Magnetic Analysis of the Deuteron-Beryllium Reactions*

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The charged particle spectra from the deuteron bombardment of Be^9 have been analyzed magnetically with a spectrograph employing a second-order focus. Previously established transitions to states in Be^{10} and Li^7 were observed, and a careful search of the proton and alpha-spectra failed to disclose additional states in these nuclei, throughout the region explored. The excitation energy of the second excited state of Li^7 was determined as 4.62 ± 0.02 Mev. The transition to the broad first excited state of Be^8, as well as to the ground state, was revealed in the triton spectrum. Alpha- and triton continue resulting from the three-particle disintegrations, $Be^9(d,\alpha)Li^{7**}(\alpha)t$ and $Be^9(d,t)Be^{8*}(\alpha)\alpha$, were also observed and examined in some detail. Other three-particle disintegrations appear improbable but cannot be definitely excluded, at the bombarding energies employed from 0.5 to 1.0 Mev.

I. INTRODUCTION

THE charged particles emitted during the deuteron bombardment of beryllium have previously been investigated by both range and magnetic analysis. With the former method two groups of alpha-particles,[1] two groups of protons,[2] and a single group of tritons[3] have been observed. With magnetic analysis several investigators[4] have examined these groups and have carefully measured the Q values. In addition, the spectrum of the alpha-particles has been observed up to an excitation energy in Li^7 of about 3.6 Mev by Buechner and Strait[4] and by Inglis,[5] at different bombarding energies. Above an excitation energy in Li^7 of 2.5 Mev, Inglis observed the rise of a broad peak or plateau of alpha-particles. Using range analysis, Gove and Harvey[6] examined the alpha-particle spectrum, at a bombarding energy of 14 Mev. In a careful series of measurements with this reaction and with the inelastic scattering of protons, deuterons, and alphas by the Li^7 nucleus itself, they found a new level in Li^7 at about 4.7 Mev. Other investigators have subsequently observed transitions to this state under a variety of conditions.[7,8] In a study of the angular distributions of the Be^9+d reactions, the emission of tritons of less energy than the ground-state group was observed by Resnick and Hanna.[9]

In the present experiment we have investigated, by means of magnetic analysis, the alpha-spectrum from the deuteron bombardment of beryllium up to an excitation energy in Li^7 of 5.3 Mev, the proton spectrum up to 4.0 Mev in Be^{10}, and the triton spectrum up to 4.8 Mev in Be^8. Bombarding energies ranging from 0.47 to 1.02 Mev were used in various phases of the work. The presence of the short-range alpha-group observed by Gove and Harvey[6] was confirmed, as previously reported.[7] In addition to the well-defined triton group forming the ground state of Be^8, broad structure was observed in a region corresponding to the known state in Be^8 at about 3 Mev. In addition to these features the alpha- and triton continua, previously observed,[5,9] have been studied in some detail. Recently, Cuer and Jung[10] have reported a similar investigation of the triton spectrum using range analysis aided by magnetic deflection.

II. EXPERIMENTAL PROCEDURE

The magnetic spectrograph used in the investigation has been described by Inglis,[5] and the theory has been given by Hafner, Donoghue, and Snyder.[11] The apparatus is now equipped with a more compact magnet and is mounted so that it can be rotated for observations at all angles from about 20° to 160° to the beam. Figure 1 shows a perspective view of the instrument in operation in the present investigation. The angular aperture in the vertical plane was approximately 5°, considerably smaller than was necessary. Because of the relatively high yield of the deuteron-beryllium reactions, the small solid angle was not inconvenient. It did, however, facilitate the identification by range in emulsion of the numerous kinds of particles observed, inasmuch as all the particles entered the emulsion with small angular divergence (at an angle of about 35° to the emulsion). The manner in which the energy coverage of the instrument varies with the magnetic field is illustrated by Fig. 2. At a field of approximately 14 kilogauss, for example, the range covered is from

* Assisted by a contract with the AEC.
[1] E. R. Graves, Phys. Rev. **57**, 855 (1940).
[2] Oliphant, Kempton, and Rutherford, Proc. Roy. Soc. (London) **A150**, 241 (1935); Lattes, Fowler, and Cuer, Proc. Phys. Soc. (London) **59**, 883 (1947).
[3] Williams, Haxby, and Shepherd, Phys. Rev. **52**, 1031 (1937).
[4] W. W. Buechner and E. N. Strait, Phys. Rev. **76**, 1547 (1949); Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948); Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951); W. Whaling and C. W. Li, Phys. Rev. **81**, 150 (1951); Williamson, Browne, Craig, and Donahue, Phys. Rev. **84**, 731 (1951); E. D. Klema and G. C. Phillips, Phys. Rev. **86**, 951 (1952).
[5] D. R. Inglis, Phys. Rev. **78**, 104 (1950).
[6] H. E. Gove and J. A. Harvey, Phys. Rev. **82**, 299, 658 (1951).
[7] Gelinas, Class, and Hanna, Phys. Rev. **83**, 1260 (1951).
[8] A. Ashmore and J. F. Raffle, Proc. Phys. Soc. (London) **A65**, 296 (1951); W. Franzen and J. G. Likely, Phys. Rev. **87**, 667 (1952).
[9] I. Resnick and S. S. Hanna, Phys. Rev. **82**, 463 (1951).
[10] P. Cuer and J. J. Jung, Compt. rend. **234**, 204 (1952).
[11] Hafner, Donoghue, and Snyder, privately circulated report.

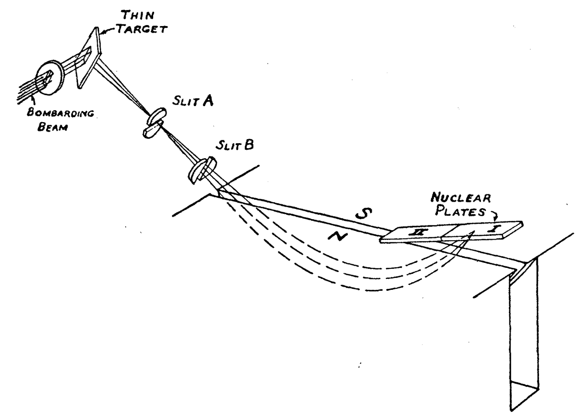

FIG. 1. Perspective view of the spectrograph in this experiment.

4.1 to 2.9 Mev on the first photographic plate, and from 2.9 to 1.95 Mev on the second plate (on a proton or alpha-energy scale, the two scales being nearly the same). At each field setting the ratio of maximum to minimum energy is about 2.1, when two 3-inch plates are used. The upper energy limit for protons (alphas) is about 6 Mev at present, the limiting factor being the heating of the field coils. Since the plate holder, which is three-sided, accommodates three pairs of plates, it is possible to cover the range from $E_p=0.8$ to 6.0 Mev, for example, in three exposures without breaking the vacuum in the spectrograph.

The energy scale for each exposure was established by using the known bombarding energy and accurate Q values to establish the energies of prominent particle groups. The energy of a group is related to its position on the plate by the expression $E=A(s-x)^2$, where E is the energy, A depends only on the magnetic field and hence is a constant for a given exposure, s is a geometrical constant of the instrument, and x is the displacement from the high energy end of the plate. By using two groups of particles of known energy (preferably protons) both A and s could be determined. The above expression is theoretically correct for a spectrograph with a uniform field in the gap and no fringing field outside. In practice, these conditions are not completely satisfied, but the procedure was satisfactory in that it predicted the location of other known peaks within the accuracy of the measurements. In establishing the energy scale, corrections were applied to account for energy losses in the target.

The chief contribution to the widths of the observed peaks came from the thickness of the targets employed. At the low bombarding energies used in this series of observations, the energy spread produced in the incident deuterons by the target thickness is relatively large, on the order of 30–40 kev, for most of the targets used. The maximum broadening of the peaks from other sources, such as fluctuations in the energy of the deuteron beam or in the magnetic field of the spectrograph, is estimated at 10–20 kev. For many of the runs an unbacked beryllium foil of approximately 0.07 mg/cm^2 was placed at an angle of 45° with respect to the beam. To reduce broadening of the observed peaks, the setting was made so that the beam impinged on the front and the reaction products emerged from the back of the foil, as illustrated in Fig. 1. The observations on the $Be^9(d,t)Be^8$ reaction were made on a beryllium layer of about the same thickness deposited on a solid backing, and the setting was made so that the reaction products emerged from the front surface. The investigation of the structure in the vicinity of the Li^{+++} recoils was obtained with a considerably thinner deposit of beryllium ($\sim$0.02 mg/cm^2) on thick backing. The best value obtained in the investigation for the ratio of the energy of a group to the width of its peak at half-maximum was about 100. The sharpest group observed had a width of 25 kev at an energy of 1.6 Mev.

In all some 15 exposures were made at 10 different field settings to obtain the spectra presented. (A cut-off valve with a wide aperture, installed between the target chamber and the spectrograph, makes it possible to change photographic plates while the target remains in vacuum.) All the observations were made at 90° to the beam. The nuclear plates (25-micron emulsions) were counted in a microscope at a magnification of 450. Swaths about 200 microns wide were counted at 1-mm intervals along the plate for a preliminary survey. When better statistics or greater resolution were needed, each adjacent swath was counted. Identification of particles was by means of their deflection in the magnetic field and range in the emulsion. Because the

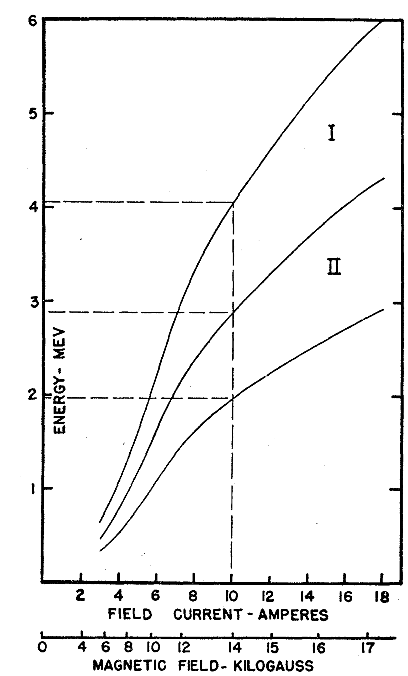

FIG. 2. Energy coverage of the spectrograph. Regions I and II correspond to the nuclear plates labeled in Fig. 1.

directions of particles striking the plate vary through the acceptance angle of the spectrograph, the projected range which was the observed quantity is not a sensitive criterion. In the present observations the method does not distinguish among H^{3+}, He^{4++}, and Li^{7+++} particles. All other particles were readily identified. In order to be acceptable, tracks had to satisfy a length criterion and enter the emulsion in the proper direction.

For convenience the spectra are plotted on an energy scale. Each type of particle therefore has a different scale, the relationship between any two scales being given by the factor $(m_1/m_2)(q_2/q_1)^2$. For alphas and protons the scales are the same to within 0.8 percent. The tracks observed in a swath of fixed width in the microscope are the count in a fixed momentum interval. This was converted to the number in a fixed energy interval by means of the factor $dx/dE=(s-x)/2E$, the symbols having been defined above. In the ideal case when the target spot is restricted so that particles passing through slit *B* (in Fig. 1) do not encounter the pole faces of the magnet, the solid angle of the spectrograph is independent of the radius of curvature. This ideal geometry is not readily achieved, and it limits the aperture of the instrument in any practical arrangement. In the present investigation, slit *B* was not employed. Although the instrumental scattering was not serious, the solid angle was no longer independent of the radius of curvature. In the vertical dimension (Fig. 1) the angular aperture is determined only by the height of the target spot and the distance of slit *A* from the target. In the horizontal dimension, however, the particle trajectories are limited by the pole faces of the magnet at the point where the rays emerge from the gap. Hence, the solid angle decreases linearly with increasing radius of curvature, the ratio of maximum to minimum solid angle being 1.24. This correction has been applied to the observations.

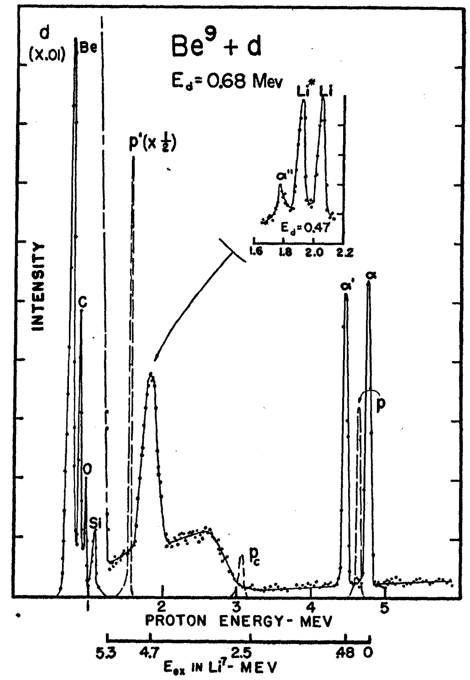

FIG. 3. The charged-particle spectrum at 90° resulting from the deuteron bombardment of Be^9. Above 1.3 Mev the solid curve represents alphas, tritons, or Li^{+++} particles; below 1.3 Mev the curve represents elastically scattered deuterons to a reduced scale. The dashed curve represents protons; the group labeled p_c is from carbon.

III. RESULTS

Figure 3 shows the spectrum of charged particles below $E_p=6$ Mev resulting from the bombardment of beryllium by 0.68-Mev deuterons. Starting at the high energy end of Fig. 3 there is a low background of tritons which declines towards lower energy. The strong alpha-peaks at about 4.8 and 4.5 Mev are from $Be^9(d,\alpha)$-Li^7, Li^{7*}. The triton background continues to fall slowly, but at about 3.2 Mev a rise in the background is evident. This rise and subsequent plateau[5,7,10] are attributed to alphas from the following three-particle disintegrations: $Be^9(d,\alpha)Li^{7**}(\alpha)H^3$, and $Be^9(d,t)Be^{8*}$-$(\alpha)He^4$. A third source of alphas might be the simultaneous three-body breakup of the compound nucleus B^{11}. The triton spectrum bears on the interpretation of this continuum, and the question is discussed below. Below 3 Mev and the alpha-yield reaches a maximum and then falls gradually until an energy of about 2.0 Mev is reached. Here a prominent peak occurs which is due to the triply charged Li^7 nuclei formed in the reactions, $Be^9(d,Li^7)He^4$ and $Be^9(d,Li^{7*})He^4$, but the two groups are unresolved. This region of the spectrum was also examined at a bombarding energy of 1.02 Mev, but no significant change in the structure was observed. Also contributing to the peak at 2 Mev is the alpha-group resulting from the $Be^9(d,\alpha)Li^{7**}$ reaction. At the time that these data were obtained, this new state in Li^7 had not yet been discovered. After Harvey and Gove had announced evidence for the state,[6] we were also able to detect it using the more favorable bombarding energy of 0.47 Mev (see Fig. 4) and a thinner target. This observation is shown in an insert in Fig. 3.

The measured separation of this short-range alpha-group from the Li^7 group is 264 ± 10 kev (alpha-energy scale), and from the Li^{7*} group it is 128 ± 10 kev, at the bombarding energy of 0.47 Mev. The corresponding excitation energy in Li^7 may be calculated from the expression:

$$E_x=(\tfrac{5}{9})Q+(\tfrac{5}{9}+4M_1/9M_2-M_1/M_3)E_1+(M_2+M_3)S/M_3.$$

Q is the energy release for a lithium group, *S* is the separation of the alpha-group from this lithium group, and E_1 is the bombarding energy. The subscripts 1, 2, and 3 refer, respectively, to the deuteron, alpha-, and lithium particle. When values for the Li^{7*} group are used, the formula gives the excitation energy above the

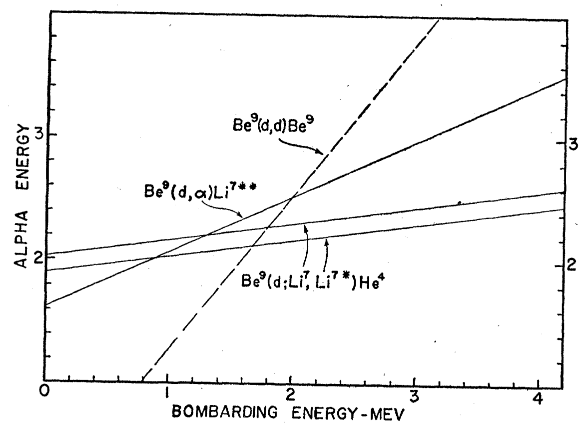

FIG. 4. The variation with bombarding energy of the energy of the alpha-group from the $Be^9(d,\alpha)Li^{7**}$ ($E_{ex}=4.62$ Mev) reaction, showing the relationship to other groups observed with magnetic deflection. The ordinate, labeled "alpha energy," must be multiplied by the factor $(m_\alpha/m)(q/q_\alpha)^2$ to give the energies of the other groups shown.

0.478-Mev state in Li^7. Using $Q=7.153\pm0.006$ Mev and the masses given by Li *et al.*,[12] we obtain an excitation energy of 4.62 ± 0.02 for the second excited state.

Below 1.6 Mev the alpha-background continues to fall and is completely obscured below 1.25 Mev by elastically scattered deuterons. Four well-resolved groups of deuterons are observed, corresponding to scattering from beryllium, carbon, oxygen, and silicon (the latter arising from the use of pump oil containing silicon). Each surface contamination, undoubtedly present on both sides of the unbacked beryllium foil, gives rise to a single peak only, because of the compensation obtained with the setting of the target. A deuteron scattered from the front surface must subsequently pass through the target to reach the spectrograph, while one from the back surface will have already traversed the foil. In either case one traversal of the target is required. The proton peaks at about 4.7 and 1.6 Mev are the well-known groups from beryllium, and the one at 3.1 Mev is from carbon. No trace of other structure which could be attributed to beryllium was observed in the proton spectrum.

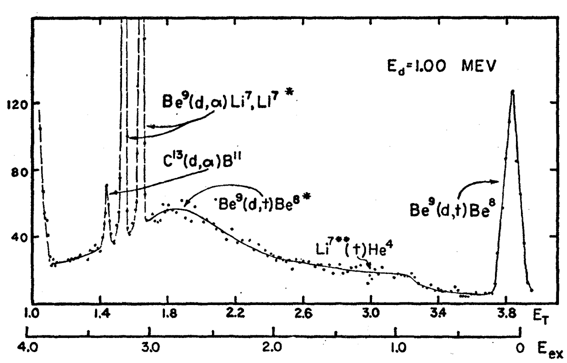

FIG. 5. The charged-particle spectrum at 90° resulting from the deuteron bombardment of Be^9. The solid curve represents tritons, the dashed curve alphas. Proton groups were not included. E_{ex} signifies the excitation energy in Be^8.

[12] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. 83, 512 (1951).

With magnetic deflection a triton having the same radius of curvature as an alpha has only one-third the energy. Thus the maximum energy of tritons which can be focused in the spectrograph is about 2 Mev, and absorbing aluminum foils were used at slit *A* (Fig. 1) to obtain the spectrum of higher energy tritons. Five runs were made at $E_d=1.0$ Mev, with a different foil thickness for each run, in order to cover the triton spectrum above 1.8 Mev. Another run without foil covered the range from 1.2 to 1.8 Mev. In the latter

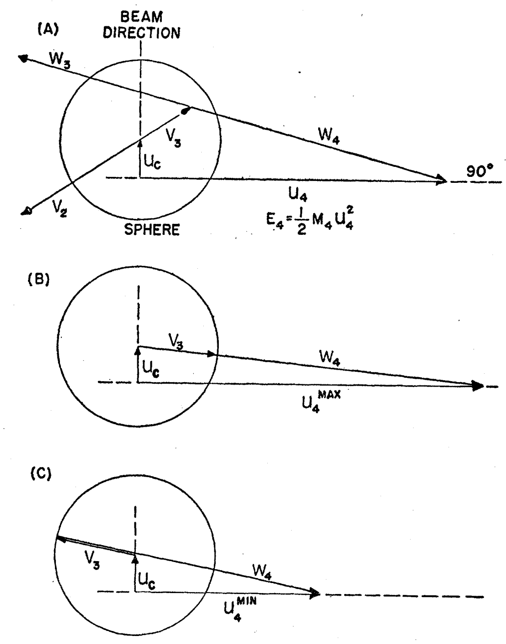

FIG. 6. Velocity diagrams for three-particle disintegrations of the type $P_0(P_1, P_2)P_3(P_4)P_5$. U_c represents the velocity in the laboratory frame of the center of mass of all the particles. V_2 and V_3 are velocities of P_2 and P_3 in the c.m. system of the particles. W_4 and W_5 represent velocities of P_4 and P_5 in the c.m. system of P_3. U_4 is the velocity of P_4 in the laboratory. (A) represents a general case in which P_4 is observed at $\theta=90°$ in the laboratory. (B) and (C) denote, respectively, orientations of the vectors for which U_4 attains its maximum and minimum, at $\theta_L=90°$.

exposure the alpha-group arising from the $C^{13}(d,\alpha)B^{11}$ reaction was detected on the trailing edge of the strong alpha-group from Be^9 (30 times more intense).

The triton spectrum covering triton energies from 1.0 to 3.9 Mev appears in Fig. 5. Again the ordinate of the energy spectrum represents the yield in a fixed energy interval and includes the solid angle correction. An additional correction was necessary because of the use of absorbing foils, which distort the energy scale. When these corrections were made, the results from the five runs joined smoothly together. The energy scale for the triton spectrum was calculated with the aid of the range energy curves for aluminum given by

Gross.[13] The nominal foil thickness as given by the manufacturer could be checked and if necessary adjusted by means of the shift in energy observed in the proton groups from carbon and oxygen impurities on the target. The ground-state triton group also provided a determination of the foil thickness used in obtaining the high energy end of the spectrum. The uncertainty in the energy scale in Fig. 5 is estimated to be $\pm$ 50 kev.

At the highest triton energy there appears the discrete triton group from the ground state $Be^9(d,t)Be^8$ reaction. The background from 3.7 to 3.3 Mev is very low, but just below 3.3 Mev it shows a definite rise. The yield remains constant to about 2.6 Mev, where it again begins to rise, reaching a broad peak at 1.8 Mev. Below 1.8 Mev the yield falls, and is about the same at 1.1 Mev as at 2.6 Mev. By referring to the scale of energy of excitation in Be^8, it will be seen that the broad peak is at the correct energy and of the proper width to be identified with the broad state at 2.9 Mev in Be^8. The rise in the background just below 3.3 Mev and subsequent plateau may be attributed to the triton

TABLE I. Maximum and minimum energies of particles produced in the various possible three-particle disintegrations. $E_d=1.0$ Mev and $\theta=90°$.

	Tritons		Alphas	
	E_{max}	E_{min}	E_{max}	E_{min}
$Be^9(d,\alpha)Li^{7*}\cdots(t)\alpha$				
$E_{ex}=4.62$ Mev	3.27 Mev	0.09 Mev	3.13 Mev	0.00 Mev
6.56	3.90	1.06	3.38	0.54
7.46	3.80	1.91	3.10	1.21
$Be^9(d,t)Be^{8*}(\alpha)\alpha$				
$E_{ex}=2.0$			2.84	0.05
2.9			3.20	0.34
3.8			3.40	0.79
$Be^9(d,t)2\alpha$	3.96	0.00	3.43	0.00

continuum which would result from the breakup into an alpha and a triton of recoiling Li^7 nuclei formed in the second excited state at 4.62 Mev. The calculated maximum energy of tritons from this reaction is 3.27 Mev at the bombarding energy of 1.0 Mev (see Fig. 6 and Table I). Considering the straggling produced by the absorbing foils, and the uncertainty in the energy scale, the agreement between the experimental rise in the background and the calculated maximum energy is quite satisfactory. The appearance of the triton spectrum in this region, and its interpretation, agree with the observations and conclusions of Cuer and Jung.[10] It is interesting on the basis of this interpretation to estimate the intensity of the triton continuum produced by the disintegration of Li^{7**} nuclei, and hence the intensity of the transition to the 4.62-Mev state. Since the shape of the continuum is not established throughout, only a rough estimate can be given. It would appear that at the bombarding energy of 1.0 Mev

[13] E. P. Gross, *Range, Energy Ionization Curves* (Princeton University Press, Princeton, 1947).

TABLE II. Relative intensities of transitions from Be^9+d. Values in most cases are only approximate, and were measured at 90° in the laboratory system. The value for $Be^9(d,\alpha)Li^{7**}$ at $E_d=1.0$ Mev was estimated from the triton continuum from the disintegration of Li^{7**}. The yields at each energy have been normalized to make the ground-state alpha-yield = 10.

	$E_d=0.47$ Mev	0.68 Mev	1.0 Mev
$Be^9(d,\alpha)Li^7$	10	10	10
$Be^9(d,\alpha)Li^{7*}$	10	9.5	7.0
$Be^9(d,\alpha)Li^{7**}$	2		10
$Be^9(d,t)Be^8$			3.5
$Be^9(d,t)Be^{8*}$		10	15
$Be^9(d,p)Be^{10}$		5	4.5
$Be^9(d,p)Be^{10*}$		8	

the transition to the 4.62-Mev state is about as probable as the transition to the ground state (Table II). This is in contrast to the situation at $E_d=0.47$ Mev, where the intensity is at most one-quarter the intensity of the ground-state transition. This relative increase is not necessarily surprising, but it may be simply a result of overestimating the number of tritons from the Li^{7**} disintegration possibly because of the presence of tritons produced by some other mechanism. Table I lists the maximum and minimum energy of the continuous distributions for the various possible three-particle processes. It is seen that the disintegration of lithium nuclei in the next two known excited states, at $E_{ex}=6.56$ and 7.47 Mev, will produce tritons throughout this region, as will also the simultaneous three-particle disintegration. All three of these processes have high energy limits beyond the limit of the distribution corresponding to the 4.62-Mev state. One or more of these processes may therefore account for the low background observed between 3.3 and 3.8 Mev in the triton spectrum, although at least some of this background may be attributed to instrumental scattering.

The high energy end of the alpha-continuum is shown in greater detail in Fig. 7, at the higher bombarding energy of 1.02 Mev. The yield first begins to rise

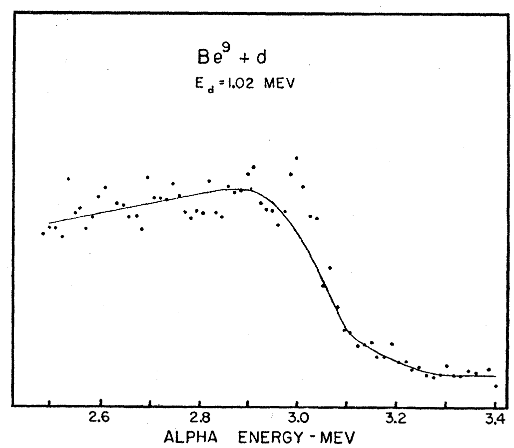

FIG. 7. Detailed view of the spectrum near the high energy limit of the alpha-continuum. The structure at 3.0 Mev is probably due to the $O^{16}(d,\alpha)N^{14}$ reaction.

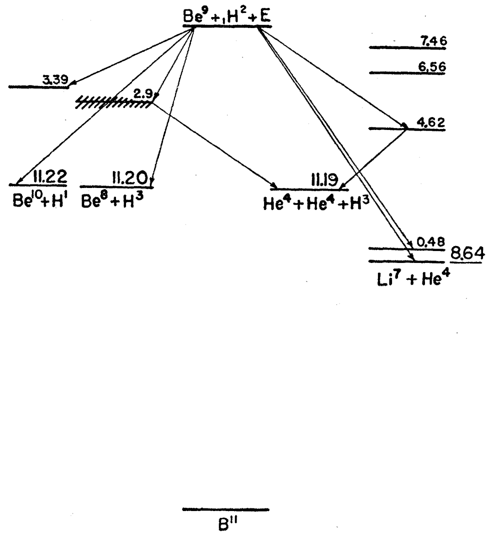

FIG. 8. Energy-level diagram showing the transitions observed in this investigation. With the exception of the value 4.62 Mev, the energies are taken from the literature.

slightly, at about an alpha-energy of 3.3 Mev. The rise becomes more pronounced at 3.1 Mev and reaches a maximum in the vicinity of 2.9 Mev, and then declines slowly. At about 3.0 Mev there appears to be a peak in the spectrum, somewhat in excess of a likely statistical fluctuation. The alpha-group from $O^{16}(d,\alpha)N^{14}$ should fall at 3.10 Mev. If this identification is correct, it establishes that there is an average loss of approximately 100 kev for alpha-particles coming from the target which was oriented as shown in Fig. 1. Taking this loss into account, it is seen from Table I that the maximum energy for alphas from the $Be^9(d,\alpha)Li^{7**}(t)\alpha$ ($E_{ex}=4.62$ Mev) process is about 3.0 Mev. For the $Be^9(d,t)Be^{8*}(\alpha)\alpha$ reaction, which is also established by the triton spectrum, a discrete upper limit cannot be given because of the great breadth of the state in Be^8. Above about 3.1 Mev, however, the yield should decline and practically vanish in the neighborhood of 3.3 Mev. Qualitatively the observed fall in the spectrum is in agreement with these high energy limits. Unfortunately, the distributions corresponding to the next two excited states in Li^7, $E_{ex}=6.56$ and 7.47 Mev, would not be detected unless they had appreciable intensities. In agreement with the triton spectrum, these reactions, as well as the simultaneous process, are apparently much less likely than the other two processes at these bombarding energies.

A summary of all the transitions observed in this investigation is given in Fig. 8. The observations extended up to 5.3 Mev in Li^7, 4.0 Mev in Be^{10}, and 4.8 Mev in Be^8. Because of the alpha-continuum from the three-particle processes, the region above 3.8 Mev in Be^8 and 2.6 Mev in Li^7 could not be examined in as great detail as elsewhere. The ratios of the alpha-yields to the doublet ground state of Li^7 where rather accurately determined and are summarized in Fig. 9, together with results of other investigators.

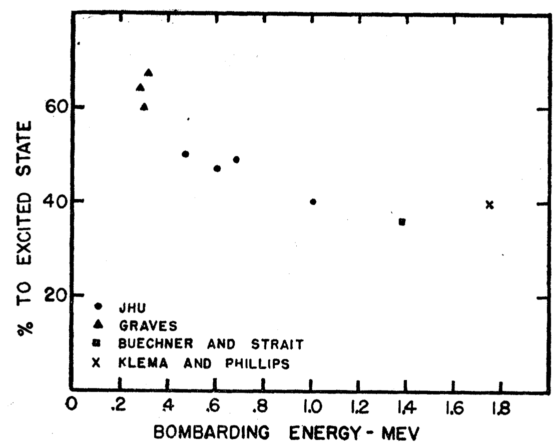

FIG. 9. Fraction of the alphas from $Be^9(d,\alpha)Li^7$, Li^{7*} which go to the 480-kev state. At about 0.3 Mev the results given by Graves (reference 1) indicate about 63 percent to the first excited state. The present work, including the measurement of Inglis (reference 5), indicates a decrease to about 40 percent at 1.0 Mev. The values at 1.4 and 1.75 Mev are estimated from the spectra presented, respectively, by Buechner and Strait and by Klema and Phillips (reference 4); they indicate a fairly constant percentage of transitions to the first excited state, above 1.0 Mev.

It is a pleasure to acknowledge the original impetus given this investigation by D. R. Inglis, who also designed and put into operation the spectrograph used in the investigation. P. Milich was responsible for a major part of the construction and assembly of the new mounting and magnet which were installed before the present investigation. We are also indebted to R. T. Frost for several helpful discussions.