Energy Levels in Li^7

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The following reactions which show a new level in Li^7 at the listed excitation energy have been studied using protons, deuterons, and alphas of energies 7.9, 14, and 31 Mev, respectively, from the MIT cyclotron:

$Li^7(p,p')Li^{7*}$	$E_x=4.67\pm0.08$ Mev
$Li^7(\alpha,\alpha')Li^{7*}$	$E_x=4.79\pm0.22$ Mev
$Li^7(d,d')Li^{7*}$	$E_x=4.86\pm0.15$ Mev
$Be^9(d,\alpha)Li^{7*}$	$E_x=4.76\pm0.15$ Mev
Mean	$E_x=4.77\pm0.10$ Mev.

In all cases the differential range spectra of the emitted groups were measured in aluminum absorbers using a gated triple proportional counter. In addition, a low energy group was found in the $Be^9(d,\alpha)$ reaction which would correspond to a level in Li^7 at 7.50 ± 0.17 Mev. No corresponding group was observed in the inelastic scattering reactions. Possible explanations of this are given. Preliminary results on the $Li^7(d,t)Li^{6*}$ and the $Li^6(p,p')Li^{6*}$ reactions indicate a level in Li^6 at 2.15 ± 0.2 Mev. There is also evidence for two levels in Li^8 at excitation energies of 1.0 ± 0.2 and 2.3 ± 0.2 Mev from the $Li^7(d,p)Li^{8*}$ reaction.

I. INTRODUCTION

CONSIDERABLE theoretical attention has been devoted to the properties of the Li^7 nucleus because it is one of the "simplest of the complex nuclei." The discovery of a 480-kev level[1] led to the prediction that the ground state and this excited level form a ^2P doublet.[2] The presence of a level at 7.48 Mev[3] has been reported but no other levels have been found to date. Considerable evidence[4,5] favors an assignment of $\frac{1}{2}$ to the angular momentum of the first excited state; however other evidence[6–9] indicates a higher value of angular momentum suggesting that this excited level forms a ^2F doublet with the ground state. The presence of any other excited levels between the 480 kev and the 7.48-Mev levels would be of some interest.[10,11]

Many investigators have searched for additional levels in Li^7 and have found none. The level at 480 kev has been found from the γ-radiation following the Be^7 decay[12] and the alpha-groups[6] from the thermal neutron capture of B^{10}. However both of these reactions are limited energetically to low excitation levels. A gamma-ray corresponding to the 480-kev level has been measured from inelastic scattering of low energy alphas[13] and protons.[14] In some recent work[15] the reaction $Li^6(d,p)Li^7$ has been employed for an accurate measurement of the excitation energy of the 480-kev level. In addition, a search was made for other levels up to an excitation energy of about 3 Mev, and none were found. Inglis[16] and Buechner and Strait,[17] using low energy deuterons to study the reaction $Be^9(d,\alpha)Li^7$, $Q_0=7.15$ Mev, have searched carefully the region from the ground state to an excitation energy of 3.5 Mev. In both cases, no evidence was found for any excited levels in Li^7 except for the level at 480 kev. The measurements by Inglis[16] show a rising background of alpha-particles starting at an excitation energy of about 3 Mev, which is attributed to the reaction $Be^9(d,2\alpha)T$. The threshold for this reaction is expected to occur at an excitation energy in Li^7 of 2.5 Mev. Measurements on the yield of alpha-particles from neutron bombardment of lithium show a resonance at a neutron energy of 270 kev.[3] This was attributed to a level in Li^7 at 7.48 Mev. Recent measurements[18] on the total neutron cross section of lithium also show a resonance at 270 kev, which is assigned to a level in Li^8 at 2.27 Mev. The close agreement between the energy of the resonances found in the two experiments leaves some doubt whether they arise from different processes.

From this discussion it can be seen that the region of excitation energies between 3.5 and 7.25 Mev has not been covered by any of the methods employed to date.

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Since there is available from the MIT cyclotron an emergent beam of either protons, deuterons, or alpha-particles of energies 8 Mev, 16 Mev, and 32 Mev, respectively, it was suggested by D. R. Inglis that an attempt be made to investigate Li^7 and in particular the unexplored region. Preliminary measurements on the $Li^7(d,d')Li^{7*}$ reaction made in this laboratory[19] indicated the presence of a level in this region.

The possible reactions which could be employed using targets of normal isotopic abundance were $Be^9(d,\alpha)Li^7$, $Li^7(d,d')Li^{7*}$, $Li^7(\alpha,\alpha')Li^{7*}$, and $Li^7(p,p')Li^{7*}$. This paper presents the results from the study of these four reactions.

II. APPARATUS

The apparatus and the general techniques of measurement have been described in a series of recent papers.[20–22]

In brief, the apparatus employs a gated triple proportional counter which responds to charged particles terminating in its third section after passing through variable aluminum absorber foils. In this way charged particles resulting from deuteron, alpha, or proton bombardment of thin targets can be identified and the differential range spectrum can be measured. The detector can be rotated to measure the variation in energy and intensity with angle.

The Q-values of excited levels are measured relative to a reference value which is usually the Q-value of the ground-state group. The approximate energy of this group is obtained from the measured range in the aluminum absorber foils to which is added the range of half the target thickness and the triple counter depth. Substituting this energy and the known Q-value into the Q-equation, we obtain the bombarding energy. Using this bombarding energy and the energies of the excited groups, their Q-values can be obtained.

III. THE REACTION $Li^7(p,p')Li^{7*}$

The lithium targets were prepared by rolling lithium metal of natural isotopic abundance between two thin aluminum foils. Chemical reactions with air were minimized by the use of mineral oil. The targets were kept under oil until ready to use and then washed in a solvent and quickly inserted into the target chamber. They retained their metallic appearance, indicating that very little surface impurities had been formed.

To study the $Li^7(p,p')Li^{7*}$ reaction a 1 mg/cm²-lithium target was bombarded with 7.9-Mev protons.

Figure 1 shows the spectrum obtained at 50°. In addition to the elastically scattered protons from Li^7 three lower energy proton groups are observed. Two of these groups are assigned to inelastically scattered protons from Li^7 and correspond to Q-values of -0.49 and -4.68 Mev. The intermediate peak is assigned to inelastically scattered protons from Li^6 and corresponds to an excitation of 2.2 Mev.[23] This agrees with a level at 2.15 Mev found from the $Li^7(d,t)Li^6$ reaction to be discussed later. The position of the elastically scattered protons from Li^6 is also indicated in Fig. 1. The 4.68-Mev group is superimposed on a broad background at all angles, which probably arises from a three-body disintegration. If any other groups due to elastic protons from Li^7 were present to about 5 percent of the intensity of the 4.68-Mev group, they would have been detected.

The inelastic proton group corresponding to the 4.68-Mev level and the elastically scattered proton group have been measured at several angles from 25° to 70°. The elastically scattered proton group was measured at 30° before and after each run to compensate for any drifts. Table I summarizes the results normalized, in energy, to the elastic peak at 30°. The mean of the Q-values at the different angles is -4.67 Mev. The accuracy is estimated to be 80 kev because of an uncertainty of 2 mg/cm² in range (equivalent to 100 kev uncertainty in bombarding energy). The resultant errors due to the uncertainty in angle and the estimation of the positions of the peaks are small, and the effects are random. The value of the excitation energy of this level in Li^7 from this reaction is 4.67 ± 0.08 Mev.

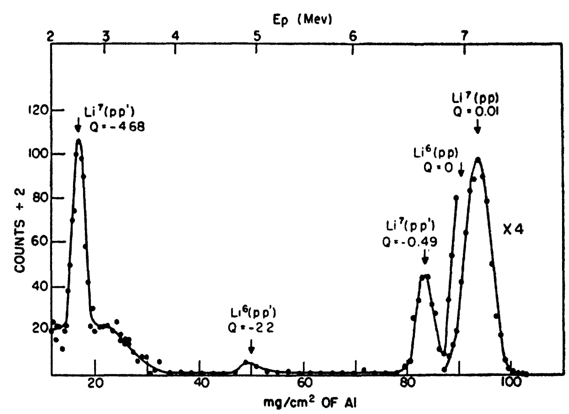

FIG. 1. A proton spectrum at 50° from a 1 mg/cm²-lithium target bombarded with 7.9-Mev protons. The three main peaks are caused by the elastic and inelastic scattering from Li^7. An inelastic peak from Li^6 also is evident. The position of the elastic peak from Li^6 is indicated. It is obscured by the elastic scattering from Li^7.

IV. THE REACTION $Li^7(\alpha,\alpha')Li^{7*}$

To study this reaction a 2-mg/cm² lithium target was bombarded with 31-Mev alpha-particles and the range spectrum of the alphas was measured. Figure 2 shows the spectrum taken at 20°. It consists of elastically and

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[23] Some preliminary work performed independently at about the same time as that reported here by W. M. Harris at the University of Rochester indicates a level at an excitation energy of about 2.2 Mev in Li^6. An enriched Li^6 target was bombarded with 6-Mev protons, and a low intensity inelastic proton group corresponding to this level was observed.

TABLE I. Q-values for the elastic and inelastic proton groups and their differences at a series of angles for the $Li^7(p,p')Li^{7*}$ reaction assuming $Q=0$ for the elastic group at 30°.

Laboratory angle (θ) (degrees)	Q_{el} (Mev)	Q_{inel} (Mev)	$Q_{inel}-Q_{el}$ (Mev)
25	0.00	−4.67	−4.67
30	0.00	−4.65	−4.65
35	+0.01	−4.67	−4.68
40	+0.05	−4.63	−4.68
45	−0.02	−4.68	−4.66
50	+0.07	−4.60	−4.67
55	−0.01	−4.67	−4.66
60	−0.01	−4.70	−4.69
65	−0.04	−4.70	−4.66
70	−0.03	−4.70	−4.67
Mean	0.00	−4.67	−4.67

inelastically scattered alphas, and alphas from the three-body disintegration $Li^7(\alpha,2\alpha)T$. If the long-range group is assumed to consist mainly of elastically scattered alphas from Li^7 with only a small contribution from the unresolved 480-kev level, the Q-value of the inelastic group is −4.79 Mev. The elastic group from lithium was measured at a number of angles up to 70° and the Q-values agreed to within 200 kev. From these it was shown that no carbon or oxygen contamination was present in the target, since no sign of an elastically scattered group from such contaminants was observed. For illustration the position of the elastically scattered group from oxygen is indicated in Fig. 2.

The presence of the three-body reaction, and the fact that the inelastic alpha-group decreases in intensity as the angle increases, makes it impossible to resolve the inelastic group for angles greater than 30°. This is illustrated in Fig. 3 which shows the spectrum at 50°. Therefore, the shift of this peak with angle cannot be used to eliminate the possibilities of contaminants. These are eliminated, however, by the absence of the corresponding elastic peaks.

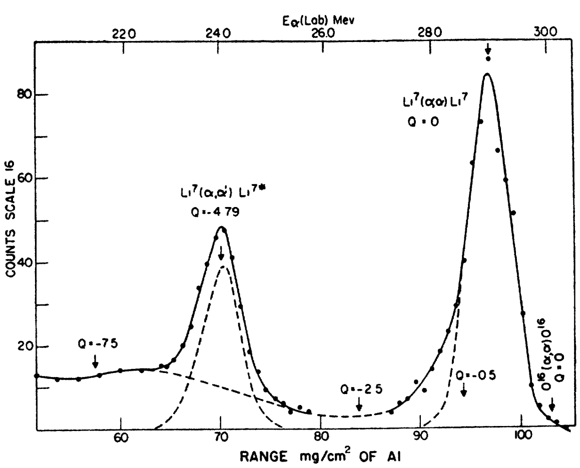

FIG. 2. An alpha-spectrum at 20° from a 2-mg/cm² lithium target bombarded with 31-Mev alphas. If an elastically scattered peak from oxygen were present, it would appear at the range indicated.

A probable error of 200 kev is ascribed to the value of 4.79 Mev for the excitation energy of the inelastic group. This rather large uncertainty results from the aforementioned inability to observe the group at a number of angles and arises from uncertainties in angle, bombarding energy, and difference in range.

The comparison between the elastically scattered alphas from aluminum ($Q=0$) and the long-range group from lithium results in a Q-value for this lithium group of $+0.2\pm0.2$ Mev. Part of the probable error in this case results from uncertainties in target thickness, since peaks from two different targets are being compared. The fact that the above Q-value is positive by 200 kev makes it rather likely that the 480-kev level is of low intensity. On the basis of this assumption, the excitation energy of the new level in Li^7 is 4.8 ± 0.2 Mev.

There is no sign of a level at 7.5 Mev. The expected position of this peak is indicated in Fig. 2.

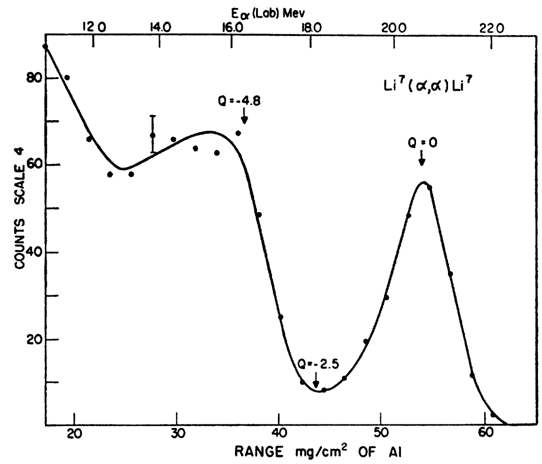

FIG. 3. An alpha-spectrum at 50° from the same lithium target as in Fig. 2 bombarded with 31-Mev alphas. The inelastic alpha-group is not resolved at the wider angles.

V. THE REACTION $Li^7(d,d')Li^{7*}$

A thin lithium target, about 4 mg/cm², was bombarded with 14-Mev deuterons, and the resulting proton, deuteron, and triton spectra were studied. Figure 4 shows the spectrum taken at 30° with discriminator settings maximized for deuterons. The longest range group of deuterons at this angle comprises mainly the elastically scattered deuterons with only a small contribution from the 480-kev level. Again a group of inelastic deuterons is found corresponding to a level in Li^7 at 4.87 Mev. This is superimposed on a rising background which can be ascribed to a three-body reaction. The expected position of a level at 7.5 Mev is shown.

The inelastic deuteron peak at 4.87 Mev has been observed at several angles up to 70°. The shift with angle agrees with that computed for deuterons from lithium rather than protons or tritons, which also occur in this energy region. Figure 5 shows the deuteron spectrum taken at 60° showing the elastic and inelastic peaks. A comparison between the ranges of the elastically scattered deuterons from a 4-mg/cm^2 carbon (polyethylene) target ($Q=0$) and the lithium target demonstrates that the long-range deuteron group from lithium at 30° is principally the elastic group ($Q=-0.04 \pm 0.08$ Mev). However, at 60° both the elastic group and the unresolved 480-kev level appear to be present to about equal intensity ($Q=-0.27\pm 0.10$ Mev). In both cases, however, the Q-values of the inelastic peak are the same.

Figure 6 shows the spectrum at 30° resulting from deuteron bombardment of lithium when the discriminator settings are maximized for tritons. Two triton groups of equal intensity are observed corresponding to the ground state and an excited level at about 2.15 Mev in Li^6. This agrees with the preliminary observations on $Li^7(d,t)Li^6$ made in this laboratory of a level at about

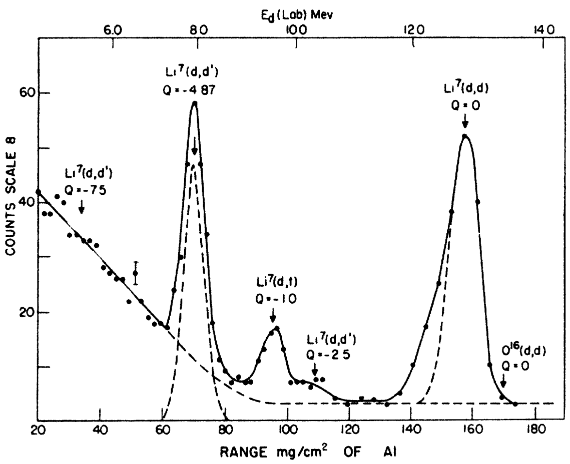

FIG. 4. A spectrum of deuterons and tritons at 30° from a 4-mg/cm^2 lithium target bombarded with 14-Mev deuterons. The discriminator settings are optimized for deuterons. There is a small triton contribution to the inelastic deuteron peak, equivalent in intensity to the triton group shown, as indicated in Fig. 6.

2.1 Mev.[19] This is to be compared with the deuteron spectrum of Fig. 4. The excited triton group coincides with the inelastic deuteron group at this angle; but since Fig. 6 demonstrates that this excited triton group is at most equal in intensity to the ground-state triton group and since the latter is shown with low intensity in Fig. 4, one must conclude that the peak in Fig. 4 is correctly assigned to deuterons. By a similar argument, using the fact that the elastic deuteron group appears in both spectra, one can conclude that the lowest energy group consists principally of tritons.

Several arguments can be used to eliminate the possibility of contaminants contributing to any of the groups observed. The most convincing proofs are the absence of the elastically scattered deuteron group corresponding to a contaminant and the correct shift of the inelastic deuteron peak with angle.

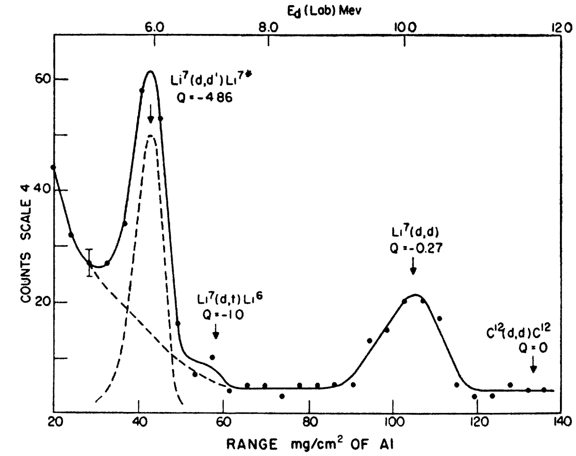

FIG. 5. A deuteron spectrum at 60° from the lithium target used in Fig. 4 bombarded with 14-Mev deuterons. If an inelastically scattered peak from carbon were present it would occur at the range indicated.

Earlier measurements of the (d,p) spectrum from lithium demonstrated that protons were not contributing to the inelastic deuteron peak of Fig. 4. This (d,p) spectrum also showed three reasonably intense proton groups beyond the range of the elastic deuteron peak. One of these corresponded to the ground-state group from $Li^7(d,p)Li^8$. The other two indicated the possible existence of excited levels at about 1.0 and 2.3 Mev in Li^8. The spectrum at greater ranges showed low intensity proton groups from carbon and oxygen contamination. These excited levels in Li^8 were not investigated in any detail and they may be due to contaminations. Greater care was exercised in preparing the subsequent lithium targets from which the inelastic scattering data were obtained.

A low intensity long-range group of protons was also observed corresponding to the unresolved ground state and 480-kev level from $Li^6(d,p)Li^7$. A search was made

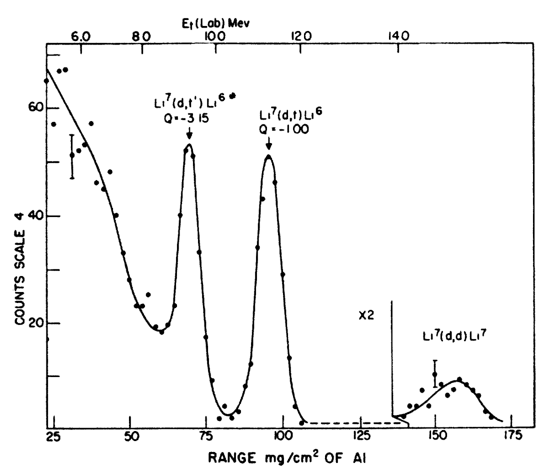

FIG. 6. A spectrum of tritons and deuterons at 30° from the lithium target used in Fig. 4 bombarded with 14-Mev deuterons. The discriminator settings are optimized for tritons.

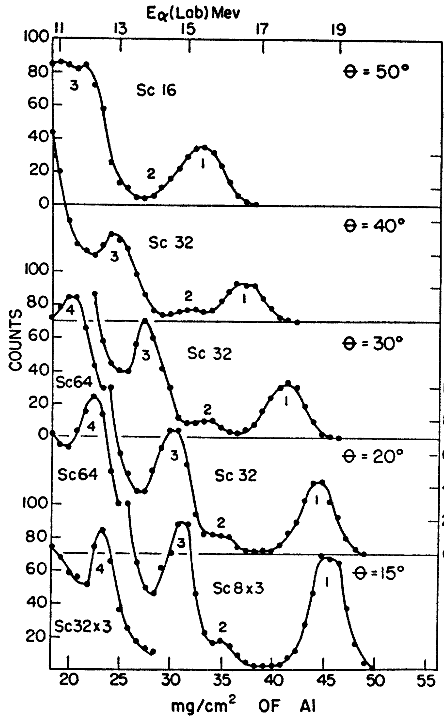

FIG. 7. $Be^9(d,\alpha)Li^7$ spectra at several angles, from a 2-mg/cm² Be-target bombarded with 14-Mev deuterons. The range, in mg/cm² of Al, includes the counter depth and half-target thickness. The alpha-energies in the laboratory system are also indicated. Peak 2 arises from an an oxygen contamination, while the remaining three are from Be. The ordinate represents the number of counts on the designated scaling factors.

for a group corresponding to the 4.8-Mev level in Li^7 which would occur about 400 kev higher than the ground-state peak from the $Li^7(d,p)Li^8$ reaction at the forward angles. However, because of the low abundance of Li^6 in the target (about 7 percent) and the fact that it is so close to the intense ground-state peak from $Li^7(d,p)Li^8$, it could not be detected.

The results obtained from deuteron bombardment of lithium show a level in Li^7 at 4.86±0.15 Mev, a level in Li^6 at 2.15±0.2 Mev, and possibly two levels in Li^8 at 1.0±0.2 Mev and 2.3±0.2 Mev. The probable errors in each case result from effects previously discussed. Again, no group corresponding to a level at 7.5 Mev in Li^7 was observed.

VI. THE REACTION $Be^9(d,\alpha)Li^7$

The spectrum of alpha-particles arising from the bombardment of Be^9 with 14-Mev deuterons is shown in Fig. 7 at a series of angles from 15° to 50°. The target employed was a 2-mg/cm² foil of Be^9. The longest range group comprises both the ground-state group and the 480-kev level. The third and fourth peaks correspond to levels at 4.76 and 7.50 Mev in Li^7.

Since the 2-mg/cm² Be targets had obvious surface discoloration, a 1-mg/cm² target apparently free from contaminants was substituted.[24] Figure 8 shows the comparison between the alpha-spectra at 30° from both targets. Except for the second peak whose Q-value agrees with that from the reaction $O^{16}(d,\alpha)N^{14}$ $Q=3.1$ Mev the spectra are identical. Further confirmation that oxygen contamination was present in the 2-mg/cm² target was obtained by investigating the $Be^9(d,p)Be^{10}$ spectra. Again, a peak due to $O^{16}(d,p)O^{17}$ was found in the proton spectrum from the 2-mg/cm² target but not from the 1-mg/cm² target.

TABLE II. Q-value differences between the long-range group and the two excited groups from the $Be^9(d,\alpha)Li^7$ reaction at several angles.

Laboratory angle (θ) (degrees)	Q_1-Q_3 (Mev)	Q_1-Q_4 (Mev)
15	4.51	7.23
20	4.47	7.28
30	4.69	7.28
40	4.40	
Mean	4.52	7.26

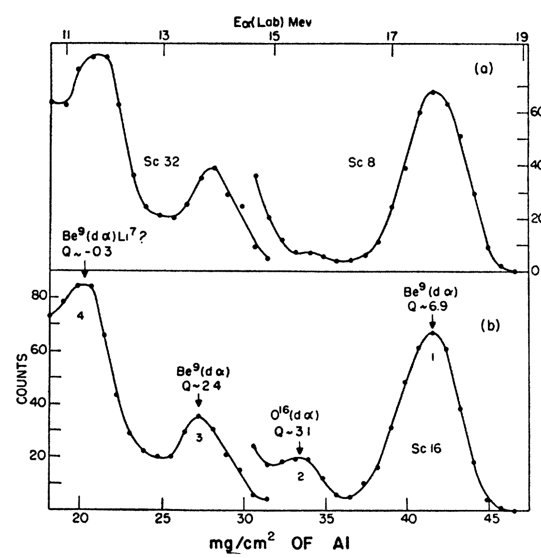

FIG. 8. A comparison of the $Be^9(d,\alpha)Li^7$-spectra at 30° with 14-Mev deuterons using 2 different target thicknesses: (a) a 1 mg/cm² and (b) a 2-mg/cm² Be target. Peak 2, arising from oxygen contamination, is observed to change in intensity.

The spectra at various angles shown in Fig. 8 were compared with the long-range group taken at 30° before and after each run. The mean value of the position of this peak was then employed to correct the range coordinates of the spectra to compensate for any changes in deuteron energy or discriminator drift. Table II lists the difference in Q-values between the third and fourth peaks and the long range peak at each angle. These values have been calculated after subtracting the rising background of alpha-particles on which the two short range groups are superimposed. This background can

[24] We wish to thank Dr. Hugh Bradner for kindly supplying us with the beryllium targets.

be attributed[16] to the three-body process $Be^9(d,2\alpha)T$ which can be expected to have a threshold at an excitation energy of 2.5 Mev.

In order to assign the measured Q-value differences of 4.52 and 7.26 Mev to energy levels in Li^7 one must decide how great a contribution the unresolved 480-kev level is making to the long-range group. Measurements made at lower bombarding energies[16] show the intensity of the excited group to be substantially the same as that of the ground state. Comparing the Q-value of this long range group with that of the oxygen group at 30° gives a value 0.25 ± 0.10 Mev lower than the known value of 7.15 Mev for the $Be^9(d,\alpha)$ reaction. Hence, it is reasonable to assume that the two groups are of about equal intensity. Since the Q-values of the long range group agree to within 30 kev at the various angles, the relative intensities are constant.

If one makes this assumption, it is necessary to add half the separation of 480 kev to the values computed above to obtain the excitation energy of these higher levels. This results in values of 4.76 ± 0.15 Mev and 7.50 ± 0.17 Mev for the excitation energies. The probable errors listed result from uncertainties in angle, counter depth, bombarding energy, and range difference, as well as the relative intensities of the two peaks in the long range group. The level at 7.5 Mev was not observed in either the inelastic scattering of deuterons or alphas from Li^7, and since it occurs in the virtual region of Li^7, there exists the possibility that it may arise from some nuclear mechanism other than the reaction $Be^9(d,\alpha)Li^{7*}$. This will be discussed subsequently.

VII. CONCLUSIONS

Charged particle groups corresponding to a level in Li^7 at about 4.8 Mev have been found by the four reactions studied. Averaging the four values gives 4.77 ± 0.10 Mev for the excitation energy. It is also clear from the data that no additional levels appear in Li^7 between the one at 480 kev and the one at 4.8 Mev despite the use of high bombarding energies.

The angular distribution of the inelastic proton group corresponding to the 4.8 level from the $Li^7(p,p')Li^{7*}$ reaction shows no significant variation in intensity between 32° and 84° in the center-of-mass system (half the points lie within ±10 percent of the mean). It is impossible to estimate intensities to better than ten percent because of the presence of a background arising from the three-body disintegration. It is possible to measure only the intensity of the alpha-group corresponding to the level in Li^7 at 4.8 Mev from the $Be^9(d,\alpha)Li^7$ reaction between 15° and 40°. While this is clearly too small an angular interval to be of any value, the intensity is approximately constant over this range. In this case and also for both the $Li^7(\alpha,\alpha')Li^{7*}$ and the $Li^7(d,d')Li^{7*}$ reactions the presence of three-body backgrounds makes any measurement of angular distribution very difficult. Hence, no estimate can be made from these experimental data of the angular momentum of this level.

A charged particle group which would indicate a level in Li^7 at 7.50 ± 0.17 Mev has been found only in the $Be^9(d,\alpha)Li^7$ reaction. This level agrees with the observations of Blair, who measured the yield of alphas from neutrons on lithium and found a resonance at $E_n=270$ kev which has been interpreted[3] as a level in Li^7 at 7.48 Mev. However, recent measurements of Adair[18] show a resonance in the total neutron cross section of lithium at 270 kev which he attributes to a level in Li^8 at 2.27 Mev. He also points out that some of the alphas contributing to the resonance found by Blair might be due to the reaction $Li^7(n,\gamma)Li^8$, where Li^8 decays to Be^{8*} which immediately breaks up into two alphas. Preliminary measurements reported here on the reaction $Li^7(d,p)Li^8$, $Q=-0.19$ Mev, indicate levels in Li^8 at about 1.0 and 2.3 Mev which confirms Adair's interpretation. It does seem unusual that both an excited level in Li^7 and one in Li^8 should be virtual against neutron emission by the same value of 230 kev.

In view of this it is possible that the low energy alpha-group found when Be^9 is bombarded with deuterons should not be assigned to a level of 7.5 Mev in Li^7. We propose as a plausible nuclear process the $Be^9(d,t)Be^8$ reaction in which tritons are emitted with low energies and the Be^8 nuclei, left in highly excited states, recoil within a small cone of angles in the forward direction. This recoiling Be^8 nucleus immediately breaks up into two alpha-particles. These high energy alphas may then correspond to the group we observe. On the other hand, it is also possible that this level is not observed in either of the inelastic scattering processes because of nuclear selection rules.

Preliminary measurements on the $Li^7(d,t)Li^6$ and $Li^7(d,p)Li^8$ reactions show a level in Li^6 at 2.15 ± 0.2 Mev and possibly two levels in Li^8 at 1.0 ± 0.2 Mev and 2.3 ± 0.2 Mev.

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