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Nuclear Physics **A126** (1969) 562—576; © *North-Holland Publishing Co., Amsterdam*

STUDY OF (p, α) REACTIONS IN LIGHT NUCLEI AT 38 MeV

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Received 5 December 1968

measurement

Abstract: Differential cross sections for (p, α) reactions at $E_p = 38$ MeV have been obtained for ^{9}Be, ^{11}B, ^{12}C, ^{16}O and ^{19}F. Some angular distributions show a well-developed diffraction pattern, others do not. The results have been compared with PWBA calculations for four direct mechanisms (pick-up, knock-out, heavy-particle pick-up and heavy-particle knock-out). No single mechanism seems able to reproduce the pattern of any observed distribution for the whole angular range investigated.

E | NUCLEAR REACTIONS ^{9}Be, ^{11}B, ^{12}C, ^{16}O, ^{19}F(p, α); $E_p = 38$ MeV; measured $\sigma(E_\alpha, \theta)$. PWBA analysis. Natural targets.

1. Introduction

The study of (p, α) reactions has been limited mainly to energies below ≈ 30 MeV. The isochronous cyclotrons made it possible to extend this study to higher energies [1-3]). Investigations at these higher energies may deepen our understanding of the (p, α) reaction mechanism, which is unsatisfactory especially in the case of light nuclei. At proton energies sufficiently high for the direct interaction processes to be responsible for the observed reactions, the study of the alpha-particle angular distributions could provide valuable information on the nuclear wave functions and on the nuclear structure. The study of the (p, α) reaction however, is intrinsically difficult. The reaction involves the transfer of more than one nucleon, and therefore the system to be dealt with has many degrees of freedom. It can be expected that the analysis of the results will be severely hindered by the shortcomings of the presently available theories.

In this work, we have investigated a few (p, α) reactions on light nuclei and attempted to identify the direct process (or processes) responsible for each reaction.

2. Experimental results

The 38 MeV external proton beam of the Milan AVF cyclotron, produced by stripping off the internal H^- beam, was focussed on the target at a distance of about 9 m from the cyclotron. The energy spread of the proton beam was of the order of

1 %. The mean divergence of the beam at the target position was 2.4 mr. The solid angle subtended by the counter was $5 \cdot 10^{-4}$ sr; this angular tolerance combined with the beam divergence resulted in an over-all angular resolution of 0.8°. The counter could be positioned with an accuracy of ±0.15°; the direction of the beam, however, was determined with an accuracy of only ±0.25°.

The α-particles were detected with a 1800 μm thick silicon surface-barrier counter. The bias voltage was set at the value required to obtain the minimum depth of the sensitive region necessary to absorb the α-particles. This procedure provides a discrimination against protons and deuterons. The (p, t) and (p, ^{3}He) reactions on the

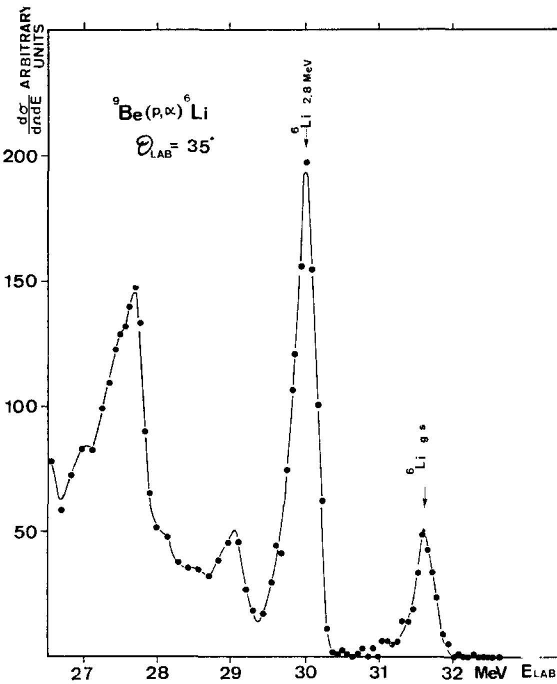

Fig. 1. Alpha-particle energy spectrum at a lab angle of 35° from the reaction ^{9}Be(p, α)^{6}Li.

nuclei investigated here have large negative Q-values. The over-all energy resolution was largely affected by target thickness. This was chosen as thick as permitted by the energy separation of the level studied. A typical energy spectrum is given in fig. 1.

The following natural targets were used: a self-supporting Be foil obtained by vacuum deposition, a layer of B prepared by deposition of amorphous boron on a mylar foil and for C, O and F, foils of Moplefan †, mylar and teflon, respectively.

Differential cross sections $d\sigma/d\Omega$ have been obtained for transitions to the ground states and in the case of Be also for the transition to the first excited state of ^{6}Li.

† Trade name of $(C_3H_4)_n$ manufactured by Montecatini-Edison SpA.

The experimental results are summarized in fig. 2, where the lines are guides to the eye. The large variety in the shapes of the angular distributions immediately raises doubts about the possibility to describe all these reactions with just one (p, α) reaction mechanism.

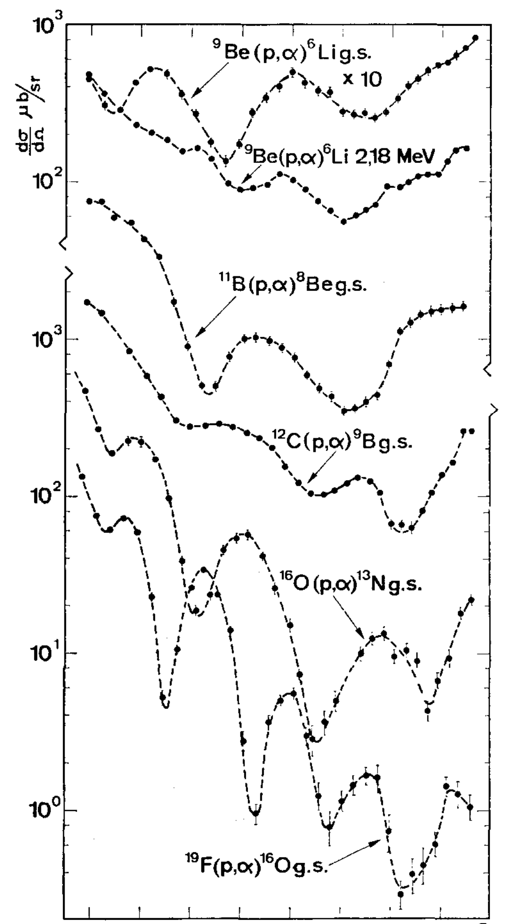

Fig. 2. Experimental differential cross sections. The curves are guides to the eye.

Table 1 lists the integrated cross sections. The nuclei investigated are too few to allow any systematic trend to be detected. The cross section for the transition to ^{6}Li (2.18 MeV) is greater than that to $^6Li_{g.s.}$; a similar behaviour was noticed [4]) for the odd-mass nuclei ^{27}Al and ^{31}P.

The errors indicated in the figures and in table 1 are those due to statistics only; the absolute values might have an error of 10–15 % arising from the uncertainties in target thickness, detector solid angle and beam monitoring.

TABLE 1
Integrated cross sections

Reaction	$\Delta\theta_{c.m.}$ (deg)	σ (μb)
$^9Be(p, \alpha)^6Li_{g.s.}$	15–170	430± 20
$^9Be(p, \alpha)^6Li$ (2.18 MeV)	15–165	1610± 30
$^{11}B(p, \alpha)^8Be$	15–165	189± 9
$^{12}C(p, \alpha)^9B$	15–170	3770±100
$^{16}O(p, \alpha)^{13}N$	15–170	760± 30
$^{19}F(p, \alpha)^{16}O$	15–170	186± 8

3. Analysis

3.1. PRELIMINARY CONSIDERATIONS

Thus far experimental and theoretical investigations of (p, α) reactions have been few in number and limited in scope. Since a suitable basis is lacking and because of the complexity of the many-nucleon (p, α) process, the analysis is bound to be more tentative than conclusive.

The analysis of direct reactions with transfer of a single nucleon, which are known to be dominated by the stripping or pick-up process, has produced a considerable amount of spectroscopic information. Similarly, the analysis of reactions with transfers of several nucleons might [5]) add to the knowledge of nuclear wave functions and structure. In order to exploit this suggestion, one should first establish the nature of the direct process predominantly responsible for the reaction.

The question of recognizing the dominant process (or processes) in any given (p, α) reaction is however rather intricate. Theoretically, four different mechanisms are predicted [6, 7]), which for (p, α) reactions can be described as follows:

(i) pick-up of a triton (hereafter abbreviated PU). The incident proton captures a triton of the target, thus forming the α-particle; the effective interaction is between the proton and the triton.

(ii) knock-out of an α-particle (KO). The incident proton knocks out an α-cluster from the target; the effective interaction is between the proton and the α-cluster.

(iii) heavy-particle pick-up (HPPU). As in the KO, the target nucleus is regarded as consisting of an α-cluster coupled to the core; the incident proton captures the core; the effective interaction is between the proton and the core.

(iv) heavy-particle knock-out (HPKO). As in the PU, the target nucleus is regarded as consisting of a triton coupled to the core; the incident proton knocks out the core; the effective interaction is between the incident proton and the core.

The first step in the analysis should be the theoretical calculation of the cross sections for each mechanism; then the comparison with the experimental curves might permit the identification of a dominant reaction process. Whether this obvious approach can give the desired answers depends of course on the adequacy of the calculations and on the degree to which one given process is effectively dominant in most of the angular range.

3.2. REACTION CROSS SECTIONS

We have calculated the differential cross sections for each of the four direct mechanisms using the plane wave Born approximation (PWBA) with zero-range interaction. Both the PWBA and the DWBA calculations of the cross section for the (p, α) reactions can be carried out only under drastic simplifications, i.e. neglecting the internal structure of the transferred particle.

An extensive DWBA analysis of the $^{19}F(p, \alpha)^{16}O$ reaction with a pick-up has been recently performed by Hird and Li [20]). The curve fits to the angular distributions are not satisfactory and depend strongly on the model assumptions and the choice of the parameters. The reactions $^{16}O(n, \alpha)^{13}C$ and $^{19}F(p, \alpha)^{16}O$ at $E_n = 14$ MeV and $E_p = 22.8$ and 30.5 MeV have been analysed [2,8,9]) with the DWBA, assuming KO+HPPU or PU+HPPU mechanisms for the first and PU only for the second. According to the authors, the results are not appreciably better than those one obtains with the simpler PWBA.

Because of the above results and the fact that the optical-model parameters are almost completely unknown we decided not to perform a DWBA analysis.

In the literature, there are no reported analyses of (p, α) or (α, p) reactions, which take into account all four mechanisms. Only in a few cases [10-13]) have the angular distributions been calculated considering one other mechanism (HPPU or KO) in addition to the PU. However, there seems to be no reason, especially when dealing with light nuclei, to disregard the two remaining mechanisms since the effective p-core interaction may not be negligible in comparison with the p-triton and p-α interactions. In the following part of this section we therefore give the cross section formulae for all four mechanisms, calculated in the PWBA.

To calculate the PU and HPKO processes in the T(p, α)R reaction, the schematization T = R+t is assumed, with (R+t)+p → R+(t+p); for the KO and HPPU, T = core + α with (core+α)+p → (core+p = R)+α. The following symbols are used:

μ_i and μ_f are the reduced masses of the systems in the initial and final states, K_p and K_α the momenta of the incident and emitted particles, μ_{xy} the reduced mass of the pair x, y (where x and y indicate particles), B_{xy} the binding energy of x+y, $\beta_{xy} = \sqrt{2\mu_{xy}B_{xy}/\hbar^2}$, ϑ_l the reduced width in Teichman-Wigner units, I_T, I_R and I_C the spins of the target, residual nucleus and core with z-components m_T, m_R and m_C, l_p, l_t and l_α the orbital angular momenta with z-components m_p, m_t and m_α, j_p and j_t the total angular momenta with z-components μ_p and μ_t, ν_p and ν_t the z-components of intrinsic spins and R_p, R_t and R_α the cut-off radii.

3.2.1. Pick-up. The cross section is given by the following expression, which was obtained along the line developed in ref. [14])

$$\frac{d\sigma}{d\Omega} = \frac{\mu_i \mu_f}{(2\pi\hbar^2)^2} \frac{K_\alpha}{K_p} \frac{1}{2(2I_T+1)} \sum_{\nu_p m_R m_T} |T|^2,$$

where the matrix element T is

$$T = (\tfrac{1}{2}\tfrac{1}{2}\nu_p - \nu_p|00)(\tfrac{1}{2}l_t \nu_t 0|j_t \nu_t)(j_t I_R \nu_t m_R|I_T m_T)$$
$$\times \left(\frac{3}{R_t^3}\right)^{\frac{1}{2}} \theta_{l_t} O_t D_0 i^{l_t} [4\pi(2l_t+1)]^{\frac{1}{2}} \frac{R_t}{Q^2+\beta_{tR}^2} J_{l_t}(Q, \beta_{tR}, R_t),$$

with

$$J_{l_t}(Q, \beta_{tR}, R_t) = QR_t j_{l_t-1}(QR_t) + C_{l_t} j_{l_t}(QR_t),$$
$$C_{l_t} = -i\beta_{tR} R_t \frac{h_{l_t-1}^{(1)}(i\beta_{tR} R_t)}{h_{l_t}^{(1)}(i\beta_{tR} R_t)}.$$

The term O_t is the overlap integral between the internal wave functions of the triton bound in the target nucleus and in the α-particle. Here $j_l(x)$ are spherical Bessel functions and $h_l^{(1)}(x)$ spherical Hankel functions of the first kind.

The momentum transferred when the recoil effects are taken into account is

$$Q = \left| \frac{M_R}{M_T} \boldsymbol{K}_p - \boldsymbol{K}_\alpha \right|.$$

Finally, for the internal wave function of the alpha particle a Yukawa-type wave function is chosen

$$D_0^2 = 8\pi \left(\frac{\hbar^2}{2\mu_{pt}}\right)^{\frac{3}{2}} B_{pt}^{\frac{1}{2}}.$$

In dealing with the relative motion of the system R+t, jj-coupling has been assumed. The wave function of this system has been approximated with that of a particle in a tri-dimensional rectangular potential well. Coulomb interaction has been disregarded.

3.2.2. Knock-out. The cross section is given by

$$\frac{d\sigma}{d\Omega} = \frac{\mu_i \mu_f}{(2\pi\hbar^2)^2} \frac{K_\alpha}{K_p} \frac{9}{2R_p^3 R_\alpha^3} \theta_{l_p}^2 \theta_{l\alpha}^2 O_\alpha^2 V_0^2 / |h_{l_p}^{(1)*}(i\beta_{pC} R_p) h_{l_\alpha}^{(1)}(i\beta_{\alpha C} R_\alpha)|^2$$
$$\times \sum_{lL} (2l_p+1)(2l_\alpha+1)(2L+1)(2j_p+1)(2I_R+1) W(l_p j_p l_p j_p; \tfrac{1}{2}L)$$
$$\times W(I_C j_p I_C j_p; I_R L) W(l_\alpha I_c l_\alpha I_C; I_T L) W(l_p l_\alpha l_p l_\alpha; lL)$$
$$\times (l_p l_\alpha 00|l0)(l_p l_\alpha 00; l0)(-1)^{I_R - I_T - \frac{1}{2}} \left| \int j_l(Qr) h_{l_p}^{(1)*}(i\beta_{pC} r) h_{l_\alpha}^{(1)}(i\beta_{\alpha C} r) r^2 dr \right|^2,$$

with

$$|l_p - l_\alpha \leqq l \leqq l_p + l_\alpha; \qquad (l_p + l_\alpha + l) \text{ even},$$
$$0 \leqq L \leqq \min\{2l_p, 2l_\alpha, 2I_C, 2j_p\}.$$

The term O_α is the overlap integral between the internal wave functions of the free α-particle and of the α-particle bound in the target nucleus. The modulus of the transferred momentum $\boldsymbol{Q}$ is defined as

$$Q = \left| \frac{M_C}{M_T} \boldsymbol{K}_p - \frac{M_C}{M_R} \boldsymbol{K}_\alpha \right| .$$

The W are Racah coefficients. The p-α interaction is taken in zero-range approximation, i.e. of the form $V = V_0 \delta(|\boldsymbol{r}_p - \boldsymbol{r}_\alpha|)$. The value of V_0 is a parameter in the calculation, for which we assumed tentatively the figure derived from the free (p, α) elastic scattering at energies comparable to ours [15]). Also in this case, the systems core + p and core + α have been considered in a *jj*-coupling scheme, and the wave functions have been approximated with the model of the rectangular potential well neglecting the Coulomb interaction.

3.2.3. Heavy-particle pick-up. The differential cross section is expressed by

$$\begin{aligned}\frac{d\sigma}{d\Omega} = {} & \frac{\mu_i \mu_f}{(2\pi\hbar^2)^2} \frac{K_\alpha}{K_p} \frac{9(4\pi)^{\frac{1}{2}}}{2R_p R_\alpha} (B_{\alpha C} + E_\alpha)^2 \frac{\theta_{l_p}^2 \theta_{l_\alpha}^2 O_\alpha^2}{(q_p^2 + \beta_{pC}^2)(q_\alpha^2 + \beta_{\alpha C}^2)} \\ & \times (-1)^{I_R - I_T - \frac{1}{2}} (2j_p+1)(2l_p+1)(2l_\alpha+1)(2I_R+1) \sum_L (2L+1)^{-\frac{1}{2}} \\ & \times W(l_p j_p l_p j_p; \tfrac{1}{2}L) W(j_p I_C j_p I_C; I_R L) W(l_\alpha I_C l_\alpha I_C; I_T L) \\ & \times (l_p l_p 00|L0)(l_\alpha l_\alpha 00|L0) Y_{L0}(\varphi) |J_{l_p}(q_p, \beta_{pC}, R_p)|^2 |J_{l_\alpha}(q_\alpha, \beta_{\alpha C}, R_\alpha)|^2,\end{aligned}$$

where J_l has the same meaning as in the PU cross section. The L-values range from 0 to 2 min $\{j_p, l_p, l_\alpha, I_c\}$. Furthermore

$$q_p = \left| -\boldsymbol{K}_p - \frac{M_p}{M_R} \boldsymbol{K}_\alpha \right|, \qquad q_\alpha = \left| \boldsymbol{K}_\alpha + \frac{M_\alpha}{M_T} \boldsymbol{K}_p \right|,$$

and φ is the angle between $\boldsymbol{q}_p$ and $\boldsymbol{q}_\alpha$. Again *jj*-coupling and the tri-rectangular potential well approximations have been assumed.

3.2.4. Heavy-particle knock-out. The expression of the differential cross section is

$$\frac{d\sigma}{d\Omega} = \frac{\mu_i \mu_f}{(2\pi\hbar^2)^2} \frac{K_\alpha}{K_p} \frac{1}{2(2I_T+1)} \sum_{\nu_p m_T m_R} |T|^2,$$

with

$$\begin{aligned}T = {} & i^{l_t}(2l_t+1)^{\frac{1}{2}} \left(\frac{3}{R_t^3}\right)^{\frac{1}{2}} \theta_{l_t} O_t \frac{(2\beta_{pt})^{\frac{1}{2}} V_0}{h_{l_t}^{(1)}(i\beta_{tR} R_t)} (\tfrac{1}{2}\tfrac{1}{2}\nu_p - \nu_p|00) \\ & \times (\tfrac{1}{2}l_t - \nu_p 0 | j_t - \nu_p)(j_t I_R - \nu_p m_R | I_T m_T) \\ & \times \int j_{l_t}(Qr) h_{l_t}^{(1)}(i\beta_{tR} r) e^{-\beta_{pt} r} r \, dr,\end{aligned}$$

where Q is defined as

$$Q = \left| \frac{M_t}{M_T} \boldsymbol{K}_p + \frac{M_t}{M_\alpha} \boldsymbol{K}_\alpha \right| .$$

For the system core+triton, jj-coupling has been assumed. The interaction potential has been written again in the zero-range approximation $V(\boldsymbol{r}_p - \boldsymbol{r}_C) = V_0 \delta(\boldsymbol{r}_p - \boldsymbol{r}_C)$ with V_0 considered as a parameter in the calculation.

3.3. COMPARISON OF THE CALCULATED CROSS SECTIONS WITH THE EXPERIMENTAL DATA

The differential cross sections have been computed assuming partial reduced widths $\theta_l O = 1$. The cut-off radius parameter has been determined by fitting the position of the forward maxima for the PU and KO cross sections and of the backward shape for the heavy-particle processes. When more than one l-value was permitted by the spin-selection rules, only the lowest one has been considered; to establish the l_p and l_α values, the core has been assumed to be in the ground state. The calculated cross sections have been smeared to allow for the angular aperture of the experimental set-up. Each curve has been independently normalised.

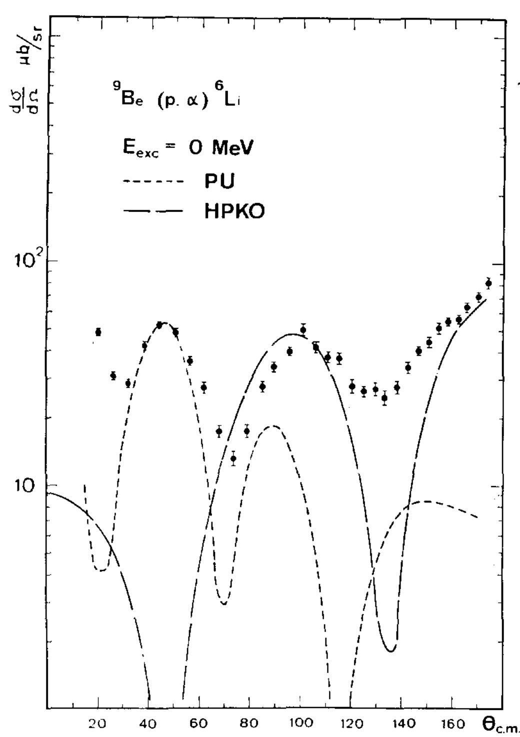

Fig. 3. Angular distribution of alpha particles to the ground state of ^{6}Li. The curves are the results of PWBA calculations with $l_t = 1$, $R = 5.2$ fm and $R = 5.6$ fm for the pick-up and the heavy-particle knock-out, respectively.

The result of these calculations is that no single mechanism seems able to reproduce the pattern of any observed distribution for the whole angular range investigated. Thus, inasmuch as the theory can be trusted, the disagreement might indicate that at least two, and possibly more, processes are responsible for the reactions investigated here.

3.4. DISCUSSION OF SPECIFIC REACTIONS

3.4.1. The ^{9}Be(p, α_0)^{6}Li, ^{9}Be(p, α_1)^{6}Li *and* ^{11}B(p, α)^{8}Be *reactions.* The experimental data for the first reaction and the calculated curves are shown in figs. 3 and 4. The PU and KO curves are practically indistinguishable; it is apparent that at least one of the "heavy-particle" processes is needed to approximate the backward angle behaviour. If the α-cluster model [16]) of ^{9}Be is valid the alpha exchange processes (KO and HPPU) might be favoured. Some evidence for the exchange mechanisms has been reported from the study of the same reaction [17]) at E_p = 18 MeV and of the inverse ^{6}Li(α, p)^{9}Be reaction [10]) at $E_\alpha \approx 30$ MeV.

A situation quite similar to the one observed for the transition to the ground state is encountered for the transition to the 2.184 MeV excited state of ^{6}Li (cf. figs. 5 and 6) and also for the reaction ^{11}B(p, α)^{8}Be (cf. figs. 7 and 8).

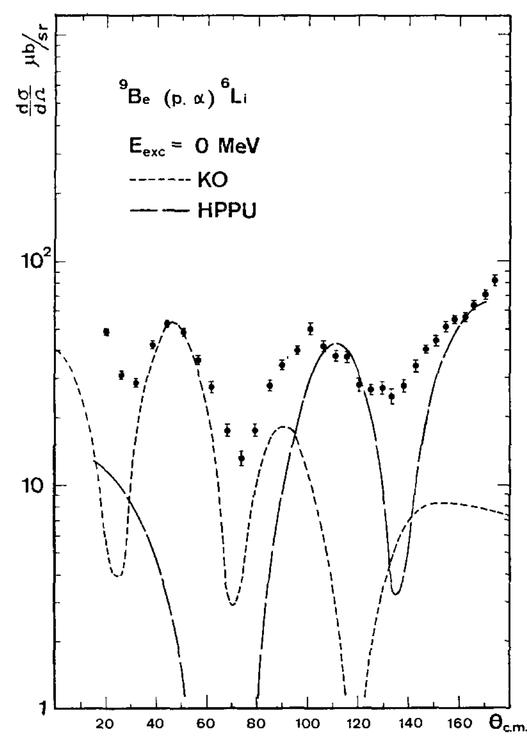

Fig. 4. As fig. 3 with $l_p = 1$, $l_\alpha = 0$, $R = 6.2$ fm and $R = 4.8$ fm for the knock-out and the heavy-particle pick-up, respectively.

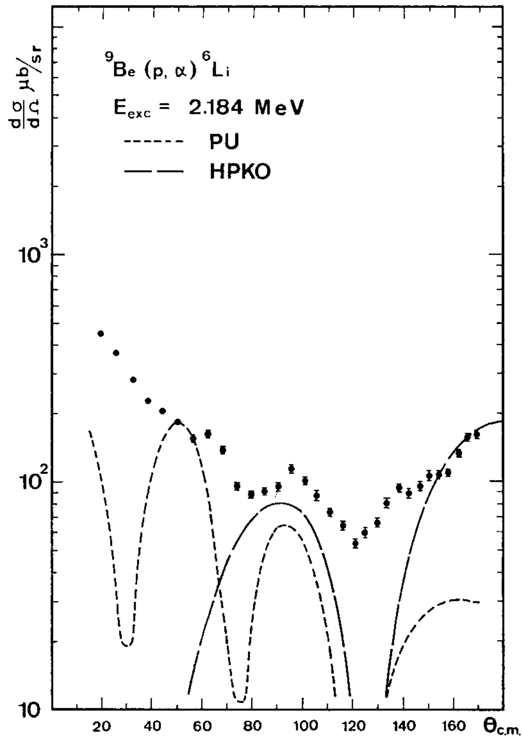

Fig. 5. Angular distribution of alpha particles to the first excited state of ^{6}Li. The curves are the results of PWBA calculations with $l_t = 1$, $R = 5.2$ and 5.6 fm for the pick-up and heavy-particle knock-out, respectively.

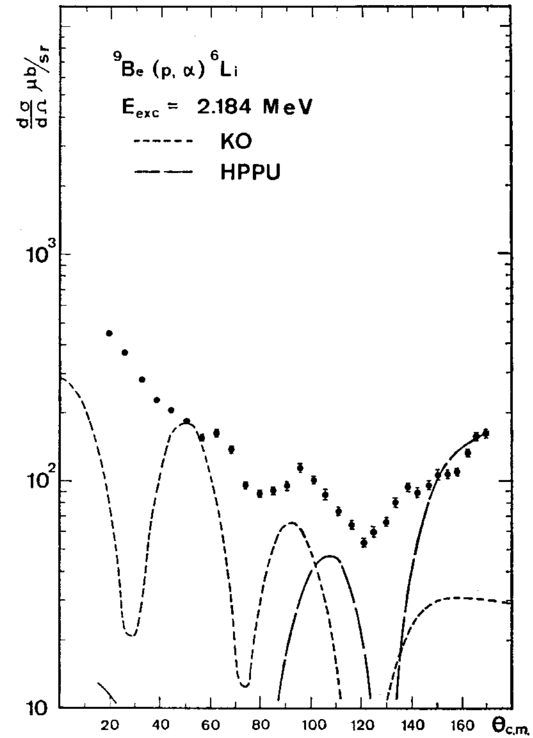

Fig. 6. As fig. 5 with $l_p = 1$, $l_\alpha = 0$, $R = 6.3$ and 4.8 fm for the knock-out and heavy-particle pick-up, respectively.

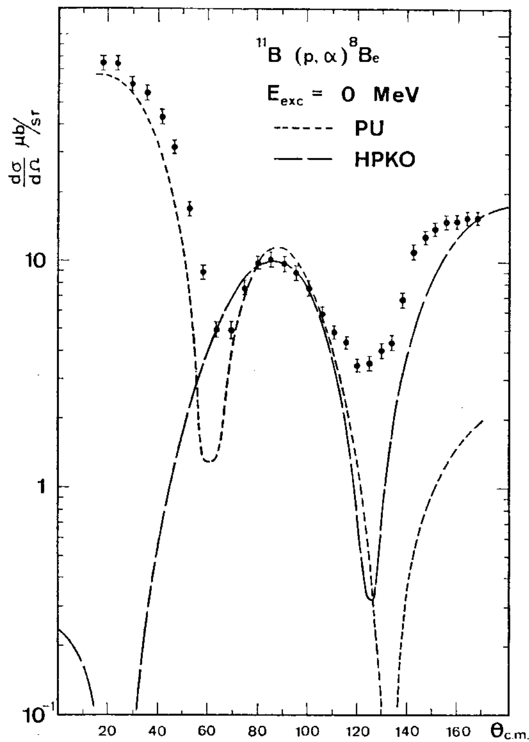

Fig. 7. Angular distribution of alpha particles to the ground state of ^{8}Be. The curves are the results of PWBA calculations with $l_t = 1$, $R = 3.2$ and 6.4 fm for the pick-up and heavy-particle knock-out, respectively.

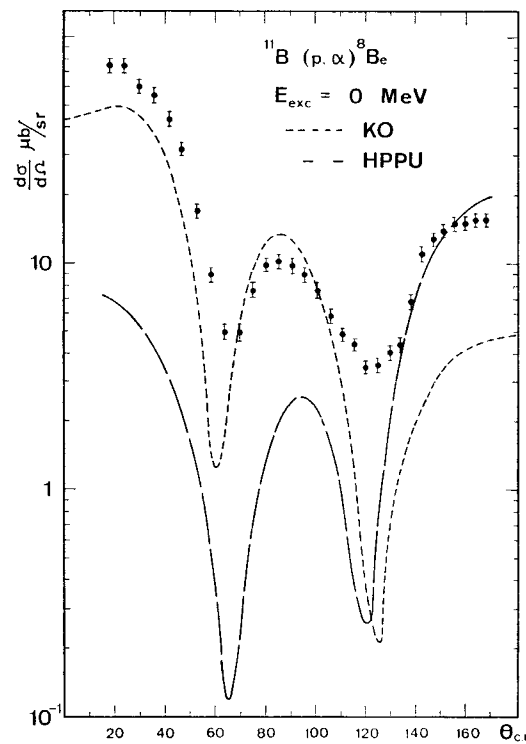

Fig. 8. As fig. 7 with $l_p = 1$, $l_\alpha = 0$, $R = 3.9$ and 3.2 fm for knock-out and heavy-particle pick-up, respectively.

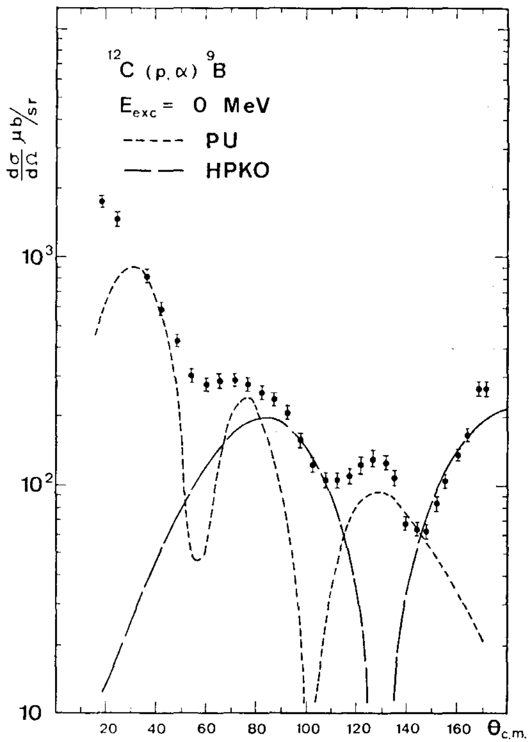

Fig. 9. Angular distribution of alpha particles to the ground state of ^{9}B. The curves are the results of PWBA calculations with $l_t = 1$, $R = 4.4$ and 5.8 fm for the pick-up and heavy-particle knock-out, respectively.

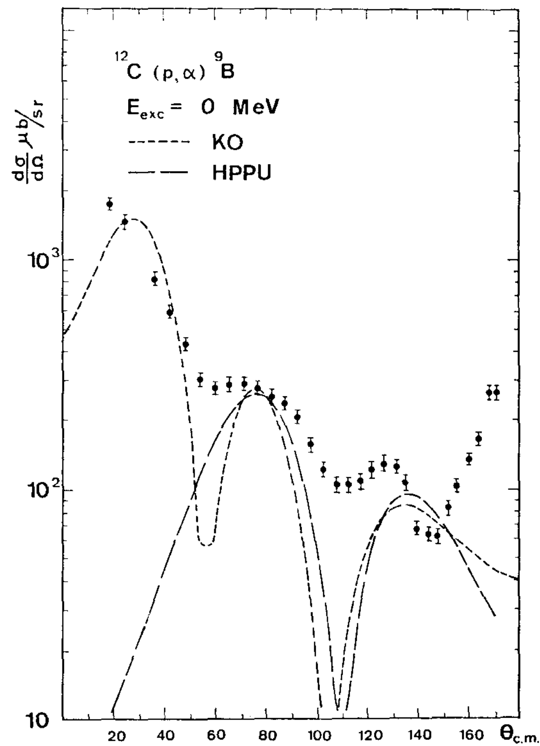

Fig. 10. As fig. 9 with $l_p = 1$, $l_\alpha = 0$, $R = 4.7$ and 4.6 fm for the knock-out and heavy-particle pick-up, respectively.

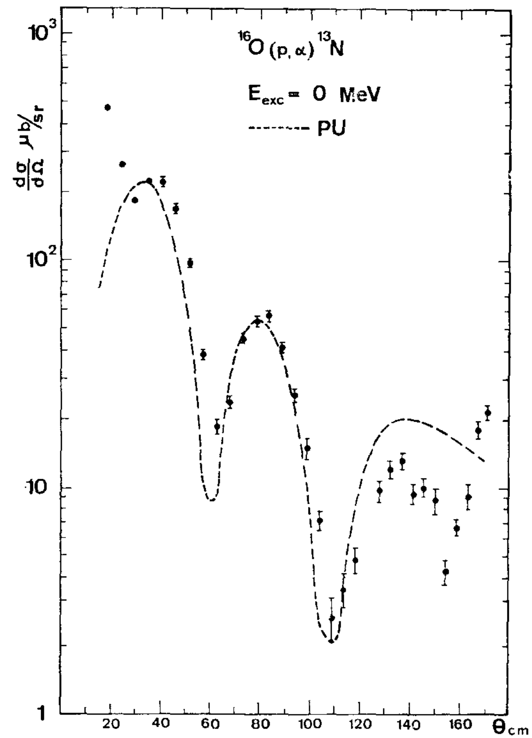

Fig. 11. Angular distribution of alpha particles to the ground state of ^{13}N. The PWBA curve for the pick-up process has been calculated with $l_t = 1$ and $R = 3.8$ fm.

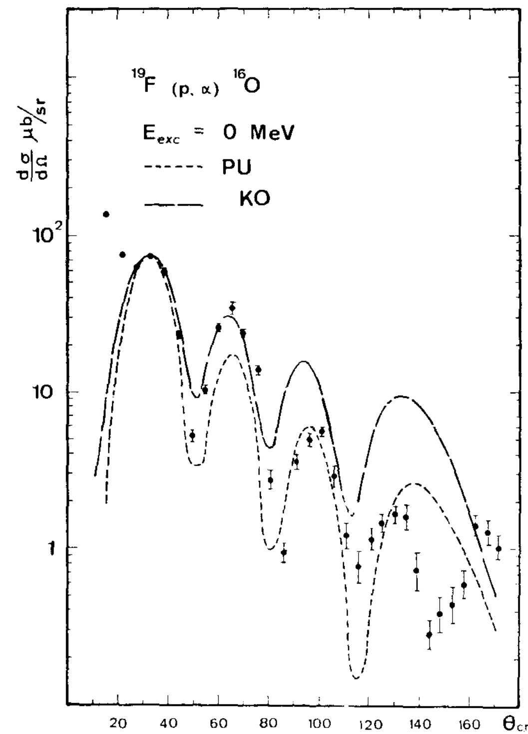

Fig. 12. Angular distribution of alpha particles to the ground state of ^{16}O. The PWBA curve for the pick-up process has been calculated with $l_t = 0$ and $R = 5.5$ fm and that for the knock-out with $l_p = 1$, $l_\alpha = 1$ and $R = 6.0$ fm.

3.4.2. The $^{12}C(p, \alpha)^9B$ *reaction.* The experimental data and the computed curves for the reaction $^{12}C(p, \alpha)^9B$ are shown in figs. 9 and 10. Again there is no evidence that any mechanism is dominant. Also for this reaction the argument of the possible α-cluster structure of ^{12}C would favour the exchange mechanisms.

This reaction has been investigated by Craig *et al.* [1]) at $E_p = 44.5$, 41.6 and 38.6 MeV. Their 38.6 MeV angular distribution agrees quite satisfactorily with ours. Their analysis, however, is limited to a PWBA calculation with the PU mechanism alone: therefore, their attempt to deduce the value of the reduced width seems rather premature. The inadequacy of a pure pick-up mechanism to describe this reaction has been indicated also at lower energies [17]).

3.4.3. The $^{16}O(p, \alpha)^{13}N$ *and* $^{19}F(p, \alpha)^{16}O$ *reactions.* The angular distributions of the α-particles from these reactions are steeper and more widely oscillating than the ones observed in the lighter elements. In fig. 11, the experimental results for the reaction $^{16}O(p, \alpha)^{13}N$ are compared with a PU curve. The KO curve calculated with a slightly different cut-off is practically coincident. Both curves produce a reasonable fit and thus the assumption of heavy particle processes is not required. At both ends of the angular range, however, the agreement is poor.

Some studies of the ^{19}F structure favour the predominance of a triton pick-up mechanism in the $^{19}F(p, \alpha)^{16}O$ reaction. According to a cluster model [18]), the ^{19}F states with positive and negative parity can be described as $^{16}O+t$ and $^{15}N+\alpha$ configurations, respectively. The PU would be favoured, since the ^{19}F ground state has a positive parity ($I = \frac{1}{2}^+$). Actually, our experimental results do not lend themselves to unambiguous interpretation. A PU calculation with $l_t = 0$ and $R = 5.5$ fm gives a curve (fig. 12) which is in phase with the measured distribution. Also a KO curve with $l_p = 1$, $l_\alpha = 1$, and $R = 6.0$ fm reproduces the position of the maxima but gives too high a cross section at backward angles. The conclusions from other studies [1,2,19,20]) of the same reaction at energies higher than 20 MeV have been obtained always by means of analyses based on the PU mechanism alone.

4. Conclusion

Our attempts to analyse the angular distributions of (p, α) reactions on light nuclei in the framework of the existing theories are rather inconclusive.

The DWBA approach normally used to describe direct reaction processes is hardly adequate in this case, since the applicability of the optical model to very light nuclei is highly questionable. Even if the method was used, one would find that very few data are available from which to extract the optical parameters needed. At the relatively high energy of 38 MeV, the use of the PWBA to interpret the shape of the angular distributions of direct reactions on light nuclei may be justified.

Our PWBA analysis of the data includes four possible direct reaction mechanisms. No single mechanism alone seems able to account for the observed differential cross sections over the entire angular range investigated. Interference terms could therefore be present, and their effect should be considered in further PWBA analysis.

The few high-energy (p, α) data thus far collected for light nuclei do not indicate yet any definite trend in the relative importance of the various mechanisms.

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