INVESTIGATION OF THE (n, p) REACTION IN Li^6

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We have derived the angular distribution of protons produced from the (n, p) reaction in Li^6, taking into account the neutron-proton correlation in the nucleus.

1. It is known that the theory of (n, p) reactions, based on the assumption of direct interaction of the incident nucleon with the nucleus, leads (in the plane wave approximation) to an angular distribution of scattered particles which is in agreement with experimental data only at relatively small angles, up to $70-90°$.[1,2] For large scattering angles, the theory gives a rapidly oscillating distribution curve which approaches zero with increasing scattering angle, whereas the experimental curve for these angles is a smooth and, in the majority of cases, monotonically decreasing curve.

It is interesting that for the case of Li^6, as shown by the work of Frye,[3] instead of a drop in the distribution at large scattering angles, one observes a rise which begins after reaching the minimum around 70°. As seen from the curve given by Frye, the effective cross section for the (n, p) reaction at 120° has the same order of magnitude as the cross section near zero, where it takes on its maximum value.

In the present paper we investigate the (n, p) reaction on Li^6 on the basis of the α-deuteron model of this nucleus which was developed by the authors.[4,5] We may expect that the study of this reaction on the basis of the α-deuteron model of Li^6 will lead to better agreement with experiment. Assuming that the neutron and proton which are outside the closed shell in Li^6 form a bound state, we must conclude that the ejection of the proton may be caused by the interaction of the incident neutron, not only directly with the ejected proton, as is assumed in existing theories of nuclear reactions, but also with the neutron which is bound to it.

It is clear that the effective cross section for the process of ejection of a proton as a result of interaction of the incident neutron directly with this proton will give a forward maximum in the angular distribution, whereas the interaction with the bound neutron, because of exchange effects, will lead to a rise in the cross section for this process at large scattering angles, in agreement with the experimental data.

2. The interaction energy of the incident neutron with the nucleus we assume to have the form

$$U = A\{\delta(\mathbf{r}_3 - \mathbf{r}_1) + \delta(\mathbf{r}_3 - \mathbf{r}_2)\}, \quad (1)$$

where $\mathbf{r}_1$ and $\mathbf{r}_2$ are the radius vectors of the proton and neutron in the Li^6 nucleus, and $\mathbf{r}_3$ is the radius vector of the incident neutron.

The wave functions of the system in the initial and final states, antisymmetrized with respect to the neutrons, have the following forms:

$$\psi_i = \frac{1}{\sqrt{2}}\Big\{e^{i\mathbf{k}_3\mathbf{r}_3}\chi_{\mu_3}(3)\,\psi_d(|\mathbf{r}_1-\mathbf{r}_2|)\,\psi_1\Big(\frac{\mathbf{r}_1+\mathbf{r}_2}{2}\Big)\chi_1(1,2) - e^{i\mathbf{k}_3\mathbf{r}_2}\chi_{\mu_3}(2)\,\psi_d(|\mathbf{r}_1-\mathbf{r}_3|)\,\psi_1\Big(\frac{\mathbf{r}_1+\mathbf{r}_3}{2}\Big)\chi_1(1,3)\Big\}, \quad (2)$$

$$\psi_f = e^{i\mathbf{k}_1\mathbf{r}_1}\chi_{\mu_1}(1)\,\psi_2\Big(\frac{\mathbf{r}_2+\mathbf{r}_3}{2}\Big)\psi_{nn}(|\mathbf{r}_2-\mathbf{r}_3|)\,\chi_0(2,3), \quad (3)$$

where $\mathbf{k}_3$ and $\mathbf{k}_1$ are the wave vectors of the incident and emerging particles in the center of mass system; $\psi_d(|\mathbf{r}_1-\mathbf{r}_2|)$ is the internal wave function of the neutron-proton pair in the Li^6 nucleus; ψ_1 is the wave function for the relative motion of this pair and the α particle; ψ_2 is the wave function for the relative motion of the center of the neutron-neutron pair in the He^6 nucleus at the end of the process (we treat the He^6 nucleus as a system of an α particle and two neutrons which are not bound to one another); $\psi_{nn}(|\mathbf{r}_1-\mathbf{r}_3|)$ is the internal wave function of this pair of neutrons; $\chi_1(1, 2)$ and $\chi_0(2, 3)$ are the spin wave functions for the triplet and singlet states of a pair of nucleons; $\chi_\mu(3)$, $\chi_\mu(1)$, and $\chi_\mu(2)$ are the spin wave functions of the individual nucleons.

Assuming that both the relative motion of the center of the (nn) pair and the α particle in the He^6 nucleus, as well as of the (np) pair in Li^6 are described by an S state, we obtain for the square of the scattering amplitude

$$|f(\theta)|^2 \sim \{I_1(q) + \psi_d(0) I_2(q, Q) + 2\psi^*_{nn}(0) I_3(q, Q)\}; \quad (4)$$

$$I_1(q) = \int e^{iqR}\psi_2^*(R)\psi_1(R)\,dR\int \psi^*_{nn}(r)\psi_d(r)e^{iqr/2}\,dr,$$

$$I_2(q, Q) = \int e^{iqR}\psi_2^*(R)\,dR\int e^{-iQr/2}\psi^*_{nn}(r)\,\psi_1\left(R + \frac{r}{2}\right)dr, \quad (5)$$

$$I_3(q, Q) = \int e^{iqR}\psi_1(R)\,dR\int e^{-iQr/2}\psi_d(r)\,\psi_2^*\left(R - \frac{r}{2}\right)dr,$$

where

$$q = k_3 - k_1, \quad Q = k_3 + k_1. \quad (6)$$

3. We use oscillator wave functions for ψ_1 and ψ_2, i.e.,

$$\psi_1(R) = \psi_2(R) = B\exp\left\{-\frac{1}{4}(R/r_0)^2\right\}, \quad (7)$$

where B is a normalization factor, r_0 is a parameter associated with the frequency of the oscillator potential. We choose for the wave function of the (np) pair in the Li^6 nucleus in the initial state the deuteron wave function

$$\psi_d = N(e^{-\alpha r} - e^{-\beta r})/r, \quad (8)$$

where N is a normalization factor, $\beta = 1.63 \times 10^{13}$ cm^{-1}, $\alpha = 0.23 \times 10^{13}\,cm^{-1}$.

In choosing the form of the wave function ψ_{nn}, we can be guided by the following considerations: We know that the binding energy of the deuteron to the α particle in Li^6 is equal, according to data on mass defects, to 1.47 Mev, which differs little from the binding energy of the pair of neutrons (which are not bound to one another) to the α particle in He^6, which is equal to 1.27 Mev. From this it follows that the energy associated with the relative motion within the (nn) pair is positive and close to zero. This fact enables us to regard the neutrons of the (nn) pair in He^6 as being correlated in the sense of Levinger,[6] so that we may ascribe zero relative energy to them. Then the function ψ_{nn} can be chosen to have the form

$$\psi_{nn} = \frac{D}{r}\left\{\frac{\sin(kr + \delta_s)}{\sin\delta_s} - e^{-\beta_s r}\right\}_{k\to 0} \approx \frac{D}{r}\{1 - e^{-\beta_s r}\}, \quad (9)$$

$$\beta_s = 1.185\cdot 10^{13}\,cm^{-1}. \quad (10)$$

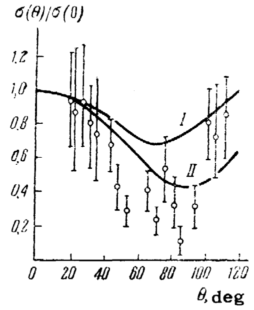
In calculating the integrals I_2 and I_3 in formula (4), we assume that the main contributions come from small R, and we set $\exp(qR) \approx 1$. As a result, we obtain for the square of the scattering amplitude

$$|f(\theta)|^2 \sim e^{-(qr_0)^2}\left\{\frac{F(q)}{qr_0} + \frac{2(\beta-\alpha)r_0C(Q)}{Qr_0} + \frac{4\beta_s r_0}{4(\alpha r_0)^2 + (Qr_0)^2} - \frac{2(\beta-\alpha)r_0 + 4\beta_s r_0}{4(\beta_s r_0)^2 + (Qr_0)^2}\right\}; \quad (11)$$

$$F(q) = \tan^{-1}\frac{2(\beta-\alpha)q}{q^2 + 4\alpha\beta} + \tan^{-1}\frac{2(\alpha-\beta)q}{q^2 + 4(\alpha+\beta)(\beta+\beta_s)}, \quad (12)$$

$$C(Q) = \int_0^\infty \sin(Qr_0x)\exp\left\{-\left(\frac{x}{2}\right)^2\right\}dx. \quad (13)$$

As we see, the square amplitude contains a term $e^{-(qr_0)^2}F(q)/qr_0$ which corresponds to an ordinary scattering process not associated with exchange. This is a decreasing function of the scattering angle and consequently describes the process of direct ejection, which has a maximum in the forward direction. As for the other three terms, they are caused by (n, p) correlations which we have taken into account via the exchange effects. As one sees easily from formula (11), for small values of $r_0 \approx 1 \times 10^{-13}$ cm the exchange part of the amplitude increases with increasing scattering angle, and leads to a corresponding rise in the effective cross section.



The angular distributions obtained from formula (11) for an incident neutron energy of 14 Mev are shown in the figure. Curve I corresponds to a value of the parameter for the oscillator potential $r_0 \approx 1 \times 10^{-13}$ cm, and curve II to the value $r_0 = 1.2 \times 10^{-13}$ cm; the points with the indicated limits of error show the experimental data. As we see from the figure, the theoretical curves correctly reproduce the dependence of the effective cross section on scattering angle, although it should be emphasized that their form depends strongly on the value of the oscillator parameter r_0. Somewhat better agreement with experiment is obtained for $r_0 = 1.2 \times 10^{-13}$ cm.

As we see, taking account of the fact that the incident neutron can interact not only with the proton which is ejected from the nucleus, but also with the neutron in the nucleus which is correlated to the proton, we get a definite contribution to the total cross section for the (n, p) reaction in Li^6, which leads to an increase in the cross section at large scattering angles. We may expect that including this effect will have an appreciable result for the case of (n, p) reactions on heavy nuclei also.

In conclusion, it is our pleasant duty to express our gratitude to V. I. Mamasakhlisov for continued interest in our work and for valuable discussion.

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