ACKNOWLEDGMENTS

The author is grateful to Professor Emilio Segrè for suggesting this experiment and supporting its execution. The author thanks Dr. Elmer Kelly for instructive discussion concerning his bismuth experiments.

Mr. Albert Ghiorso lent the use of the alpha pulse-height analyzer. Mr. Dan O'Connell of the Accelerator Technicians, University of California Radiation Laboratory, carried out the enriched-lead isotope evaporations. The enriched Pb^{206} and Pb^{207} were supplied by the Oak Ridge National Laboratory, the Pb^{208} by the nuclear chemistry group of the Radiation Laboratory. The high-purity natural lead and its spectroscopic analysis were supplied by Mr. George M. Gordon, U.C. Division of Mineral Technology. Dr. Hans Bichsel and Dr. R. F. Mozley kindly supplied their range-energy data for protons in aluminum. Dr. Ann Birge lent the use of some target apparatus. The 60-inch cyclotron staff gave efficient cooperation for the bombardments. Mr. George Merkel assisted with the bombardments.

PHYSICAL REVIEW VOLUME 103, NUMBER 3 AUGUST 1, 1956

Excited States in B^{10}†

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(Received April 23, 1956)

Energy levels in B^{10} have been investigated by observing the neutrons from the $Be^9(p,n)B^9$ reaction and the γ rays from the $Be^9(p,\alpha\gamma)Li^6$ reaction in the range of bombarding energy from 2 Mev to 5 Mev. At $E_p=2.562\pm0.006$ Mev both the neutrons and the γ rays are resonant. The width of the γ-ray peak is 38 ± 3 kev while the width of the neutron peak is 85 ± 10 kev. The results are analyzed in terms of two B^{10} states at 8.89 Mev which probably are the analogs to the 7.37- and 7.54-Mev states in Be^{10}. The neutron reduced widths for the B^{10} states are in good agreement with those for the Be^{10} states (which is to be expected on the basis of charge symmetry of nuclear forces) if the neutron and γ-ray resonances have $J=3^+$, $T=1$ and $J=2^+$, $T=1$, respectively. In addition, a broad resonance in the neutron yield at $\theta=90°$ near 3.2 Mev indicates a wide level ($\Gamma\approx0.7$ Mev) in B^{10} at 9.5 Mev. Angular distributions of the neutrons have been measured and total cross sections obtained at bombarding energies of 2.56, 2.92, 3.06, 3.56, and 4.56 Mev.

INTRODUCTION

THE proton bombardment of Be^9 at energies above 2 Mev has revealed several resonances in the yield of neutrons from the $Be^9(p,n)B^9$ reaction and of γ rays from the $Be^9(p,\alpha\gamma)Li^6$ reaction. Neutron resonances have been found at 2.56 Mev,[1–4] 4.70 Mev,[3,4] and 4.94 Mev[4]; a γ-ray resonance has been observed at 2.565 Mev.[3,5–7] The width of the γ-ray resonance has been determined to be 39 ± 2 kev[5–7]; however, the 2.56-Mev neutron resonance is superposed on a rising background and, although it appears to be somewhat wider than the γ-ray resonance, an accurate determination of the width has not previously been made. It is the purpose of this investigation to obtain more information concerning the 2.56-Mev resonance and to study the nature of the rising background observed in the $Be^9(p,n)B^9$ reaction.

Gamma radiation from Be^9+p can arise either from proton capture (which is relatively weak) or from the $Be^9(p,\alpha)Li^{6*}(\gamma)Li^6$ reaction involving the 3.57-Mev level in Li^6. For bombarding energies below about 5 Mev no other reactions are expected to yield γ rays. The Li^6 state at 3.57 Mev[8] has $J=0^+$, $T=1$; therefore only B^{10} states with parity $\pi=(-)^J$ and isotopic spin[9] $T=1$ can give rise to this α-particle group and the corresponding γ ray. There are no isotopic spin restrictions on the $Be^9(p,n)B^9$ reaction; consequently, neutrons can be emitted from B^{10} states which have either $T=0$ or $T=1$ while γ rays can arise only from $T=1$ states.

The 8.89-Mev state in B^{10}, corresponding to the 2.56-Mev γ-ray resonance probably has[10] $J=2^+$, $T=1$. The $T=1$ character of this state has been confirmed by Malm and Inglis[6] and by Marion, Weber, and Davis[11]

† A portion of this work was done at the Rice Institute, Houston, Texas, and was supported in part by the U. S. Atomic Energy Commission; at the California Institute of Technology, the work was supported by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
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[8] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).
[9] The isotopic spin restriction is, of course, much less stringent because of the possibility of large isotopic spin impurities.
[10] R. J. Mackin, Jr., Phys. Rev. **94**, 648 (1954).
[11] Marion, Weber, and Davis (to be published).

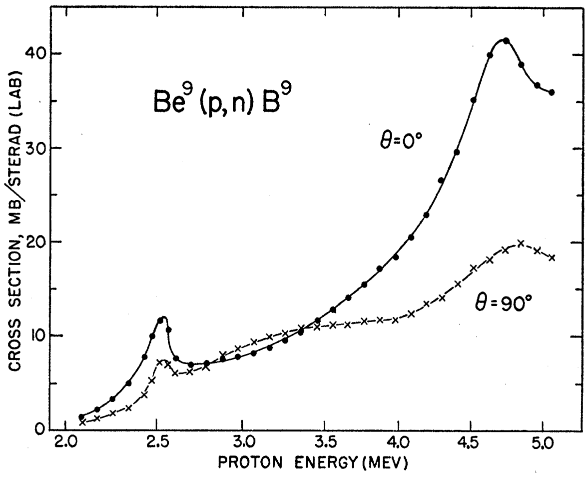

FIG. 1. Thin target excitation curves for the $Be^9(p,n)B^9$ reaction from 2 Mev to 5 Mev at laboratory angles of 0° and 90°.

who do not find a resonance at this energy for the ground-state deuterons from the $Be^9(p,d)Be^8$ reaction; this reaction, involving $T=0$ particles in the exit channel, should show only $T=0$ resonances. A weak resonance in the $Be^9(p,\alpha)Li^6$ (ground state) reaction has been found[11] at $E_p=2.56$ Mev with $\Gamma\cong 40$ kev, suggesting a small $T=0$ impurity either in the 8.89-Mev, $J=2^+$ state or in the Li^6 ground state. At this relatively high excitation, the energy levels are not expected to be isotopic-spin pure. This B^{10} state is probably the analog to the 7.54-Mev level in Be^{10} which is known[12,13] from neutron scattering experiments on Be^9 and has[12] $J=2$. A nearby state in Be^{10} at 7.37 Mev is known[13,14] to have $J=3^+$; the corresponding B^{10} level has not been detected previously.

EXPERIMENTAL PROCEDURE

The neutron detector used was a paraffin-moderated BF_3 counter, similar to that employed by Marion, Brugger, and Bonner.[15] The response of such a counter is not independent of the neutron energy but tends to have a higher efficiency for counting low-energy neutrons.[16] However, for neutron energies considered in this investigation, $E_n \lesssim 2.5$ Mev, the response does not vary strongly with energy, the difference in sensitivity being about 20% between neutron energies of 0.2 Mev and 2 Mev. No correction for counter sensitivity has been applied; consequently the cross section for the $Be^9(p,n)B^9$ reaction at bombarding energies near 4–5 Mev is probably too low by 15 to 20%. Since the counter sensitivity may be considered flat over a small range of neutron energy, the neutron angular distributions that were measured are probably correctly given although the cross sections in the backward hemisphere, where the neutron energy is low, may be high by a few percent. An absolute cross section for the $Be^9(p,n)B^9$ reaction was determined by comparing the yield from a weighed beryllium target with that from a weighed lithium target at bombarding energies such that the neutrons from both the $Be^9(p,n)$ and $Li^7(p,n)$ reactions had an energy of 0.4 Mev; the cross section for the $Li^7(p,n)Be^7$ reaction measured by Taschek and Hemmendinger[17] was then used to obtain a value for the $Be^9(p,n)B^9$ cross section.[4] The cross section for the $Be^9(p,n)B^9$ reaction is correct to within 15–20% at $E_p=2.5$ Mev.

The γ-ray detector was a NaI(Tl) crystal 1.5 in. in diameter and 1.5 in. in length. In order to reduce the counting rate due to neutrons, the counter was shielded with $\frac{1}{2}$ in. of lead and a $\frac{1}{32}$ in. sheet of cadmium; further shielding was provided by 2 in. of boron-loaded paraffin. Under these conditions the NaI(Tl) crystal was fairly well shielded from neutrons; no indication of the $Be^9(p,n)B^9$ threshold was observed in this counter. The crystal was biased so that only pulses in the energy range $2.7<E<5.2$ Mev were recorded, thus selecting the 3.6-Mev γ ray from Li^{6*}.

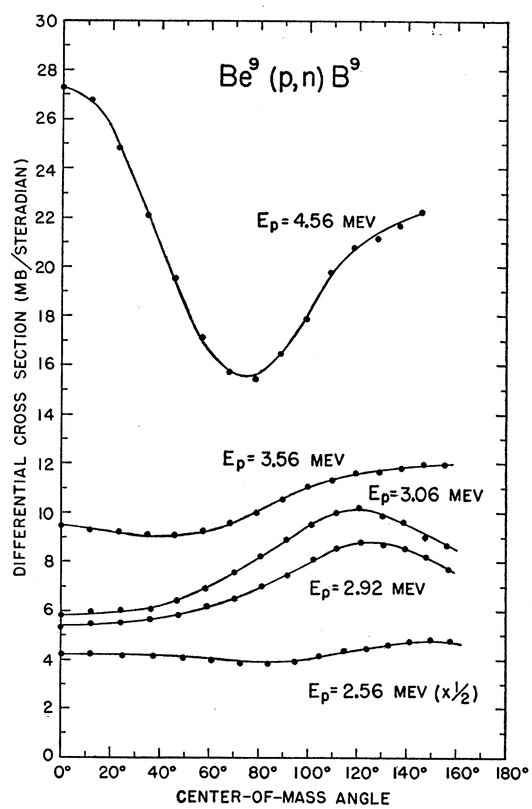

FIG. 2. Angular distributions of the neutrons from the $Be^9(p,n)B^9$ reaction at bombarding energies of 2.56, 2.92, 3.06, 3.56, and 4.56 Mev. The angular resolution was ±5°.

[12] Bockelman, Miller, Adair, and Barschall, Phys. Rev. 84, 69 (1951).
[13] Willard, Bair, and Kington, Phys. Rev. 98, 669 (1955).
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RESULTS

Excitation curves for the $Be^9(p,n)B^9$ reaction were measured for bombarding energies from 2 Mev to 5 Mev at laboratory angles of 0° and 90°. These results are shown in Fig. 1. The target was beryllium metal evaporated on to a tungsten backing and was approximately 5-kev thick to 2-Mev protons. The known resonances at $E_p=2.56$ and 4.7 Mev were observed at both angles. The 90° curve shows the latter peak shifted to 4.8 Mev. Insufficient data were obtained to show the 4.94-Mev resonance.[4] In addition to the two known resonances, the 90° curve shows a broad maximum centered about $E_p=3.2$ Mev with a width of about 0.7 Mev and corresponds to a B^{10} state at excitation of 9.5 Mev. The effect of this level is obscured in the forward direction by the relatively larger nonresonant background upon which the 2.56- and 4.7-Mev resonances are superposed.

Angular distributions of the neutrons were measured at bombarding energies of 2.56, 2.92, 3.06, 3.56, and 4.56 Mev. These data are shown in Fig. 2. The angular resolution was ±5°. The transformation from laboratory to center-of-mass coordinates was performed by using the tables of Marion and Ginzbarg.[18] The distribution at the 2.56-Mev resonance is almost isotropic but shows a weak increase in the forward direction and near 150°. At $E_p=2.92$, 3.06, and 3.56 Mev, the effect of the wide resonance is to produce a broad maximum in the distribution near 120°. As the 4.7-Mev resonance is approached, the forward and backward yields are strongly enhanced. Similar effects have been noted by the Wisconsin group.[19] The total cross sections obtained by integrating these angular distributions are given in Table I. The variation with energy of the total cross section also indicates the 3.2-Mev resonance.

In order to investigate more closely the region near $E_p=2.56$ Mev, the neutron yield at 0° and the γ-ray yield at 90° were measured simultaneously from $E_p=2.0$ to 2.9 Mev. These results are presented in Fig. 3. The angular resolution of the neutron counter was ±25° and that of the γ-ray detector was ±5°. The energy scale was calibrated by observing the $Be^9(p,n)B^9$ threshold at 2.059±0.002 Mev.[2] A pulse-height distribution in the NaI crystal taken at $E_p=2.56$ Mev showed that only the 3.6-Mev γ ray from the $Be^9(p,\alpha\gamma)Li^6$ reaction is produced with an appreciable intensity. The measured width of the γ-ray resonance

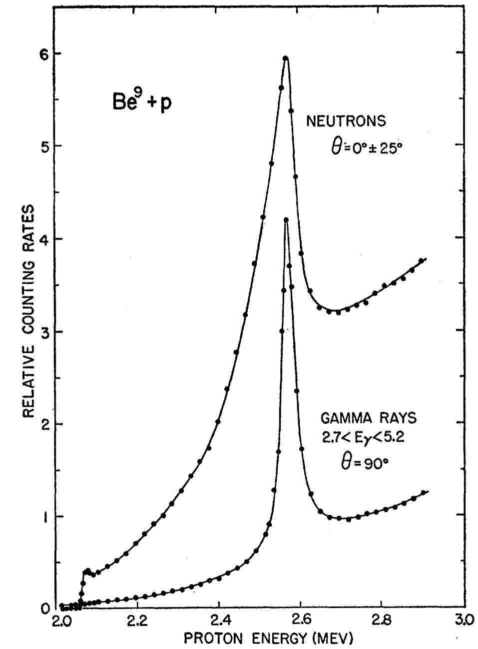

FIG. 3. Thin target excitation curve for the neutrons from the $Be^9(p,n)B^9$ reaction at 0°±25° and the γ rays from the $Be^9(p,\alpha\gamma)Li^6$ reaction at 90°±5°.

is 38±3 kev; the resonance energy is 2.562±0.004 Mev. Figure 3 shows that the width of the neutron resonance is considerably greater than that of the γ-ray peak. An accurate measurement of the width of the neutron resonance, however, must be obtained from the total cross section. Furthermore, interference effects between the resonance and the nonresonant background could influence the width. In order to investigate this latter point and to obtain data from which a total cross section could be constructed, excitation curves for the neutrons were measured at angles of 0°, 45°, 90°, and 120°, in each case with an angular resolution of ±25°. Interference effects do not seem to be appreciable since the shape of the resonance was approximately the same in the four curves. When these curves were transformed to angular distributions at each bombarding energy and converted to the center-of-mass coordinate system, the distributions did not differ strongly from isotropy. Consequently, a total cross-section curve could be constructed; the points obtained are shown in Fig. 4. The absolute cross-section scale was obtained by normalizing the 2.56-Mev peak to 101 mb (see Table I). The dashed curve in Fig. 4 represents the background assumed in order to analyze the resonance. The solid curve is that obtained when the background is added to a single-level resonance curve with the parameters $\Gamma=85\pm10$ kev, $\sigma_R=45\pm15$ mb, and $E_R=2.562\pm0.006$ Mev. Most of the uncertainty results from the impossibility of obtaining a unique determination of the background. It is clear that the experimental data are

TABLE I. Total cross section for the $Be^9(p,n)B^9$ reaction.

E_p (Mev)	2.56	2.92	3.06	3.56	4.56
σ (mb)	101	90	103	126	241

[18] J. B. Marion and A. S. Ginzbarg, *Table for the Transformation of Angular Distribution Data from the Laboratory System to the Center of Mass System* (Shell Development Company, Houston, 1955).

[19] Richards, Laubenstein, Johnson, Ajzenberg, and Browne, Phys. Rev. **81**, 316(A) (1951).

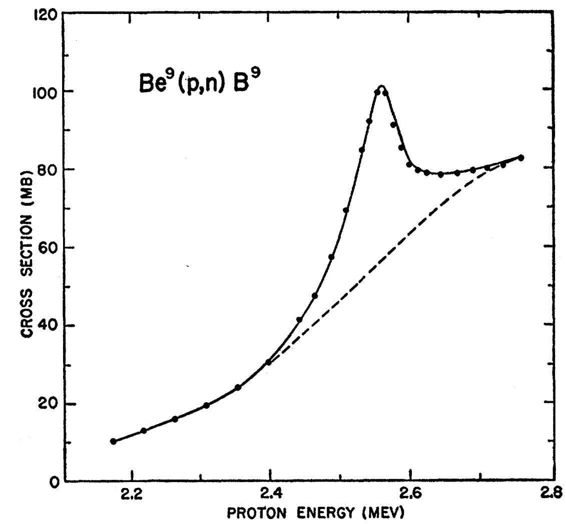

FIG. 4. Total cross section for the $Be^9(p,n)B^9$ reaction. The experimental points were obtained from excitation curves taken at angles of 0°, 45°, 90°, and 120°. The dashed curve represents the assumed background. The solid curve is the sum of the background and a single-level resonance curve, the parameters for which are given in the text.

well represented by assuming only one resonance with a width about twice that of the γ-ray resonance.

DISCUSSION

In the vicinity of $E_p=2.6$ Mev, the γ-ray yield above background from the $Be^9(p,\alpha\gamma)Li^6$ can be accounted for in terms of a single resonance at $E_p=2.562\pm0.004$ Mev with $\Gamma=38\pm3$ kev; similarly, the neutron yield above the nonresonant background from the $Be^9(p,n)B^9$ reaction can be explained on the basis of a single resonance at $E_p=2.562\pm0.006$ Mev with $\Gamma=85\pm10$ kev. Clearly then, at least two B^{10} states are involved which are energy-degenerate (to within a few kev). The following analysis will be based on the assumption of two states, one of which is observed in the $Be^9(p,n)B^9$ reaction and the other in the $Be^9(p,\alpha\gamma)Li^6$ reaction. The partial width of the narrow resonance for α-emission to the ground state of Li^6 has been neglected in comparison with the other partial widths.[11] Mackin[10] has analyzed the γ-ray resonance and finds that the corresponding B^{10} state at 8.89 Mev has $J=2^+$, $T=1$. The analysis assumes the equality of the neutron and proton reduced widths, which is to be expected on the basis of charge symmetry of nuclear forces, since neutron and proton emission from this state form mirror levels. The $J=2^+$ assignment gives for the neutron (or proton) dimensionless reduced width, $\theta_n^2=\gamma_n^2(2Ma/3\hbar^2)=\theta_p^2=0.0053$ or 0.0016, where $a=1.45(A^{\frac{1}{3}}+1)\times10^{-13}$ cm. When one uses these values, the corresponding total resonant cross sections for the $Be^9(p,n)B^9$ reaction would be 21 mb or 1.9 mb, respectively. Since a cross section as large as 21 mb should be readily observable, and no corresponding narrow resonance was found, the value $\theta_n^2=0.0053$ is ruled out. A cross section of only 1.9 mb, however, would not appreciably influence the shape of the $Be^9(p,n)B^9$ excitation curve since the 2.56-Mev neutron resonance has $\Gamma=85$ kev and $\sigma_R=45$ mb.

The $J=2^+$, $T=1$ state in B^{10} at 8.89 Mev probably corresponds to the $J=2$ state at 7.54 Mev [12,13] in Be^{10}. The width of this Be^{10} state is 8 kev[13] and therefore it has a reduced width $\theta_n^2=0.0034$.[20] The choice of $\theta_n^2=\theta_p^2=0.0016$ for the $J=2^+$ B^{10} state is consistent with this value since θ_n^2 for the Be^{10} state must be compared with $\theta_n^2+\theta_p^2=2\theta_n^2=0.0032$ for the B^{10} state.[21]

In the region of excitation near 7.5 Mev in Be^{10}, in addition to the $J=2$, 7.54-Mev state, there is a level at 7.37 Mev with $J=3^+$.[13,14] This fact suggests that the second state at 8.89 Mev in B^{10} is the analog to this state and has $J=3^+$, $T=1$. This J value would account for the absence of the effects of this state in the $Be^9(p,\alpha\gamma)Li^6$ reaction since the transition to this state would be spin-forbidden. Furthermore, the $T=1$ assignment would explain the absence of resonances in the $Be^9(p,\alpha)Li^6$ (ground state) and $Be^9(p,d)Be^8$ reactions at this energy.[6,11] (The weak resonance in the $Be^9(p,\alpha)Li^6$ reaction appears to correspond to the narrow, 2^+ state.[11]) Under the assumption of $J=3^+$ for the state giving rise to the 2.56-Mev resonance for the neutrons, and further assuming the equality of the neutron and proton reduced widths, these reduced widths were calculated to be $\theta_n^2=\theta_p^2=0.013$. For the corresponding Be^{10} state, $\Gamma=25$ kev,[13] and therefore $\theta_n^2=0.014$[22]; however, this must be compared with $\theta_n^2+\theta_p^2=2\theta_n^2=0.026\pm0.008$ for the B^{10} state.[23] The reduced widths of the Be^{10} and B^{10} states are compared in Table II. With the choice of $J=3^+$ and $J=2^+$ for the B^{10} states, there is good agreement between the corresponding 2^+ states and, in spite of the rather large error in $\theta_n^2+\theta_p^2$ for the 3^+ state in B^{10}, quite satisfactory agreement between the corresponding 3^+ states. It therefore seems reasonable to identify these states as analog $T=1$ states in the $Be^{10}-B^{10}-C^{10}$ triad. These are the only two cases thus far for which direct comparisons of experimentally

TABLE II. Reduced widths[a] of the 3^+ and 2^+ states in Be^{10} and B^{10}.

(Be^{10}) E* (Mev)	(Be^{10}) Γ(kev, lab)	θ_n^2 (c.m.)	J, π	E* (Mev)	(Be^{10}) Γ(kev, lab)	$\theta_n^2+\theta_p^2$ (c.m.)
7.37	25	0.014[b]	3^+	8.89	85 ± 10	0.026 ± 0.008[c]
7.54	8	0.0034[d]	2^+	8.89	38 ± 3	0.0032

[a] $\theta^2=\gamma^2(2Ma/3\hbar^2)$, with $a=1.45(A^{\frac{1}{3}}+1)\times10^{-13}$ cm. $(\theta_n^2+\theta_p^2)$ for B^{10} should equal θ_n^2 for Be^{10}; see reference 21.
[b] See reference 22.
[c] See reference 23.
[d] See reference 20.

[20] θ_n^2 was calculated under the assumption of a p-wave resonance and a $J=2^+$ state.

[21] R. K. Adair, Phys. Rev. **96**, 709 (1954).

[22] A value of 0.017 was obtained in reference 14 where a slightly different radius was used.

[23] The indicated uncertainty arises from the uncertainties in the width and cross section of the neutron resonance, due in part, to a lack of exact knowledge of the nonresonant background.

determined reduced widths have been possible for corresponding $T=1$ states. Figure 5 shows the currently known correspondences in the $A=10$ triad. Table III summarizes the data concerning B^{10} states known from Be^9+p for $E_p>2$ Mev. The B^{10} doublet at 10.8–11.07 Mev may correspond to the 9.27–9.4-Mev doublet in Be^{10}.

Recent results[24,25] on the elastic scattering of protons from Be^9 up to 3 Mev show a large anomaly with a peak near 2.56 Mev. The width appears to be about 100 kev, although a detailed analysis has not yet been made. The contribution from a state with $\Gamma=38$ kev (an exact value for which must await the analysis), appears to be small. This is to be expected since $(2J+1)\Gamma_p/\Gamma$ for the wide state is a factor of 35.6 larger than that for the narrow state and $(2J+1)\Gamma_p/\Gamma$ occurs as the first and second powers in the elastic scattering cross-section formula.

Kurath[26] has calculated on an intermediate coupling model the energies of the $T=0$ and $T=1$ states in B^{10} arising from excitations within the $1p$ shell. Other configurations [e.g., excitations from the $1p$ shell to the $(2s,1d)$ shell or from the $1s$ shell to the $(1d)$ shell, etc.] must certainly contribute in the energy region considered (up to about 10 Mev), since many more states have been observed than result from the calculations. One possible mechanism which could account for a 2^+-3^+ doublet is the excitation of one of the $1s$ nucleons into the $1d_{\frac{5}{2}}$ shell, giving the configuration $(1s_{\frac{1}{2}})^3(1p_{\frac{3}{2}})^6(1d_{\frac{5}{2}})^1$. Such a configuration would yield four states: $J=2^+$ and 3^+, $T=0$ and $J=2^+$ and 3^+, $T=1$. Calculations of the energies of these "hole" states have not yet been made, and consequently it is not yet possible to predict where they might occur.

TABLE III. Excited states in B^{10} from Be^9+p for $E_p>2$ Mev.

E_p (Mev)	Emitted particles	σ_R (mb)[a]	Γ (kev)	E^* (Mev)	J, π, T
$2.29\ \pm0.03$[b]	d_0		≈400	8.65	
2.562 ± 0.006	$n(\alpha_0)$	45	85 ± 10	8.89	(3, +, 1[c])
2.562 ± 0.004	$\alpha_2(n)$	110[d]	$38\pm\ 3$	8.89	2, +, 1
3.2	n		≈700	9.5	
4.7[e,f]	n		≈500	10.8	(+)
4.94 ± 0.03[e]	n		≈100	11.07	

[a] Cross section above background.
[b] See references 11 and 6.
[c] There may be a small $T=0$ impurity in this state; see reference 11.
[d] Cross section for the $Be^9(p,\alpha\gamma)Li^6$ reaction; see reference 5.
[e] See reference 4.
[f] See reference 3.

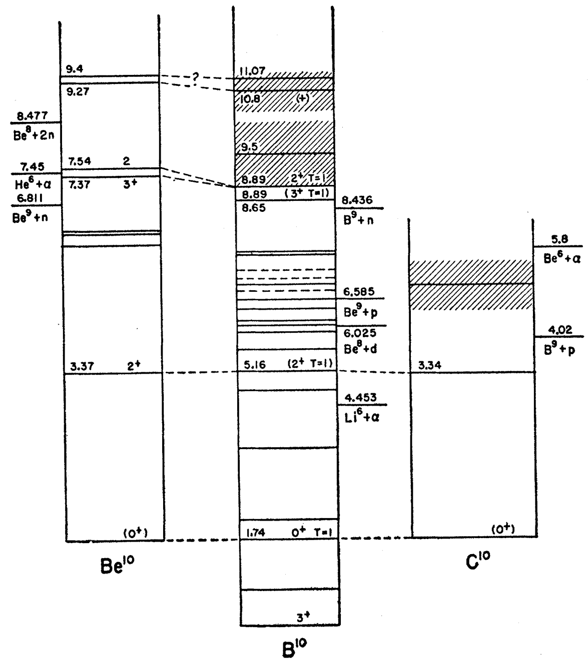

FIG. 5. Energy-level diagram for the $T=1$ triad $Be^{10}-B^{10}-C^{10}$. The excitation energies and J values are given for corresponding $T=1$ states.

ACKNOWLEDGMENTS

The author would like to thank Professor William A. Fowler, Professor R. F. Christy, and Professor T. Lauritsen for several helpful discussions.

[24] F. Mozer (private communication).
[25] G. Dearnaley (private communication to F. Mozer).
[26] D. Kurath, Phys. Rev. **101**, 216 (1956).