Scarcity of States of Li^7, from Magnetic Observation of $Be^9(d,\alpha)Li^7$

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The alpha-spectrum of the reaction $Be^9(d,\alpha)Li^7$ is observed at a bombarding energy 600 kev. Above the well-known 480-kev excited state of Li^7 there is no further excited state, having a transition as much as 5 percent as intense as the ground-state transition, in the range of excitation energies up to 2.5 Mev and from there, where the $(d,2\alpha)$ reaction begins to obscure the observations, up to 3.6 Mev there is no sharp line more than 10 percent as intense as the ground-state line. The observations are made with a magnetic heavy-particle spectrograph giving an extended spectrum with a second-order focus on a photographic plate.

THE mirror nuclei Li^7 and Be^7 are of particular interest because they are the "simplest complex nuclei," where one expects most simply to encounter the general problems of nuclear structure, including the coupling of angular momentum vectors. The well-known 480-kev excited state[1] of Li^7 discovered by Rumbaugh and Hafstad has been suggestive of theoretical developments[2–4] and the previous indications that it had no near neighbors have seemed to favor the simple interpretation[2] that the ground state and this excited state together form a ^2P. Difficulties with this interpretation have led to a more complex interpretation[4] in which one can find no reason for a singular isolation of the 480-kev state. This situation lends interest to the extended search for further excited states here reported, which serves to emphasize the apparent isolation of the 480-kev state. The recent discovery[5] of the mirrored counterpart of the excited state at 429 kev in Be^7 (perhaps just by chance a few percent lower than in Li^7 as was to be anticipated on the basis of the original interpretation[2] of the supposed doublet splitting) heightens interest in the problem.

APPARATUS

The small horizontal statitron used to accelerate the deuterons has been described elsewhere.[6] The magnetically deflected beam passes, at a distance of about three meters from the magnet, through a slit, the insulated sides of which form pick-up electrodes which actuate the voltage regulation of the statitron. About a meter beyond this, the beam passes obliquely through the thin Be^9 target foil, covering an area roughly 3×6 mm. Of the alphas leaving the target at right angles to the beam some enter the 0.2-mm slit of the magnetic spectrograph and are bent in a plane normal to the beam to focus, at various positions according to their energy, on a photographic plate.

The spectrograph with its target chamber is shown in Fig. 1, in which the incident beam is to be imagined entering normal to the plane of the figure. The figure differs slightly from the situation in this experiment: The entrance slit has been removed from the tube near the target to be put in the path of the incident beam instead, and the photographic plate has been laid aside and replaced by a proportional counter used in a later experiment. The spectrograph is of a type[7] characterized by its second-order focus along a straight line, different positions on this "plate line" corresponding to different energies. The nature of the second-order focus may be described by considering a ray from the target varied in angle slightly about a central ray. The first-order focus, an intersection which remains steady in first order of this small angle, moves along a curve as the direction of the central ray is varied, and this curve has a cusp at that particular angle of the central ray which gives a second-order focus and is employed in the construction of the spectrograph. This angle of incidence is $\sin^{-1} 3^{-\frac{1}{2}} \approx 35°$ from the vertical, and the plate line makes an angle $\tan^{-1} 8^{-\frac{1}{2}} = 19\frac{1}{2}°$ with the horizontal flat side of the pole faces. The particles being focused enter and leave the same flat edge of the segment-shaped region ("infinite half-space") containing the magnetic field normal to the plane of the figure. The distance between the pole faces is only 0.794 cm, so the effect of fringing field is small. This cuts down the solid angle

* Now at Argonne National Laboratory, Chicago, Illinois.
† This work was aided by a contract with the U. S. AEC.
1 L. H. Rumbaugh and L. R. Hafstad, Phys. Rev. **50**, 681 (1936); Rumbaugh, Roberts, and Hafstad, Phys. Rev. **54**, 657 (1938); E. R. Graves, Phys. Rev. **57**, 855 (1940); Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948); Rubin, Snyder, Lauritsen, and Fowler, Phys. Rev. **74**, 1564 (1948); L. C. Elliott and R. E. Bell, Phys. Rev. **74**, 1869 (1948); Rasmussen, Lauritsen, and Lauritsen, Phys. Rev. **75**, 199 (1948); J. K. Boggild, Kgl. Danske Vid. Sels. Math.-fys. Medd. **23**, 4, 26 (1945). *Note added during publication:* Observations very similar to those here discussed, made at quite a different bombarding energy, have recently been reported by W. W. Buechner and E. N. Strait, Phys. Rev. **76**, 1547 (1949).
2 D. R. Inglis, Phys. Rev. **50**, 783 (1936).
3 W. H. Furry, Phys. Rev. **50**, 784 (1936); G. Breit and J. R. Stehn, Phys. Rev. **53**, 459 (1938); G. Breit and J. K. Knipp, Phys. Rev. **54**, 652 (1938).
4 S. S. Hanna and D. R. Inglis, Phys. Rev. **75**, 1767 (1949).
5 Brown, Chao, Fowler, and Lauritsen and T. Lauritsen and R. G. Thomas, Phys. Rev. **78**, 88 (1950).
6 Inglis, Krone, and Hanna, Rev. Sci. Inst. **20**, 834 (1949).
7 Information concerning this type of focus was received from Drs. E. M. Hafner and H. S. Snyder in valued discussions at Brookhaven in 1948. They have described a more general type of focus which includes this as a special case in a privately circulated report (see also an abstract with W. F. Donoghue, Phys. Rev. **75**, 331 (1949). The idea for the type of focus used in this work apparently originated with T. H. Fowler of the University of Bristol, who intends to describe it further.

in one direction, but the second-order focus helps in the other direction.

The pole faces themselves form part of the vacuum chamber. The Armco iron pole pieces, each 5 cm thick, are separated by the trapezoidal-shaped brass spacers shown, and the vacuum space is closed by a bent brass strip soldered around the curved edge of the poles and by a flat brass plate soldered to the flat edge of the poles. The flat plate had appropriate holes milled in it for the entrance and exit of the particles, the exit hole being wide enough to allow the plate holder to slide down along its axis until the photographic plate contacts the iron surface.

The plate holder accommodates two standard 2.54 $\times$7.62 cm plates (Ilford C-2, 50 micron), end to end, on each of its three faces. Thus, three exposures can be made on each loading (by retracting and rotating the holder through an o-ring seal), and for each exposure the 15.2 cm of plate subtends a spectrum of particle energies differing by a factor of 2.08 between the two ends of the plate. The minimum and maximum radii of curvature are 14.0 and 20.38 cm, with fringing field neglected, or 14.37 and 20.72 cm if one extends the edge of the field by half the distance between the pole faces, as a rough allowance for fringing field.

The spectrograph, including the two pole pieces, is slipped down between the poles of an electromagnet which weighs about 700 kg, constructed in 1941 in connection with a spectrograph somewhat similar to the one here described but of the more conventional 90° type. The poles may be moved horizontally, sliding on the faces of the yoke above the coils, to fit snugly around the spectrograph. The magnet is fed by an "Edison" battery sufficiently steady that the use of a regulating circuit is unnecessary. Currents up to 14 amperes at 150 volts have been used, 8.2 amperes for the exposure here reported. The field was shown to be homogeneous within about $\frac{1}{2}$ percent in the significant region by exploration with a "gaussmeter" (permanent-magnet torsional torque-balance) and it was later found convenient to mount the probe of such an instrument in a hole in a wooden block to fix its position but permit its rotation in the fringing field, for comparison of fields of different exposures. Provision for such a probe in the homogeneous field while running would have been convenient.

It was thought, but has not been adequately verified, that the inhomogeneities near the flat edge would be mainly of such a nature as to alter the relation between plate position and target position from the ideal theoretical one, not to blur the focus. Preliminary observations were made with a Po alpha-sources replacing the target outside of a narrow slit, to locate the best entrance-slit position by trial. In this spectrograph the distance between the points where the plate line and central ray meet the top edge of the field is 22.8 cm, and the calculated vertical distance from the top edge to the entrance slit is $2^{\frac{1}{2}}/3$ as great, or 10.7 cm, if one neglects edge effects. The fringing field correction extends the latter distance to 11.6 cm. Experimentally, a target position 11.1 cm above the plane of the edge of the field gave a slightly sharper focus. The observed half-width of the Po alpha-line was about 2 mm on the plate, with an entrance slit 0.2 mm wide. (The Po deposit on a Ni button was 5 months old.) The sharpness of the focus did not vary significantly with the position of the line over a little more than half of the plate span, where it could be observed—a field strong enough to focus the Po alphas at the near end of the plate span was not available.

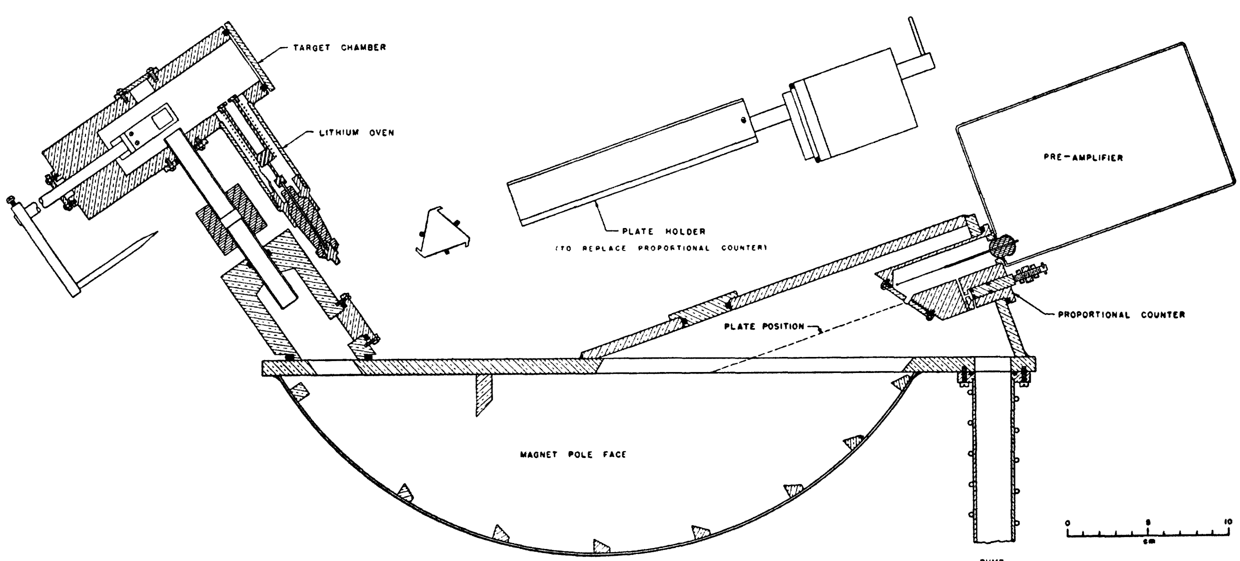

FIG. 1. Heavy-particle magnetic spectrograph. The photographic plate holder and the proportional counter are interchangeable. In the present work the photographic method is used, with the plates in position along the broken line. The proportional counter is used for reactions having low energy product particles, particularly $B^{10}(p,\alpha)Be^7$.

The principal advantage of this type of a spectrograph for this type of work is the wide range of energies covered by a single exposure. This may more than compensate the low intensity inherent in the narrow gap between the pole faces and the consequent lack of "double focusing" to bring particles back into the central plane. In other instruments double focusing is available only at one point of a spectrum, and is therefore more appropriately used with a counter than a photographic plate. This spectrograph fully exploits the advantage of the photographic plate, and is a poor instrument when used with a counter as depicted in Fig. 1. (This counter was later introduced to help with the identification of the rather low energy alphas in the reaction $B^{10}(p,\alpha)Be^7$, which, however, are also recognizable as short tracks in an emulsion. No report of that work need be made now that much more complete data on it are available elsewhere.[5]) The greater sharpness of focus resulting from the second-order focus was not fully exploited in this work, being masked in part by the target thickness used to obtain convenient intensity (see below). When not needed for sharpness, the second-order focus is still an advantage in permitting a wide entrance angle (and to this end the entrance tube should have been a little larger at the lower end, and also arranged with baffles to minimize background from wall scattering).

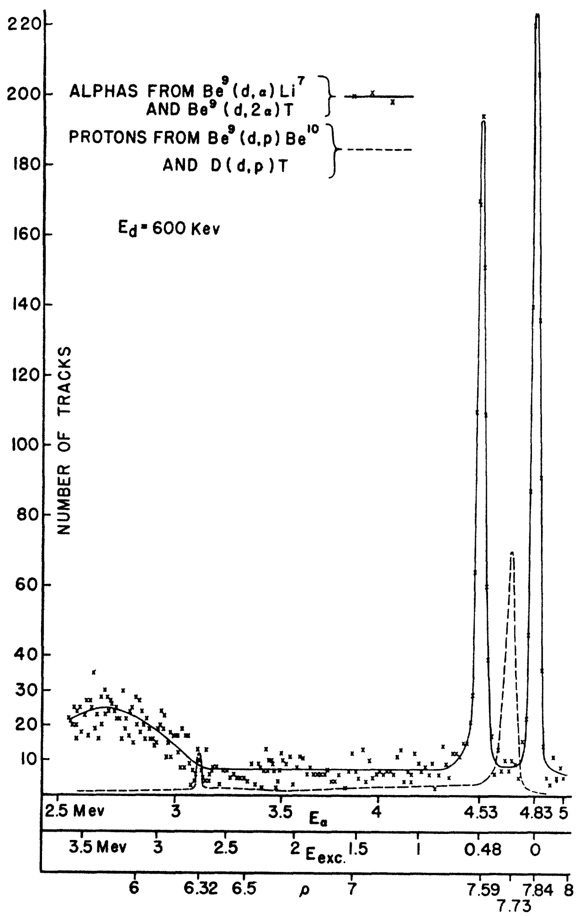

FIG. 2. Alpha-spectrum and proton spectrum from Be^9 bombarded by 600-kev deuterons. The small crosses represent alpha-counts in small swaths of the plate. In the background region the plotted points are numerous enough to be statistically significant, although the individual counts represent statistically uncertain small numbers of observed alpha-tracks. Individual proton counts are not shown.

RESULTS

The spectrum of alphas arising from the bombardment of Be^9 by 600-kev deuterons is shown in Fig. 2. The intensity of the alphas arriving at various positions along the length of the plate span is plotted against their energy, E_α, with subsidiary scales giving the corresponding excitation energy E_{exc} of the residual Li^7 nucleus, as well as radius of curvature, ρ, of the alphas arriving at each point from the entrance slit, determined from the geometry of the spectrograph. The right side of Fig. 2 corresponds to the right end, or high energy end, of the plate span in Fig. 1. The peaks corresponding to the reaction $Be^9(d,\alpha)Li^7$ going to the ground state and the well-known 480-kev state are prominent at the high alpha-energy or low excitation-energy end of the spectrum, but further to the left beyond the 0.48-Mev peak, one sees a region of low background intensity extending to beyond 2.5-Mev excitation in which the plotted points scatter by no more than would be expected of the fluctuations in such small numbers of counts. The points are sufficiently numerous to establish the absence of peaks above the background (about 3 percent of the ground-state peak) in this region. Then from about 3 Mev to the edge of the plate at 3.6-Mev excitation energy is a region of intensity about three times the background intensity, and this is attributed to the high energy alpha from the reaction $Be^9(d,2\alpha)T$, the threshold for which is expected to be at $E_{exc}=2.51$ Mev.

Each plotted point represents the number of alpha-tracks counted in a swath across the middle of the exposed strip of the plates, the swath being 4 mm long in the transverse direction of the plate by 0.3 mm wide. The tracks are distinct enough that they can be counted most conveniently with an intermediate magnification of 450 without oil immersion. Swaths have been counted at intervals of 1 mm along the length of the plates, and in the most interesting regions intermediate swaths were counted without overlapping. At the junction of the two plates a short gap in energy where the emulsion was marred, from $\rho=6.76$ to 6.9 in., is filled in with data obtained from another plate at a slightly higher magnetic field.

In the region away from the peaks the background of alphas with the proper energy (and $H\rho$) to have come from near the target is sufficiently low that some care is taken to distinguish the tracks from other background tracks. This is done by requiring that they have the right direction and length, within a reasonable spread. The acceptable range of lengths varies with position on the plate, and is determined by observing the range of straggling of the easily recognizable alphas in the high energy peak, and then scaling this down according to the energy expected at other points on the plate, by use of the range-energy relation. In some swaths in the background region the rejected tracks are more numerous than the acceptable tracks, but most of them are unacceptable by a wide margin; so the trend of the observations is not critically affected by the criteria for acceptance, and in almost all cases the acceptability is judged at a glance without actually measuring the track.

In order to minimize the contribution of target thickness to line width the fairly thin target was supported in a frame without backing and was oriented at an appropriate angle, with the deuterons entering one face and the observed alphas leaving the other face of the target, as shown in Fig. 3. It is then, of course, in principal possible to set an ideally flat target at such an angle that the energy loss along the path *ab* of the deuteron before causing a reaction at *b* is just equal to the energy loss of an alpha along the path *ac* after a reaction at *a*, so that the two alphas emerge from the target with the same energy, apart from straggling. For this, $\tan\theta = (dE_d/ds)/(dE_\alpha/ds)$, the ratio of stopping powers of Be for deuterons and alphas. For deuterons at 600 kev or protons at 300 kev, the stopping power of Be is available[8] (394 kev/(mg/cm^2)), but not of Be for alphas, so we make use of the usual assumption that the ratio of stopping powers for deuterons to alphas is the same in Al as in Be. The angular setting used in this work was 18°, and at this angle the effective thickness of the target[9] for the 600-kev deuterons passing obliquely through it is about 43 kev (obtained by using the nominal thickness, 15 micro-inches or 0.10 mg/cm^2, and Warshaw's value for Al, 294 kev/(mg/cm^2)), and the effective thickness for the high energy group of alphas is the same. Thus, the net contribution to the line width vanishes at the right side of Fig. 2, but toward the left the energy loss of the alphas increases until at an alpha-energy of 2.5 Mev, the alpha-energy loss is about 67 kev, the difference contributing about 24 kev to the width of a hypothetical line at the left side of Fig. 2.

The broken line in Fig. 2 shows the distribution of protons observed on the same pair of plates. Their tracks were of course much longer and easily distinguishable from the alphas. The statistical scattering of the individual points is not shown in Fig. 2, but is similar to that of the alphas. The energy scale E_α in Fig. 2 applies, of course, also to proton energy E_p. The peak at $\rho = 7.73$ corresponds to the reaction $Be^9(d,p)Be^{10}$ going to the ground state. The little peak at $\rho = 6.62$ falls at the right position to be identified

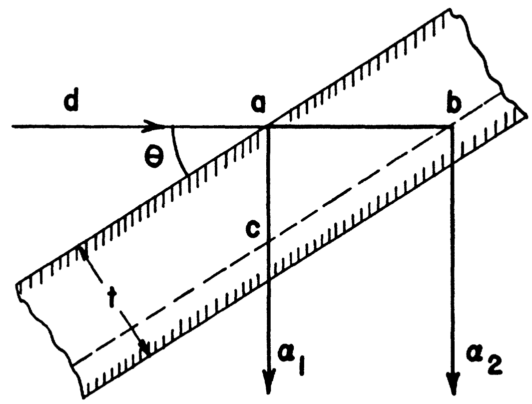

FIG. 3. Geometry of particles penetrating ideal target.

with the reaction D(d,p)T associated with a deuterium contamination of the target. It is interesting to note that the small D(d,p) peak is narrower than the high peaks arising from the Be in the target, only about half as wide as the $Be^9(d,p)$ proton peak, or two-thirds as wide as either of the main alpha-peaks, apparently because the deuterium contamination exists principally on the surface of the Be. That the $Be^9(d,p)$ peak is broader than the main alpha-peaks (by about 20 kev) is understandable because the target angle is set for the latter, and the protons lose less energy than the alphas in penetrating the target obliquely (by about 30 kev as estimated from target thickness).

The question arises whether a transition of appreciable intensity to a sharp higher excited state of Li^7 might be missed because of imperfections in the method which might on some parts of the plate broaden a peak to such an extent that it might be lost in the background. The sharpness of the small $D(d,p)$ peak indicates even more clearly than does the preliminary investigation with Po alphas that there is no deterioration of the focusing properties of the spectrograph itself as one goes to the left in Fig. 2. We must still inquire whether any property of the target geometry might introduce trouble. Neither the straggling in the target nor, as we have seen, deviation of the target setting from the ideal angle can account for the observed width of the main alpha peaks, which is about 75 kev. The width of these lines would then be expected to arise either from variations in the thickness of the target, which is apt to be appreciable,[8] or local variations in its orientation because of small-scale wrinkles (which the appearance of the target, mounted by allowing the surface tension of a cement to draw it fairly taught in a frame, would not preclude). Of these target defects the wrinkles would affect the energy loss of the deuterons, which enter at near-grazing incidence, much more than that of the product particles, which leave almost normal to the target. This contribution from the deuterons is the same at all energies of the product particles. The effect of variations in target thickness is proportional to the total energy loss by deuterons plus

[8] S. D. Warshaw, Phys. Rev. **76**, 1759 (1948).

[9] The evaporated Be targets used were very generously supplied by Dr. Hugh Bradner of the University of California Radiation Laboratory. The nominal thickness used is a rough value given by him for the batch. Our results are not sensitively dependent on it.

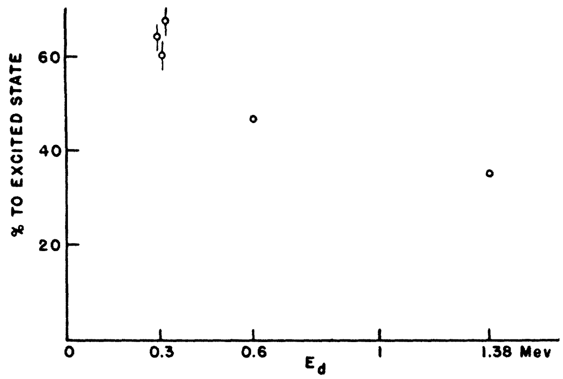

FIG. 4. Fraction of the alphas from $Be^9(d,\alpha)Li$ going to the 480-kev state. In the neighborhood of 300-kev bombarding energy, the curves given by Graves (reference 1) indicate about 64 percent to the excited state and 36 percent to the ground state. At 600 kev, the present work gives 47 percent and at 1.38 Mev the work of Buechner, Strait, Stergiopoulos, and Sperduto indicates 36 percent to the excited state.

alphas, which is greater by about 20 percent, according to the figures quoted above, at the left side of Fig. 2 than at the right. Even if this were responsible for the entire width of the main peaks, peaks arising from transitions to higher single excited states of Li^7 would thus be only very slightly wider than these. We thus conclude that no peaks have been missed because of instrumental broadening. The resolution is sufficient to have permitted detection of any transition in the empty region more intense than about 5 percent of either of the main peaks. Against the background of the continuum of alphas from the competing $(d,2\alpha)$ reaction in the neighborhood of $E_{exc}=3$ Mev a transition to a sharp state as much as 10 percent as intense as the main peaks would have been detected.

The energy scale E_α on the pair of plates represented by Fig. 2 was determined by equating the Q of the high energy peak to that determined from the similar work of Buechner, Strait, Stergiopoulos, and Sperduto,[1] since they, being primarily interested in accurate energy determinations, took care to calibrate by exposing the same plate to Po alphas under identical conditions. (In this work the Po alphas were observed on other plates under nearly identical conditions.) From the relative positions of the high energy group and the Po alphas on their Fig. 2, one finds for $Be^9(d,\alpha)Li^7$ to the ground state the energy release $Q=7.16$ Mev, which is here used. The energies of the proton peaks in our Fig. 2 are then $E=3.12$ and 4.69 Mev, corresponding to $Q=3.96$ and 4.68 Mev for the reactions $D(d,p)T$ and $Be^9(d,p)Be^{10}$, respectively.

The relative number of alphas involved in transitions to the ground state and to the 480-kev excited state is given by the ratio of the areas under the two peaks, above an estimated background level. Measurement of these areas shows that about 46.6 percent of the transitions go to the excited state at this bombarding energy, 600 kev. This is compared with the results at other bombarding energies, taken from the data of other workers, in Fig. 4. One notes an apparent decline in the relative transition probability to the excited state with increasing bombarding energy.

DISCUSSION OF RESULTS

The failure to observe peaks in the alpha-spectrum between $E_{exc}=0.48$ and 2.5 Mev does not necessarily mean that states of Li^7 do not exist in this region of excitation. It means rather that the transition probabilities to any states that might exist in this region are anomalously small, and one must judge the likelihood of encountering such weak transitions and compare with the results of other reactions before drawing a conclusion concerning the lack of states. Most of the work on the other reactions leading to the same two

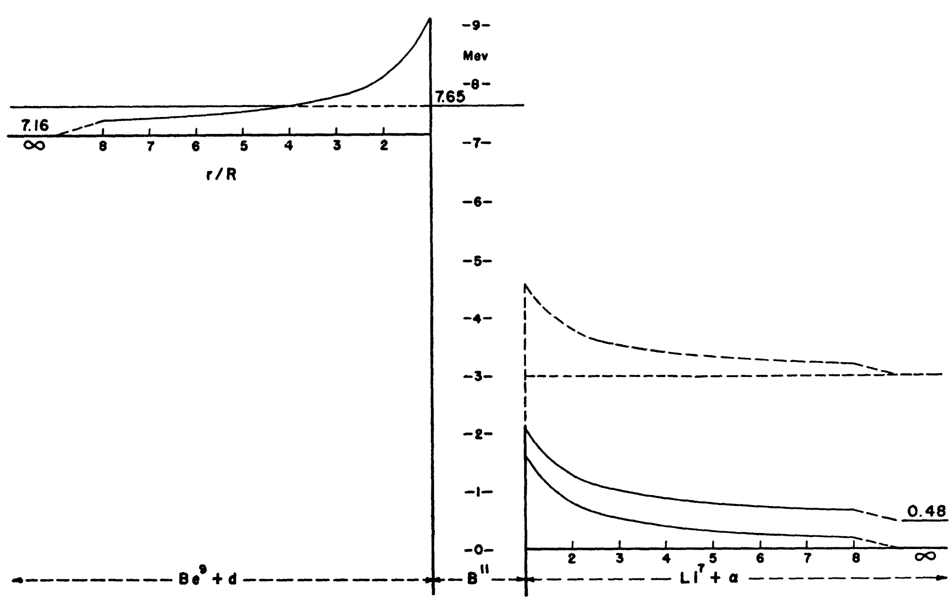

FIG. 5. Potential barriers associated with the formation and disintegration of the compound nucleus B^{11} in the reaction $Be^9(d,\alpha)Li^7$.

states of Li^7 has been carried out as investigation of the properties of transitions involving these known states, and not as exploration for unknown states. Nevertheless, the region of excitation energy up to 1 or 1.5 Mev above the ground state has been explored in a preliminary way in $Li^6(d,p)Li^7$, and more thoroughly in the gamma-spectrum from $Li^7(\alpha,\alpha')$ at $E_\alpha = 5.3$ Mev by Seigbahn and Slätis.[10] Thus there is a considerable coverage of a part of the energy region by other reactions, with no indication of any excited states of Li^7 above 480 kev.

The low probability of penetrating a Coulomb barrier associated with a high excited state of the final nucleus might in principle depress the transition probability to an excited state relative to the ground state, but the reaction here investigated is much too highly exoergic to allow this mechanism to account for our failure to observe higher excited states. The situation is indicated schematically in Fig. 5. The left side of the figure represents the energy of the system as a function of the static separation of the two constituents involved in the formation of the compound nucleus, and the right side similarly represents the subsequent disintegration. In the approximation in which the constituent particles are considered separated and without influence on one another's internal motion when beyond an idealized "nuclear radius," we may draw a Coulomb barrier for the 480-kev state which is everywhere displaced just 480 kev upward from that of the ground state. That is, the alpha is considered separated either from Li^7 or Li^{7*} from the beginning. Even up to the highest excitation energies in which we are here interested, the top of the excited Coulomb barrier falls far short of the excitation energy of the compound nucleus provided by the experimental synthesis, as is suggested by the dotted curve.

In a very rough approximation one may then conclude that there is for any excited state in the range investigated plenty of energy available and no problem of penetration at all. A more refined approach would take into account the partitions of energy among nucleons in the compound nucleus and might indeed find the barrier more of a deterrent for a hypothetical higher excited state of the final nucleus in spite of the presence of ample total energy to pass over it. This would be expected to bring in a comparatively small factor from relative volumes of momentum space, not a large factor from relative penetrabilities, so is probably not adequate to account for the blank region in the alpha-spectrum. This consideration suggests that this reaction might be significantly better than $Li^6(d,p)Li^7$, which has a smaller energy release but still gets over the excited barrier, and surely better than $B^{10}(n,\alpha)Li^7$ as a tool for searching for excited states of Li^7. Inelastic scattering, especially with very high energy particles, might be still better.

Above the threshold at 2.51-Mev excitation energy, the failure to observe excited states in Li^7 might in principle be due to the energy indeterminacy of such states arising from the possibility of disintegration of Li^7 into an alpha and a triton. Actually, this mechanism by no means precludes the existence of states of Li^7 in this region as sharp as our experimental main peaks, as is clear from the general prevalence of resonant levels in nuclei even at much higher excitation energies, and in particular in Li^7 at 7.38 Mev, as observed[11] in the reaction $Li^6(n,\alpha)T$. This mechanism, involving the disintegration of Li^7 into an alpha and a triton is, of course, to be distinguished from the effect of the competing reaction $Be^9(d,2\alpha)T$, which contributes alphas on our plates only above this threshold, but which competes with the entire spectrum of $Be^9(d,\alpha)Li^7$ indiscriminately (at a given bombarding energy) and is not expected to affect, in any systematic way depending on alpha-energy, the *relative* intensity of lines in this spectrum. Thus our failure to observe peaks seems quite as significant above the threshold as below.

I thank Drs. S. S. Hanna and I. Resnick, who were investigating other problems concurrently, for their cooperation in the statitron maintenance.

[10] K. Siegbahn and S. Slätis, Arkiv. f. Mat. Astr. o. Fys. **34A**, No. 6 (1946).

[11] Goldsmith and Ibser, quoted by Hornyak and Lauritsen, Rev. Mod. Phys. **20**, 192 (1948).