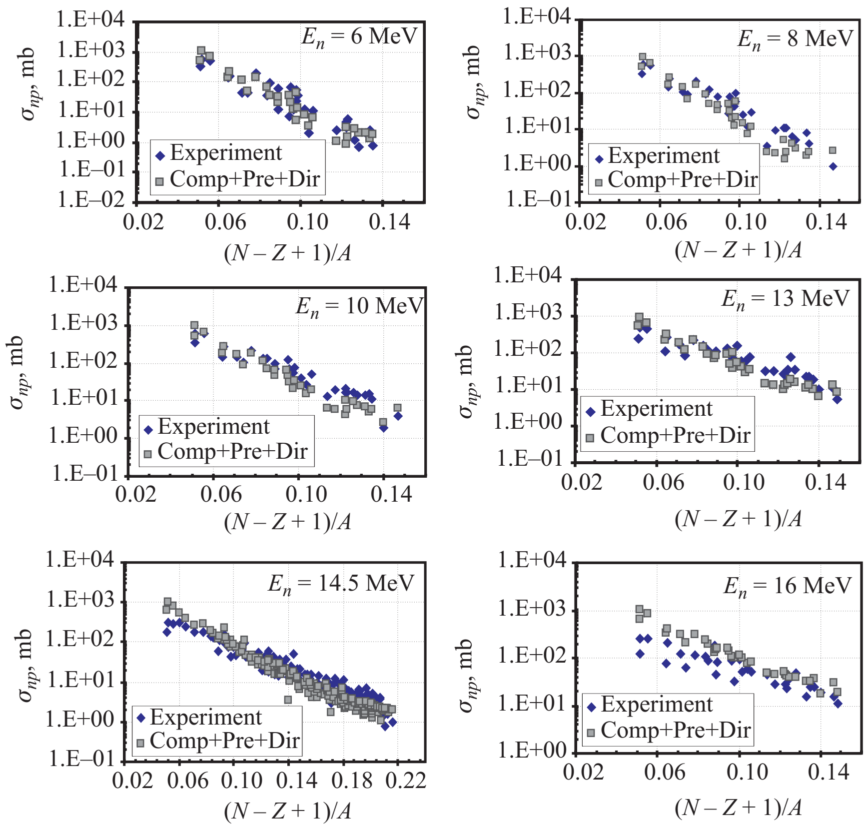

Fig. 2. Experimental and theoretical total (n,p) cross sections

4. CONCLUSIONS

1. In the framework of the direct reaction mechanism and using the plane-wave Born approximation the simple formula for the (n,p) reaction cross sections was obtained. The Coulomb interactions, spins of the nucleus and particles are neglected. Also, the perturbation operator is considered as constant.

2. Using the statistical model, exciton model and PWBA a systematical analysis for the fast neutron induced (n,p) reaction total cross sections was carried out.

It was shown that the theoretical and experimental (n,p) cross sections at energy of 6, 8, 10, 13, 14.5 and 16 MeV are in satisfactory agreement.

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REFERENCES

1. *Khuukhenkhuu G., Gledenov Yu., Sedysheva M., Unenbat G.* JINR Communication E3-93-466. Dubna, 1993.

2. *Khuukhenkhuu G., Unenbat G., Gledenov Yu., Sedysheva M.* // J. Nucl. Sci. Tech. Supplement 2. 2002. Proc. of the Intern. Conf. on Nucl. Data for Sci. and Tech., Tsukuba, Japan, 2001. P. 782.

3. *Khuukhenkhuu G.* // Scientific Transactions. National University of Mongolia, 2001. No. 8(160). P. 21 (in Mongolian).

4. *Khuukhenkhuu G.* // Proc. of the 2nd Intern. School on Contemporary Physics, Ulaanbaatar, Mongolia, 2002. P. 84.

5. *Malyarov V. V.* Theory of the Nucleus. M.: Nauka, 1967 (in Russian).

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