(p,d) and (p,α) Reactions in Be^9†

G. WEBER,* L. W. DAVIS, AND J. B. MARION‡
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California
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Excitation curves for the $Be^9(p,d)Be^8$ (ground state) reaction have been measured at observation angles of 15°, 45°, 70°, 90°, 110°, and 135° for proton energies between 0.8 and 3.0 Mev. These curves show pronounced resonance structure and strong interference effects between different levels. About 60 angular distributions and the total cross-section curve were constructed from the 6 differential cross-section curves. The angular distributions are peaked forward, except in the region near 1.6 Mev, where a broad resonance, interfering with nonresonant amplitudes, causes the angular distribution to become almost symmetric about 90°. The occurrence of forward peaking at all energies and the good agreement of the angular distribution at 2.84 Mev with a theoretical stripping curve suggest that a pickup process can account for a sizeable fraction of the reaction cross section, even at energies as low as 1 Mev. The total cross section indicates a resonance at 0.93 and weak maxima at 1.25, 1.65, and 2.3 Mev, but not at the $T=1$ level at 2.56 Mev. The differential cross section for the $Be^9(p,\alpha)Li^6$ (ground state) reaction was measured at 90° from 0.8 to 3.0 Mev. In addition to the 0.93-Mev peak, this curve shows a pronounced minimum near 1.4 Mev and a weak anomaly at 2.56±0.02 Mev indicating a slight violation of the isotopic spin selection rule. An upper limit of 4×10^{-3} is obtained for the $T=0$ impurity of the 2^+, $T=1$ state at 8.89 Mev in B^{10}.

INTRODUCTION

THE proton bombardment of Be^9 has been used by many investigators[1–5] to explore the level structure of B^{10} for excitation energies greater than 6.585 Mev. Excitation curves for the reactions $Be^9(p,\alpha)$-Li^6 (ground state) $Be^9(p,d)Be^8$ (ground state), and $Be^9(p,p)Be^9$ for proton energies between 0.2 and 1.3 Mev were obtained by Thomas, Rubin, Fowler, and Lauritsen[1] and angular distributions below 1 Mev were measured by Neuendorffer, Inglis, and Hanna.[2] These measurements are in agreement with the recent work on the elastic proton scattering by Mozer[6] who interprets the data in terms of five B^{10} levels at proton energies of 0.330, 0.980, 0.998, 1.084, and 1.33 Mev. Six additional levels have been identified in the energy range from 2 to 5 Mev by studies of the (p,d), $(p,\alpha\gamma)$ and (p,n) reactions.[5]

Most interesting in the region above 2 Mev is the existence of a degenerate 2^+-3^+, $T=1$ doublet at 2.562 Mev, recently investigated by Marion,[4] who also gives a summary of the properties of the other levels. Since the ground states of Li^6 and Be^8 as well as the α particle and the deuteron have $T=0$, neither the (p,α_0) nor the (p,d_0) reactions should be resonant at 2.56 Mev, unless there is an appreciable isotopic-spin impurity in one of these doublet members or in the residual nuclei. One of the reasons for the present investigation was to look for the effects of possible isotopic-spin impurities in the (p,d_0) and (p,α_0) reactions, since earlier attempts[3] to detect these effects had failed. In view of the $Be^9(p,p)Be^9$ investigations[6] which reveal a relatively large level density near $E_p=1$ Mev, it seemed worthwhile to study the excitation curves of at least one of the reactions at several observation angles, in order to estimate the effects due to interference of different levels. The Q values of the reactions studied are:

$$Be^9(p,d)Be^8, \quad Q=0.559 \text{ Mev},$$
$$Be^9(p,\alpha)Li^6, \quad Q=2.132 \text{ Mev}.$$

Since, in the energy range investigated (0.8 Mev$\leqslant E_p \leqslant$ 3.0 Mev), the magnetic analysis of the ground-state deuterons is relatively easy over a wide range of angles, it was decided to study the (p,d) reaction as a function of both angle and energy, whereas for the (p,α) reaction, only one excitation curve at $\theta=90°$ was obtained.

Apart from a study of the level structure of B^{10}, a thorough investigation of the $Be^9(p,d)Be^8$ reaction seemed of interest from the point of view of reaction theories. It has been found that the angular distributions of (d,p) and (d,n) reactions in light nuclei can be well described by the Butler[7] theory, for deuteron energies larger than about 4 Mev, i.e., above the Coulomb barrier. For very low energies, say less than 1 Mev, stripping effects are in general relatively unimportant and the reactions proceed predominately by compound nucleus formation. Finally, between 1 and 3 Mev, both compound nucleus effects and stripping contribute to the reaction cross section.[8–11] Similar effects are ex-

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* International Cooperation Administration Research Fellow; now at the Max Planck Institut für Chemie, Mainz, Germany.
‡ National Science Foundation Postdoctoral Fellow; now at the University of Rochester, Rochester, New York.
1 Thomas, Rubin, Fowler, and Lauritsen, Phys. Rev. **75**, 1612 (1949).
2 Neuendorffer, Inglis, and Hanna, Phys. Rev. **82**, 75 (1950).
3 R. Malm and D. R. Inglis, Phys. Rev. **95**, 993 (1954).
4 J. B. Marion, Phys. Rev. **103**, 713 (1956).
5 Further references are given by F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955) and in references 1 and 4 of the present paper.
6 F. S. Mozer, Phys. Rev. **104**, 1386 (1956), this issue.
7 T. S. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951); W. Tobocman (unpublished).
8 Bonner, Eisinger, Kraus, and Marion, Phys. Rev. **101**, 209 (1956).
9 Holmgren, Blair, Simmons, Stratton, and Stuart, Phys. Rev. **95**, 1544 (1954).
10 J. B. Marion and G. Weber, Phys. Rev. **103**, 167 (1956).
11 J. B. Marion and G. Weber, Phys. Rev. **103**, 1408 (1956).

pected for (n,d), (p,d), (d,t) reactions, which at low energies should proceed mainly through compound-nucleus formation, whereas at higher energies the pickup mechanism[12] should account for the largest part of the reaction cross section. At very high energies, the $Be^9(p,d)Be^8$ reaction has indeed been found to proceed through a pickup-type process.[13] The energy region in which the pickup process becomes noticeable will, of course, depend on the properties of the target nucleus. In Be^9 the binding energy of the last neutron is only 1.7 Mev, compared to an average of about 7 Mev for light nuclei, and hence the wave function has a very long tail. It is therefore to be expected that in the $Be^9(p,d)Be^8$ reaction the pickup process will become important at much lower energies than for reactions in other nuclei.

EXPERIMENTAL PROCEDURE

A. Thick-Target Measurements

For the (p,d) measurements at observation angles $\geqslant 70°$, the thick-target technique[14] was used, the Kellogg Laboratory's 16-in. magnetic spectrometer serving as the analyzer for the dueterons. The target was a $\frac{3}{4}$ in.$\times\frac{3}{4}$ in. plate of metallic beryllium about $\frac{1}{8}$ in. thick, the surface of which had been polished and etched to a mirror finish. A thin CsI crystal was used for particle detection. The ground-state deuteron group was always well separated in momentum from the other particle groups and integral biasing was used only to discriminate against noise pulses.

After it was verified at a few angles and energies that the target surface was sufficiently smooth and free of contamination layers to give a clean momentum step, the excitation curves were obtained by measuring the number of counts at the top of the step at each proton energy setting. The absolute differential cross sections per unit solid angle were obtained from the formula[14]

$$\frac{d\sigma}{d\Omega}=\frac{R\epsilon_{\text{eff}}N}{2\Omega E}\ \text{cm}^2/\text{steradian},$$

where R is the momentum resolution and Ω the solid angle of the spectrometer, E is the average energy (in Mev) of the emitted particles at the point of their production, N is the number of particles detected per incident proton and ϵ_{eff} is the effective stopping cross section[14] (in Mev cm^2) of the target material, which was computed from the recent measurements of Bader, Pixley, Mozer, and Whaling.[15] For the 90°, 110°, and 135° measurements, the target was oriented such that the angle between the direction of the beam and the normal to the target surface was 135°; for the 70° measurements this angle was 125°. A number of points of the 90° curve were remeasured at the latter target angle. The cross sections computed for both target angles agreed to within 2.5%.

For the (p,α) curve, an unsupported Be foil was used, which was thin enough to give a line profile for the deuteron group but thick enough to give a step profile for the α particles. In this way, the thick-target technique and integral biasing could be used, since the tail of the deuteron peak did not interfere with the α profile. The correction for the α^+/α^{++} ratio was made.[1]

B. Thin-Target Measurements

For observation angles forward of 70°, a thin (≈ 10 kev) layer of metallic beryllium, evaporated onto a thin (≈ 50 kev) Cu foil, was used. Contrary to the experience with unsupported Be foils of the same thickness, which tend to break under bombardment, Cu-backed targets were found to be quite stable under thermal and mechanical stress.

With this target placed at 135° with respect to the beam, complete momentum profiles were taken in steps of about 250 kev over the entire energy range at 15°, 45°, and 70°. For these points, the absolute cross sections were obtained by normalizing the data to the 70° thick-target curve. For $\theta=15°$ and 45°, the ratio of the cross section to the maximum number of counts in the line profile was plotted *versus* energy and a smooth curve drawn through each set of points. These curves were used to correct the experimental excitation curves, i.e., the maximum number of counts in the line profile *versus* energy, to absolute cross sections. A more detailed description of this procedure has been given in an earlier paper.[16]

C. Accuracy of the Cross-Section Measurements

In the present experiments the spectrometer had a solid angle of 1.13×10^{-3} steradians and a momentum resolution $(p/\Delta p)$ of 452. In a recent check[16] on the accuracy of these spectrometer constants, it was found that the ratio $p/\Delta p\Omega$ which enters into the expression for the cross sections is accurate to about 1.5%.

The absolute cross sections derived from the thick-target measurements, i.e., for $\theta\geqslant 70°$, are probably accurate to about 7%. This error arises from the uncertainties in the spectrometer constants (1.5%), the effective stopping power ϵ_{eff} (5.0%), the target angles (2.0%), counting statistics (generally about 3%), and the integrator calibration (1.0%). The relative probable errors amount to about 3 or 4%.

For the thin-target measurements a larger uncertainty (about 12%) arises from the application of the

[12] Cuer, Morand, and van Rossum, Compt. rend. **228**, 481 (1949); J. Hadley and H. York, Phys. Rev. **80**, 345 (1950); C. F. Chew and M. L. Goldberger, Phys. Rev. **77**, 470 (1950).

[13] W. Selove, Phys. Rev. **101**, 231 (1956); S. Glashow and W. Selove, Phys. Rev. **102**, 200 (1956); J. B. Reynolds and K. G. Standing, Phys. Rev. **101**, 158 (1956).

[14] Brown, Snyder, Fowler, and Lauritsen, Phys. Rev. **82**, 159 (1950).

[15] Bader, Pixley, Mozer, and Whaling, Phys. Rev. **103**, 32 (1956).

[16] J. B. Marion and G. Weber, Phys. Rev. **102**, 1355 (1956).

correction curve and the normalization. Consequently, the absolute cross sections for the 15° and 45° curves are probably accurate to about 15%. The relative errors are of the order of 5%.

Table I gives a comparison of the differential cross sections at $E_p=1.00$ Mev for the $Be^9(p,d)Be^8$ and $Be^9(p,\alpha)Li^6$ reactions obtained by Thomas, Rubin, Fowler, and Lauritsen[1] at $\theta_{lab}=138°$ with values found in the present work. The comparison is made in the center-of-mass system, since our (p,d) cross section at $\theta_{lab}=138°$ had to be obtained from the angular distribution, which is given in center-of-mass coordinates (see next section). Since in the work described here, the (p,α) cross section had been determined only at $\theta_{lab}=90°$, the relative angular distribution measured by Neuendorffer, Inglis, and Hanna[2] was used to transform the (p,α) cross section of Thomas *et al.*[1] to the corresponding center-of-mass angle (98.5°). There is good agreement between the cross sections for both reactions. (The values of Thomas *et al.* are accurate to about 15%.)[17]

RESULTS

A. $Be^9(p,d)Be^8$

The excitation curves obtained for the (p,d) reaction at $\theta_{lab}=15°$, 45°, 70° and at $\theta_{lab}=90°$, 110°, 135° are shown in Fig. 1 and in Fig. 2, respectively. The differential cross sections in millibarns per steradian are plotted against the bombarding energy, without a correction for the energy loss in the target. The curves show pronounced resonance structure and change quite drastically with angle. The maxima near 0.93 Mev and 2.3 Mev are common to all 6 curves. In the forward direction additional maxima show up near proton energies of 1.2 and 1.6 Mev. At 90° the 1.2- and 1.6-Mev peaks do not occur, but a maximum is observed near 1.4 Mev, about the same energy at which the forward curves have dips. At $\theta_{lab}=110°$ and 135°, a strong minimum appears at about 1.1 Mev and the peaking near 1.4 Mev is stronger than at 90°. Near 1.75 Mev, where the 90° curve has a minimum, the 110° curve shows the indication of a broad maximum which has grown to a strong peak at 135°. Careful studies were made of the energy regions near 1.084 Mev where Mozer[6] finds an s-wave resonance in the elastic proton scattering, and in the region of the 2.562-Mev, $T=1$

TABLE I. Comparison of differential cross sections for the $Be^9(p,d)Be^8$ and $Be^9(p,\alpha)Li^6$ reactions at $E_p=1.00$.

Reaction	θ(c.m.)	Cross section in mb/sterad (c.m.) Thomas *et al.*[a] Neuendorffer *et al.*[b]	Present work
$Be^9(p,d)Be^8$	143°	9.4	8.5±0.7
$Be^9(p,\alpha)Li^6$	98.5°	19.5	23.7±1.9

[a] See reference 1.
[b] See reference 2.

[17] W. A. Fowler (private communication).

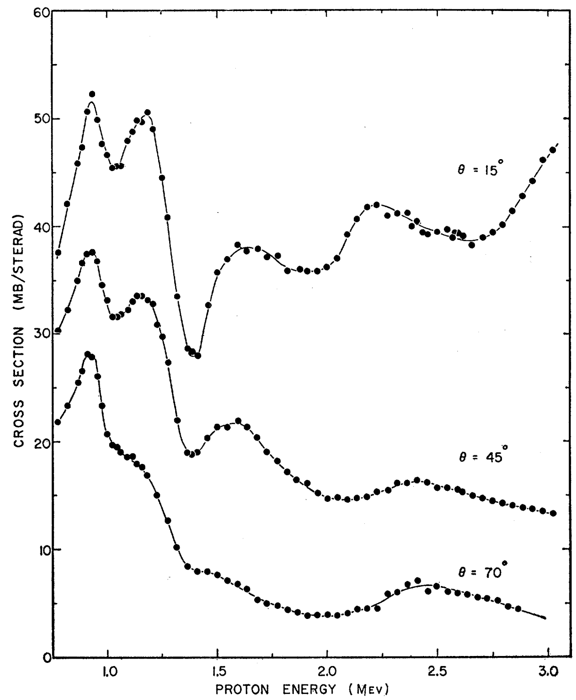

FIG. 1. Differential cross section curves for the $Be^9(p,d)Be^8$ (ground state) reaction as a function of bombarding energy (uncorrected for target thickness) at observation angles of 15°, 45°, 70°.

resonance.[4,18] No resonance structure within experimental error was found at either energy. The rapid variation with angle of the energy dependence of the cross section suggests that strong interference effects between states of opposite parity are operative, especially for proton energies between 1 and 2 Mev.

In order to determine the true locations of the resonances, the energy dependence of the total cross section was computed from the data of Figs. 1 and 2. The following procedure was applied: for each energy at which 15° data had been taken, the differential cross section for all six angles was transformed to the center-of-mass system by using the tables of Marion and Ginzbarg[19] and was plotted against the cosine of the center-of-mass angle. In this way more than 60 angular distributions were obtained, from which the total cross sections were derived by integration. The total cross-section curve thus obtained is shown in Fig. 3. There are maxima at 0.93, 1.25, 1.64, and 2.3 Mev, superposed on a monotonically decreasing background. The peaks in Fig. 3 are relatively weak, indicating that the large variations in the differential cross-section curves are due mainly to the interference terms.

[18] R. J. Mackin, Jr., Phys. Rev. **94**, 648 (1954).
[19] J. B. Marion and A. S. Ginzbarg, *Tables for the Transformation of Angular Distribution Data from the Laboratory System to the Center-of-Mass System* (Shell Development Company, Houston, 1955).

To demonstrate the energy dependence of the angular distributions, nine typical distributions are shown in Fig. 4, along with the more complete angular distribution at $E_p=1.820$ Mev, which was measured in 5° intervals from $\theta=15°$ to 140°. For proton energies less than about 1.25 Mev, the distributions are strongly peaked forward, the forward-to-backward ratio going through a maximum at about 1.1 Mev. Near 1.25 Mev the asymmetry starts decreasing and near 1.6 Mev the angular distribution is almost symmetric about 90°. Up to 1.8 Mev the distributions can be represented approximately by an expansion of the form:

$$d\sigma/d\Omega=2\pi[a(E)+b(E)\cos\theta+c(E)\cos^2\theta]. \quad (1)$$

The coefficients a, b, and c for the data below 1.8 Mev are plotted against the proton energy in Fig. 5. The total cross section, plotted on an arbitrary scale, is shown for comparison.

For proton energies greater than about 1.8 Mev, the angular distributions become increasingly peaked forward. Fitting the angular distributions for $E_p \gtrsim 1.8$ Mev with a cosine expansion of the form (1) is neither possible nor sensible, in view of the contribution from the pickup process for these energies.

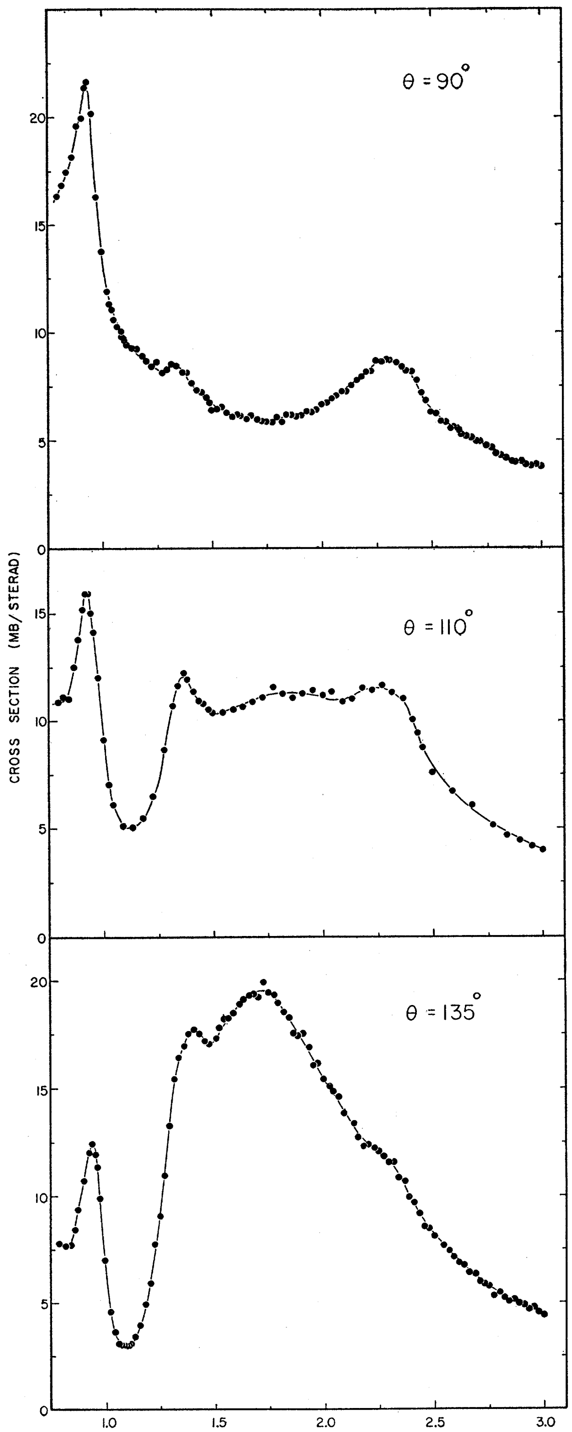

FIG. 2. Differential cross-section curves for the $Be^9(p,d)Be^8$ (ground state) reaction as a function of bombarding energy (uncorrected for the energy loss of the protons in the target) at observation angles of 90°, 110°, 135°.

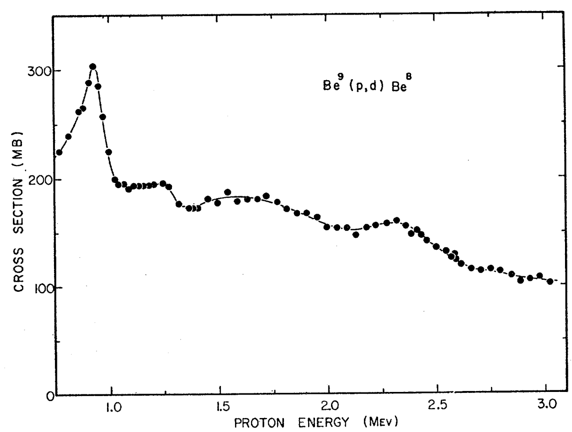

FIG. 3. Total (p,d) cross section as a function of bombarding energy. The points shown were obtained by integrating the angular distributions which had been constructed from the differential cross sections of Figs. 1 and 2.

B. $Be^9(p,\alpha)Li^6$

The differential cross section measured at $\theta_{lab}=90°$ for the $Be^9(p,\alpha)Li^6$ (ground state) reaction is shown in Fig. 6. After passing through the 0.93-Mev resonance, the cross section shows a broad maximum near 1.25 Mev and decreases rapidly, reaching a minimum at 1.4 Mev. Up to this energy the (p,α) excitation curve looks very similar to the (p,d) curves at 45° and 15°. Between 1.4 Mev and 1.8 Mev the (p,α) cross section increases and is fairly constant between 1.8 and 2.1 Mev. For $E_p \gtrsim 2$ Mev the yield shows an over-all decrease interrupted by a small resonance anomaly at 2.56 ± 0.02 Mev. The region near the resonance is shown on an expanded scale in the insert of Fig. 6. The width of this resonance is 40±10 kev which is in good agreement with the known width[3,4,18] for the $J=2^+$, $T=1$ resonance. The identification of the resonance with this level is supported by the smallness of the effect, since the decay $B^{10*}\rightarrow Li^6+\alpha$ involves a change of isotopic spin by one unit and consequently the transition rate is expected to be small.

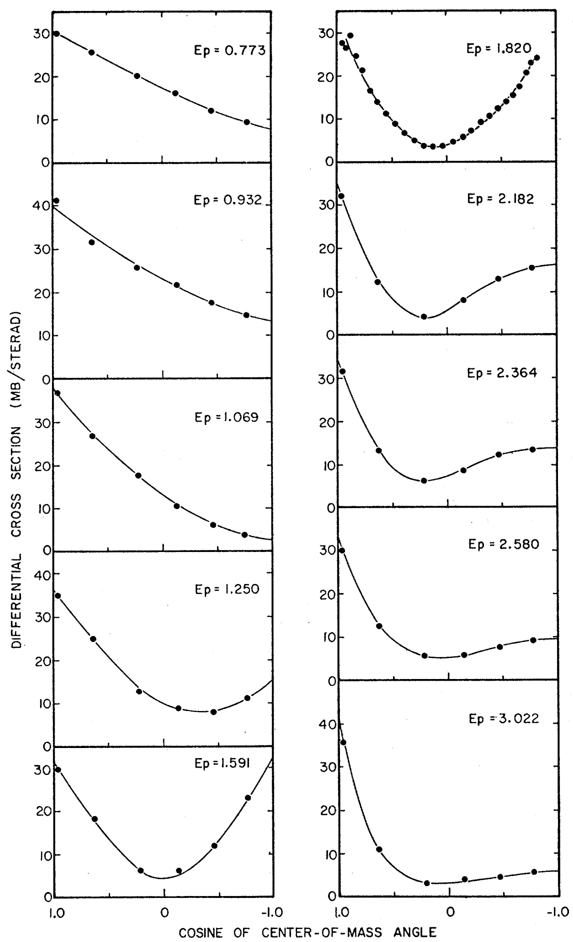

FIG. 4. Typical angular distributions of the $Be^9(p,d)Be^8$ reaction. The differential cross sections were taken from Figs. 1 and 2, transformed to center-of-mass coordinates, and plotted against the cosine of the center-of-mass angle.

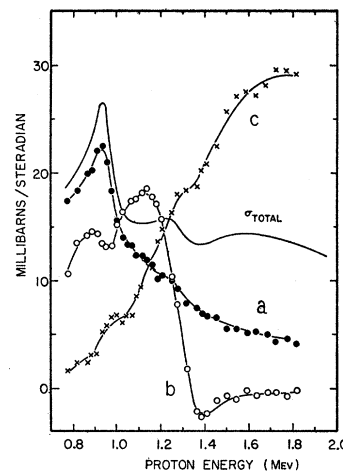

FIG. 5. The coefficients a, b, c of the expansion $d\sigma/d\Omega = 2\pi(a+b\cos\theta+c\cos^2\theta)$ as a function of proton energy. The total cross section, plotted on an arbitrary scale, is shown for comparison.

DISCUSSION

A. Angular Distributions and Excitation Curves

It seems probable that the small peak near 1.25 Mev in the (p,d) total cross-section curve (Fig. 3) corresponds to the 1.33-Mev resonance observed by Mozer.[6] The larger width, derived from proton scattering, may result from the neglect of a level near $E_p=1.6$ Mev in the analysis of the scattering experiments.[20] That the 1.084-Mev resonance was not observed either in the (p,d) or (p,α) experiments is consistent with a $J=0^+$ assignment[6] for the corresponding 7.56-Mev level in B^{10} which forbids the emission of ground state deuterons and α particles. Near 1.6 Mev where a strong peak appears in the differential cross-section curves at backward angles, only a weak maximum is visible in the total cross section. Strong interference effects with neighboring levels and the nonresonant (probably pickup) background must be responsible for this behavior.

The total (p,d) cross-section curve shows a resonance at $E_p=0.93$ Mev with a width of 130±30 kev. The equality of the width of the 0.930-Mev resonance found in the (p,d) reaction and that of the 0.998-Mev resonance found in the elastic scattering[6] suggests that the corresponding levels are actually identical. Why the resonance energies do not agree is not clear; it is possible that the peak in the (p,d) experiments is shifted to a lower energy by the interference with a level or levels of the same parity, or by the interference of resonant and nonresonant (possibly pickup) amplitudes of the same parity. It is known[1] that the resonance level at $E_p=0.33$ Mev ($B^{10*}=6.88$ Mev) strongly emits deuterons and α particles as well as intense $E1$ radiation[21] to the $T=1$ level at 1.74 Mev. The 6.88-Mev level is therefore identified[21] as a $J=1^-$, $T=0$ state formed by s-wave protons; the deuteron and α-particle widths arise from a sizable $T=1$ impurity resulting from strong coupling to another $J=1^-$ state with $T=1$ at a higher energy. If one assumes that this latter state is the $T_\xi=0$ analog of one of the levels at 5.96, 6.18, and 6.26 Mev in Be^{10}, it should correspond to a proton energy of about 1.5 Mev. The broad maximum near 1.6 Mev in the total (p,d) cross-section curve (Fig. 3) or (less likely) the one at 2.3 Mev may be due to this level. It is possible that a similar situation obtains for the 7.48-Mev state ($E_p=0.998$ Mev). Since this level has[6] $J=2^-$, the large radiation width for the transition to the ground state[22]

[20] F. S. Mozer (private communication).

[21] D. H. Wilkinson and A. B. Clegg, Phil. Mag. 1, 291 (1956).

[22] W. F. Hornyak and T. Coor, Phys. Rev. 92, 675 (1953).

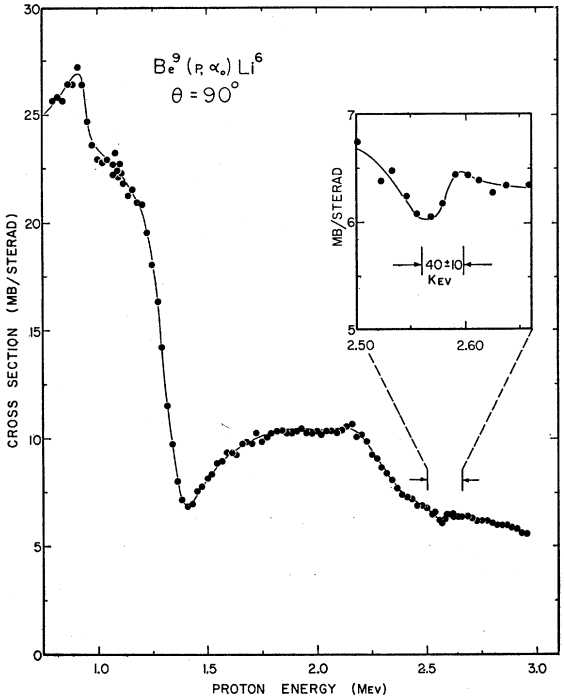

FIG. 6. Differential cross-section curve for the $Be^9(p,\alpha)Li^6$ (ground state) reaction at $\theta=90°$ as a function of bombarding energy. The portion of the curve near the 2.56-Mev resonance is shown in the insert on an enlarged scale. The proton energies have not been corrected for the energy loss in the target (≈ 3 kev). The resonance energy is 2.56 ± 0.02 Mev.

requires $E1$ radiation, and therefore the isotopic spin must be $T=1$. If the 0.930-Mev resonance is indeed due to this level, then the fact that deuteron and α-particle emission is rather strong indicates an appreciable $T=0$ impurity. Such an impurity would result from coupling to a $J=2^-$, $T=0$ state in the neighborhood; this level may be the 7.75-Mev state ($E_p\cong 1.3$ Mev) found in elastic scattering[6] and in the present experiments. It is possible, however, that the 0.930-Mev (p,d) resonance is distinct from the scattering resonance and corresponds to a different B^{10} state at 7.42 Mev. The fact that the (p,α) resonance also occurs at 0.930 Mev may support this hypothesis.

The angular distributions below and above the 1.6-Mev region are peaked forward and do not change very strongly with the bombarding energy, suggesting that part of the reaction cross section is due to a pickup process over the whole energy range studied. This behavior is not surprising in view of the structure of Be^9; because of the low binding energy of the last neutron (1.7 Mev) the Be^8 core and the neutron are during part of the time fairly well separated, and there is a good probability for the incoming proton to pick up the neutron without interacting with the core. That the pickup mechanism can account for the largest part of the reaction cross section near 3 Mev is demonstrated in Fig. 7, where the angular distribution, taken at $E_p=2.84$ Mev, has been fitted by a Bhatia-type[23] stripping curve for $l_n=1$, using a radius[24] of 6.14×10^{-13} cm. The good agreement between the experimental points and the theoretical curve at forward angles leaves little doubt that the reaction proceeds mainly via a pickup process.

B. 2.56-Mev Resonance

None of the six (p,d) excitation curves (Figs. 1 and 2) shows indications of an anomaly near 2.56 Mev, i.e., no systematic deviations of the experimental points from the smooth curves are noticeable. From the maximum deviations of the points from the curves it can be concluded that, if there are contributions to the differential cross sections of a narrow resonance near 2.56 Mev, they must be smaller than about 1.2 mb/sterad at all angles. Since a weak resonance, superimposed on a nonresonant background, is usually visible mainly by virtue of the interference terms, the actual resonance cross section σ_R is probably much smaller. However, since no such effect was observed, one has to rely on the total cross-section curve. From Fig. 3 it can be seen that the total resonance cross section $\sigma_T\lesssim 13$ mb, and from this an upper limit for the deuteron width can be obtained. Taking Marion's value[4] for the reduced proton width $\gamma_p^2=2.5\times10^{-15}$ Mev cm and using the tables of Breit and co-workers[25] to get the penetration factor, a proton width of $\Gamma_p=7$ kev is obtained.[26] With the known total width[3,4,18] of 38 kev, the Breit-Wigner formula yields an upper limit for the deuteron width of $\Gamma_d\lesssim 13.5$ kev for d waves (for $l_p=1$ and $J=2^+$ or 3^+, the angular momenta of the outgoing deuterons, and α_0 particles are uniquely determined to be $l_\alpha=l_d=2$, no matter whether the channel spin in the entrance channel is 1 or 2). The ratio of the reduced width to the sum rule limit is $\theta_d^2\lesssim 4.5\times10^{-3}$. This value is certainly much too large to be used for an estimate of the isotopic spin impurity of the 8.89-Mev state in B^{10}.

The deviation $\Delta\sigma=|\sigma-\sigma_B|$ of the (p,α) cross section from a smooth curve (Fig. 6) in the resonance region is of the order of 0.45 mb/sterad. The cross section at resonance can be expressed as the sum of 3 terms:

$$\sigma(90°)=\sigma_B+\sigma_R+\sigma_I, \qquad (2)$$

where σ_B is the cross section of the nonresonant background, σ_R the resonance cross section, and σ_I is the cross section resulting from the interference of resonant

[23] Bhatia, Huang, Huby, and Newns, Phil. Mag. 43, 485 (1952).

[24] This value is consistent with the radii found in the fitting of (d,p) data from other nuclei with the theory of A. B. Bhatia *et al.* A compilation of these radii has been given by R. Huby [Progr. Nuclear Phys. 3, 177 (1953)].

[25] Bloch, Hull, Broyles, Bouricius, Freeman, and Breit, Revs. Modern Phys. 23, 147 (1951).

[26] The radii for the α-particle and proton channels were obtained from the formula $R(A_1+A_2)=1.45\times10^{-13}(A_1^{1/3}+A_2^{1/3})$ cm. For the estimate of the deuteron width, $R(Be^8+d)$ was taken equal to the stripping radius $R=6.14\times10^{-13}$ cm (see reference 24) which was used to fit the angular distribution of Fig. 7.

and nonresonant amplitudes. Assuming that the entire background is interfering with the resonance amplitude, and that both contributions are completely in phase, one obtains an upper limit for σ_I:

$$|\sigma_I| \leqslant 2\sigma_R^{\frac{1}{2}}\sigma_B^{\frac{1}{2}}. \quad (3)$$

Since $\sigma_R \ll \sigma_B$, Eqs. (2) and (3) give a lower limit for σ_R:

$$\sigma_R \geqslant (\Delta\sigma)^2/4\sigma_B.$$

The opposite extreme case that the resonant and the nonresonant amplitudes have a phase difference of 90°, i.e., $\sigma_I=0$, is evidently not realized, since the shape of the anomaly clearly indicates destructive interference. The pure resonance cross section certainly amounts to less than $\Delta\sigma/2$. The total resonance cross section is $\sigma_{TR}=(16\pi/3)\sigma(90°)$ for entrance channel spin 1 or $\sigma_{TR}=(16\pi/5)\sigma(90°)$ for entrance channel spin 2. Therefore, using $\Delta\sigma(90°)\cong 0.45$ mb/sterad, one obtains

$$0.08 \lesssim \sigma_{TR} \lesssim 3.9 \text{ mb}.$$

For the resonance parameters, one obtains in the same way as for the deuteron case:

$$0.08 \lesssim \Gamma_\alpha \lesssim 4.0 (\text{kev}),$$
$$1.2\times10^{-17} \lesssim \gamma_\alpha^2 \lesssim 6.0\times10^{-16} (\text{Mev cm}),$$
$$2.2\times10^{-5} \lesssim \theta_\alpha^2 \lesssim 1.1\times10^{-3}.$$

Since θ_α^2 must arise from a $T=1$ admixture to the Li^6 ground state and/or a $T=0$ admixture to the $T=1$ state in B^{10},

$$\theta_\alpha^2 = p(Li^6)\theta_{\alpha1}^2 + p(B^{10*})\theta_{\alpha0}^2,$$

where $p(Li^6)$ and $p(B^{10*})$ are the impurities of the states involved. $\theta_{\alpha1}^2$ and $\theta_{\alpha0}^2$ are the dimensionless reduced widths resulting from $T=1$ and $T=0$ parts of the wave functions. For the $(T=1)\to(T=1)$ transition $B^{10}(8.9)\to Li^6(3.57)+\alpha$, Mackin[18] has found a reduced width of $\theta_\alpha^2 \cong 0.25$. If one takes this value for both $\theta_{\alpha0}^2$ and $\theta_{\alpha1}^2$, and uses the estimate of MacDonald[27] for the $T=1$ impurity of Li^6, $p(Li^6)=10^{-4}$, then the upper limit on the isotopic spin impurity of the B^{10} level is $p(B^{10*}) \lesssim 4\times10^{-3}$. About the same upper limit holds for the 3^+ member of the 8.89-Mev doublet, since this state would have been more difficult to observe because of its larger total width.

For $T=0$ states in B^{10} excited to less than about 10 Mev, MacDonald[27] estimates $T=1$ impurities of the order of 10^{-3}. The present result seems to indicate that the $T=1$ states in this region have $T=0$ impurities of the same order of magnitude.

[27] W. M. MacDonald, Phys. Rev. **101**, 271 (1956).

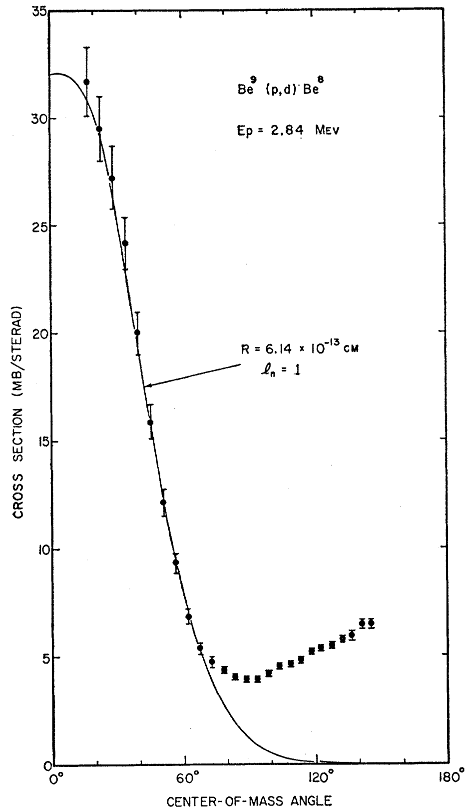

FIG. 7. The angular distribution of the $Be^9(p,d)Be^8$ (ground state) reaction at $E_p=2.84$ Mev in the center-of-mass system. The relative errors are indicated by vertical lines. The solid curve was computed from the stripping theory of Bhatia *et al.*[23] for $l_n=1$ and a radius[24] of 6.14×10^{-13} cm.

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