Gamma-Ray Studies in Boron-10

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Gamma rays emanating from the 7.56-Mev level of B^{10} were analyzed with a five-crystal pair spectrometer. Cascade gamma rays were investigated by recording the spectra in coincidence with the 2.40, 0.72, 2.15, and 5.41-Mev gamma-ray transitions. The branching ratios for the decay of the 7.56-Mev level were found to be 76%, 9%, and 15% for 6.84, 5.41, and 2.40-Mev gamma rays, respectively. For the 2.15-Mev level, the respective branching ratios for 2.15, 1.43, and 0.41-Mev gamma rays were shown to be 16%, 29%, and 55%. The partial width for the 3.01-Mev transition was found to be less than 1% of the total width of the 5.16-Mev state in B^{10}. Combining this result with the data of Meyer-Schützmeister and Hanna, the gamma-ray width of the 5.16-Mev level was found to be 0.51 ev and the alpha width $32<\Gamma_\alpha<500$ ev. Although the upper limit for the alpha width of the 5.16-Mev level is quite small, this result is shown to be consistent with the alpha transition being isotopic spin allowed. The conflict between our result $\Gamma_{\gamma 3.01}/\Gamma<0.01$ and other evidence requiring larger relative partial gamma-ray widths may be resolved if the 5.16-Mev state in B^{10} is assumed to be a doublet.

INTRODUCTION

SEVERAL investigators[1–5] have made suggestions as to which of the levels in B^{10} at about 5.1 Mev is the isotopic spin analog of the spin 2^+ levels at 3.37 Mev in Be^{10} and 3.34 Mev in C^{10}. Recent evidence indicates that neither of the most likely states at 5.16 and 5.11 Mev (Fig. 1) has the required $J^\pi=2^+$, $T=1$ assignment. The 5.16-Mev level has been shown[4] to have $J^\pi=1^+$, while the large width of the 5.11-Mev level indicates $T=0$ for that state.[6] The 4.77-Mev state is believed to have the required 2^+ spin assignment,[6] but the energy displacement from the analogous mirror states in Be^{10} and C^{10} would appear to be exceptionally large. The present work investigates further the 5.16-Mev level by measuring the gamma-ray spectrum in coincidence with the 2.40-Mev gamma rays cascading from the 7.56-Mev level to feed the 5.16-Mev state.

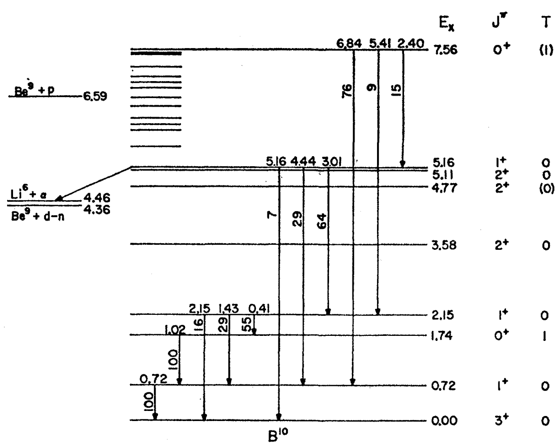

FIG. 1. Decay of the 7.56-Mev state in B^{10}. Pertinent levels are extended to the right and identified by the excitation energy E_x, total angular momentum J, parity π, and isotopic spin T (figures in parenthesis are least certain). Vertical lines indicate gamma-ray transitions; the number above the line refers to the energy (Mev) and the number to the left refers to the branching (%). The branching ratios for the 7.56- and 2.15-Mev levels are taken from our results, as is also the isotopic spin of the 5.16-Mev level. The J^+ assignments of the 7.56- and 5.16-Mev levels were taken from reference 4 and for the 4.77-Mev level from reference 1. All other information is taken from Ajzenberg-Selove and Lauritsen.[6,6a]

In order to conserve isotopic spin, states of B^{10} below 8.02 Mev with large alpha particle widths would be expected to have $T=0$, since $T=0$ for both alpha particles and the residual nucleus Li^6. Conversely, a low-lying state of B^{10} with excitation energy above 4.5 Mev that has a small alpha particle width would be expected to have an isotopic spin, $T=1$ (except for 0^+ states for which alpha decay would be parity forbidden). Meyer-Schützmeister and Hanna[1] investigating $Li^6(\alpha,\gamma)B^{10}$ reactions found, for the 5.16-Mev level of B^{10}, that $\omega\Gamma_\alpha\Gamma_\gamma/(\Gamma_\alpha+\Gamma_\gamma)=0.32$ ev (c.m.) for the predominant 3.01-Mev transition to the 2.15-Mev level. In the present work 2.40–3.01 Mev coincidences provide a measurement of $\Gamma_\gamma/(\Gamma_\alpha+\Gamma_\gamma)$ so that the alpha- and gamma-ray widths of the 5.16-Mev level may be obtained from a combination of the two width ratios. Since the mirror states of Be^{10} and C^{10} are both $T=1$, a large alpha-particle width for the 5.16-Mev state of B^{10} would provide further definitive evidence that this state is not the mirror analog, whereas a small alpha-particle width would indicate either that the 1^+ spin assignment is in error or that the configuration of the state is such that alpha-particle emission is inhibited.

EXPERIMENTAL PROCEDURE AND RESULTS

A thin target of beryllium mounted on a tantalum backing was bombarded with protons from the Aeronautical Research Laboratory Van de Graaff. The excitation function (Fig. 2) shows a sharp peak corre-

[1] L. Meyer-Schützmeister and S. S. Hanna, Phys. Rev. **108**, 1506 (1957).
[2] W. E. Meyerhof and L. F. Chase, Phys. Rev. **111**, 1348 (1958).
[3] W. F. Meyerhof, N. W. Tanner, and C. M. Hudson, Phys. Rev. **115**, 1227 (1959).
[4] N. W. Tanner and S. S. Hanna, Nuclear Phys. **23**, 319 (1961).
[5] E. K. Warburton, Phys. Rev. **113**, 595 (1959).
[6] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).
[6a] *Note added in proof.* A doublet has indeed been recently identified at 5.16 Mev. (See footnote 12a).

sponding to the 1.08-Mev proton resonance ($\Gamma_{lab}=3.8$ kev). The observed 8.5-kev half-width of the resonance results primarily from the target thickness and the energy spread of the proton beam. A pair spectrometer spectrum taken on resonance (Fig. 3) shows peaks corresponding to resonant 2.40, 5.41, and 6.84-Mev gamma rays emanating from the 7.56-Mev level and the nonresonant ground-state transitions from the states centered at 7.48 and 7.78 Mev. At 10 kev above and below the 1.08-Mev proton resonance the resonant gamma rays were about a factor of 3 lower in intensity, whereas the intensity of the nonresonant ground-state transition remained the same.

The five-crystal pair spectrometer was composed of a central cylindrical NaI(Tl) crystal $1\frac{1}{2}$ in. in diameter and 4 in. long surrounded by four *C*-shaped crystals which formed a 4-in. long annular ring of outside diameter 8 in. Coincident pulses were required from the central crystal and from the 0.511-Mev channels of any two side crystals. Coincident events including pulses from more than two side crystals were not recorded. The

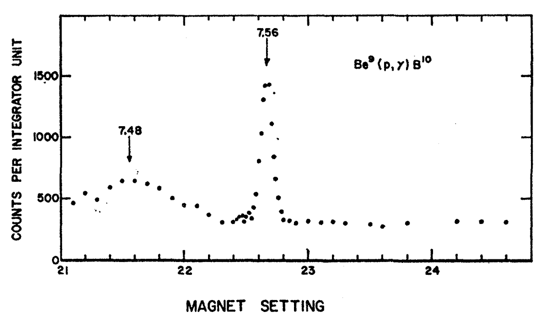

FIG. 2. Yield curve for 0.72-Mev gamma rays. The excitation energies (Mev) for states in B^{10} are indicated.

energy calibration of the pair spectrometer was made with the ThC″ gamma ray and the resonant 6.84-Mev gamma ray of B^{10}. The fraction of events not recorded in a peak corresponding to gamma-ray energy E Mev, because of the escape of either bremsstrahlung or the negatron member of an electron pair, was taken as $0.066(E-1.02)$, estimated from other pair spectrometer measurements. The relative areas for the peaks corresponding to 6.84, 2.40, and 5.41-Mev gamma rays, when corrected for bremsstrahlung and negatron escape, yielded branching ratios of 76%, 15%, and 9%, respectively, for the gamma-ray decay of the 7.56-Mev state. These branching ratios may be compared, respectively, with the results of Meyerhof, Tanner, and Hudson[3]: 81%, 19%, and <6%, and the results of Hornyak and Coor[7]: 87%, 13%, and <4%.

The scintillation pair spectrometer spectrum (Fig. 3) shows no peak corresponding to the 3.01-Mev transition, for which the branching ratio from the 5.16-Mev level is 64%. The intensity of the 2.40-Mev transition feeding

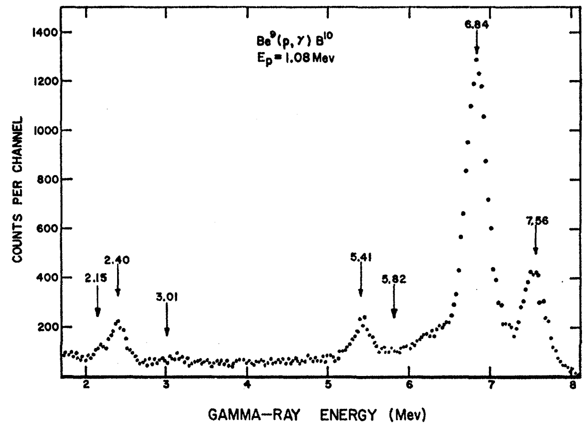

FIG. 3. Five-crystal pair spectrometer spectrum for a thin beryllium target. The spectrometer is described in the text.

the 5.16-Mev level indicates that this level must decay almost exclusively by alpha emission. The peak corresponding to the 2.40-Mev transition is broadened on the low-energy side by 2.15-Mev transitions. Since there is no evidence for 3.01-Mev transitions, the 2.15-Mev gamma ray must be a member of the 5.41–2.15 Mev cascade rather than the 2.40–3.01–2.15 Mev cascade. The 2.40-Mev peak appears to be somewhat broadened on the high energy side also, as the full width at half-maximum for the 2.61-Mev ThC″ gamma ray was only 6 channels. Thus a weak transition from the 7.56-Mev level to the 5.11-Mev level is not excluded by our results. Decay of the 7.56-Mev level, through gamma rays in the energy range of 5 to 6 Mev, is shown to be entirely through the 5.41-Mev transition to the 2.15-Mev level. Absence of 5.82-Mev transitions to the 1.74-Mev 0^+ level supports the 0^+ assignment of Tanner and Hanna[4] to the 7.56-Mev level. The only evidence conflicting with the 0^+ assignment of the 7.56-Mev level was the suggested existence of a 5.82-Mev transition by Meyerhof, Tanner, and Hudson[3] to explain the intensity of 1.02-Mev gamma rays that they observed. In order to balance the intensity of secondary gamma rays, they estimated that the intensity of the suggested 5.82-Mev transition was approximately equal to the intensity of the 5.41-Mev transition. Reference to Fig. 3 indicates that this objection to the 0^+ assignment of the 7.56-Mev level has now been removed.

For the coincidence measurements, two NaI(Tl) crystals 5 in. in diameter and 5 in. long were positioned at a distance of 4 in. from the target at 0° and 90° with respect to the beam. Coincidences produced by crystal-to-crystal scattering were suppressed by insertion of a lead wedge between the crystals. The pulses from the photomultiplier tubes were amplified and fed into a fast-slow coincidence circuit which gated a 256-channel analyzer. The singles spectrum obtained on resonance with the 0° crystal is shown in Fig. 4. The singles spectrum taken with the 90° crystal was similar. Figures

[7] W. F. Hornyak and T. Coor, Phys. Rev. 92, 678 (1953).

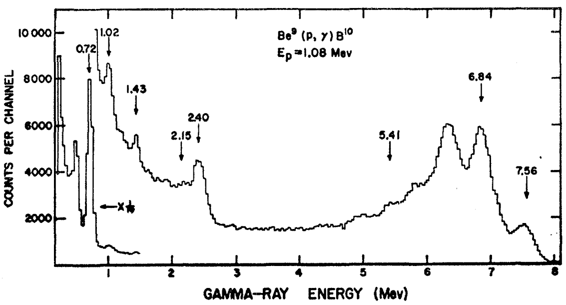

FIG. 4. Gamma-ray singles spectrum for 5-in. diam×5-in. long NaI(Tl) detector at 0° with respect to the proton beam.

5–8 show the spectra in coincidence with the 5.41, 2.15, 0.72, and 2.40-Mev gamma rays, respectively. The contributions of accidental coincidences to the total number of coincidences measured were respectively 1.6%, 3.8%, 0.73%, and 5.4% and therefore negligible. The widths of the fixed channels centered on the 2.15, 0.72, and 2.40-Mev gamma rays, detected in the 90° crystal, were 250, 75, and 210 kev, respectively. The width of the fixed-channel recording 5.41-Mev gamma rays extended from 3.3 to 6.1 Mev.

The spectrum in coincidence with 5.41-Mev gamma rays (Fig. 5) provided branching ratios for the 2.15-Mev level. The photofractions and detection efficiencies were derived from graphs interpolated from the tables of Miller *et al.*[8] Interpolation of the detection efficiencies for a source distance of 4 in. was aided by recording the spectra of a ThC″ source at distances of 0, 4, and 6 in. from the crystal. The areas of the 2.15, 1.43, and 1.02-Mev peaks, corrected for addition with their respective cascade members and the crystal peak efficiencies discussed above, provided branching ratios of 16%, 29%, and 55% for 2.15, 1.43, and 0.41-Mev gamma rays, respectively. The intensity of 0.41- and 0.72-Mev gamma rays indicated that the contribution to the 1.02-Mev peak by annihilation radiation summing was very small. Our results (Fig. 5) are in good agreement with the results of Shafroth and Hanna[9] (their lower curve, Fig. 5) obtained in a similar experiment using 1.5-in. diam×2-in. long crystals.

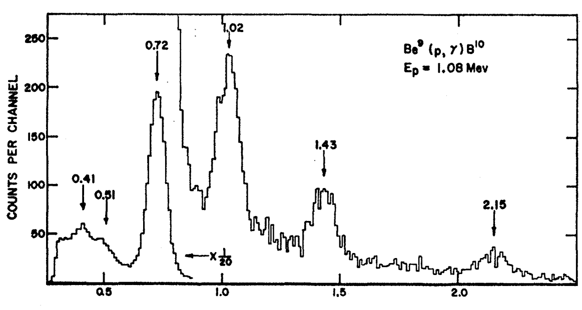

FIG. 5. Gamma-ray spectrum in coincidence with 5.41-Mev transitions. The fixed channel extended from 3.3 to 6.1 Mev and thus included pulses resulting from Compton scattering of 6.84-Mev gamma rays.

The ratio for the decay of the 7.56-Mev state through 5.41-Mev transitions relative to the decay through 6.84-Mev transitions was determined from a comparison of 5.41–2.15 Mev gamma-ray coincidences (Fig. 6) and 6.84–0.72 Mev gamma-ray coincidences (Fig. 7) normalized to equal monitor counting rates. For the crystal peak efficiency of the 6.84-Mev gamma rays the experimentally determined value 0.0072 was used, and for all other gamma rays the crystal peak efficiencies were interpolated from the tables of Miller *et al.*[8] The branching ratio for 2.15-Mev gamma rays decaying from the 2.15-Mev level was taken as 16%, derived from the spectrum in coincidence with 5.41-Mev gamma rays (Fig. 5). The ratio of 5.41-Mev transitions relative to 6.84-Mev transitions was thus found to be 11% in good agreement with the value 12% derived from the pair spectrometer measurement.

The crystal peak efficiency for 6.84-Mev gamma rays was determined by measuring the number of 6.84-Mev events in coincidence with 0.72-Mev gamma rays (corrected for the angular correlation[4]) relative to the number of 0.72-Mev gamma rays recorded in the fixed channel (corrected for the fraction of 0.72-Mev gamma rays not in coincidence with the 6.84-Mev transition). The number of coincident 6.84-Mev transitions was 1.1×10^4 (Fig. 7), and the number of 0.72-Mev transitions recorded in the fixed channel was 1.5×10^6. The crystal peak efficiency for 6.84-Mev gamma rays in the geometry used was therefore found to be 0.0072. The photofraction for 6.84-Mev gamma rays (Fig. 7) was estimated to be 0.17 and thus the detection efficiency found to be 0.042. Since the detection efficiency remains essentially constant above 2.5 Mev for the particular experimental arrangement used,[8] the detection efficiency for gamma rays in the range 2.5 to 6.8 Mev was taken as 0.042. For comparison, the value obtained from the tables of Miller, Reynolds, and Snow[8] and adjusted according to our distance relation above was 0.034, the values agreeing within 20%.

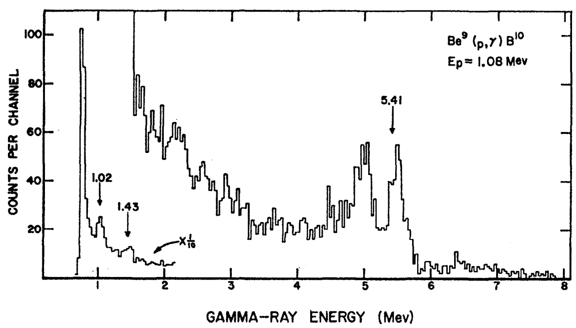

FIG. 6. Spectrum in coincidence with 2.15-Mev gamma rays.

[8] W. F. Miller, J. Reynolds, and W. J. Snow, Argonne National Laboratory Report ANL-5902, 1958 (unpublished).

[9] S. M. Shafroth and S. S. Hanna, Phys. Rev. **95**, 86 (1954).

The spectrum obtained with the fixed channel centered on 2.40-Mev gamma rays (Fig. 8) shows only peaks corresponding to the 1.02-, 1.43-, and 2.15-Mev transitions. There is no evidence for peaks corresponding to the 3.01, 4.44, and 5.16-Mev transitions (respective branching ratios 64%, 29%, and 7%) emanating directly from the 5.16-Mev level. Thus the peaks at 1.02, 1.43, and 2.15 Mev must result from coincidences with electrons, Compton scattered by the 5.41-Mev gamma rays, which appear in the 2.40-Mev fixed channel. About 40% of the events in the 2.40-Mev fixed channel were found to be contributed by Compton scattered 6.84- and 5.41-Mev gamma rays and background radiation.

In the present experiment the 5.16-Mev level of B^{10} was fed entirely by 2.40-Mev transitions from the 7.56-Mev level. The fraction of the number of decays of the 5.16-Mev level which yield 3.01-Mev gamma rays, $\Gamma_{\gamma 3.01}/(\Gamma_\alpha+\Gamma_\gamma)$, may be deduced from the number of 3.01-Mev transitions in coincidence with 2.40-Mev gamma-ray transitions (corrected for solid angle and detection efficiency) relative to the number of 2.40-Mev transitions recorded in the fixed channel. The number of coincident 3.01-Mev transitions was estimated to be <150. In the fixed channel were recorded 9.9×10^5 events corresponding to 2.40-Mev transitions. The efficiency for detecting 3.01 Mev gamma rays with a 5-in. diam$\times$5-in. long crystal at a distance of 4 in. from the source was shown above to be about 0.042. The photofraction for 3.01-Mev gamma rays detected under the conditions mentioned was 0.36, interpolated from the tables of Miller, Reynolds, and Snow.[8] Combination of the above values leads to an upper limit of <0.01 for the relative partial width of the 3.01-Mev transition from the 5.16-Mev state.

DISCUSSION

The alpha and gamma-ray widths of the 5.16-Mev level were calculated from the measured relative partial width for the 3.01-Mev transition and $\omega\Gamma_\alpha\Gamma_{\gamma 3.01}/(\Gamma_\alpha+\Gamma_\gamma)=0.32$ ev, determined by Meyer-Schützmeister and Hanna.[1] The factor ω is equal to $(2J+1)(2j_t+1)^{-1}\times(2j_\alpha+1)^{-1}$ where the spins J, j_t, and j_α refer to the capturing state, the target nucleus, and the captured particle, respectively.[2] In the reaction $Li^6(\alpha,\gamma)B^{10}$ studied

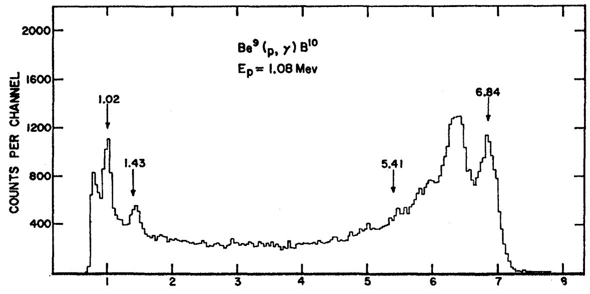

FIG. 7. Spectrum in coincidence with 0.72-Mev gamma rays.

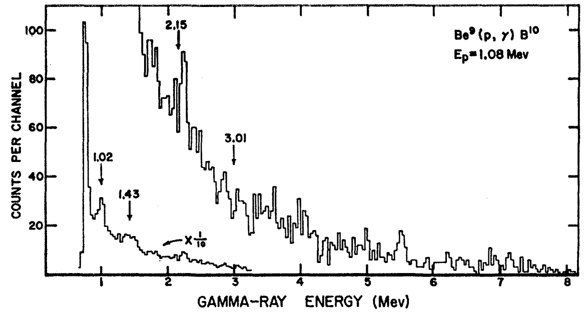

FIG. 8. Spectrum in coincidence with 2.40-Mev gamma rays.

by Meyer-Schützmeister and Hanna,[1] the respective spins are 1, 1, and 0 for the Li^6 nucleus, the 5.16-Mev state of B^{10}, and the captured alpha particle. Thus the alpha-particle width of the 5.16-Mev level is >32 ev and the total gamma-ray width is 0.51 ev. Hanna has reported[2] that the intrinsic c.m. width of the 5.16-Mev level of B^{10} can be shown to be less than 500 ev. This places the limits for the width of the 5.16-Mev state as $32.5<\Gamma<500$ ev.

The partial reduced alpha width γ_α^2 is related to the observed partial width Γ_α (c.m.) by the following expression: $\Gamma_\alpha=2k_\alpha A_l^{-2}\gamma_\alpha^2$, where k_α is the c.m. wave number of the alpha particle and the penetrability A_l^{-2} for a given relative angular momentum l is the reciprocal of $F_l^2(\rho)+G_l^2(\rho)$, the sum of the regular and irregular Coulomb wave functions, provided by the graphs of Sharp, Gove, and Paul.[10] The dimensionless partial reduced alpha width θ_α^2 is given by: $\gamma_\alpha^2=\theta_\alpha^2 3\hbar^2/2Ma$, where M is the reduced mass of the $Li^6+\alpha$ system and a is the interaction radius $1.45(A_t^{\frac{1}{3}}+A_\alpha^{\frac{1}{3}})\times 10^{-13}$ cm calculated from the mass numbers (A) of the target nucleus and alpha particle.

For the formation of a 1^+ B^{10} level from $Li^6+\alpha$, the relative angular momentum of the alpha particle may be $l=0$ or 2. Meyer-Schützmeister and Hanna[1] have shown that the angular distributions of gamma rays from the 5.16-Mev level require the relative intensity of d to s-wave alpha capture to be: $I_\alpha(2)/I_\alpha(0)\simeq 1.5$ for a 1^+ spin assignment. For $l=0$ and $l=2$, we therefore find the limits for the dimensionless reduced alpha widths to be

$$8.5\times 10^{-5}<(\theta_\alpha^2)_{l=0}<1.3\times 10^{-3},$$
$$2.2\times 10^{-3}<(\theta_\alpha^2)_{l=2}<3.5\times 10^{-2}.$$

The s-wave capture is seen to be greatly inhibited with respect to d-wave interaction in accord with $I_\alpha(2)/I_\alpha(0)\simeq 1.5$ being much greater than the expected value of about 0.06.

From a survey of the dimensionless reduced widths for isotopic-spin-allowed alpha transitions in light nuclei ($A\leqslant 20$), Wilkinson[11] found that θ_α^2 ranged from 10^{-3} to

[10] W. T. Sharp, H. E. Gove, and E. B. Paul, Chalk River Laboratory Report AECL-268, 1955 (unpublished).

[11] D. H. Wilkinson, *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), Session IV, p. 175.

1 with the distribution centered at 5×10^{-2}. For an isotopic-spin-forbidden alpha transition from a $J^{\pi}=1^+$, $T=1$ state at a distance of 1 Mev from an interfering $J^{\pi}=1^+$, $T=0$ level, the most probable value of θ_α^2 would be 5×10^{-4} with a range of values from about $2\times10^{-5} < \theta_\alpha^2 < 2\times10^{-2}$.

The nearest interfering 1^+ level below the 5.16-Mev state is separated by 3 Mev, but within 3 Mev above the state are nine levels for which there are as yet no spin assignments.[6] A separation of 1 Mev from contaminating levels was chosen as a reasonable estimate, although this region contains the 5.58-Mev level for which neither the spin nor decay scheme are known. Since the value of θ_α^2 for isotopic-spin-forbidden transitions depends upon the inverse square of the separation distance from contaminating levels, the values of θ_α^2 stated above would have to be lowered by an order of magnitude if the separation distance were established to be as large as 3 Mev.

A comparison of the limits of the dimensionless reduced width for the $l=2$ component $(\theta_\alpha^2)_{l=2}$ with the ranges of values acceptable for isotopic spin allowed and forbidden transitions makes it impossible to provide a definite isotopic spin assignment to the 5.16-Mev level. However, the range of $(\theta_\alpha^2)_{l=2}$ values does agree somewhat better with the range of values found for isotopic-spin-allowed transitions in light nuclei than with the values calculated for isotopic-spin-forbidden transitions. It is probable therefore that the narrow width (<500 ev) of the 5.16-Mev state results from an inhibition of *s*-wave alpha capture (and emission) rather than participation in a transition which does not conserve isotopic spin. The $J^{\pi}=1^+$, $T=0$ assignment of the 5.16-Mev level would certainly be preferable to a $J^{\pi}=1^+$, $T=1$ assignment as the latter designation cannot be reconciled with the $T=1$ system of levels in the mirror nuclei Be^{10} and C^{10}.

Meyerhof, Tanner, and Hudson[3] studied $Be^9(p,\gamma)B^{10}$ reactions for B^{10} excitation energies of 6.95 and 7.16 Mev. From the spectra in coincidence with capture gamma rays to the 5.16-Mev level they concluded that "the 3.0-Mev coincident gamma ray has an intensity such that some finite fraction (within a factor of five of $\frac{1}{10}$) of the 5.16-Mev level decays by gamma transition." Their estimated lower limit of 0.02 for the relative partial width for 3.01-Mev gamma-ray decay from the 5.16-Mev level may be compared with our upper limit of <0.01. Further evidence in contradiction to our results is provided by Meyerhof and Chase[2] in a scintillation pair spectrometer spectrum of gamma rays emitted from the interaction of 2.8-Mev deuterons with a thick beryllium target. The 4.44-Mev gamma-ray transition from the 5.16-Mev level is apparent and the 3.01-Mev transition was unraveled from the spectrum. In a preliminary investigation of the $Be^9(d,n)B^{10}$ reaction, Warburton and Chase[12] report a neutron threshold, but no gamma-ray threshold, for the 5.11-Mev level and both a neutron and a gamma-ray threshold for the 5.16-Mev level with $\Gamma_\gamma > 0.04\Gamma$ for the latter level.

The apparent contradiction of our results with the results from the three experiments noted above may be resolved by postulating the existence of a doublet state in B^{10} at 5.16 Mev. The state observed in the other three experiments, and possibly in the $Li^6(\alpha,\gamma)B^{10}$ experiment of Meyer-Schützmeister and Hanna,[1] would then be the state *not* observed in the present experiment. In the two coincidence measurements of Meyerhof, Tanner, and Hudson[3] with B^{10} excitation energies at 400 and 421 kev below the narrow 7.56-Mev resonance ($\Gamma_{lab}=3.8$ kev), the capture gamma rays were most likely emanating from the 6.88-Mev level ($\Gamma_{lab}=160$ kev) and thus the other member of the 5.16-Mev doublet could have been populated. This same doublet level could also be the one populated in the (d,n) reactions. The evidence is certainly not definitive, but the existence of a doublet state at a B^{10} excitation energy of 5.16 Mev is most attractive.[12a]

In the case of the existence of a doublet state at 5.16 Mev, the state seen in the present research would then have spin 1 with odd or even parity and most likely isotopic spin $T=0$. The other member of the doublet would partially decay by 3.01- and 4.44-Mev gamma-ray transitions and would hopefully be a 2^+ state with isotopic spin $T=1$. It is impossible at the present time to tell to what extent the gamma-ray decay scheme for the 5.16-Mev level shown in Fig. 1 would be representative of the individual doublet states or whether the decay scheme corresponds to only one of the doublet states. Since our calculations for the alpha and gamma-ray widths of the 5.16-Mev level were based on the data of Meyer-Schützmeister and Hanna,[1] the calculations would be invalidated if the two experiments were performed with different members of a doublet state. In this event the only information provided by the present research would be that $\Gamma_\gamma < 0.01\Gamma$ for the spin 1, odd or even parity, member of the 5.16-Mev doublet state.[12a]

There are several inconsistencies with the $J^{\pi}=1^+$ assignment of the 5.16-Mev level (Fig. 1). On the basis of stripping theory, Ajzenberg[13] has shown from the analysis of angular distributions in the reaction $Be^9(d,n)B^{10}$ that one or both of the 5.1-Mev levels should have $J^{\pi}=1^-$ or 2^-. On the other hand, from the analysis of angular distributions in the reaction $Li^6(\alpha,\gamma)B^{10}$,

[12] E. K. Warburton and L. F. Chase (to be published).

[12a] *Note added in proof.* A broad state ($\Gamma_{c.m.}=200$ kev) has recently been reported at 5.18 Mev in B^{10} by Sprenkel, Olness, and Segel [Phys. Rev. Letters **5**, 174 (1961)]. The 7.56-Mev level in B^{10} decays by 2.38-Mev gamma rays to feed the $J=1$, $T=0$ broad level centered at 5.18 Mev, leaving the previously known narrow 5.16-Mev level for the long sought $J^{\pi}=2^+$, $T=1$ state. These assignments allow reconciliation of all conflicting results from the previous experiments described above. The newly found state centered at 5.18 Mev in B^{10} decays predominantly by 3.44-Mev gamma rays to the $J^{\pi}=0^+$, $T=1$ state at 1.74 Mev. For the 5.18-Mev state, E. L. Sprenkel, J. W. Olness, and R. E. Segel have reported $\Gamma_\gamma/\Gamma=3\times10^{-7}$, which value is in agreement with the upper limit $\Gamma_\gamma/\Gamma<10^{-2}$ reported in the present paper.

[13] F. Ajzenberg, Phys. Rev. **88**, 298 (1952).

Meyer-Schützmeister and Hanna[1] have shown that neither of these assignments are possible for the 5.11-Mev level. For the 5.16-Mev level the 1^- assignment is possible, but since this would make the ground-state transition $M2$, the assignment is unlikely.[1] For a 2^- assignment, good agreement is achieved for the angular distributions of gamma rays to excited states, but only fair agreement for the transition to the ground state. Meyer-Schützmeister and Hanna[1] consider a 2^- assignment to the 5.16-Mev level unlikely. In the B^{10} level diagram (Fig. 1), both the 5.11- and 5.16-Mev levels are assigned positive parity, in disagreement with the angular distributions of the $Be^9(d,n)B^{10}$ reaction.

Another discrepancy with the $J^\pi=1^+$ assignment of the 5.16-Mev level is the apparent absence of transitions to the $J^\pi=0^+$, $T=1$, 1.74-Mev level in B^{10}. Although Meyer-Schützmeister and Hanna[1] do not quote an upper limit for the intensity of this 3.42-Mev gamma ray, a reasonable estimate may be taken as equivalent to the intensity of the weakest gamma ray from the 5.16-Mev level that they observed. We therefore conclude that $\Gamma_\gamma<0.04$ ev, or in Weisskopf units $|M|^2<0.05$, which would be a small (but permissable) value for an isotopic spin allowed $M1$ transition.[5] Conversely the 3.01-Mev gamma ray has a reduced width $|M|^2=0.6$, which would be a large value for an isotopic spin forbidden $M1$ transition.[5] For a $J^\pi=1^+$, $T=0$ assignment to the 5.16-Mev level, Morpurgo's rule[14] predicts that the reduced width for the 3.01-Mev transition should be about one hundred times smaller than for the 3.42-Mev transition, whereas in fact, the reduced width of the 3.01-Mev transition is an order of magnitude larger.

CONCLUSION

The objection to a 0^+ assignment of the 7.56-Mev state in B^{10}, because of the possible existence of a transition to the 0^+ 1.74-Mev level, has been removed by showing the absence of this transition. For the 5.16-Mev level, coincidence measurements showed that $\Gamma_\gamma<0.01\Gamma$. This result was shown to be consistent with the alpha transition being isotopic spin allowed. Apparent contradiction of our results with other evidence, as well as inconsistencies with the $J^\pi=1^+$ assignment of the 5.16-Mev level, may be explained by assuming the 5.16-Mev state to be a doublet.[12a]

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[14] G. Morpurgo, Phys. Rev. **110**, 721 (1958).