The $B^{10}(He^3, paaa)$ Reaction Process

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The interaction of He^3 with B^{10} frequently leads to a four-body final state consisting of one proton and three α particles even at low bombarding energies. The detailed study of reactions such as the $B^{10}(He^3, p\alpha\alpha\alpha)$ reaction leading to multibody final states can often yield conclusive information about the structure of the nuclear systems involved. However, the question concerning the nature of the process by which the multibody final state is formed, that is, whether such reactions proceed to the multibody final state by a single-stage, quasi-instantaneous breakup or by a series of sequential processes—or in both manners—is of particular interest. The following sequential processes are energetically possible for the $B^{10}(He^3, p\alpha\alpha\alpha)$ reaction at low bombarding energies:

$B^{10}+He^3 \rightarrow$

- $p+C^{12}+19.69$
  - $\rightarrow \alpha_1+Be^8-7.37$
    - $\rightarrow \alpha_2+\alpha_3+0.094$ (I)
- $\alpha_1+B^9+12.14$
  - $\rightarrow p+Be^8+0.187$
    - $\rightarrow \alpha_2+\alpha_3+0.094$ (II)
  - $\rightarrow \alpha_2+Li^5-1.69$
    - $\rightarrow \alpha_3+p+1.97$ (III)
- $\rightarrow Li^5+Be^8+10.37$
  - $\rightarrow \alpha_2+\alpha_3+0.094$
  - $\rightarrow p+\alpha_1+1.97.$ (IV)

The Q values shown are those for the ground states of the nuclei involved.

Many of the intermediate systems involved in the above sequential processes, which are accessible even at low bombarding energies, are extremely short-lived. In such cases it may be more accurate to describe these systems as resonances in the interactions between their cluster components rather than as complex nuclear states in which many degrees of freedom are excited. To illustrate this point consider the sequence, labeled IV above, proceeding through the "ground state" of Li^5 and the "first excited state" of Be^8. In this case it may be more appropriate to consider the Li^5 system as the $p_{\frac{3}{2}}$ resonance in p–α scattering and the Be^8 as the $L=2$ resonance in α–α scattering than as nuclear states of Li^5 and Be^8 and thus this reaction as proceeding by a single-stage, quasi-instantaneous breakup modulated by these particular two-body interactions, rather than by a series of sequential processes.

The meaning of the question of whether the four-body final state is reached via a single-stage, quasi-instantaneous breakup or a series of sequential processes can thus become ambiguous. A more meaningful and useful question in the case of short-lived systems may be one concerning the extent to which the various possible interactions among the components of the final state modulate the phase-space distribution of these components.

Consideration of the various types of interference that may occur in the process(es) leading to the multibody final state is also of interest but cannot be discussed here.

For a reaction which proceeds to a four-body final state it is impossible to specify completely the nature or state of the intermediate systems by the study of single-particle spectra or even by measurement of the energies and directions of two particles in coincidence, E_1, E_2, θ_1, θ_2. However, if the relative momentum of the two unobserved particles corresponds to a discrete state (or resonance) in the intermediate system, the third body, then the kinematic behavior of the two observed particles is the same as in the case of a three-body final state—even though the third body may eventually break up into two or more particles. In such cases a kinematic curve will appear in the two-dimensional energy spectrum $E_1(E_2)$ corresponding to each available state of the third body. The curve will be broadened into a band when the state is broad. The various states of intermediate systems in the sequential processes which lead to this effective three-body final state will appear as points (segments for broad states) on the kinematic curve corresponding to the three-body final state.

When the relative motion of the two unobserved particles does not correspond to a state of the third body, the loci for the various sequential processes on the two-dimensional energy spectrum are somewhat less narrowly restricted, though kinematics still limit each sequential process to certain regions of the spectrum.

The kinematic regions associated with a given process change in a characteristic manner with the angles at which the particles are observed. The changes in shape

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and size, as well as the position of the region, often enable one to identify the process associated with the region.

In our initial study of the $B^{10}(He^3, p\alpha\alpha\alpha)$ reaction we have chosen to measure the energy and direction of the proton and one of the α particles. Two solid-state detectors were used, one placed at θ_p and one at θ_α. In order to ensure that only protons were observed in the detector at θ_p, a 0.003-in. aluminum foil, sufficiently thick to stop all α particles from the reaction, was placed in front of this detector for many observations. The second solid state detector, placed at θ_α, had a depletion depth somewhat greater than the range of the maximum energy α particle produced in the reaction. Such a detector permitted the high energy α-particle groups to be identified easily in the single-particle spectrum of this detector.

Figure 1 represents a two-dimensional energy spectrum $E_p(E_\alpha)$ at fixed θ_p and θ_α for coincident events observed in the two detectors. This particular figure is for $\theta_p = +60°$, $\theta_\alpha = -100°$ and a bombarding energy of 2.45 MeV. The picture was obtained by applying the signal from the proton detector to the x axis and the signal from the α-particle detector to the y axis of an xy oscilloscope and intensifying the trace whenever a coincidence occurred between the two signals

Although low energy protons were observed in the spectrum of the α-particle detector at θ_α these events did not cause any confusion in the two-dimensional energy spectrum since the α particles coincident with such events could not be detected in the detector at θ_p. The $B^{10}(He^3, 2p)B^{11}$ reaction is the only competing reaction which could be observed in the two-dimensional energy spectrum of coincident events (except for two-body reactions which appear at certain narrowly restricted angular regions).

Figure 2 shows the kinematic regions, for the same combination of angles and bombarding energy as Fig. 1, for sequential processes of the types II, III, and IV through most of the energetically accessible combinations of intermediate states and for the various possible combinations of observed α particle (α_1, α_2, or α_3) in coincidence with the proton. Each kinematic region in this figure is labeled and the corresponding series of sequential processes, states of the intermediate systems, and the particles observed are given in Table I. The sequential series of the type I yield kinematic curves on the two-dimensional energy spectrum which are just vertical lines, i.e., discrete-energy proton groups observed at θ_p associated with the formation of C^{12} in the various accessible excited states. The positions of these proton groups are indicated along the proton energy axis in Fig. 2 and labeled with the appropriate energy of excitation of C^{12}. If a particular state of C^{12} decays by the emission of an α particle leaving the two remaining α particles in a state of Be^8 and if the first α particle is observed at the angle θ_α, the event would appear at the

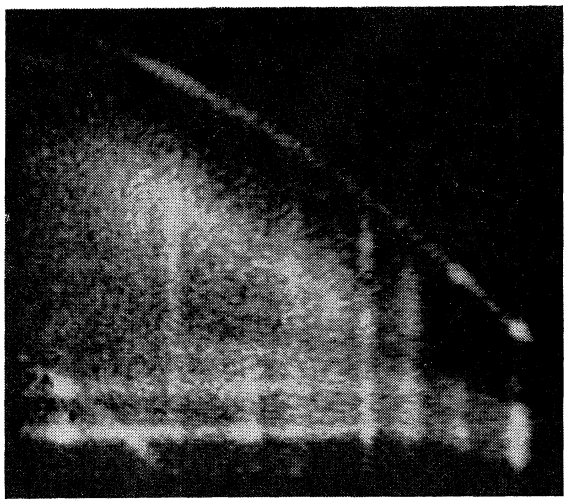


FIG. 1. The experimental two-dimensional energy spectrum of coincident proton and α particle from the reaction $B^{10}(He^3, p\alpha)2He^4$ at $\theta_p = +60°$, $\theta_\alpha = -100°$ for a bombarding energy of 2.45 MeV.

intersection of the vertical line corresponding to the state of C^{12} with the kinematic curve corresponding to the state of Be^8 which is formed. Events in which one of the α particles from the breakup of the Be^8 is seen instead are restricted to other segments of the vertical line. In many cases the kinematic segments overlap.

Under the experimental conditions of our measurements and at a bombarding energy of 2.45-MeV effects could have been observed due to states of C^{12} in the range of excitation energy extending from about 9 to 18 MeV, of B^9 from 0 to 12.5 MeV, of Be^8 from 0 to 8 MeV, and of Li^5 from 0 to 10 MeV.

Comparison of Fig. 1 with Fig. 2 and in particular a comparison of such figures at various angles, enables one to identify many of the various processes which can occur. The allowed kinematic regions on the experimental spectrum of Fig. 1 are of course broadened, compared to those of Fig. 2, by level width, target thickness and the finite solid angles of the detectors.

Vertical lines, proton groups form reactions of type I for a number of states of C^{12}, are clearly seen in Fig. 1, and are labeled with the energy of excitation of the corresponding state of C^{12}. Along the vertical E_α axis the expected positions of the α particle groups from reactions of type II and III, where α_1 is detected, are indicated for the 2.34- and 2.81-MeV states of B^9, as well as the 11.62-MeV state recently observed by Fisher and Whaling.[1] There is no evidence for the formation of other states in B^9 in the energy range studied. The intense horizontal line near the position corresponding to the formation of the 11.62-MeV state B^9 is primarily due to accidental coincidences between He^3 particles

[1] T. R. Fisher and W. Whaling, Bull. Am. Phys. Soc. **8**, 598 (1963).

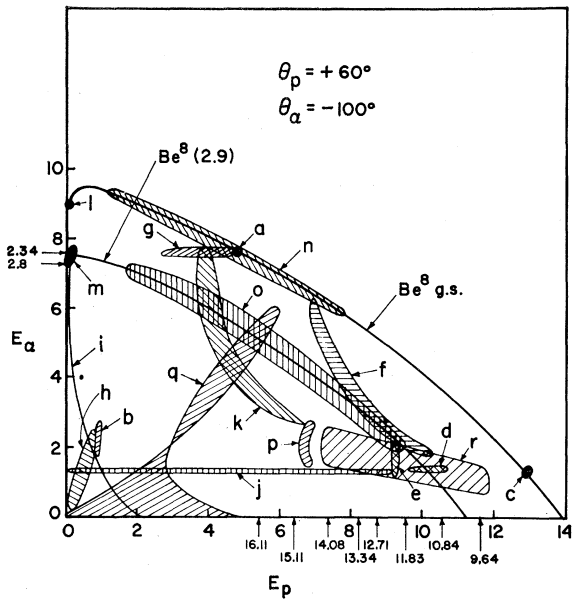


FIG. 2. The calculated two-dimensional energy spectrum of coincident particles from the reaction $B^{10}(He^3, p\alpha)2He^4$ at $\theta_p = +60°$, $\theta_\alpha = -100°$ for a bombarding energy of 2.45 MeV. The process corresponding to each kinematic region is indicated by a letter explained in Table I. The position of each of the discrete-energy proton groups produced by process I is indicated by an arrow along the E_p axis labeled with the energy of excitation of the associated state of C^{12}. A vertical line passing through $E_p = 3$ MeV represents the minimum energy proton which can pass through the absorber in front of the proton detector, and therefore that region of the two-dimensional spectrum of Fig. 2 which is excluded in the experimental spectrum of Fig. 1.

elastically scattered at θ_α and reaction protons at θ_p. The rather intense spot on this line near the intersection of the 15.11-MeV proton group arises mainly from such accidental events in which the protons are due to the $C^{12}(He^3, p_0)N^{14}$ reaction in the carbon foil target backing.

The Be^8(g.s.) kinematic curve and the Be^8(2.9) kinematic band are also clearly visible in Fig. 1. Only the center of the Be^8(2.9) band is shown in Fig. 2. The rather large width of the 2.9-MeV state of Be^8 (the $L=2$ α–α scattering resonance) broadens its curve into a band. The very large width of the 11.4-MeV state of Be^8 (the $L=4$ α–α resonance) and the restriction due to the available energy produces a kinematic region in the low energy corner of the two-dimensional energy spectrum. Little can be said about this from Fig. 1.

The horizontal line corresponding to the emission of an α particle, which is detected at θ_α, with the formation of the first excited state of B^9 can be clearly seen in Fig. 1. This line extends into the region between the Be^8(g.s.) and Be^8(2.9) kinematic curves and corresponds to the decay of B^9(2.34) by sequence III into an α particle and Li^5(g.s.) which then decays into an α particle and the observed proton. The corresponding region in Fig. 2 is (g). At many combinations of angle process (g) is more pronounced than at $\theta_p = +60°$, $\theta_\alpha = -100°$. It was incorrectly concluded in a previous paper[2] that the intense region near the intersection of this line and the kinematic curve for the Be^8(g.s.) was associated with the decay of the B^9(2.34) into the observed proton and Be^8(g.s.), point (a) of Fig. 2. Detailed studies of this region of the spectrum now indicate that the intense region on the Be^8(g.s.) kinematic curve is due to the decay of the B^9(2.8) state via sequence II to Be^8(g.s.) and a proton. The 2.34-MeV state of B^9 appears to decay mainly by α emission to Li^5(g.s.), sequence III; whereas the 2.8-MeV state of B^9 decays predominately by proton emission to Be^8(g.s.), sequence II.

The rather intense broad region (r) which corresponds to the reaction $B^{10}(He^3, Li^5)Be^8$(g.s.) can also be seen. Other contributions from this reaction and similar ones leading to Be^8(2.9) are possibly indicated by the continuous distribution of events along the Be^8(g.s.) kinematic curve and the Be^8(2.9) kinematic band. In addition, the intense area near the intersection of (q) and (o) may be due to this process.

Another intense area is observed near the intersection of the kinematic regions (f) and (o). Since process (f) results from the reaction proceeding through the 11.62-MeV state of B^9, this intense area may suggest that the 11.62-MeV state is excited in the present experiment. However, it has not been possible to identify other contributions from this state because of the competing processes which occur in the same regions of the two-dimensional energy spectrum.

The large contribution from reactions of the type IV is particularly interesting. This may indicate that such reactions proceed by the pickup of a neutron and proton from B^{10} by the He^3 forming Li^5 which is often in the first excited state. Or possibly the process is more appro-

TABLE I. Kinematic regions shown in Fig. 2.

	Reaction	Particles	B^9	Be^8	Li^5
a	II	$p\alpha_1$	2.34	g.s.	···
b	II	$p\alpha_2$	2.34	g.s.	···
c	II	$p\alpha_1$	11.62	g.s.	···
d	II	$p\alpha_1$	11.62	2.9	···
e	II	$p\alpha_2$	11.62	g.s.	···
f	II	$p\alpha_2$	11.62	2.9	···
g	III	$p\alpha_1$	2.34	···	g.s.
h	III	$p\alpha_2$	2.34	···	g.s.
i	III	$p\alpha_3$	2.34, 11.62	···	g.s.
j	III	$p\alpha_1$	11.62	···	g.s.
k	III	$p\alpha_2$	11.62	···	g.s.
l	IV	$p\alpha_1$	···	g.s.	g.s.
m	IV	$p\alpha_1$	···	2.9	g.s.
n	IV	$p\alpha_1$	···	g.s.	$\frac{1}{2}^-$
o	IV	$p\alpha_1$	···	2.9	$\frac{1}{2}^-$
p	IV	$p\alpha_2$	···	g.s.	g.s.
q	IV	$p\alpha_2$	···	2.9	g.s.
r	IV	$p\alpha_2$	···	g.s.	$\frac{1}{2}^-$

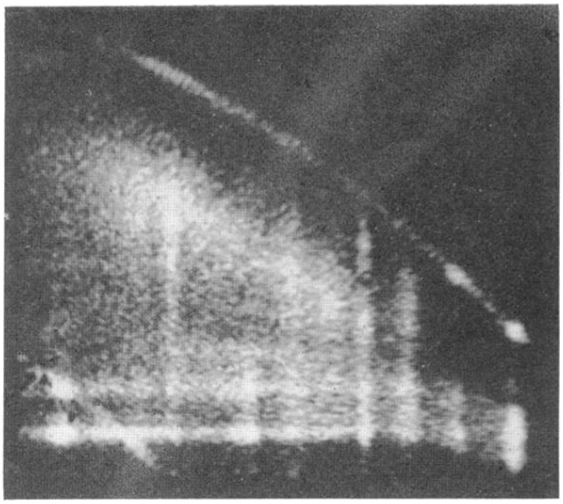
[2] J. E. Etter, M. A. Waggoner, H. D. Holmgren, C. Moazed, and A. A. Jaffe, Phys. Letters **12**, 42 (1964).

priately described as the pickup of a neutron by He^3 to form an α particle which then interacts strongly with the proton in the final state through the very broad $p_{\frac{3}{2}}$ resonance seen in the elastic scattering of protons on He^4.

Another interesting feature of the reaction is the fact that the 2.34-MeV state of B^9 decays only via alpha-particle emission to the ground state of Li^5, i.e., by a reaction of the type III, though the Q value favors the decay by proton emission to the ground state of Be^8 (reaction II). The 2.8-MeV-state of B^9, on the other hand, decays primarily by proton emission to the ground state of Be^8.

The lack of events in the region between the Be^8(g.s.) kinematic curve and the $Be^8(2.9)$ kinematic band is particularly striking. It is also apparent that there are high intensities in various areas of the two-dimensional spectrum where one would expect contributions from sequential processes—and from those processes which are perhaps more appropriately described as quasi-instantaneous breakup processes in which the final state is strongly modulated by the interactions between the various cluster components. These observations lead us back to the question posed at the beginning of this paper concerning the manner in which the reaction proceeds to the four-body final state. The general conclusion which one can draw from the above observations is that the $B^{10}(He^3, p\alpha\alpha\alpha)$ reaction proceeds to the four-body final state primarily through sequential two-body decays or by processes in which two-body interactions among the components of the final state strongly modulate the phase-space distribution.

Another way of looking at the results is the following. The system has an energy which is determined by the arbitrary bombarding energy. One would therefore not expect the criteria for resonance in the two-body interaction of the components into which the system breaks up to be satisfied by all pairs of components. One component or pair of components will have to separate from the others at a nonresonant energy except, perhaps, in special cases. The results of the experiment indicate that the remaining components are left with a characteristic resonant energy. In case the remaining system consists of three particles and it undergoes further decay, two of the particles are again left at an appropriate relative energy to interact strongly. In other words, the total energy of the system appears to be partitioned among the components of the final state in such a manner that as many of the components as possible have a relative energy such that they interact strongly.



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