Spectroscopic Studies with the $B^{10}(He^3, paaa)$ Reaction

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The four-body final state $p\alpha\alpha\alpha$ resulting from the bombardment of B^{10} with low-energy He^3 is produced by various sequential two-body decays or by processes in which resonances in the interactions among the various combinations of particles strongly modulate the momentum distribution of the particles in the final state. The basis for and meaning of this statement, and the problem of whether the concept of state or resonance in the interaction of the components is appropriate for the description of intermediate systems involved in the decay of the $B^{10}+He^3$ system to the $p\alpha\alpha\alpha$ final state, have been discussed in an earlier paper on the $B^{10}(He^3, p\alpha\alpha\alpha)$ reaction.[1] For simplicity in the presentation of the information relevant to the present paper we use the notation of states in referring to the various intermediate systems.

The sequential processes by which the $B^{10}(He^3, p\alpha\alpha\alpha)$ reaction can proceed are the following:

$$B^{10}+He^3 \rightarrow p+C^{12}+19.69,\quad C^{12} \rightarrow \alpha_1+Be^8-7.37,\quad Be^8 \rightarrow \alpha_2+\alpha_3+0.094 \qquad \text{(I)}$$

$$B^{10}+He^3 \rightarrow \alpha_1+B^9+12.14,\quad B^9 \rightarrow p+Be^8+0.187,\quad Be^8 \rightarrow \alpha_2+\alpha_3+0.094 \qquad \text{(II)}$$

$$B^9 \rightarrow \alpha_2+Li^5-1.69,\quad Li^5 \rightarrow \alpha_3+p+1.97 \qquad \text{(III)}$$

$$B^{10}+He^3 \rightarrow Li^5+Be^8+10.37,\quad Be^8 \rightarrow \alpha_2+\alpha_3+0.094,\quad Li^5 \rightarrow p+\alpha_1+1.97, \qquad \text{(IV)}$$

where the Q values shown are for the ground states of the systems involved.

Studies of the $p\alpha$, $\alpha\alpha$, and pC^{12} two-dimensional energy spectra at many sets of angles and with various criteria imposed upon the observed particles have yielded information about a number of states of the intermediate systems involved in the processes leading to the final state $p\alpha\alpha\alpha$.

STATES OF Li^5 AND Be^8

No new spectroscopic information concerning the two lowest states of Li^5 and of Be^8 has been obtained in the present experiment. The previously assigned spins and parities of these states were taken to be known quantities[2] in this study. However, evidence for the existence of these states of Li^5 and Be^8 is strikingly exhibited through their effect on the $p\alpha\alpha\alpha$ final state. For example, referring to the two-dimensional energy spectrum of Figure 1 the existence of the ground state of Be^8 is indicated by the large number of events along the ground-state kinematic curve, and the first excited state of Li^5 by the intensity in the well-defined, although broad, kinematic region corresponding to the $B^{10}(He^3, Li^5)Be^8$ reaction.

An interesting point concerning the states of Li^5 was noted. The effective mass of Li^5 appear to be less than that given in the tables of consistent set of Q values[3] by about 200 keV.

STATES OF B^9

Excited states of B^9 were observed in the present study at 2.34 and 2.8 MeV of excitation. The 2.34-MeV state has been previously classified[2] as having $J^\pi > \frac{1}{2}^-$; the latter state has not been classified. The 2.34-MeV state has been seen in the $B^{10}(p, d)$ reaction,[4] for example, and the deuteron angular distribution indicated that $l_n = 1$ and thus restricted the J^π assignment to $\frac{3}{2} \leq J \leq \frac{9}{2}$, negative parity. The 2.8-MeV state has been more elusive for reasons which perhaps can now be better understood.

Our results indicate that the relatively narrow 2.34-MeV state decays predominately by alpha-particle emission to the ground state of Li^5 whereas the 2.8-MeV

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[1] M. A. Waggoner, J. E. Etter, H. D. Holmgren, and C. Moazed, Rev. Mod. Phys. **37**, 358 (1965), this conference.

[2] T. Lauritsen and F. Ajzenberg-Selove, "Energy Levels of Light Nuclei," NAS-NRC, **61**, −5, 6 (May 1962).

[3] F. Everling, L. A. Koenig, J. H. E. Mattauch, and A. H. Wapstra, "Consistent Set of Energies Liberated in Nuclear Reactions," Part I. NAS-NRC (February 1961).

[4] J. B. Reynolds and K. G. Standing, Phys. Rev. **101**, 158 (1956).

state, with $\Gamma_{cm}=1\pm0.3$ MeV, decays primarily by proton emission to the ground state of Be^8. The Q values for the decay of the 2.34-MeV state of B^9 to $p+Be^8$ and to $\alpha+Li^5$ are 2.53 and 0.65 MeV, respectively. The corresponding Q values for the 2.8-MeV state are 3.00 and 1.12 MeV. Table I summarizes the angular momenta that could be involved in these two modes of decay for various J^π assignments to the states of B^9.

Since the 2.34-MeV state of B^9 decays primarily by alpha-particle emission to the ground state of Li^5 rather than by proton emission to the ground state of Be^8, angular momentum considerations indicate that $J\geq\frac{3}{2}$, regardless of the parity of this state. The similarity of the decay of this state to the decay observed for the 2.430-MeV state of Be^9, which has been observed to decay preferentially to $He^5+\alpha$ rather than Be^8+n,[5] strongly suggests that the 2.34-MeV state of B^9 is the isospin analog state of the 2.430-MeV, $J^\pi=\frac{5}{2}^-$ state of Be^9. Arguments similar to those given by Henley and Kunz[6] for the Be^9 state could then be applied to the 2.34-MeV state of B^9 to explain the α decay of this state in preference to proton decay. It thus seems reasonable to assign $J^\pi=(\frac{5}{2})^-$ to this state.

On the other hand, the decay of the 2.8-MeV state of B^9 by proton emission to the ground state of Be^8 rather than by alpha-particle emission to the ground state of Li^5, favors an assignment of $J=\frac{1}{2}$ for this state but places no restriction on its parity. Hence it is not clear whether or not this state is the analog of the 3.04-MeV state of Be^9.

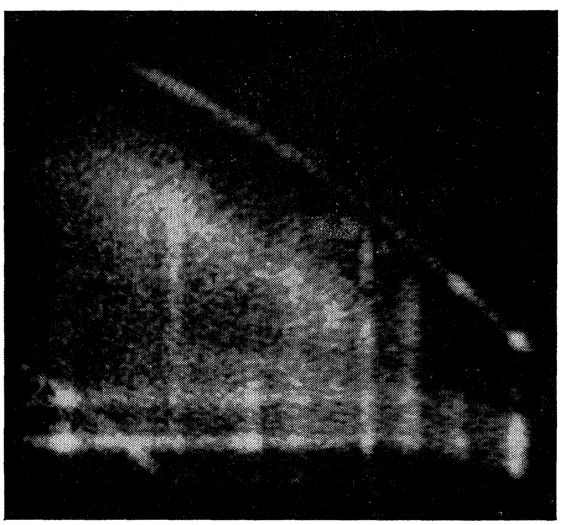

FIG. 1. The experimental two-dimensional energy spectrum of coincident proton and α particle from the reaction $B^{10}(He^3, p\alpha)2He^4$ at $\theta_p=+60°$, $\theta_\alpha=-100°$ for a bombarding energy of 2.45 MeV.

TABLE I. Information relevant to the J^π assignments to states of B^9 formed by $B^{10}(He^3, \alpha)B^9$ which decay by proton emission to states of Be^8 or α-particle emission to the $\frac{3}{2}^-$ state of Li^5.

$J_{B^9}{}^\pi$	$^lP\ Be_0{}^{+8}$	$^l\alpha Li_{\frac{3}{2}-}{}^5$
$\frac{1}{2}^-$	1	2
$\frac{3}{2}^-$	1	0, 2
$\frac{5}{2}^-$	3	2, 4
$\frac{7}{2}^-$	3	2, 4
$\frac{9}{2}^-$	5	4, 6
$\frac{1}{2}^+$	0	1
$\frac{3}{2}^+$	2	1, 3
$\frac{5}{2}^+$	2	1, 3
$\frac{7}{2}^+$	4	3, 5
$\frac{9}{2}^+$	4	3, 5

If the $J=\frac{1}{2}$ assignment to the 2.8-MeV state is correct, then this state cannot be reached by the pickup of a $p_{\frac{3}{2}}$ neutron from $B^{10}(3+)$ in (p, d), (d, t), and (He^3, α) reactions. Such a level could, however, be formed by an exchange interaction in the $B^{10}(He^3, \alpha)$ reaction at the low bombarding energy used in this study. The fact that Fisher and Whaling[7] did not observe the 2.8-MeV level may not be inconsistent with the $J=\frac{1}{2}$ assignment, since exchange interactions are expected to become less important at higher bombarding energies.

STATES OF C^{12}

16.11 MeV. This state has been classified[2] as $J^\pi=2+$; $T=1$. We find that it is produced by the reaction I and that it decays by alpha-particle emission weakly to the ground state of Be^8 and strongly to the 2+ state of Be^8, with the decay to the 4+ undetermined. It is known[8] that Γ_γ/Γ is about 0.03.

Since the angular correlations between the initial proton from the $B^{10}(He^3, p)C^{12}$ reaction and the alpha particles resulting from the decay of C^{12} to different states of Be^8 may be different, an accurate measurement of the branching ratio for the α decay of the state of C^{12} to any particular level of Be^8 requires the measurement of the angular correlations for the decays to all levels. Such measurements would be very difficult. An estimate of the order of magnitude of the branching ratio for the α decay to the ground state of Be^8 can be obtained by measuring this ratio at several angles by the following procedure. A diagonal window is set on the Be^8 ground-state band in the two-dimensional, $p\alpha$ energy spectrum. An analysis of the projections of this band and the remainder of the spectrum upon the E_p axis yields the relative amount of the alpha-particle decay of the 16.11-MeV state of C^{12} to the Be^8 ground state and to the Be^8 2+ and 4+ states combined. (The

[5] D. Bodansky, S. F. Eccles, and I. Halpern, Phys. Rev. **108**, 1019 (1957).

[6] E. M. Henley and P. D. Kunz, Phys. Rev. **118**, 249 (1960).

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

[8] F. Ajzenberg and T. Lauritsen, Rev. Mod. Phys. **27**, 77 (1955).

TABLE II. Information relevant to the J^π assignments for states of C^{12} formed by $B^{10}(He^3, p)C^{12}$ which decay by α-particle emission to the 0^+ and/or 2^+ states of Be^8.

$J_{C^{12}}{}^{\pi}$	$^{l}\alpha Be_0{}^{+8}$	$^{l}\alpha Be_2{}^{+8}$
0^-	x	x
1^-	1	1, 3
2^-	x	1, 3
3^-	3	1, 3, 5
4^-	x	3, 5
0^+	0	2
1^+	x	2
2^+	2	0, 2, 4
3^+	x	2, 4

latter projection of course includes not only the alpha particles leading directly to the Be^8 2+ and 4+ states—the α_1's in reaction I—but also the breakup alpha particles $-\alpha_2$ and α_3 in reaction I—associated with the formation of the ground state as well as the 2+ and 4+ states of Be^8.) The two projections can be corrected for background due to other processes producing events in the relevant portion of the E_pE_α spectrum when the angles are chosen so that other processes do not produce peaks in that region of the E_p projections corresponding to the 16.11-MeV state of C^{12}.

With the above qualifications understood, we obtain a value for the ratio of the probability of the alpha-particle decay of the 16.11-MeV state of C^{12} to the Be^8 ground state to the probability of its decay to the excited states of Be^8 of 0.051 at $\theta_p=+60°$, $\theta_\alpha=+-60°$ and 0.12 at $\theta_p=+90°$, $\theta_\alpha=-120°$.

The previous assignment of $T=1$ to the 16.11-MeV state[2] is not inconsistent with the observed α-particle decay since only a small isospin impurity could account for the large α-decay width of this level.

Information relevant to the assignment of J^π to states of C^{12} which decay by alpha-particle emission to the Be^8 ground state and/or 2+ state is summarized in Table II. Since the 16.11-MeV state of C^{12} decays to the ground state of Be^8 it must have natural parity. J^π of 0+ or 1− are improbable on the basis of the branching ratio for the alpha-particle decay of the state. $J\geq 2$, natural parity, remain as assignments consistent with the present data.

15.11 MeV. This state has been classified[2] as $J^\pi=1^+$, $T=1$. The state is known to decay primarily by gamma emission.

Although it would have been difficult to have observed a small peak in that region of the $p\alpha$ spectrum corresponding to the formation of the 15.11-MeV state of C^{12} because of the large number of accidental events which frequently appeared in that region as a result of the prolific proton group from the $C^{12}(He^3, p_0)N^{14}$ reaction, several observations were performed under conditions which minimized this effect. Even in these cases, however, a peak resulting from an α-particle width of less than 10% for this state would have been difficult to observe because of the large contributions from other competing reactions generally found in this region of the $p\alpha$ spectrum.

An independent measurement of $\Gamma_\alpha/\Gamma_\gamma$ was made by detecting protons leading to the 15.11-MeV level of C^{12} in one counter and observing the corresponding recoil C^{12} nuclei in a second counter. The ratio of the number of protons leading to the 15.11-MeV state of C^{12} observed without coincident C^{12} recoils to the number of pC^{12} coincidences is $\Gamma_\alpha/\Gamma_\gamma$. The measurements yield a ratio of about 10%. Corrections for multiple scattering and recoil from the γ decay would tend to lower the observed ratio.

14.08 MeV. The 14.08-MeV state is excited rather strongly in the $B^{10}(He^3, p)$ reaction and decays by alpha-particle emission to the ground state and to the 2+ (and 4+?) states of Be^8. A value for the branching ratio for the alpha-particle decay to the ground state ranging from 14 to 38% for θ_α ranging from −40 to −120 deg and $\theta_p=+60°$ was obtained in the manner summarized in the discussion of the 16.11-MeV state and also by studying the projections on the E_α axis of a proton window set on the 14.08-MeV peak in the E_pE_α spectrum as well as the E_α projections for similar proton windows set on each side of this peak. The total width of the state, the alpha-decay width, as determined in this experiment is 320±50 keV, a value to be compared with the previously measured value of 252±15 keV.[9] The branching ratio for the alpha decay of this state makes the 0+ and 1− assignments unlikely, although these arguments are relatively weak. Proton–alpha angular correlation studies were made for this state as a function of θ_α for fixed θ_p at $\theta_p=30°$ and 60°. These correlations are shown in Figs. 2 and 3

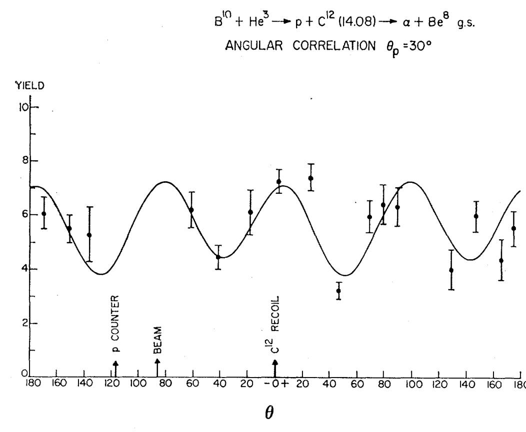

FIG. 2. $p\alpha$ angular correlation for the 14.08-MeV state of C^{12} at $\theta_p=30°$. The curve represents the fit obtained with

$$W(\theta)=\sum_{n=0}^{4} A_n \cos n(\theta-\theta_n).$$

[9] C. P. Browne, W. E. Dorenbusch, and J. R. Erskine, Phys. Rev. **125**, 992 (1962).

with the fits which have been obtained using a

$$\sum_{n=0}^{4} A_n \cos n(\theta-\theta_n)$$

series, where θ is the angle of emission of the α particle in the rest frame of the C^{12} (14.08) nucleus. The values of the A_n's for which the fits were obtained are given in Table III. The results clearly indicate that $J\pm2$. Thus the J^π assignment for the 14.08-MeV level of C^{12} is $J\pm2$, natural parity.

13.34 MeV. The 13.34-MeV state is formed in the $B^{10}(He^3, p)$ reaction and decays by alpha-particle emission to the 2+ (and 4+?) state of Be^8, but not to the ground state. The observed width of this state is 390 ± 70 keV which is consistent with the previous measurement of 430 ± 100 keV.[9] The J^π assignment is $J\geq1$, unnatural parity, with a preference for 2^- on the basis of the large width.

12.71 MeV. This state has been classified[2] as $(1\pm)$. Gamma decay of the state has been reported.[10] The 12.71-MeV state is excited rather strongly in the $B^{10}(He^3, p)$ reaction and is observed to be rather narrow. We have observed its α-particle decay to the 2+ (and 4+?) states of Be^8, but not to the ground state of Be^8. The J^π value is therefore restricted to $J\geq1$, unnatural parity. The previous assignment of (1+) is consistent with the observed alpha decay and narrow width of this level, as well as its observed gamma decay.

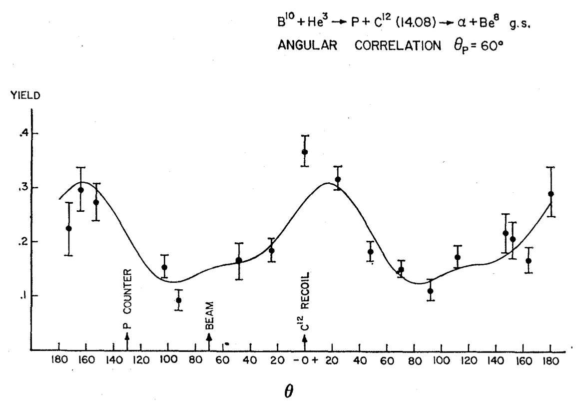

FIG. 3. $p\alpha$ angular correlation for the 14.08-MeV state of C^{12} at $\theta_p=60°$. The curve represents the fit obtained with

$$W(\theta)=\sum_{n=0}^{4} A_n \cos n(\theta-\theta_n).$$

[10] E. Almqvist, D. A. Bromley, A. J. Ferguson, H. E. Gove, and A. E. L. Therland, Phys. Rev. **114**, 1040 (1959).

TABLE III. Coefficients of the $p\alpha$ angular correlation function

$$W(\theta)=\sum_{n=0}^{4} A_n \cos n(\theta-\theta_n)$$

for the 14.08-MeV state of C^{12}.

θ_p	n	A_n	θ_n
30°	0	5.66 ± 0.16	
	2	0.33 ± 0.19	$-47.3°\pm21.8°$
	4	1.52 ± 0.21	$6.8°\pm 2.1°$
60°	0	0.201 ± 0.006	
	2	0.082 ± 0.009	$12.3°\pm 2.9°$
	4	0.029 ± 0.008	$21.4°\pm 4.9°$

11.83 MeV. It has been suggested[2] that the 11.83-MeV state has $J^\pi=1^-$. The state is excited rather strongly in the $B^{10}(He^3, p)$ reaction. It decays by alpha-particle emission to the Be^8 2+ (and 4+?) states, but not to the Be^8 ground state, although our uncertainty in the determination of the absence of the decay to the ground state is larger than for the preceding two states. The $J^\pi=1^-$ assignment thus seems unlikely. A value of $J\geq1$, unnatural parity, seems indicated with the 2^- value possibly more probable. The 2^- assignment is consistent with the $B^{11}(He^3, d)$ results.[11]

10.84 MeV. It has also been suggested[2] that the 10.84-MeV state has $J^\pi=1^-$. This state is also excited relatively strongly in the $B^{10}(He^3, p)$ reaction. It decays by alpha-particle emission primarily to the ground state of Be^8 and not to the 2+ state. The Q value for the latter decay is, of course, very small. The assignment of natural parity thus appears to be indicated with $J^\pi=0^+$ or 1^- more probable. The 1^- assignment is consistent with the $B^{11}(He^3, d)$ results.[11]

9.64 MeV. The 9.64-MeV state has been classified[2] as $J^\pi=3^-$. We find it produced very strongly in the $B^{10}(He^3, p)$ reaction and observe its decay by alpha-particle emission to the ground state of Be^8. We cannot determine whether it decays to the 2+ state since the energy of the alpha particles associated with this is too low to be observed in the present experiment. (See Fig. 1.) The state must have natural parity.

Discussion

WEGNER: Would not the errors on your data points allow a straight line fit as well as the curve that you used?

HOLMGREN: The calculated errors of coefficients in the angular correlation expression clearly show that the coefficients up to those of fourth order are significant and that the data cannot be fitted with a straight line.

[11] S. Hinds and R. Middleton, Proc. Phys. Soc. (London) **78**, 81 (1961).

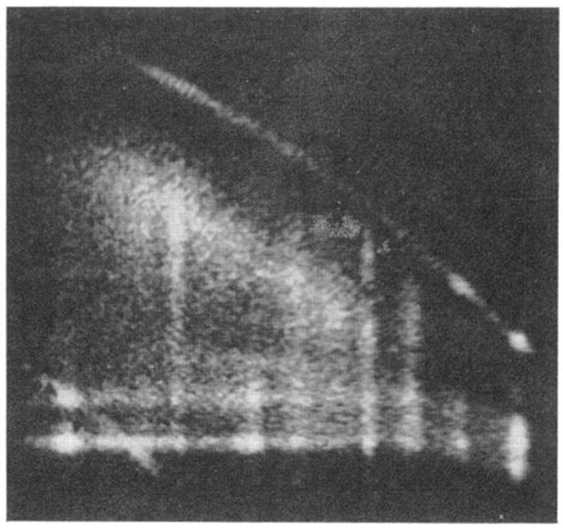

FIG. 1. The experimental two-dimensional energy spectrum of coincident proton and α particle from the reaction $B^{10}(He^3, p\alpha)2He^4$ at $\theta_p = +60°$, $\theta_\alpha = -100°$ for a bombarding energy of 2.45 MeV.