Pickup Behavior in $Li^6(p,He^3)He^4$ and $F^{19}(p,\alpha)O^{16}$ at 18 Mev*

J. G. LIKELY† AND F. P. BRADY‡
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received June 20, 1956)

Differential cross sections were measured for $F^{19}(p,\alpha)O^{16}$, to the ground state, and for $Li^6(p,He^3)He^4$. The angular distribution from $F^{19}(p,\alpha)O^{16}$ shows three maxima, which can be fitted approximately by the Born approximation for triton pickup. Empirical adjustment of phase, in the theoretical distribution, gives a better fit with a smaller nuclear radius. The cross section at 18.5 Mev is 1.5 times larger than at 16 Mev. The angular distribution of He^3 particles from $Li^6(p,He^3)He^4$ shows a maximum at zero degrees, explained qualitatively by deuteron pickup. Cross sections, at 18.5 and 15 Mev, are 1.1 and 1.7 times smaller, respectively, than expected, through pickup theory, from published 14-Mev data on $Li^6(n,t)He^4$. Maxima observed at 110 and 180 degrees are examined in terms of direct interaction between the proton and alpha particle in Li^6; results are inconclusive, due to inadequacies of current theory. The pickup cross sections give reasonable values of triton and deuteron reduced widths in F^{19} and Li^6, respectively.

I. INTRODUCTION

CONSIDERABLE experimental and theoretical work[1–4] has been done on stripping and pickup reactions, to increase our understanding of the process, and to provide information on bound nuclear states from observed angular distributions, with the aid of the Butler theory.[5] Most experimental work in this field has concerned single nucleon exchange reactions of the type (d,p) and (d,t), or the corresponding mirror and inverse (pickup) reactions. The possibility of pickup occurring in reactions involving the exchange of two or three nucleons has remained relatively unexplored. Cohen[6] observed pickup angular distributions in a few cases of the (p,t) reaction on nuclei having two loosely bound neutrons. Dabrowski and Sawicki[7] showed that the angular distribution from $Li^6(n,t)He^4$, observed by Frye[8] at 14 Mev, is consistent with deuteron pickup. Experiments on reactions which might show effects of double nucleon pickup, such as (p,t) and (n,t), are difficult because, with few exceptions, these reactions have large negative Q values. Recently, experiments on (He^3,p) reactions have become possible. In some cases, for example $Be^9(He^3,p)B^{11}$,[9] the angular distributions suggest stripping of a deuteron from the He^3 particle. In this paper, experimental results are presented for two reactions which show pickup angular distributions. These are $Li^6(p,He^3)He^4$, the mirror of the reaction studied earlier by Frye, and $F^{19}(p,\alpha)O^{16}$ which is interpreted in the following as a triton pickup reaction.

* This work was supported by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.
† Now at Department of Physics, University of Minnesota, Minneapolis, Minnesota.
‡ Now at Canadian Aviation Electronics, Winnipeg, Manitoba, Canada.
[1] P. B. Daitch and J. B. French, Phys. Rev. **87**, 900 (1952).
[2] J. Horowitz and A. M. L. Messiah, Phys. Rev. **92**, 1326 (1953).
[3] W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).
[4] R. G. Thomas, Phys. Rev. **100**, 25 (1955).
[5] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).
[6] B. L. Cohen and T. H. Handley, Phys. Rev. **93**, 514 (1954).
[7] J. Dabrowski and J. Sawicki, Phys. Rev. **97**, 1002 (1955).
[8] G. M. Frye, Phys. Rev. **93**, 1086 (1954).
[9] Wolicki, Geer, Holmgren, and Johnston, Bull. Am. Phys. Soc. Ser. II, **1**, 196 (1956). See also Almqvist, Bromley, Gove, Litherland, and Paul, Bull. Am. Phys. Soc. Ser. **II**, **1**, 195 (1956).

II. EXPERIMENT

Experimental Technique

Protons, from the 18-Mev Princeton FM cyclotron, bombarded targets placed at the center of a 60-inch scattering chamber, previously described.[10] A counting system, mounted on an arm centered at the target, inside the evacuated chamber, could be placed at any angle with respect to the proton beam. The technique for detecting alpha particles, and most of the equipment, including counters, electronic circuits, and beam current integrator, were essentially the same as in previous work on (p,d) reactions.[11] Alpha and He^3 particles were identified by their large energy loss in a thin proportional counter, through which they passed before stopping in the NaI crystal of a scintillation counter. Scintillation counter pulses were displayed on a 20-channel pulse-height analyzer. Large proportional counter pulses, produced by doubly charged particles, were selected by an integral discriminator, and then used to trigger a coincidence gate in the 20-channel analyzer. This scheme eliminated proton and deuteron background, because these particles produced much smaller pulses, in the proportional counter, than alpha particles having the same energy. Perfect elimination was impossible, because the upper (Landau) tail of the proton and deuteron energy-loss distributions, in the proportional counter, extended into the alpha-particle region. Background was reduced further by the use of a thin (0.014-inch) NaI crystal in the scintillation counter; as this could stop only 6.5-Mev protons and 8.5-Mev deuterons, all proton and deuteron scintillation counter pulses were smaller than those from high-energy alpha particles, of most interest here.

Details of the counters are given elsewhere.[11] The proportional counter, having a 2-cm path, was filled

[10] J. L. Yntema and M. G. White, Phys. Rev. **95**, 1226 (1954).
[11] K. G. Standing, Phys. Rev. **101**, 152 (1956).

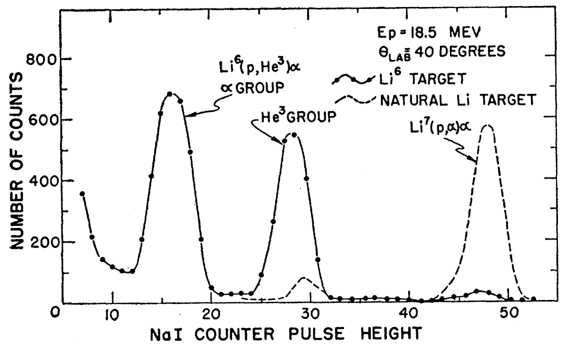

FIG. 1. Scintillation counter pulse-height spectra from proton bombardment of natural Li and Li^6, taken with proportional counter gate.

with argon, containing 4% N_2, to 18 cm of mercury. As both counters were sealed off separately from the scattering chamber vacuum, the particles lost considerable energy in absorbers (8 mg/cm² of Al equivalent) between the target and NaI crystal; however the system was adequate for these experiments.

The proton energy was determined by measuring the range in aluminum of protons scattered elastically from a platinum foil, as described elsewhere,[12] and using the experimentally determined range-energy relation.[13]

Results for $Li^6(p,He^3)He^4$

The target was a self-supporting foil, 3.8 mg/cm² thick, of lithium metal enriched to approximately 95% in Li^6.[14] The scintillation counter was calibrated for energy, approximately, by observing the alpha group from $Li^7(p,\alpha)He^4$ ($Q=17.3$ Mev[15]) and correcting the pulse-height scale for the nonlinear response of NaI to alpha particles.[16] Particles from $Li^6(p,He^3)He^4$ could then be identified from their pulse height, and the known Q value[15] of the reaction (4.02 Mev). As shown in Fig. 1, the He^3 and recoiling alpha particles, from the reaction, appeared as two widely separated groups; by kinematics, the alpha group is the lower one. The complete angular distribution, in the center-of-mass system, was obtained by observing the He^3 group from 4 to 80 degrees in the laboratory, and the alpha group from 8 to 65 degrees. At each angle, the proportional counter bias was set to match the particle energy; for alpha particles, the bias was set slightly higher than for He^3 particles. The proper bias was found experimentally at three angles, by taking bias curves, and, at other angles, by interpolation with the aid of energy-loss curves.[17] Representative scintillation counter spectra, from which cross sections were obtained, are shown in Fig. 2. The rise in background, below the alpha group, can be attributed to a continuous spectrum of alpha particles, probably from disintegration of excited states of Li^6 formed by inelastic proton scattering; although the maximum energy of this continuum should lie at least 3 Mev below the alpha group, it overlapped with it slightly, due to poor resolution, and was subtracted. As shown in the 50-degree alpha spectrum, Fig. 2,

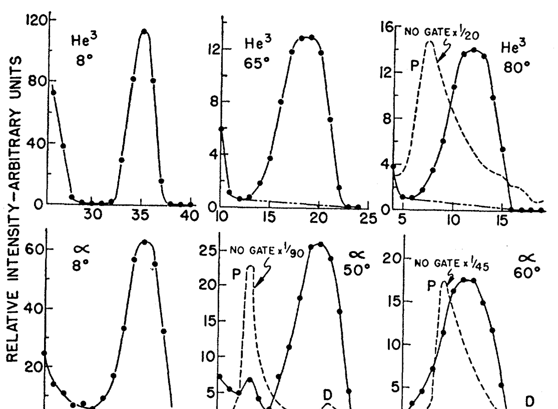

FIG. 2. Gated scintillation-counter spectra of He^3 and He^4 groups, from Li^6, at representative (lab) angles, plotted on common scales. Double-dashed lines show background subtracted. Dashed curves are ungated spectra, showing proton (P), and deuteron (D) energy loss in thin NaI crystal.

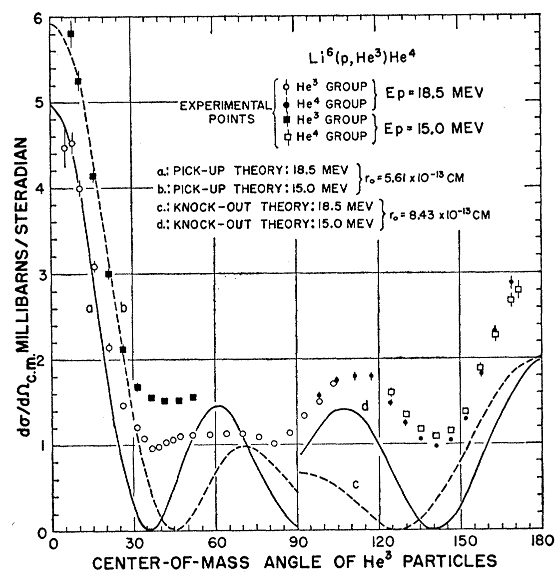

FIG. 3. Differential cross section, in center-of-mass system, of $Li^6(p,He^3)He^4$, *versus* center-of-mass angle between He^3 particles and proton beam. Circles indicate data at 18.5-Mev proton (lab) energy; squares show data at 15 Mev. Whether He^3 or He^4 particles were observed is also indicated. Errors shown are relative.

[12] G. Schrank, Rev. Sci. Instr. **26**, 677 (1955).
[13] H. Bichsel and R. F. Mozley, Phys. Rev. **94**, 764 (1954).
[14] Loan from Oak Ridge National Laboratory authorized by U. S. Atomic Energy Commission.

[15] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).
[16] F. S. Eby and W. K. Jentschke, Phys. Rev. **96**, 911 (1954).
[17] Aron, Hoffman, and Williams, U. S. Atomic Energy Commission Report AECU-663 (unpublished).

protons "leaked through" the gate slightly; this effect was subtracted at larger angles, where the alpha and He^3 groups overlap the proton peak. Figure 3 shows the differential cross section, observed at 18.5 Mev. Results of measurements taken at 15.0 Mev, at laboratory angles from 8 to 40 degrees, are included.

The target was prepared by rolling a small piece of lithium against a glass plate with a glass rod, under dry mineral oil; shims, placed on each side of the lithium, controlled the thickness. After washing in *n* decane, the foil was preserved *in vacuo* continuously. The average foil thickness was found, to within 1%, by a cross section comparison, for proton scattering, with a thicker lithium target which was later dissolved in water and titrated against HCl. The actual foil thickness was known to only 4%, because of nonuniformity. This error was eliminated from angular distribution measurements by using a monitor counter, which detected proton scattering at 10 degrees, instead of the beam current integrator. Relative errors affecting the angular distributions are the statistical error and, where necessary, uncertainty in background subtraction. The estimated error of absolute cross sections is 8%. (Errors in figures and text are standard deviations.)

Results for $F^{19}(p,\alpha)O^{16}$

A Teflon foil, 2.8 mg/cm², served as the target. The alpha group, corresponding to the ground state of O^{16}, was identified from its known Q value (8.12 Mev[15]) and the energy calibration of the scintillation counter, discussed above. As these alpha particles were more energetic than all other reaction products from the target, no background difficulties were encountered. The angular distribution, observed from 10 to 120 degrees at 18.5 Mev, is shown in Fig. 4. A few points, taken at 16.0 Mev are shown in Fig. 5.

III. DISCUSSION OF $F^{19}(p,\alpha)O^{16}$

The angular distribution, Fig. 4, shows two maxima with the suggestion of a third. It would be difficult to explain this behavior by compound nucleus formation; the angular distribution from such a process should be symmetric about 90 degrees, when many overlapping levels of the compound nucleus are excited,[18] which is probably true here at such a high excitation in the compound nucleus (30 Mev).

The strong interference effects, in the angular distribution, suggest a coherent process. Triton pickup offers the simplest explanation, because of the structure of F^{19}, which has two neutrons and a proton in the 2*s* and *d* shells outside the closed O^{16} core. In a pickup process, the triton would be separated from F^{19} with $l=0$, the only possibility consistent with the spins and parities of the triton ($\frac{1}{2}+$), of F^{19} ($\frac{1}{2}+$), and of O^{16} ($0+$).

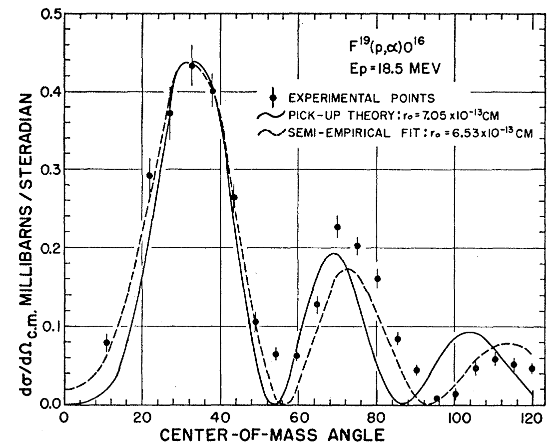

FIG. 4. Differential cross section, in center-of-mass system, of ground-state alpha group from $F^{19}(p,\alpha)O^{16}$ at 18.5-Mev proton (lab) energy. Errors shown are relative.

Intermediate-coupling calculations,[19] which are in reasonable agreement with information on the lowest even-parity states of F^{19}, show that the ground state is almost entirely an S state, with a probability of about 90%; the total orbital angular momentum, of all three particles, is zero, and the spins of the two neutrons couple to zero. The symmetry of the state is very close to that of the triton; thus the probability, of finding a triton at the nuclear surface, may be appreciable.

Pickup Theory

For a qualitative test of triton pickup, the "plane-wave" Born approximation theory[1] is adopted, with the assumptions commonly made for (d,p) and (p,d) reactions: neglect of the Coulomb field, of nuclear interactions between the incident and outgoing particles with the final nucleus, and of any contribution to the process from the interior of the target nucleus. Also, to estimate the probability of virtual proton-triton cap-

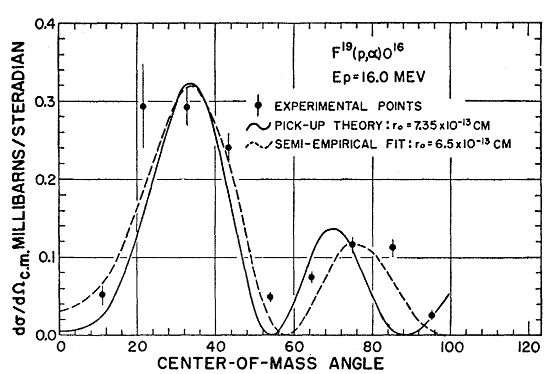

FIG. 5. Differential cross section, in center-of-mass system, of ground-state alpha group from $F^{19}(p,\alpha)O^{16}$ at 16-Mev proton (lab) energy. Errors shown are relative.

[18] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952). See also Brookhaven National Laboratory Report BNL-331 (C-21) (unpublished).

[19] J. P. Elliot and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955). Also M. G. Redlich, Phys. Rev. **99**, 1427 (1955).

ture, the wave function of a proton, in the alpha particle, must be assumed. One can show, by calculating explicit cases,[20] that the precise form of this wave function, at small distances, has no effect on the qualitative shape of the angular distribution; at most, it affects only the amplitude of oscillations at large angles. As the whole calculation is approximate, the simplest assumption is adopted, namely, a triton-proton interaction of zero range. The incorrect normalization of the alpha particle wave function, implied by this assumption, introduces uncertainty into the absolute cross section. However, this is a minor objection, because the Born approximation is known to overestimate cross sections of (d,p) reactions by factors of 2 to 6,[2,3] and the same may be true for the present case.

With these assumptions, the differential cross section for a pickup reaction of the type $A(x,y)B$, in which A virtually emits a particle z (with $l=0$), and x captures z (also with $l=0$) to form the outgoing particle y, is as follows[21]:

$$\frac{d\sigma}{d\Omega}=\frac{\mu_{xA}\mu_{yB}k_y(2I_y+1)6\beta|F|^2\theta^2[\cos(Kr_0-\eta)]^2}{\mu_{xz}{}^2k_x(2I_x+1)(2I_z+1)r_0K^2(K^2+\alpha^2)} \tag{1}$$

where $K=|\mathbf{k}_y-\mathbf{k}_xm_B/m_A|$ is the characteristic momentum transfer; $\mathbf{k}_x$ and $\mathbf{k}_y$ are relative (center-of-mass) momenta, in units of $\hbar$; θ^2 is the reduced width, for separation of A into B and z, in units of $3\hbar^2/2r_0\mu_{Bz}$; β^{-1} and α^{-1} are the decay lengths of the tails of the wave functions for z, separated from y, and from A, respectively; $\tan\eta=\alpha/K$; μ is a reduced mass, and m an ordinary mass; I is a spin; r_0 is the interaction radius between z and B. The factor $|F|^2$ is the overlap of the spin wave functions of x and z, with that of y; $|F|^2=1$ for a (p,α) reaction, and $\frac{3}{4}$ for a (p,He^3) reaction.

Angular Distribution

The solid curves, in Figs. 4 and 5, were calculated from Eq. (1) for radii of 7.05×10^{-13} cm and 7.35×10^{-13} cm, at 18.5 and 16 Mev, respectively. These values of r_0 were chosen to produce exact agreement at the first maximum, and best agreement with the others. Qualitatively, these curves differ, from those for typical (p,d) reactions for $l=0$, by decreasing in amplitude more gradually towards larger angles, and by not reaching maxima at zero degrees. These differences arise mainly from the Q values of the reactions. In (p,d) reactions, the (usually) negative Q value causes K to be small; in the present case, the positive Q value makes K large. In fact, as $Kr_0\simeq3\pi$ at the first maximum, the positions of the maxima depend sensitively on r_0.

Note that a single value of r_0 is not consistent with the data at both energies. Also, while the theoretical curve, in Fig. 4, is very similar to that observed, its period of oscillation is too small. While a smaller r_0 would match the observed oscillation period, the maxima would be shifted in phase from their observed locations. This situation always occurs in attempting to fit (p,d) and (d,p) angular distributions with the plane-wave Born approximation. When Coulomb effects are small, this discrepancy may be removed[2,6] by considering the distortion, of incoming and outgoing waves, caused by nuclear interaction. Empirically, this theoretical refinement has the effect of decreasing η, in Eq. (1), below the values prescribed by the plane-wave Born approximation. In the absence of detailed calculations for $F^{19}(p,\alpha)O^{16}$, it is perhaps more realistic to find r_0 from the separation between the maxima in the observed angular distributions, and to treat η as an adjustable parameter. The results of this "semiempirical" approach are shown by the dashed curves in Figs. 4 and 5; both were calculated from (1), with η equal to 0 and -20 degrees, at 18.5 and 16 Mev, respectively, and for $r_0=6.53\times10^{-13}$ cm in both cases. Although possible variation of η with angle is ignored, the agreement at 18.5 Mev is quite good. While the 16-Mev data is not sufficiently extensive to be fitted separately, it appears that a single radius is consistent with the data at both energies. This new radius, although smaller, is still larger than the sum of O^{16} and triton radii; the sum is 5.8×10^{-13} cm according to $r_0=1.45A^{\frac{1}{3}}\times10^{-13}$ cm. However as the radius in a pickup reaction is not well defined, this is a minor discrepancy. We conclude that, within limitations of the theory, the angular distributions agree with the pickup interpretation.

Absolute Cross Section

The theoretical curves, in Figs. 4 and 5, were plotted as absolute cross sections, by adjusting θ^2, in (1), to fit the intensities of the first maximum; θ^2 is 0.15 at 18.5 Mev, and 0.10 at 16 Mev. As mentioned earlier, Eq. (1) may overestimate the cross section; these values of θ^2 are probably underestimates of the triton reduced width in F^{19}. The width[22] is expected to be considerably less than the single-particle limit ($\theta^2<1$), because the triton wave function, constructed from s shell wave functions, can overlap only partially with the $2s$ and d shell wave functions from which the F^{19} wave function is constructed. Within these uncertainties, θ^2 agrees with expectations and therefore the pickup model is consistent with the observed cross section.

Alternative Model

An alternative model for (p,α) reactions, which may show strong interference effects in the angular distribu-

[20] The corresponding problem in (d,t) reactions is discussed by H. C. Newns, Proc. Phys. Soc. (London) **A65**, 916 (1952).

[21] R. G. Thomas (unpublished). The derivation and result are essentially the same as for (p,d) reactions, discussed in references 1, 3, and 4. The (p,He^3) reaction is treated explicitly in reference 7.

[22] Explicit calculations of triton reduced widths are not available; general methods are given by A. M. Lane, Atomic Energy Research Establishment, Harwell Report T/R1289, 1954 (unpublished).

tion, is a direct interaction process, analogous to that proposed by Austern *et al.*[23] for (p,n) reactions; the incident proton undergoes virtual scattering, with an alpha particle within the target nucleus, resulting in emission of the alpha particle, and capture of the proton to form the final nucleus. While this process may be important in (p,α) reactions on nuclei with large alpha-particle reduced widths, its contribution to $F^{19}(p,\alpha)O^{16}$ is probably small; because the O^{16} core must be broken to produce a large alpha width in F^{19}.

IV. DISCUSSION OF $Li^6(p,He^3)He^4$

The angular distribution, in Fig. 3, shows a peak in the forward direction, similar to that observed by Frye[8] from $Li^6(n,t)He^4$ at 14 Mev. Following Dabrowski and Sawicki,[7] we interpret this as due to deuteron pickup for $e=0$. In addition, a smaller peak occurs for He^3 particles at 180 degrees, i.e., alpha particles in the forward direction. This may arise from a direct interaction of the incident proton with an alpha particle in the nucleus. At any angle, both processes presumably contribute to the reaction amplitude, and may interfere. We assume that, in the extreme forward and backward directions, one process predominates over the other; so that, in these regions, each may be analyzed separately.

Angular Distribution

The theory, outlined in the previous section, is adopted here. Curves (a) and (b), in Fig. 3, were calculated from Eq. (1) for bombarding energies of 18.5 and 15 Mev, respectively. The lack of a definite minimum in the data, which is just perceptible at 35 degrees, makes the choice of r_0 uncertain. However, a single radius of 5.6×10^{-13} cm seems to be consistent with the data at both energies. This large radius probably results from neglect, in the theory, of any contribution to the reaction from pickup inside the target nucleus, an effect which cannot be ignored in a nucleus consisting, for present purposes, of only two particles. By using a square well for the deuteron-alpha interaction, Dabrowski and Sawicki[7] fitted the angular distribution from $Li^6(p,He^3)He^4$, at 14 Mev, with the more reasonable radius of 4×10^{-13} cm. An analysis of the same data by Eq. (1), requires a much larger radius of 5.8×10^{-13} cm; thus the effect of neglecting the nuclear interior is apparent. Qualitatively, at least, the angular distribution in the forward direction is consistent with deuteron pickup.

Absolute Cross Section

Values of θ^2, used to normalize the theoretical curves in Fig. 3, are 0.45 at 18.5 Mev, and 0.30 at 15 Mev. A similar analysis of Frye's data,[8] at 14 Mev on $Li^6(n,t)He^4$, gives $\theta^2=0.5$. At the same energy, the (p,He^3) and (n,t) reactions can differ only in the Coulomb effect, which tends to depress the (p,He^3) cross section. This may explain the low value of θ^2 for the (p,He^3) reaction at 15 Mev. Note that, within experimental error (at least 5% for each reaction), the values of θ^2, for the (n,t) reaction at 14 Mev, and for the (p,He^3) reaction at 18.5 Mev, are the same; apparently the Coulomb effect is small, in the latter, at 18.5 Mev.

Although the plane-wave Born approximation usually overestimates the cross section, it may not in this case; the contribution, from the interior of the nucleus, may be sufficiently large to cancel partially the effects which, normally, depress the cross section. The true deuteron reduced width in Li^6 may then be of the order of 0.5, the greatest value of θ^2 above, or even greater, if the cancellation is not complete.

The only independent information on the deuteron width in Li^6 comes from the s wave shift, in alpha-deuteron scattering, which arises both from the tail of the ground state resonance, and from hard-sphere scattering. Because of uncertainty in the interaction radius, the analysis[24] permitted all values for the deuteron width from zero to the single particle limit. However, for a preferred radius equal to the sum of deuteron and alpha particle radii as determined by electron scattering, the authors found the deuteron width to be $\theta^2=0.5$, which is the value estimated from the pickup reactions. While this agreement may be partly fortuitous, the pickup process seems to be consistent with the order of magnitude of the observed cross sections.

Direct Interaction

As mentioned earlier, the oscillations between 90 and 180 degrees, in Fig. 3, corresponding to forward alpha particles, may be produced by a direct interaction, analogous to the model of Austern *et al.* for (p,n) reactions; the alpha particle is presumably "knocked out" of the nucleus by virtual proton-alpha scattering, while the proton is captured by the remainder to form He^3. No detailed calculations of the model are available for (p,α) reactions. The results of Austern *et al.* cannot be applied here, because, while the p-n scattering amplitudes are nearly isotropic, the proton-alpha scattering amplitudes are not. However, if this fact is ignored, and the scattering amplitudes replaced by suitable averages, then, from an approximate evaluation of the integral in Eq. (9) of reference 23, the angular distribution, appropriate for s states in initial and final nuclei, is proportional to $[\cos(Zr_0-\eta)]^2Z^{-2}(Z^2+\gamma^2)^{-1}$, where $Z=|\mathbf{k}_p(A-4)/A-\mathbf{k}_\alpha(A-4)/(A-3)|$ is the characteristic momentum transfer (modified from that in reference 23 to allow for finite masses); $\mathbf{k}_p$ and $\mathbf{k}_\alpha$ are momenta in units of $\hbar$; A is the mass number of target nucleus; $\gamma=\alpha+\beta$, where α^{-1} and β^{-1} are the decay

[23] Austern, Butler, and McManus, Phys. Rev. 92, 350 (1953).

[24] A. Galonsky and M. T. McEllistrem, Phys. Rev. 98, 590 (1955).

lengths in the wave functions for the alpha particle in Li^6, and for the proton in He^3, respectively; η is defined, approximately, by $\tan\eta = \gamma/Z + 1/Zr_0$.

This result has the same form as the deuteron pickup angular distribution. However, because Z is smaller than the corresponding K, appropriate for deuteron pickup, the oscillations in the backward direction can be fitted only with a much larger radius than for the other process. This is illustrated by curve d in Fig. 4, computed from the relation above, at 18.5 Mev for $r_0 = 8.4\times10^{-13}$ cm, with arbitrary normalization. Also, the angular distribution should shift considerably on lowering the proton energy. This is illustrated by curve c, in Fig. 3, calculated for the same radius, at 15 Mev. The impossibly large radius, and the fact that no shift is observed between the angular distributions at the two energies, suggest that the minimum, observed at 140 degrees, cannot be explained in this simple way. For a reasonable nuclear radius, say 5×10^{-13} cm, the relation above gives an almost isotropic angular distribution from 90 to 180 degrees; lack of isotropy must be due to the angular dependence of the proton-alpha scattering amplitudes. While the minimum at 140 degrees, in Fig. 3, might be related to the minimum observed in proton-alpha scattering,[25] a full explanation must await further developments in the theory.

It is a pleasure to thank Professor R. Sherr, Professor P. C. Gugelot, and Professor M. G. White for their interest and advice in this work. We are also indebted to Dr. K. G. Standing, Dr. J. B. Reynolds, and Dr. G. Schrank for valuable comments, and for the use of their equipment.

[25] K. W. Brockman, Phys. Rev. **102**, 391 (1956).

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Alpha-Alpha Scattering at Low Energies*

N. P. HEYDENBURG AND G. M. TEMMER
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.
(Received June 13, 1956)

We have measured the differential cross section for the scattering of alpha particles in helium between laboratory angles of 10 and 80 degrees and in the energy range 150 kev to 3 Mev, using He^+ ions from our electrostatic generators. Below 400 kev no nuclear interaction occurs within the accuracy of the experiments ($\pm1\%$), and Mott's formula for the Coulomb scattering of identical zero-spin particles is verified in detail. Above 400 kev the nuclear s-wave interaction begins to contribute, starting at a phase shift K_0 near π, and smoothly decreasing with increasing energy to about 128 degrees at 3 Mev. Starting at 2.5 Mev, a small d-wave phase shift, K_2 is found necessary to account for the observed angular distributions, reaching a value of 2.5 degrees at 3 Mev. Absolute values of the cross sections were determined by fitting the relative angular distributions with the single parameter K_0 below 2 Mev, and by comparison with Rutherford scattering in argon above 2 Mev. The phase shift analysis was facilitated by a simple mechanical monograph described in Appendix III. A careful survey of the low-energy region containing the ground state of Be^8, and the absence of any measurable effect leads to a *lower* limit for the mean life of the ground state of Be^8 of 2×10^{-16} sec. Combined with a recently established *upper* limit of 4×10^{-15} sec, this locates the lifetime to within a factor of twenty.

I. INTRODUCTION

THE alpha particles from natural emitters in the heavy elements, whose energies lie in the range between 4 and 8 Mev, were the first projectiles to be used in the exploration of the nuclear force field. Rutherford and his co-workers[1] were able to demonstrate deviations from the Coulomb law of force at large scattering angles, thus establishing a rough value for the nuclear radius. During these early measurements the scattering of alpha particles in helium, among many other elements, was investigated as a function of energy by slowing down natural alpha particles with absorbers. These measurements were necessarily crude because of the extremely low available intensities, and consequent large spreads in energy and angle. Although it was realized that the ordinary Rutherford scattering expression had to be modified because of the impossibility of distinguishing the scattered from the scattering particle, this modification was considered merely a technical necessity. Experiments were not extended to sufficiently low energies to permit the discovery of a fundamental discrepancy. In fact, the ratio of observed cross section to Rutherford cross section, at 45 degrees in the laboratory, happened to pass through unity around 4 Mev, and hence there was no apparent incentive to pursue the investigation to still lower energies, since the interest centered on deviations from Rutherford scattering.

* Preliminary accounts of this work may be found in Cowie, Heydenburg, Temmer, and Little, Phys. Rev. **86**, 593(A) (1952), and G. M. Temmer and N. P. Heydenburg, Phys. Rev. **90**, 340(A) (1953).

[1] For discussion of the earliest work on $\alpha-\alpha$ scattering, see Rutherford, Chadwick, and Ellis, *Radiations from Radioactive Substances* (Cambridge University Press, Cambridge, England, 1930).