The $C^{13}[He^3,Be^8(g.s.)]Be^8(g.s.)$ Reaction*†

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The differential cross sections for the $C^{13}[He^3, Be^8(g.s.)]Be^8(g.s.)$ reaction have been measured as a function of angle at bombarding energies of 3.30, 5.00, and 5.75 MeV, and as a function of the bombarding energy over the range extending from 2.50 to 5.00 MeV at a laboratory angle of 40°. The reaction exhibits a pronounced resonance at about 5.6 MeV corresponding to an excited state of O^{16} at an excitation energy of 16.75 MeV. The angular distribution on the resonance suggests an assignment of $J^\pi = 2^+$. The total off-resonance cross section for the reaction is surprisingly large: 0.18 mb at 3.30 MeV and 0.37 mb at 5.00 MeV. The behavior of the off-resonance differential cross section suggests the possibility of direct reaction. The angular distributions at 3.30 and 5.00 MeV have been fitted with a distorted-wave Born-approximation calculation in which a five-nucleon system was assumed to be transferred from C^{13} to He^3 as a point particle. The gross approximations which had to be employed in the calculation do not allow a meaningful spectroscopic factor to be extracted. The reaction, however, plays a significant part in the interaction of He^3 with C^{13}.

INTRODUCTION

In recent years a number of nuclear reactions have been observed in which rather complex particles such as Li^6, Li^7, Be^7, Be^8 are emitted. In many cases, such reactions have surprisingly large cross sections that are frequently comparable to the cross sections for the emission of nucleons or α particles. The study of reactions leading to complex outgoing particles is particularly interesting in that the mechanism by which these reactions take place must depend intimately upon the structure of the nuclear systems involved.

The $C^{13}(He^3,4\alpha)$ reaction has been found to proceed to the four-α-particle final state primarily through sequential processes of the form

$$\begin{array}{l} C^{13}+He^3 \rightarrow \alpha_1 + C^{12} \\ \qquad\qquad\qquad\quad \searrow \\ \qquad\qquad\qquad\qquad \alpha_2 + Be^8 \\ \qquad\qquad\qquad\qquad\qquad \searrow \\ \qquad\qquad\qquad\qquad\qquad\quad \alpha_3+\alpha_4 . \end{array} \tag{1}$$

The four-body final state can, in principle, also be reached by a sequential process of the form

$$\begin{array}{l} C^{13}+He^3 \rightarrow Be^8 \quad + \quad Be^8 \\ \qquad\qquad\qquad \searrow \qquad\qquad \searrow \\ \qquad\qquad\qquad \alpha_1+\alpha_2 \quad \alpha_3+\alpha_4 . \end{array} \tag{2}$$

The work reported in this paper is an attempt to determine the magnitude of the cross section for the $C^{13}[He^3,Be^8(g.s.)]Be^8(g.s.)$ reaction and to obtain information regarding the mechanism by which this reaction takes place.

Denes and Daehnick[1] found that it was possible to interpret the results of their studies of the (d,Li^7) and (d,Be^7) reactions on various light nuclei in terms of a direct pickup process involving the transfer of a He^5 or Li^5 cluster from the target nucleus to the projectile. On the other hand, Chevallier *et al.*[2] have found that the $C^{12}(\alpha,Be^8)$ reaction exhibits a number of resonances suggesting a rotational band[3] built upon a 0^+ compound nucleus state in O^{16} at an excitation energy of 16.75 MeV. It is possible for reaction (2) to proceed by either such a compound nucleus process and/or a direct process similar to the (d,Li^7) reaction involving the transfer of five nucleons. The differential cross section was measured as a function of energy and angle in order to obtain an insight into the mechanism of the $C^{13}[He^3,Be^8(g.s.)]Be^8$ (g.s) reaction.

In the study of reaction (2), certain experimental difficulties were encountered since both components of the reaction are unstable and must be observed in the background of the four-α-particle final state produced by reaction (1) proceeding through various states of C^{12}. Considerable effort was required to establish that the measured effects were actually due to reaction (2). Some of the procedures used to identify such events are discussed in the next section.

EXPERIMENTAL TECHNIQUES

Doubly charged He^3 ions were accelerated by the University of Maryland Van de Graaff accelerator. The analyzed beam entered a 12-in.-diam scattering chamber through a set of four collimators. After passing through the target the beam was stopped in a Faraday cup located at the exit of the scattering chamber. The charge collected was measured by a current integrator to an accuracy of 1%. The targets were carbon films containing 60% enriched C^{13} and ranging in thickness from 50 to 70 mg/cm².

The detector arrangement and the block diagram of the electronics is shown in Fig. 1. Detection of Be^8(g.s.) nuclei was accomplished by a coincidence technique similar to that employed by Weinman *et al.*[4] and Brown *et al.*[5] The breakup α particles emitted by the recoiling

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† Computer time provided by Computer Science Center of the University of Maryland (Project 205/65/063).
[1] L. J. Denes and W. W. Daehnick, Phys. Rev. **154**, 928 (1967).
[2] P. Chavallier, F. Scheilbing, G. Goldring, I. Plisser, and M. W. Sachs (private communication).
[3] Y. Abgrall, E. Caurier, and G. Monsonego, Phys. Letters **24B**, 609 (1967); Y. Abgrall, G. Baron, E. Caurier, and G. Monsonego, *ibid.* **26B**, 53 (1967).
[4] J. A. Weinman and R. K. Smither, Nucl. Phys. **45**, 260 (1963).
[5] T. E. Brown, J. S. Blair, D. Bodansky, N. Cue, and C. D. Kavaloski, Phys. Rev. **138**, B1394 (1965).

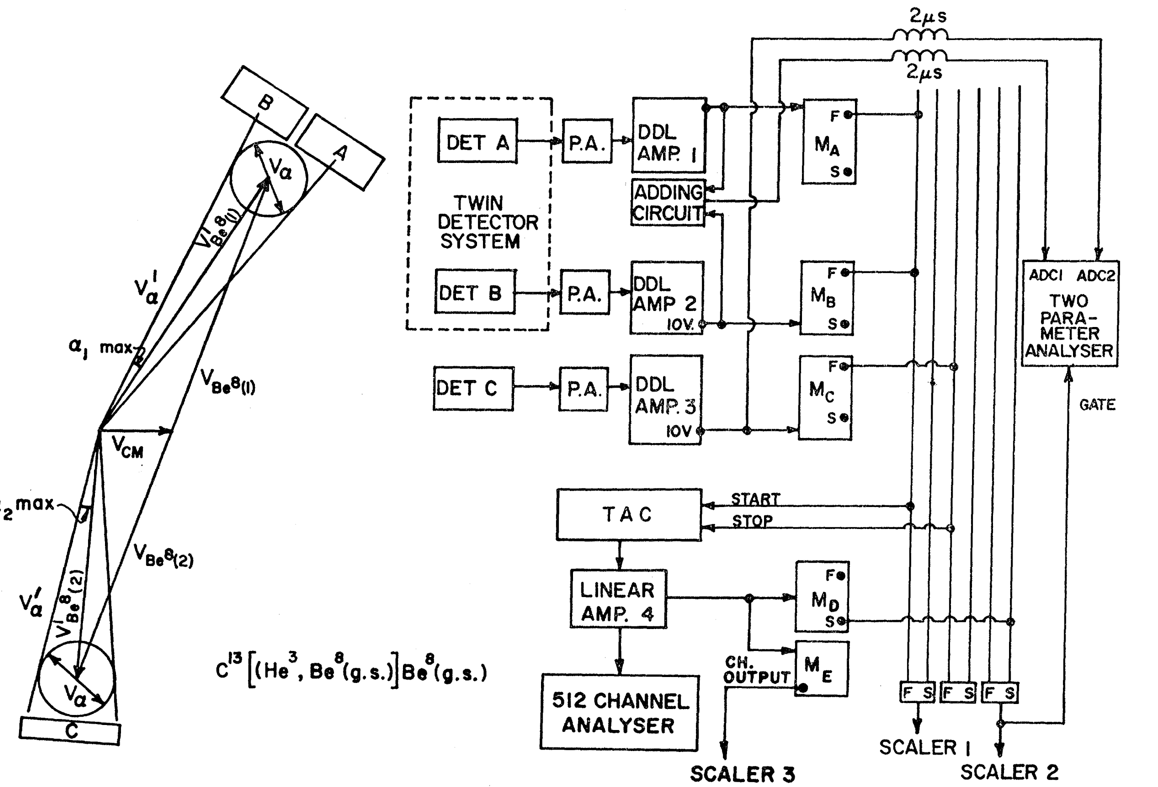

FIG. 1. Block diagram of electronics and experimental arrangements, showing the velocity vector diagram for the $C^{13}[He^3,Be^8(g.s.)]Be^8(g.s.)$ reaction.

Be^8(g.s.) nuclei are confined to a narrow cone about the angle of emission of the Be^8. At a bombarding energy of 5.0 MeV the cone angle varies from 12° to 19°, depending on the angle of observation. Two rectangular detectors (0.25×0.22 in.) mounted adjacent to each other, A and B, were placed at a distance from the target such that the combined solid angle subtended was always sufficient to intercept a cone at least 4° larger than the breakup cone. A conventional zero-crossover, fast coincidence circuit (Cosmic model 801) with a resolving time of about 80 nsec was employed to establish a coincidence between the signals from detectors A and B. The third counter C subtended a cone of angle of approximately 26° and was centered

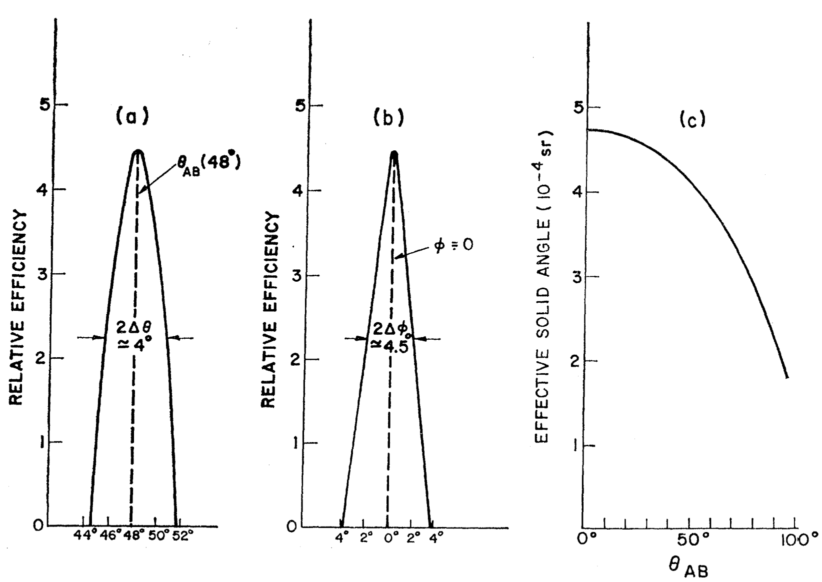

FIG. 2. (a) The relative efficiency of the counter array AB as a function of θ_{Be^8} relative to θ_{AB} in the reaction plane. (b) The relative efficiency of the counter array AB as a function of the angle of emission ϕ of the Be^8(g.s.) out of the reaction plane. (c) The effective solid angle Ω_{AB} of the counter array AB as a function of θ_{AB} for the $C^{13}[He^3, Be^8(g.s.)]$-Be^8(g.s.) reaction at 5.00 MeV.

about the recoil direction of the second Be^8 nucleus. The solid angle of detector C was sufficiently large to ensure that both of the breakup α particles from the second Be^8 nucleus would be stopped in the sensitive volume of this detector. Hence, the detection efficiency of the three-counter system for triple coincidence events corresponding to reaction (2), in which both Be^8 nuclei are in their ground state, was determined entirely by the geometry of detectors A and B. The efficiency of detector system AB for Be^8(g.s.) particles has been calculated using a procedure similar to that of Brown *et al.*[5] The detailed procedure is described in Ref. 6. Figure 2(a) illustrates the relative efficiency of the detector array as a function of the angle of emission of the Be^8(g.s.) in the reaction plane relative to the angle of the center of the array; Fig. 2(b), the relative efficiency as a function of the angle out of the chamber plane; and Fig. 2(c) the effective solid angle as a function of the counter array angle θ_{AB} at a bombarding energy of 5.00 MeV.

The triple coincidences of pulses from detectors A, B, and C were established by the addition of a time-to-amplitude converter (TAC). The start signals for TAC were provided by the fast coincidence output of A and B. A zero-crossover discriminator (the fast discriminator of another Cosmic module) on signals from detector C provided the "stop" pulses. A single-channel analyzer was set on the TAC spectrum corresponding to triple coincidence events. The typical width of the "coincidence peak" in the TAC spectrum was about 15 nsec. The output of the single-channel analyzer was used to gate a 4096-channel, two-parameter analyzer (Packard Instrument Co.) operated in a 64×64 mode. The amplified signals from detectors A and B were added

FIG. 3. A two-dimensional energy spectrum of $E_{Be^8}(E_A+E_B)$ versus $E_\alpha(E_c)$ for the $C^{13}(He^3,4\alpha)$ reactions at $\theta_{AB}=+48°$ and $\theta_C=-105°$ and $E_{He^3}=5.00$ MeV.

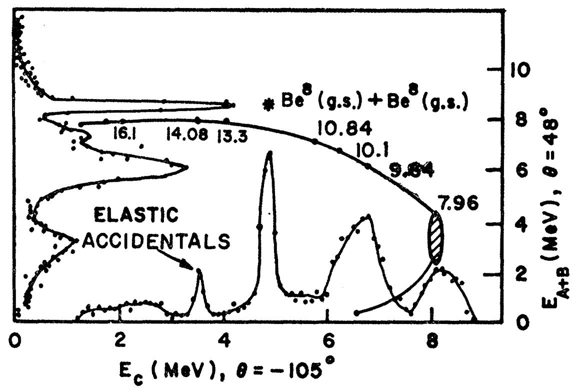

FIG. 4. Projections of the three-body kinematic curve and the four-body kinematic region for the reactions

$$C^{13}+He^3 \begin{cases} \to \alpha_1 + C^{12} \searrow Be^8(g.s.)+\alpha_C \\ \to Be^8(g.s.)+Be^8(g.s.) \end{cases}$$

onto the E_A+E_B axis ($\theta_{AB}=+48°$) and the E_C axis ($\theta=-105°$). The calculated three-body kinematic curve and the four-body kinematic region are shown with the position corresponding to the various intermediate excited states of C^{12} indicated.

in a summing circuit. The summed pulses were fed to one ADC of the two-parameter analyzer and the pulses from detector C, to the second ADC.

The typical two-dimensional coincident spectrum obtained at a bombarding energy of 5.00 MeV with the detectors positioned so as to observe the two recoiling Be^8(g.s.) nuclei (+48° and −105°) is shown in Fig. 3. The sum spectrum is displayed along the vertical axis. The population of events along the three-body kinematic curve corresponds to reaction (1), where one of the α particles, α_1 or α_2, has stopped in detector C and the Be^8(g.s.) in AB. The positions along the curve corresponding to the various possible intermediate states of C^{12} are indicated in Fig. 4. The events populating the well-defined region above the three-body kinematic curve arise from the detection of all the four α particles, corresponding to the Be^8(g.s.)+Be^8(g.s.) two-body breakup process. Although such a two-body process should manifest itself in the spectrum of the summed pulses as a discrete peak, it would have been very difficult to identify in the background due to reaction (1), which results in a continuum of Be^8 energies. The addition of the third detector C helped to overcome this difficulty as well as to reduce the number of accidental coincidences. It should be noted that reaction (2) proceeding to the 2.9-MeV state of Be^8 (or any higher excited state) could not be seen with the present setup, as the breakup cone for the 2.9-MeV state is six times larger than the Be^8(g.s.) and the efficiency for the detection of such events was 130 times less than that for the ground state.

A source of error in the determination of the absolute cross section of the Be^8(g.s.)+Be^8(g.s.) process arises

[6] K. S. Jayaraman, Ph.D. thesis, University of Maryland, 1967 (unpublished).

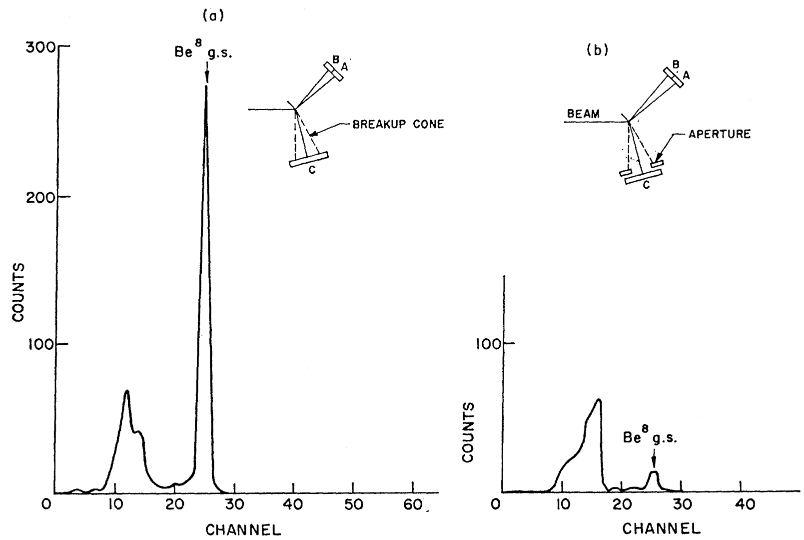

FIG. 5. Test for the indentification of $C^{13}[He^3,Be^8(g.s.)]Be^8(g.s.)$ reaction. (a) Spectrum of sum pluses (A+B) showing the Be^8+Be^8 events when the recoil detector could see the entire breakup cone. (b) Result of an identical experiment as in (a) except that the cone edges were off by an aperture.

because of the possibility of observing both α_1 and α_2 from reaction (1) in detector C. For certain intermediate states of C^{12} (depending upon the bombarding energy) such an accidental observation of all four α particles is indistinguishable from the reaction of interest. At a beam energy of 5.0 MeV, this "kinematical indistinguishability" appears if C^{12} is left in the 15.11-MeV state. Fortunately, this state has $J^\pi=1^+$ and cannot α-decay to Be^8(g.s.). However, as a result of the large solid angle of detector C, the above kinematic condition is almost satisfied for the 14.08- and 16.11-MeV states of C^{12}. (Levels above 14 MeV, which could have contributed, are known to decay primarily by proton emission.)

In order to verify that events in the four-α-particle kinematic region above the three-body kinematic curve were primarily due to the reaction proceeding through the ground states of both Be^8 nuclei, the following measurements were preformed:

(a) The diferential cross sections for the $C^{13}(He^3,\alpha)$-C^{12} reaction leading to the 14.08- and 16.11-MeV states were measured using the University of Maryland Magnetic Spectrometer. At a bombarding energy of 5.00 MeV and a laboratory angle of 120°, the differential cross section for the 14.08-MeV state was found to be 3 mb and for the 16.11-MeV state, 20 mb.

(b) The α-decay branching ratios of the 14.08- and 16.11-MeV levels to the Be^8(g.s.), as determined by another measurement were found to be of the order of 0.2 for both states. These values are consistent with those reported by Wagonner *et al.*[7]

(c) Since the four α particles from reaction (2) involving the Be^8(g.s.) are highly correlated in direction by virtue of the quasi-two-body nature of the reaction and the very low breakup energy available in each of the recoiling systems, the efficiency for the detection of these four α particles is determined entirely by the effective solid angle of detector A and B, Ω_{AB}, for a recoiling Be^8(g.s.). On the other hand, in the sequential reaction (1) the angular correlation between α_1 and Be^8 is restricted only by the angular momenta involved in the decay. In the case of reaction (1) the detection efficiency for the four α particles resulting from the decay of a state of C^{12} that satisfies the above kinematic conditions is proportional to $W(\theta_{\alpha_1},\theta_{Be^8})$-$\Omega_{AB}\Omega_C$. If we assume the angular correlation function to be of order of magnitude unity, the ratio of the four-α-particle detection efficiency for reaction (1) to that for reaction (2) is of the order of 1/80. The above values for the ratio of the efficiencies, the differential cross sections, and α-decay branching ratio yield an effective differential cross section of the order of 0.05 mb/sr for the contribution from the 16.11-MeV state of C^{12} and about 0.01 mb/sr from the 14.08-MeV state at 120°. The angular distributions of α_1 for these levels were also measured and found to increase by less than a factor of 5 in the forward direction.

(d) Although reactions (1) and (2) are kinematically indistinguishable, it is possible to identify contributions from these reactions experimentally by making use of the angular correlations resulting from their decays. The breakup α particles are emitted isotropically in the rest frame of the Be^8(g.s.), but when transformed to the laboratory system, the distribution is very strongly peaked at the edges of the breakup cone and decreases rapidly within the cone. Hence, for practical purposes, it is reasonable to assume that the Be^8(g.s.) breakup α particles are confined essentially to the cone edges. No such stringent correlation exists between α_1 and α_2 (or Be^8) from reaction (1). Two experimental runs, similar to those used to obtain the two-dimensional spectrum of Fig. 3, were carried out: (1) with an aperture in front of detector C that cut off the cone edges of distribution of α particles resulting

[7] M. A. Waggoner, J. E. Etter, H. D. Holmgren, and C. Moazed, Nucl. Phys. 88, 81 (1966).

from the breakup of a recoiling Be^8(g.s.), and (2) with no aperture. The results of these runs projected into the E_c axis are shown in Fig. 5. In case (1) the coincident events are mainly due to reaction (1) [some of the Be^8(g.s.) breakup α particles within the cone also contribute]. After correcting for the reduction in the solid angle of C introduced by the aperture, an upper limit of 4% was placed on the contribution of reaction (1) to the four-α-particle kinematic region.

The above results clearly indicate that the contribution from reaction (1) to the four-α-particle kinematic region above the three-α-particle kinematic curve can be ignored.

RESULTS

The excitation function for the $C^{13}[He^3,Be^8(g.s.)]$-Be^8(g.s.) reaction at a laboratory angle of 40° was measured as a function of the bombarding energy over the energy range from 2.50 to 6.00 MeV, in approximately 0.3-MeV intervals. At each energy, detector C was positioned at the appropriate recoil angle. The two-dimensional coincident energy spectrum was then obtained. The yields were normalized on the basis of the charge collected by the Faraday cup and corrected for the energy variation of the effective solid angle of the Be^8 detector system AB. The results are shown in Fig. 6.

The angular distributions of the Be^8(g.s.) from reaction (2) obtained at bombarding energies of 5.75, 5.00, and 3.30 MeV are shown in Fig. 7. The data were obtained in the same manner as the yield curve except that the individual runs were normalized to monitor counts rather than to the charge. As a result of the large solid angles subtended by both the combination of detector A and B and the detector C, it was extremely difficult to obtain reliable data at the forward angles. The practical lower limit for realistic lengths of runs was about 24° in the laboratory (about 30° in the center-of-mass system). The yield curve was used to establish the relative normalization between the three angular distributions. The total cross sections obtained by integration of angular distributions at 3.30, 5.00, and 5.75 MeV are 0.18, 0.37, and 0.57 mb, respectively.

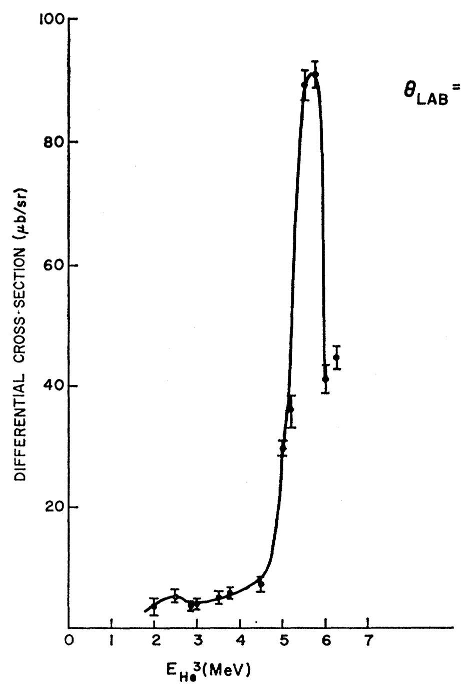

FIG. 6. Excitation function for $C^{13}[He^3,Be^8(g.s.)]Be^8(g.s.)$ reaction at 40°.

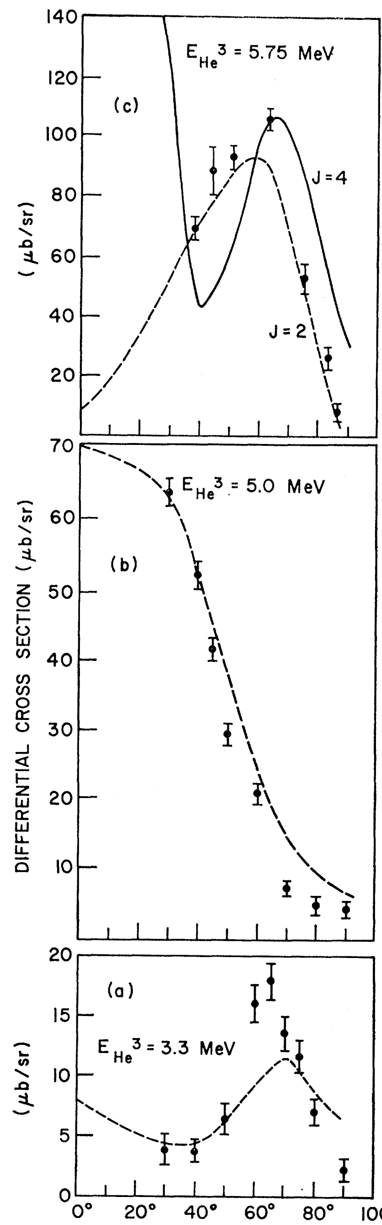

FIG. 7. Angular distribution of Be^8 in $C^{13}[He^3,Be^8(g.s.)]Be^8(g.s.)$ reaction. The theoretically calculated angular distributions shown by curves are discussed in the text.

TABLE I. Possible values of the relative angular momentum of the Be^8+He^5 clusters in the C^{13}(g.s.), L_C, and the He^3+He^5 clusters in the Be^8(g.s.), L_B, and the associated J^π of the transferred He^5 cluster.

L_C	J^π	L_B
0	$\frac{1}{2}^-$	1
1	$\frac{1}{2}^+$	0
	$\frac{3}{2}^+$	2
2	$\frac{3}{2}^-$	1
	$\frac{5}{2}^-$	3

DISCUSSION

The yield curve of Fig. 6 exhibits pronounced structure in the region of 5.6 MeV. Although the yield curve represents the behavior of the cross section at only one angle, the integrated cross section at the three energies at which angular distributions were obtained also suggests a maximum of the total cross section at the same energy indicative of a compound nucleus state in O^{16} at an excitation energy of 27.4 MeV. Similar Be^8-emitting states at lower excitation energies in O^{16} have recently been reported by Chevallier *et al.*[2] and have been interpreted as states belonging to a rotational band built upon an axially symmetric 0^+, 8p-8h state of O^{16} at 16.75 MeV.[3] In order to be a member of the same rotational band, the state at 27.4 MeV would have to have a spin of 14. Angular momentum barrier penetrability considerations make such an assignment highly improbable. Furthermore, as is shown below, the angular distribution at 5.75 MeV is not consistent with the decay of a 14^+ state of O^{16}.

The angular distribution of the emitted 0^+ Be^8(g.s.) nuclei from an 0^{16} compound state with spin J can be expressed as[8]

$$F(\theta) \propto |\beta_l|^2 f_{ll} + 2\,\mathrm{Re}(\beta_l \beta_{l'}^*) f_{ll'} + |\beta_{l'}|^2 f_{l'l'},$$

where

$$f_{ll} = \sum_L W(JlJl;1L) \begin{bmatrix} J & J & L \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} l & l & L \\ 0 & 0 & 0 \end{bmatrix} P_L(\cos\theta)$$

and the interference term

$$f_{ll'} = \sum_L W(JlJl';1L) \begin{bmatrix} J & J & L \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} l & l' & L \\ 0 & 0 & 0 \end{bmatrix} P_L(\cos\theta).$$

Here W is the Racah coefficient and the square brackets are the usual Clebsch-Gordan coefficients. L is the order of Legendre polynomial and the values of l and l' are $J\pm1$. β_l is the amplitude factor for the various incoming orbital momenta. The angular distributions were calculated for $J=2$ and 4. Reasonable agreement with the experimental angular distribution at 5.75 MeV was obtained for $J=2$ with the ratio of amplitude parameters $\beta_3/\beta_1=1.3$. It was not, however, possible to find a reasonable fit for $J=4$. Higher values of J produce an even poorer fit to the data. The calculated angular distributions for both $J=2$ and 4 are shown in Fig. 7.

The resonance observed in the $C^{13}(He^3,Be^8)Be^8$ reaction at 5.75 MeV may be the result of a potential resonance in the exit channel similar to those observed in the entrance channel of the $O^{16}+O^{16}$ reactions.[9] In order to investigate such a possibility calculations using code Abacus were carried out to see if a $J=2$ resonance in the Be^8+Be^8 system could be obtained at the appropriate energy using a potential of the same general type as that used by Block and Malik[10] to describe the $O^{16}+O^{16}$ interaction. It was found that with a real, attractive Woods-Saxon potential of 17.5 MeV, a radius of 5 F (approximately the diameter of a Be^8 nucleus), and a diffuseness of 0.5 F, it was possible to produce such a $J=2$ resonance at the observed energy. Although the fit of a single energy level is not very significant, it is nonetheless interesting that the parameters required are so similar to those used for the $O^{16}+O^{16}$ system.

The relatively smooth energy variation of the off-resonance yield at the lower bombarding energies suggests that a direct-interaction process may be primarily responsible for the reaction in this energy region. In view of the success of Denes and Daehnick[1] in fitting the (d,Li^7) and (d,Be^7) reactions with a five-nucleon (He^5 or Li^5 cluster) pickup calculation, similar calculations were carried out for the $C^{13}(He^3,Be^8)Be^8$ reaction in order to see if it would be possible to fit the 3.3- and 5.0-MeV angular distribution data using such a simple model for the interaction. In the calculation performed it was assumed that a five-nucleon system (He^5 cluster) is transferred from C^{13} to He^3 and that the five-nucleon system could be treated as a point particle. Distorted-wave Born-approximation (DWBA) calculations were performed using code JULIE.

Code JULIE employs the zero-range interaction approximation, and in a pickup reaction the interaction that is assumed to have zero range is that between the projectile and the pickedup cluster. In the case of the $C^{13}[He^3,Be^8(g.s.)]Be^8(g.s.)$ reaction, the C^{13} target wave function must be decomposed into a Be^8(g.s.)$+He^5$ cluster wave function, and the outgoing Be^8(g.s.) wave function must be formed from a He^3+He^5 cluster wave function in which the He^5 cluster is in the same internal state in both systems. Table I gives the possible combinations of values of the relative angular momenta of the clusters in the C^{13} system, L_C, and the Be^8 system, L_B, as well as the spins and parities of the transferred He^5 cluster, J^π. The dominant term in any cluster-model wave-function expansion of either C^{13} or Be^8 in their ground states would be expected to involve a He^5 cluster in either the $\frac{3}{2}^-$ ground state or the $\frac{1}{2}^-$ first excited state. On the basis of energy and angular momentum coupling considerations, the cluster-

[8] Symmetry arguments require that a Be^8-emitting state of O^{16} have even values of J and positive parity.

[9] R. H. Siemssen, J. V. Maher, A. Weidinger, and D. A. Bromley, Phys. Rev. Letters **19**, 369 (1967).

[10] B. Block and F. B. Malik, Phys. Rev. Letters **19**, 239 (1967).

TABLE II. Optical-model parameters used.

Channel	E_{He^3} (MeV)	V (MeV)	r_0 (F)	r_c (F)	a (F)	W' (MeV)	r_0' (F)	a' (F)	V_s (MeV)
Incident	5.0	83	1.6	1.6	0.8	56	1.6	0.5	0
(C^{13}, He^3)	3.3	83	1.3	1.3	0.5	56	1.5	0.65	0
Exit	5.0	40	1.3	1.3	0.8	20	1.6	0.5	0
(Be^8, Be^8)	3.3	50	1.2	1.3	0.6	20	1.4	0.5	0

model expansion of the C^{13} ground state would be expected to have a much larger amplitude for the $L_C=0$, $J^\pi=\frac{1}{2}^-$ combination than for the $L_C=2$, $J^\pi=\frac{3}{2}^-$ combination, even though the latter involves the ground state of He^5. Hence, it was assumed that the combination $L_C=0$, $J=\frac{1}{2}^-$, $L_B=1$ would result in the primary contribution to the pickup reaction. This combination leads, however, to a calculational difficulty when employing a zero-range approximation for the He^3-He^5 interaction, as the $L_B=1$ relative-motion cluster wave function vanishes at the origin and yields no contribution to the zero-range calculated cross section.[11] A calculational trick can be employed to avoid this artificial difficulty as the reaction can be considered as the stripping of a He^5 cluster from a C^{13} projectile, in which case the zero-range interaction approximation is made for the He^5-Be^8 interaction where the relative-motion wave function is an S state. It should be noted that the He^5-Be^8 relative-motion wave function must be a $3S$ wave function in order to have the correct symmetry properties. This again leads to calculational difficulties since the higher-order S relative-motion cluster wave functions also vanish at the origin when the entire wave function is antisymmetrized. In order to avoid performing finite-range calculations, an unantisymmetrized cluster wave function was used and the calculations, were carried out for the stripping of a C^{13} projectile incident upon a He^3 target.

The optical-model parameters employed in the incident and exit channels are shown in Table II. The exit-channel (Be^8+Be^8) parameters were estimated on the basis of those normally used in scattering of heavy ions. The depth of the real potential well had to be increased at 3.3-MeV bombarding energy in order to obtain an angular distribution with the same general shape as the observed angular distribution. Attractive real potentials of the Woods-Saxon volume form were used in both channels. The imaginary potentials were of the surface absorption form. The Coulomb potentials were those of a uniform spherical charge distribution. As previously noted, it was necessary to assume that the He^5 cluster had the same internal structure in C^{13} as in Be^8, in order to evaluate the form factor. A Woods-Saxon well with a radius parameter $\eta_0=1.6$ and diffusivity of 0.8 F was used to generate the cluster wave function. The orbital angular momentum was restricted to $l_B=1$, and the principal quantum number to $N=2$ (compatible with the shell-model wave function of the five-nucleon cluster).

The experimental angular distributions at 3.3 and 5.0 MeV are compared with the DWBA calculations in Figs. 7(a) and 7(b) (shown as dashed lines). The ratio of the total experimental cross section σ_{expt} to the calculated σ_{DWBA} is about 0.010 at 5.0 MeV and 0.016 at 3.3 MeV. For properly normalized calculations the ratio should be the product of the "cluster spectroscopic factor" for both Be^8 and C^{13}. Although the values obtained at both energies are in reasonable agreement they are highly questionable as a result of the gross approximations made in the calculations and the uncertainties in many of the parameters used. Furthermore, the effect of internal structure of the clusters and finite-range effects have been ignored. Since the angular distribution at 5.00 MeV was strongly peaked in the forward direction the interference term, which results from the symmetrization of the final state (Be^8+Be^8) and is required because of identity of the particles, was relatively small; but at 3.3 MeV the interference term plays a significant part and some of the difficulty in fitting the angular distribution at this energy may be attributable to the effect of the interference term.

[11] The He^5 ground-state combination also encounters the same difficulty.

CONCLUSION

A state has been found at an excitation energy of 27.4 MeV in O^{16} with a width of about 0.6 MeV which decays into two Be^8 nuclei. This state appears to have $J^\pi=2^+$. The existence of such a state in O^{16} is consistent with the assumption that the interaction between the two Be^8 nuclei in the final state can be represented by a potential similar to that used to describe the interaction of two O^{16} nuclei.[10]

The total off-resonance cross section for the C^{13}-$[He^3,Be^8(g.s.)]Be^8(g.s.)$ reaction (at 3.3 and 5.0 MeV) is comparable to the total cross sections for the C^{13}-$(He^3,\alpha)C^{12}$ reactions to many of the levels of C^{12}. In view of the complexity of the former reaction, this result is surprising. As such complex reactions appear to play a significant part in the total reaction, considerably more theoretical investigation of such reactions is warranted.

FIG. 3. A two-dimensional energy spectrum of $E_{Be^8}(E_A+E_B)$ versus $E_\alpha(E_c)$ for the $C^{13}(He^3,4\alpha)$ reactions at $\theta_{AB}=+48°$ and $\theta_C=-105°$ and $E_{He^3}=5.00$ MeV.