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# DIRECT REACTION MECHANISM IN THE $^{11}$B(p, α) REACTION

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**Abstract:** Absolute differential cross sections for the $^{11}$B(p, α) reaction leading to the ground state of $^{8}$Be have been measured at $E_p$ = 12, 20, 24 and 30 MeV. These results and previous results at $E_p$ = 26.7 and 38 MeV have been compared with PWBA calculations taking into account direct mechanisms and their interference term. Two possibilities have been investigated: firstly, pick-up and heavy-particle pick-up, secondly, knock-out and heavy-particle pick-up. Both possibilities agree well with experimental results.

E | NUCLEAR REACTIONS $^{11}$B(p, α); $E$ = 12, 20, 24 and 30 MeV; measured $\sigma(\theta)$. PWBA analysis. Enriched target.

## 1. Introduction

The mechanism of (p, α) or (α, p) reactions on light nuclei has been previously studied by several authors [1-6]. However the parameters used for these investigations often show important variations with incident energy. These variations can be observed in the $^{11}$B(p, α) reaction [5] below 12 MeV probably because of compound nucleus formation. It seems interesting to extend this analysis to higher incident energies. Angular distributions at 12, 20, 24, 30 MeV have been measured and other experiments [7] at 26.7 and 38 MeV have also been analysed.

## 2. Experimental details

The experiment at 12 MeV was performed with the CEN Bruyeres le Chatel Van de Graaff tandem and the experiments at higher energies with the Grenoble cyclotron. The reaction products were detected by silicon surface-barrier detectors 500 to 1000 μm thick. These thicknesses were chosen to stop α-particles and not the other particles. Self-supporting isotopic $^{11}$B targets were used at 12 MeV and gaseous diborane (99 % $^{11}$B enriched) at higher energies. The chemical and isotopic purity of these gaseous targets permits a measurement of the absolute cross section with an accuracy of the order of 10 %. The usual contaminations such as carbon and oxygen which exist in all solid boron targets are also eliminated. The observed resolution on the $\alpha$-spectrum was about 40 keV at 12 MeV and 150 keV at higher energies.

### 3. General considerations

First of all a comment must be made on the possibility of compound nuclear effects. All the six angular distributions are asymmetric about 90° (fig. 2). Their shapes and amplitudes show a regular behaviour with changes in energy. Both of these observations are compatible with the hypothesis of a direct reaction. In order to estimate compound nuclear contributions the excitation curves at three angles in 40 keV steps and four other angular distributions have been measured in the energy range 10–12 MeV. Between 11 and 12 MeV the angular distributions vary very slowly with energy and the excitation curves do not show fine structure despite the smallness of the energy spread of the tandem beam (2 keV). So one can think, even at 12 MeV, that compound nuclear effects are small and do not disturb the main conclusions extracted from the PWBA analysis.

Calculations have been performed in the cut-off plane wave Born approximation. The choice of the cut-off plane wave Born approximation in this paper was made for the following reasons.

The validity of DWBA for the T(p, $\alpha$)R reaction for light nuclei has not been satisfactorily examined. The neglected interaction potential, $V_{pR} - U_{pT}$, seems to have a large effect compared with the case of the (d, p) reaction [8]. In the preliminary DWBA calculations of the triton pick-up mechanism for the $^{11}$B(p, $\alpha$) reaction carried out at 20, 30 and 38 MeV by Yoshida †, the fit is not good mainly at backward angles. These results and other previous (p, $\alpha$) reaction analyses [6, 7] show that several reaction mechanisms (pick-up, exchange) are required to fit the data. An exact DWBA calculation for the heavy-particle pick-up is rather difficult [10, 11].

The $Q$-value and large momentum transfer in the $^{11}$B(p, $\alpha$) reaction produce "wave function mismatching" (angular momentum mismatching) [9]. A great number of partial waves contribute in the reaction cross section while only a small number of partial waves are determined by the elastic scattering. Further, for this reaction, $\alpha$-particle optical parameters cannot be determined exactly from elastic scattering due to the instability of the nucleus $^8$Be and all other mass-eight nuclei. Then again the Coulomb distortion effect is expected to be small because of high incident energies, large $Q$-value and the lightness of the nuclei under study.

The cut-off procedure introduces the idea of the nucleon cluster reduced width. The conception of nucleon cluster on the nuclear surface is not unrealistic in the light nuclei. Recent coupled channel calculations for the (d, p) reaction seem to assure this procedure for the composite particle [12, 13].

† H. Yoshida, private communication. The authors would like to thank him for the kind communication of the result.

The four most important direct mechanisms for (p, $\alpha$) reactions are:

(i) Triton pick-up (fig. 1a) with an interaction between the incident proton and $\alpha$-particle in the target nuclei.

(ii) Alpha-particle knock-out (fig. 1b) with p-$\alpha$ interaction.

(iii) Heavy-particle pick-up (fig. 1c) with $\alpha$-like structure in the target and a proton-core interaction.

(iv) Heavy-particle knock-out (fig. 1d) with triton-like structure in the target and a proton-core interaction.

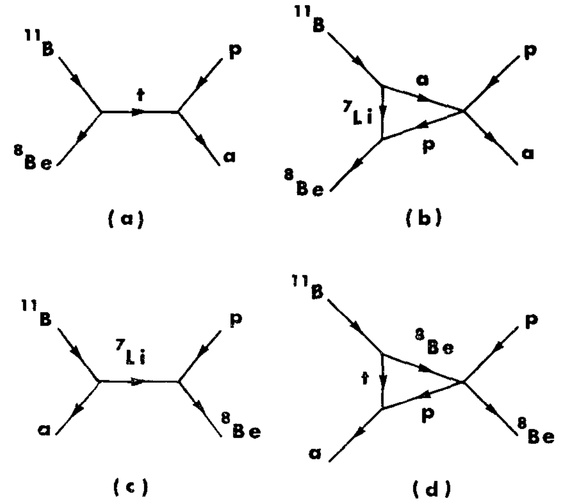


Fig. 1. Feynman graphs for the four mechanisms.

## 4. Matrix elements

### 4.1. PICK-UP

The matrix element for the pick-up mechanism can be written:

$$M_{(\mathrm{pu})} = -\frac{2\hbar^2}{\sqrt{3}M_{\mathrm{pt}}}(8\pi)^{\frac{1}{2}}4\pi(\beta R_t)^{\frac{1}{2}}R_t \sum_{l_t j_t} S_t O_t \theta_{0t}\, i^{-l_t} \frac{1}{(K_t R_t)^2+(\chi_t R_t)^2}$$
$$\times J_{l_t}(K_t R_t, \chi_t R_t) \sum_{m_t \mu_t \nu_t} (\tfrac{1}{2}\nu_p \tfrac{1}{2}\nu_t|00)(\tfrac{1}{2}\nu_t\, l_t\, m_t|\, j_t\, \mu_t)(I_R\, m_R\, j_t\, \mu_t|I_T m_T) Y_{l_t m_t}(\boldsymbol{K}_t)$$

wheie $M_{\mathrm{pt}}$ is the reduced mass of a proton in the $\alpha$-particle.

Symbols and $J_l(KR, \chi R)$ functions have the same meaning as in refs. [1,14]). The p-t system is described with a Yukawa-type wave function. Momentum transfer is defined by the relation: $\boldsymbol{K}_t = \boldsymbol{k}_\alpha - (M_R/M_t)\boldsymbol{k}_p$ where $\boldsymbol{k}_\alpha$ and $\boldsymbol{k}_p$ are the momenta of the out-going and incident particle. The $O$-factors are overlap integrals between the internal wave function of the transferred group of nucleons when bound in the target nucleus and in the $\alpha$-particle. Spectroscopic factors $S$ are calculated in $LS$-coupling and transformed into $jj$-coupling [15]. The radial reduced widths $\theta_0$ are assumed to be independent of the transferred angular momentum and were found by comparison with experimental data.

### 4.2. KNOCK-OUT

The matrix element is given by:

$$M_{(\mathrm{ko})} = -(4\pi)^{\frac{3}{2}} V_{\mathrm{p}\alpha} R_k^3 \sum_{l_\mathrm{p} j_\mathrm{p} I_\mathrm{c} l_\alpha L} S_\mathrm{p} S_\alpha \theta_{0\alpha} O_\alpha i^{-L} (2l_\mathrm{p}+1)^{\frac{1}{2}} (2l_\alpha+1)^{\frac{1}{2}} (2L+1)^{-\frac{1}{2}}$$

$$\times (l_\mathrm{p} 0 l_\alpha 0 | L0) \frac{1}{(K_k R_k)^2 + (\chi_k R_k)^2} J_L(K_k R_k, \chi_k R_k) \sum_{\mu_\mathrm{p} m_\mathrm{p} m_\mathrm{c} m_\alpha} (\tfrac{1}{2} \nu_\mathrm{p} l_\mathrm{p} m_\mathrm{p} | j_\mathrm{p} \mu_\mathrm{p})$$

$$\times (I_\mathrm{c} m_\mathrm{c} j_\mathrm{p} \mu_\mathrm{p} | I_\mathrm{R} m_\mathrm{R})(I_\mathrm{c} m_\mathrm{c} l_\alpha m_\alpha | I_\mathrm{T} m_\mathrm{T})(l_\mathrm{p} - m_\mathrm{p} l_\alpha m_\alpha | LM)(-)^{m_\mathrm{p}} Y_{LM}(\boldsymbol{K}_k),$$

with

$$\boldsymbol{K}_k = \frac{M_\mathrm{c}}{M_\mathrm{R}} \boldsymbol{k}_\alpha - \frac{M_\mathrm{c}}{M_\mathrm{T}} \boldsymbol{k}_\mathrm{p}, \qquad \boldsymbol{K}_k = \frac{M_\mathrm{c}}{M_\mathrm{R}} \boldsymbol{K}_\mathrm{t},$$

where $V_{\mathrm{p}\alpha}$ is the zero-range interaction potential $V(\mathrm{p}, \alpha) = -V_{\mathrm{p}\alpha} \frac{4}{3}\pi R_k^3 \delta(r_\mathrm{p} - r_\alpha)$ and so $R_k = R_\mathrm{p} = R_\alpha$. The value of $V_{\mathrm{p}\alpha}$ is found by comparison with experimental data

### 4.3. HEAVY PARTICLE PICK-UP

The matrix element is given by

$$M_{(\mathrm{hppu})} = -\frac{\hbar^2}{2M_\mathrm{p}^{**}} \left(\frac{9R_\alpha^3}{R_\mathrm{p}}\right)^{\frac{1}{2}} (4\pi)^{\frac{3}{2}} \sum_{l_\mathrm{p} j_\mathrm{p} I_\mathrm{c} l_\alpha} S_\mathrm{p} S_\alpha \theta_{0\alpha} O_\alpha i^{l_\mathrm{p} - l_\alpha} (2l_\mathrm{p}+1)^{\frac{1}{2}}$$

$$\times J_{l_\mathrm{p}}(K_\mathrm{p} R_\mathrm{p}, \chi_\mathrm{p} R_\mathrm{p}) \frac{1}{(K_\alpha R_\alpha)^2 + (\chi_\alpha R_\alpha)^2} J_{l_\alpha}(K_\alpha R_\alpha, \chi_\alpha R_\alpha) \sum_{\mu_\mathrm{p} m_\mathrm{p} m_\mathrm{c} m_\alpha} (\tfrac{1}{2} \nu_\mathrm{p} l_\mathrm{p} m_\mathrm{p} | j_\mathrm{p} \mu_\mathrm{p})$$

$$\times (I_\mathrm{c} m_\mathrm{c} j_\mathrm{p} \mu_\mathrm{p} | I_\mathrm{R} m_\mathrm{R})(I_\mathrm{c} m_\mathrm{c} l_\alpha m_\alpha | I_\mathrm{T} m_\mathrm{T}) Y_{l_\alpha m_\alpha}(\boldsymbol{K}_\alpha) \delta_{m_\mathrm{p} 0},$$

where $M_\mathrm{p}^{**}$ is the reduced mass of the p-core system, the p-core interaction is eliminated since residual nuclear states are eigenstates of this interaction. Momentum transfers are $\boldsymbol{K}_\alpha = \boldsymbol{k}_\alpha + m_\alpha \boldsymbol{k}_\mathrm{p}/m_\mathrm{T}$ and $\boldsymbol{K}_\mathrm{p} = \boldsymbol{k}_\mathrm{p} + m_\mathrm{p} \boldsymbol{k}_\alpha/m_\mathrm{R}$. There are two cut-off radii corresponding respectively to the α- and p-core system.

We have also calculated the heavy-particle knock-out angular distribution. Its shape is almost isotropic and does not reproduce the very structured experimental distributions. So we assume that the heavy-particle knock-out amplitude is small and we neglect it in the following calculations.

## 5. Spectroscopic factors

The following configuration will be adopted for the $^{11}$B (ground state) wave function:

$$-0.672[43]^{22}\mathrm{P}_{\frac{3}{2}} + 0.741[43]^{22}\mathrm{D}_{\frac{3}{2}}.$$

These values are obtained [16]) with $a/K = 6$ and $L/K = 6.8$. For triton pick-up the spectroscopic factor has to be calculated with the configuration $P^7[43]^{22}P_{\frac{3}{2}}$ corresponding to $^8$Be(ground state)$P^4[4]^{11}S_0$ and to a triton $P^3[3]^{22}P\frac{3}{2}$. We get $S_t = 0.641$ with $l_t = 1$ and $j_t = \frac{3}{2}$.

For knock-out and heavy-particle pick-up two types of configurations are to be considered: first the $^{11}$B as $^7$Li and an $\alpha$-particle, second the $^8$Be as $^7$Li and a proton. For the $^{11}$B we have:

$$P^7[43]^{22}L_{T\frac{3}{2}} \rightarrow P^3[3]^{22}P_{I_c} + P^4[4]^{11}l_\alpha,$$

with $L_T = 1$ or 2 and $l_\alpha = 0$ or 2. We consider also two states of the $^7$Li core $I_c = \frac{3}{2}$ and $\frac{1}{2}$ because these two first states have very close energies. In the same way for $^8$Be

$$P^4[4]^{11}S_0 \rightarrow P^3[3]^{22}P_{I_c} + P[1]^{22}P_{j_p}.$$

The values of the spectroscopic factors $S_p$ and $S_\alpha$ are listed in table 1.

TABLE 1

Spectroscopic factors $S_\alpha$ for the ground state of $^{11}$B and $S_p$ for the ground state of Be

| $l_\alpha$ | $I_c$ | $l_p$ | $j_p$ | $S_p$ | $S_\alpha(^{22}P)$ | $S_\alpha(^{22}D)$ | $S_\alpha$ $-0.672$ P$+0.741$ D | $S_pS_\alpha$ |
|---|---|---|---|---|---|---|---|---|
| 0 | $\frac{3}{2}$ | 1 | $\frac{3}{2}$ | 1.234 | (−) 0.637 | 0 | 0.428 | 0.528 |
| 2 | $\frac{3}{2}$ | 1 | $\frac{3}{2}$ | 1.234 | 0.422 | (−) 0.617 | (−) 0.741 | (−) 0.914 |
| 2 | $\frac{1}{2}$ | 1 | $\frac{1}{2}$ | 0.873 | (−) 0.422 | (−) 0.617 | (−) 0.173 | (−) 0.151 |

## 6. Comparison with experiments

One can see from the mathematical form of the matrix elements that the angular distributions due to the knock-out and pick-up processes are roughly the same. If $K_t R_t = K_k R_k$ the differences come only from $\chi_t \neq \chi_k$. It is therefore impossible to distinguish these two processes and so we never consider them simultaneously but we use each of them separately with a process of heavy-particle pick-up.

The cross section is given by

$$\frac{d\sigma}{d\Omega} = \frac{M_p^* M_\alpha^*}{(2\pi\hbar^2)^2} \frac{k_\alpha}{k_p} \frac{1}{2(2I_T+1)} \sum_{\nu_p m_T m_R} |M_{(x)} + M_{(hppu)}|^2,$$

where $M_{(x)} = M_{(pu)}$ or $M_{(ko)}$. In each case the three cut-off radii and the two amplitude parameters are found by a least-squares programme. At each energy several different values are used to start the programme in oder to be sure that the solutions do not depend on the choice of starting values. As can be seen from fig. 2 the theoretical curves fit the experimental results fairly well except at 20 MeV where the central peak is not well reproduced. These fits are much better than those obtained using only one mechanism without heavy particle pick-up. Similar investigations of nucleon transfer reactions for light nuclei in the same energy range have also shown the importance of the heavy-particle pick-up process. So for instance the $^{9}Be(p, \alpha)$ [ref. [17])], $^{16}O(p, \alpha)$ [ref. [15])], $^{15}N(p, \alpha)$ [ref. [15])], $^{16}O(n, \alpha)$ [ref. [11])], $^{12}C(\alpha, p)$ [ref. [1])] and $^{12}C(t, \alpha)$ [ref. [14])] angular distributions display the same trend and are well explained by the heavy-particle pick-up mechanism. It can be noticed that for the $^{16}O(n, \alpha)$ [ref. [11])] reaction the PWBA and DWBA calculations lead to the same

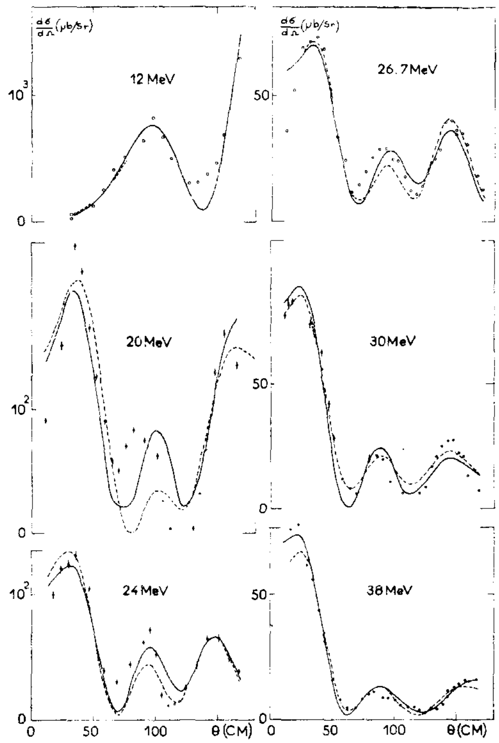


Fig. 2. The differential cross sections predicted by PWBA. The solid curves are calculated cross sections for the heavy-particle pick-up plus pick-up reactions. The dashed curves are the calculated cross sections for the heavy particle pick-up plus knock-out reactions. Statistical errors are not reported for the Milan group data (26.7 and 38 MeV). At 12 MeV they are smaller than the size of the points.

conclusion. For some other reactions such as $^{19}F(p, \alpha)$ [refs. [18, 7])] the evidence for a single reaction mechanism seems to be due to the preponderance of the triton structure in the target nucleus.

The analysis with pick-up or knock-out mechanism are equivalent, and the heavy-particle pick-up parameters are not very sensitive to the choice of the other mechanism. The same ambiguity has been pointed out by Maxson [17]) for the $^{9}Be(p, \alpha)$ and $^{12}C(p, \alpha)$ reactions and by Lamot [11]) for the $^{16}O(n, \alpha)$ reaction.

TABLE 2

The cut-off radii and the amplitude factors found for the six energies under study with pick-up and heavy-particle pick-up mechanisms

| $E$ (MeV) | $\theta_{ot} O_t$ | $O_\alpha \theta_{o\alpha}$ | $R_T$ (fm) | $R_p$ (fm) | $R_\alpha$ (fm) |
|---|---|---|---|---|---|
| 12 | 0.234 | 1.22 | 3.55 | 4.09 | 5.82 |
| 20 | 0.223 | 0.830 | 3.60 | 4.55 | 5.80 |
| 24 | 0.219 | 0.900 | 3.50 | 4.00 | 5.20 |
| 26.7 | 0.173 | 0.790 | 3.22 | 3.72 | 4.94 |
| 30 | 0.219 | 0.298 | 3.55 | 4.91 | 5.54 |
| 38 | 0.214 | 0.223 | 3.13 | 5.35 | 5.00 |

TABLE 3

The cut-off radii and the amplitude factors found for the six energies under study with knock-out and heavy-particle pick-up mechanisms

| $E$ (MeV) | $V_{p\alpha}$ (MeV) | $\theta_\alpha O_{o\alpha}$ | $R_k$ (fm) | $R_p$ (fm) | $R_\alpha$ (fm) |
|---|---|---|---|---|---|
| 12 | 34.6 | 1.170 | 4.42 | 3.94 | 5.82 |
| 20 | 57.9 | 0.854 | 4.60 | 4.55 | 5.80 |
| 24 | 48.4 | 0.900 | 4.20 | 4.05 | 5.20 |
| 26.7 | 45.6 | 0.806 | 4.00 | 3.75 | 4.95 |
| 30 | 88.5 | 0.412 | 4.15 | 5.35 | 5.40 |
| 38 | 145.0 | 0.251 | 3.79 | 5.55 | 4.81 |

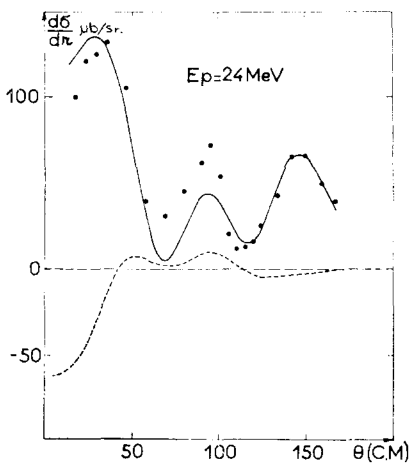


Fig. 3. The differential cross section and the interference term calculated for the heavy-particle pick-up plus pick-up reactions. Solid curve is the differential cross section, dashed curve is the interference term between the two mechanisms.

The interference term between the two mechanisms contributes significantly to the shape and the magnitude of the angular distribution and cannot be disregarded. An example of this term in the pick-up plus heavy-particle pick-up case is shown at $E_p = 24$ MeV (fig. 3). The values of the parameters (tables 2 and 3) do not show the irregular variations found at lower energies.

The ratio between the amplitudes of the heavy-particle pick-up and the knock-out or the pick-up process decreases smoothly with increasing incident energy, and at 38 MeV the $^{11}B(p, \alpha)$ reaction looks like a pure knock-out or pick-up reaction.

In order to compare the pick-up and knock-out probability it seems worthwhile to add some discussions from dispersion theory. In the cos $\theta$ plane the pick-up singularity is the nearest to the physical region (fig. 4). However the knock-out singularity

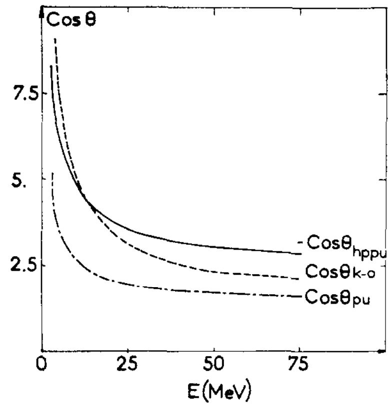


Fig. 4. Energy dependence of the singularities in the cos $\theta$ plane for the $^{11}B(p, \alpha)^8Be$ (g.s.) reaction.

comes closer to the physical region with increasing energy whereas the heavy-particle pick-up one moves slowly at high energies. That is in agreement with a large heavy-particle pick-up amplitude at low energies and a smaller one at high energies. On the contrary the energy dependence of the pick-up singularity compared to that of the heavy-particle pick-up singularity cannot explain a pure pick-up reaction at 38 MeV.

## 7. Conclusion

Our analysis indicates clearly the existence of more than one reaction mechanism and shows that at low energy the interaction between the incident proton and the core is very important. However by this analysis it is impossible to know which of these structures ($\alpha$ or triton particle) is preponderant. The existence of $\alpha$-clusters is often found in light nuclei. So the exchange reactions seem more probable than the pick-up reaction. Furthermore in the exchange reaction case dispersion theory can explain the energy dependence of the ratio between the two amplitudes.

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