the phase space function. Unfortunately, decay via the 1st excited state of ^{5}He and the 2nd excited state of ^{8}Be is also possible at these angles and the relative contribution from sequential and nonsequential decay cannot be determined.

It is interesting to note that the neutron spectrum[3] from ^{7}Li(d, n)^{8}Be measured at a bombarding energy of 2 MeV shows a background which has been attributed[4] to nonsequential decay. Also observed in this neutron spectrum was a strong peak due to sequential decay via the 1st excited state of ^{8}Be. We think that this decay mode may not have been observed in the present experiment (Fig. 2) because of the relatively very small volume in phase space at values of θ_M and the projection angle where this decay mode is expected to appear.

In summary, we observed: (1) sharp peaks whose positions are consistent with the assumption of sequential decay via known levels of the possible intermediate nuclei, (2) broader structure which might be either sequential or nonsequential decay, and (3) no yield which may be unambiguously interpreted as nonsequential decay.

Discussion

HOLMGREN: You say that you see the 16.7 level. Do you see any evidence for the next higher level in Be^8?

JONES: In the data at 2 MeV this is not kinematically possible. We have taken data at higher bombarding energies. At these energies the two levels are so close together that it is not possible to separate them. So the answer to your question is no.

---

[4] C. H. Johnson and C. C. Trail, Phys. Rev. **133**, B1183 (1964).

REVIEWS OF MODERN PHYSICS VOLUME 37, NUMBER 3 JULY 1965

Particle–Particle Angular Correlation for the Be^9(He^3, α)Be^8→$\alpha\alpha$ Reaction

C. MOAZED, J. E. ETTER, H. D. HOLMGREN, M. A. WAGGONER
University of Maryland, College Park, Maryland*

The Be^9(He^3,$\alpha\alpha\alpha$) reaction has been observed to proceed to the three-α-particle final state more than 50% of the time through the 16.92-MeV state of Be^8. In view of the prominence of this level in the Be^9(He^3, α)2He^4 reaction, it would be of considerable interest to investigate the nature of the Be^8(16.92) state. Since the Be^8(16.92) state has a half-width of 85 keV it satisfies the criterion for sequential processes; i.e., the decay of the state occurs long after the initial α particle is beyond the range of interactions. Hence, it should be possible to determine the spin of this state as well as information concerning the nature of the initial reaction mechanism through a study of the particle–particle angular correlations for the Be^9(He^3, α)Be^8(16.92)$\to\alpha\alpha$ reaction. In addition the analysis of such correlations should be the same as the theory used in the study of particle–γ correlations. If the Be^9(He^3, α)Be^8(16.92) reaction proceeds by a pickup mechanism, the Be^8(16.92) would favor an α–α configuration, whereas an exchange mechanism leading to the 16.92-MeV level would favor the Be^7–n configuration. In any case, it would be difficult to reach a Li^7–p configuration by means of a direct interaction.

Particle–particle angular correlations for the Be^9(He^3, α)Be^8(16.92)$\to 2\alpha$ have been measured as a function of the angle of the breakup of the Be^8(16.92) state for the initial α particle emitted at 20°, 40°, 60°, 90°, and 140°. The apparatus and experimental techniques used were essentially the same as those employed in the B^{10}(He^3, $p\alpha\alpha\alpha$)[1] experiment. Thin self-supporting Be^9 targets were bombarded with 3.00-MeV He^3 particles. In order to obtain reasonable real coincidence counting rates for this reaction and still keep the accidental counting rates below an acceptable level it was necessary to use solid angles of 1.2×10^{-2} sr for both counters. Although rectangular apertures were employed to minimize the kinematical energy variation of the particles within this solid angle, it was not generally possible to resolve the 16.92- and 16.62-MeV states of Be^8. On the other hand, the study of the α-particle spectrum for the Be^9(He^3 α) Be^8 reaction with 3-MeV incident He^3 particles by Dorenbusch and Browne[2] has shown that the differential cross sections for Be^9(He^3, α)Be^8 reaction leading to the 16.92-MeV state is an order of magnitude larger than those for 16.62-MeV level of Be^8 at most angles.

The measured angular correlations have been transformed to the rest system of the 16.92-MeV state of Be^8 and are shown in Fig. 1. In the case of a well defined sequential process for the reaction a periodicity of 180°

---

* Research supported in part by the U. S. Atomic Energy Commission.

[1] J. E. Etter, M. A. Waggoner, C. Moazed, H. D. Holmgren, and C. Han, Rev. Mod. Phys. **27**, 444 (1965), this conference.

[2] W. E. Dorenbusch and C. P. Browne, Phys. Rev. **131**, 1212 (1963).

TABLE I. The values of the amplitudes and phase angles of the angular correlation function $A_0+A_2\cos 2/(\theta-\theta_2)+A_4\cos 4(\theta-\theta_4)$ in the rest system of Be^8(16.92) for the initial α emitted at lab angles of 20°, 40°, 60°, 90°, and 140°.

$\theta_{\alpha 1}$ (lab)	A_0	A_2	θ_2 (deg)	A_4	θ_4 (deg)
20°	+1.77 +0.0114	+1.066 ±0.0168	−69.02 ±0.42	−0.204 ±0.17	−7.05 ±1.00
40°	0.818 ±0.0101	+0.496 ±0.0154	−45.47 ±0.78	+0.158 ±0.0132	−25.155 ±1.337
60°	0.553 ±0.0083	−0.234 ±0.0134	+62.48 ±1.07	+0.222 ±0.0101	−24.07 ±0.80
90°	0.437 ±0.0049	−0.121 ±0.0077	−40.28 ±1.51	+0.117 ±0.0064	−42.35 ±0.98
140°	4.478 ±0.0691	−1.909 ±0.1016	+57.35 ±1.45	+1.669 ±0.1053	−39.87 ±0.80

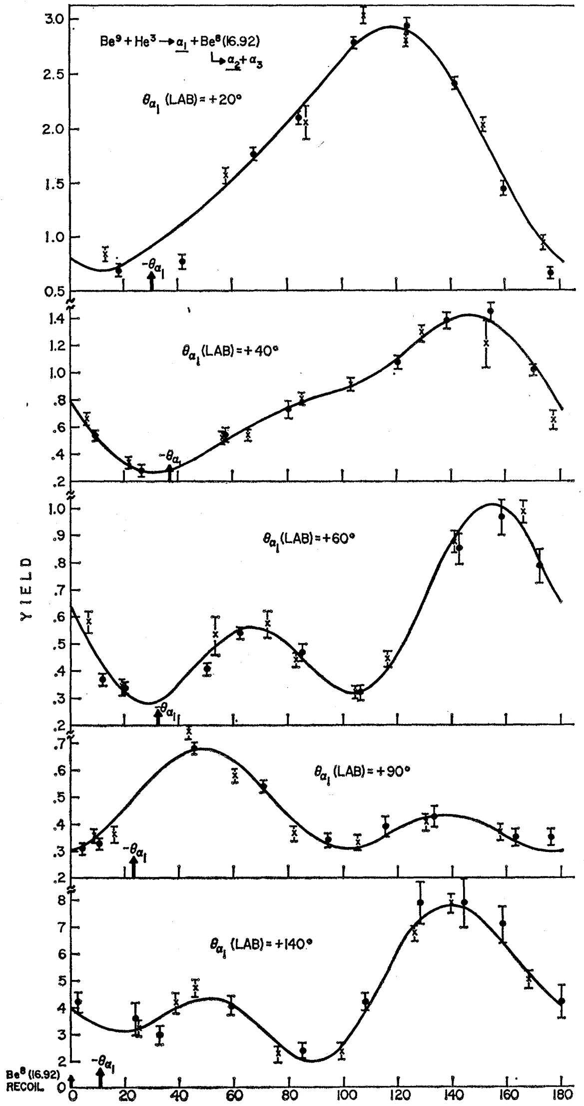

FIG. 1. Graphs of the angular correlation function $A_0+A_2\cos 2(\theta-\theta_2)+A_4\cos 4(\theta-\theta_4)$ least-square fitted to the observed angular correlations (initial α emitted at lab angles of 20°, 40°, 60°, 90°, and 140°) in the rest system of Be^8(16.92) for the $Be^9(He^3, \alpha)Be^8(16.92)\rightarrow 2\alpha$ reaction with 3.00-MeV incident He^3.

is expected in this system. This periodicity is quite apparent in Fig. 1. In Fig. 1 the x's denote data obtained at angles θ and the dots, data at the angles $\theta+\pi$. The rather large uncertainties indicated for several of the points in Fig. 1 takes into account the difficulties in making corrections to the data for the contribution from other levels of Be^8 and/or for the effects of accidental coincidences at these particular angles. The angular correlation function $A_0+A_2\cos 2(\theta-\theta_2)+A_4\cos 4(\theta-\theta_4)$ has been fitted to the observed angular correlations by the least-square procedure.[3] The amplitudes and phase angles for the angular correlation functions are given in Table I. Although the observed angular correlations are the superposition of the angular correlations for the (2^+)[4] 16.62 and the 16.92-MeV states of Be^8, the ratio of the amplitudes, A_2/A_0 and A_4/A_0, are clearly too large to be accounted for by an isotropic contribution from the 16.92-MeV level of Be^8 in view of the known ratio of the differential cross sections for the $Be^9(He^3, \alpha)Be^8$ reaction proceeding to these levels. The amplitudes primarily reflect the character of the 16.92-MeV state of Be^8. Using the fact that the 16.92 state of Be^8 has been previously classified as 0^+ or 2^+,[4] the prenagular correlations establish the 2^+ assignment for this level. Recent α–α scattering studies confirm this assignment.[5]

Figure 2(a) is a plot of the θ_2 phase angles vs the angle of emission of the initial α particle. The phase angles are measured relative to the beam direction in the recoiling Be^8 system. The θ_2 phase angle is undetermined to within an additive term of $\pm n\pi$, and $\pm\pi/2$ simply reverses the sign of the amplitude. In Fig. 2(a), the x's correspond to positive A_2's and the dots to negative A_2's. The curves (a), (b), (c), and (d) represent the angular variation of the possible symmetry axes for various reaction mechanisms. If the $Be^9(He^3, \alpha)2He^4$ proceeds through a compound nucleus at 28.5 MeV of excitation in C^{12}, then under certain restricted

---

[3] M. E. Rose, Phys. Rev. **91**, 610 (1953).

[4] T. Lauritsen and F. Ajzenberg-Selove, *Nuclear Data Sheets*, compiled by F. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D. C. 1962).

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

conditions the symmetry axis could correspond to the direction of the center-of-mass recoil velocity of the 16.92-MeV Be^8 state, curve (a), and under other conditions, to the beam direction. In the plane-wave approximation for a direct pickup mechanism the symmetry axis would correspond to the direction of the laboratory recoil velocity of $Be^8(16.92)$, curve (b). For heavy-particle stripping two possible symmetry axes can appear in the plane wave approximation. If the He^3 particle is captured by He^5 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 in the final He^3–He^5 system, curve (d). Figure 2(b) is the plot of A_2/A_0 vs the angle of emission of the initial α particle. Similarly Fig. 3(a) is a plot of the θ_4 phase angles as a function of the angle of emission of the initial α particle. Again the phase angles are measured in the recoiling Be^8 system and curve (a), (b), (c), and (d) are the same as in Fig. 2(a) The θ_4 phase angle is ambiguous by $\pm\pi/2$, and $\pm\pi/4$ reverses the sign of A_4. The plot of A_4/A_0 vs the angle of emission of the initial α particle is given in Fig. 3(b).

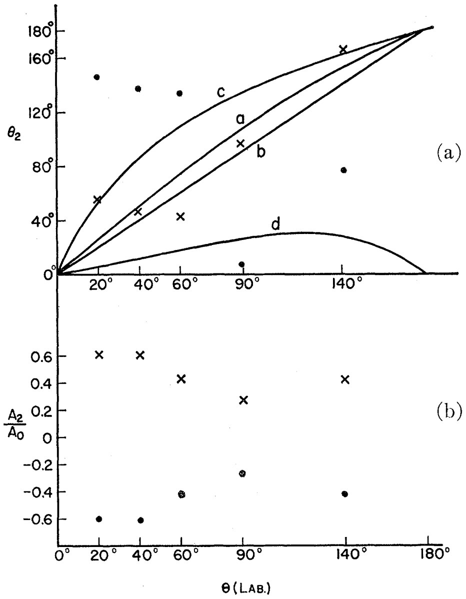

FIG. 2. (a) A plot of the θ_2 phase angles relative to the beam direction in the rest system of $Be^8(16.92)$ vs the lab angle of emission of the intial α. (b) A plot of the A_2/A_0 amplitudes vs the lab angle of the emission of the initial α for the reaction $Be^9(He^3, \alpha)$ $Be^8(16.92) \rightarrow 2\alpha$ with 3.00-MeV incident He^3.

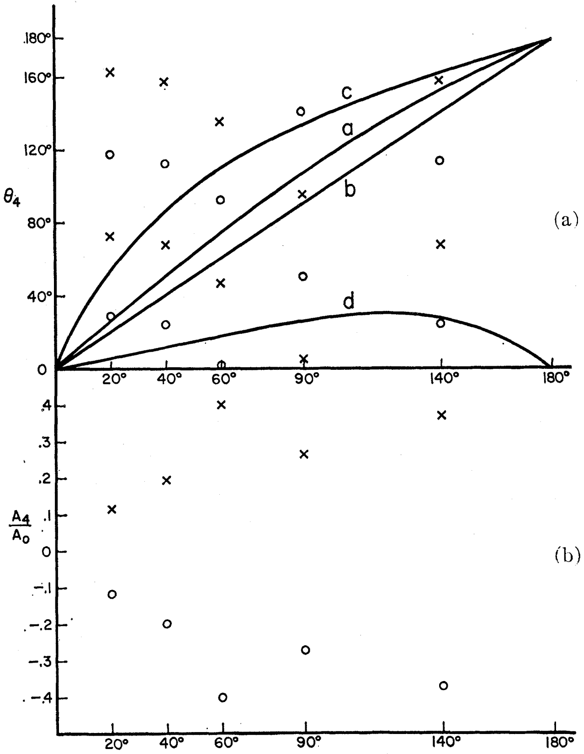

FIG. 3. (a) A plot of the θ_4 phase angles relative to the beam direction in the rest system of $Be^8(16.92)$ vs the lab angle of emission of the initial α. (b) A plot of A_4/A_0 amplitudes vs the lab angle of emission of the initial α for the reaction $Be^9(He^3, \alpha)$ $Be^8(16.92) \rightarrow 2\alpha$ with 3.00-MeV incident He^3.

Although there is considerable ambiguity in the functional behavior of the phase angles θ_2 and θ_4, the requirement that any choice of a set of θ_2's and θ_4's must be consistent with a smooth variation of the amplitudes A_2/A_0 nor A_4/A_0 with the angle of emission of the initial α particle does impose considerable restrictions. In both cases it appears that a choice of either all positive or all negative amplitudes would be preferable.

An examination of Figs. 2 and 3 quickly shows that the behavior of neither θ_2 and θ_4 is predicted by any of these simple models for the initial interaction. Clearly much more detailed calculations including distortions effects and possibly interferences between various modes will have to be made before one can determine the nature of the intial interaction.