Decay of the 2.34- and 2.71-MeV States of B^9†

D. H. WILKINSON
Brookhaven National Laboratory, Upton, New York
and
Nuclear Physics Laboratory, Oxford, England
AND
J. T. SAMPLE* AND D. E. ALBURGER
Brookhaven National Laboratory, Upton, New York
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Proton emission from B^9 states at 2.34 and 2.71 MeV has been investigated by populating the states in the $B^{10}(He^3,\alpha)B^9$ reaction and by measuring α-p coincidences with a 2-dimensional pulse-height analyzer. The 2.34-MeV $J^\pi=\frac{5}{2}^-$ level decays less than 0.5% by proton emission to the ground state of Be^8, while the 2.71-MeV level decays nearly 100% by this route. The $1f$ proton reduced width of the 2.34-MeV level for the ground state of Be^8 (in units of $\hbar^2/mR^2$) is then less than 5×10^{-3} when R has the value 4.35 F. The coincidence method clearly resolves the 2.71-MeV $J^\pi=\frac{5}{2}^+$ state from the 2.34-MeV state and background, its excitation and width being 2.71 ± 0.03 MeV and 0.71 ± 0.06 MeV, respectively. These figures imply a $1d$ proton reduced width of the 2.71-MeV state for the ground state of Be^8 of about 0.7.

INTRODUCTION

THE purity of shell-model wave functions is a matter of intense and continuing interest in nuclear physics. To what degree is the lowest order shell-model wave function, with particle-particle interaction but without break-up of the basic configuration, an adequate representation of the real situation? To what degree are configuration mixing, two-particle two-hole excitation, and so on present even in the lowest-lying states? The necessity for departing from the lowest order shell model in certain regions of the periodic table is well known. It is most important to gain experimental information about the form which that supplementation takes. To do this we must examine experimentally the properties of states that are as well-described as any by the lowest order wave functions, testing them explicitly for the hypothesized admixtures.

The only extensive region where full shell-model calculations can be done in terms of the basic configuration is the $1p$ shell where we have $(1s)^4(1p)^{A-4}$. It has been well known for many years[1] that the shell model can give an excellent account of the positions of essentially all the low-lying states of the $1p$ shell of parity $(-)^A$. The latest versions of the model[2,3] in which the levels are fitted using all matrix elements of the $1p$-$1p$ nucleon-nucleon interaction as parameters give a most impressive fit to the entire body of well-established levels, leaving out of account only a very few states for which there is good independent evidence that $(2s,1d)^2$ or similar excitations constitute the bulk of the wave function. The fact that the matrix elements generated by this fitting procedure are quite close to those calculated from empirical nucleon-nucleon scattering potentials gives considerable credence to the picture. When these wave functions are used to calculate magnetic moments, beta decay, and $M1$ transition matrix elements, good general agreement is found with experiment, although these static and dynamical quantities have not themselves been used as part of the fitting procedure. All this adds up to a coherent picture in which the bulk of the $1p$-shell wave functions must be recognized to be $(1s)^4(1p)^{A-4}$. However, it must also be recognized that this cannot be the whole story. This is because of the $E2$ moments, both diagonal and off-diagonal. These are frequently much bigger than are given by the shell-model wave functions. For example, in $A=10$ alone there are seven $E2$ transitions between states well-described in position and in their $M1$ transitions by the shell model which are all about 2 to 10 times faster than prescribed by the same shell-model wave functions that are so satisfactory in other respects.[4–6] The phenomenon extends to the lightest nuclei in the shell and even in Li^6 one finds the $E2$ transition between the ground and first excited states[7] a factor of 5–10 faster than given by the shell-model wave functions. In fact throughout the shell the strong $E2$ transitions run a factor of 4 or so faster than given by the shell-model wave functions. Of course quantitative statements about the discrepancy between theory and experiment for $E2$ transitions depend on our ideas about $\langle r^2\rangle_p$, the expectation value of r^2 for the $1p$-shell nucleons, which enters squared in the theoretical transition rates. Our present remarks are based on values of $\langle r^2\rangle_p$ extracted from electron scattering data in the manner described earlier.[4] It seems very unlikely

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* On leave from the University of Alberta, Edmonton, Canada.
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that the true single-particle $E2$ speeds can exceed those used here by as much as 60% if we are guided by the error limits associated with the analysis of the electron scattering data. Making generous allowance for our uncertainty in $\langle r^2\rangle_p$ therefore still leaves us with a minimum discrepancy between theory and experiment by a mean factor of 2–3 for the strong transitions and by considerably more than this mean factor in some cases, for example the transition between the $J^\pi=3^+$ 4.77-MeV level and the $J^\pi=1^+$ 0.72-MeV level of B^{10} where the discrepancy is[5] by a factor 13.5 ± 2.5 (in terms of the "best" value for $\langle r^2\rangle_p$).

It is therefore quite clear that $(1s)^4(1p)^{A-4}$ is not an adequate description for the $E2$ transitions and yet the other considerable successes of the model are equally insistent that it make up the bulk of the wave functions. In general terms we must consider a more generalized shell-model wave function for the "$1p$ shell":

$$\psi=a_0\psi_0+\sum\nolimits_1 a_1\psi_1+\sum\nolimits_2 a_2\psi_2+\cdots, \quad (1)$$

where ψ_0 represents the basic configuration $(1s)^4(1p)^{A-4}$ and where ψ_1 represents all single-particle excitations such as $(1s)^3(1p)^{A-4}(2s)$ and where ψ_2 represents all two-particle excitations such as $(1s)^4(1p)^{A-6}(1d)^2$ and so on. The question is now whether the very considerable enhancements of the $E2$ transitions (and the static quadrupole moments about which less is known but which also show considerable enhancement) can be accounted for by such a generalized wave function which yet leaves $a_0\approx1$.

Some idea of an upper limit for $a_1, a_2, \cdots$, is given by another class of phenomena, namely reactions of nucleon removal such as $(p,2p)$, (p,d), etc. If we have only ψ_0 and if the reaction mechanism is a clean single-particle mechanism such as a classic direct interaction then we can form residual states only of parity $(-)^{A-1}$, where A is the target nucleus, and only of spin J_f where $|J_f-J_i|=\frac{3}{2}$ or $\frac{1}{2}$ if the nucleon removed belongs to $1p$ and the target nucleus has spin J_i. If, in such a reaction, we excite states of the "wrong" parity at energies far below those expected for the removal of a $1s$ nucleon it signals the presence in ψ of such a_1 terms as $(1s)^3\times(1p)^{A-4}(2s)$ or such a_2 terms as $(1s)^4(1p)^{A-6}(1d)^2$. Excited states of the correct parity that we have identified as good states of ψ_0 but which do not conform to the above limits on J_f signal the presence in ψ of such a_1 terms as $(1s)^4(1p)^{A-5}(1f)$. To be specific on the point of this latter admixture, which is the one with which we shall be chiefly concerned in this paper, consider the reactions $C^{12}(p,pn)C^{11}$, $C^{12}(n,np)B^{11}$, $C^{12}(p,2p)B^{11}$, and $C^{12}(p,d)C^{11}$. If these reactions take place through one-stage conventional mechanisms, and if we have only ψ_0, they cannot excite the second excited state of $A=11$ (at 4.46 MeV in B^{11} and at 4.32 MeV in C^{11}) which is of $J^\pi=\frac{5}{2}^-$. This state is well described by ψ_0 in respect of its position and $M1$ transition to ground. [In B^{11} the $M1$ width is[8] 0.54 ± 0.08 eV while the prediction of ψ_0 is[3] 0.54 eV. We may note in passing that this transition also shows the $E2$ syndrome discussed above: Its $E2$ component is[8–10] 2.1×10^{-2} eV which is 3.1 single-particle units $(1p_{3/2}\rightarrow1p_{3/2})$ for $\langle r^2\rangle_p=7.9\times10^{-26}$ cm^2.] Similarly these direct interactions cannot excite the $J^\pi=\frac{7}{2}^-$ states at 6.76 MeV in B^{11} and at 6.49 MeV in C^{11}. These states are also well described in position by ψ_0, and again show the $E2$ syndrome, the $E2$ transition in B^{11} having a strength[9] of 1.1 single-particle units. However, at a proton bombarding energy of 50 MeV, at which we may well expect the simple direct-interaction mechanism to have some validity, reactions $(p,2p)$ and (p,d) do in fact excite the $J^\pi=\frac{5}{2}^-$ and $\frac{7}{2}^-$ states.[11] These "forbidden" excitations are a factor of 6–8 or so weaker than that of the $J^\pi=\frac{3}{2}^-$ ground state whose excitation is certainly allowed by ψ_0. However, the ground state is excited very strongly and the "forbidden" excitations are in fact quite comparable in strength to the "allowed" excitations of the ψ_0 states of $J^\pi=\frac{1}{2}^-$ and $\frac{3}{2}^-$ at 2.14 and 5.03 MeV (B^{11}) and 2.00 and 4.81 MeV (C^{11}). Similarly in the reactions (n,np), (p,np), and $(p,2p)$ at 100–150 MeV[12,13] the "forbidden" states are excited comparably to the "allowed" with the exception of the ground state which is some 10 times stronger.

If these results were to be interpreted literally as one-stage knockout or pickup processes they would imply that $(1s)^4(1p)^{A-5}(1f)$ is present in the wave functions to 10% or perhaps tens of percent by intensity. Since this is not the only component of ψ_1 and since ψ_2 may also be expected to be strongly populated if ψ_1 has large components it would imply that ψ_0 could not dominate the over-all wave function in the way that we have seen we should expect.

The alternative explanation for such results as these is that they depend on multiple mechanisms of some sort. In the cases just discussed, for example, an initial interaction could excite C^{12} into its first excited $J^\pi=2^+$ state at 4.43 MeV; this could then act as target for the second stage of the process thereby enabling the $J^\pi=\frac{5}{2}^-$ and $\frac{7}{2}^-$ states to be reached by the pickup or knockout of a $1p$ particle rather than demanding the involvement of a $1f$ particle as in the one-stage picture. On general grounds one expects high-energy direct-interaction processes to be dominated by an over-all diffraction-like angular distribution that does not depend much on the detailed mechanism of the reaction but chiefly on kR, where k is the momentum transfer and R is a radius

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parameter. In particular one can never be sure in a reaction involving both ingoing and outgoing particles that a multiple-stage process is not responsible for the orbital angular momentum transfer. It follows that such reactions cannot be used for detecting small admixtures of higher configurations such as we are now discussing. Only in the case of single-nucleon emission between well-defined states where a particular l value is allowed or demanded for the outgoing nucleon by the spins and parities can the associated width be confidently interpreted in terms of an amplitude of a particular orbital angular momentum in the wave function of the emitting state. (Or similarly in the case of the formation of a definite J^π state in nucleon bombardment.)

In order, therefore, to inquire experimentally into the amplitude for the admixture of, say, $1f$-state orbitals into the predominantly $1p$-state wave functions of typically good "$1p$-shell" states in cases where one may expect such admixture to be largest we must find states which: (1) are good ψ_0 states in the sense that their excitations are typically well predicted by the shell model; (2) are good ψ_0 states in the sense that their $M1$ transitions are typically well predicted by the shell model; (3) are good ψ_0 states in the sense that other dynamical properties involving them such as beta-decay are typically well predicted by the shell model; (4) demonstrate strongly the $E2$ syndrome so that strong configuration mixing of some sort is demanded; (5) are single-nucleon unstable by $l=3$ nucleon emission, preferably to another good ψ_0 state. A measurement of the $l=3$ absolute width may then be related, using the usual procedures, to the corresponding a_1 coefficient of (1), namely that of $(1s)^4(1p)^{A-5}(1f)$, if the residual state of $A-1$ is indeed a good ψ_0 state. Call this coefficient a_{1f}. Of course what we shall measure is not the entire coefficient a_{1f} since the parent configuration $(1s)^4(1p)^{A-5}$ represents all parent states of $A-1$:

$$a_{1f}(1s)^4(1p)^{A-5}(1f)=\sum_\pi a_{1f\pi}\psi_\pi\psi_{1f}, \qquad (2)$$

where the ψ_π are the parent states in $A-1$. Our measurement will then relate to that coefficient $a_{1f\pi}$ that refers to the particular residual or parent state involved in our reaction. In general the coefficients $a_{1f\pi}$ are related to the associated reduced widths via various vector coupling coefficients in the spin and isotopic spin. In the particular case where the emitting state is of $T=\frac{1}{2}$ and the final state of $T=0$, $J^\pi=0^+$ the vector coupling coefficients are unity and the measured width, appropriately expressed in single-particle units, is the square of the desired amplitude of the wave function.

Before describing the experimental situation chosen for investigation here we will comment briefly on what might be expected for the magnitude of the coefficients a_{1f}. Few explicit calculations have been performed in the $1p$ shell. If only the ψ_1 excitations are used the situation is tractable. Kurath[14] has calculated the amplitudes a_1 for Li^7 in order to account for the ground-state static quadrupole moment using a quadrupole interaction term to mix the higher configurations into ψ_0. He finds that $a_{1f}\approx 0.2$ is required, i.e., a mixture of about 4% by intensity of the $1f$ state. Calculations on C^{12} directed at an understanding of the enhanced $E2$ transition from the first excited state[15] have also given intensities of several percent for the admixture of the $1f$ state both with and without the inclusion of certain ψ_2 terms. The $E2$-based theoretical picture therefore does not call for the tens-of-percent admixture by intensity that the reactions cited above would demand if they were one-step processes but at the same time seems to call for admixtures of the order of several percent by intensity. If experimentally it turns out that the admixtures of these simple excited configurations are significantly weaker than several percent we must presumably conclude that the admixtures responsible for the $E2$ enhancement are of a more complicated character involving more excited configurations and particle-hole correlation of a higher order.

We will now discuss our choice of state to be investigated.

THE 2.34-MeV LEVEL OF B^9

We have listed the *desiderata* of the levels suitable for our search for the admixture of $1f$ states into the $1p$ shell. It is not easy to find such levels. As explained, we must study a continuum state. Such states are usually at fairly high excitation where reliable identification with states of the shell model may be difficult and where, witnessed by the increasing level density, more complicated configurations are in any case becoming more important and where their admixture to the shell-model states is becoming encouraged by the small spacing. It is above all desirable to study low-lying levels where adventitious admixtures will be least and yet where the $E2$ syndrome is well-developed. In these conditions departure from ψ_0 is demanded and yet the situation may be sufficiently simple to be susceptible to an explicit calculation of the admixtures on the basis of some specific hypothesis about their character.

The state that we wish to discuss is the 2.34-MeV level of B^9, the mirror of the 2.43-MeV level of Be^9. These states are established to have $J^\pi=\frac{5}{2}^-$ by a combination of results on (γ,n), (e,e'), and (p,p') reactions on Be^9 as discussed in the forthcoming compilation by Lauritsen and Ajzenberg-Selove.[16] This assignment is expected by the shell model as we shall now discuss and is also consistent with their being the second states of the $K=\frac{3}{2}$ rotational band-like systematization of Be^9-B^9 that is encouraged by their strong $E2$ transition properties that we shall also now present. We note that this assignment requires that

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their de-excitation by nucleon emission to the $J^\pi=0^+$ ground state of Be^8 should be by $l=3$ nucleons only.

These $J^\pi=\frac{5}{2}^-$ states of Be^9 and B^9 appear to be good ψ_0 states in the sense of the Introduction. They satisfy criterion (1) in that they are predicted[3] to lie at about 2.4 MeV as against their experimental excitation of 2.34–2.43 MeV. They satisfy criterion (2) in that the $M1$ radiative width of the Be^9 state is[17] (0.12±0.02) eV (as determined by electron scattering at 180°) which compares adequately well with the prediction[3] of 6×10^{-2} eV. They satisfy criterion (3) in that the predicted[3] logft value for the beta decay of Li^9 to the 2.43-MeV state of Be^9 is about 5.0 while the experimental value[18] is 4.7±0.2. These criteria establish these states as being as good ψ_0 states as are found. They are the first excited states of the $A=9$ system belonging to $(1p)^5$ and so satisfy the condition of being low-lying just discussed. They also satisfy criterion (4) of displaying the $E2$ syndrome. In fact the $E2$ transition to the ground state is extremely strong in Be^9. It has been determined in two ways. The first of these is electron scattering[19] which gives $\Gamma_\gamma(E2)=(2.6\pm0.1)\times10^{-3}$ eV. The second method is that of the inelastic scattering of energetic (185-MeV) protons which is dominated by the same matrix element as determines the $E2$ transition. The angular distribution[9] of the inelastically scattered protons leading to this state is very closely the same as that of protons leading to the first excited $J^\pi=2^+$ state in the scattering from C^{12}. Since distortion effects must be rather closely similar in Be^9 and C^{12} we may directly relate the $E2$ radiative width in Be^9 to the known width in C^{12} finding for Be^9 $\Gamma_\gamma(E2)=(2.5\pm0.5)\times10^{-3}$ eV. The error quoted here contains no allowance for the uncertainties in transforming the relative inelastic scattering cross sections into relative radiative widths and simply reflects the error in the assumed value $\Gamma_\gamma=(1.1\pm0.2)\times10^{-2}$ eV for the C^{12} transition. This latter width derives from three concordant values.[8,20] [This same (p,p') method was used in our remarks above on $E2$ transitions in B^{11}.] These two values for $\Gamma_\gamma(E2)$ in Be^9 are in excellent accord and correspond to 5.9 single-particle $(1p_{3/2}\rightarrow 1p_{3/2})$ units (based on[21] $\langle r^2\rangle_p=8.4\times10^{-26}$ cm^2). This very great strength (the well-known C^{12} transition used as comparator in the second method and usually thought of as a very strong $E2$ transition has a strength of only 1.9 such units using[21] $\langle r^2\rangle_p=7.2\times10^{-26}$ cm^2) shows that the $E2$ syndrome is indeed very well developed and that whatever configuration mixing is responsible for it must also be well developed. Finally note that criterion (5) is satisfied: The decay of these states to the ground state of Be^8, a good ψ_0 state, can take place only by $l=3$ nucleon emission. Since the transition is $T=\frac{1}{2}$ to $T=0$ and is to a $J^\pi=0^+$ final state the vector-coupling coefficients are unity and the reduced width for the transition, appropriately computed, is equal to the square of the amplitude of the $J^\pi=\frac{5}{2}^-$ $A=9$ state representing the ground state (g.s.) of Be^8 plus a $1f$-nucleon, neutron for Be^9, proton for B^9; i.e., is equal to $|a_{1f\,\mathrm{g.s.}}|^2$ in the expansion:

$$\psi=\psi_0+\cdots+a_{1f\,\mathrm{g.s.}}\psi_{\mathrm{g.s.}}(\mathrm{Be}^8)\psi(1f)+\cdots,$$

where $\psi_{\mathrm{g.s.}}(Be^8)$ represents the ground state of Be^8.

These $J^\pi=\frac{5}{2}^-$ states therefore represent a very propitious circumstance for the determination of $1f$-state admixture into $1p$-shell states. (It may be remarked that we have tended to speak tacitly in LS-coupling rather than jj-coupling terms. In $A=9$ we are closer to the former coupling scheme. In the older[1] "a/K" version of the independent-particle model Be^9-B^9 required $a/K\approx3$ which is not far removed from LS coupling. It would be particularly inappropriate to discuss Be^9-B^9 in jj-coupling terms and an explicit confrontation of the results of an experiment such as the present one with the expectation of a configuration-mixing model must certainly be made in the proper intermediate coupling. We must therefore beware of speaking of the $1f$ nucleon involved in our present considerations as a $1f_{5/2}$ nucleon in the jj-coupling sense: It is associated with a total angular momentum of $\frac{5}{2}$ only by virtue of the J^π value of the state of which it is a part and the fact that we are interested in the $J^\pi=0^+$ ground state of Be^8 as parent.)

EXPERIMENTAL PROCEDURE AND RESULTS

The reaction $B^{10}(He^3,\alpha)B^9$ was chosen to study the region of excitation near the 2.34-MeV level of B^9. Two-dimensional recording of alpha-particle coincidences with protons from the breakup[22,23] of B^9 permits detailed examination of this region. The target chamber contains a rotatable target mount and two movable arms to rotate detectors in the horizontal plane. The beam-collimating system was fitted with apertures to produce a 1-mm-diam beam. The alpha-particle detector, a silicon surface barrier detector 95 μ thick, was mounted 3.2 cm from the target with a tantalum slit 1 mm wide and 3 mm high placed in front of it. A 3-mm-thick lithium-drifted silicon detector 1.5 cm from the target was covered by a 15.9 mg/cm^2 aluminum foil to exclude alpha particles. A 9-mm diam aperture defined the range of proton angles accepted by this detector. Pulses from the detectors were fed, after amplification, to a TMC 128×128-channel pulse-height analyzer and to a coincidence circuit which gated the analyzer.

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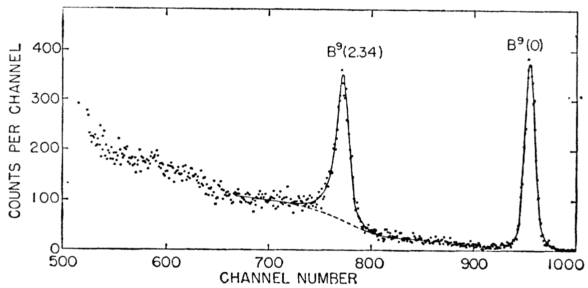

FIG. 1. Alpha-particle singles spectrum from the $B^{10}(He^3,\alpha)B^9$ reaction observed at 105° to the beam in a 95-μ thick detector ($E_{He^3}=2.62$ MeV; integrated charge$=50$ μC). The dashed line shows the estimated background used to extract the area under the $B^9(2.34)$ peak.

A portion of the pulse-height spectrum from the alpha-particle detector placed at 105° with respect to the beam at a He^3 beam energy of 2.62 MeV is shown in Fig. 1. Only peaks corresponding to the ground and 2.34-MeV states of B^9 are seen in this part of the spectrum, the weak group[24,25] to the broad 2.7-MeV level being obscured by a continuum. Figure 2 shows a map display of the summed results of three coincidence runs totaling 42 h with a beam current of 0.04 μA and bombarding energy of 2.62 MeV. The alpha-particle detector was positioned as above and the proton detector at $-51°$, the B^9 recoil direction when the 2.34-MeV state is excited. The x axis covers proton energies between the foil cutoff energy, approximately 2.6 MeV, and 9.5 MeV. The range of alpha-particle energies on the y axis is 4.9 to 9.3 MeV. In obtaining the photograph in Fig. 2 the z intensification threshold control was set so that only those channels containing more than 50 counts appear as bright dots. Starting at the top left and curving downward toward the right, the Be^8 ground-state kinematic line is plainly visible, as well as a heavy horizontal line centered on channel $y=72$ corresponding to breakup of the B^9 2.34-MeV level via such modes as $Li^5+\alpha\rightarrow 2\alpha+p$. Figure 2 indicates immediately that the 2.34-MeV level decays rarely if at all through $Be^8(0)+p$, while the broad 2.7-MeV level centered on channel $y=65$ decays mainly by this route. The spectrum of alpha particles coincident with protons, i.e., the summed projection of Fig. 2 on the y axis, is shown in Fig. 3. The weak B^9 ground-state group at channel 118 results from random coincidences, while the group to the 2.7-MeV level, although visible in the vicinity of channel 65, is largely obscured by the strong group to the 2.34-MeV level and a continuum.

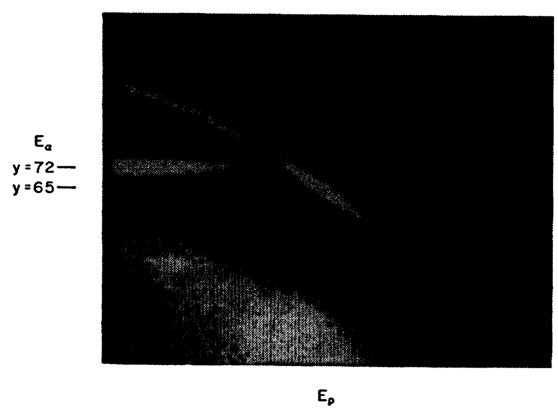

FIG. 2. Map display (128×128 channels) of the alpha-proton two-dimensional pulse-height coincidence spectrum from $B^{10}+He^3$. Detector angles were $\theta_\alpha=105°$ and $\theta_p=-51°$, and the integrated charge was 7090 μC. The alpha-particle energy is along the y axis, channels 1 through 128 corresponding approximately to channels 513 through 1024 in Fig. 1; proton energy is along the x axis. The two coincidence regions of interest are (1) that corresponding to the B^9 2.34-MeV level, which is the horizontal band centered at alpha-particle channel $y=72.5$ and which appears to lie mostly inside the Be^8 ground-state kinematic line and (2) that corresponding to the broad B^9 2.7-MeV level which is in the neighborhood of alpha-particle channel $y=65$ and which appears to lie mostly on the curving Be^8 ground-state kinematic line.

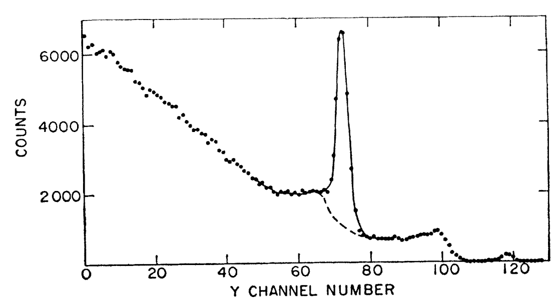

FIG. 3. Spectrum of alpha particles in coincidence with all protons detected in the $B^{10}+He^3$ reaction. This figure represents a projection and summing onto the y axis of all coincidences in Fig. 2. The dashed line shows the estimated background used to extract the area under the B^9 (2.34) peak. The small peak at channel 118 is due to random coincidences with B^9 ground-state alpha particles.

In order to determine the number of events in which the 2.34-MeV level decayed by proton emission to the ground state of Be^8, sums over the kinematic line were evaluated for each alpha-particle channel. Typical coincident proton spectra are shown for two alpha-particle channels in Fig. 4. Curve A, for $Y=62$, corresponds to alpha particles on the high-excitation side of the group to the 2.7-MeV level, while curve B, for $Y=72$, corresponds to alpha particles leaving B^9 in its 2.34-MeV state. The number of counts at proton energies less than that of the kinematic peak is seen to be much greater on the 2.34-MeV peak than elsewhere. Peak area less the estimated background (indicated by the dashed lines in Fig. 4) is plotted versus alpha-particle channel number in Fig. 5A. No contribution from the 2.34-MeV level (expected at channel 72.5) is noticeable on the low-excitation side of the peak due to the 2.7-MeV level. A small peak at channel 26 has

[24] R. R. Spencer, G. C. Phillips, and J. E. Young, Nucl. Phys. 21, 310 (1960).
[25] L. G. Earwaker, J. G. Jenkin, and E. W. Titterton, Nucl. Phys. 46, 540 (1963).

not been identified. It corresponds to 4.7-MeV excitation in B^9 and to 12.9 MeV in C^{12} [via $B^{10}(He^3,p)$-$C^{12*}(\alpha)Be^8$].

A more sensitive check for events on the kinematic line involving the 2.34-MeV state was carried out by comparing the 2.7-MeV level shape to the Breit-Wigner single-level formula. The sloping background and the contribution from the small peak in Fig. 5A were estimated and subtracted from the total counts in each channel. Correction factors for center-of-mass to laboratory-solid-angle transformation, alpha-particle penetrability, and proton penetrability were applied. Since the proton detector was placed at the recoil angle corresponding to B^9 in its 2.34-MeV state, the solid-angle factor is, with very small error, $(1-\cos\theta_{c.m.})/(1-\cos\theta_L)$ across the 2.7-MeV level. θ_L and $\theta_{c.m.}$ are, respectively, the half-angle subtended by the proton detector and its analog in the recoil center-of-mass system for each excitation energy. Because of the high alpha-particle energy, the s-wave penetrability factor[26] $kR/[F_0^2(kR)+G_0^2(kR)]$ varies almost linearly with k, and changes only by 12% across the 2.7-MeV level [using $R=1.45(A_1^{1/3}+A_2^{1/3})$ F$=4.35$ F]. Since the Be^9 mirror state of the 2.7-MeV state has been tentatively assigned $J^\pi=\frac{5}{2}^+$,[16] a d-wave penetrability factor[26] $kR/[F_2^2(kR)+G_2^2(kR)]$ has been applied for the outgoing protons. All correction factors were normalized to unity at 2.34-MeV excitation, so that in the neighborhood of the 2.34-MeV level, the ordinate of Fig. 5B is equal to coincidence counts per alpha-particle channel.

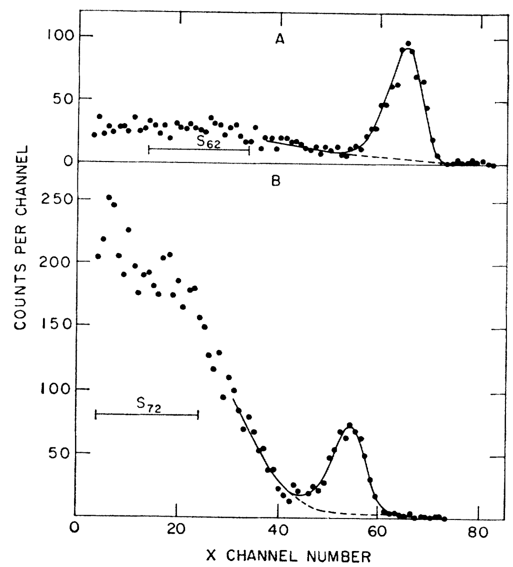

FIG. 4. Proton spectra in coincidence with selected alpha-particle energies in Fig. 2. Curve A is for $y=62$ and curve B is for $y=72$. In each case the sharp peak lies on the Be^8 ground-state kinematic line. Dashed lines in these plots are estimated backgrounds used to extract the net area under the Be^8 ground-state kinematic peak. The regions S_{62} and S_{72} are explained in connection with Fig. 6.

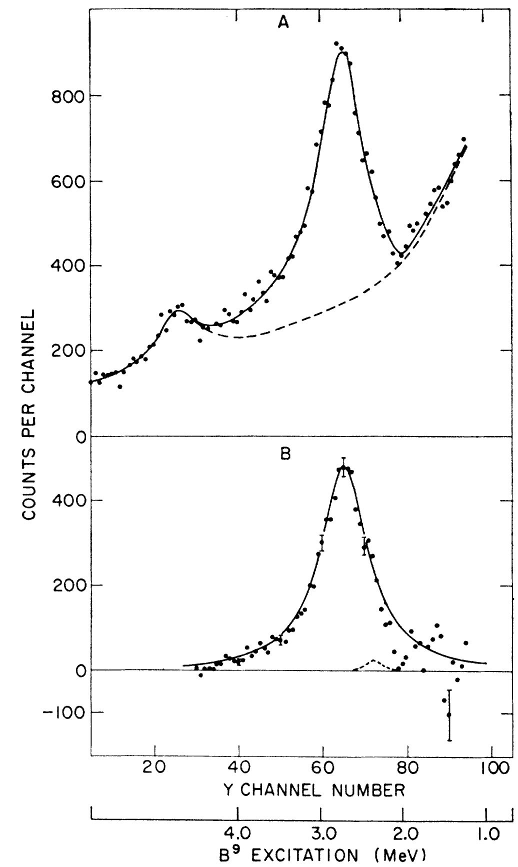

FIG. 5. Coincidence yield of the Be^8 ground-state kinematic line obtained by plotting the area under the kinematic peak in the x direction, as indicated in Fig. 4, versus alpha-particle (y) channel number. Curve A shows the raw data, the large peak corresponding to the 2.7-MeV state of B^9. The origin of the small peak at channel 26 is not known. The dashed line in A is an estimated background hand-fitted to points below and above the main peak. Curve B was obtained by subtracting the background from curve A and correcting with solid-angle and penetrability factors as described in the text. The solid line is a Breit-Wigner fit with $E_r=2.71$ MeV, $\Gamma=0.71$ MeV. The dashed peak in curve B has the position and shape of the alpha-particle group to the B^9 2.34-MeV level and its amplitude is the maximum that could be present without showing up as a bulge on the side of the broad 2.7-MeV peak.

Figure 5B shows the data of Fig. 5A treated as outlined above. the errors shown are standard deviations of the points in Fig. 5A divided by the three correction factors. The solid curve is a Breit-Wigner fit to the data with $E_x=2.71$ MeV, $\Gamma=0.71$ MeV. Level shift and width shift factors have not been explicitly computed and are effectively absorbed into the E_x and Γ parameters in the usual way. When p-wave or f-wave penetrability factors are applied instead of d-wave for the protons, the fit is noticeably poorer. This, while not strong evidence, indicates that d-wave is the correct choice. This experiment indicates then that the broad level is at $E_x=2.71\pm0.03$ MeV with $\Gamma=0.71\pm0.06$

[26] W. J. Sharp, H. E. Gove, and E. B. Paul, Chalk River Report No. TPI-70, 1953 (unpublished).

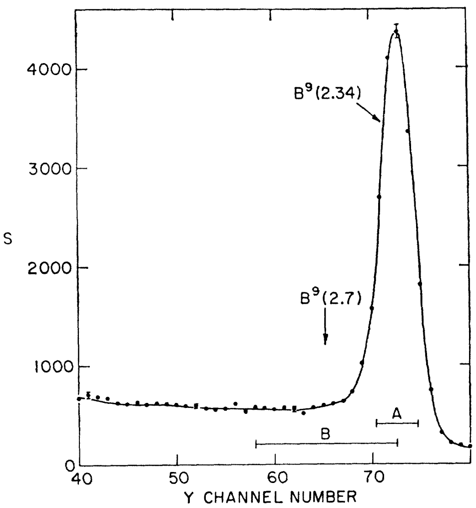

FIG. 6. Coincidence yield of the region inside the Be^8 ground-state kinematic line obtained by plotting the area S under a 21-channel section of each proton spectrum (adjusted so that the last channel of the section is 30 channels lower than the center of the Be^8 ground-state kinematic line (see regions S_{62} and S_{72} in Fig. 4) versus alpha-particle channel number. The horizontal lines labeled A and B are the widths (FWHM) of the peak due to the 2.34- and 2.7-MeV levels in Figs. 3 and 5, respectively. No structure due to the 2.7-MeV level appears to be present in this region.

MeV, as compared with other measurements[16] giving mean values $E_x=2.83\pm0.03$ MeV and $\Gamma=0.70\pm0.16$ MeV.

The large width of the 2.7-MeV level and the loss of coincidences due to the proton detector foil prevent an accurate estimate of the fraction of decays of this level by modes other than $Be^8(0)+p$. Some measure is obtained by plotting the counts in a representative portion of the region of Fig. 2 well inside the Be^8 ground-state kinematic line versus B^9 excitation. Sums over regions indicated by S in Fig. 4 are plotted in Fig. 6. S was chosen to be 21 channels wide, with the highest channel 30 channels below the kinematic peak of each slice parallel to the proton axis. For the eight highest alpha-particle channels in Fig. 6, S extended below proton channel 0, and the missing channels were assumed to contain a number of counts equal to the average of the six lowest proton channels. These points lie on the large peak in Fig. 6 due to the 2.34-MeV state. Over the width of the 2.7-MeV state, indicated by B in Fig. 6, there is no structure indicative of decay of the 2.7-MeV level. We conclude that it decays almost completely via $Be^8(0)+p$.

No evidence for decay of the 2.34-MeV level is visible in Fig. 5B. We assume that an increase of the counts in channels 70 to 75 inclusive, covering the region of 2.34-MeV excitation, by the amount of their standard deviations would have produced a noticeable bulge on the side of the 2.7-MeV peak. This number of counts, 144, is shown in Fig. 5B by a dotted Breit-Wigner distribution with the experimental linewidth

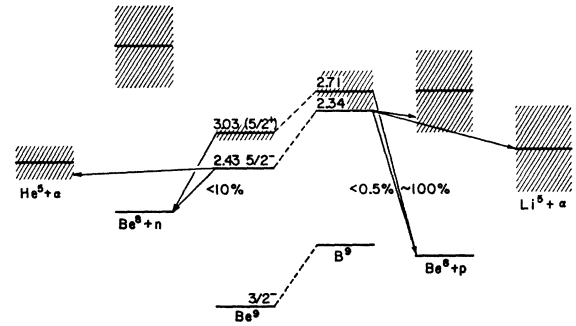

FIG. 7. The energy levels of Be^9 and B^9 of interest in this experiment. Information from this experiment is included.

of the 2.34-MeV level. This number has been adopted as an upper limit to the number of events in which the 2.34-MeV level decayed via $Be^8(0)+p$.

The upper limit of the fraction of decays to the Be^8 ground state has been calculated in two ways. In the first method, the area under the 2.34-MeV coincidence peak in Fig. 3 less estimated background was taken as a measure of the number of events in which the 2.34-MeV level was populated. The ratio of the above limit on ground-state events to this area, 0.6%, is high as an upper limit to the percentage of ground-state decay because of the loss of coincidence events due to protons stopping in the foil in front of the proton counter. In the second method, the population of the 2.34-MeV level was taken to be the area under the 2.34-MeV peak in the singles spectrum of Fig. 1, multiplied by the ratio of integrated beam current in the runs of Figs. 2 and 1 and by the solid angle subtended by the proton detector in the recoil center-of-mass system. This assumes that the p-α angular correlation is isotropic. The resulting limit is 0.4%. We adopt 0.5% as an upper limit to the fraction of Be^8 ground-state transitions of the B^9 2.34-MeV level. Results of this experiment and others[16] are shown in Fig. 7.

ANALYSIS OF THE 2.34-MeV STATE

We have seen that the probability for the B^9 2.34-MeV state to de-excite by the emission of a proton to the ground state of Be^8 is less than 0.5%. Since the total width of the state is [24,27] 82 ± 8 keV we have

$$\Gamma_{l=3}<410\pm40 \text{ eV},$$

where $\Gamma_{l=3}$ stands for the partial width for the $l=3$ emission that we have failed to find. We must now convert this into a limit on the square of the desired amplitude $|a_{1f\,g.s.}|^2$ that measures the fraction of the time for which the 2.34-MeV state looks like the ground state of Be^8 with an orbiting $1f$ proton. We may do this, conventionally, via the reduced width formalism

$$\Gamma_{l=3}=2kRP(\hbar^2/mR^2)\theta_{l=3}^2,$$

[27] B. Povh, Phys. Rev. 114, 1114 (1959).

where the symbols have their usual meanings [with this usage P is defined as $(F^2+G^2)^{-1}$], and where the dimensionless reduced width $\theta_{l=3}{}^2$ is supposed to be approximately equal to the square of the desired amplitude,

$$\theta_{l=3}{}^2 \approx |a_{1f\ \mathrm{g.s.}}|^2 .$$

To translate Γ into θ^2 we must fix the radius R. This we do through the canonical formula that appears[28] to work well enough in the $1p$ shell: $R=1.45(A_1{}^{1/3}+A_2{}^{1/3})\times 10^{-13}$ cm. This procedure gives

$$\theta_{l=3}{}^2 < 5.1\times 10^{-3} .$$

The sensitivity of the procedure to R is such that a 15% increase in R lowers the limit by a factor of 2.1 while a 15% decrease raises it by a factor of 2.6. It therefore appears that $\theta_{l=3}{}^2$ is almost certainly less than 0.02, probably less than 0.01 and with a "best value" limit of less than 5×10^{-3}.

On the supposition that $\theta^2 \approx |a|^2$ we see that the $1f$-state admixture is at most of the percentage order rather than the few or several percent suggested by the configuration mixing calculations. Of course it must be noted that our experiment is sensitive only to the parentage of the Be^8 ground state.

THE MIRROR STATE IN Be^9

It is interesting to inquire about the mirror decay: neutron emission by the 2.43-MeV state of Be^9 to the Be^8 ground state. An experimental search for this decay must, of course, beware of confusing with the genuine ground-state decay of this state the ground-state decay of the broad 3.04-MeV state (the mirror of the 2.7-MeV state in our present study) which will overlap the 2.43-MeV state to some degree to provide a background underneath it especially in poor resolution; similar care is needed for the ground-state decay of the general background excitation the underlies the 2.43-MeV region of excitation. As we have seen from B^9 both the broad state and the background in fact decay preferentially to the Be^8 ground state and ascertaining that the ground-state decay, if any, of the $J^\pi = \frac{5}{2}^-$ state is really resonant at the appropriate energy is the crucial point of the experiment. Of course, if no ground-state decay is observed from the region of excitation containing the resonant state then the limit may be combined with the relative intensities with which the resonant state and the rest are populated in that region of excitation to give a limit on the ground-state decay of the resonant state. If, however, ground-state decay is detected, then it must be shown to be resonant before it can be associated with the resonant state rather than with the background.

A recent study[29] of the reaction $C^{12}(n,\alpha)Be^9(n)2\alpha$ has been represented as establishing a ground-state decay probability of 13±5% for the 2.43-MeV state. However, the resonant behavior of the ground-state decay, just discussed, was not demonstrated and in fact the magnitude of the background in the region of excitation investigated containing the 2.43-MeV peak was of the order of 10–20% relative to the peak so that its ground-state decay, which we known from our present results on B^9 to be the dominant mode, would produce just the observed result. This possibility was explicitly recognized by the authors.[29] We can, therefore, only interpret these results as establishing an upper limit of about 20% on the ground-state decay probability of the 2.43-MeV state itself. This limit could be sharpened somewhat by an analysis of the decay modes of the regions of excitation in Be^9 on either side of that containing the 2.43-MeV peak in analogy to the method adopted by us for B^9 but this has not been reported.

In an earlier investigation[30] an upper limit of 10% for the ground-state decay was reported.

A figure of (12±5)% for the ground-state decay has been reported[31] from a study of the reaction $Be^9(n,2n)Be^8$. The experimental data are consistent with such an interpretation but do not demand it since the production of the state was not authenticated separately from the neutron group taken to represent its decay.

The total width of the Be^9 2.43-MeV state is (0.87±0.16) keV. This comes from combining the radiative width of the level,[17] $\Gamma_\gamma = (0.12\pm0.02)$ eV, with its fractional gamma branch[32] of $(1.39\pm0.12)\times 10^{-4}$. Using the preferred channel radius of 4.35 F as in the above analysis of the B^9 decay gives then

$$\theta_{l=3}{}^2 = 0.24B .$$

where B is the fractional ground-state branch. Thus the limit $B<0.1$ means $\theta^2 < 2.4\times 10^{-2}$.

The present status of the neutron study therefore corresponds to a limit on the $1f$-state neutron admixture consistent with our present proton result in the mirror state but some 5 times coarser. *Note added in proof.* P. R. Christensen and C. L. Cocke [Bull. Am. Phys. Soc. **11**, 301 (1966)] report that the Be^9 2.43-MeV state decays (7.5±1.5)% to the Be^8 ground state. This corresponds to $\theta_{l=3}{}^2 \simeq 2\times 10^{-2}$.

ANALYSIS OF THE 2.71-MeV STATE IN B^9

We may convert the resonance parameters of the 2.71-MeV level into a reduced proton width for the ground state of Be^8 assuming, as is very probable, that decay is by d-wave protons and is, as we have shown, chiefly to the ground state of Be^8. Using the definitions

[28] A. M. Lane, Rev. Mod. Phys. **32**, 519 (1960).
[29] J. Mösner, G. Schmidt, and J. Schintlmeister, Nucl. Phys. **64**, 169 (1965).
[30] D. Bodansky, S. F. Eccles, and I. Halpern, Phys. Rev. **108**, 1019 (1957).
[31] J. B. Marion, J. S. Levin, and L. Cranberg, Phys. Rev. **114**, 1584 (1959).
[32] P. Purdom, P. A. Seeger, and R. W. Kavanagh, Bull. Am. Phys. Soc. **9**, 704 (1964).

and methods of the previous section we find

$$\theta_{l=2}{}^2 = 0.74.$$

This figure is not very sensitive to reasonable changes of R, increasing only to 1.13 when R is decreased from 4.35 to 3.5 F.

A more careful analysis must take proper account of the energy dependence of the level parameters but our present figure is adequate to show that the state is fairly closely represented by $Be^8(0)1d_{5/2}$, the loose coupling of a d-wave proton to the ground state of Be^8. In this it, and its analog at 3.03 MeV in Be^9 resemble the $J^\pi = \frac{5}{2}^+$ states at 3.85 MeV in C^{13} and 3.56 MeV in N^{13} which show a very large d-wave nucleon reduced width for the ground state of C^{12}.

DISCUSSION

The conclusions that we have drawn about the breakup of the B^9 2.34-MeV and the Be^9 2.43-MeV states may be compared with earlier discussions. Spencer, Phillips, and Young,[24] on the basis of the relative widths of the Be^9 and B^9 states, concluded that the dominant mode of decay could not be by ground-state nucleon emission as we indeed see to be true. Their quantitative analysis of the decay cannot be complete, however, because they ignored the He^5, Li^5, and He^4 modes which may be significant and, indeed, according to the alpha-particle model of Henley and Kunz,[33] are dominant. This latter model, which is one of an orbital neutron (for Be^9) moving in a potential made up of two alpha particles, provides for some ground-state emission since the dumbbell-like Be^8 potential is noncentral and so mixes some $1f$-state into the dominant $1p$-state neutron orbital. This model predicts a ground-state decay probability (for Be^9) of 5–20% which we can see by inference from our B^9 results to be somewhat of an overestimate. However, literal alpha-particle models, while they can often be made consistent with the level schemes, are notoriously deficient in describing the dynamics—as witness the model of Henley and Kunz[33] which overestimates the strength of the $M1$ gamma-ray transition from the level in question by a factor of 10.

We return to the discussion of the magnitude of $|a_{1f\ g.s.}|^2$. If our assumption, the one usually made, that $\theta^2 \approx |a|^2$ (in cases such as the present where the vector coupling coefficients are unity) is correct then it may appear that the $1f$-state admixture is unexpectedly small. This conclusion could be falsified in two chief ways: (1) In a trivial sense if our reduction from the limit on the width for the ground-state transition to $|a|^2$ is incorrect. Although the procedure adopted here is the standard one that appears empirically to be satisfactory in the $1p$ shell[28] it would be desirable to perform the $\Gamma \to |a|^2$ translation using a "realistic" model. This is under way. It is most unlikely to change the limit on $|a|^2$ by a large factor but it could possibly convert the present rather small value into something closer to the expected figure. (2) In a fundamental sense if a proper configuration-mixing calculation, while requiring $1f$-state admixture to the usual degree of some percent by intensity into the $J^\pi = \frac{5}{2}^-$ states, requires or admits weak parentage by the Be^8 ground state so that while $|a_{1f}|^2$ in the loose sense of Eq. (2) is large $|a_{1f\ g.s.}|^2$ is small.

Since all the relevant properties of the states are now known a full-dress configuration mixing calculation in intermediate coupling would be justified and would be most interesting.

So far as further experimental work is concerned it would appear rather difficult to sharpen the present limit on the B^9 decay by a significant factor. This could be done if a mechanism could be found for preferentially populating the $J^\pi = \frac{5}{2}^-$ state but none is obviously available. (Perhaps at some future date C^9 decay—see below.) Such a preferential mechanism may, however, be available for the mirror state in Be^9. This is the beta decay of Li^9 which is chiefly to the $J^\pi = \frac{5}{2}^-$ level[18] and which, in particular, will not populate significantly the broad even-parity state at about 3.0 MeV. A mysterious feature of the $A = 9$ level scheme is the nonappearance to date of the $J^\pi = \frac{1}{2}^-$ state expected[3] in the immediate vicinity of the $J^\pi = \frac{5}{2}^-$ state. This state could well be quite broad since it would have a ground-state decay by $l = 1$ neutrons or protons; this fact may have inhibited its discovery. This state is predicted[3] as enjoying about the same $\log ft$ value for population in the Li^9 beta decay as the $J^\pi = \frac{5}{2}^-$ state and may be responsible for the observation[18] of beta transitions to the region above the $J^\pi = \frac{5}{2}^-$ level. The situation could be clarified considerably by a neutron-time-of-flight experiment in which the ground-state decay of the $J^\pi = \frac{5}{2}^-$ level would be signaled by a monokinetic neutron group in coincidence with beta particles and in which the relative intensities of transitions to the $J^\pi = \frac{5}{2}^-$ state and to higher states could hopefully be sorted out from the shape of the neutron continuum. This method might prove to be one of high sensitivity for detecting the desired ground-state neutron transitions. The appropriate experiment is in preparation.

At some time in the future the decay of a clean source[34] of C^9 might enable the same study to be made from the B^9 side.

[33] E. M. Henley and P. D. Kunz, Phys. Rev. **118**, 248 (1960).

[34] J. C. Hardy, R. I. Verrall, R. Barton, and R. E. Bell, Phys. Rev. Letters **14**, 376 (1965).

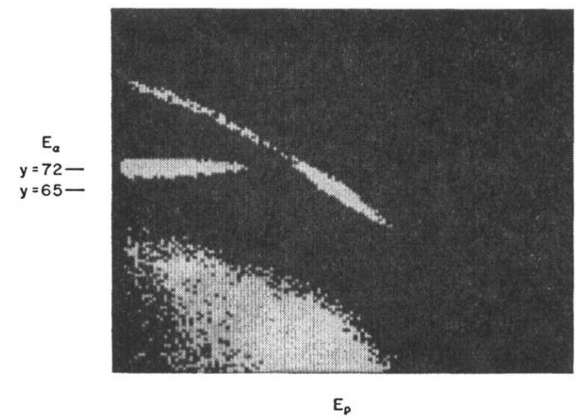

FIG. 2. Map display (128×128 channels) of the alpha-proton two-dimensional pulse-height coincidence spectrum from $B^{10}+He^3$. Detector angles were $\theta_\alpha=105°$ and $\theta_p=-51°$, and the integrated charge was 7090 μC. The alpha-particle energy is along the y axis, channels 1 through 128 corresponding approximately to channels 513 through 1024 in Fig. 1; proton energy is along the x axis. The two coincidence regions of interest are (1) that corresponding to the B^9 2.34-MeV level, which is the horizontal band centered at alpha-particle channel $y=72.5$ and which appears to lie mostly inside the Be^8 ground-state kinematic line and (2) that corresponding to the broad B^9 2.7-MeV level which is in the neighborhood of alpha-particle channel $y=65$ and which appears to lie mostly on the curving Be^8 ground-state kinematic line.