Yield and Angular Distribution of Protons from $Li^6(d,p)Li^7$†

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The relative yields *versus* energy of protons from the reactions $Li^6(d,p)Li^7$, Li^{7*} have been measured for deuteron energies up to 3.0 Mev. A marked difference in the energy dependence of the yields for the two reactions is noted. The yield for the reaction $Li^6(d,p)Li^7$ shows a broad maximum centered about 1.1-Mev deuteron energy, whereas the yield from the $Li^6(d,p)Li^{7*}$ reaction shows a slow increase throughout the whole energy range covered. Above 2.5 Mev the yield from $Li^6(d,p)Li^{7*}$ exceeds the yield from $Li^6(d,p)Li^7$. The angular distributions of the two proton groups have been observed at 0.825, 2.0, and 3.0 Mev. The angular distributions of the two groups are quite similar at all energies covered. The Butler analysis of the angular distribution data indicates that in both reactions the neutron is captured with one unit of orbital angular momentum. Since Li^6 has even parity and spin 1, this gives odd parity for the ground state and the first excited state of Li^7 and possible values of $\frac{1}{2}$, $\frac{3}{2}$, and 5/2 for the spins of the ground state and the first excited state. These possible values include the known spin of $\frac{3}{2}$ for the ground state and the currently accepted spin of $\frac{1}{2}$ for the first excited state.

I. INTRODUCTION

THE bombardment of lithium six by deuterons gives rise to two reactions producing long range protons.[1–4] The reactions are

$$Li^6+H^2\rightarrow Li^7+H^1+Q_1,$$
$$Li^6+H^2\rightarrow Li^{7*}+H^1+Q_2,$$

where $Q_1=5.020$ Mev and $Q_2=4.542$ Mev. Deuteron bombardment of natural lithium targets as was done in the present experiment does give rise to other reactions producing protons and alpha particles but none of them are of such energy as to interfere with the measurements on the two proton groups above. The angular distribution of these two groups of protons has been studied by several investigators.[5–9] The studies have been made for deuteron energies up to 1.4 Mev. There are some minor discrepancies[10] among the data of different investigators but all data except that by Neuert[5] show fore and aft asymmetry, more protons being observed in the forward direction. Neuert's data were at the very low deuteron energy of 180 kev. His conclusion was that the distribution was spherically symmetric within his statistical error, which, however, was rather large. Yield data have been reported up to 1.8-Mev deuteron energy.[7] The previously reported data indicate a general increase of the asymmetry with increased deuteron energy; also a maximum at approximately 35° to the deuteron beam becomes more pronounced. The present investigation extends the angular distribution and yield measurements up to 3.0 Mev and interprets the results in terms of the theory by Butler.[11]

II. APPARATUS

The deuteron beam for this work was supplied from the pressurized Van de Graaff generator at the State University of Iowa. Beam intensities of several microamperes are attainable, but usually much lower intensities were used. A very intense beam may cause undesirable changes in the target or target backing due to heating.

The target chamber (see Fig. 1) is a brass cylinder approximately $3\frac{1}{4}$-in. inside diameter with $\frac{1}{8}$-in. diameter observation ports at 10° intervals from 0° to 30° and at 15° intervals thereafter to 135°. Targets were prepared by evaporation in vacuum of natural metallic lithium from an electrically heated furnace mounted in the target chamber. The thickness of lithium de-

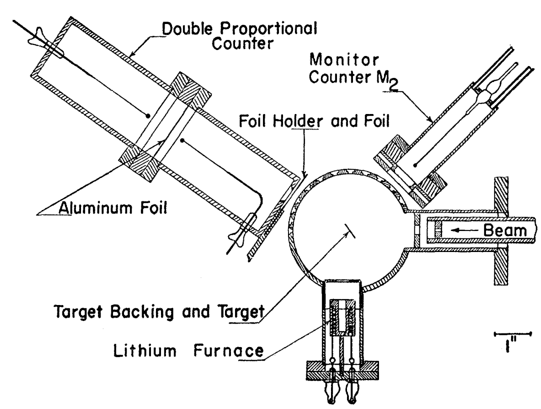

FIG. 1. Target chamber and counters.

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posited was controlled by the furnace power and the time of exposure to the furnace. Targets of 20- to 40-kev thickness for the deuteron beam were used. Target thicknesses were estimated from counting rate *versus* integrated beam current data and known cross-section data.[7] The current integrator utilizes the standard scheme of collecting charge on a condenser and discharging the condenser when a predetermined voltage is reached. Each discharge is registered on a mechanical register. No attempt was made to determine target thicknesses with precision since the purpose was only to make targets thin enough to allow separation of the two proton groups. Considerable difficulty was encountered in making targets. In many cases there appeared to be something other than lithium present which contributed protons of range comparable to the range of the lithium protons. This contaminant is believed to have been nitrogen but this was not definitely determined. Whether a target was considered satisfactory was determined from the ratio of protons, of range greater than the shorter of the two groups under investigation, to the alpha particles from the reaction $Li^6(d,\alpha)He^4$. These alpha particles are so energetic that it is extremely unlikely any other reaction will produce alpha particles of comparable range. Consequently the proton-to-alpha ratio is a good measure of the relative abundance of contaminant. Various targets showed a wide range in the ratio of protons to alpha particles. The targets used were those which gave a ratio near the lowest of all targets made. The targets used for the 0.825-Mev data were evaporated directly onto an eight sided stainless steel block. This block was carried on the end of a shaft extending through "O" ring seals in one end of the chamber so that it could be rotated and positioned from outside. At 2.00 Mev and above, the background counting rate from the bare stainless steel block made it unsuitable and thin silver plates were attached to serve as target backing. Silver foils were used as target backing for the forward angle observations. These silver foils were held on a different block but one similar to that described above. Particles observed in the forward directions 0° to 30° passed through the thin backing.

The protons were detected in a double proportional counter (see Fig. 1) designed for this experiment and operated at 36 cm of mercury pressure. The counter gas used was a mixture of 95 percent argon and 5 percent carbon dioxide flowed continuously through the counters. Figure 2 is a block diagram of the counting apparatus. Pulse size discrimination was by the coincidence analyzer discriminators. The double proportional counter base was provided with locating pins and the counter table with locating holes to match so that the counter could be quickly and accurately located to face any desired observation port. The counter table was attached to the target chamber.

Monitoring of the deuteron beam was accomplished by detection of the alpha particles from the reaction $Li^6(d,\alpha)He^4$ in another proportional counter (see Fig. 1). The monitor counter M_2 shown in Fig. 1 was used in taking the forward angle data. Another counter M_1 similar to M_2 was mounted at 90° to the deuteron beam; it was used in taking the data at 45° and larger angles. The monitor counters were calibrated against each other at each energy since they were used at different angles to the deuteron beam and the solid angles seen by the counters were different.

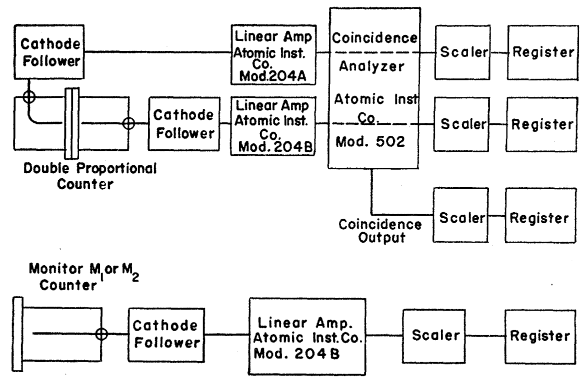

FIG. 2. Block diagram of counting apparatus.

III. PROCEDURE IN TAKING DATA

The first step was to determine by trial the proper thickness of aluminum foil to insert between the monitor counter and the target so as to have the alpha particles detected near the end of their range. The alpha particles then make pulses near the maximum possible for given counter pressure and voltage operating conditions. Counter pressure was set to 36 cm of mercury and counter voltage and amplifier gain were adjusted to give approximately 70-volt pulses for alpha particles. A number *versus* discriminator curve was then taken to determine the best discriminator setting to use so as to count practically all alphas and exclude all of the very numerous protons which also enter the counter.

Sufficient aluminum foil was inserted between the double proportional counter and the target to exclude the aforementioned alpha particles. The counter voltages and associated amplifier gains were then adjusted to give output pulses of approximately 35 volts for protons. A number *versus* discriminator setting curve was then run for each of the two channels to determine the best discriminator setting to use. The object in this last setting is to use the highest discriminator level possible without missing any of the protons. Using a lower level would insure counting all protons but would greatly increase the background counting rate because of neutrons.

The adjustments mentioned above having once been determined were left fixed. All counters were operated at the pressure 36 cm of mercury held constant by a

Cartesian manostat. The voltage applied to either monitor counter was 1050 volts; both sections of the double proportional counter were operated at 1225 volts. The data recorded at each angle were the count in each channel of the double proportional counter for a fixed count in the monitor channel and for a wide range of aluminum foil absorber inserted between the target and the double proportional counter. Coincidences between the two channels were also recorded. Figure 3 is a plot of the number of counts in the front section of the double counter *versus* aluminum foil added between target and counter. Corresponding data were recorded from the back section at the same time. For a given thickness of added aluminum foil the two sections operate approximately 12 mg/cm^2 of aluminum apart on such a curve; part of this is due to 8.60 mg/cm^2 of aluminum between the two sections and the remainder is due to the depth of the front section. No such complete curve of counts *versus* added foil need be determined for every angle. A brief preliminary survey along such a curve allows one to determine the amount of added foil necessary to put the back section of the counter in the region enclosed in dotted lines. This portion of the curve may then be investigated very carefully and at the same time data for the portion farther back are obtained from the front section.

Inspection of Fig. 3 shows that for added foil thickness greater than 80 mg/cm^2 the count remains constant. This is background due to neutrons and changes very little even for as much as $\frac{1}{16}$ in. of aluminum added. As the amount of added foil is decreased the count rises rapidly for a ways and then very slowly. The count in this region of nearly constant count is background plus the long range protons under investigation. Still further decrease in the added foil brings further rise in the count until at 56 mg/cm^2 a steady count again obtains and further decrease causes no increase in the count. The count here is background plus both groups of protons. Of course the amount of absorber can be decreased enough to admit protons from contaminant reactions such as $C^{12}(d,p)C^{13}$ and $O^{16}(d,p)O^{17}$. A curve such as Fig. 3 for each angle serves to determine the net number of protons of each group. Actually, as mentioned above, only parts of such a curve were generally obtained.

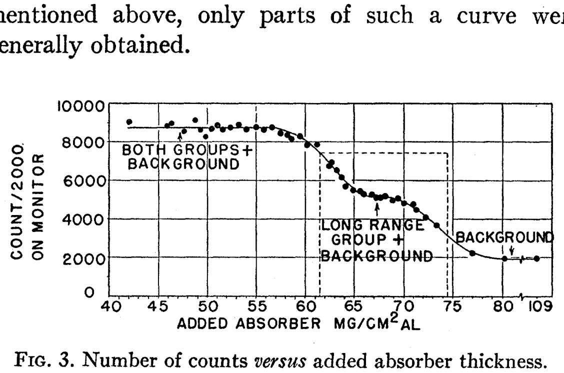

FIG. 3. Number of counts *versus* added absorber thickness.

Experimentally it is found that the net count in the back section is approximately 8 percent lower than the count in the front section at a corresponding location along the curve. This is due to multiple scattering of some particles so that they do not enter the back section, and to stopping of some particles by the wire and bead in the front section. The effect of this is that, in obtaining the number of short-range protons by subtracting the net long range group measured in the back section from the net total measured in the front section, too large a number is obtained. A correction for this effect has been made to all of the data at 0.825 Mev and at 2.00 Mev. Complete curves were determined from the front section at 3.00 Mev for 90° and smaller angles but not for larger angles. The 8 percent loss in the back section was then taken into account in determining the count to be used for the larger angles.

In addition to the angular distribution data taken as described above, data of yield *versus* integrated deuteron beam were taken at 0° and deuteron energies 1.0, 1.4, 1.8, 2.0, and at 0.1-Mev intervals to 3.0 Mev. In taking these data, the thickness of aluminum foil between the counter and target was adjusted so that the front section of the counter received both proton groups. Following each such run, a background run was taken with enough added foil to stop both groups. The ratio of each group to the total was known at 2.0 Mev and at 3.0 Mev from the angular distribution data. The ratio was also determined at 2.5 Mev and at 1.0 Mev. The ratio found at 1.0 Mev was in good agreement with that determined by Whaling and Bonner.[7] Their ratio results were used at 1.8 Mev and lower energy to divide the total count into short- and long-range groups.

The only use made of the coincidence count between the front and back sections of the double proportional counter was as a check on the efficiency of the front section when taking data with only a small amount of absorber. Under these conditions the energy of protons in the front section is relatively high and consequently the proton pulse size is reduced. Good agreement between the net count in the back section and the coincidence count was taken as evidence that the front section was counting all the protons passing through it.

IV. RESULTS AND DISCUSSION

Angular distributions of the two groups of protons separately have been determined over the range of angles 0° to 135° at 2.0 Mev and at 3.0 Mev. The distribution of each group at 0.825 Mev was determined over the range 45° to 135°. In general sufficient counts were taken at each point on the curve (see Fig. 3) used to obtain the data at each angle and bombarding energy to get statistical accuracy of better than $1\frac{1}{2}$ percent. Because of straggling, the two proton groups are not completely separated and there is no level plateau

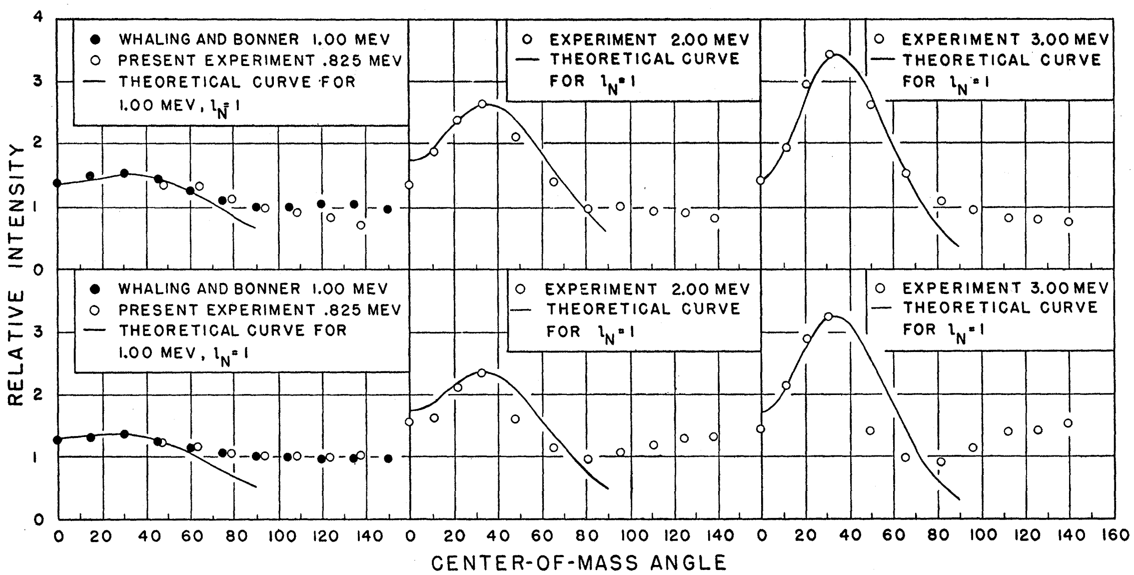

FIG. 4. Angular distribution of the two proton groups in the center-of-mass system of coordinates. The short-range group is shown in the three top curves and the long-range group in the three bottom curves. In all cases the data are normalized to unity at 90°. The theoretical curves are computed from the Butler theory using $r_0 = 4.14 \times 10^{-13}$ cm.

on the curve corresponding to the long-range group alone. There is then some error in selecting the most nearly level portion or, in most instances, in selecting the inflection point on the curve. It is estimated that the probable error in the final results is less than 4 percent.

The results of the angular distribution measurements are shown in Fig. 4. The relative intensity normalized to unity at 90° is plotted as ordinate and the center-of-mass angle as abscissa. The proper center-of-mass intensity correction factors have been applied to all data. The results of Whaling and Bonner[7] at 1.0 Mev are shown in Fig. 4 along with the results of the present experiment at 0.825 Mev. The agreement with their results for both groups is quite satisfactory except for the short-range group at backward angles. Their results for the short-range group show an increase in the backward direction reaching a maximum at approximately 130° and then a decrease, whereas for this low energy the present experiment shows no such increase for the backward angles. In their experiment, as well as in the present experiment, the short-range data are obtained as a difference between two numbers and are consequently subject to larger error than are the data for the long-range group; nevertheless the difference seems larger than can be explained by errors. The data at 2.00 Mev and at 3.00 Mev show greater fore and aft asymmetry than has been observed at lower energies, together with a more pronounced maximum at approximately 32° to the deuteron beam.

The relative yield *versus* energy data are shown in Fig. 5. The agreement with the results of Whaling and Bonner[7] over the energy range common to both experiments is quite good. Their results are also shown in Fig. 5. The relative yields of the two groups differ considerably in their dependence on the incident deuteron energy. The yield from the reaction leading to the ground state shows a broad maximum centered about 1.1 Mev. The other group shows increasing yield throughout the energy range covered. The yield of the short-range group, which at low bombarding energy is less prominent, becomes equal to the long-range group at 2.5 Mev, and above this energy exceeds the long-range yield.

Butler[11] has developed a theory and formulae from which the angular distributions to be expected from a stripping process in (d,p) and (d,n) reactions can be calculated. The theoretical expression involves the masses of the reacting particles, the reaction energy,

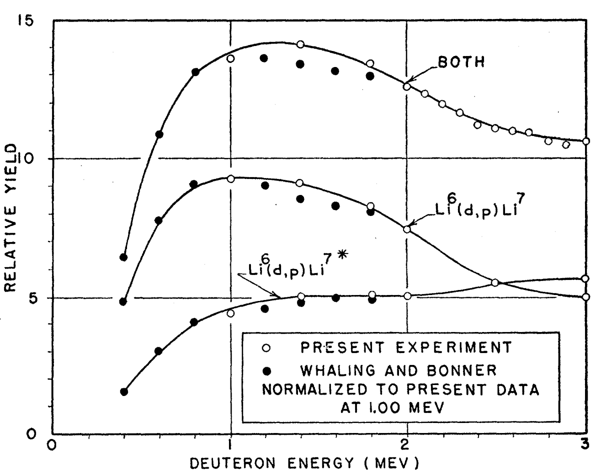

FIG. 5. Relative yield of long- and short-range protons at 0°.

the bombarding energy, the radius assumed for the target nucleus, the deuteron binding energy, and the orbital angular momentum of the captured particle. For a particular reaction, at one bombarding energy, all these quantities except the last remain fixed. A separate theoretical curve of intensity *versus* angle is determined for each value of orbital angular momentum of the particle captured. In any single case there is often found good agreement between the experimental data and only one of the possible theoretical curves. Butler has used these results to infer spins and parities of final nuclear states from known spins and parities of initial states. His results have also been successfully applied by other experimenters.[12,13]

Figure 6 shows Butler curves for the reaction $Li^6(d,p)Li^7$ for deuteron energy of 2.0 Mev. These curves were calculated using $r_0=3.92\times10^{-13}$ cm for the Li^6 nucleus. Qualitatively the character of the curves does not change rapidly with change of bombarding energy and reaction energy. These curves, therefore, may be used for data taken at higher and lower energies and even for data on the reaction $Li^6(d,p)Li^{7*}$ to the extent of determining which of the possible curves will best fit the experimental data. Examination of the experimental data shown in Fig. 4 indicates a best fit by the $l_n=1$ type curve at each energy and for each group. The solid curve shown on each plot of experimental data is the $l_n=1$ curve computed for that particular reaction and energy. The fit of the theoretical curve to the experimental data at 2.0 Mev was found better for $r_0=4.14\times10^{-13}$ cm than for $r_0=3.92\times10^{-13}$ cm, and consequently this larger value was used to compute all the $l_n=1$ curves shown in Fig. 4. It is evident as has been pointed out by others[14] that qualitatively the character of the curve is unchanged and the location of the maximum is shifted only slightly for such a change in r_0.[15]

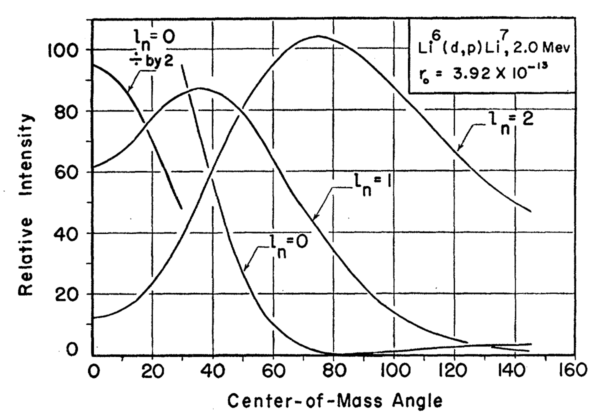

FIG. 6. Theoretical curves computed from the Butler theory. Computed for the reaction $Li^6(d,p)Li^7$ at 2.0-Mev deuteron energy and $r_0=3.92\times10^{-13}$ cm.

The fit by the $l_n=1$ curve for both reactions $Li^6(d,p)Li^7$ and $Li^6(d,p)Li^{7*}$ indicates that the ground state of Li^7 and the first excited state both have parity opposite to the parity of Li^6 in the ground state. Since Li^6 has even parity,[16,17] this gives odd parity for the first excited state of Li^7 and the ground state of Li^7. These results are in accord with the accepted odd parity of the first excited state[17] and with the expectation of odd parity for the ground state on the basis of shell structure. The addition of a neutron with orbital angular momentum 1 to the Li^6 nucleus with spin 1 gives 1/2, 3/2, and 5/2 as possible spins for the ground state and the first excited state of Li^7. The spin of Li^7 in the ground state is 3/2 and the currently accepted spin of the first excited state is 1/2.[17,18] Both of these values are included in the possible values determined by the present experiment.

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