(p,α) Reactions in Li^7, Be^9, and C^{12} at 15.0–18.6 MeV*

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(Received June 20, 1962)

Angular distributions of alpha particles from the $Li^7(p,\alpha)He^4$ reaction were measured at bombarding energies of 15.0 and 18.6 MeV, and $Be^9(p,\alpha)Li^6$ and $C^{12}(p,\alpha)B^9$ angular distributions were each measured at 15.6 and 18.6 MeV. Absolute cross sections were measured for all of the reactions. The main features of the $Li^7(p,\alpha)He^4$ angular distributions, which are symmetric about 90 deg, can be reproduced by the appropriately symmetrized triton pickup theory. The $Be^9(p,\alpha)Li^6$ ground state and $Be^9(p,\alpha)Li^{6*}$ (2.2 MeV) reactions exhibit backward peaking which suggests a possible contribution from heavy particle stripping. The $C^{12}(p,\alpha)B^9$ angular distributions are oscillatory but cannot be fitted satisfactorily using the plane wave triton pickup or knock-on theories. The oscillations in the $Li^7(p,\alpha)He^4$ and $C^{12}(p,\alpha)B^9$ angular distributions do not shift in angle as the bombarding energy is changed, so that the value used for the interaction radius must be decreased as the proton energy is raised. None of the angular distributions are strongly energy dependent, and all of the cross sections decrease with increasing bombarding energy.

I. INTRODUCTION

IN several recent investigations of (p,α) and (α,p) reactions at bombarding energies from 5 to 40 MeV, angular-distribution measurements have shown that direct rather than compound nuclear processes predominate in reactions proceeding to low-lying levels of the final nuclei. Plane-wave direct-reaction theories have been used with some success to describe the main features of the experimental results, but quantitatively satisfactory fits to (p,α) and (α,p) angular distributions generally have not been obtained. Recent efforts have been directed primarily toward gaining a better understanding of the reaction mechanism. In this paper, experimental angular distributions for the reactions $Li^7(p,\alpha)He^4$, $Be^9(p,\alpha)Li^6$, and $C^{12}(p,\alpha)B^9$ are compared with cross sections calculated from various plane-wave direct-reaction theories. Almost all of these results have been presented previously in a series of oral reports.[1–3]

Three different reaction mechanisms have been assumed in deriving theoretical cross sections for direct (p,α) reactions. In the triton pickup interpretation[4] of a reaction $X(p,\alpha)Y$, the initial nucleus X is assumed to resemble a triton and a core Y coupled together. The incident proton picks up the triton to form the emergent alpha particle, and the core Y is left as the residual nucleus. Thus, the reaction can be written as $(Y+t)+p\rightarrow Y+(t+p)$, where $X=(Y+t)$ and $\alpha=(t+p)$. The knock-on theory due to Butler[5] is based on a different model, in which the alpha particle is initially coupled to a core C to form the target X. The incoming proton interacts with the alpha particle and knocks it out ofthe nucleus, but the proton is caught in an orbit about the core. Schematically, $(C+\alpha)+p\rightarrow(C+p)+\alpha$, where $X=(C+\alpha)$ and $Y=(C+p)$. A third possible direct-reaction mechanism is heavy-particle stripping, first suggested by Madansky and Owen.[6,7] This is similar to the knock-on process except that the relevant interaction is that between the core C and one of the light particles, instead of that between the proton and the alpha particle. The heavy core C is exchanged between the alpha and the proton, just as the triton is exchanged in the triton pickup mechanism.

Plane-wave Born approximation calculations based on the triton pickup and knock-on models lead to theoretical cross sections characterized by oscillatory, forward-peaked angular distributions. The predicted cross sections are so nearly alike that these two processes probably cannot be distinguished by angular-distribution measurements. The theoretical cross section for heavy-particle stripping is peaked in the backward direction. The theory of all three of these processes has been discussed in a recent review article by Banerjee.[8] The $Li^7(p,\alpha)He^4$ and $C^{12}(p,\alpha)B^9$ results presented here are generally consistent with a triton pickup or a knock-on interpretation, but heavy-particle stripping seems to be important in the $Be^9(p,\alpha)Li^6$ reaction.

The triton pickup cross section for the case of orbital angular momentum $l=1$ in the system $X=(Y+t)$, as derived using the plane-wave Born approximation and assuming a zero-range triton-proton interaction in the alpha particle, is[4]

$$d\sigma/d\omega \propto [w(x)/(\alpha^2+q^2)]^2, \qquad (1)$$

where $x=qR$ and the Wronskian w is given by

$$w(x)=xj_0(x)+[\alpha^2R^2/(1+\alpha R)]j_1(x).$$

The momentum transfer q is

$$q=|\mathbf{k}_\alpha-(m_Y/m_X)\mathbf{k}_p|,$$

* This work was supported by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.
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1 D. R. Maxson and H. Horie, Bull. Am. Phys. Soc. **2**, 29 (1957).
2 D. R. Maxson and J. H. Terrell, Bull. Am. Phys. Soc. **3**, 381 (1958).
3 D. R. Maxson, Bull. Am. Phys. Soc. **4**, 286 (1959).
4 R. G. Thomas, Los Alamos Scientific Laboratory Report, 1953 (unpublished).
5 S. T. Butler, Phys. Rev. **106**, 272 (1957).
6 L. Madansky and G. E. Owen, Phys. Rev. **99**, 1608 (1955).
7 G. E. Owen and L. Madansky, Phys. Rev. **105**, 1766 (1957).
8 M. K. Banerjee, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Chap. V. B. 2, Part B, p. 695.

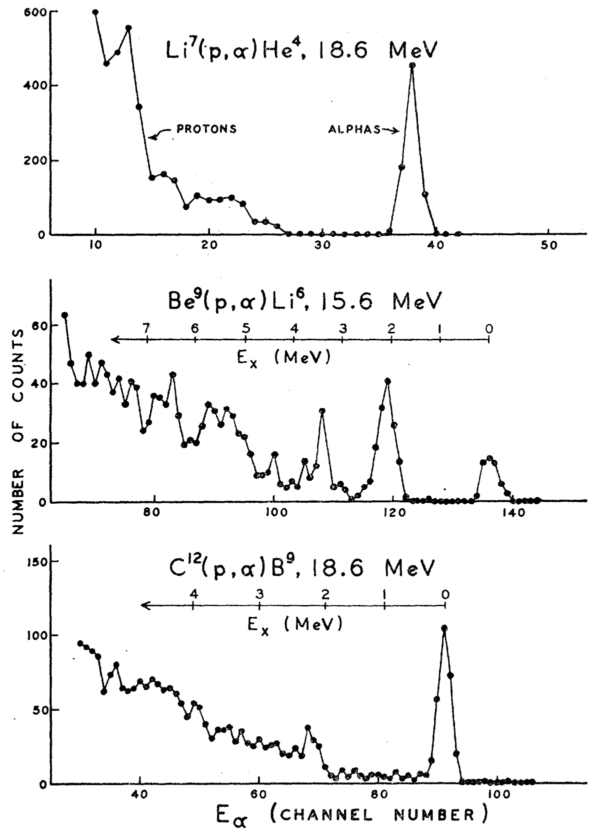

FIG. 1. Energy spectra of alpha particles from (p,α) reactions on Li^7, Be^9, and C^{12}. The spectra shown were all observed at $\theta_{lab}=45°$.

where $\mathbf{k}_\alpha$ and $\mathbf{k}_p$ are the (center-of-mass) momenta of the alpha and the proton, expressed in units of $\hbar$. Physically, q represents the change of linear momentum of the core Y. R is the interaction radius and α^{-1} is the decay length of the radial wave function of the system $(Y+t)$. In terms of the reduced mass μ and the binding energy B of $(Y+t)$, $\alpha=[(2\mu/\hbar^2)B]^{\frac{1}{2}}$. If the radial integrals which appear in the derivation of (1) are evaluated by the prescription of Bhatia *et al.*,[9] a simpler expression for the cross section is obtained:

$$d\sigma/d\omega \propto |j_1(qR)|^2. \qquad (2)$$

The angular distributions given by (1) and (2) are quite similar, although (2) requires a somewhat larger value of R.

If different expressions for q and α are used, formulas (1) and (2) also give the cross section for a knock-on process[5] characterized by orbital angular momenta $l_1=0$ and $l_2=1$ in the systems $(C+\alpha)$ and $(C+p)$. In this model

$$\alpha=[(2\mu_1/\hbar^2)B_1]^{\frac{1}{2}}+[(2\mu_2/\hbar^2)B_2]^{\frac{1}{2}},$$

where the subscripts refer to $(C+\alpha)$ and $(C+p)$, respectively. The momentum transfer q represents the change of momentum of the core C, and is given by

$$q=|(m_C/m_Y)\mathbf{k}_\alpha-(m_C/m_X)\mathbf{k}_p|.$$

For a heavy-particle stripping process involving the exchange of the core C between the system $(C+\alpha)$ in which $l_1=0$ and $(C+p)$ in which $l_2=1$, the formula analogous to (2) is [10]

$$d\sigma/d\omega \propto |j_0(QR)j_1(Q'R')|^2. \qquad (3)$$

Here R is the core-alpha interaction radius, R' is the core-proton interaction radius, Q is the change of momentum of the alpha, and Q' is the change of momentum of the proton. Explicity,

$$Q=|(m_\alpha/m_X)\mathbf{k}_p+\mathbf{k}_\alpha|$$

and

$$Q'=|\mathbf{k}_p+(m_p/m_Y)\mathbf{k}_\alpha|.$$

The appearance of only one spherical Bessel function in (2) is a consequence of the assumption of a zero-range trition-proton interaction; neither interaction radius is negligible in (3), and without that simplification the reaction amplitude contains two angular-dependent factors. If $m_\alpha \ll m_X$, the momentum transfers Q and Q' change relatively little as the angle between $\mathbf{k}_p$ and $\mathbf{k}_\alpha$ changes from zero to 180 deg. As a result, the angular dependence of the differential cross section is usually less pronounced for heavy-particle stripping than for knock-on or triton pickup. For the three reactions considered in this paper, $m_\alpha/m_X \geq 1/3$, and expression (3) has an appreciable angular dependence. The experimental $Be^9(p,\alpha)Li^6$ angular distribution does have a peak at large angles which can be roughly fitted by formula (3). Less information about heavy-particle stripping could be obtained from the other two reactions, since the $Li^7(p,\alpha)He^4$ angular distribution must be symmetric about 90 deg regardless of the mechanism, while the alphas from $C^{12}(p,\alpha)B^9$ were of such low energy that the observations could not be extended to extreme back angles.

II. EXPERIMENTAL PROCEDURE

Target foils were bombarded with protons from the the Princeton FM cyclotron, and the counters were mounted in the 60-in. scattering chamber.[11] The proton energy was measured to ± 0.1 MeV by a method previously described.[12]

In the Li^7 experiment, the alpha particles were detected by means of a proportional counter-scintillation counter telescope. NaI(Tl) crystals 8 to 14 mils thick were used in the scintillation counter. The proportional counter, which measured the (dE/dx) of the particles,

[9] A. B. Bhatia, K. Huang, R. Huby, and H. C. Newns, Phil. Mag. 43, 485 (1952).

[10] John S. Blair (unpublished).

[11] J. L. Yntema and M. G. White, Phys. Rev. 95, 1226 (1954).

[12] G. Schrank, Rev. Sci. Instr. 26, 677 (1955).

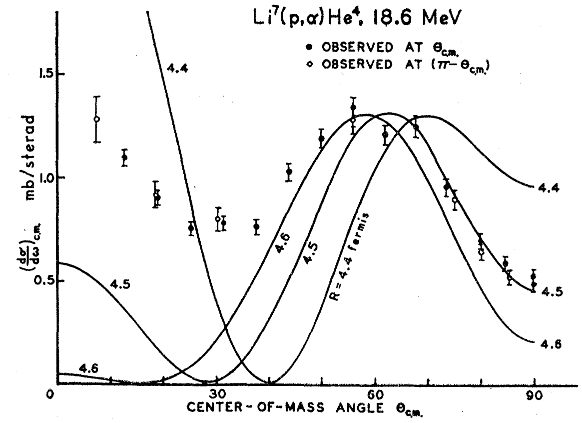

FIG. 2. The $Li^7(p,\alpha)He^4$ angular distribution observed at $E_p=18.6$ MeV (lab), compared with the symmetrized triton pickup formula (4). The angular distribution is symmetric about 90°.

was about 3 cm thick, and was filled with a mixture of argon plus 2% CO_2 at a pressure of about 16 cm Hg. In the measurements on Be^9 and C^{12}, an ionization chamber was used to detect the alphas. The chamber was of the cylindrical type employing a Frisch grid. A commercial mixture of argon plus 10% methane was used in the counter, and the pressure was adjusted so that the range of the most energetic alphas was somewhat shorter than the length of the chamber. Scattered protons then produced pulses not more than about one-third the height of the largest alpha pulses. The angle subtended by the counter aperture was not greater than 3 deg in any run with either counter. Typical spectra of alpha particles from (p,α) reactions in Li^7, Be^9, and C^{12} are shown in Fig. 1.

Some of the Li^7 targets were made by rolling natural lithium metal (93% Li^7) under dried mineral oil, and thinner ones were prepared by vacuum evaporation of Li onto thin (0.5 mg/cm^2) nickel backings. The weight of the lithium layer within a known area of one target (1.0 mg/cm^2) was determined by chemical analysis. The $Be^9(p,\alpha)Li^6$ measurements were made with a 0.13 mg/cm^2 target of pure Be metal, and the $C^{12}(p,\alpha)B^9$ reaction was studied using a polystyreme foil 0.13 mg/cm^2 thick. The beryllium and polystyrene targets were too thin and fragile to be removed from their supporting frames for weighing, so thicker foils of the same materials were weighed, and the relative thicknesses of the targets were determined by proton scattering measurements. An independent check on the thicknesses of the beryllium and carbon targets was obtained by comparing the proton scattering results with the absolute measurements of Dayton and Schrank.[13] The absolute cross sections indicated in the following figures are believed to be accurate to within ±10% for the $Li^7(p,\alpha)He^4$ and $C^{12}(p,\alpha)B^9$ ground-state reactions, and to within ±15% for the $Be^9(p,\alpha)Li^6$ reactions.

[13] I. E. Dayton and G. Schrank, Phys. Rev. **101**, 1358 (1956).

III. RESULTS AND DISCUSSION

A. $Li^7(p,\alpha)He^4$

In any of the direct-reaction models discussed above, the Li^7 target nucleus (3/2−) is regarded as a two-particle system consisting of a triton (1/2+) coupled to an alpha particle (0+) with orbital angular momentum $l=1$. After the reaction the triton and the incident proton are coupled together with $l=0$ to form one of the two alpha particles. In the derivation of Eq. (1), particles α and Y are assumed to be distinguishable, but in the special case of $Li^7(p,\alpha)He^4$ the reaction products are identical Bose particles. Because of this, the wave function of the system must be symmetric, and the (center-of-mass) angular distribution must be symmetric about 90 deg. With symmetrization of the wave function the cross-section formula corresponding to Eq. (1) becomes[1]

$$\frac{d\sigma}{d\omega}\propto\left[\left(\frac{w(x)}{\alpha^2+q^2}\right)^2+\left(\frac{w(x')}{\alpha^2+q'^2}\right)^2+2\left(\frac{w(x)}{\alpha^2+q^2}\right)\left(\frac{w(x')}{\alpha^2+q'^2}\right)\cos\Theta\right] \quad (4)$$

The first term is the cross section as given by Eq. (1) for alphas emerging in the direction $\mathbf{k}_\alpha$ at an angle θ with respect to the incident proton beam. The second term is the same as the first with θ replaced by $(\pi-\theta)$, corresponding to recoil alphas detected at angle θ, and the third term expresses the interference effects. Θ is the angle ($\leq\pi$) between the momentum-transfer vectors q and q', where $x'=q'R$,

$$\mathbf{q}=\mathbf{k}_\alpha-(4/7)\mathbf{k}_p,$$
$$\mathbf{q}'=-\mathbf{k}_\alpha-(4/7)\mathbf{k}_p,$$

and in magnitude $q'(\theta)=q(\pi-\theta)$. The "recoil alpha" term is actually a heavy-particle stripping term, q' in (4) corresponding to Q in (3). In the derivation of (4) the unbound-pair interaction, which is responsible for the knock-on process, was neglected. The opposite assumption of pure knock-on would lead to a similar formula involving momentum transfers smaller by the factor 3/4. Modification of (4) to include knock-on would introduce two squared knock-on terms and a knock-on interference term, plus cross terms involving knock-on with triton pickup and heavy-particle stripping.[14]

Figure 2 shows the angular distribution of alphas observed at a laboratory bombarding energy of 18.6 MeV. The experimental angular distribution is symmetric about 90 deg c.m. This is shown in the figure; the points represented by solid circles were observed at angles $\theta_{c.m.}$, whereas those represented by open circles were observed at $(\pi-\theta_{c.m.})$. The three theoretical curves were calculated from Eq. (4) for triton-alpha interaction radii of 4.4, 4.5, and 4.6 F. As can be seen from the figure, the predicted angular distribution is

[14] M. K. Banerjee (private communication).

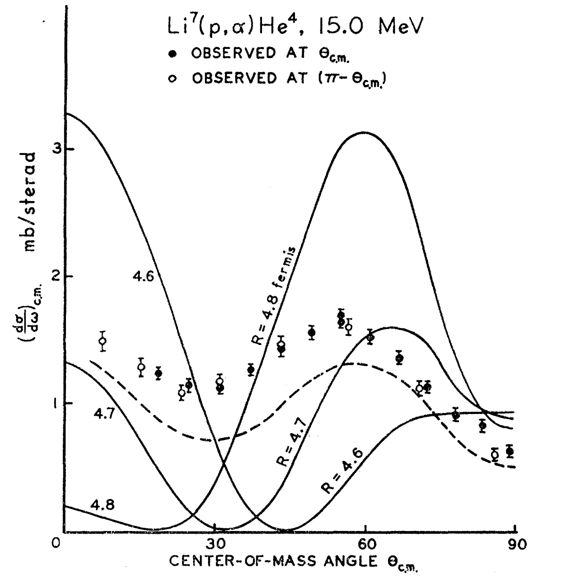

FIG. 3. Experimental and theoretical $Li^7(p,\alpha)He^4$ angular distributions at $E_p=15.0$ MeV (lab). The dashed line shows the 18.6-MeV experimental results of Fig. 2.

extremely sensitive to the choice of the interaction radius. This strong dependence on the radius arises partly from the large energy release in the reaction, for which $Q=+17.4$ MeV, and is especially pronounced because of the interference effect introduced by symmetrization of the wave function. Except for the filled-in minima, the main features of the experimental angular distribution can be reproduced by using a radius between 4.4 and 4.5 F. Other values ranging from 3 to 5 F were tried, but for radii substantially different from 4.5 F the theoretical curves were entirely different from the observed distribution.

The angular distribution at 15.0 MeV is shown in Fig. 3. The dotted curve represents the 18.6-MeV experimental distribution, replotted for comparison with the 15-MeV data. The two angular distributions are almost identical, but the cross section is larger at the lower energy. The theoretical curves in Fig. 3 were calculated from Eq. (4) using the same normalization constant, whereas the three curves in Fig. 2 were normalized individually to equal the observed cross section at 55 deg. At 15 MeV the best fit is obtained with a radius of about 4.7 F, compared with 4.45 F at 18.6 MeV. Figures 2 and 3 show that the radius required at either one of these two bombarding energies is completely unacceptable at the other energy.

Figure 4 shows the relative cross section at $\theta=45$ deg plotted as a function of the proton energy. This angle corresponds to 55.1 deg c.m. at 15 MeV and to 55.7 deg c.m. at 18.6 MeV, so that the measurements were made at the second maximum of the angular distribution. The dotted line indicates only that the variation of the cross section is linear to within the accuracy of the experiment. Because of the complication introduced by the observed interrelation between the interaction radius and the proton energy, no attempt was made to fit the data of Fig. 4. Qualitatively, however, the slow monotonic decrease of cross section with bombarding energy is consistent with the expected result for a direct reaction.

The $Li^7(p,\alpha)He^4$ angular distribution has recently been measured at a bombarding energy of 12 MeV.[15] The authors report that the angular distribution "shows direct interaction characteristics."

Total cross sections were obtained by plotting the experimental differential cross sections of Fig. 2 and Fig. 3 vs $\cos\theta_{c.m.}$, and integrating with a planimeter. The total $Li^7(p,\alpha)He^4$ cross section was found to be 15.4 ± 1.5 mb at 15.0 MeV and 12.0 ± 1.2 mb at 18.6 MeV.

B. $Be^9(p,\alpha)Li^6$

The $Be^9(p,\alpha)Li^6$ alpha-energy spectrum of Fig. 1 shows three peaks corresponding to (p,α) reactions proceeding to the ground state of Li^6 and to the excited levels at 2.2 and 3.6 MeV. The ground-state alpha group and the $E_x=2.2$-MeV group were the only ones clearly observed at all angles.

Angular distributions measured at 15.6 and at 18.6 MeV are shown in Fig. 5. From the general appearance of these distributions, it is evident that the data are inconsistent with the assumption of a simple triton pickup or knock-on mechanism. The rise in the cross sections at large angles suggests that heavy particle stripping may be important. The ground-state angular distribution at 18.6 MeV is roughly symmetric about 90 deg, and compound nuclear effects cannot be ruled out, but no such symmetry is evident in the other three curves. When the bombarding energy is increased by 3 MeV, the cross sections decrease somewhat, but there are no pronounced changes in the shapes of the angular distributions. Both of these observations are consistent with the assumption of a direct reaction.

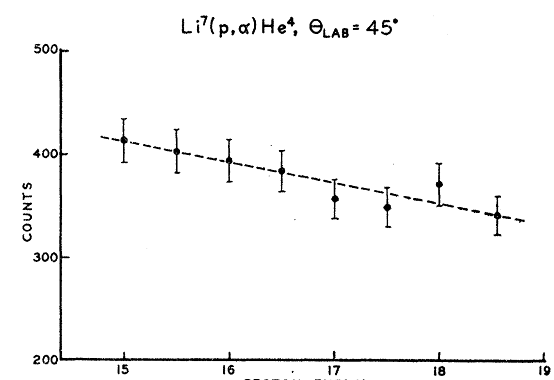

FIG. 4. Energy dependence of the $Li^7(p,\alpha)He^4$ differential cross section. The angle $\theta_{lab}=45°$ corresponds to $\theta_{c.m.}=55°$, so the data refer to the second maximum of the angular distribution.

[15] J. Alster and J. Gonzales-Vidal, Bull. Am. Phys. Soc. 5, 493 (1960).

The results shown in Fig. 5 for the $Be^9(p,\alpha)Li^6$ ground-state reaction at 18.6 MeV are in good agreement with the measurements of Klein *et al.*,[16] who observed the $Li^6(\alpha,p)Be^9$ angular distribution at an alpha energy of 30 MeV. This alpha-particle energy is equivalent to a proton energy of 17.6 MeV in the $Be^9(p,\alpha)Li^6$ reaction.

In the heavy-particle stripping interpretation of a $Be^9(p,\alpha)Li^6$ reaction, a He^5 core is exchanged between an alpha particle and a proton. For either of the reactions considered here, the relative orbital angular momenta are $l_1=0$ in the $Be^9=(\alpha+He^5)$ target and $l_2=1$ in the final Li^{6*} or $Li^6=(p+He^5)$ nucleus. Attempts to fit the $Be^9(p,\alpha)Li^{6*}$ (2.2 MeV) angular distributions with formula (3) were not successful. It is interesting, however, that the maxima and minima of the experimental distributions are displaced toward larger angles as the proton energy is increased. A shift in this direction is consistent with a heavy-particle stripping interpretation, whereas a displacement in the opposite direction would be expected (for constant radius) in a triton pickup or knock-on process.

Figure 6 shows an attempt to fit the 15.6-MeV ground-state angular distribution by assuming a combination of knock-on and heavy-particle stripping. The three interaction radii appearing in formulas (2) and (3) were arbitrarily assumed to be equal, so that, except for normalization, only two parameters (R and C_2/C_1) were adjusted to obtain the "theoretical" curve. For the

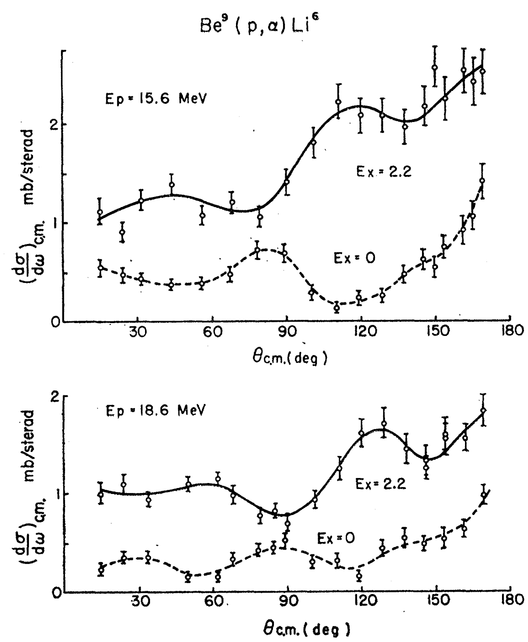

FIG. 5. Experimental angular distributions of alpha particles from the $Be^9(p,\alpha)Li^6$ ground state and $Be^9(p,\alpha)Li^{6*}$ (2.2 MeV) reactions, at laboratory bombarding energies of 15.6 and 18.6 MeV.

[16] P. R. Klein, N. Cindro, L. W. Swenson, and N. S. Wall, Nuclear Phys. **16**, 374 (1960).

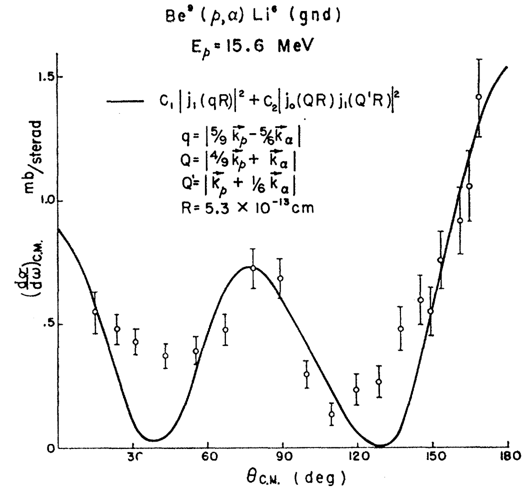

FIG. 6. An attempt to fit the $Be^9(p,\alpha)Li^6$ ground-state angular distribution by assuming contributions from both knock-on and heavy particle stripping.

curve shown, $R=5.3$ F and $C_2/C_1=19.5$. This large value of C_2/C_1 was required because of the occurrence of two Bessel functions in the second term and only one in the first, each Bessel function having a magnitude much less than unity. The maxima near zero and 80 deg are almost entirely due to the knock-on term, and the backward peak is almost entirely due to the heavy-particle stripping term. Since the knock-on amplitude is large where the heavy-particle stripping amplitude is small (for the particular case considered and with the above assumptions), and vice versa, interference between the two processes would not substantially change the shape of the calculated curve. The fit leaves much to be desired, but the figure illustrates that the main features of the angular distribution can be reproduced using a reasonable value for the interaction radius. Similar attempts to fit $Si^{28}(\alpha,p)P^{31}$ angular distributions by knock-on plus heavy-particle stripping have been reported recently by Ploughe *et al.*[17]

Although the results shown in Figs. 5 and 6 suggest that heavy-particle stripping may be important in these reactions, attempts to fit backward peaks in several other (p,α) and (α,p) reactions have been unsuccessful. Strong maxima near 180 deg have been observed in (p,α) reactions on oxygen,[18] fluorine,[19,20] and aluminum,[21] and in (α,p) reactions on lithium,[16] carbon,[22–24]

[17] W. D. Ploughe, E. Bleuler, and D. J. Tendam, Phys. Rev. **124**, 818 (1961).
[18] Donald R. Maxson, Phys. Rev. **123**, 1304 (1961).
[19] H. Ogata, J. Phys. Soc. Japan **14**, 707 (1959).
[20] J. G. Likely and F. P. Brady, Phys. Rev. **104**, 118 (1956).
[21] I. Kumabe, C. L. Wang, M. Kawashima, M. Yada, and H Ogata, J. Phys. Soc. Japan **14**, 713 (1959).
[22] R. Sherr, M. Rickey, and G. W. Farwell, Annual Progress Report, 1957, University of Washington (unpublished); R. Sherr and M. Rickey, Bull. Am. Phys. Soc. **2**, 29 (1957).
[23] I. Nonaka, H. Yamaguchi, T. Mikumo, I. Umeda, T. Tabata, and S. Hitaka, J. Phys. Soc. Japan **14**, 1260 (1959).
[24] J. R. Priest, D. J. Tendam, and E. Bleuler, Phys. Rev. **119**, 1301 (1960).

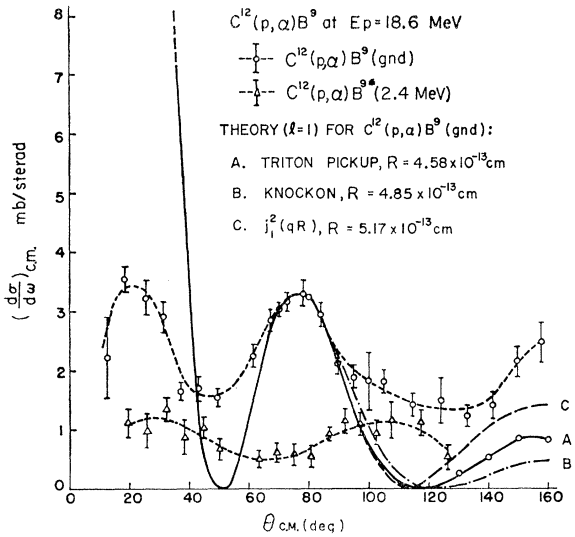

FIG. 7. The experimental $C^{12}(p,\alpha)B^9$ angular distribution at $E_p=18.6$ MeV (lab), compared with curves calculated from the plane-wave triton pickup and knock-on formulas. Experimental results for the $C^{12}(p,\alpha)B^{9*}$ (2.4 MeV) reaction are also shown.

and fluorine.[24] In most of these cases the momentum transfers Q and Q' of Eq. (3), and hence the heavy-particle stripping cross sections, change too slowly with angle to fit the experimental angular distributions. In the $Be^9(p,\alpha)Li^6$ reaction these momenta change somewhat more rapidly with angle because of the small mass of the target, with the result that the fit of Fig. 6 could be obtained. A survey of the available (p,α) and (α,p) data suggests that in some instances where maxima are observed near 180 deg, the backward peaks may be more strongly energy dependent than the forward portions of the angular distributions. This effect, which is most clearly evident in Ogata's[19] data on $F^{19}(p,\alpha)O^{16}$, may also be hard to reconcile with a heavy-particle stripping interpretation. Recent calculations by Tobocman[25] indicate that in some reactions distortion alone may be sufficient to account for strong backward peaks, even without heavy-particle stripping.

Total $Be^9(p,\alpha)Li^6$ cross sections were determined by graphical integration of the differential cross sections in Fig. 5. For the $Be^9(p,\alpha)Li$ reaction proceeding to the ground state of Li^6, $\sigma=6.0\pm0.9$ mb at 15.6 MeV and 4.6 ± 0.7 mb at 18.6 MeV. For the reaction leaving Li^6 in its first excited level at 2.2 MeV, $\sigma=20.3\pm3$ mb at 15.6 MeV, and 14.6 ± 2 mb at 18.6 MeV.

C. $C^{12}(p,\alpha)B^9$

The $C^{12}(p,\alpha)B^9$ energy spectrum in Fig. 1 has two peaks due to the (p,α) reactions proceeding to the ground and 2.4-MeV levels of B^9. No other monoenergetic alpha groups were observed, but weak groups could have been missed because of the continuum. The alpha continuum may result from $C^{12}(p,p')C^{12*}$ inelastic scattering followed by breakup of the excited C^{12} nucleus into three alpha particles, or it may be due to a direct 4-body breakup reaction. Knowles[26] has studied the continuum produced by bombardment with 32-MeV protons, and has reported that at that energy the direct 4-body breakup predominates.

Figure 7 shows the angular distributions observed at a bombarding energy of 18.6 MeV. The data for the reaction to the 2.4-MeV level were subject to large statistical uncertainties, so no theoretical comparisons were attempted. For the reaction proceeding to the ground state of B^9, three theoretical angular distributions are shown. Two of these were calculated from the triton pickup and knock-on formulas, and the third curve is a plot of j_1^2. In each case the interaction radius was adjusted to fit the second maximum of the experimental curve. Below 20 deg the experimental cross section decreases, while the theoretical curves rise to a strong maximum at zero degrees. The value used for the interaction radius could not be increased or decreased enough to reproduce the experimental maximum near 20 deg without completely destroying the fit at large angles. In addition, the over-all forward peaking of the experimental angular distribution is much smaller than that of any of the theoretical curves. According to Knowles,[26] the angular distribution obtained with 32-MeV protons can be fitted with $l=2$ just as satisfactorily as with $l=1$. We have not tried $l=2$, since that would imply even parity for the ground state of B^9.

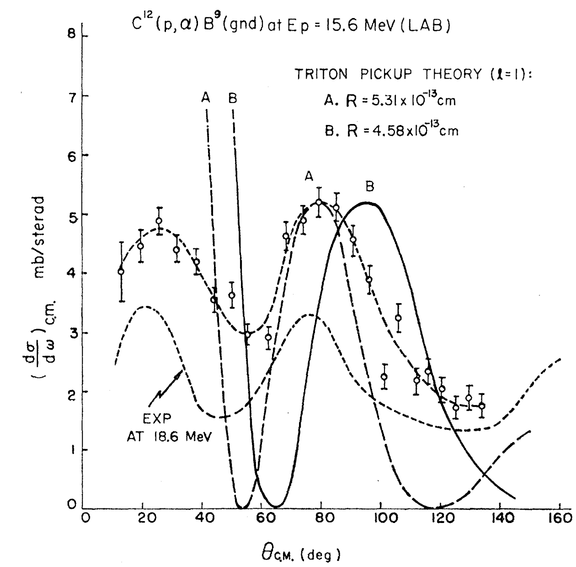

FIG. 8. The experimental $C^{12}(p,\alpha)B^9$ angular distribution observed at 15.6 MeV (lab), compared with triton pickup curves calculated for two different values of the interaction radius. Curve B corresponds to the radius giving the best fit at 18.6 MeV. The 18.6-MeV results from Fig. 7 are indicated by a dashed line.

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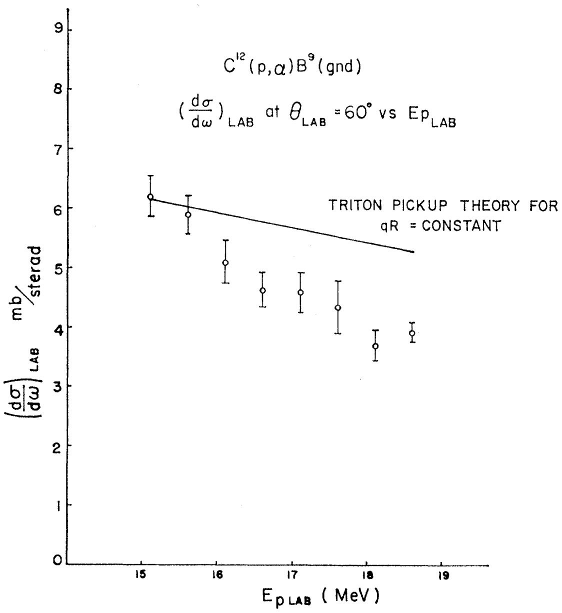

FIG. 9. Energy dependence of the $C^{12}(p,\alpha)B^9$ differential cross section at the second maximum of the angular distribution. The curve is the result given by the triton pickup formula (1) if the interaction radius is assumed to decrease with increasing energy so that qR=const.

A similar failure of the plane-wave theory to reproduce a decreasing cross section at small angles was found by Fischer *et al.*[27] in their work on the $Al^{27}(p,\alpha)Mg^{24}$ reaction. In their experiment the proton energy was only 10.9 MeV, or about equal to the maximum alpha energy in the present experiment, so that in both cases distortion of the alpha and proton waves might be important. In contrast to these results, unexpectedly large cross sections at forward angles have been observed in the $C^{12}(\alpha,p)N^{15}$ reaction.[22–24] Much less forward peaking of the over-all distribution than predicted by the plane-wave theory was also observed by Fischer, *et al.*,[27] and just the opposite effect was found by Hunting and Wall[28,29] in the $Al^{27}(\alpha,p)Si^{30}$ reaction. A modified form factor like that used by the latter authors would make the disagreement worse in the present case. In some simpler reactions, angular distributions differing greatly from the predictions of plane-wave theories have been successfully fitted by distorted wave calculations,[30–32] but no comparable theoretical treatment has yet been applied to (p,α) reactions.

The angular distribution measured at 15.6 MeV is shown in Fig. 8. The dashed line in this figure reproduces the 18.6-MeV experimental results, and shows that the maxima and minima occur at almost the same angular positions at the two bombarding energies. Since the Bessel functions in the theoretical cross section have the argument qR, the smaller value of q at the lower bombarding energy must be compensated by a larger R. This is illustrated by the two calculated triton pickup angular distributions. Curve B, which does not fit the angular position of the second maximum, was obtained with the interaction radius which gave the best fit at 18.6 MeV. Curve A was obtained with the (larger) R required to give the same value of qR at 15 MeV as at 18.6 MeV (at the second maximum in each case). A similar decrease in R with increasing energy was noted by Sherr and Rickey[22] in their work on the $C^{12}(\alpha,p)N^{15}$ reaction.

Figure 9 shows the energy dependence of the differential cross section at 60 deg in the laboratory system. The corresponding center-of-mass angle is 74 deg at 15 MeV, and changes by only 1.5 deg between 15 and 18.6 MeV, so that the data represent the cross section at the second maximum of the angular distribution. The energy dependence given by Eq. (1) is shown for comparison. Because of the observed variation of R with energy, the interaction radius was assumed to decrease with increasing energy to maintain the product qR constant. When this assumption was made, the energy dependence predicted by the triton pickup theory was found to be qualitatively correct.

Total cross sections for the $C^{12}(p,\alpha)B^9$ (ground-state) reaction were found from the results of Figs. 7 and 8 by graphical integration. The differential cross sections were plotted vs $\cos\theta_{c.m.}$, extrapolated to $\cos\theta_{c.m.}=+1$ and -1, and integrated with a planimeter. The 15.6-MeV angular distribution data extended only to 134 deg, so that in that case the extrapolation to 180 deg spanned a 46-deg angular interval. It seems reasonable to believe that this could introduce an error of only a few percent, however, since the corresponding solid angle was only $0.15\times 4\pi$ and the angular distribution out to 155 deg could be inferred from the 18.6-MeV data. The values obtained for the $C^{12}(p,\alpha)B^9$ (ground-state) total cross section were 43±8 mb at 15.6 MeV and 27±4 mb at 18.6 MeV.

IV. SUMMARY

$Li^7(p,\alpha)He^4$ angular distributions observed at 15.0 and 18.6 MeV can be fitted crudely with the appropriately symmetrized form of the triton pickup theory. The theoretical curves are extremely sensitive to the value of the interaction radius, and a smaller radius must be assumed at the higher energy.

Cross sections for the $Be^9(p,\alpha)Li^6$ ground state and $Be^9(p,\alpha)Li^{6*}$ (2.2 MeV) reactions, observed at 15.6 and 18.6 MeV, are found to increase at large angles in a manner suggesting that heavy-particle stripping may be important. An approximate fit to the $Be^9(p,\alpha)Li^6$

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ground-state angular distribution can be obtained by assuming contributions from both knock-on and heavy-particle stripping. The possibility that the backward peaking may result from distortion effects rather than heavy-particle stripping can not be excluded, but a check of this hypothesis must await further theoretical developments.

The $C^{12}(p,\alpha)B^9$ angular distribution roughly resembles that expected for a triton pickup or knock-on process, but the plane-wave theories predict far too much forward peaking of the over-all distribution, and also fail to match an observed decrease of the cross section at small angles. The oscillations in the angular distribution can be fitted at both 15.6 and 18.6 MeV only by assuming a smaller interaction radius at the higher bombarding energy.

The (p,α) reactions on Li^7, Be^9, and C^{12} all exhibit angular distributions which are not strongly dependent on the bombarding energy, and all of the cross sections decrease with increasing proton energy.

ACKNOWLEDGMENTS

The author is indebted to Professor H. Horie for permission to publish the results of his theoretical work on the $Li^7(p,\alpha)He^4$ reaction. J. H. Terrell and C. E. Fichtel assisted in the development of the counters and in taking data. The author is grateful to Professor J. R. Cameron and Professor E. K. Warburton for the beryllium target, to Professor R. W. Detenbeck for the polystyrene target, and to Professor R. A. Naumann for the chemical analysis of a lithium target. It is a pleasure to thank Professor R. Sherr for his continued interest and for many valuable discussions. Thanks are due to Professor J. S. Blair and Professor C. A. Levinson, and especially to Professor M. K. Banerjee, for information pertinent to the theory.

PHYSICAL REVIEW VOLUME 128, NUMBER 3 NOVEMBER 1, 1962

Neutrons from Deuteron Breakup on D, T, and He^4†

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(Received May 25, 1962)

The continuous neutron spectra produced by deuteron bombardment of D, T, and He^4 have been studied at deuteron energies near 9 MeV with a time-of-flight spectrometer. Angular distributions of the continuous spectra from $D+d$ and He^4+d were obtained for deuteron energies of 9 and 10 MeV. The center-of-mass angular distributions are peaked forward for neutrons of all energies. Two maxima present in the 0° spectrum from He^4+d at $E_d=10$ MeV are consistent with the interpretation that He^5 and Li^5 are produced in their ground states as alternative intermediate steps in the reaction. Two maxima are also present in the continuous neutron spectrum from $T+d$. The higher energy maximum occurs near the maximum possible neutron energy from the $T(d,np)T$ reaction and cannot be caused by the $T(d,2n)He^3$ reaction. If this peak is caused by an excited state in He^4, it would correspond to an excitation in He^4 of 20.0 ± 0.2 MeV, and be unbound.

INTRODUCTION

THIS paper reports on the investigation of deuteron breakup on isotopes of hydrogen and helium. The occurrence of deuteron breakup in the $D+p$, He^3+d, $T+d$, and He^4+d reactions was first demonstrated by Henkel *et al.*[1] Deuteron breakup in the $D+d$ reaction was first observed far above threshold by Bogdanov *et al.*[2] and was studied near threshold by Cranberg *et al.*[3] The $T+d$ reaction has also been studied by Vlasov *et al.*[4] and an anomalous peak was observed in the neutron spectrum.

The energy spectrum of neutrons or protons from deuteron breakup has been shown to provide information about the interactions between the final state nuclei. Heckrotte and MacGregor,[5] and Komarov and Popova[6] have been able to explain the presence of an anomalous peak in the continuous neutron spectrum from $D+p$ breakup[7] by considering the final state n-p and p-p interactions as S-wave scattering interac-

† Work supported by the U. S. Atomic Energy Commission and by the Wisconsin Alumni Research Foundation.

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