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Alpha-Particle Spectra Produced in the Reactions of Deuterons on Li^7†

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The alpha particle spectra from the Li^7+d reactions were determined for deuteron energies from 0.7 to 3.0 MeV. Alpha-particle groups resulting from the breakup of Be^9 and Be^8 are identified. In the excitation functions of the different groups, states in Be^9 are seen at $E_d=1.75$ and 2.5 MeV, and in Be^8 at $E_d=2.05$ MeV and probably also at 2.5 MeV. They are presumably to be identified with the states at 18.1 and 18.6 MeV in Be^9 tentatively assumed from earlier work and the states at 16.62 and 16.92 MeV in Be^8 as also seen in earlier work.

I. INTRODUCTION

ONE of the possible tests of the conserved vector current theory of β decay in the $A=8$ isotopic spin triplet[1] has recently focused new interest on the excited states in Be^8 between 16 and 18 MeV, in particular, the first $T=1$ state in Be^8. The work reported here was initially undertaken in order to determine production cross sections for the first $T=1$ state as a preliminary to obtaining the gamma-ray width of the state, essential to the test metnioned above. This region in Be^8 is readily accessible by the following four reactions[2]:

1. $Li^7(d,n)$, $Q=15.026$ MeV;
2. $Li^6(He^3,p)$, $Q=16.786$ MeV;
3. $Be^9(He^3,\alpha)$, $Q=18.911$ MeV;
4. $B^{10}(d,\alpha)$, $Q=17.89$ MeV.

All four reactions have been used recently to study the region between 16 and 18 MeV.

Dietrich and Cranberg[3] investigated the neutrons from reaction 1 by a time-of-flight method. They found states at 16.62, 16.92, and 17.4 MeV in the region of interest. A good stripping pattern for the first state and isotropy for the second state suggests that the state at 16.62 MeV is the equivalent state to the ground state of Li^8 with $J=2^+$, $T=1$, which also shows such a stripping pattern. The state at 17.4 MeV was identified with the well known $J=1^+$, $T=1$ state, generally placed at 17.64 MeV.[2]

Erskine and Browne[4] looked for protons and alphas in reactions 2, 3, and 4. They again found states in Be^8 at 16.62 and 16.92 MeV with widths of (95 ± 20) and (85 ± 20) keV, respectively, as well as the state at 17.64 MeV.

A wide state at 16.08 MeV reported previously by Slattery *et al.*,[5] cannot be entirely excluded but no evidence for it was found in the work quoted above. No direct determination of the spin of any of the states of interest has yet been made. The tentative level scheme for Be^8 is shown in Fig. 1.[6]

These states are unstable only with respect to alpha, proton, and gamma emission. In reaction 1 the deuteron (laboratory) energies corresponding to threshold excitation energies of 16.62 and 16.92 MeV in Be^8 are $E_d=2.05$ and 2.45 MeV, respectively. The alphas have been looked for by Weber[7] using reaction 1. Weber used deuteron energies from $E_d=1$ to 2.2 MeV, but found no evidence of an alpha group related to these states. Bilwes *et al.*[8] have reported finding the 16.62-MeV state by an $\alpha-\alpha$ coincidence method using the $Li^7(d,n)$ reaction but do not report any cross sections. It was, therefore, considered worthwhile to look again for these alpha groups. Reaction 1 was used again, since it seemed particularly suited for this purpose, being the only one in which an excitation curve can be measured going over the threshold for production of the states of interest. In the same reaction, Be^9 is formed by compound nucleus compound nucleus capture of the deuteron, with a Q value of 16.693 MeV.[2] As shown in Fig. 2,[9] there are four known levels in the region of deuteron bombardment energies up to about 3 MeV. The two at 17.28 and 17.48 MeV corresponding to $E_d=0.68$ MeV and $E_d=0.98$ MeV in the reaction Li^7+d, are well known.[2] Indications of a state at 18.1 MeV have been seen in the reactions $Li^6(t,d)$,[7] $Li^7(d,p)$,[10] and $Li^7(d,n)$.[5] Another level at 18.6 MeV is suggested by the results of $Li^6(t,\alpha)$[11] and $Li^7(d,n)$.[5] In the latter reaction, the two levels should occur at deuteron energies of about 1.8 and 2.5 MeV, respectively.

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[1] M. E. Nordberg, F. B. Morinigo, and C. A. Barnes, Phys. Rev. **125**, 321 (1962).

[2] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).

[3] F. S. Dietrich and L. Cranberg, Bull. Am. Phys. Soc. **5**, 493 (1960).

[4] J. R. Erskine and C. P. Browne, Phys. Rev. **123**, 958 (1961).

[5] J. C. Slattery, R. A. Chapman, and T. W. Bonner, Phys. Rev. **108**, 809 (1957).

[6] See also, Landolt-Börnstein, "Energy Levels of Nuclei: $A=5$ to $A=257$" (Springer-Verlag, Berlin, 1961), Group I, Vol. I, pp. 1-16.

[7] Gustav Weber, Phys. Rev. **110**, 529 (1958).

[8] R. Bilwes, B. Bourotte, and D. Magnac-Valette, J. Phys. Radium **22**, 568 (1961).

[9] Reference 6, pp. 1-20.

[10] L. S. Bezrukos, D. A. Panov, and D. V. Timoshuk, Soviet J. At. Energy **4**, 609 (1956).

[11] R. W. Crews as quoted in report LA-2014, 1952 Los Alamos Scientific Laboratory Report (unpublished).

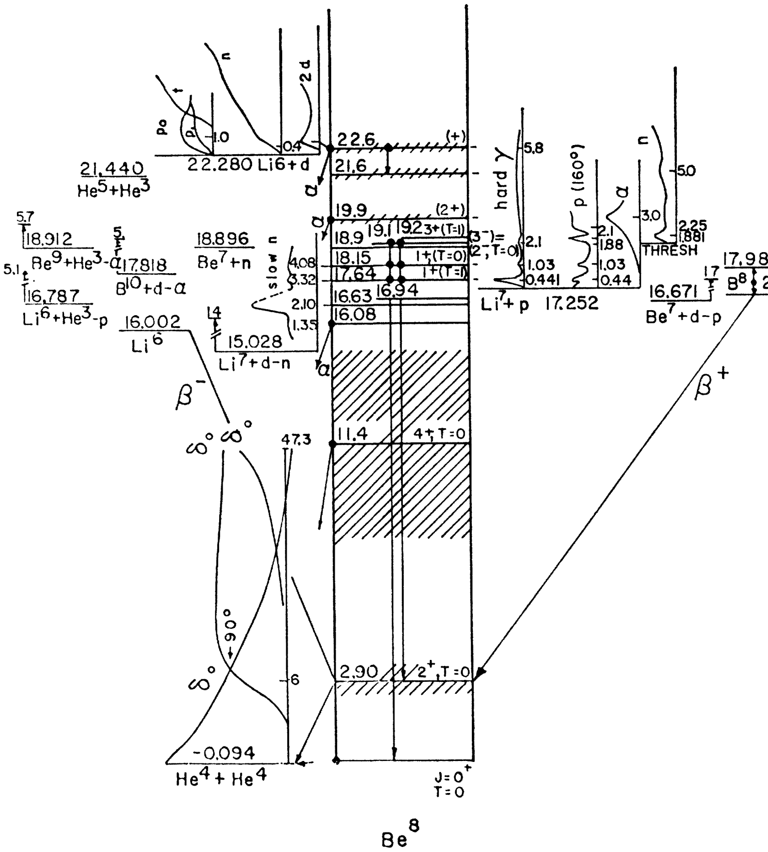

FIG. 1. An energy level diagram for Be^8 including some of the pertinent information on the reactions leading to this nucleus. Taken from an Ajzenberg-Selove and Lauritsen report of August 1960 (California Institute of Technology) with, however, deletion of some material not relevant to this work.

II. EXPERIMENTAL PROCEDURE

In this experiment, thin targets of lithium were bombarded with deuterons of (laboratory) energy $E_d = 0.8$ to 3.1 MeV in steps of 100 keV, except that 50 keV steps were taken around $E_d = 2.1$ MeV, where the 16.62-MeV state in Be^8 should first appear. For each excitation energy, the energy distribution of all outcoming charged particles was measured at 90° to the beam axis.

The target consisted of natural metallic lithium evaporated in the target chamber onto a 0.004-mil nickel foil. The thickness of each target was determined by inserting a second target containing fluorine behind the first one. With a proton beam, the resonances at $E_p = 874$ and 935 keV in the (α,γ) reaction of $F^{19}+p$ were excited and the resulting high energy gammas detected. The measured shift of the positions of the rising edges of both resonances before and after Li evaporation was used to compute the target thickness. The thickness of the target used for the data quoted below was 57 keV for 874-keV protons. The shape of the observed resonances also turned out ot be a good check on the uniformity of the Li targets.

A liquid nitrogen cooling trap enclosed the target almost completely in an attempt to prevent carbon build up. This was done primarily because the amount of carbon deposition seemed to determine the useful

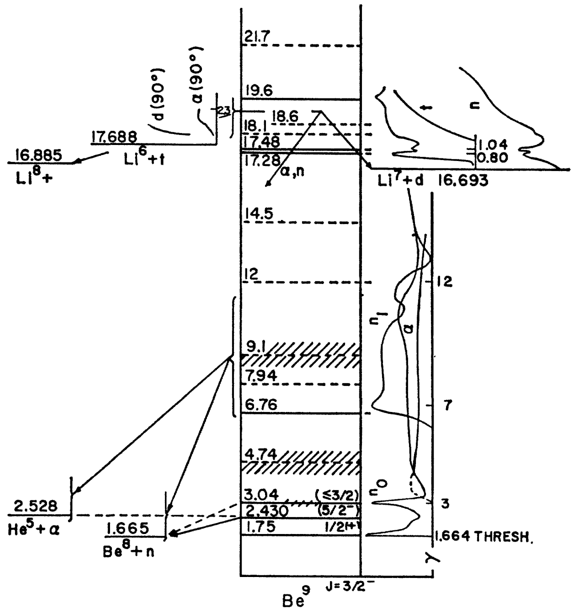

FIG. 2. An energy level diagram for Be^9 including some of the pertinent information on the reactions leading to this nucleus. Taken from an Ajzenberg-Selove and Lauritsen report of August 1960 (California Institute of Technology) with, however, deletion of some material not relevant to this work.

lifetime of a target foil. However, the improvement noted with the trap was small.

The charged particles were detected in a diffused surface layer silicon solid state counter made by RCA. At a bias voltage of 45 V, the detector stopped all particles that could be expected from the reactions of deuterons on lithium and all likely contaminations in the range of deuteron energies used in the experiment. The detector sensitive area was 5 mm^2, but a mask shielding the front face left only a 40-mil-diam aperture in the center. The pulses coming from the detector were fed into a Fairstein type charge sensitive preamplifier, an A-61 main amplifier and were then analyzed and stored in an RCL 256-channel pulse-height analyzer. The resolution of the detection system was checked with the reaction $\mathrm{Li}^6(d,\alpha)^2$ which produces a nonresonant α group at about 12 MeV. With a bias voltage of 45 V, the width was approximately 1.3%, half of which is estimated to result from kinematic spread.

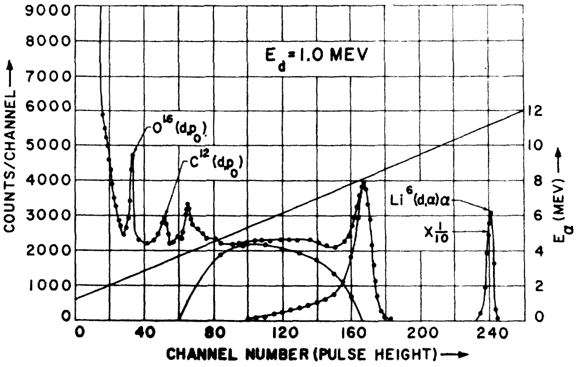

FIG. 3. Alpha-particle spectrum from the reactions of deuterons on natural lithium at a deuteron energy of 1.0 MeV. The high energy group at about 11 MeV (which is scaled up by a factor of 10) results from the reaction $\mathrm{Li}^6+d\rightarrow 2\alpha$. The prominent and broad peak at about 8 MeV results from the breakup of (Be^{9*}) into He^4 and He^5 (ground state). The sharp peaks at lower energies are due to protons from the (d,p) reactions on various target contaminations. The significance of the additional curves drawn in is explained in the text of the paper.

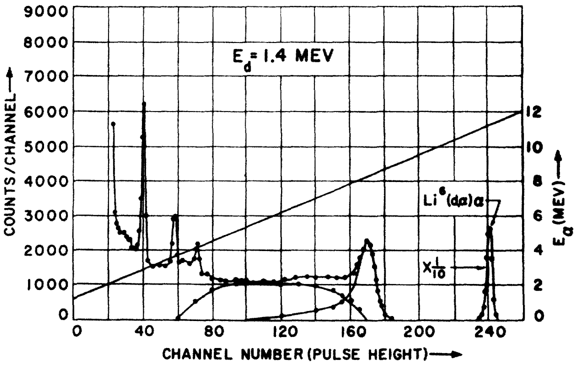

FIG. 4. Alpha-particle spectrum from the reactions of deuterons on natural lithium at a deuteron energy of 1.4 MeV. General features are as explained in Fig. 3.

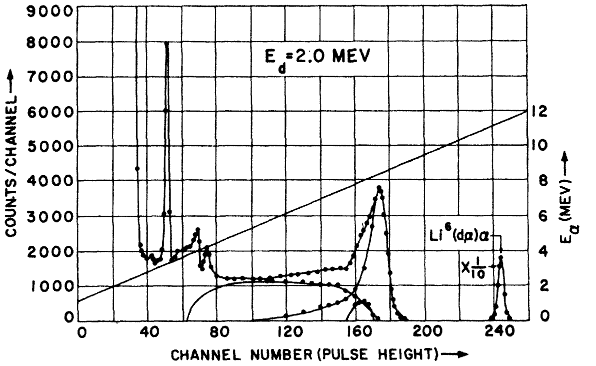

FIG. 5. Alpha-particle spectrum from the reactions of deuterons on natural lithium at a deuteron energy of 2.0 MeV. General features are as explained in Figs. 3 and 4 except for the appearance of a distinct α-particle group at about 8 MeV which is attributed to the production and breakup of the 16.62-MeV state of Be^8. See text of paper for further discussion.

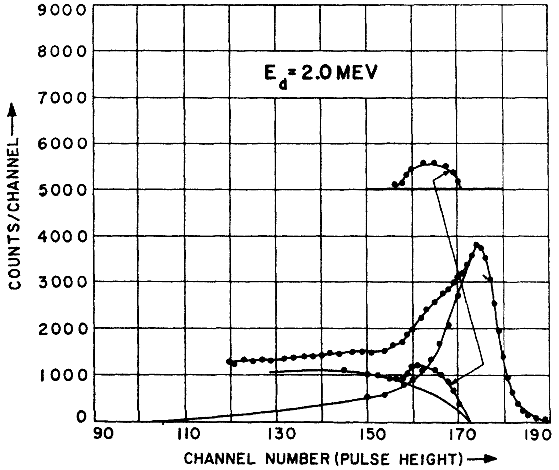

FIG. 6. The region around 8 MeV of Fig. 5 is shown here in an enlarged scale in order to more clearly show the decomposition into the various groups.

The deuterons were accelerated in the Stanford 3-MeV High Voltage Engineering Corporation Van de Graaff generator. The beam current used was about 0.3 μA. It was monitored with cooling trap, target holder, and beam catcher connected together electrically. The beam system was carefully lined up, so that the current on the cold trap was kept below 2% of the total. This was checked before and after each run. The energy of the deuterons was determined by a 25° analyzing magnet which was calibrated with protons using the (α,γ) resonances of the $\mathrm{F}^{19}+p$ reaction mentioned above.

III. EXPERIMENTAL RESULTS AND EVALUATION

Typical spectra for five different excitation energies are shown in Figs. 3–8, inclusive. The narrow peak at high energy is the α group from $\mathrm{Li}^6(d,\alpha)$. The narrow peaks at low energy are proton groups associated with

(d,p) reactions with various target contaminations. From energy and excitation functions, the groups belonging to $O^{16}(d,p_0)$, $O^{16}(d,p_1)$ and $C^{12}(d,p_0)$ were identified. The subscripts 0 and 1 refer to ground states and first excited states, respectively. All these groups were used to fix the energy scale in each spectrum.

Apart from the narrow lines, all spectra show a rather flat distribution with one broad peak at the upper end. The α spectrum expected from Li^7+d is quite complex, containing all groups originating in the two possible reactions:

$$1(a).\quad Li^7+d \to (Be^{9*}) \to Be^{8*}+n \to 2\alpha+n,$$

$$1(b).\quad Li^7+d \to (Be^{9*}) \to He^5+\alpha \to 2\alpha+n.$$

(Hereafter, these α groups are referred to as the $Be^8-\alpha$, $Be^9-\alpha$, and $He^5-\alpha$ groups, respectively.) These reactions may of course proceed through either a direct interaction, e.g., stripping in the reaction 1(a), or via a compound nucleus intermediate state.

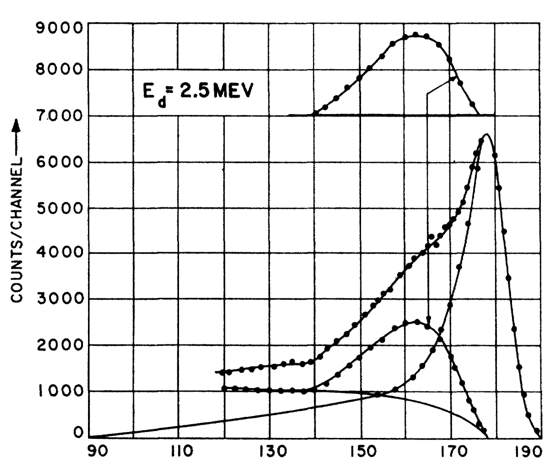

FIG. 7. The further growth of the Be^8 group (or groups; the groups corresponding to the 16.62- and 16.92-MeV state of Be^8 cannot be distinguished in this experiment) which first appeared at about 1.95-MeV deuteron energy is shown here for a deuteron energy of 2.5 MeV. The indicated decomposition is discussed in the text of the paper.

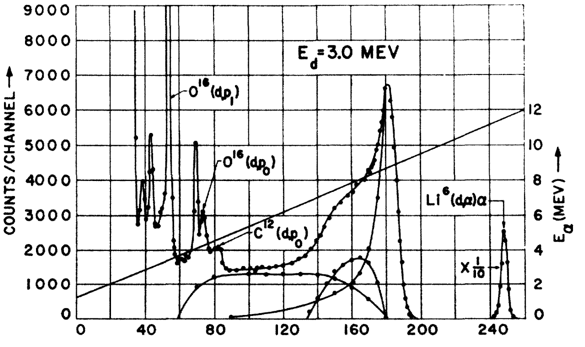

FIG. 8. Alpha-particle spectrum from the reactions of deuterons on natural lithium at a deuteron energy of 3.0 MeV. General features are as explained in Fig. 5. Note the considerable increase in the magnitude of the group attributed to the production and breakup of the 16-MeV state (or states) of Be^8. For further discussion of this decomposition into the various components see the text of the paper.

It is convenient to start the analysis of the spectra at a deuteron energy $E_d=1$ MeV. For this energy the α production has been investigated in considerable detail by Weber.[6] He shows that the broad peak, around 8 MeV, comes from reaction 1(b), principally via the state at 17.48 MeV in Be^9. The line shape is assumed to be given by the probability of the $Be^9-\alpha$ to emerge multiplied by the density of final states in the He^5 ground state:

$$\frac{dN(E_\alpha)}{dE_\alpha} \sim \Gamma_\alpha(Q_1) \times \frac{\Gamma_n(Q_2)}{[E_2+\Delta_2(Q_2)-Q_2]^2+[\frac{1}{2}\Gamma_n(Q_2)]^2},$$

where Q_1 is the Q value of the breakup of Be^{9*} into $He^5+\alpha$; Γ_n, E_2, Q_2, and Δ_2 are the parameters which pertain to the ground state of He^5;

$$\Delta_2(Q_2) = -\frac{(k_na)^2}{1+(k_na)^2} \times \frac{\gamma_0^2}{a},$$

$$\Gamma_n(Q_2) = \frac{2(k_na)^3}{1+(k_na)^2} \times \frac{\gamma_0^2}{a} \quad \text{(for } p \text{ wave neutrons)},$$

$$k_n = (2M_nQ_2/h^2)^{1/2},$$

$E_\alpha = (5/9)Q_1 + (1/3)E_d$, and $Q_1+Q_2 = 15.11$ MeV.

Weber[7] was able to fit his data, which was taken with high resolution, with the parameters: $a=2.9\times10^{-13}$ cm, $\gamma_0^2=1.76\times10^{-12}$ MeV-cm, and $E_2=2.7$ MeV. Since Q_1 is quite large (e.g., 14.16 MeV for a transition to the peak of the He^5 ground state), the energy dependence of $\Gamma_\alpha(Q_1)$ can be neglected for all possible partial waves.

We took the above theoretical line shape but folded the resolution function of the detection system into it. This function was taken from the Li^6+d α-particle peak at about 11 MeV. The $Li^6(d,\alpha)$ reaction is nonresonant in the range of our excitation energies.[2] This line shape thus includes, in addition to the detector resolution, the influence of the target thickness. The resulting line for the Be^9-α group at $E_d=1.0$ MeV was normalized to the experimental peak height at 8-MeV α energy. The agreement with the experimental points of the upper edge of the peak was found to be quite good.

Since the theoretical line shape for the Be^9-α group is essentially given by the final state in He^5, the same shape should be good also for higher excitation energies. A change in the partial wave of the outcoming α should, in our approximation, lead only to a renormalization of the peak height. The resolution function as given by the $Li^6(d,\alpha)$ peak was in most cases sufficiently close to the one at $E_d=1$ MeV so that this line shape could be directly used for the higher excitation energies. The height of the computed peak was normalized to the data at the point in the spectrum where the Be^9-α peak should have its maximum as calculated from kinematics which in most cases coincided with the maximum of the experimental line. In all cases this procedure gave a good fit of the data along the upper edge of the peak.

Subtracting the Be^9-α peak from the spectra leaves, at low excitation energies, only rather flat and smooth α-particle distributions. (See Figs. 3 and 4.) Beginning at about $E_d = 1.95$ MeV, however, another group begins to appear which becomes more pronounced with increasing excitation energy. (See Figs. 5 through 8.) At a deuteron energy of about 2.05 MeV an α group from the 16.62-MeV state in Be^8 might be expected to appear [via reaction 1(a)]. The theoretical energy distribution of this group is rather tedious to calculate since the breakup produces a three-particle final state. The state in Be^8 can be populated in two ways: by stripping or by compound nucleus capture of the deuteron into Be^9 with subsequent breakup of the Be^9. Both amplitudes should add coherently. Since there is no clear indication[12] of a state in Be^9 very close to 2.1 MeV deuteron energy, we assume that stripping is predominant near threshold.

Assuming that the breakup of (Be^{9*}) takes place in two steps, the energy distribution for particles detected at 90° to the beam axis in the laboratory system can be given by

$$\frac{dN(E_\alpha)}{dE_\alpha} \sim \int |M_1|^2 |M_2|^2 \quad f(E_d, Q_1, Q_2, \cos\theta) d\theta,$$

where θ is the opening angle of the emerging neutron with respect to the beam axis. The width of the 16.62-MeV state is neglected here; otherwise, one additional integration has to be done, e.g., over the azimuthal angle of the neutron in the first breakup. M_1 and M_2 are the matrix elements for the first and second steps respectively. $f(E_d, Q_1, Q_2, \cos\theta)$ is a complicated function of θ and the integral cannot be expressed in closed form. Putting $|M_1| = |M_2| = 1$, numerical integration over θ gives a rectangular distribution with a width of about 1.2 MeV for $E_d = 2.3$ MeV.

The experimental distribution is rounded and has a maximum near the middle. This, presumably, is the effect of angular dependences in the matrix elements. For stripping the matrix element M_1 should be quite isotropic[13] since the Q value is negative and the excitation energy is close to threshold. The angular dependence of M_2 is given, e.g., by the (n,α) angular correlation. This can easily be computed, assuming that the captured proton is via p wave and that $J = 2^+$ for the 16.62-MeV state. Possible channel spins in the formation of Be^{9*} are 1 and 2. Since one distribution is peaked around the neutron axis while the other one is peaked at 90° to it, a wide range of angular correlation is possible depending on the channel spin ratio. The observed rounding of the experimental peak suggests that the Be^{8*} has a tendency to break up at 90° to its direction of flight.

Normally one would have to calculate the three-dimensional geometrical factor contained in $dN(E_\alpha)/dE_\alpha$ to determine the detection efficiency of the counter. In the present case, however, the Q value of the Be^{8*} breakup, Q_2, is so much larger than the energy of the neutron-induced recoil or of the center-of-mass motion of the Be$^8 + n$ system, that the reaction, to a good approximation, can be treated as occurring only in a plane and the solid angle of the counter then determines the detection efficiency in a straightforward way. As long as the center-of-mass motion is neglected and the first step of the reaction is isotropic, no angular dependence in the second step can play any role in this approximation.

Because of the above-mentioned ambiguity in channel spin, no accurate determination of the line shape could be attempted. The width as given by kinematics alone, and the position of the line were in good agreement with the data. The shape of the distribution that remained after subtracting the Be^9-α group found at low deuteron energies was used for the remaining subtraction of the lower energy α particles at deuteron energies of about 2 MeV and higher. The resulting line was then integrated without any further corrections. The resulting values are shown in Fig. 9 as the excitation function labeled: Be$^8-\alpha$[16-MeV state(s)].

The broad distribution between about 5 and 7 MeV (see Figs. 3–8 inclusive) can consist only of α's that come from the breakup of He^5 in reaction 1(b) or from the breakup of the broad state at 11.7 MeV in Be^8 (see Fig. 1) fed through reaction 1(a).

The energy for the He^5-α group is given by

$$E_\alpha = \tfrac{4}{5} E_5 [\cos\psi \pm (Q_2/4E_5 - \sin^2\psi)^{1/2}]^2,$$

with

$$E_5 = (5/9) E_d \left[\cos\theta \pm \left(\frac{28E_d + 36Q_1}{10E_d} - \sin^2\theta \right)^{1/2} \right]^2,$$

where E_5 is the energy of the recoiling He^5 nucleus, and where θ is the angle of the first breakup, ψ the angle for the second breakup, both in the lab system; $Q_1 + Q_2 = 15.12$ MeV and, e.g., for the center of the He^5 ground state $Q_1 = 14.16$ MeV and $Q_2 = 0.96$ MeV. The limits of the α-particle energy as given by kinematics, calculated from these relations for the center of the He^5 ground state, are 3.7 and 7.7 MeV at $E_d = 2.3$ MeV (for detection at 90° to the beam axis). These limits are practically constant over the range of excitation energies studied. The long tail toward higher neutron energies in the He$^4(n,n)$ data[14] extends the upper limit of the

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[12] Some indication of a state near $E_d = 2.0$ MeV is reported in the Li$^7(d,p)$ work of reference 8. However, the energy calibration might be doubted and the reported resonance could be the one at 1.8 MeV. Preliminary results of an investigation of Li$^7(d,p)$ made by one of the authors (P.P.) shows no indication of a resonance at $E_d = 2.0$ MeV.

[13] E. K. Warburton and F. L. Chase, Jr., Phys. Rev. **120**, 2095 (1960).

[14] Robert K. Adair, Phys. Rev. **86**, 155 (1952).

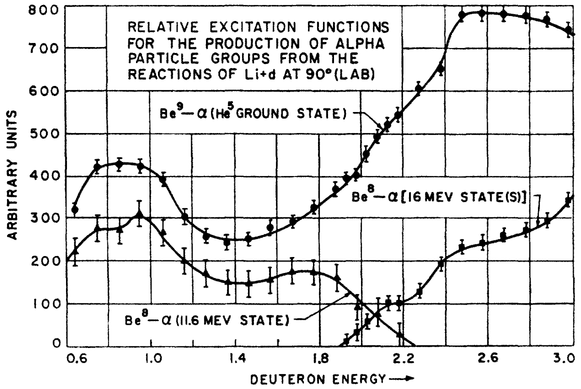

FIG. 9. Relative excitation functions for production cross sections of the high energy α-particle groups from the reactions of Li^7+d as a function of deuteron energy. See the text for detailed discussion of the results and also for an evaluation of the absolute magnitude of the corresponding cross sections.

$He^5-\alpha$ energy up to that of the peak of the $Be^9-\alpha$ group. The lower energy side of this group is rounded off with a half width of about 500 keV. The Q values of both steps are such that the neutron emerges primarily along the flight axis of the He^5 nucleus in the laboratory system. The same distribution is favored by the He^4+n scattering distribution.[14] This should enhance the wings of the group relative to the middle. In the region of overlap between $Be^9-\alpha$'s and $He^5-\alpha$'s, interference effects presumably could modify the line shape. No attempts have been made to actually compute this line shape. Since the Q value of one step again dominates the reaction, it can, to a good approximation, be treated as if occurring only in a plane. The solid angle for the $He^5-\alpha$ group is then the same as for the $Be^9-\alpha$ group. The total number of counts in each group should then be approximately equal.

The Q value for the breakup of the 11.7-MeV state in Be^8 again is much larger than the Q value of the first step. No calculation of the line shape for this group was possible since it is not known how this state is populated in the Li^7+d reaction. The kinematic limits computed for the center of the state, for α-particle detection at 90° to the beam axis are 4.8 and 7.0 MeV. Since the width of the state is roughly[2] 6 MeV these limits can be pushed outward considerably. The breakup of the next lower state in Be^8, at 2.9 MeV, produces α particles with energy less than 4.1 MeV at $E_d=2.3$ MeV. We could not find any other reaction or state that would produce α-particle energies in the range between 4 and 7 MeV. At first it seems surprising that this region of the distribution, containing a large contribution of $He^5-\alpha$'s, should stay almost constant over a wide range of excitation energies while at the same time the $Be^9-\alpha$ peak increases so strongly. We, therefore, made a crude check on internal consistency by determining whether the spectra at all excitation energies contained enough counts within the kinematic limits of the $He^5-\alpha$ peak to match the $Be^9-\alpha$ peak in each spectrum. This was the case in all spectra. The number of counts beyond that required for the $He^5-\alpha$'s can presumably come only from the breakup of the 11.6-MeV state in Be^8. Since the kinematic limits for both groups are similar, the number of counts over the remaining distribution above 4 MeV is then taken as an indication of how strongly this state is populated in the Li^7+d reaction.

The relative excitation functions for the $Be^9-\alpha$ group, and the groups belonging to the states at 16 and 11.7 MeV in Be^8 are plotted in Fig. 9. The excitation energies have been corrected for target thickness. The error bars given are estimated from the range of possible ways to make the separation of the different α groups. It should be emphasized that while the data for $Be^9-\alpha$ and $Be^8-\alpha$ at 16 MeV have a quantitative meaning, the curve for Be^8 (11.6-MeV state) is only qualitative. A scale of production cross sections for the quantitative curves can be obtained from the following: assuming isotropy of all matrix elements, a value of 100 units in Fig. 9 corresponds to a total production cross section for α-particles of 30 mb. However, for the Be^8 curves, the factor 2 in the α-particle production has to be considered when determining the Be^8 production, i.e., the Be^8 production cross sections are one half the values appearing on the graph.

IV. DISCUSSION OF RESULTS

The excitation function for the $Be^9-\alpha$ group in Fig. 9 apparently shows an indication of the familiar resonances at deuteron energies $E_d=0.7$ and 1.0 MeV[2] which are presumably associated with the states at 17.28 and 17.48 MeV in Be^9. Since these states are broad and the target thickness for 1-MeV deuterons is about 100 keV, they are not resolved. Another broad resonance seems indicated at a deuteron energy of about 2.5 MeV. This would correspond to an energy of 18.6 MeV in the Be^9 nucleus. This is most likely the same state that has been seen in the reaction $Li^6(t,\alpha)$ at 18.63 MeV,[10,11] and also possibly in the reaction $Li^7(d,p)$.[15] The limitation in machine energy did not permit a determination of the width, but in both reactions the state appears to be quite wide. There is no indication of a resonance at a deuteron energy of about 1.8 MeV in the excitation function of this group. In addition, it should be noted that the $Li^6(t,\alpha)$ data[9] do not show any resonance at this energy.

The $Be^8-\alpha$ group that we associate with the state at 11.6 MeV in Be^8 apparently shows at low deuteron energies a production via the two states at 17.28 and 17.48 MeV in Be^9. Angular correlation measurements in the region of $E_d=0.9$ MeV have indicated the possible spin and parity assignments $\frac{5}{2}^-$ or $\frac{3}{2}^-$ for the 17.48-MeV state predominant at this energy.[16] The region of the 17.48-MeV state in the excitation function seems to be enhanced over that of the lower state, as compared

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[15] Preliminary results by one of the authors (P. P.) also show this state in the $Li^7(d,p)$ reaction.

[16] A. C. Riviere and P. B. Treacy, Australian J. Phys. **10**, 209 (1957).

to the $Be^9-\alpha$ excitation function. If one takes this fact seriously, this would suggest the spin and parity $\frac{5}{2}^-$ rather than $\frac{3}{2}^-$ for the 17.48 state, since then the 4^+ state in Be^8 can be reached by *p*-wave neutrons instead of the *f*-wave neutrons required for the $\frac{3}{2}^-$ assignment. It should be pointed out, though, that the errors in this excitation function are very large.

The Be^8 (11.6-MeV) α group also seems to indicate a pronounced resonance at a deuteron energy of about 1.75 MeV. This is likely the broad state at 18.1 MeV in Be^9 as seen in the neutrons from $Li^7(d,n)$ and in the reactions $Li^6(t,d)$[9] and $Li^7(d,p)$.[8] The fact that this state is seen at all in the transition to the 4^+ state in Be^8 suggests a spin larger than $\frac{1}{2}$. There is no evidence of the 18.6-MeV state in this excitation function which perhaps could be explained by assuming a spin of $\frac{1}{2}$ for this state.

The $Be^8-\alpha$ group that we associate with the states at 16 MeV shows a threshold at a deuteron energy of about 1.95 MeV. This would correspond reasonably well to the known state at 16.62 MeV.[4] The $Li^7(d,n)$ data at a somewhat higher deuteron energy[3] show that this reaction has a good stripping pattern. Since there is no indication of a state in Be^9 corresponding to a deuteron energy near 2.0 MeV, the phase space of an outcoming stripped neutron should roughly determine the excitation function up to the next state in Be^9. Close to threshold this should give an *s*-wave increase and, hence, vary with $(E_d-2.05\ \text{MeV})^{1/2}$. Into this rise was folded a Breit-Wigner resonance curve with a width, Γ, equal to 95 keV corresponding to the 16.62-MeV state. The observed trend in the experimental curve was found to be compatible with such a theoretical shape. If one disregards the large errors and atrributes some significance to the sequence of the measured points then very good agreement is achieved up to about $E_d=2.20$ MeV, allowing normalization of the theoretical curve at one point, e.g., 2.00 MeV. Above this energy the curve begins to deviate considerably. One reason for this could be that the stripping distribution is beginning to deviate from isotropy. But, of course, the large experimental errors allow a considerable range of curve shapes compatible with the proposed general theoretical behavior. Beginning at about 2.3 MeV, there seems to be a further increase in the strength of the group corresponding to the 16-MeV states in Be^8. This could be from compound nucleus feeding of the 16.62-MeV state through the 18.6-MeV state in Be^9. It could also be the appearance of the 16.92-MeV state in Be^8, being fed by either or both a compound nucleus reaction and stripping. Because of the unfortunate position of the 18.6-MeV level in Be^9, these two processes cannot be separated in the excitation curve for reasons of insufficient energy resolution. The $Li^7(d,n)$ [3] data favor strongly a compound nuclear reaction feeding of the 16.92-MeV state of Be^8. That the 18.6-MeV state in Be^9 should decay by neutron emission to either the 16.62- or 16.92-MeV states of Be^8 both with suggested spin 2^+, but not to the 11.6-MeV state of Be^8 with a spin of 4^+, might be explained by assigning a spin of $\frac{1}{2}$ to the 18.6-MeV state of Be^9. The experimental and theoretical line shapes for the distribution of the alphas belonging to this group are too uncertain to say how much in this region corresponds to each state.

The question arises as to why the alphas from the 16.62-MeV state of Be^8 have not been reported in an earlier work.[6] One possible explanation might be the following. Earlier spectra had been taken with high resolution but unfortunately with poor statistics. It might be then that the group in question was overlooked at excitation energies corresponding only to deuteron energies up to 2.2 MeV where it is not yet very prominent.

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