Angular Correlations for the Reaction $Be^9(He^3,\alpha)Be^8(16.92) \rightarrow \alpha+\alpha$

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Angular correlations for the $Be^9(He^3,3\alpha)$ reaction proceeding via the 16.92-MeV state of Be^8 have been obtained by measuring the energies of two α particles in coincidence. The measurements were made by varying the angle of observation of the breakup α particle, a constituent of $Be^8(16.92)$, with respect to the angle of emission of the initial α particle fixed at laboratory angles of 0°, 20°, 40°, 60°, 90°, and 140°. These measurements were carried out in the initial reaction plane and in the plane perpendicular to the reaction plane. The observed angular correlations involving the formation of the $Be^8(16.92)$ are consistent with the assignment of $J^\pi=2^+$ for this state and exclude the possibility of $J^\pi=0^+$. The distorted-wave pickup description was used in the analysis of the angular correlations from the reaction $Be^9(He^3,\alpha)Be^8(16.92) \rightarrow 2\alpha$, which was assumed to be a two-step process in which the first step is a direct pickup.

INTRODUCTION

THE studies of spectra and angular distributions for the $Be^9(He^3,\alpha)2He^4$ reaction at bombarding energies of 3 and 4 MeV by Browne *et al.*[1,2] have demonstrated that the 16.92-MeV level of Be^8 is the strongest populated level from the $Be^9(He^3,\alpha)Be^8$ reaction at low bombarding energies. The existence of the large continuum in the α-particle spectra, however, was interpreted[3] to imply that the $Be^9(He^3,\alpha)2He^4$ reaction also proceeds by the simultaneous breakup into the 3 α-particle final state. The preliminary results of energy and angular correlations previously reported[4,5] provide, on the other hand, direct evidence that the $Be^9(He^3,\alpha)2He^4$ reaction proceeds predominantly through intermediate states of Be^8. Coincidence observations which allow one to study the intermediate resonance formation explicitly have demonstrated that the $Be^9(He^3,3\alpha)$ reaction proceeds to the 3 α-particle final state more than 50% of the time through the 16.92-MeV state of Be^8 at a bombarding energy of 3 MeV.

As a result of the dominant role which the 16.92-MeV level plays in the $Be^9(He^3,3\alpha)$ reaction, as well as the possibility of isotopic spin mixing suggested for this state,[6] it was of interest to investigate both the spectroscopic properties of the $Be^8(16.92)$ state as well as the nature of the reaction mechanism by which the state is formed. The relatively long lifetime of the $Be^8(16.92)$ state ($\Gamma=85$ keV) suggests that the angular distribution of the α decay from the state can be determined by studying the angular correlation between the initial α particle from the $Be^9(He^3,\alpha)Be^8$ reaction leading to this state and the subsequent breakup α particle. Furthermore, the angular correlation should satisfy the Bohr conditions[7]: 180° periodicity and reflectional symmetry about the plane of the initial reaction of the angular correlation.

The angular distribution of the α decay from the $Be^8(16.92)$ is determined by its spin and m-substate population. The population of the m substates of the $Be^8(16.92)$ depends on the mode of the initial interaction leading to the intermediate state. The comparison of the angular correlation with the theoretical predictions of various reaction mechanisms can thus provide information concerning the initial interaction process as well as the spin and parity of the intermediate state. The angular correlations presented were compared to the results of the distorted-wave Born-approximation (DWBA) calculations[8] in which it was assumed that the reaction proceeds by a two-step reaction mechanism where the first is a direct interaction.

EXPERIMENTAL PROCEDURE

The experiment was performed using the University of Maryland 3-MeV Van de Graaf accelerator as a source of 3-MeV He^3 ions. The beam was energy analyzed and collimated to a diameter of 0.032 in. before entering a 12-in.-diam scattering chamber. The chamber permitted two solid-state detectors to be rotated independently, one in a horizontal plane and the other in both the horizontal and vertical planes. The thicknesses of the solid-state detectors were chosen such that they would just stop 17-MeV α particles, the highest-energy α particles expected from the $Be^9(He^3,\alpha)Be^8$ reaction.

Thin, self-supporting foils of beryllium of the order of 20 $\mu g/cm^2$ thickness were used as targets. In order to reduce the accidental counting rates at forward angles, absorbers of the appropriate thickness to stop the elastically scattered He^3 ions were placed in front of the detectors. Rectangular slits with a height-to-width ratio of 2:1 were used in order to minimize the

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[6] M. Wilson and J. B. Marion, Phys. Letters **14**, 313 (1965).
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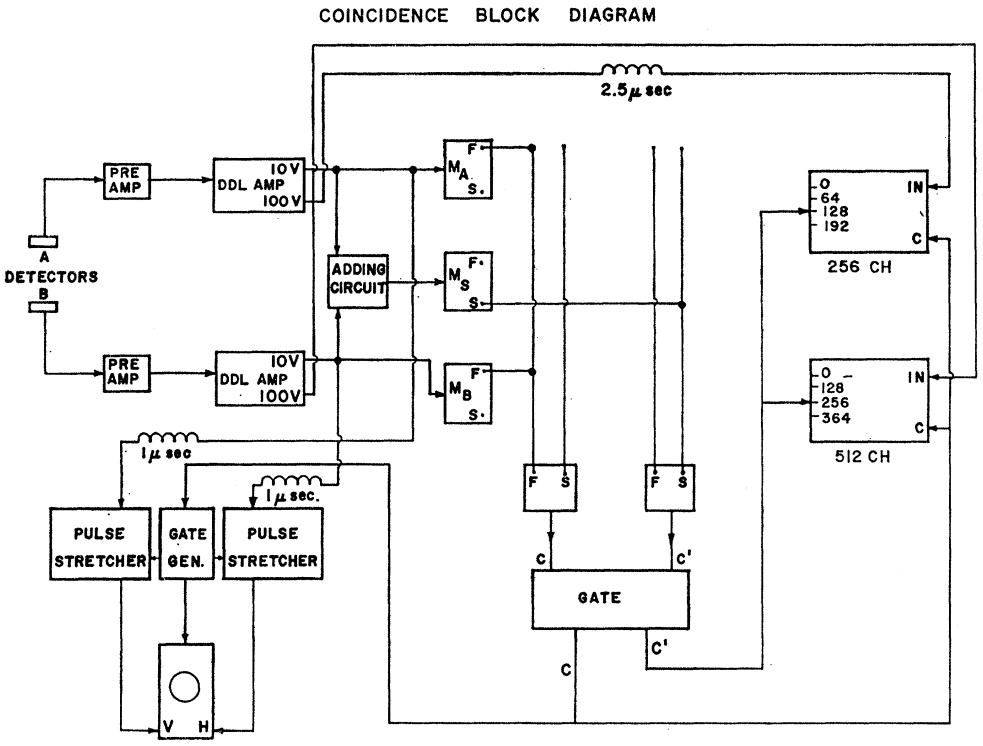

FIG. 1. Block diagram of the coincidence circuitry and recording system.

kinematic energy spread in the detector. The sensitive area of the detectors generally subtended a solid angle at the target center of 1.2×10^{-2} sr. The observed width of the α particle group from the $Be^8(He^3,\alpha)Be^8$ reaction proceeding through the 16.92-MeV state was largely due to the kinematic effects resulting from the solid angles accepted by the detectors and to the energy spread produced by the absorbers at low angles.

Whenever a reaction proceeds to a three-particle final state and the energies of two of these particles are measured in coincidence at fixed angles, the conservation of energy and momentum confines the two-dimensional spectrum of the reaction to a kinematic curve. The kinematic curves for the $Be^9(He^3,3\alpha)$ reaction at bombarding energy of 3 MeV were found to be nearly linear at most combinations of angles, and the following technique was employed to set a diagonal window about the kinematic curve. The coincident pulses were summed as follows: $E_s=\gamma E_A+(1-\gamma)E_B$. With the proper choice of (γ), the sum coincident pulses (E_s) of the α particles from the two detectors appeared as a single peak in the sum spectrum. The signals from this peak were used in the gating requirements for the pulse-height analyzer which observed the energy signals generated by each detector, thereby yielding only the projections onto the E_A and E_B axes of the intensity distribution along the kinematic curve. Standard fast-slow coincidence units with a resolving time of about 35 nsec were used to select coincidence pulses within the "diagonal" window set about the kinematic curve. A block diagram showing the usual coincident circuitry is represented schematically in Fig. 1. Random coincidences were measured separately by taking similar runs with a large delay in one side of the coincident circuit.

Typical projections of the two-dimensional energy spectrum of $Be^9(He^3,3\alpha)$ reaction with $\varphi_A=60°$ and $\varphi_B=-100°$ are illustrated on the horizontal and vertical axes of Fig. 2. The calculated regions of manifestation of Be^8 states are reconstructed along the kinematic curve. Each intermediate Be^8 state can contribute to only certain distinct portions of the allowed kinematic curve. The length of the segments are representative of the half-widths of the corresponding states. Spots (a), (b), (c) and (d) denote the expected positions of the 16.92-MeV state of Be^8. If the reaction proceeds in a manner $Be^9(He^3,\alpha)Be^8(16.92)\rightarrow 2\alpha$, the spot (a) corresponds to the initial α particle emitted at 60°, with the other α particle, a constituent of $Be^8(16.92)$ state, emitted at $-100°$. Spot (d) corresponds to these α particles being detected in the opposite counters, and locations (b) and (c) correspond to the observation of both of the breakup α particles with the initial α particle not observed. The kinematic identification of the intermediate Be^8 states has been previously reported.[4] Frequently the regions of manifestation of various Be^8 states coincide or overlap at particular angles. This phenomenon is quite distinct from that encountered because of poor energy resolution and is exemplified in the Fig. 2, in which locations (a), (b), (c), and (d) correspond to the regions of occupation of the Be^8 (g.s.) as well as the $Be^8(16.92)$.

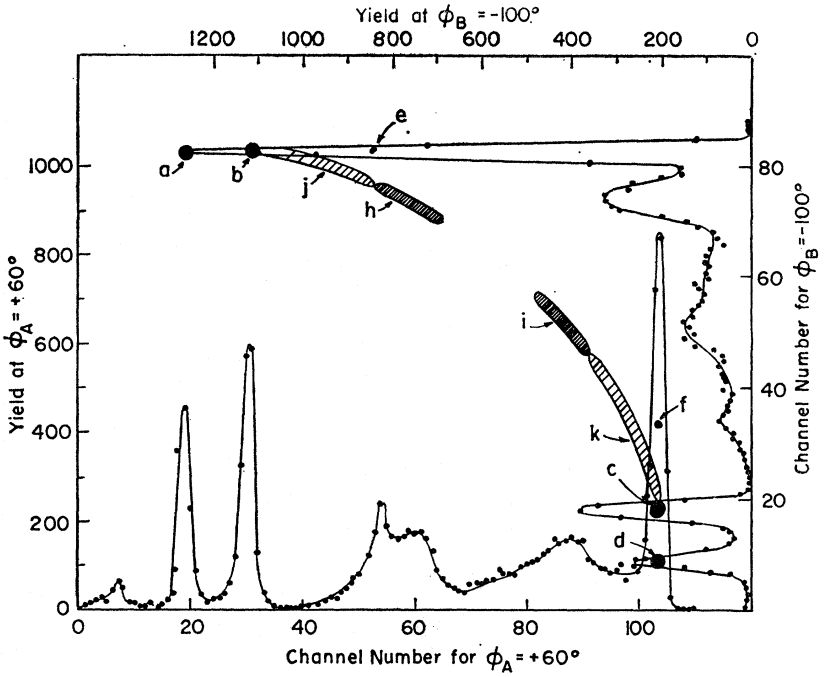

FIG. 2. The projections of the two-dimensional energy spectrum onto the E_A and E_B axes and the constructed kinematic curve for $\varphi_A = 60°$ and $\varphi_B = -100°$.

Figure 3(A) represents the two-dimensional energy spectrum of the $Be^9(He^3,\alpha)Be^8$ reaction with $\varphi_A = +60°$ and $\varphi_B = -60°$ and Fig. 3(B), the projection of the energy-correlation spectrum on the $+60°$ axis. At this combination of angles, the peak associated with the first excited state of Be^8 overlaps with that of the 16.92-MeV state. One of the peaks corresponds to the initial α particle of the 16.92-MeV state being emitted at $+60°$, and the other to the initial α particle of the first excited state being emitted $-60°$. The 4^+ state of Be^8 also gave rise to similar effects. The angles of observation were generally chosen to minimize the extent of such overlaps.

In the angular-correlation measurement corresponding to the initial α particle emitted at 90°, a double-focusing magnetic spectrometer was employed to resolve the α particle group leaving the Be^8 in the 16.92-MeV level from the group resulting from the 16.62-MeV state. For this series of measurements, the analyzed beam of He^3 particles was collimated to a diameter of $\frac{1}{16}$ in. prior to entering a 6-in.-diam scattering chamber. This chamber permitted an internal solid-state counter and the magnetic spectrometer to be rotated independently about the same axis.

The magnetic spectrometer was used as the fixed detector oriented at 90.° The charged particles emitted from the target were momentum analyzed by the spectrometer and observed by a solid-state detector placed behind the exit slits of the magnet. The protons and α particles of the same energy were differentiated by using a thin solid-state detector.

A simple coincidence measurement between the α particles selected by the magnetic spectrometer and charged particles detected by the internal solid-state detector was sufficient for this measurement, as no other competing three-body reaction could be observed and the number of random coincidences were negligible in this experimental arrangement. All angles were chosen such that the contributions from other levels were minimized.

Most of the angular-correlation measurements consisted of 16 runs. In each run the counter which defined the angle of emission of the initial α particle from the reaction $Be^9(He^3,\alpha)Be^8(16.92) \rightarrow 2\alpha$ was kept fixed and the other counter was rotated in steps of about 20°, usually covering a range of 360°.

RESULTS

The measurement of the angular correlations for reaction proceeding through the 16.92-MeV state of Be^8 is equivalent to measuring the angular distribution of the α decay of the $Be^8(16.92)$ state prepared under the specific conditions of the experiment. Since the alignment of the $Be^8(16.92)$ state depends on the direction of emission of the initial α particles for almost any reaction mechanism which could lead to the formation of this state, the angular distributions of the subsequent α decay were measured for the initial α particle emitted at fixed laboratory angles of 0°, 20°, 40°, 60°, 90°, and 140°. The observed angular correlations were transformed to the rest system of the 16.92-MeV state and are shown in Figs. 4 and 5. If the coordinate system is chosen with the z axis along the direction of $\mathbf{K}_{He^3} \times \mathbf{K}_{\alpha_i}$ (α_i is the initial α particle emitted in the reaction) and the x axis along the recoil direction, the angular

correlations shown correspond to the angular distributions of the decay from $Be^8(16.92)$ measured in the x-y ($\theta=\pi/2$) plane for each fixed angle of emission of the initial α particle indicated above, and in the x-z plane ($\varphi=0°$) for one fixed angle of emission.

The error bars associated with each datum include

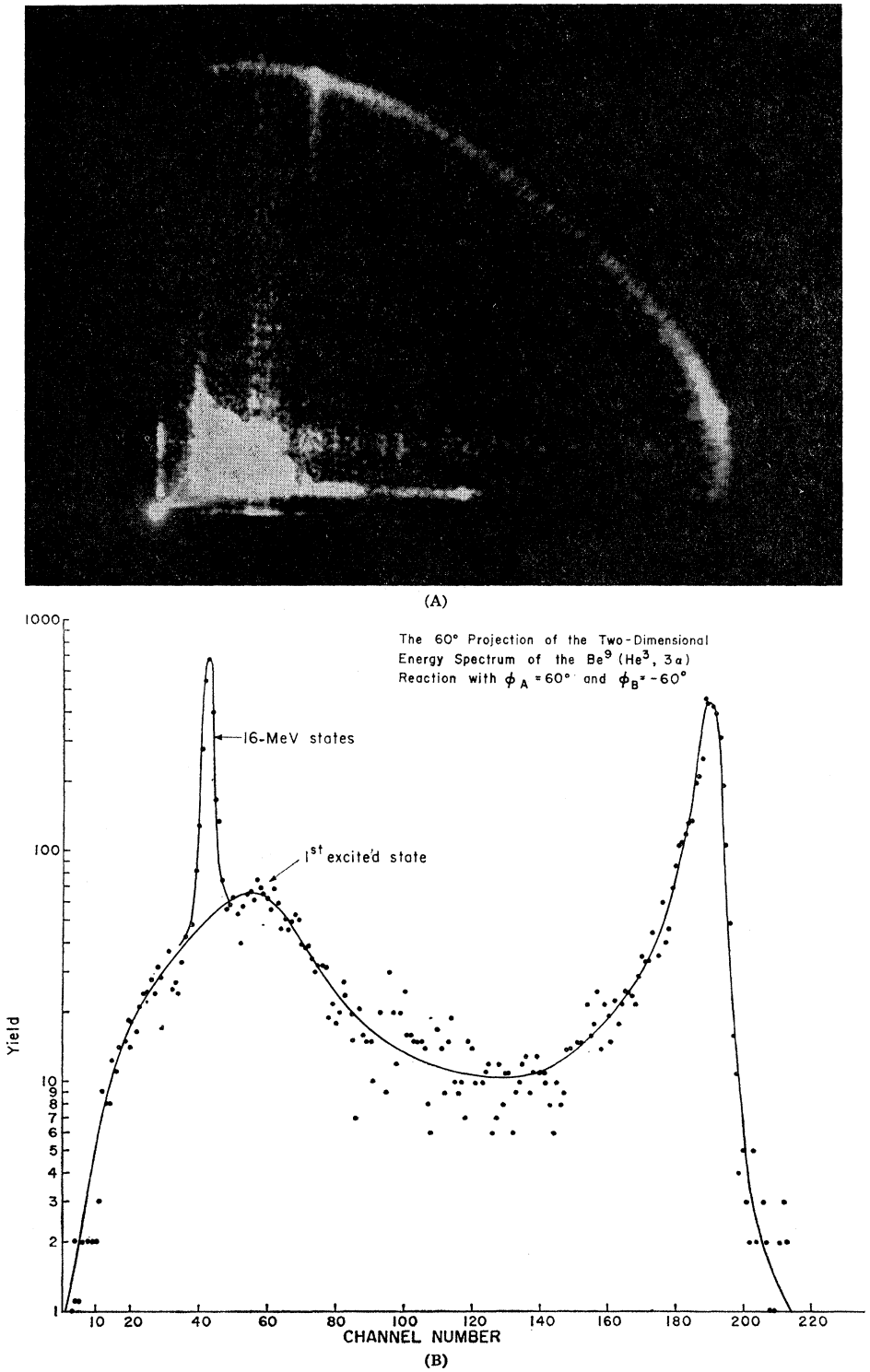

FIG. 3. The display of the two-dimensional energy spectrum from the $Be^9(He^3,3\alpha)$ reaction with $\varphi_A=+60°$ and $\varphi_B=-60°$ (A) and projection onto $+60°$ axis (B).

only the statistical uncertainty of the data. Corrections were made for random events and for contributions due to other Be^8 states (except the 16.62-MeV state). In making the latter corrections, no interference was assumed between the various contributions. No corrections were made for contributions from the Be^8(16.62) state whose peak was generally unresolved from that of the 16.92-MeV level. In all but the 90° data, the observed angular correlations are the superposition of the angular correlations for both states. The study of Dorenbusch and Browne,[2] however, has shown that the differential cross section of the $Be^9(He^3,\alpha)Be^8$ reaction proceeding to the 2^+ (16.62-MeV) state is less than 10% that of the 16.92-MeV state at all angles, except near 90°. In the measurements corresponding to the initial α particle observed at 90°, the magnet spectrometer was used to resolve these states; hence, the 90° angular correlation shown in Fig. 5(A) is free of the contribution of the 16.62-MeV state. A 90° angular-correlation measurement has also been carried out by Sullivan and Treacy[9] in which the 16.62- and 16.92-MeV states were experimentally unresolved. Their estimate of the angular correlation for the reaction proceeding through the 16.92-MeV state is therefore somewhat uncertain because of the large contribution of the 16.62-MeV state (>35%) at this angle.

The measured angular correlations were fitted by the least-square procedure to the function $W(\varphi) = \sum_{k \text{ even}} A_k \cos(\varphi - \varphi_k)$ for α decay observed in the $\theta = \pi/2$ plane (same coordinate system as previously defined) and to the function $W(\theta) = \sum_{k \text{ even}} B_k \cos k\theta$ for α decay detected in the $\varphi = 0°$ plane. The dashed and solid curves represent the best fit to the data for $k_{\max} = 2$ and 4, respectively. The amplitudes and phase angles of the angular-correlation functions for $k_{\max} = 4$ are given in Table I. A statistical analysis of the data indicates a nominal preference for $k_{\max} = 4$ over $k_{\max} = 2$, even in the case of the 0° and 20° data, whereas the remaining angular correlation require $k_{\max} = 4$. [The large ratios of A_2/A_0 and A_4/A_0 also imply that the measured angular correlations primarily characterize the angular distribution of the α decay from the Be^8(16.92) state.] Since $k_{\max}$ greater than 4 is not required to fit the data, the observed angular correlations are consistent with the spin assignment of 2^+ for the Be^8(16.92) state.

For a well-defined sequential process in which the decay occurs between states of definite parity, the angular-correlation function is expected to possess a periodicity of 180° [7,10] (in the center of mass of the intermediate system). The α decay angular distribution should also exhibit reflectional symmetry through the primary reaction plane, $W(\theta,\varphi) = W(\pi - \theta, \varphi)$. The 180° periodicity is apparent from the data obtained in the $\theta = \pi/2$ plane which is shown in Figs. 4(B), 4(C), 4(D), and 5(B), where the dots denote the data ob-

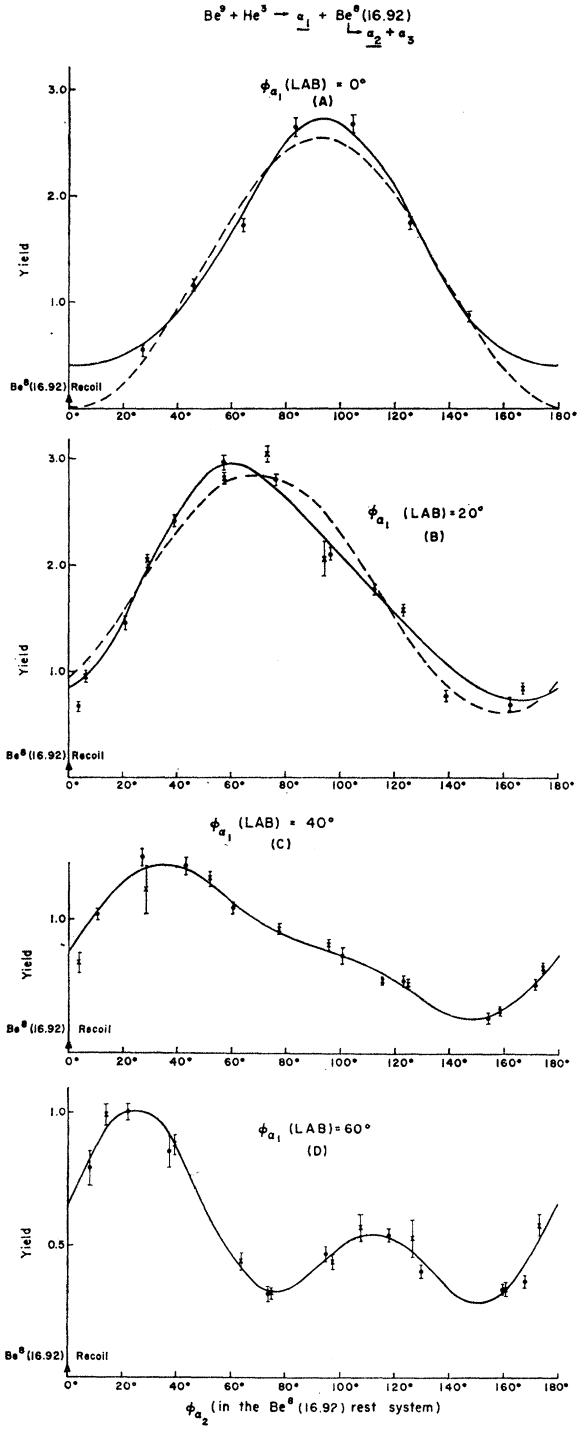

FIG. 4. The measured angular correlations for the $Be^9(He^3,\alpha_1)Be^8(16.92) \rightarrow \alpha_2 + \alpha_3$ with the initial α particle (α_1) emitted at (A), 0°; (B), 20°; (C), 40°; (D), 60°; and with (α_2) detected the initial reaction plane. The solid curve is a least-squares fit to the data of the function $W(\varphi) = \sum_{k \text{ even}} A_k \cos k(\varphi - \varphi_k)$ with $k_{\max} = 4$ and the dashed curve corresponds to $k_{\max} = 2$.

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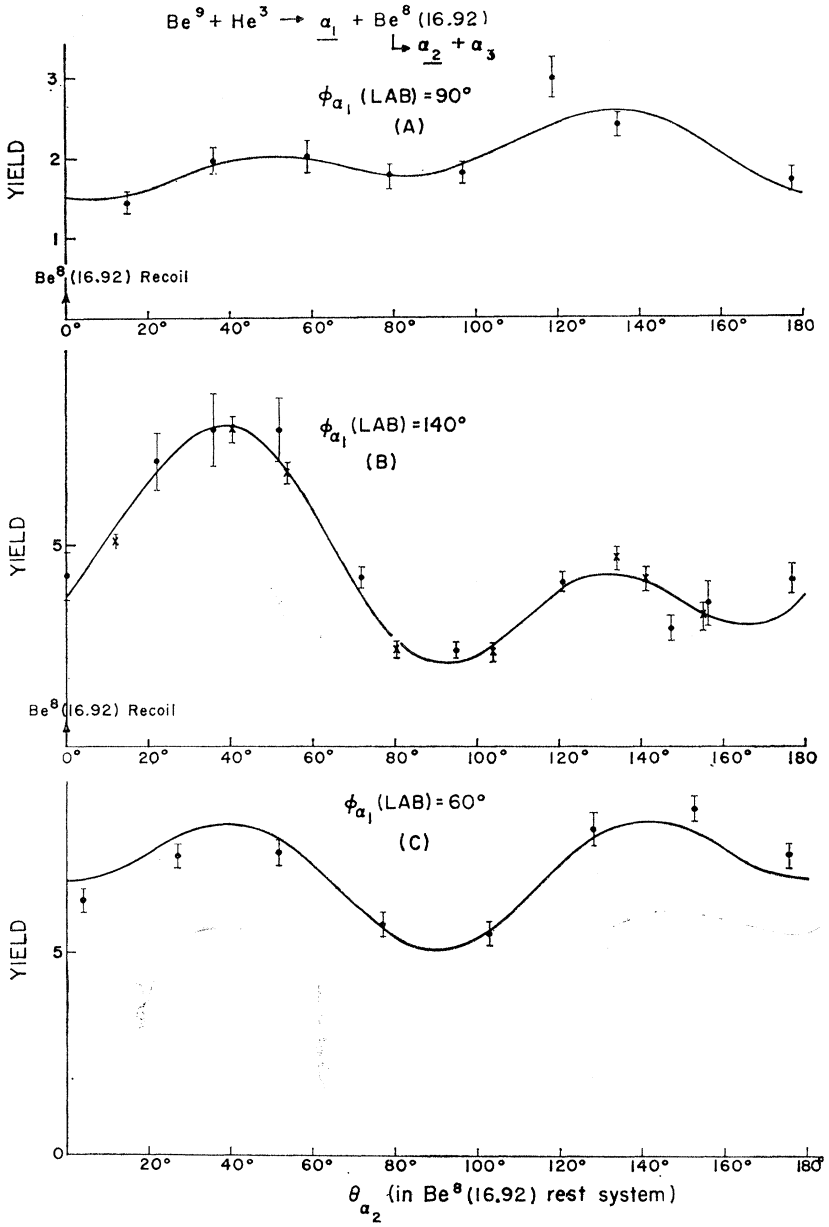

FIG. 5. The measured angular correlation with the initial α particle emitted at 90° (A) and 140° (B) and with (α_2) detected in initial reaction plane. The solid curve represents the least-squares fit to the data of the function $W(\varphi)=\sum_{k\,\text{even}} A_k \cos k(\varphi-\varphi_k)$, with $k_{\max}=4$. (C) The data with (α_1) at 60° and (α_2) detected in the plane perpendicular to the initial reaction. Solid curve represents the least-squares fit to the data of the function $W(\theta)=\sum_{k\,\text{even}} B_k \cos k\theta$.

tained at the angles φ, and the x's the data at the angles $\varphi+\pi$. The reflectional symmetry can be seen in Fig. 5(C) for the data obtained in the $\varphi=0°$ plane with $W(\theta, \varphi=0°)=W(\pi-\theta, =0°)$.

The investigation of the behavior of φ_2 and/or φ_4 can often provide information about the nature of the initial reaction mechanism. An examination of the phase angles φ_2 and φ_4 indicates that the angular-correlation functions are not characterized by an axis of symmetry. The angular-correlation functions generally fail to satisfy the phase requirement $2\varphi_2=4\varphi_4+(0 \text{ or } \pi)$ required for existence of an axis of symmetry. (The ambiguity in the phase angles corresponds to allowing the amplitudes A_2 and A_4 to be either positive or negative.) The angular behavior of φ_2 and φ_4 as functions of the angle of emission of the initial particle was also determined. Figure 6(A) shows the φ_2 phase angles plotted as a function of the angle of emmision of the initial α particle. The phase angles are measured relative to the beam direction in the rest frame of the recoiling $Be^8(16.92)$. The x's and dots correspond to allowing the amplitudes to be either positive or negative.

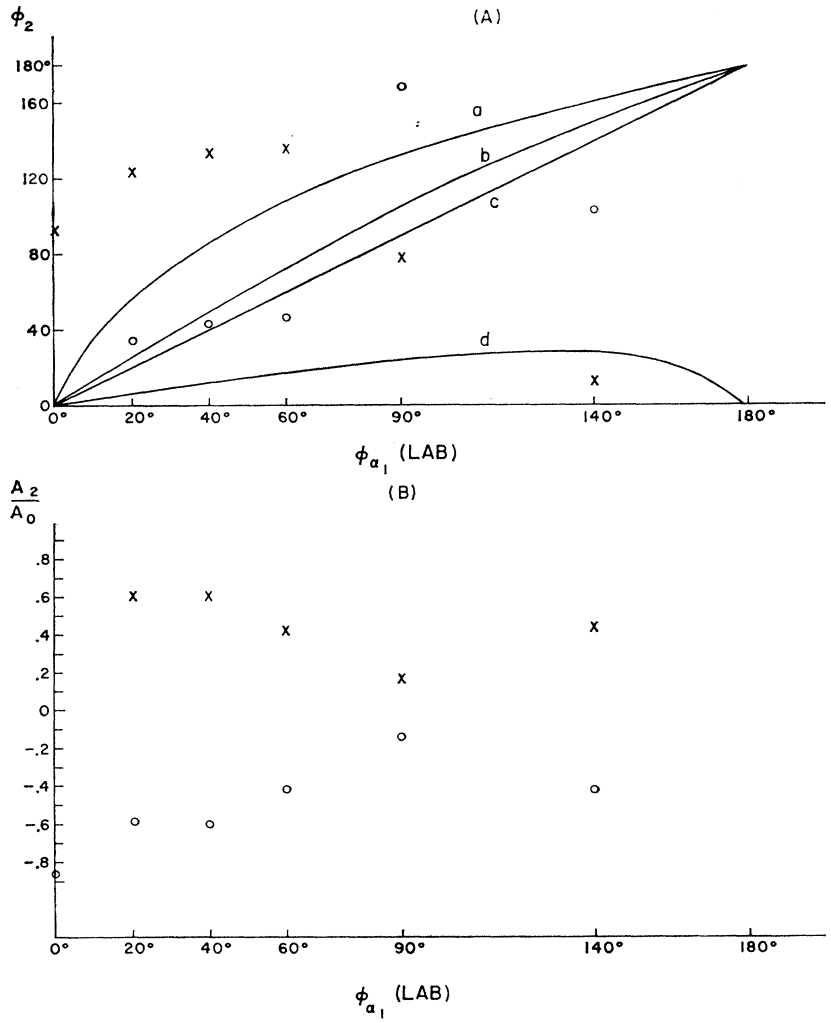

FIG. 6. (A) A plot of the φ_2 phase angles relative to the beam direction in the rest system of Be^8(16.92) versus the laboratory angle of emission of the initial α particle. (B) A plot of the A_2/A_0 amplitudes of the angular-correlation function $W(\varphi)$ with $k_{max}=4$ versus the laboratory angle of emission of the initial α particle.

Similarly, Fig. 7(A) shows the behavior of the φ_4 phase angles as a function of the angle of emission of the initial α particle, referred to the same coordinate system as Fig. 6(A). Curves (a), (b), (c), and (d) delineate the angular variation of the possible symmetry axes for various reaction mechanisms. (The descriptions are presented in the following section.) Figures 6(B) and 7(B) depict the behavior of the ratio A_2/A_0

TABLE I. The amplitudes and phase angles of the correlation function.

$$W(\theta=\tfrac{1}{2}\pi,\ \varphi)=\sum_{k\,\text{even}} A_k \cos k(\varphi=\varphi_k),\quad k_{max}=4.$$

φ_{χ_1}(Lab)	A_0	A_2	A_4	φ_2	φ_4
0°	13.46 ±0.31	11.64 ±0.49	1.95 ±0.44	−87.0±0.6°	+6.0±3.0°
20°	1.770±0.011	1.066±0.017	0.204±0.018	69.0±0.4°	−38 ±1°
40°	0.818±0.010	0.496±0.015	0.158±0.013	45.5±0.8°	25.2±1.4°
60°	0.553±0.008	0.234±0.013	0.222±0.01	27.5±1.1°	24.1±0.8°
90°	1.983±0.058	0.313±0.019	0.312±0.068	−54.5±7.4°	−43.8±4.5°
140°	4.48 ±0.07	1.91 ±0.10	1.67 ±0.11	32.6±1.5°	39.9±0.8°

$$W(\theta,\ \varphi=0°)=\sum_{k\,\text{even}} B_k \cos k\theta,\quad k_{max}=4.$$

φ_{α_1}(Lab)	B_0	B_2	B_4
60°	7.04±0.11	0.88±0.14	−1.1±0.16

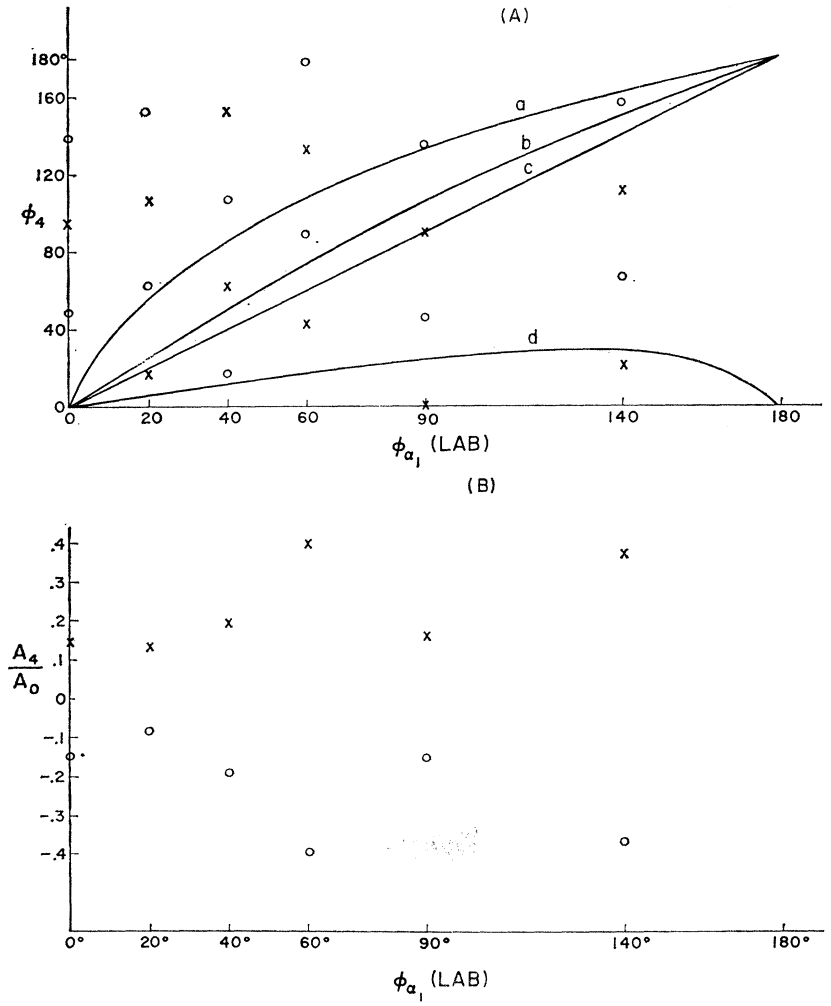

FIG. 7. (A) A plot of the φ_4 phase angle relative to the beam direction in the rest system of $Be^8(16.92)$ versus the laboratory angle of emission of the initial α particle. (B) A plot of the A_4/A_0 amplitudes of the angular-correlation function $W(\varphi)$ with $k_{max}=4$ versus the laboratory angle of emission of the initial α particle.

and A_4/A_0 versus the angle of emission of the initial α particle. One would expect that the correct choice of A_2/A_0 or A_4/A_0 as a function of the angle of emission of the initial α particle should result in a smooth curve.

DISCUSSION

The validity of the description of the $Be^9(He^3,3\alpha)$ reaction as a sequential process proceeding through the $Be^8(16.92)$ state depends largely upon the extent to which the short-range nuclear field of the initial α particle affects the decay of the $Be^8(16.92)$ state. If the decay of the intermediate Be^8 state occurs while the initial α particle is within a distance comparable to the range of the nuclear interaction between two α particles, the presence of the third particle may alter the angular pattern of the α decay from Be^8 as well as change the energy distribution of decay α particles. The decay of the $Be^8(16.92)$ state occurs at a mean distance of separation of 120 F, as determined by its lifetime (85 keV width) and the kinematics of the reaction. The 180° periodicity and reflectional symmetry exhibited by the measured angular correlation provide direct evidence that the angular dependence of the α decay is not significantly affected by the initial α particle and that the reaction can be considered as occurring sequentially. This conclusion is further supported by the agreement of excitation energy of the $Be^8(16.92)$ state as determined by α-α scattering[11] (without the presence of the third α particle) with that determined in the $Be^9(He^3,\alpha)Be^8$ reaction (with the third α particle present).

The initial interaction in the reaction $Be^9(He^3,\alpha)$ $Be^8(16.92) \rightarrow 2\alpha$ can occur via compound-nucleus formation and/or a direct-reaction mechanism. The mode of interaction by which the initial reaction occurs determines the phase angles φ_2 and φ_4. Frequently, there

[11] H. E. Conzett, P. Darriaulat, H. G. Pugh, E. Shield, and R. J. Slobodrian (private communication).

arises a definite prediction as to the existence and direction of a symmetry axis. If the initial interaction proceeds by a pickup mechanism, the plane-wave treatment gives rise to a symmetry axis along the laboratory recoil direction of the Be^8(16.92) system. The measured angular correlations do not generally exhibit such an axis of symmetry. Nevertheless, if A_2 or A_4 reflects predominantly the character of a single reaction mode, then the angular behavior of φ_2 or φ_4 as a function of the angle of emission of the initial α particle may exhibit the angular dependence similar to that of the expected axis of symmetry. Curve b of Figs. 6(A) and 7(A) depicts the angular behavior of the phase angles as predicted by PW theory for a pickup reaction. If the $Be^9(He^3,3\alpha)$ reaction proceeds through a compound nucleus at 28.5 MeV of excitation in C^{12}, in the special case where the angular momentum of either the incident or exit channel is zero, the symmetry axis would correspond to the direction of the center-of-mass recoil velocity of the 16.92-MeV Be^8 state, curve a of Figs. 6(A) and 7(A) or to the beam direction, respectively. For heavy-particle stripping, two possible symmetry axes can appear in the plane-wave approximation. If the He^3 particle is captured by the He^5 particle with zero relative angular momentum, the symmetry axis may be in the direction of the laboratory velocity of the initial α particle (curve c). On the other hand, if the initial α particle is emitted from Be^9 with zero relative angular momentum, the symmetry axis can correspond to the direction of the relative velocity of the final He^3-He^5 system (curve d). It is apparent that neither φ_2 nor φ_4 possess such angular dependence. It should be noted that such symmetries do not generally occur in either the DW description of direction reactions or compound-nucleus formation.

If the initial interaction involves a compound-nucleus formation, the bombarding energy of 3.0 MeV corresponds to an excitation energy of 28.5 MeV in the C^{12} system. Although reactions which lead to α particle emission[12] have been observed to proceed through discrete states of C^{12} at such an excitation energy, all Be^9+He^3 reactions studied to date exhibit very smooth energy dependence of the total cross section in this region of excitation. Hence, if compound-nucleus formation is the major contributor to the reaction, it must involve a system with many overlapping levels. The measured angular distributions of the $Be^9(He^3,\alpha)Be^8$(16.92) reaction at 3- and 4-MeV bombarding energies[2] are, however, very similar in shape: Both exhibit a strong angular dependence which is not symmetrical about 90°. These features suggest that the reaction $Be^9(He^3,\alpha)Be^8$(16.92) proceeds largely by a direct process.

If we assume that the initial reaction occurs primarily by a simple pickup mechanism, the failure of the measured angular correlations to possess rotational symmetry about the recoil direction indicates that PW is not adequate and that the data must be compared with the DW theory. On the basis of only the spin and parity of the initial and final nuclei ($\frac{3}{2}^-$ and 2^+, respectively) the angular-momentum transfer is restricted to $l=1,3$ for a simple pickup interaction. The angular distribution of the initial α particle from the $Be^9(He^3,\alpha)$ Be^8(16.92) reaction exhibits a relatively large peak in the forward direction characteristic of $l=1$ transfer. Moreover, if one assumes that the last three neutrons of the Be^9 ground state are in the 1p shell, an $l=1$ transfer pickup process would be expected. Consequently, the observed angular correlations were compared to the prediction of the DW theory based upon the assumption that the initial reaction occurs only via a $l=1$ reaction pickup.

The angular-correlation function formulated by Satchler *et al.* [10,13,14] is applicable under the above assumptions. Satchler *et al.* present a form of the angular-correlation function for a two-step sequential process in which the first step proceeds by a direction-reaction mechanism followed by the decay of the residual nucleus. The angular-correlation function representing the angular distribution of radiation from the oriented intermediate state is given by

$$W(\theta,\varphi,\bar{k}_a,\bar{k}_b) = \sum_{K,Q}\left[\frac{4\pi}{(2k+1)}\right]^{\frac{1}{2}}\rho_{KQ}(J_BJ_B)F_KY_{KQ}(\theta,\varphi), \quad (1)$$

where

$$F_K=\sum_{LL'} D_LD_{L'}F_K(LL'J_CJ_B)b_K(LL').$$

Thus for a process $A(a,b)B^* \rightarrow c+C$, W describes the angular distribution of c measured in coincidence with b which is emitted along $\bar{k}_b$. The separation of W into the product of ρ_{KQ} and F_KY_{KQ} consists in representing the properties of the intermediate state (its m-state population) by ρ_{KQ} and the properties of the subsequent decay by F_KY_{KQ}. The factor D_L denotes the reduced matrix element which selects the contribution to the various angular-momentum components of the radiation. The γ angular-correlation coefficient $F_K(LL',J_BJ_C)$ and the parameter b_K which refers to particle emission rather than γ decay have been tabulated by Biedenharn and Rose.[15] The order of W is limited by $K\leq 2l$, $j+j'$, $L+L'$, or $2J_B$, where l and j are the appropriate orbital and total-angular-momentum transfer associated with the initial reaction, J_B represents the spin of the intermediate state (B^*), and L denotes the relative angular momentum of the emitted radiation.

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TABLE II. Optical-model parameters used in the analysis of the $Be^9(He^3,\alpha)Be^8(16.92)$ reaction. $E_{He^3}=3.0$ MeV.

	Entrance channel							Exit channel				
	V MeV	W MeV	r F	r_c F	a F	r_w F	a_w F	V MeV	W MeV	r F	r_c F	a F
Option 1	131.0	7.0	1.03	1.4	0.893	2.06	0.508	79.0	9.0	1.4	1.4	0.7
Option 2	88.0	9.0	1.5	1.5	0.7			79.0	9.0	1.4	1.4	0.7

If one neglects spin-orbit interaction in the distorted waves as well as the difference in the radial wave functions of the neutron in the Be^9(g.s.) in the $p_{3/2}$ and $p_{1/2}$ shells, the angular-correlation function describing the formation of the $Be^8(16.92)$ by a $l=1$ pickup process and its subsequent decay is of the form

$$W(\theta,\varphi)\propto 1+A_2{}^0P_2{}^0(\cos\theta)+A_2{}^2P_2{}^2(\cos\theta)\cos2(\varphi-\varphi_2). \quad (2)$$

(The coordinate system is the same as defined previously.) Equation (2) depicts a process in which a $l=1$ neutron is picked up from the Be^9 target ($J_A{}^\pi=\frac{3}{2}^-$) to form the $Be^8(16.92)$ state ($J_B{}^\pi=2^+$) which then α decays with $L=2$ to a final α particle state ($J_C{}^\pi=0^+$). The theoretical parameters[13] B_{lm} are contained in $A_2{}^0$, $A_2{}^2$, and φ_2 in the following manner:

$$A_2{}^0=-\tfrac{1}{2}\left[\sum_{jj}\frac{A_{l(1/2)j}A^*_{l(1/2)j'}}{\sum_j|A_{l(1/2)j}|^2}\eta_2(jj'J_AJ_B)\right]\times\sum_{LL'}C_LC_{L'}F_2(LL'J_CJ_B)b_2(LL'),$$

$$\frac{-2A_2{}^2}{A_2{}^0}=2\Big/\left(\left|\frac{B_{1-1}}{B_{1\,1}}\right|+\left|\frac{B_{1\,1}}{B_{1-1}}\right|\right)\equiv\lambda,$$

$$2\varphi_0=\mathrm{Arg}\left(\frac{-B_{1-1}}{B_{1\,1}}\right).$$

The factors A_{lsj} refer to the reduced width amplitude and η_k (a product of Wigner and Racah coefficients) and have been tabulated by Satchler.[16]

The angular-correlation function for the reaction $Be^9(He^3,\alpha)Be^8(16.92)\rightarrow 2\alpha$ with $\theta=\pi/2$, when the initial reaction is assumed to take place via an $l=1$ pickup mechanism, is given by

$$W\left(\theta=\frac{\pi}{2},\varphi\right)\propto\left(1+\frac{\gamma}{4}\right)+\frac{3\gamma}{4}\lambda\cos2(\varphi-\varphi_2), \quad (3)$$

where γ denotes

$$2\,\mathrm{Re}[A_{1(1/2)(1/2)}A^*_{1(1/2)(3/2)}/\textstyle\sum_j|A_{1(1/2)j}|^2].$$

It is interesting to note that the pure $j=\frac{3}{2}$ term contained in the amplitudes vanishes (the Racah coefficient associated with $j=\frac{3}{2}$ is zero). Since a pure $j=\frac{1}{2}$ pickup also yields an isotropic angular correlation, $k=0$, only the mixture $j=\frac{1}{2}$ and $j=\frac{3}{2}$ terms can lead to an anisotropic angular correlation.

Selection rules imposed by the $l=1$ assumption restrict the order of the angular-correlation function to two ($k_{\max}\leq 2$). The angular correlations observed at 0° and 20° are almost consistent with $k_{\max}=2$ (although a small component with $k=4$ is required to fit the data); but the data at other angles requires a large contribution from $k=4$. Hence only 0° and 20° data were compared with the prediction of the zero-range DW calculation using code SALLY.[8] Furthermore, the forward peak observed in the differential cross section for the $Be^9(He^3,\alpha)Be^8(16.92)$ reaction by Browne *et al.*[2] would be expected to be associated primarily with the pickup process.

The optical-model parameters used in determining λ and φ_2 were selected by fitting the observed angular distribution for the $Be^9(He^3,\alpha)Be^8(16.92)$ reaction with the DW calculations. It is possible to obtain an acceptable fit to the data with parameters which are in reasonable agreement with those found by Alford *et al.*[17] The comparison of the angular-distribution data (obtained by Browne *et al.*[2]) to the shape predicted for the simple $l=1$ pickup mechanism is shown in Fig. 8. The two sets of optical parameters used are given in Table II. Independent Woods-Saxon shapes were chosen for both the real and imaginary part of the optical potentials.

The DW calculation for the initial α particle emitted at 0° yields $\lambda=1$ and $\varphi_2=0$ [see Eq. (3)] independent of the optical parameter (the distortions vanish when the initial particle is emitted at 0° or 180°). The observed angular correlation at 0° was found to be given by

$$W=1-1\cos2\varphi,$$

which leads to $\gamma=-1.00\pm0.04$. The dashed curve of Fig. 4(A) represents the fit of this expression to the data. The determination of γ, which is a measure of the interference term of the reduced amplitude for $j=\frac{3}{2}$ and $\frac{1}{2}$, does not rely on optical parameters in the special case of the emission of the initial α particle at 0° and 180°.[8] $\gamma=1$ implies that if the initial reaction proceeds by a simple $l=1$ pickup, the reaction must involve an equal admixture of $j=\frac{1}{2}$ and $j=\frac{3}{2}$ transfer.

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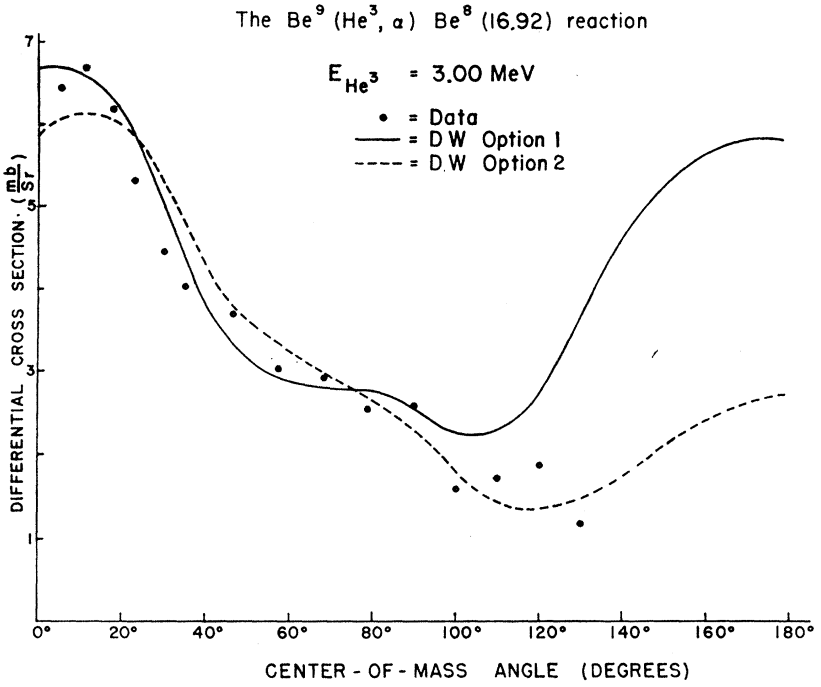

FIG. 8. The comparison of the measured anglular distribution from the $Be^9(He^3,\alpha)Be^8(16.92)$ reaction (data points) with the shape predicted by DW code SALLY for the two sets of optical parameters given in Table II.

For the emission of the initial α particle at 20° the theoretical parameter φ_2^{th} was found to be quite sensitive to the choice of optical-model parameters. The sensitivity of φ_2 to optical-model parameters does not permit one to infer directly the nature of the initial reaction as was the case in the PW treatment. λ, on the other hand, appears to be rather insensitive to the choice of optical-model parameters. The predicted value of φ_2^{th} is in better agreement with the observed φ_2^{ob} when the optical-model parameters are such that the imaginary potential has a larger radius than the real potential ($\varphi_2^{th}=-17°$ as compared to $\varphi_2^{ob}=-21°$). The predicted angular-correlation function using such a set of optical-model parameters for the initial α particle emitted at 20° may be expressed as

$$W(\theta=\tfrac{1}{2}\pi,\ \varphi) \propto (1+\tfrac{1}{4}\gamma)+\tfrac{3}{4}\gamma(0.999)\cos 2(\varphi+17°),$$

and the corresponding measured angular correlation was found to be given by

$$W_{expt}(\theta=\tfrac{1}{2}\pi,\ \varphi) \propto 1-0.645\cos 2(\varphi+21°),$$

yielding a value for $\gamma=0.65\pm0.01$. See the dashed curve of Fig. 4(B).

It is noteworthy to point out again that although the fourth-order contribution of W is more pronounced at backward angles (away from the stripping peak), it is also statistically significant at forward angles.

The large ratio of A_4/A_0 at backward angles suggests that $l=3$ pickup, exchange, or possibly higher-order processes contribute significantly to the reaction if the $Be^9(He^3,\alpha)Be^8(16.92)$ reaction is assumed to proceed largely by a direct mechanism. Moreover, the inclusion of spin-orbit coupling does not affect the order of $W(l=1$ imposes the condition of $k_{max}\leq 2)$.

CONCLUSION

The angular-correlation data exhibits a 180° periodicity and reflectional symmetry about the initial reaction plane, demonstrating that the $Be^9(He^3,\alpha)Be^8$-(16.92) $\rightarrow 2\alpha$ proceeds via a sequential process through states of well-defined symmetries. The orders of the angular-correlation functions were all found to be consistent with the assignment of $J^\pi=2^+$ for the Be^8-(16.92) state and exclude the possibility of $J^\pi=0^+$. Furthermore, the observed angular-correlation functions failed to exhibit the symmetry properties predicted by a PW treatment for pickup mechanisms. Qualitative agreement was obtained in the comparison of the 0° and 20° data with the results of the DW calculation for a $l=1$ pickup process. The remaining angular-correlation data, however, provided evidence that if the $Be^9(He^3,\alpha)Be^8(16.92)$ reaction occurs largely by a direct process, mechanisms other than $l=1$ pickup also contribute to the reaction.

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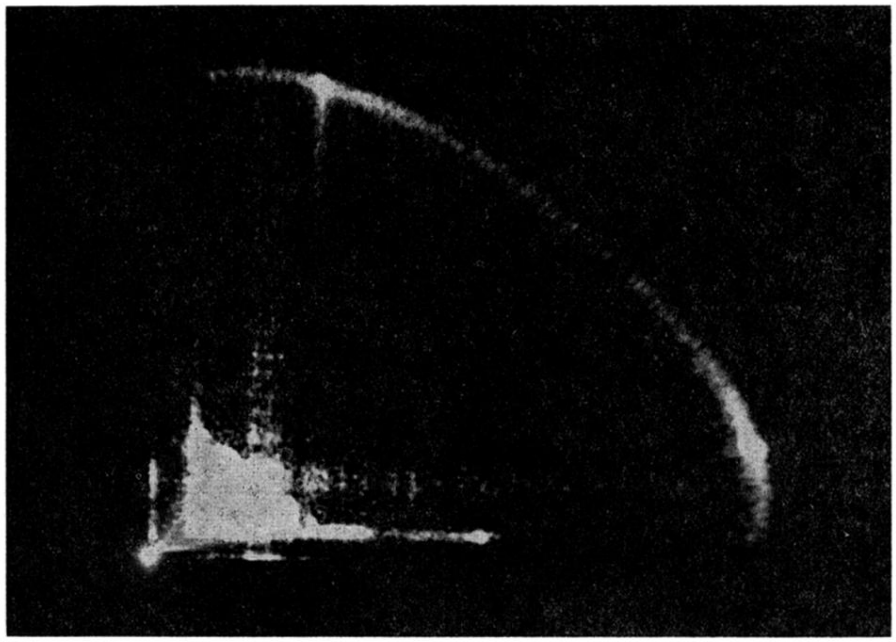
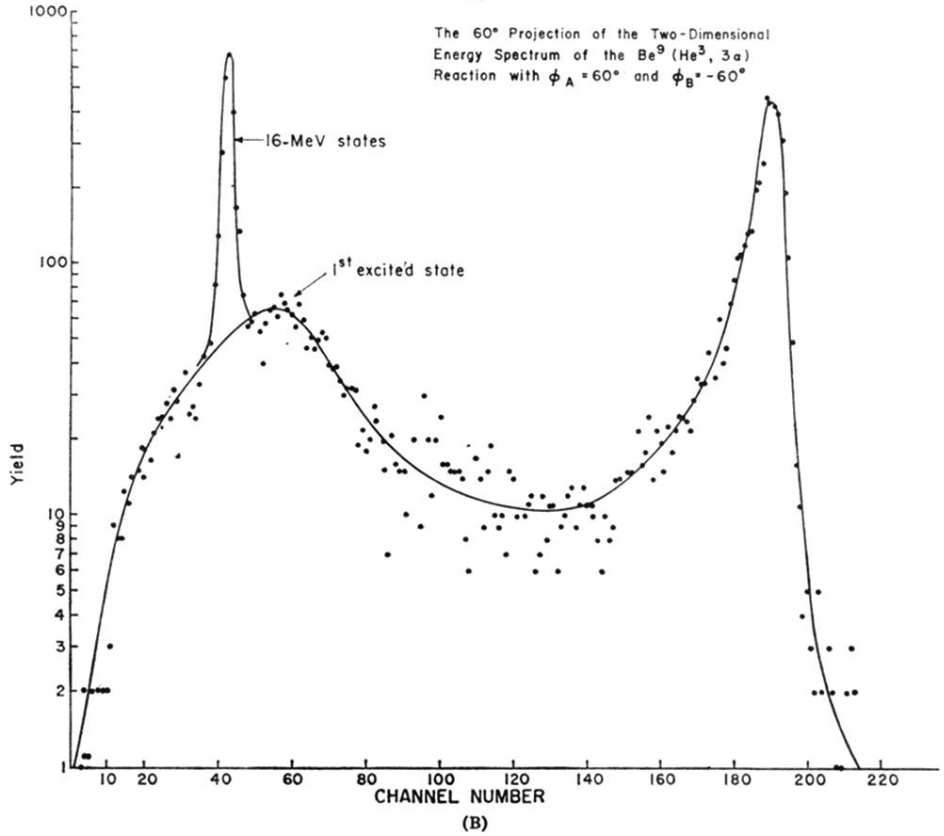


(A)



(B)

FIG. 3. The display of the two-dimensional energy spectrum from the $Be^9(He^3,3\alpha)$ reaction with $\varphi_A = +60°$ and $\varphi_B = -60°$ (A) and projection onto $+60°$ axis (B).