Continuum Spectra from the Be^9 (He^3, α)$2He^4$ Reaction†

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Alpha particles from the $Be^9(He^3,\alpha)2He^4$ reaction were recorded at observation angles from 5 to 140 deg using a broad-range spectrograph. Bombarding energies were 3.00 and 4.00 MeV. The alpha continuum was measured from the reaction threshold up to a corresponding excitation energy of 15.5 MeV in the $Be^9(He^3,\alpha)Be^8$ reaction. The continuum is analyzed in terms of two possible decay modes involving spontaneous three-alpha disintegration of C^{12*} or stepwise two-body decay through states in Be^{8*}. When Coulomb barrier effects are taken into account, qualitative agreement with the data is obtained by assuming the reaction proceeds via the three-body process. The low-energy anomaly seen in the reactions $B^{11}(p,\alpha)Be^8$ and $Be^9(p,d)Be^8$ was not observed.

INTRODUCTION

In a recent study[1] of the $Be^9(He^3,\alpha)Be^8$ reaction, alpha particles leading to the ground state and the first excited state of Be^8 were observed to be superimposed on an alpha-particle continuum attributable to the $Be^9(He^3,\alpha)2He^4$ reaction. The threshold for the multibody reaction lies 94 keV below the Be^8 ground state. Two possible reaction sources of continuum-alpha particles involve either (1) the immediate breakup of the excited C^{12} nucleus into three-alpha particles, or (2) the intermediate formation of an alpha particle and localized Be^8 system followed by the decay of Be^8 into two-alpha particles.

Beckner, Jones, and Phillips[2] have measured alpha-particle spectra from the reaction $B^{11}(p,\alpha)Be^8$ and observed anomalous structure in the region of 0.75-MeV excitation in Be^8. Spontaneous three-alpha decay was incapable of explaining the observed anomaly. The spectra were interpreted on the basis of sequential two-body reactions for the decay of the excited C^{12} compound nucleus through intermediate states in Be^8. These authors also observed the anomaly in the spectrum of deuterons from the reaction $Be^9(p,d)Be^8$. The structure observed in this reaction was similar to that seen in the $Be^9(d,t)Be^8$ reaction by Gelinas and Hanna.[3] In the latter case, however, the structure was attributed to the $Be^9(d,\alpha)Li^{7*}(t)He^4$ reaction on the basis of the observed triton and alpha-particle spectra.

In the present work, alpha particles from the $Be^9(He^3,\alpha)2He^4$ reaction were recorded at 16 observation angles for He^3 bombarding energies of 3.00 and 4.00 MeV. The continuum was studied from threshold up to a corresponding excitation energy of 15.5 MeV in the $Be^9(He^3,\alpha)Be^8$ reaction. Calculations based on spontaneous three-body decay and on sequential two-body decay were made in an attempt to explain the observed continuum shape.

EXPERIMENTAL PROCEDURE

An electrostatic accelerator provided He^{3+} ions at bombarding energies of 3.00 and 4.00 MeV. These ions passed through an analyzing magnet whose entrance and exit slits were set for an energy resolution of 0.16%. Reaction alphas were analyzed with a broad-range spectrograph and recorded on nuclear track plates. Targets were prepared by evaporating beryllium metal onto thin Formvar and solid aluminum backings. Target thickness to 4.00-MeV He^{3+} ions ranged from 10 to 30 keV.

Alpha particles from the $Be^9(He^3,\alpha)2He^4$ reaction were observed at laboratory angles from 5 to 140 deg. At each angle the continuum spectrum was recorded from threshold up to a corresponding excitation energy of about 5 MeV in Be^8. A separate series of measurements was taken in which alpha particles scattered into the continuum were recorded from the reaction threshold up to a corresponding Be^8 excitation energy of 15.5 MeV. Over this excitation range the range in alpha-particle energy was greater than that which could be recorded by the spectrograph in a single exposure. Three exposures were taken to cover this excitation region. Thick aluminum-backed targets were used at a bombarding energy of 3.00 MeV and a laboratory angle of 90 deg. Since these exposures were not all taken with the same target, it was necessary to correct for the effect of target thickness on the observed yield. In order at the same time to correct for the variation in spectrograph solid angle along the focal surface, the number of alpha tracks recorded in each exposure was first averaged over 10-mm intervals along the track plate. The solid angle correction was then applied to these average values and the exposures normalized to each other. Exposures were taken to cover the excitation regions: threshold to 5.2, 4.6 to 11.6, and 10.8 to 15.5 MeV. The normalizations were made in the regions of overlap.

RESULTS AND DISCUSSION

Representative alpha-particle spectra taken at an observation angle of 90 deg and covering the range of

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[1] W. E. Dorenbusch and C. P. Browne, Phys. Rev. **131**, 1212 (1963).
[2] E. H. Beckner, C. M. Jones, and G. C. Phillips, Phys. Rev. **123**, 255 (1961).
[3] R. W. Gelinas and S. S. Hanna, Phys. Rev. **89**, 483 (1953); **104**, 1681 (1956).

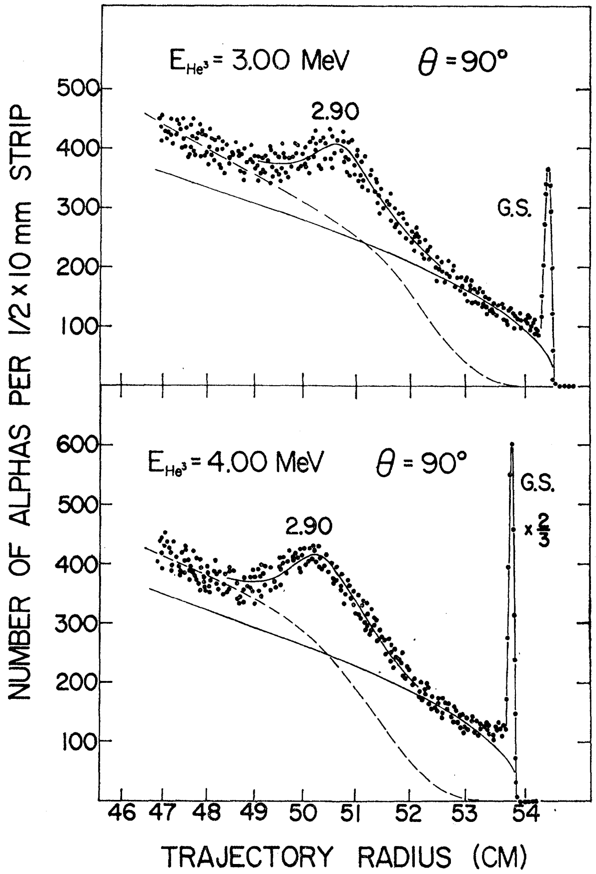

FIG. 1. Alpha-particle spectra observed at 90 deg with He^3 bombarding energies of 3.00 and 4.00 MeV. Groups from the $Be^9(He^3,\alpha)Be^8$ reaction leading to the ground state and the level at 2.90 MeV are seen. Fits to the $Be^9(He^3,\alpha)2He^4$ continuum are shown for statistical three-body decay (solid curve) and sequential two-body decay (dashed curve). The curves were corrected for the variation in spectrograph solid angle.

excitation from the ground state up to about 5 MeV are shown in Fig. 1. Groups from the $Be^9(He^3,\alpha)Be^8$ reaction leading to the ground state and the first excited state at 2.90 MeV are seen superimposed on the $Be^9(He^3,\alpha)2He^4$ continuum. The yield above the continuum to the 2.90-MeV level was fitted with the Breit-Wigner single-level formula.

Continuum alpha particles were assumed to have two possible origins, the three-body reaction

$$Be^9+He^3 \rightarrow C^{12*} \rightarrow 3\alpha$$

for the spontaneous decay of C^{12*}, or the stepwise two-body reactions

$$Be^9+He^3 \rightarrow C^{12*} \rightarrow \alpha+Be^{8*}$$

and

$$Be^{8*} \rightarrow 2\alpha$$

for decay through states in Be^{8*}. The spontaneous three-alpha decay spectra shown in Fig. 1 were calculated following the statistical treatment of Uhlenbeck and Goudsmit.[4] In this analysis there is assumed to be no interaction between the decay alphas, and Coulomb barrier effects are neglected. The predicted energy distribution is an ellipse symmetric about one third the $C^{12*}-3\alpha$ mass difference. The two-body decay spectra were calculated following Beckner *et al.*[2] In this decay process the interaction between two of the alpha particles results in the formation of localized states in Be^{8*}. The localized Be^{8*} system then breaks up into two alpha particles. The main contribution to the density-of-states function,[5] which in turn largely determines the continuum shape, is made[2] by the decay of D states in Be^{8*}.

As seen in Fig. 1 the shape of the continuum in the region of threshold appears to follow that predicted by statistical three-alpha decay. The calculated two-body spectra rise very slowly from threshold and greatly underestimate the continuum yield in this region. Alpha spectra observed in the present work did not exhibit anomalous structure in the region of 0.75-MeV excitation. It was the observance of such an anomaly in alpha spectra from the $B^{11}(p,\alpha)Be^8$ reaction that led Beckner *et al.*[2] to interpret the decay of C^{12*} in terms of a sequence of two-body decays. If this decay mechanism were playing an important role in the $Be^9(He^3,\alpha)2He^4$ reaction, the yield in the neighborhood of the continuum threshold would have to be accounted for by alpha particles from $Be^9(He^3,\alpha)Be^8$ populating the 2.90-MeV level. This assumption, however, requires a much larger level width for this state than seems reasonable in view of the many previous level-width measurements[1,6,7] from various reactions. These considerations

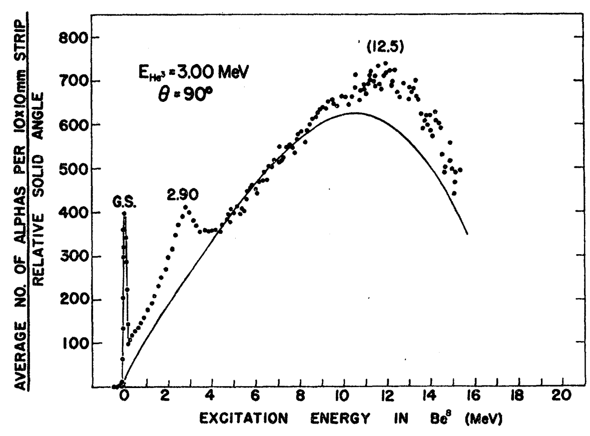

FIG. 2. Spectrum of alpha particles observed at 90 deg with a bombarding energy of 3.00 MeV covering the range of Be^8 excitation up to 15.5 MeV. Groups from the $Be^9(He^3,\alpha)Be^8$ reaction corresponding to the ground state, the first excited state, and a broad state at about 12.5 MeV are seen. The solid curve is a fit to the $Be^9(He^3,\alpha)2He^4$ continuum discussed in the text.

[4] G. E. Uhlenbeck and S. Goudsmit, *Zeeman Verhandelingen* (M. Nijhoff, The Hague, 1935), pp. 201–211.
[5] G. C. Phillips, T. A. Griffy, and L. C. Biedenharn, Nucl. Phys. **21**, 327 (1960).
[6] R. W. Kavanagh, Nucl. Phys. **18**, 492 (1960).
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indicate that the observed continuum results primarily from the spontaneous three-alpha decay of the C^{12*} compound nucleus.

At higher excitation the measured spectra rise more steeply than is predicted by statistical three-alpha decay. However, this discrepancy is shown below to result from the neglect of Coulomb barrier effects.

Figure 2 shows the alpha-particle spectrum observed at 90 deg with a bombarding energy of 3.00 MeV covering the range of Be^8 excitation from the ground state up to 15.5 MeV. The curve shown in the figure was calculated on the basis of spontaneous three-alpha emission. Over this large energy range penetrability effects are appreciable. The purely statistical formulation used to calculate the solid curves in Fig. 1 was modified[2] to include the effect of the Coulomb barrier. Inclusion of barrier effects increases the slope of the three-alpha spectrum above threshold and betters the agreement with the measured continuum in this region. The calculation was done under the assumption that all three alpha particles are emitted with $l=0$. It was further assumed that two of the emitted alphas share equally in the energy available to them. The penetrabilities were calculated using the tables of Bloch *et al.*[8]

The effect of the Coulomb barrier on the continuum shape is shown in Figs. 3 and 4 where $f(\epsilon)$ is the statistical distribution for emission of three alpha particles,[4]

$$f(\epsilon)=N\epsilon^{1/2}[W-\tfrac{3}{2}\epsilon]^{1/2},$$

and $P_l(\alpha 1)$, $P_l(\alpha 2)$, and $P_l(\alpha 3)$ are the penetrabilities for emission with energies $\epsilon(\alpha 1)$, $\epsilon(\alpha 2)$, and $\epsilon(\alpha 3)$. The total energy available to the three-alpha particles is W, and N is a normalization constant. The choice of l-value has only a small effect on the shape of the continuum although $l=0$ emission does result in a spectrum which rises more sharply from threshold. The manner in which the energy $W-\epsilon(\alpha 1)$ is shared between $\alpha 2$ and $\alpha 3$ has its largest effect near threshold. In this region $\epsilon(\alpha 1)$ is close to its maximum value and, consequently, the energy available to $\alpha 2$ and $\alpha 3$ is small. If this energy $W-\epsilon(\alpha 1)$ is shared unequally between $\alpha 2$ and $\alpha 3$, then one of them acquires less and less energy as the inequality increases. The probability of this alpha particle penetrating the Coulomb barrier decreases, causing the suppression of the spectrum in the region of the threshold. Note that the shape of the spontaneous three-alpha decay spectrum for the case of a large inequality between $\epsilon(\alpha 2)$ and $\epsilon(\alpha 3)$ is similar to that of the sequential two-body decay spectrum.

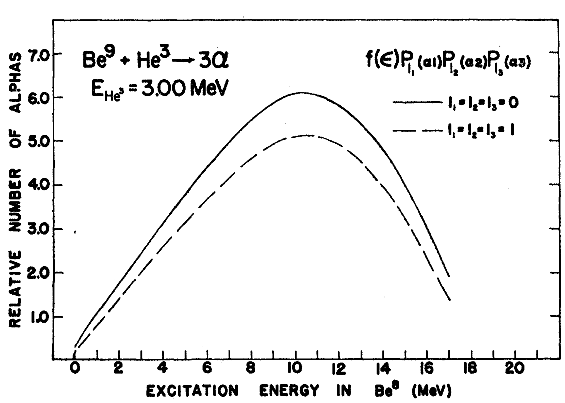

FIG. 3. Predicted spectral distribution for spontaneous three-alpha decay when the statistical distribution is modified to include Coulomb barrier effects. The curves illustrate the effect of the l-value characterizing the emission. Both curves are for $\epsilon(\alpha 2)=\epsilon(\alpha 3)$.

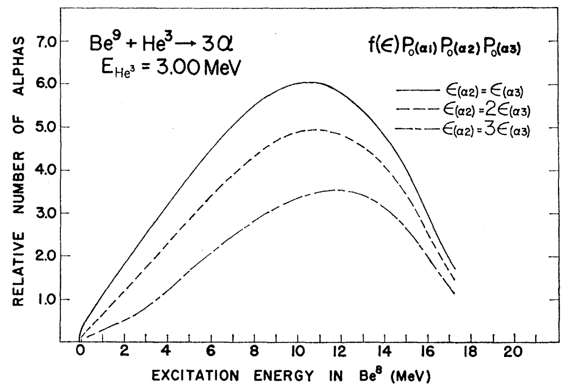

FIG. 4. Predicted spectral distribution for spontaneous three-alpha decay when the statistical distribution is modified to include Coulomb barrier effects. The curves illustrate the effect of the division of energy between $\alpha 2$ and $\alpha 3$. All three curves are for $l=0$ emission.

The level scheme of Be^8 was recently investigated by the authors using the $Be^9(He^3,\alpha)Be^8$ reaction.[1] Figure 2 shows alpha-particle groups from this reaction leading to the ground state, the first excited state at 2.90 MeV, and possibly a very broad level in the region of 12-MeV excitation. Information concerning the level structure of Be^8 in this latter region has come mainly from alpha-alpha scattering experiments[9,10] which indicate the existence of a broad level at an excitation of 11.7 MeV with a width of 6.7 MeV. Subtraction of the three-body curve from the measured spectrum of Fig. 2 results in a broad group ($\Gamma\approx 5$ MeV) centered about an excitation energy of about 12.5 MeV. Although these values are subject to considerable uncertainty, this level is most probably that seen in alpha-alpha scattering.

That the observed continuum spectrum does arise solely from the $Be^9(He^3,\alpha)2He^4$ reaction and is not influenced by competing reactions is readily established. Relevant alpha-particle reactions from the He^3 bombardment of Be^9 are given in Fig. 5 with corresponding threshold energies shown as a function of excitation in

[8] I. Bloch, M. H. Hull, A. A. Broyles, W. G. Bouricius, B. E. Freeman, and G. Breit, Rev. Mod. Phys. **23**, 147 (1951).

[9] J. L. Russell, G. C. Phillips, and C. W. Reich, Phys. Rev. **104**, 135 (1956).

[10] R. Nilson, W. K. Jentschike, G. R. Briggs, R. O. Kerman, and J. N. Snyder, Phys. Rev. **109**, 850 (1958).

Be^8. Of the competing multibody reactions, those which are energetically possible for 3.00-MeV He^3 projectiles are

$$He^3+Be^9 \rightarrow Li^7+\alpha+p\,,$$
$$\rightarrow 2\alpha+t+p\,,$$
$$\rightarrow Be^7+\alpha+n\,,$$
$$\rightarrow 2\alpha+He^3+n\,.$$

The threshold for each of these reactions lies above the range of the continuum measurements. Hence, alpha particles from these reactions do not contribute to the observed continuum. Of the competing two-body reactions, those which give isolated peaks in the excitation region of interest are

$$He^3+Be^9 \rightarrow C^{11}+n\,,$$
$$\rightarrow B^{11}(\text{G.S.})+p\,,$$
$$\rightarrow B^{11}(2.13)+p\,,$$
$$\rightarrow B^{11}(4.46)+p\,.$$

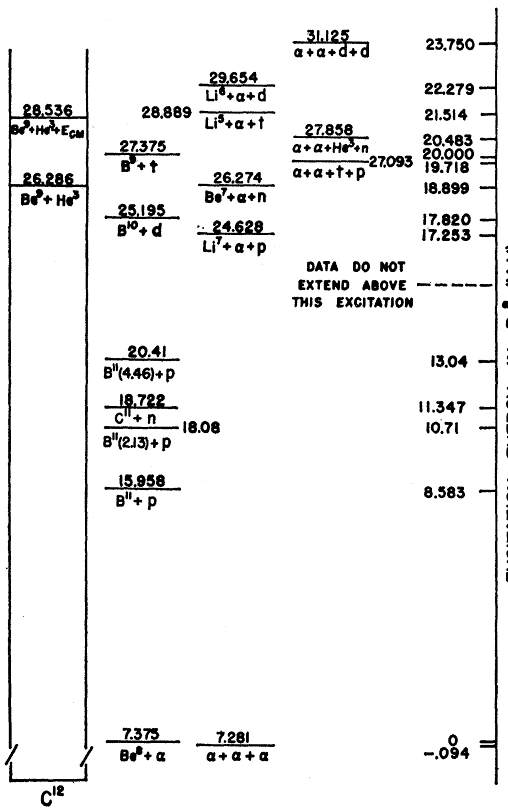

FIG. 5. Center-of-mass diagram for He^3-induced reactions on Be^9. The threshold for each multibody reaction and the position of isolated groups from the two-body reactions are given in terms of the corresponding Be^8 excitation energy. The dashed line denotes the upper limit of the $Be^9(He^3,\alpha)2He^4$ continuum measurements shown in Fig. 2.

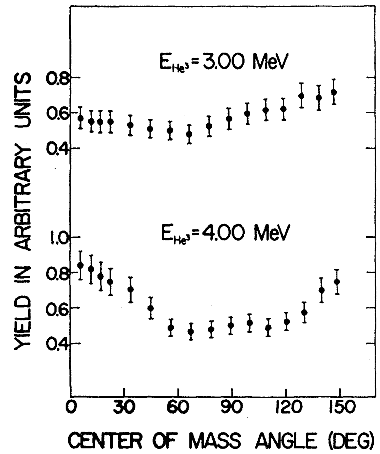

FIG. 6. Center-of-mass angular distributions of continuum alpha particles with energies corresponding to the range of Be^8 excitation of 4.0 to 4.5 MeV. The estimated uncertainty in the yield is $\pm 10\%$.

Neutrons from the first reaction are not detected by the track plate. Protons from the latter three reactions are distinguishable from alpha particles. These proton groups were observed. The ratio of the proton track length to the alpha track length was about 2.5.

Angular distributions of alpha particles from $Be^9(He^3,\alpha)2He^4$ are given in Fig. 6 for He^3 energies of 3.00 and 4.00 MeV. The angular distributions are for those continuum alpha particles whose energies correspond to Be^8 excitations of 4.0 to 4.5 MeV. This region of the continuum was chosen as providing adequate statistics and lying outside the region of the broad state in Be^8 at 2.90 MeV. The upper limit was dictated by the data taking procedures. Within the estimated uncertainty the center-of-mass yield at both bombarding energies is nearly symmetric about 90 deg. Such behavior is consistent with the formation of C^{12*} in the He^3 bombardment of Be^9 followed by the spontaneous emission of three alpha particles.

ACKNOWLEDGMENTS

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