Investigation of the $Be^9(p,n)B^9$ and $Be^9(p,\alpha\gamma)Li^6$ Reactions*†

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A pulsed-beam time-of-flight technique has been used to study neutrons and γ rays from the proton bombardment of Be^9 in the energy range from 2.3 to 5.4 Mev. Excitation curves for the ground-state neutron group from the $Be^9(p,n)B^9$ reaction have been measured at 0° and 90°. These curves show the well-known resonances at 2.56 and 4.6 Mev and, in addition, show a broad maximum near 3.5 Mev. The γ-ray excitation curve also indicates maxima at 2.56, 3.5, and 4.5 Mev. The 3.5- and 4.6-Mev resonances are tentatively assigned to p- and d-wave states having ($J=2^+$, $T=1$) and ($J=3^-$, $T=1$), respectively. The previously observed maximum near 4.9 Mev appears to be the result of the effect of the 3.5-Mev resonance on the n_1 group immediately above its threshold. The cross section for the production of continuum neutrons is appreciable for proton energies above about 3 Mev. A large fraction of these neutrons appear to result from the neutron decay of the 2.43-Mev Be^9 level following the inelastic excitation of this level.

INTRODUCTION

THE isotope Be^9 is unique in that it has the lowest neutron binding energy (1.67 Mev) of any stable isotope. As a result, the three-body breakup of Be^9 under proton bombardment [the $Be^9(p,p'n)Be^8$ reaction] can take place for incident energies above 1.85 Mev. Although this energy is below the threshold for the $Be^9(p,n)B^9$ reaction at 2.059 Mev, the neutron yield below the (p,n) threshold is very weak,[1] indicating an extremely small cross section for the three-body process in this energy region. The shape of the neutron yield curve for higher bombarding energies,[2–4] however, is largely nonresonant and suggests that the three-body cross section has become appreciable by 3 Mev or so. A continuum of neutrons, presumably from the $(p,p'n)$ reaction and/or the $(p,p')(n)$ reactions,[5] has been observed in a photographic plate experiment at 6.6 Mev.[6]

Using the Los Alamos pulsed-beam time-of-flight system,[7] a study of the $Be^9(p,n)B^9$ reaction and the competing continuum reactions has been made in the range of proton bombarding energy from 2.3 to 5.4 Mev. In addition to neutron data, information regarding the $Be^9(p,\alpha\gamma)Li^6$ reaction has been obtained by observing the time-of-flight-separated γ rays. Previous experiments on this reaction[2,8,9] have experienced severe difficulties above bombarding energies of about 2.7 Mev because of the interference of the intense neutron yield.

EXPERIMENTAL PROCEDURE

Protons were accelerated in the large Los Alamos vertical electrostatic generator and bombarded an evaporated beryllium target which was about 20-kev thick to 4-Mev protons. Neutrons and γ rays were detected in a plastic scintillator; the flight path was 1 meter. The efficiency of the neutron detector as a function of energy was measured[10] by comparing the counting rate with the known yield from the p-T and d-D reactions over the range of neutron energy from

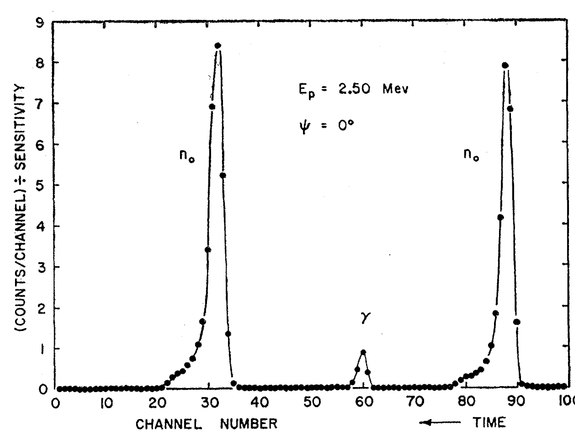

FIG. 1. Time-of-flight spectrum of neutrons and γ rays from the proton bombardment of Be^9 at 2.50 Mev. The ground-state group from the $Be^9(p,n)B^9$ reaction is designated n_0.

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† A preliminary report of this work was given at the New York meeting of the American Physical Society, January, 1959 [Bull. Am. Phys. Soc. 4, 16 (1959)].

‡ Summer visitor, 1957.

[1] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).

[2] Hahn, Snyder, Willard, Bair, Klema, Kington, and Green, Phys. Rev. **85**, 934 (1952).

[3] Marion, Bonner, and Cook, Phys. Rev. **100**, 91 (1955).

[4] R. L. Macklin and J. H. Gibbons, Bull. Am. Phys. Soc. Ser. II, 3, 26 (1958), and private communication.

[5] The *direct* three-body process is designated by $(p,p'n)$ whereas the *indirect* process which involves an inelastic excitation of Be^9 is designated by $(p,p')(n)$ and indicates any of the reactions $Be^9(p,p')Be^{9*}(n)Be^8(\alpha)He^4$, $Be^9(p,p')Be^{9*}(n)Be^{8*}(\alpha)He^4$, or Be^9-$(p,p')Be^{9*}(\alpha)He^5(n)He^4$. We neglect the possibility of the four-body breakup, $Be^9(p,p'n)2He^4$.

[6] F. Ajzenberg and W. W. Buechner, Phys. Rev. **91**, 674 (1953).

[7] See, for example, L. Cranberg and J. S. Levin, Phys. Rev. **103**, 343 (1956).

[8] See F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).

[9] J. B. Marion, Phys. Rev. **103**, 713 (1956).

[10] We are indebted to Haddad, Smith, and Perry for measuring the efficiency curve.

200 kev to 7 Mev. For neutron energies near 2 Mev, the product of the detector efficiency and solid angle (in steradians) was approximately 7×10^{-4}. Under the particular conditions used in this experiment, the efficiency decreased rapidly for neutron energies below about 300 kev; consequently, measurements were not attempted in this energy region.

Figure 1 shows the time spectrum obtained at a bombarding energy of 2.50 Mev at an observation angle of 0°. Peaks corresponding to γ rays and the ground-state neutrons (n_0) from the $Be^9(p,n)B^9$ reaction are present. The data are shown in the "double presentation" form, typical of the Los Alamos pulsed-beam system[7]; the right-hand γ-ray peak is off scale. At this bombarding energy, there is almost no continuous background which could energetically result from the $(p,p'n)$ reaction.[11] The separation of the n_0 group and the calculation of the (p,n) cross section therefore present little difficulty at these low bombarding energies. However, as is shown in Figs. 2 and 3, the situation is much more complicated at 4.50 Mev. Figure 2 shows a *time* spectrum typical of the 4.50-Mev data, while Fig. 3 shows energy spectra at four observation angles. In the latter curves the n_0 peak (of discrete energy) has been artificially spread out since the time-to-energy conversion was performed as if the entire spectrum were composed of a continuous energy distribution. Although this procedure seriously distorts peaks of discrete energy (in this case, only n_0), the shape of the continuum is correctly given. At the forward angles it is apparent that there is an appreciable background of continuum neutrons; these probably result from both the $(p,p'n)$ and $(p,p')(n)$ reactions. The continuum underlies the entire n_0 peak and extends beyond to a cutoff determined by the Q value of the $(p,p'n)$ reaction (-1.67 Mev). The 90° and 150° spectra suggest much smaller continuum contributions than do the 0° and 45° curves; however, since there may be a relatively large contribution from the low-energy region which was not studied, no conclusions can be drawn regarding the angular distribution of the integrated continuum yield.

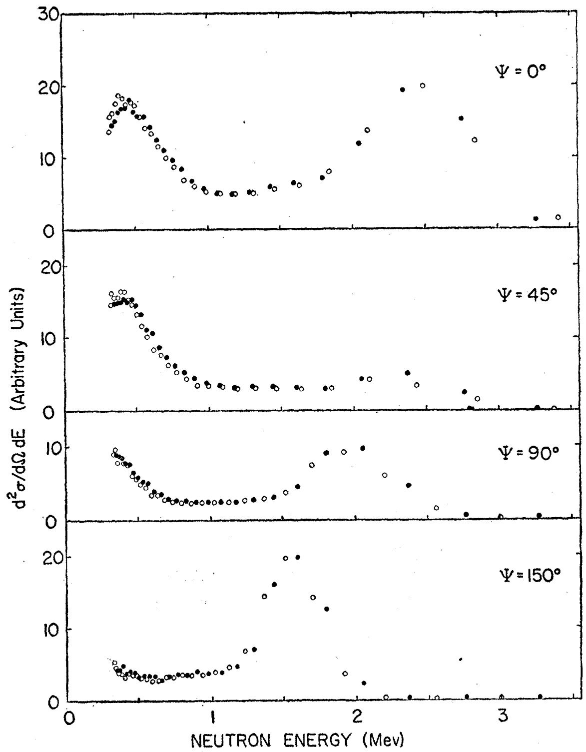

FIG. 3. Energy spectra of neutrons from the proton bombardment of Be^9 at 4.50 Mev. The observation angles are 0°, 45°, 90°, and 150°. The reason for the spread of the ground-state neutron group, the energy of which varies with angle from 2.5 to 1.5 Mev, is explained in the text. The open and closed circles refer to the two halves of the pulsed-beam cycle.

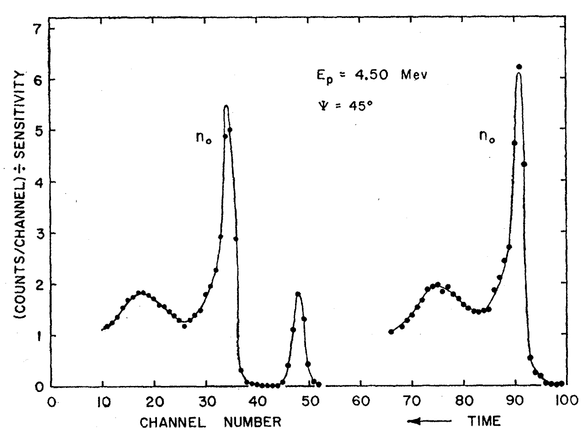

FIG. 2. Time-of-flight spectrum of neutrons and γ rays from the proton bombardment of Be^9 at 4.50 Mev. The observation angle is 45°.

Figure 4 shows the even more complicated spectrum obtained at 5.3 Mev. At this energy a new neutron

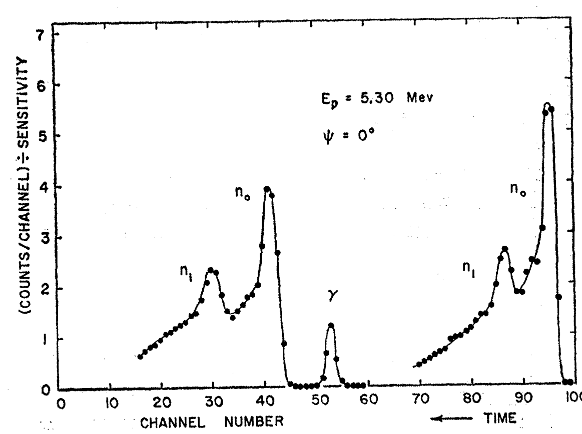

FIG. 4. Time-of-flight spectrum of neutrons and γ rays from the proton bombardment of Be^9 at 5.3 Mev. The observation angle is 0°.

[11] The threshold for the $(p,p')(n)$ reaction proceeding through the 2.43-Mev level is at 2.70 Mev.

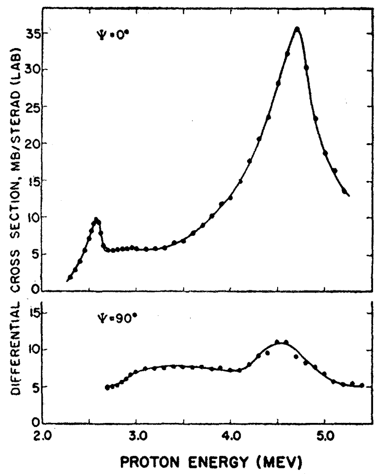

FIG. 5. Excitation curves for the ground-state neutrons from the $Be^9(p,n)B^9$ reaction at 0° and 90°.

energy group (n_1) is present, which leaves B^9 in the 2.3-Mev excited state.[3]

In order to obtain a cross section for the (p,n) reaction, it is necessary to separate the n_0 group from the background of continuum neutrons. This has been done approximately by two methods: (1) the shape of the discrete n_0 group was extrapolated into the continuum, or (2) the shape of the continuum was extrapolated under the n_0 peak to its cutoff position. Since these methods are only approximate (there is in principle *no* exact method for the extraction of a discrete group from a continuous background of unknown shape[12]), errors in the absolute cross section up to about 30% are introduced. The relative accuracy is slightly better since the shape and yield of the continuum vary slowly with bombarding energy and change smoothly with angle. This method of analysis (which is necessitated by the nature of the problem) suffers from some personal bias in the extrapolations. However, the possibility of extracting some useful information seems to justify this rather crude approach.

Absolute cross sections were obtained by normalizing the data to the accurately measured total neutron production cross-section values of Macklin and Gibbons.[4] The normalization point was chosen to be 2.4 Mev since at this energy the neutron yield is almost entirely from the (p,n_0) reaction and the angular distribution is known to be isotropic.[9]

The cross-section scale for the 90° excitation curve (see Fig. 5) was obtained from the 0° curve by using the energy spectra of Fig. 3 for the normalization.

RESULTS AND DISCUSSION

A. Neutron Data

The excitation curves for the ground-state neutrons (n_0) from the $Be^9(p,n)B^9$ reaction which result from the type of analysis described above are shown in Fig. 5. These curves, for observation angles of 0° and 90°, show the well-known resonances at 2.56 and 4.6 Mev. In addition, there appears to be evidence to support the suggestion previously made[4,9] that a broad resonance occurs near a proton energy of 3.5 Mev. In particular, it does not seem possible to account for the rather large cross section between the 2.56- and 4.6-Mev peaks in terms of these two resonances alone.

The 4.5-Mev resonance for the n_0 group is much more symmetrically shaped than previous long-counter data have indicated,[2,3,9] since the latter included the rising continuum yield together with the yield from the n_1 group, the threshold for which occurs at 4.64 Mev.[3] The long-counter data at 0°, for example, show a decrease on the high-energy side of the 4.6-Mev resonance of less than 20% from the peak value,[3] compared to at least 65% as indicated by the n_0 data.

A detailed long-counter excitation curve was obtained at 90° simultaneously with the n_0 data for proton energies from 2.3 to 5.8 Mev. These data[13] are shown in Fig. 6. The broad resonance-like behavior centered about a bombarding energy of 3.5 Mev is again evident. A doublet structure is found near 4.7–4.8 Mev, confirming previous observations of this effect.[3,4] A comparison of the 90° data for the n_0 group with those obtained with the long counter strikingly shows the effect of the continuum neutrons. Whereas the cross section for the n_0 group is essentially the same at 5.3 Mev as at 2.7 Mev, the cross section for the production of *all* neutrons shows an increase of a factor of 3 at the higher energy. At energies below the threshold for the n_1 group, the difference between the two cross sections must be attributed to the $(p,p'n)$ and $(p,p')(n)$ reactions. At 4.6 Mev, the continuum cross section at 90° is 25 mb/sterad, compared to only 11 mb/sterad for the n_0 group. The corresponding figures at 2.7 Mev are 6 and 5 mb/sterad. Due to the fact that these cross sections were obtained by extrapolations, normalizations, and subtraction, they are subject to considerable error. These figures are, however, indicative of the substantial contribution of the continuum neutrons.

The doublet structure near 4.8 Mev has been observed only in long-counter data. At 0°, these data show maxima at 4.70 Mev (average of two measurements[2,3]) and at 4.94 Mev.[3] The resonance energy for the n_0 group at 0° is 4.69 Mev (corrected for target thickness), in good agreement with the long-counter data, but the n_0 curve shows no indication of a peak near 4.94 Mev. A similar statement holds for the 90° data. The most reasonable explanation then is that the 4.9-Mev peak

[12] If the separation is set up analytically, incorporating the known shape of the discrete energy group, there is always one more unknown than there are simultaneous equations. The only exactly soluble case is that for perfect energy resolution, i.e., when the discrete group appears as a line.

[13] The cross sections shown in Fig. 6 are approximately 60% higher than the previously published[9] 90° values. The major part of this discrepancy is the result of using old $Li^7(p,n)$ cross-section data as a comparison standard in the earlier work. These $Li^7(p,n)$ cross sections have recently been shown to be in error by 40% [Gabbard, Davis, and Bonner, Phys. Rev. **114**, 201 (1959)].

is due to the n_1 group. It was not possible to confirm this hypothesis by obtaining an excitation curve for the n_1 group since the extraction of this group from the continuum was too uncertain.

Table I shows the various energies which have been obtained for these peaks. The fact that the different methods of measurement yield such a variation in these energies indicates that strong interference effects are present which drastically distort the curves and act in different ways depending on the particular quantity measured. Consequently, all that can be said is that there appear to be at least two maxima in this energy region which occur near proton energies of 4.6 and 4.9 Mev.

The highly asymmetric character of the angular distribution of the n_0 group (see Fig. 3) indicates interference between states of opposite parity, probably corresponding to the resonances at 3.5 and 4.6 Mev. An angular distribution taken at 3.50 Mev (not shown) also indicated considerable asymmetry.

B. The Continuum Neutrons

All of the above comments on the continuum neutrons are based on the *difference* between the n_0 data and the measurements of the total yield of neutrons. Some information, however, may be derived from direct observation of the continuous neutron distribution. Figure 3 is illustrative of these types of data. The 0° spectrum at 4.5 Mev shows, in addition to the n_0 and γ-ray peaks, a broad maximum due to the continuum neutrons, centered about a neutron energy of approximately 0.45 Mev. (The 4.5-Mev bombarding energy is below the threshold for the production of the n_1 group; hence, the 0.45-Mev peak must be due to one of the continuum reactions.) Since the Be^9 level at 2.43 Mev is intensely populated in the $Be^9(p,p')Be^{9*}$ reaction,[14] it is natural to seek an explanation for this neutron peak in terms of the $(p,p')(n)$ reaction proceeding through the 2.43-Mev state. If the 2.43-Mev level were to decay by neutron emission to the ground state of Be^8 ($Q=0.76$ Mev), the decay-in-flight would give these neutrons a mean energy of approximately 1 Mev. The 0.45-Mev peak in the neutron energy distribution clearly cannot be the result of this decay. The fact that no peak is

TABLE I. Peak energies for the Be^9+p reactions near 4.8 Mev.

Detection method	Peak energy I (Mev)	Peak energy II (Mev)	Reference
All neutrons (0°)	4.72±0.01	Not observed	2
	4.68±0.03	4.94±0.03	3
All neutrons (90°)	4.64±0.06	4.82±0.06	Present data
All neutrons (σ_t)	4.60	4.85	4
n_0 (0°)	4.69±0.03	Absent	Present data
n_0 (90°)	4.51±0.04	Absent	Present data
γ rays	4.49±0.03	Absent	Present data

[14] See, for example, Gossett, Phillips, Schiffer, and Windham, Phys. Rev. **100**, 203 (1955).

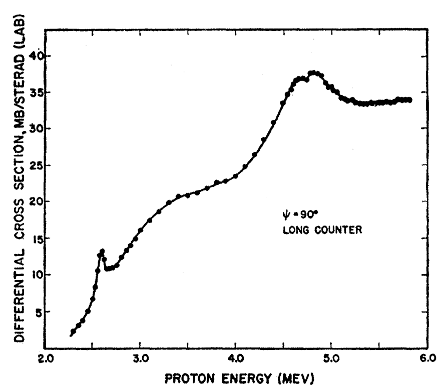

FIG. 6. Excitation curve for the production of all neutrons from the Be^9+p reactions at an angle of 90°. The curve was measured with a long counter.

observed near 1 Mev is consistent with the result[15] that only 12±5% of the decays lead to the Be^8 ground state.

Four other possibilities exist for the explanation of the 0.45-Mev peak: (1) the three-body breakup, $Be^9(p,p'n)Be^8$; (2) the $Be^9(p,p')Be^{9*}(\alpha)He^5(n)He^4$ reaction; (3) the $Be^9(p,p')Be^{9*}(n)Be^{8*}(\alpha)He^4$ reaction, through the tail of the 2.9-Mev level; and (4) the $Be^9(p,p')Be^{9*}(n)2He^4$ reaction, through a final state *s*-wave potential interaction of the two α particles. Bodansky, *et al.*,[16] have suggested that process (2) is the dominant decay mode; however, it is difficult to see how a peak as narrow as the 0.45-Mev peak could be produced in this reaction. If the three-body breakup [process (1)] were responsible for the peak, then a corresponding peak would be *expected* (but not strictly *required*) in the proton spectrum from the Be^9+p reactions; no such peak has been observed at the appropriate energy.[14]

It appears, then, that some process following inelastic scattering is responsible for the 0.45-Mev peak. Processes (3) and (4) seem to be the most likely and they are being investigated further.

C. γ-Ray Data

When Be^9 is bombarded with protons in the energy range from 2 to 6 Mev, the following reactions can take place: $Be^9(p,\gamma)B^{10}$, $Be^9(p,\alpha\gamma)Li^6$, $Be^9(p,d)Be^8$, $Be^9(p,n)B^9$, $Be^9(p,p')Be^9$, and the continuum-producing reactions. Of these, only the first two produce γ radiation. The excited states of Be^9 and B^9 and the low-lying levels of Be^8 have negligibly small radiation widths. Since the (p,γ) reaction has a very small cross section, γ rays from Be^9+p reactions originate predominately in the $(p,\alpha\gamma)$ reaction. Only one state in Li^6 (3.57 Mev) is known to emit γ radiation, so that the γ-ray spectrum from Be^9+p is dominated by this single γ ray.

[15] Marion, Levin, and Cranberg (to be published).
[16] Bodansky, Eccles, and Halpern, Phys. Rev. **108**, 1019 (1957).

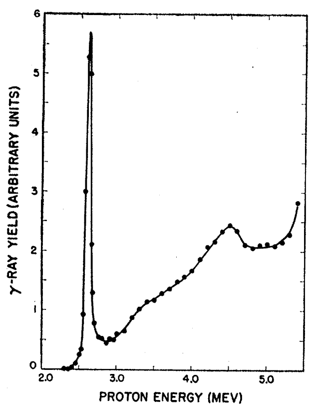

FIG. 7. The 0° excitation curve for γ rays from the $Be^9(p,\alpha\gamma)Li^6$ reaction.

The separation of γ rays from neutrons can be made quite cleanly with the time-of-flight apparatus, as the spectra of Figs. 1, 2, and 4 demonstrate. Since very little γ-ray contribution was expected from other than the 3.57-Mev radiation, no effort was made to select only a portion of the γ-ray energy spectrum for the measurement of the excitation curve.

Figure 7 shows the 0° γ-ray excitation function over the range of bombarding energy from 2.3 to 5.4 Mev. Two distinct maxima are observed, at 2.56 Mev (which is different from the neutron resonance at this same energy[9]) and at 4.49 Mev. Between these peaks there is again evidence for the 3.5-Mev resonance.

The Li^6 state which gives rise to the observed 3.57-Mev γ ray has $T=1$. Hence, only compound nucleus states in B^{10} which have $T=1$ can emit the α-particle group corresponding to the observed γ ray. The 2.56-Mev resonance has previously been analyzed[8,9] from this standpoint. On the basis of the present data, the states corresponding to the 3.5- and 4.6-Mev resonances must also have $T=1$. As such, they must be mirror to levels in Be^{10}, and, in fact, two broad levels in the corresponding energy range are known[17] from neutron scattering experiments on Be^9. One of these is a broad p-wave state centered about $E_n=3.0$ Mev and is the state responsible for the maximum in the $Be^9(n,\alpha)He^6$ cross section at this energy.[18] That this resonance should be identified as the analog of the 3.5-Mev peak observed in the (p,n_0) and $(p,\alpha\gamma)$ reactions is supported by the analysis[4] of the total neutron yield from Be^9+p which indicates predominant p-wave effects in the cross section which underlies the 2.56-Mev resonance (i.e., the 3.5-Mev resonance). The other resonance (and the *only* other resonance) observed in this energy region in the Be^9+n elastic scattering and total cross-section measurements is a d-wave state at $E_n=2.75$ Mev, which is presumably the analog of the 4.6-Mev resonance found in the (p,n_0) and $(p,\alpha\gamma)$ excitation curves. The peak total neutron cross section indicates[17] that the J-value for the Be^{10} level must be near the maximum allowed for a d-wave resonance; i.e., $J\leq 4$. The parity is, of course, odd. Since both the α particle and the 3.57-Mev state of Li^6 have $J=0^+$, the B^{10} states which produce resonances in the $Be^9(p,\alpha\gamma)Li^6$ reaction are limited to spin and parity values of 0^+, 1^-, 2^+, 3^-, etc., and must have $T=1$. If the d-wave neutron resonance is the analog of the level responsible for the $(p,\alpha\gamma)$ resonance near $E_p=4.6$ Mev, then the parity must be odd, and if J is to be near 4, then the spin and parity are almost certainly 3^-. The 3.5-Mev p-wave resonance and the 4.6-Mev d-wave resonance then interfere to produce the asymmetric angular distribution of neutrons referred to earlier.

If the resonance in Be^9+p at 4.6 Mev is to be identified with the resonance in Be^9+n at 2.75 Mev, it is not clear why the former appears in the $Be^9(p,\alpha\gamma)Li^6$ reaction while the latter is absent in the $Be^9(n,\alpha)He^6$ reaction since these reactions are "mirror reactions" (i.e., they both lead to the lowest $T=1$ levels in the residual nuclei). Both the (n,α) and $(p,\alpha\gamma)$ reactions show the resonances at $E_n=3.0$ Mev and at $E_p=3.50$ Mev as expected.

DISCUSSION

A. The 4.9-Mev Peak

It has already been concluded that the maximum in the total yield of neutrons from Be^9+p which occurs at 4.9 Mev is the result of neutrons leaving B^9 in the excited state at 2.3 Mev (threshold energy 4.64 Mev). In the Be^9+n experiment[15] the measurement of the excitation curve for the neutrons inelastically scattered from the mirror 2.43-Mev state of Be^9 shows a maximum at an energy slightly above that corresponding to the d-wave resonance at 2.75 Mev. Since there appear to be only two Be^{10} states in this energy region[17] and since the threshold for the inelastic scattering of neutrons from this Be^9 level occurs at 2.70 Mev, this peak in the n' excitation curve was attributed[15] not to a new state but to the broad p-wave level; the nearby threshold and the resonance combine to produce a peak apparently more narrow than the resonance. It seems likely that a similar effect occurs in the $Be^9(p,n_1)B^9$ reaction since the yield of neutrons leaving B^9 in the 2.3-Mev state is thought to proceed predominantly by p-waves in the energy region immediately above threshold.[3] The 4.9-Mev peak would then be the result of the 3.5-Mev resonance and not a new level.

B. Possibility of a New B^9 Level

Although the continuum neutrons which were observed have been discussed above as arising from the $(p,p'n)$ and $(p,p')(n)$ reactions, an additional possible source should be pointed out. There is now fairly good evidence[19] that the artifact long observed in reactions

[17] J. L. Fowler and H. O. Cohn, Bull. Am. Phys. Soc. Ser. II, **3**, 305 (1958), and private communication.

[18] P. H. Stelson and E. C. Campbell, Phys. Rev. **106**, 1252 (1957).

[19] D. W. Miller, Phys. Rev. **109**, 1669 (1958).

in which Be^{9*} is the residual nucleus actually corresponds to a true nuclear level near 1.7 Mev with $J=\frac{1}{2}$. A careful examination[20] of the α-particle spectrum from the $B^{10}(He^3,\alpha)B^9$ reaction has failed to reveal a mirror level in B^9. Also, on the basis of the present results on the continuum neutrons, it now seems more reasonable to ascribe the anomaly in the slow neutron yield from the $Be^9(p,n)B^9$ reaction which was observed[3] at bombarding energies near 3.5 Mev to the fall off with increasing energy of the slow neutron detector sensitivity together with rising continuum yield (see above) rather than to a B^9 level near 1.4 Mev. If, however, the B^9 level were radically shifted in energy from its position in Be^9, then it may have so far remained undetected. Consequently, it seems necessary to qualify the statements above regarding the origin of the continuum to include the possibility that at least a portion of these neutrons arise from the $Be^9(p,n)B^9$ reaction, but leave the residual nucleus in a low-lying level mirror to the Be^9 1.7-Mev state.

C. $T=0$ States in B^{10}

The various experiments on Be^9+p reactions in the energy range from 2 to 6 Mev have revealed the presence of 4 resonance levels: two at 2.56 Mev ($J=2^+$ and $J=3^+$), one at 3.5 Mev ($J=2^+$), and one at 4.6 Mev ($J=3^-$). All of the states have apparent analogs in Be^{10} and therefore have $T=1$. In fact, in the range of excitation energy from 8.7 to 11 Mev in B^{10} all known levels have $T=1$. The highest known $T=0$ occurs at 8.65 Mev.[21] It seems rather unlikely that in an energy range of over 2 Mev there would be a complete absence of $T=0$ states. Perhaps these levels, if they exist, are so broad as to have escaped detection thus far. An obvious way in which to search for these states would be to extend the (p,d) and (p,α_0) excitation curves[21] to higher energies.

[20] Spencer, Phillips, and Young (to be published).

[21] Weber, Davis, and Marion, Phys. Rev. **104**, 1307 (1956).

CONCLUSIONS

The investigation of neutron-producing reactions which yield discrete neutron groups as well as continuous distributions is a difficult task. The present results are of necessity crude and are able to give only rather elementary information regarding the neutrons from Be^9+p. The only firm conclusion that can be reached regarding the continuum neutrons is that the cross section for their production is far from negligible, and is, in fact, comparable with the n_0 cross section for proton energies near 5 Mev. The mechanism by which the continuum neutrons are produced is uncertain, but a large fraction appear to result from the $(p,p')(n)$ reaction.

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