Heavy-Particle Stripping in the $Be^9(He^3,\alpha)Be^8$ Reaction and Energy Levels of Be^8†

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Angular distributions of alpha particles from the $Be^9(He^3,\alpha)Be^8$ reaction leading to the ground state and the levels at 2.9, 16.6, 16.9, and 17.6 MeV were measured at bombarding energies of 3.00 and 4.00 MeV. Reaction alphas were momentum-analyzed with a broad-range spectrograph. Angular distributions for the ground state and the levels at 2.9 and 16.9 MeV are analyzed with a direct reaction theory which includes both the pickup and the heavy-particle stripping amplitudes. Yield measurements for the 17.6-MeV level were not made for angles larger than 100 deg. Over this limited range in angle the angular distributions for this level are in agreement with the predictions of Butler theory. The formation of the 16.6-MeV level apparently proceeds via the compound nucleus. Absolute differential cross sections were found by comparison with the known cross section for the $Be^9(d,p)Be^{10}$ reaction. Cross sections for the $Be^9(He^3,\alpha)Be^8$ reaction vary from 0.5 mb/sr to 7.6 mb/sr. The level structure of Be^8 was studied from the ground state up to 17.6-MeV excitation. Levels were found at excitation energies of 2.90 ± 0.04, 16.633 ± 0.015, 16.928 ± 0.015, and 17.639 ± 0.010 MeV, with the indication of a very broad level in the region of 12.5 MeV. Widths of the 2.9-, 16.6-, and 16.9-MeV levels are 1350 ± 150, 96 ± 20, and 80 ± 15 keV, respectively.

I. INTRODUCTION

HEAVY-PARTICLE stripping was proposed by Madansky and Owen[1] as a possible means of accounting for the large-angle yield observed in some direct reaction angular distributions. This reaction mechanism, in which the target nucleus undergoes a stripping reaction, was introduced with the idea that the center-of-mass motion of the target nucleus provides nucleons moving in the direction of large reaction angles. Analyses of the angular distributions of direct reaction products have furnished evidence that heavy-particle stripping may in some cases accompany the ordinary stripping (or pickup) process.

In the $Be^9(He^3,\alpha)Be^8$ reaction the low binding energy of the last neutron in Be^9 is expected to favor a direct interaction between the loosely bound neutron and the He^3 projectile. Both the angular distribution of the deuterons from the $Be^9(p,d)Be^8$ reaction[2] over a range of energies from 4.8 to 7.8 MeV, and of the tritons from the $Be^9(d,t)Be^8$ reaction[3] at 3.6 MeV have been successfully analyzed in terms of neutron pickup. This suggests that the pickup interaction might play an important role in the $Be^9(He^3,\alpha)Be^8$ reaction. That, in addition to neutron pickup, heavy-particle stripping can also contribute to the production of final-state alpha particles is supported by the recent work of Brown and Knowles.[4] They examined the spectrum of alpha particles from the reactions $Be^9(\alpha;3\alpha,n)$ and $Be^9(\alpha;\alpha,n)Be^8$ and concluded that the three-cluster configuration $\alpha+\alpha+n$ is apparently preferred over the two-cluster configuration Be^8+n in the Be^9 ground state. This result implies that heavy-particle stripping might reasonably be expected to liberate alpha particles in the $Be^9(He^3,\alpha)Be^8$ reaction.

Information concerning the level structure[5] of Be^8 up to about 12-MeV excitation has come mainly from phase shift analyses of alpha-alpha scattering experiments. In this excitation range three states are found: the ground state, and broad levels at 2.9 and 11.7 MeV. Evidence for other states at 4.1, 5.3, and 7.5 MeV has been reported,[6] although the existence of these states appears uncertain. Observed widths of the 2.9- and 11.7-MeV levels are about 1.2 and 6.7 MeV, respectively, although there is considerable disagreement among measured values of the width of the first excited state. Reported values[5] range from 0.9 to 2.0 MeV. More recently, Kavanagh,[7] using the $Be^7(d,p)Be^8$ reaction, reported the excitation energy and the width of the first excited state to be 2.90 ± 0.06 and 1.53 ± 0.04 MeV, respectively.

Erskine and Browne,[8] using a broad-range spectrograph, studied the level structure of Be^8 at higher excitation with the reactions $B^{10}(d,\alpha)Be^8$, $Li^6(He^3,p)Be^8$, and $Be^9(He^3,\alpha)Be^8$. Particle groups were observed corresponding to levels at 16.623 ± 0.010, 16.921 ± 0.010, and 17.637 ± 0.006 MeV. Level widths were found to be 95 ± 20 keV, 85 ± 20 keV, and <15 keV, respectively.

In the present work angular distributions of alpha particles from the $Be^9(He^3,\alpha)Be^8$ reaction were measured at 3.00 and 4.00 MeV. Distributions were measured for the ground state and the levels at 2.9, 16.6, 16.9, and 17.6 MeV. Some of the angular distributions were analyzed with a direct-reaction theory which included both the pickup and heavy-particle stripping amplitudes. The level structure of Be^8 was studied from the

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[1] L. Madansky and G. E. Owen, Phys. Rev. **99**, 1608 (1955).
[2] J. A. Harvey, Phys. Rev. **82**, 298A (1951).
[3] H. W. Fulbright, J. A. Bruner, D. A. Bromley, and L. M. Goldman, Phys. Rev. **88**, 700 (1952).
[4] Lynn B. Brown and H. B. Knowles, Phys. Rev. **125**, 1339 (1962).
[5] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).
[6] F. Ajzenberg-Selove and T. Lauritsen, Rev. Mod. Phys. **27**, 77 (1955).
[7] R. W. Kavanagh, Nucl. Phys. **18**, 492 (1960).
[8] J. R. Erskine and C. P. Browne, Phys. Rev. **123**, 958 (1961).

ground state up to 17.6-MeV excitation. Widths of the 2.9-, 16.6-, and 16.9-MeV levels were determined.

II. EXPERIMENTAL PROCEDURE

He^{3+} ions provided by an electrostatic accelerator passed through a magnetic analyzer whose energy resolution was 0.16%. Higher resolution was not necessary because of the widths and separation of the levels investigated. Reaction products were analyzed with a broad-range spectrograph and recorded on nuclear track plates. Bombarding energies were 3.00 and 4.00 MeV. Thin targets were prepared by evaporating beryllium metal from a tantalum boat onto thin Formvar backings. Some of the exposures were taken using thick evaporated targets on solid aluminum backings. Target thickness to 4.0-MeV He^{3+} ions ranged from 10 to 30 keV. The data were taken in two series of exposures at each of the two bombarding energies. One series was made to record the ground-state alpha group and the group leading to the first excited state at 2.9 MeV. The second recorded the alpha groups leading to the levels at 16.6, 16.9, and 17.6 MeV.

Each angular distribution measurement was made in three series of exposures covering the angular ranges 5 to 20 deg, 20 to 70 deg, and 70 to 140 deg, respectively. In any one series of exposures the position of the target remained fixed. Alpha particles leading to the levels at high excitation were not recorded at laboratory angles greater than 120 deg because of the difficulty of counting the very short tracks. Target stability was checked at the end of each set of exposures. No significant evaporation of the target material was found to take place under bombardment.

The alpha-particle yield to the Be^8 level of interest was determined from the total number of tracks in the appropriate particle group. Those alpha groups corresponding to levels whose width was much larger than the target thickness were fitted with an expression having the form of the Breit-Wigner single-level formula. Those groups for which the target thickness was not small compared to the level width were fitted with a Gaussian distribution. To aid in fitting the broad alpha groups the number of tracks was averaged over intervals of ten $\frac{1}{2}$-mm counting strips. This reduces statistical fluctuations by effectively reducing the resolution of the spectrograph. The total number of tracks was then found by integrating the Breit-Wigner or Gaussian distribution.

The ratio of the yield to the 2.9-MeV level to the ground-state yield was calculated at each angle, taking into account the variation in the spectrograph solid angle along the track plate. For the high-excitation groups the ratios of the yields to the 16.6- and 17.6-MeV levels to the yield to the 16.9-MeV level were calculated in the same manner. Absolute differential cross sections were then found by comparing the yield from the $Be^9(He^3,\alpha)Be^8$ reaction to the ground state and the 16.9-MeV level to the yield from the $Be^9(d,p)Be^{10}$ reaction. The results of Fulbright *et al.*[3] were used for the cross section of the latter reaction at a laboratory angle of 90 deg and 3.6-MeV bombarding energy. This reaction was run under these conditions and then, with the target fixed, the $Be^9(He^3,\alpha)Be^8$ reaction was run at the bombarding energy at which the angular distribution measurements were made. The laboratory differential cross sections for formation of Be^8 in the remaining three states were found from the calculated yield ratios.

Level widths were measured for Be^8 states at 2.9-, 16.6-, and 16.9-MeV excitation. The full width at half-maximum for these alpha groups was read off the calculated Breit-Wigner or Gaussian distribution. This width in plate distance was converted to an energy width using the known dispersion of the spectrograph. The target width was next found from either the ground-state group or the group leading to the 17.6-MeV level. These groups gave the energy spread in the incident and the outgoing particles caused by the target thickness. The latter energy spread was adjusted for variation in the alpha energy along the track plate. The net energy spread from the subtraction of target effects was then used to find the level width by computing the resultant spread in the Q value. Contributions to the observed width caused by energy spread in the incident beam, target-spot size, and spectrograph aberration were negligible compared to the target thickness.

Alpha particles leading to the ground state and the first excited state were recorded simultaneously. The large (18.9 MeV) ground-state Q value made it necessary to run the spectrograph magnetic field near the upper limit of the range over which the calibration is known to be independent of field. This may introduce considerable uncertainty in the measured Q values for these states. Values of the ground-state Q values found in the various runs were in agreement with the value[5] calculated from the masses to within ± 15 keV. More reliance, however, was placed on the difference between the measured Q values for the ground and first excited states. The energies of the higher excited states were based on a ground-state Q value of 18.911 MeV.[5]

III. RESULTS

Angular Distributions

Figure 1 shows a representative spectrum of alpha particles taken at 3.00-MeV bombarding energy at an observation angle of 90 deg using a thick target. Groups leading to the ground state and the first excited state at 2.9 MeV are seen in the figure. The yield above background to the 2.9-MeV level was fitted with a Breit-Wigner distribution. The curve shown for this group results from adding the Breit-Wigner curve back onto the assumed background. In each exposure alpha particles leading to the ground state and the first excited state were superimposed on an alpha-particle

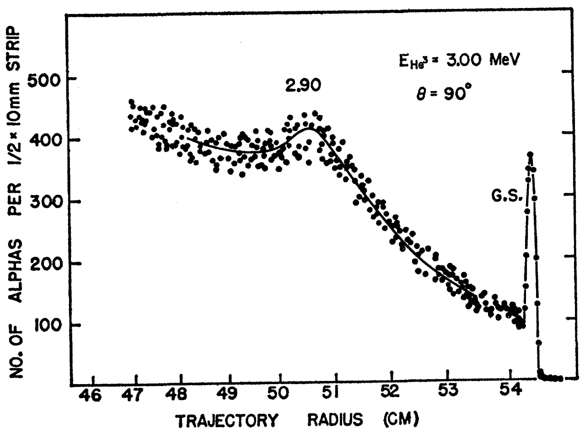

FIG. 1. Spectrum of alpha particles observed at 90 deg with a He^3 bombarding energy of 3.00 MeV. Groups from the $Be^9(He^3,\alpha)Be^8$ reaction leading to the ground state and the level at 2.9 MeV are seen.

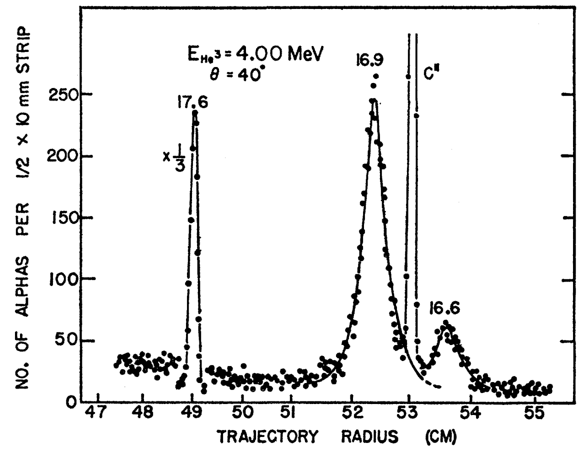

FIG. 2. Spectrum of alpha particles observed at 40 deg with a He^3 bombarding energy of 4.00 MeV. Groups from the $Be^9(He^3,\alpha)Be^8$ reaction are labeled with the excitation energy of the residual Be^8 state. The group from the $C^{12}(He^3,\alpha)C^{11}$ reaction is labeled with the symbol of the residual nucleus.

continuum from the $Be^9(He^3,\alpha)2He^4$ reaction. The threshold for the multibody reaction lies 94 keV below the Be^8 ground state. An attempt was made to interpret the observed spectrum shape in terms of possible reaction mechanisms whereby alpha particles are scattered into a continuum. The analysis has been carried out and will be reported later.

An alpha-particle spectrum taken at 4.00-MeV bombarding energy at an observation angle of 40 deg is shown in Fig. 2. This exposure was taken with a thin, Formvar-backed target. Groups from the $Be^9(He^3,\alpha)Be^8$ reaction leading to levels at 16.6, 16.9, and 17.6 MeV are seen. The groups leading to the 16.6- and 16.9-MeV levels were fitted with a Breit-Wigner distribution after subtracting out the background. The fit to the total number of tracks is shown in the figure. The very intense group labeled C^{11} comes from the $C^{12}(He^3,\alpha)C^{11}$ reaction on the carbon present in the Formvar backing.

Table I gives the ratios of the $Be^9(He^3,\alpha)Be^8$ differential cross sections to the $Be^9(d,p)Be^{10}$ differential cross section used as a reference. A value[3] of 1.0 mb/sr was used for the cross section of the (d,p) reaction at 90 deg and 3.6 MeV to convert the relative (He^3,α) differential cross sections to absolute cross sections. The differential cross sections are plotted in Figs. 3–7. The error bars shown in the figures represent the estimated uncertainty in the yield. Where error bars are not shown, the estimated uncertainty is less than the size of the data point. The uncertainty in the absolute cross section

TABLE I. Ratios of the laboratory differential cross sections for formation of Be^8 levels in the $Be^9(He^3,\alpha)Be^8$ reaction to the $Be^9(d,p)Be^1$ differential cross section at 90 deg. He^3 bombarding energies are 3.00 and 4.00 MeV. The deuteron bombarding energy is 3.6 MeV. Uncertainties are ±5% except where otherwise noted.

Observation angle (degrees)	E_{He^3}=3.00 MeV Ground state	2.9 level	16.6 level	16.9 level	17.6 level	E_{He^3}=4.00 MeV Ground state	2.9 level	16.6 level	16.9 level	17.6 level
5	0.17[a]	1.55		8.36		0.19	2.22		13.12	
10	0.17[a]	1.60	0.090[a]	9.02	2.35	0.19	2.22	0.21[a]	12.82	3.04
15	0.13[a]	1.72	0.081[a]	8.15	2.12	0.18	2.31	0.27[a]	12.29	3.19
20	0.10	1.24	0.22[a]	7.05	2.51	0.16	2.02	0.66	10.02	4.26
25				5.84	2.41					
30	0.086	1.15	0.16[a]	5.20	2.68	0.14	1.48	0.76	8.35	4.18
40	0.090	1.09	0.13[a]	4.65	2.97	0.13	1.07	0.88	3.85	2.84
50	0.085	0.98	0.11[a]	3.79	2.37	0.13	0.87	0.73	2.82	2.04
60	0.075	0.71		3.39	1.73	0.13	0.64	0.65	2.99	1.75
70	0.070	0.50	0.55	2.78	1.24	0.14	0.55	0.71	3.68	
80	0.12	0.92	0.64	2.70		0.27	0.74	0.53	2.90	1.16
90	0.14	0.76	0.55	1.57	0.32	0.25	0.78	0.50	2.73	
100	0.13	0.71	0.44	1.61		0.17	0.78	0.33	1.87	
110	0.12	0.75	0.35	1.67		0.13	0.77	0.45	1.51	
120	0.11	0.72				0.12	0.77			
130	0.14	0.71				0.17	0.78			
140	0.16	0.71				0.20	0.82			

[a] These values are ±10%.

for the $Be^9(d,p)Be^{10}$ reaction used as a reference is not included in this estimate.

The angular distributions for the ground state and the levels at 2.9, 16.9, and 17.6 MeV were analyzed from the point of view of a direct reaction. Angular distribu-

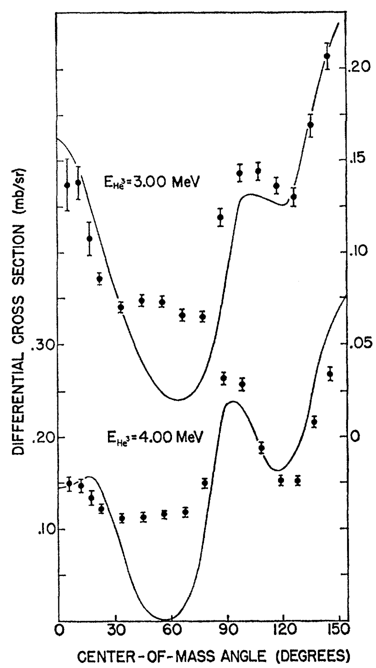

FIG. 3. Angular distributions of alpha particles leading to the ground state at bombarding energies of 3.00 and 4.00 MeV. The theoretical curves were calculated using the parameters given in Table II. The scale on the right is for the upper curve.

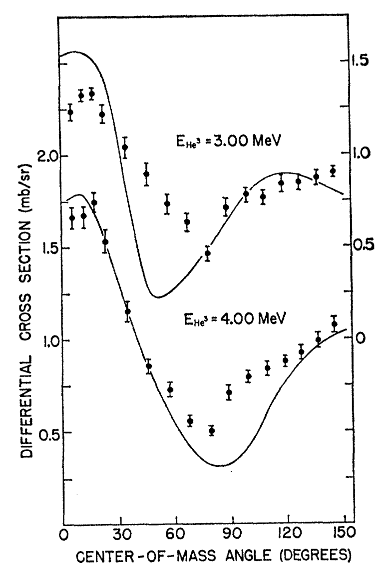

FIG. 4. Angular distributions of alpha particles leading to the 2.9-MeV level at bombarding energies of 3.00 and 4.00 MeV. The theoretical curves were calculated using the parameters given in Table II. The scale on the right is for the upper curve.

tions for the first three of these states were analyzed following the treatment given by Owen, Madansky, and Edwards[9] for the $C^{13}(He^3,\alpha)C^{12}$ reaction, and by

[9] G. E. Owen, L. Madansky, and S. Edwards, Phys. Rev. 113, 1575 (1959).

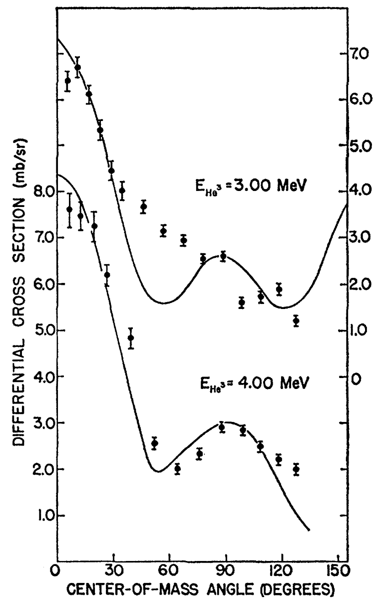

FIG. 5. Angular distributions of alpha particles leading to the 16.9-MeV level at bombarding energies of 3.00 and 4.00 MeV. The theoretical curves were calculated using the parameters given in Table II. The scale on the right is for the upper curve.

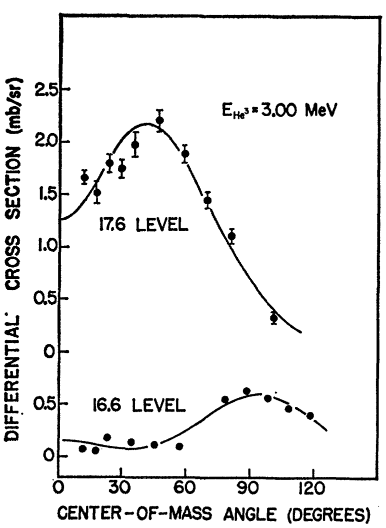

FIG. 6. Angular distributions of alpha particles leading to the levels at 17.6 and 16.6 MeV at a bombarding energy of 3.00 MeV. The curve for the 17.6-MeV level is the prediction of neutron pickup with $l_n=1$ and $r_0=3.1$ F. The curve for the 16.6-MeV level is a least-squares fit.

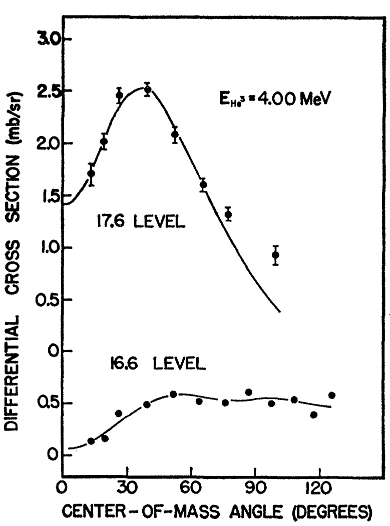

FIG. 7. Angular distributions of alpha particles leading to the levels at 17.6 and 16.6 MeV at a bombarding energy of 4.00 MeV. The curve for the 17.6-MeV level is the prediction of neutron pickup with $l_n=1$ and $r_0=3.0$ F. The curve for the 16.6-MeV level is a least-squares fit.

TABLE II. Parameters used in the theoretical curves of Figs. 3, 4, and 5. Radii are given in fermis.

Bombarding energy (MeV)	Excitation energy (MeV)	$l(nBe^8)$	$l(nHe^3)$	$l(\alpha He^5)$	$l(He^3/He^5)$	a_1	R_1	a_2	R_2	Λ_2/Λ_1	J^π
3.0	0	1	0	0	1	4.0	5.0	4.2	5.5	0.11	0^+
3.0	2.9	1	0	0	1	4.2	5.7	3.8	3.5	0.05	2^+
3.0	16.9	1	0	0	1	3.8	5.5	4.7	6.0	0.20	0^{+a}
4.0	0	1	0	0	1	3.8	4.6	4.0	6.5	0.30	0^+
4.0	2.9	1	0	0	1	4.0	6.5	4.4	6.1	0.35	2^+
4.0	16.9	1	0	0	1	3.0	3.5	3.7	3.2	0.61	0^{+a}

a See Ref. 8.

Edwards.[10] Both the pickup mode and the heavy-particle stripping mode were included, as well as the interference between the two modes. The theoretical curves are in qualitative agreement with the measured distributions. The fit to the 3.00-MeV angular distribution for the 16.9-MeV level is less satisfactory partly because of a lack of data at large angles. The angular distribution for the 17.6-MeV level can be reproduced, over the angular range covered, on the basis of neutron pickup. The pickup curves were calculated following Macfarlane and French.[11] The curves shown for the 16.6-MeV level are least-squares fits roughly symmetric about 90 deg, indicating that the formation of this level may proceed through the compound nucleus. No attempt was made to fit these distributions on the basis of a direct interaction process.

The parameters used in the two-mode calculations are given in Table II. The He^3 bombarding energy and the final-state excitation are given in columns one and two, respectively. Columns three through six, respectively, give the orbital angular momentum quantum number of the relative motion of the neutron and Be^8 core in Be^9, the neutron and He^3 in the emerging alpha, the alpha and the He^5 core in Be^9, and the He^3 and the He^5 core in Be^8. The first two configurations are those of the target and the emerging alpha in the pickup mode and the latter two are those of the target and the recoil nucleus in the heavy-particle stripping mode. The respective interaction radii for these configurations are given in columns seven through ten. The ratio of the heavy-particle stripping amplitude to the pickup amplitude is given in column eleven. Column twelve gives the spin and parity of the final state in Be^8. The 16.9-MeV level was assumed to have spin and parity 0^+, following a suggestion of Kurath.[12]

Average differential cross sections are given in Table III. The yield to each state is larger at the higher bombarding energy, with the formation of Be^8 in its 16.9-MeV level more strongly favored. Estimated uncertainties include the uncertainty in the cross section of the $Be^9(d,p)Be^{10}$ reaction used as a reference.

TABLE III. Average center-of-mass differential cross sections for the $Be^9(He^3,\alpha)Be^8$ reaction at 3.00 and 4.00 MeV. The average is taken over the indicated angular range. Estimated uncertainties include the uncertainty in the cross section for the $Be^9(d,p)Be^{10}$ reaction used as a reference.

Bombarding energy (MeV)	Angular range (deg)	Average differential cross section (mb/sr): Ground state	2.9 level	16.6 level	16.9 level	17.6 level
		0–145	0–145	0–125	0–125	0–100
3.0		0.12±0.03	0.91±0.19	0.29±0.07	3.6±0.7	1.6±0.3
4.0		0.17±0.04	1.04±0.21	0.45±0.09	4.0±0.8	1.8±0.4

Level Positions

The range of Be^8 excitation from the ground state up to 17.6 MeV was covered in this work. The energy of the first excited state was found to be 2.90±0.04 MeV compared to 2.90±0.06 MeV reported by Kavanagh.[7] Using a ground-state Q value of 18.911 MeV[5] the energies of the third-, fourth-, and fifth-excited states were found to be 16.633±0.015, 16.928±0.015, and 17.639±0.010 MeV, respectively, compared to 16.623 ±0.010, 16.921±0.010, and 17.637±0.006 MeV reported by Erskine and Browne.[8] The agreement is seen to be good. The larger uncertainties attached to the first three values reported here result mainly from the uncertainty in determining the center of the wide groups leading to these levels. All energies reported in this work are based on a value of 5.3056 MeV[13] for the energy of the alpha particles from Po^{210}. The investigation of the continuum spectrum from the $Be^9(He^3,\alpha)2He^4$ reaction supplied evidence for the existence of a very broad level in the region of 12.5-MeV excitation. Although this excitation energy is subject to considerable uncertainty, this wide level is most probably that seen in alpha-alpha scattering.

No other levels in this excitation range were observed. A level at 16.07-MeV excitation, seen in the $Li^7(d,n)Be^8$

[10] S. Edwards, "Lectures on the Theory of Direct Reactions. The Plane-Wave Two-Mode Theory of Angular Distributions of Particles in Direct Reactions," The Florida State University. Notes distributed by K. L. Warsh.

[11] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. **32**, 567 (1960).

[12] D. Kurath (private communication to J. R. Erskine and C. P. Browne); Phys. Rev. **123**, 958 (1961).

[13] C. P. Browne, J. A. Galey, J. R. Erskine, and K. L. Warsh, in *Proceedings of the International Conference on Nuclidic Masses* (University of Toronto Press, Toronto, 1960).

reaction by Slattery, Chapman, and Bonner,[14] would have been seen in the present work if its intensity were at least as great as the intensity of the 16.6-MeV level and if it had the same width. A narrower level of proportionately lower intensity would have been seen. The null result is in agreement with the findings of Erskine and Browne.[8]

Level Widths

A comparison of the present level-width results with previous work is made in Table IV. Widths of the 16.6- and 16.9-MeV levels were found from the thin-target exposures in which target effects were small. Values of the 2.9-MeV level width were found from both thin-target and thick-target exposures. The correction to the observed width of this particle group for energy loss in the target was negligible since the level width itself is very large. Level widths found from the various exposures were weighted according to the uncertainty in determining the position and width of the particle group. Estimated uncertainties in the weighted averages are given in the table. The observed width of the 2.9-MeV level is in only fair agreement with that reported by Kavanagh[7] and with the average of eight independent investigations reported by Ajzenberg-Selove and Lauritsen.[5] The present measurement is hindered by the considerable background from the three-body reaction. Widths of the 16.6- and 16.9-MeV levels reported here are in excellent agreement with those reported by Erskine and Browne.[8]

TABLE IV. Widths of Be^8 levels determined in this work and comparison with previous work.

Excitation energy (MeV)	Level width (keV) Previous work	Present work
2.9	1200±300[a]	1350±150
	1530±40[b]	
16.6	95±20[c]	96±20
16.9	85±20[c]	80±15

[a] This value is average of eight independent measurements given in Ref. 5.
[b] See Ref. 7.
[c] See Ref. 8.

IV. DISCUSSION

The strongest evidence of heavy-particle stripping in the $Be^9(He^3,\alpha)Be^8$ reaction is provided by the angular distributions for the ground state and the 2.9-MeV level. Although it is known that nuclear distortion of the incoming and outgoing plane waves can give rise to backward peaking in some reactions, it seems unlikely that the observed angular distributions for these two states can be accounted for solely on the basis of distorted-wave pickup. Since the ground-state Q value of the $Be^9(He^3,\alpha)Be^8$ reaction is large (18.9 MeV), the requisite neutron momentum transfer in the pickup process is very large at back angles. Introducing distortion effects in the manner suggested by Rodberg,[15] it is found that at a center-of-mass angle of 150 deg the required momentum transfer corresponds to a neutron energy of about 500 MeV. In comparison, the necessary neutron energy at 30 deg is about 40 MeV. Consequently, neutron pickup is expected to make its largest contribution at forward angles where the momentum requirements are less stringent. The observed large-angle yield to both the ground state and the first excited state is, however, comparable to, or greater than, the small-angle yield.

In calculating the theoretical two-mode curves, the interaction radii were not varied extensively in order to obtain the best fit. Rather it was thought that a better approach would be to use reasonable values of these parameters and require the kinematic factors to account for the variations among the different distributions. Some variation in these parameters is to be expected since they reflect the distortion of the plane waves. In some cases a better fit could be obtained if one or more radii were allowed to take on extreme values. In view of the plane-wave nature of the theory it is perhaps unreasonable to expect more than qualitative agreement with the measured distributions.

Satchler[16] has suggested that the ratio of the heavy-particle stripping amplitude to the pickup amplitude might be related to the cluster-model parameters for the target and the residual nucleus. If this ratio can be interpreted in terms of the cluster model, then it should be independent of bombarding energy for a given final-state excitation. Furthermore, since in the $Be^9(He^3,\alpha)Be^8$ reaction both modes proceed through the same configuration of the target, the ratio Λ_2/Λ_1 should be nearly unity.[17] It is apparent from Table II that neither of these expectations is realized. This failure may be due to distortion effects, since the amplitude ratio is a sensitive function of the interaction radii. A cluster-model interpretation of Λ_2/Λ_1 may be possible in a distorted-wave treatment of the two-mode theory.

The formation of the higher excited states at 16.9 MeV ($Q=2.0$ MeV) and 17.6 MeV ($Q=1.3$ MeV) is more favorable to neutron pickup over the entire angular range. Although the yield to the 16.9-MeV level was analyzed on the basis of pickup and heavy-particle stripping, distorted-wave pickup calculations might provide equally satisfactory fits. Over the angular range covered, the angular distributions for the 17.6-MeV level can be reproduced on the basis of neutron pickup.

The angular distributions for the 16.6-MeV level suggest compound nucleus formation. The average

[14] J. C. Slattery, R. A. Chapman, and T. W. Bonner, Phys. Rev. **108**, 809 (1957).
[15] L. S. Rodberg, Nucl. Phys. **21**, 270 (1961).
[16] G. R. Satchler (private communication to G. E. Owen, L. Madansky, and S. Edwards); Phys. Rev. **113**, 1575 (1959).
[17] S. Edwards (private communication).

differential cross section for formation of this level is about 0.1 times the cross section for the 16.9-MeV level. The opposite behavior was observed in the $Li^7(d,n)Be^8$ reaction. Dietrich and Cranberg[18] found that the angular distribution of the neutrons leading to the 16.6-MeV level exhibits a stripping pattern, whereas the distribution for the 16.9-MeV level is isotropic with an intensity about 0.04 times the maximum intensity to the 16.6-MeV level. These large differences in the behavior of the yields to these states indicate that they have rather different configurations. Erskine and Browne[8] conclude that the 16.6-MeV level has spin and parity $J^\pi=2^+$ and isobaric spin $T=1$, and that the 16.9-MeV level has $J^\pi=0^+$ or 2^+ and $T=0$. Both of these states decay by alpha-particle emission and have approximately the same width. The angular distributions for the 16.9-MeV level from the present reaction show a large yield at forward angles. If, as suggested by the work of Brown and Knowles,[4] the ground-state configuration of Be^9 is $\alpha+\alpha+n$, then in the pickup interaction the residual Be^8 state is left in an alpha-alpha configuration. For this configuration, however, it is difficult to explain the relatively narrow width of this level. Its alpha decay is not inhibited by isobaric spin conservation, unlike the decay of the $T=1$ 16.6-MeV level. The small-angle yield to the 16.9-MeV level might possibly arise from the knock-out of an alpha particle from Be^9. The subsequent alpha decay would then be inhibited by the necessary rearrangement time which would result in a smaller level width.

[18] F. S. Dietrich and L. Cranberg, Bull. Am. Phys. Soc. 5, 493 (1960).

V. SUMMARY

The calculated angular distributions for the ground state and the first excited state are considered to be in satiafactory agreement with the experimental results, suggesting the operation of heavy-particle stripping. Arguments are presented for the inclusion of this direct reaction mode based on the large ground-state Q value. An attempt to interpret the ratio of the heavy-particle stripping amplitude to the pickup amplitude in terms of the cluster model is unsuccessful. Evidence is presented for a direction reaction mechanism in the formation of the 16.9- and 17.6-MeV levels, while the formation of the 16.6-MeV level may proceed through the compound nucleus. The levels at 16.6 and 16.9 MeV appear to have quite different configurations in spite of their similar widths and excitation energies. The level scheme of Be^8 up to 17.6-MeV excitation is presented and the results are in agreement with previously published work.

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