$Be^9(p,p\alpha)He^5$ Reaction at 57 MeV*

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The $Be^9(p,p\alpha)He^5$ reaction was studied using 57-MeV protons from the Oak Ridge isochronous cyclotron. The correlated energies of both the emitted protons and α particles were measured at detection angles (θ_p,θ_α) of (94°, −35.3°), (105°, −30°), and (116°, −25.1°), where the detectors were coplanar with the beam. In addition, an angular correlation was measured by fixing θ_p at 105° and varying θ_α from −21° to −39° in 3° steps. The data for the reaction leading to the ground state of He^5 were found to be consistent with quasifree scattering of the incident protons by S-state α-particle clusters in Be^9. Analysis in terms of a plane-wave impulse approximation yields a momentum density distribution for the struck α particles which has a half-width of 0.27 F^{-1}, and a probability of finding an α-particle cluster in Be^9 of $0.25_{-0.12}^{+0.25}$.

I. INTRODUCTION

The cluster model has been suggested as possibly a more appropriate model than the shell model for describing properties of the light elements.[1] It is, however, difficult to make critical tests of the cluster model, as both models predict similar experimental results which differ only in a quantitative comparison.[2–4] Neudachin and Smirnov,[5] in a comprehensive review article, have emphasized that quasifree p-α scattering studies provide just such a test. In the present work we report a study of quasifree p-α scattering in Be^9 at 57 MeV.

The bombarding energy of 57 MeV is undoubtedly not ideal for the observation of quasifree scattering. However, it is possible that the experimental advantages of working at medium energies outweigh the advantage of having a simpler reaction mechanism at high energies. Furthermore, very few such measurements have been reported at higher energies. The present work is regarded as exploratory, to determine the extent to which the quasifree p-α scattering may be identified at 57 MeV. We have chosen Be^9 as a target since it should present especially good circumstances for the existence of α-particle clustering. In addition, we have concentrated our studies on those regions of phase space which should be especially favorable to quasifree scattering. We have also attempted to measure the same nuclear quantities in several different ways in order to provide a consistency check on the interpretation.

II. PLANE-WAVE IMPULSE APPROXIMATION

In this section we outline briefly the simplest theory of quasifree p-α scattering, the plane-wave impulse approximation (PWIA), which is the framework in which the experiment was conceived and which we have used to interpret the results.

In the PWIA we make several very drastic assumptions for purposes of simplification. Not all of these assumptions are necessary and some of them may be relaxed without serious difficulties. Discussions of the validity of these assumptions have been made in many papers for $(p,2p)$ reactions and recently the features special to $(p,p\alpha)$ and (p,pd) reactions have been discussed by Jackson.[6]

Our assumptions are as follows:

(a) The wave function of the Be^9 ground state may be separated into the form

$$\Phi(Be^9\text{ g.s.})=\sum_i a_i\phi(\alpha)\phi_i(He^5)\phi_i(\mathbf{r}),$$

where $\phi(\alpha)$ is the internal wave function of an α particle in its ground state, $\phi_i(He^5)$ is the internal wave function of He^5 in a state i, and $\phi_i(\mathbf{r})$ is the relative motion wave function of the α particle and He^5 in the state i. The sum is to be taken over all discrete and continuum states of He^5. This form of the wave function ignores antisymmetrization of the nucleons in the target nucleus but this can be corrected by taking an appropriate linear combination of such wave functions.

(b) The interaction between the incident proton and the target nucleus occurs through a collision between the proton and an α particle in the nucleus, and the effect on the residual He^5 may be ignored. This has two

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[1] K. Wildermuth and W. McClure, in *Springer Tracts in Modern Physics* (Springer-Verlag, Berlin/Vienna, 1966), Vol. 41.

[2] D. R. Inglis, Rev. Mod. Phys. 34, 165 (1962).

[3] J. K. Perring and T. H. R. Skyrme, Proc. Phys. Soc. (London) **69**, 600 (1956).

[4] D. Brink, in *Proceedings of the International School of Physics "Enrico Fermi," Varenna* (Academic Press Inc., New York, 1966), Course 36, p. 247.

[5] V. G. Neudachin and Y. F. Smirnov, At. Energ. Rev. 3, 157 (1965).

[6] D. F. Jackson, Nuovo Cimento **40B**, 109 (1965); **51B**, 49 (1967).

important consequences. First, by measuring the recoil momentum and excitation energy of the residual He^5 *after* the collision we may deduce directly what those quantities were *before* the collision when the He^5 was bound in the nucleus. Second, the interaction between the proton and the struck α particle is then the same as that for free p-α scattering. This assumption ignores the fact that the struck α particle is bound and ignores scattering of the incident and outgoing particles by the residual nucleus, an effect which is known to be important at medium energies and which is usually allowed for by distorted-wave methods.

(c) Antisymmetrization of the total wave function including the incident proton may be ignored. This assumption generally becomes better as the bombarding energy is increased until the incident and outgoing particles have momenta which are large compared with any found in the nucleus. The p-α subsystem is automatically antisymmetrized when we use the free p-α cross section. The explicit dependence of this effect on energy has been shown for the (p,pd) reaction by Dwight and Elton.[7]

The above assumptions would not appear in quite the same form if the whole reaction were discussed in terms of individual nucleons rather than cluster substructures. In detailed analyses it is always necessary to antisymmetrize the wave function with respect to the nucleons. If, however, the above assumptions turn out to be approximately valid, the cluster formulation may be the most convenient starting point for a more sophisticated analysis.

On the basis of these assumptions the cross section for the reaction may be written for a transition to a given final state i of the He^5 nucleus as

$$\frac{d\sigma}{d\Omega_p d\Omega_\alpha dE_p} = (\text{slowly varying factor}) \times \left(\frac{d\sigma}{d\Omega}\right)_{p-\alpha} a_i^2 |\phi_i(\mathbf{q})|^2 ,$$

where E_p is the energy of the observed proton.

In this expression the first factor is due to phase-space and kinematical factors; the second factor is the free p-α scattering cross section, and $\phi_i(\mathbf{q})$ is the momentum wave function of the struck α particle, where $\mathbf{q}$ is equal and opposite to the recoil momentum of the residual He^5. It should be remarked that $\mathbf{q}$ is the momentum conjugate to the separation distance $\mathbf{r}$ between the α particle and the He^5, such that $\mathbf{q}=md\mathbf{r}/dt$, where m is the reduced mass of the He^4-He^5 two-body system. The value of a_i^2 then corresponds to the probability of finding an α particle in the specified state of the target nucleus. If this interpretation of the experimental cross section is correct, we will obtain consistent values for $|\phi(\mathbf{q})|^2$ when it is measured in different ways.

[7] J. R. Dwight and L. R. B. Elton, P. L. A. Progress Report No. RHEL/R136, 7 (viii), 1966 (unpublished).

Our experiment consisted of measuring the quantity $d\sigma/d\Omega_p d\Omega_\alpha dE_p$ as a function of E_p for the reaction $Be^9(p,p\alpha)He^5$(g.s.) and analyzing it to give the distribution $a_i^2|\phi(\mathbf{q})|^2$. We repeated the measurement for different combinations of angles θ_p and θ_α such that the first two factors in the expression for the cross section were different. The comparison between the various deduced values for $a_i^2|\phi(\mathbf{q})|^2$ then indicates whether the procedure followed is reasonable.

III. EXPERIMENT

The experiment was performed using the 57-MeV proton beam from the Oak Ridge isochronous cyclotron. The beam was energy-analyzed to give an energy spread of about 100 keV on 4.5-mg/cm² beryllium-foil target placed at the center of a 30-in.-diam scattering chamber.

Coincident pairs of particles emitted from the target were detected in two counter telescopes on opposite sides of and coplanar with the beam. The proton telescope consisted of a 500-μ ΔE_p totally depleted silicon surface-barrier detector and a NaI(Tl) E_p detector of thickness 1.25 in. The α-particle telescope consisted of two silicon surface-barrier detectors: a 100-μ-totally depleted ΔE_α detector and a 1500-μ E_α detector. The solid angles were defined by rectangular slits to be 5.54×10^{-3} sr for the proton detector and 1.95×10^{-3} sr for the α-particle detector. Each slit was twice as high as it was wide.

Figure 1 shows a schematic block diagram of the electronics. The timing signals for the proton–α-particle coincidences were taken from the two ΔE counters, using zero-crossover circuits and a time-to-amplitude converter (TAC). The total real-to-accidental ratio was kept at about 5:1, while in the region of principal interest (transitions to the ground state of He^5) the ratio was usually about 35:1. The time resolution was about 15 nsec full width at half-maximum (FWHM) so that consecutive rf beam bursts were well separated. The output of a single-channel analyzer set on the TAC spectrum was used to gate the linear signals from the two counter telescopes. For the α-particle

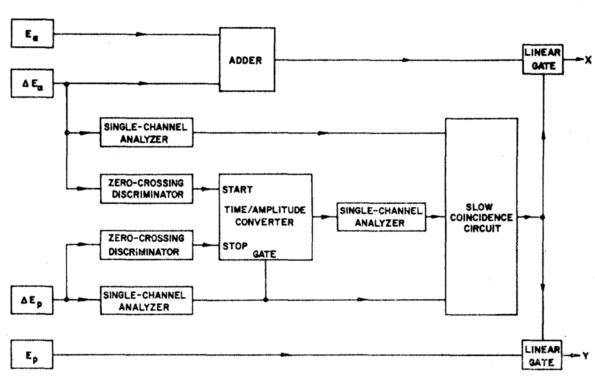

FIG. 1. A schematic block diagram of the electronics. The letters X and Y symbolize the two analog-to-digital converters of a 20 000-channel pulse-height analyzer.

telescope the linear signal was $(\Delta E_\alpha + E_\alpha)$, while for the proton telescope only the E_p pulse was used. Since the ΔE_p pulse was not added to the E_p pulse, the ΔE_p detector acted as an absorber giving complete discrimination against He^3 and He^4 with energies less than about 32 MeV, with only a slight degradation of energy resolution for the protons. Single-channel analyzers on the signals from the ΔE_p and ΔE_α detectors performed the remainder of the particle discrimination, giving the result that the proton telescope accepted singly charged particles and the α-particle telescope accepted only doubly charged particles. The energy signals were recorded on a 20 000-channel pulse-height analyzer operated in a 100×200 two-dimensional array. Further details of the experimental procedure may be found in Ref. 8.

Measurements were made at angles where one might expect to observe the quasifree scattering process. First, three correlated energy spectra were measured at the pairs of angles (θ_p,θ_α) equal to (94°, −35.3°), (105°, −30°), and (116°, −25.1°). At each of these pairs of angles the residual He^5 nucleus is kinematically allowed to have almost zero recoil momentum so that each of the three spectra should independently reveal the full internal momentum distribution of α-particle clusters in Be^9. In addition, with θ_p fixed at 105° a series of correlated energy spectra was measured for values of θ_α between −21° and −39°. This second series of measurements permits the construction of an angular correlation curve which gives yet another measure of the internal momentum distribution of the struck α particles.

IV. ENERGY SPECTRA

The principal objective was to study the quasifree scattering contribution to the cross section for the $Be^9(p,p\alpha)He^5$(g.s.) reaction. In order to identify the events of interest it is necessary to consider the properties of the two-dimensional energy spectra before proceeding to further analysis.

First, it is necessary to be sure that the measurement was of the appropriate transition, namely, $Be^9(p,p\alpha)$-He^5(g.s.). This problem requires a discussion of the kinematics of the various reactions possible, together with consideration of some experimental details. Second, once the transition has been isolated it is necessary to consider how much, if any, of the cross section is due to quasifree scattering as opposed to other possible reaction mechanisms. This problem can only be properly solved by considering various theoretical fits to the data, some of which fits will be shown in a later section. In the present section we isolate from the two-dimensional spectra the contribution due to the $Be^9(p,p\alpha)He^5$(g.s.) kinematic line. Once that has been done, the cross section for that transition can be projected onto the E_p energy axis and further analysis can proceed on the one-dimensional spectra.

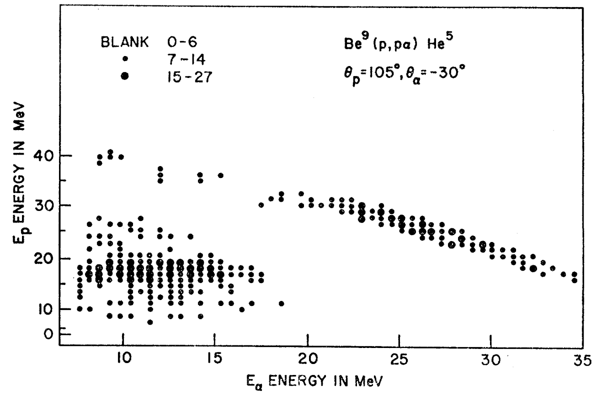

FIG. 2. A two-dimensional E_p-E_α spectrum, measured at $\theta_p=105°$, $\theta_\alpha=-30°$. The size of each spot indicates the number of counts in each channel.

Figure 2 shows the two-dimensional E_pE_α spectrum for the angles $(\theta_p,\theta_\alpha)=(105°, -30°)$. Since the experimental setup permitted detection of protons, deuterons, and tritons in the proton telescope, we have had to consider many competing reactions that could produce background near or on the $Be^9(p,p\alpha)He^5$(g.s.) kinematic curve. Most of the allowed reactions have Q values that are much more negative than the value of −2.53 MeV for the transition of interest. The only possible three-body breakup reaction whose kinematic curve partially overlaps that for the $Be^9(p,p\alpha)He^5$(g.s.) reaction is the $Be^9(p,d\alpha)He^4$ reaction. This might occur as a sequential process $Be^9(p,d)Be^{8*}$; $Be^{8*}\rightarrow \alpha+\alpha$. To estimate the contributions from this reaction we have measured the $Be^9(p,d)Be^{8*}$ cross sections at the same angles and bombarding energy used in the present experiment. Assuming that the excited Be^8 nucleus decays isotropically in its center-of-mass system, we find that the cross section for the $Be^9(p,d\alpha)He^4$ reaction is too small to interfere with the measurements of the $Be^9(p,d\alpha)He^5$ reaction. In addition, the sequential process would produce discrete peaks along the kinematic line, corresponding to discrete states in Be^9. No such peaks were observed.

There is evidence in the spectra for a rather strong process which does not, however, cause any difficulties for the present study. It lies in a region of the spectrum of Fig. 2 near $E_p=17$–20 MeV and distributed over a considerable range of E_α channels. We are not able to identify unambiguously the reactions occurring in this region on the basis of the present measurements. Several possible reactions may contribute here, and measurements with improved particle identification would be necessary to distinguish between them.

We now consider the problem of separating transitions to the ground state of He^5 from transitions to the $\frac{1}{2}^-$ first excited state. Both these states are unstable against breakup into $(n+\alpha)$, and the ground state cannot be

[8] M. B. Epstein, Ph.D. thesis, University of Maryland (unpublished).

cleanly separated on the basis of energy alone. The best evidence for the existence of the first excited state comes from the $P_{1/2}$ and $P_{3/2}$ phase shifts in n-α scattering. In our spectra, the yield in the region of the first excited state is rather weak. For our analysis of the ground state we have summed events lying within ± 2 MeV of the expected position of the ground-state kinematic curve. We find for a typical spectrum the contribution in the region of the first excited state is about 15% of the ground-state yield. The contamination of the ground-state yield due to overlap with the first excited state must be much less than this. On the other hand, it is possible that this contribution is due to the tail of the ground state and should have been included in the summation. In either case our conclusions would not be appreciably altered.

Having chosen a criterion (energy agreement within ± 2 MeV) for accepting ground-state transitions, we can proceed to study these transitions in more detail. Figure 3 shows a projection of the accepted events onto the proton energy axis. The shape of this projection is determined by the reaction mechanism. If quasifree scattering is present, the projection should show a broad peak determined by the momentum space wave functions of α particles in Be^9. If a sequential process occurs involving either sharp states of Be^9 or of Li^6, we would see sharp peaks at the corresponding proton energy.

In the spectrum of Fig. 3 we see mainly a broad peak with a maximum near zero recoil momentum for the residual He^5. We interpret this as due to quasifree knockout of S-state α particles from the target nucleus. There is also evidence for a much sharper peak at a proton energy corresponding to excitation of the 6.66-MeV state in Be^9 by inelastic scattering and its subsequent decay to He^5(g.s.) by α-particle emission. The energy resolution of the experiment was not adequate to separate this transition cleanly.

Since the most prominent feature of the spectra at all the angles we have measured was due to the postulated quasifree scattering mechanism, the remainder of this paper is devoted to the examination and analysis of this process.

V. PWIA ANALYSIS OF THE DATA

The assumptions involved in our use of the PWIA have been stated in Sec. II. There are several further details which need to be defined. These are (a) the derivation of the phase-space and kinematical factors in the cross section, and (b) the choice of values of $(d\sigma/d\Omega)_{p\text{-}\alpha}$ to use for the off-energy-shell collision inside the nucleus.

No unique prescription for either (a) or (b) exists. We have used an expression derived by one of us[8] which is based on transforming the p-α collision into a frame of reference in which the struck α particle is stationary.[9]

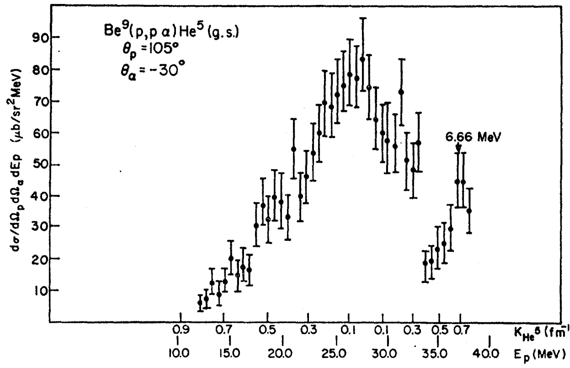

FIG. 3. A projection of the spectrum of Fig. 2 onto the E_p axis. The scale of k_{He^5} is shown for comparison.

In this frame the wave number k_0' of the incident proton defines an effective bombarding energy and the direction of the outgoing proton with respect to the direction of k_0' defines the two-body scattering angle. With this basic assumption and with the recoil of the residual He^5 being allowed for, the expression for the cross section becomes

$$\frac{d\sigma}{d\Omega_\alpha d\Omega_p dE_p}=\frac{v_0'}{v_0}\frac{k_p k_\alpha^2}{(k_p')^2}E_{He^5}\frac{E_0'}{E_0}\frac{E_{\alpha i}'}{E_{\alpha i}}\frac{1}{\hbar c}\times\frac{(E_p'+E_\alpha')k_p'-E_p'k_0'\cos\theta_p'}{k_\alpha(E_\alpha+E_{He^5})+E_\alpha[k_p\cos(\theta_\alpha+\theta_p)-k_0\cos\theta_\alpha]}\times\frac{d\sigma}{d\Omega_p}(k_0',k_p',k_\alpha')a^2|\phi(q)|^2.$$

Here E, v, k refer to total mass energy, velocity, and wave number; the subscripts 0, i, p, α, and He^5 refer to the incident proton, the struck α particle before collision, the outgoing proton, the outgoing α particle, and the recoiling He^5, and primed quantities are measured in the frame of reference in which the struck α particle is stationary before the collision, while all others are measured in the laboratory frame. The momentum distribution $\phi(\mathbf{q})$ is given in terms of the momentum $\mathbf{q}$ of the struck α particle before the collision, measured in the laboratory system, so that $\mathbf{q}=\mathbf{k}_p+\mathbf{k}_\alpha-\mathbf{k}_0$. As remarked before, the momentum $\mathbf{q}$ is the momentum conjugate to the separation distance $\mathbf{r}=\mathbf{r}_\alpha-\mathbf{r}_{He^5}$ in the model chosen for the Be^9 wave function.

To analyze the data the quantity $d\sigma/d\Omega_p(k_0',k_p',k_\alpha')$ was replaced by the free p-α elastic scattering cross section $d\sigma/d\Omega_p(k_0',k_p')$, for which experimental values were obtained by interpolating between the measurements shown in Fig. 4, which were obtained at 31.0

[9] The expression and its derivation are slight extensions of ones given by B. Gottschalk in his Ph.D. thesis, Harvard, 1962 (unpublished). Copies of Ref. 8 are available on request.

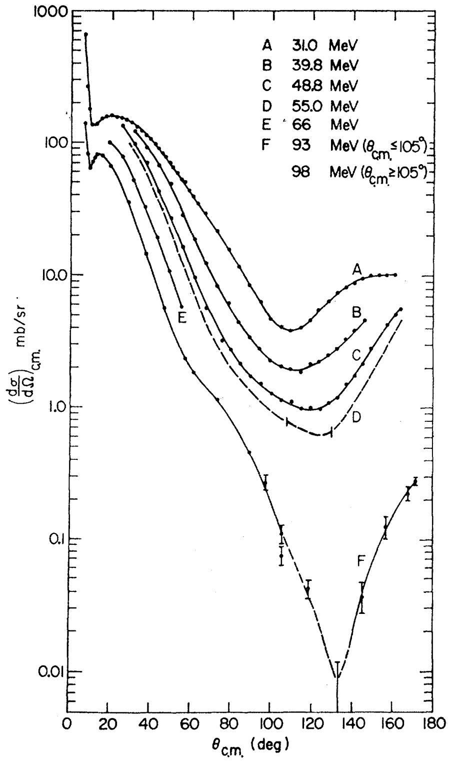

FIG. 4. The differential cross section for free p-α elastic scattering at various energies. The data labelled A through F are taken from Refs. 10–15, respectively. The 55.0-MeV data are shown only as a dashed line since no tabulation of the data was available. On the 55.0-MeV curve, the range of scattering angles (110°–130°) relevant to the present experiment is indicated; the experimental points fluctuate about the smooth curve by about ±10% in this range.

MeV,[10] 39.8 MeV,[11] 48.8 MeV,[12] 55.0 MeV,[13] 66 MeV,[14] and 95 MeV.[15] The effective c.m. scattering angles relevant for the present experiment lie in the region 110° to 130°, indicated in Fig. 4 on the 55-MeV curve, while the effective bombarding energy ranged from about 48 to 67 MeV.

Figure 5 shows the projected proton energy spectra for the three pairs of angles $(\theta_p,\theta_\alpha)=(94°, -35.3°)$, $(105°, -30°)$, and $(116°, -35.1°)$. The error bars indicate the relative uncertainty of the data points. The absolute values of the cross sections are accurate within ±30%. Along the energy scale for these spectra the corresponding value of k_{He^5} is also indicated. Note that for each value of E_p the value of k_{He^5} occurs twice, corresponding to two different directions for the struck α particle. Each spectrum shows the large quasifree peak near $k_{He^5}=0$ and also, at high proton energies, structure corresponding to sequential transitions via excited states of Be^9, i.e., $Be^9(p,p')Be^{9*}$, $Be^9 \rightarrow He^5+\alpha$. The low-energy sides of the spectra appear relatively free from such structure, indicating that the process $Be^9(p,\alpha)Li^{6*}$; $Li^{6*} \rightarrow He^5+p$ does not contribute significantly in the region of phase space studied. The low-energy side of the spectrum may thus be more reliable for the extraction of quasifree scattering data.

Figure 6 shows the same spectra after reduction to the momentum distribution, $a^2|\phi(\mathbf{q})|^2$. The solid curves, whose form will be discussed later, are the same for all three spectra. The momentum distribution has a maximum near $q=0$ corresponding to the removal of an S-state α particle from Be^9, though the position of the maximum is shifted slightly from $q=0$. Angular momentum and parity considerations permit the α particles to be either in $L=0$ or $L=2$ states relative to the He^5 "core." The $L=0$ contribution is dominant in these spectra. This should not, however, be taken to mean

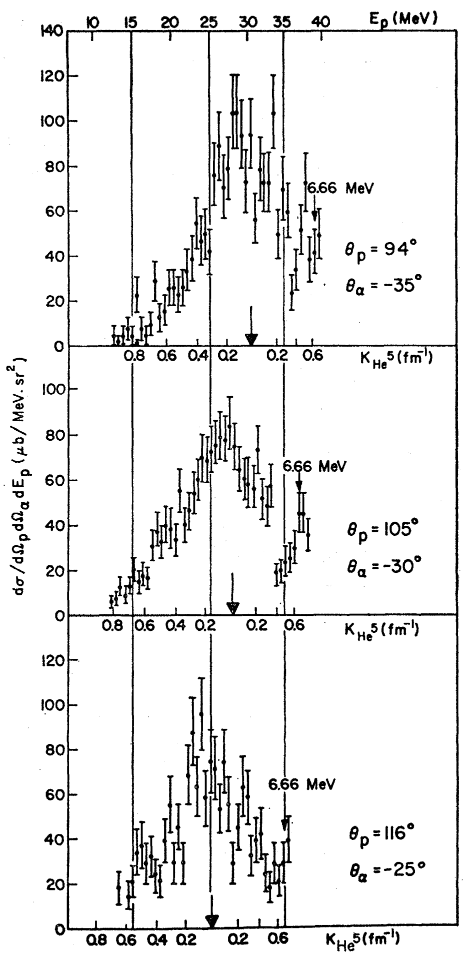

FIG. 5. Projected proton energy spectra at the pairs of angles (θ_p,θ_α) given by (94°, −35°), (105°, −30°), and (116°, −25°). The scale of k_{He^5} is shown, and the heavy arrow in each spectrum indicates the position at which the quasifree peak should appear if the PWIA is valid.

[10] S. M. Bunch, H. H. Forster, and C. C. Kim, Nucl. Phys. 53, 241 (1964).
[11] M. K. Brussel and J. H. Williams, Phys. Rev. 106, 286 (1957).
[12] B. W. Davies, M. K. Craddock, R. C. Hanna, Z. J. Moroz, and L. P. Robertson, Nucl. Phys. A97, 241 (1967).
[13] S. Hayakawa, N. Horikawa, R. Kajikawa, K. Kikuchi, H. Kobayakawa, K. Matsuda, S. Nagata, and Y. Sumi, J. Phys. Soc. Japan 19, 2004 (1964).
[14] A. M. Cormack, J. N. Palmieri, N. F. Ramsey, and R. Wilson, Phys. Rev. 115, 599 (1959).
[15] W. Selove and J. M. Teem, Phys. Rev. 112, 1658 (1958).

that in the *integrated* yield the $L=2$ contribution is negligible. The measurements indicate the value of $a^2|\phi(\mathbf{q})|^2$, whereas the integrated yield is obtained by evaluating the integral $\int a^2|\phi(\mathbf{q})|^2 q^2 dq\, d(\cos\theta)d\phi$, which because of the q^2 factor, contains reduced contributions from near $q=0$ where $|\phi(q)|^2$ is dominated by the S-state part.

We may examine the distributions $a^2|\phi(q)|^2$ to see if we obtain consistent distributions from all the measurements. The solid curves, the same for all three spectra, serve as a useful standard in this comparison. If we compare the three distributions, we see that the left-hand sides (corresponding to low proton energies) are in good agreement both in shape and absolute magnitude. We note, however, two deviations from the PWIA predictions, namely, the maximum is slightly shifted from $q=0$ and the right-hand sides (corresponding to high proton energies) contain appreciable contributions from sequential processes, emphasized somewhat unnaturally in this presentation of the data by the conversion from cross section to $|\phi(q)|^2$. Within each energy spectrum the effective c.m. scattering angle is approximately constant, at $\theta_{\text{c.m.}}=108°$, 119.5°, and 129° for the spectra at $\theta_p=94°$, 105°, and 116°, respectively. The effective c.m. energy varies considerably, however, roughly from 48 to 67 MeV over which range the free p-α scattering cross section varies by a factor of 3. The required values of $d\sigma/d\Omega_p$ were obtained by interpolating as a function of energy assuming $\theta_{\text{c.m.}}$ to be fixed.

The comparison of the maxima of the momentum distributions of Fig. 6, at $q\approx 0$, may be less subject to systematic error than other features. At $q=0$ the effective bombarding energy is close to 55 MeV and the p-α data of Ref. 13 could be used directly without interpolating in energy. We used the experimental values $d\sigma/d\Omega_p=0.9$ mb sr^{-1} at $\theta_{\text{c.m.}}=109°$, 0.65 mb sr^{-1} at 119.5°, and 0.7 mb sr^{-1} at $\theta_{\text{c.m.}}=129°$. These values must be regarded as uncertain within about 10% since the data of Ref. 13 fluctuate about a smooth curve by about that amount. It is interesting to note that use of smoothed values for $d\sigma/d\Omega_p$ would give an improved account of the relative magnitude of the three momentum distributions.

To circumvent the difficulties introduced by the sequential processes at large proton energies we also measured an angular correlation, with $\theta_p=105°$ and θ_α varied between $-21°$ and $-39°$. At each angle we estimated the cross section for $E_p=27.4$ MeV by averaging over a band of width 1.8 MeV centered about this value. This procedure has several advantages. First, the proton energy is always low enough that no sequential processes are evident in the energy spectra. The excitation energy of the intermediate state of Be^9 would, if the reaction were sequential, be about 16.5 MeV. Second, in this geometry the momentum transfer to the proton is essentially constant. Finally, the constancy of the proton and α-particle energies in the angular correlation may make this measurement more useful in terms of a full distorted wave analysis since optical model potentials at only one energy would be needed.

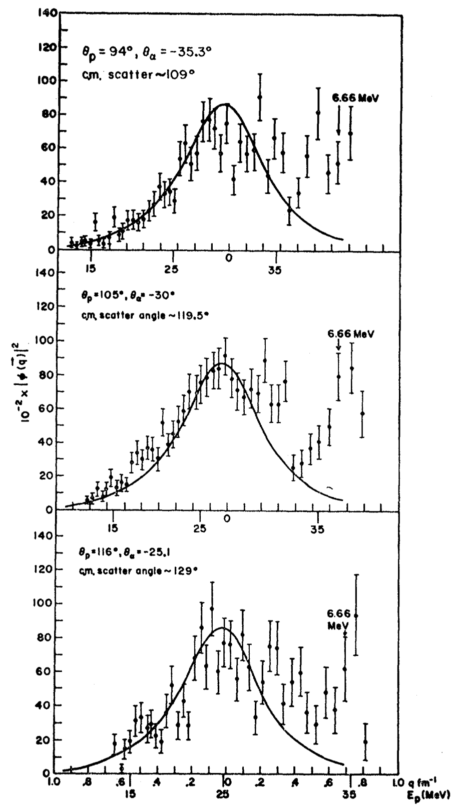

FIG. 6. Momentum distribution $|\phi(\mathbf{q})|^2$ deduced from the proton energy spectra shown in Fig. 5. The curve is the same for each of the three distributions and is a parametrized fit using the PWIA.

For this angular correlation both the effective c.m. energy and effective c.m. scattering angle vary. However, the momentum transfer to the proton remained approximately constant and proved a useful quantity for interpolation. The effective p-α cross section is sufficiently constant throughout the angular correlation that it was taken as exactly constant and equal to 0.6 mb sr^{-1}. The angular-correlation measurement, after reduction to $|\phi(q)|^2$, is shown in Fig. 7. It should be borne in mind that the point for $\theta_\alpha=-30°$ is taken from the spectrum for Fig. 6 for $\theta_p=105°$, $\theta_\alpha=-30°$ so that the agreement of absolute magnitude is no surprise. The width is, however, also in agreement, but again the center is shifted from $q=0$, in this measurement by 0.04 F^{-1} (8 MeV/c). We find that in all the data the maximum occurs on the side of $q=0$ corresponding to lower effective bombarding energy.

To obtain some quantities from the data which may be compared with other experimental results and to facilitate intercomparison of our various measurements we have parametrized our momentum distribution in terms of simple harmonic oscillator wave functions. A single $1S$ wave function was found to be inadequate.

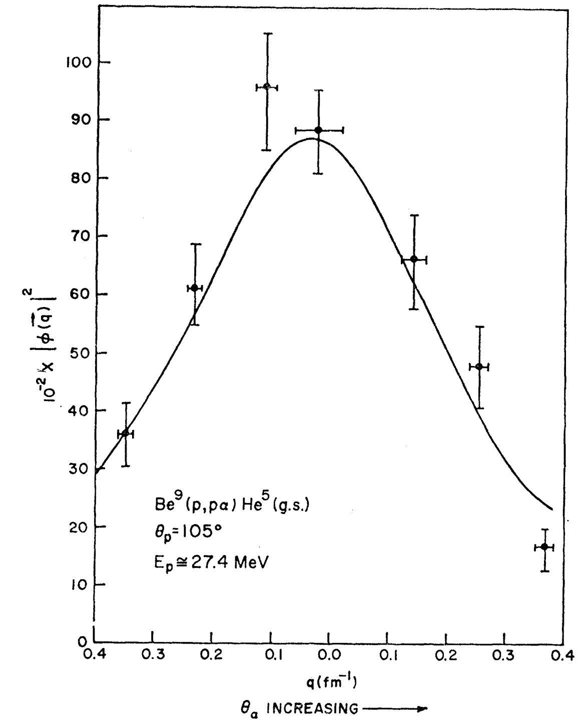

FIG. 7. The angular correlation measured with $\theta_p=105°$ and with θ_α varied between $-21°$ and $-39°$. The cross sections have been reduced to the momentum distribution $|\phi(\mathbf{q})^2$ and are plotted as a function of q. The curve is the parametrized PWIA fit and is the same as the curves shown in Fig. 6.

Additional parameters can be introduced in many ways. We arbitrarily chose to use the incoherent sum of two $1S$ oscillator wave function with different spring constants. There is no good justification for this choice except that the data do not demand a more sophisticated approach. This distribution is

$$|\phi(\mathbf{q})|^2=N_1\left(\frac{1}{\sigma_1\sqrt{\pi}}\right)^3e^{-q^2/\sigma_1^2}+N_2\left(\frac{1}{\sigma_2\sqrt{\pi}}\right)^3e^{-q^2/\sigma_2^2},$$

where $N_1=0.031$, $N_2=0.223$, $\sigma_1=0.23$ F^{-1}, and $\sigma_2=0.53$ F^{-1}.

In fitting the above momentum distribution to the data we have in each case shifted the theoretical distribution relative to the data by approximately 0.04 F^{-1} following the procedure of Riou *et al.*[16] for $(p,2p)$ reactions, where such shifts were necessitated by refraction effects. The fits to the energy spectra are shown in Fig. 6 and the fit to the angular correlation is shown in Fig. 7. It will be seen that all the fits are fairly good.

The effective number of α particles in the target nucleus is obtained by calculating the integral

$$N=\int|\phi(\mathbf{q})|^2d\mathbf{q}.$$

[16] J. P. Garron, J. C. Jacmart, M. Riou, C. Ruhla, J. Teillac, and K. Strauch, Nucl. Phys. **36**, 126 (1962).

For our distribution $N=N_1+N_2=0.25$. This result is, however, very sensitive to the form of the high-momentum part of the distributions. Curves consistent with our data could give values of N as much as a factor of 2 greater or smaller than this.

VI. DISCUSSION

The main observations in this experiment on the $Be^9(p,p\alpha)He^5$ g.s. reaction were:

(a) A large part of the cross section may plausibly be identified as due to the quasifree knockout of α particles or clusters from Be^9, while there are also sequential contributions due to inelastic proton scattering to α-particle-unstable excited states of the target nucleus.

(b) The PWIA gives a fairly consistent description of the quasifree part of the cross section.

(c) The relative motion wave function of α clusters in Be^9 contains an important S-wave component.

(d) The half-width at half-maximum of the α-cluster momentum distribution $|\phi(q)|^2$ is $q_{1/2}=0.27\pm0.04$ F^{-1}.

(e) The effective number of α particles in Be^9, $N=0.25_{-0.12}^{+0.25}$, depends very sensitively on our fitting procedure and upon the assumption that the PWIA is valid.

The following discussion elaborates on these observations and correlates them with results from other experiments.

First, the identification (a) of the quasifree knockout contribution is very interesting. The angles of measurement were carefully chosen to optimize the chances of seeing this process, and rather few angles were measured so that it is not possible from this experiment to make any sweeping statements about the relative probability of "direct" and "sequential" processes. The latter processes were, however, strongly present but were not studied in any detail. It is very interesting to compare the present result with the measurement of the $C^{12}(p,p\alpha)Be^8$ reaction at 57 MeV.[17] In that reaction, with equally favorable angles, *no quasifree knockout could be unambiguously identified.* Instead, the E_pE_α spectrum contained a series of partly resolved groups corresponding to very highly excited α-unstable states of C^{12} produced by inelastic scattering. The main differences between Be^9 and C^{12} relevant here are probably:

(1) The α particle in C^{12} is bound by 7.37 MeV as opposed to 2.53 MeV in Be^9, so that the wave function representing an α particle in C^{12} extends less into the surface of the nucleus where the reaction is probably localized.

(2) C^{12} has discrete excited states at very high energies. These may modulate the quasifree cross section strongly via final-state interactions.

[17] P. G. Roos, C. A. Ludemann, C. D. Goodman, M. Epstein, H. D. Holmgren, and N. S. Wall, Bull. Am. Phys. Soc. **11**, 26 (1966).

(3) It is possible that the C^{12} ground state does not have as good an overlap with an α-cluster wave function as does Be^9. Calculations[18,19] of C^{12} using a model of three α particles have been rather unsuccessful.

However, measurements at Harvard at 160 MeV (B. Gottschalk, private communication) show that at this higher energy the quasifree scattering contribution can be identified in the $C^{12}(p,p\alpha)Be^8$ reaction over a wide region of phase space.

We have subsequently made measurements on the $Li^6(p,p\alpha)H^2$ and $Li^7(p,p\alpha)H^3$ reactions at 57 MeV.[20,21] Both of these display quasifree scattering together with sequential mechanisms.

We next consider item (b), the apparent success of the PWIA for the reaction. By this apparent success we mean that the model predicts the peak in the cross section at essentially the correct place and that the measurements of recoil-momentum distribution are consistent in width and magnitude in the various experimental configurations. We do not consider this success to be a very strong indicator of the reaction mechanism since other interpretations are possible. It does, however, indicate that refraction effects are rather small. We may make a rough estimate of the refraction from the appearance of the quasifree peak at $q=0.04$ F^{-1} rather than $q=0$. If we do this by considering that the reaction occurs in a real potential $-V_0$, which is the same for incoming and outgoing particles, and thereby modifying the kinematic momentum balance, we find $V_0=3$ MeV. Such a small value of V_0 compared with the usual optical potentials may plausibly be explained if strong absorption effects limit the reaction to large radii where the real part of the potential has become small.

An important feature of the PWIA is that the cross section factorizes. We cannot, however, claim to have made a sensitive test of this since $(d\sigma/d\Omega)_{p\text{-}\alpha}$ does not change very dramatically between our various experimental configurations. Furthermore, the kinematical term does not vary greatly in the region studied.

The relative motion wave function $\phi(\mathbf{q})$ of α clusters in Be^9 is shown by our measurements to have an important S-wave component. It should be noted that the $Be^9(p,p\alpha)He^5$(g.s.) reaction proceeds from an initial state in Be^9 of $J^\pi=\frac{3}{2}^-$ to a final state in He^5 of $J^\pi=\frac{3}{2}^-$. Thus, orbital angular momenta of $L=0$ and $L=2$ are possible for the knocked-out α particle. The relative amounts of these will depend on the details of the nuclear model. The knockout of D-state particles would be characterized by a minimum in the cross section at $q=0$. In our experiment, where the S-state component is clearly present, such a minimum would be masked by the S-state cross section. We are unable to assign any relative probability for the S state and D state. Our integral cross section is for the sum of the two.

TABLE I. The effective number N of α particles in Be^9, and the half-value point $q_{1/2}$ of the recoil-momentum distribution as observed in various experiments. For definitions of N and $q_{1/2}$, see the text.

Reaction	Reference	N	$q_{1/2}$ (F^{-1})
$Be^9(p,p\alpha)He^5$ at 155 MeV	a	$0.065\pm(\approx 50\%)$	0.35
$Be^9(\alpha,2\alpha)He^5$ at 28 MeV	b	0.12	0.25
	c	0.31	0.33
$Be^9(p,p\alpha)He^5$ at 57 MeV	(this work)	$0.25_{-0.12}^{+0.25}$	0.27 ± 0.04

a C. Ruhla, M. Riou, M. Gusakow, J. C. Jacmart, M. Liu, and L. Valentin, Phys. Letters 6, 282 (1963).
b T. Yanabu, S. Yamashita, K. Takimoto, and K. Ogino, J. Phys. Soc. Japan 20, 1303 (1965).
c K. Takimoto, Mem. Coll. Sci. Univ. Kyoto A31, 267 (1967). This contains a reanalysis of the data of footnote b, in which an increased value of $q_{1/2}$ is preferred, giving the increased value of N shown in the table.

We do not have any satisfactory theoretical predictions for the shape of the recoil-momentum distribution with which to compare our data. Nor do we have a satisfactory prediction for the effective number of α particles. It is of interest, however, to compare the observed values with those from other experiments.[22–24] The various results are collected in Table I. All the results are consistent within the very large uncertainties. The uncertainty in the effective number of α particles (N) is particularly large. Even given a fixed shape for the momentum distribution, the integral over it depends on $(q_{1/2})^3$, and of course when the shape is also uncertain there will be large systematic uncertainty.

In conclusion, we have established the existence of a contribution to the $Be^9(p,p\alpha)He^5$ reaction at 57 MeV which appears in most respects to resemble quasifree scattering. The numerical results of the experiment are in agreement within the very large errors with those from other knockout reactions performed under very different conditions. This is to some extent a surprise. More careful experimental work to reduce the experimental uncertainties together with a more sophisticated analysis would be useful.

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18 P. Darriulat, Nucl. Phys. 76, 118 (1966).
19 D. R. Harrington, Phys. Rev. 147, 685 (1966).
20 M. Jain, M. Epstein, H. D. Holmgren, H. G. Pugh, and P. Roos, Bull. Am. Phys. Soc. 12, 466 (1967).
21 H. G. Pugh, M. Jain, M. Epstein, H. D. Holmgren, and P. G. Roos, Bull. Am. Phys. Soc. 12, 1176 (1967).
22 C. Ruhla, M. Riou, M. Gusakow, J. C. Jacmart, M. Liu, and L. Valentin, Phys. Letters 6, 282 (1963).
23 T. Yanabu, S. Yamashita, K. Takimoto, and K. Ogino, J. Phys. Soc. Japan 20, 1303 (1965).
24 K. Takimoto, Mem. Coll. Sci. Univ. Kyoto 31, 267 (1967).