Angular Yield of Both Proton Groups from $Li^6(d,p)Li^7$

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The simultaneous measurement of the intensities of two energy groups of product particles is accomplished by sorting out their proportional-counter pulses in an electronic ten-channel discriminator. The angular yields of protons leading to the ground state and to the 480-kev state of Li^7 in the reaction $Li^6(d,p)Li^7$ have been measured at deuteron energies between 400 and 800 kev. At the higher bombarding energies the angular yields of the two groups are complex and somewhat similar, both containing terms at least as high as $\cos^4\theta$. As the deuteron energy is reduced, the short-range group retains this complexity while the long-range group becomes more nearly spherically symmetric.

I. INTRODUCTION

EVER since its discovery by Rumbaugh and Hafstad[1] in 1936, the interpretation of the 480-kev level of Li^7 in its relation to the ground level has provided a stimulating challenge to theories of nuclear structure. At the time this investigation was undertaken, the only specific proposal that had been made[2] interpreted the ground state as $^2P_{\frac{3}{2}}$ and the excited level as $^2P_{\frac{1}{2}}$, but this was doubted partially because of the lack of a theory to explain so large a spin-orbit coupling. More recently a consideration of the relative yields[3] of the alpha-groups in the $B^{10}(n,\alpha)Li^7$ reaction seems to indicate,[4] although perhaps not conclusively, a value of I as great as 5/2 for the excited state. This investigation was motivated by the hope that detailed comparison of the angular yields of the two groups of protons arising from transitions to these two states would shed further light on their nature.

II. METHOD OF OBSERVATION

The usual methods of observing the intensities of two energy groups involve the use of a shallow counter either with high bias so that two peaks may be plotted as range is varied, or with low bias so that two plateaus may be measured, the difference of which is required for the intensity of the short-range group. The method used in this work was developed to eliminate the uncertainty, as well as the tedium, of making successive intensity measurements at each angle and bombarding energy. It requires instead a single run, during which sufficient data are recorded to give the intensities of both groups of product particles directly.

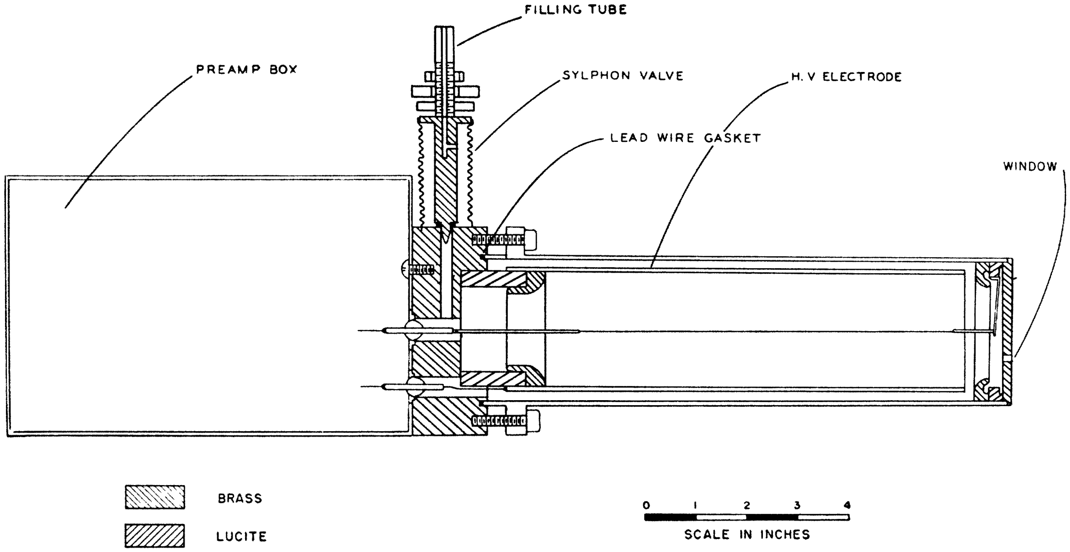

FIG 1. Deep proportional counter used in measuring the intensities of the two ranges of protons from $Li^6(d,p)Li^7$. In the present experiment the central (2-mil tungsten) wire was 4.5 in. long.

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[1] L. H. Rumbaugh and L. R. Hafstad, Phys. Rev. **50**, 681 (1936).
[2] D. R. Inglis, Phys. Rev. **50**, 783 (1936); G. Breit and J. R. Stehn, Phys. Rev. **53**, 459 (1938).
[3] J. K. Bøggild, Kgl. Danske Vid. Sels. Math-Fys. Medd. **23**, 4, 26 (1945).
[4] D. R. Inglis, Phys. Rev. **74**, 1876 (1948).

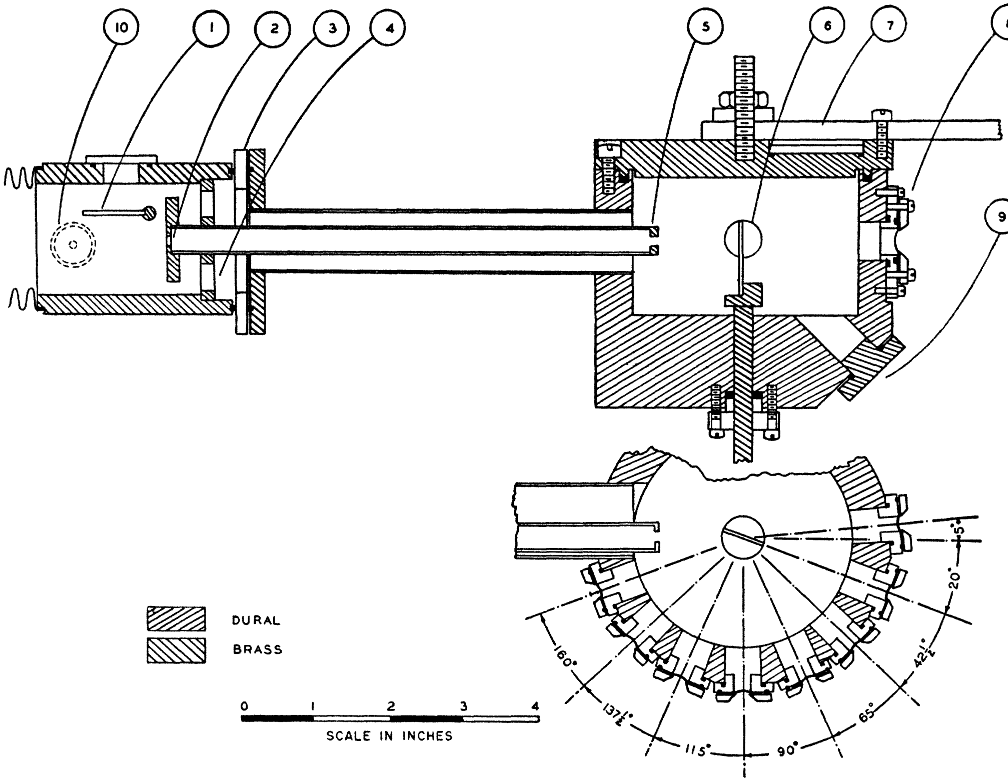

FIG. 2. Target chamber assembly. (1) Quartz plate which can be rotated so as to intercept the beam. (2) Collimating slit. (3) Lucite insulating ring. (4) Openings in flange to provide greater pumping speed. (5) Entrance slit into chamber. (6) 90° window (one on each side of chamber). (7) Rotating arm on which the proportional counter is mounted. (8) 5° window showing assembly detail. (9) Port in which the lithium oven is inserted. (10) Stupakoff insulators supporting the two members of a slit which intercepts the edges of the beam and thereby provides a signal for regulating the statitron voltage. Three Lucite windows are provided in the top of the chamber. The 5° port was later enlarged so that observations could also be made at 0°.

A proportional counter is employed deep enough that the energy absorbed in its active volume is comparable with the energy difference of the two groups of particles being observed. One way of using such a counter to advantage in resolving two groups of particles consists in letting both groups come to rest inside the counter. A long-range particle then produces a larger pulse than does a short-range particle. An alternative setting allows the short-range particles to come to rest just at the end of the sensitive volume of the counter, while the long-range particles pass through the chamber. In this case, a short-range particle by virtue of its greater ionizing power near the end of its range will produce the larger pulse. With either setting of the counter a recording system capable of discriminating and sorting the pulses according to their amplitude, will make it possible to observe in one experimental run the individual intensities of both groups.

III. APPARATUS AND PROCEDURE

In the present experiment the pulses from the deep proportional counter, after suitable amplification, were sorted in a ten-channel electronic discriminator. A "sliding pulser" was provided for calibrating the discriminator channels, which could be made approximately 2, 5, or 10 volts wide. All the circuits employed are of the Los Alamos design.[5]

The counter, which was filled with argon, is shown in detail in Fig. 1. The pressure in the counter is critical if maximum resolution of two groups of particles is desired. In the $Li^6(d,p)Li^7$ reaction the difference in range between the groups is about 4 cm of air. With a central wire 11.5 cm in length it was found necessary to fill the counter to a pressure of about 50 cm Hg in order to resolve the groups, when all the protons were allowed to end in the chamber. In practice however it proved more convenient to use the alternative setting in which the short-range protons passed to the end of the chamber. In this case extensive investigation showed that a pressure of about 20 cm Hg in the chamber yielded the best result.

Preliminary tests also revealed that the resolution depended very critically on the range setting. This was especially true because it was found desirable to obtain at each angle and energy that setting of the counter which would produce a similar distribution of pulses in

[5] W. C. Elmore and M. Sands, *Electronics* (McGraw-Hill Book Company, Inc., New York, 1949).

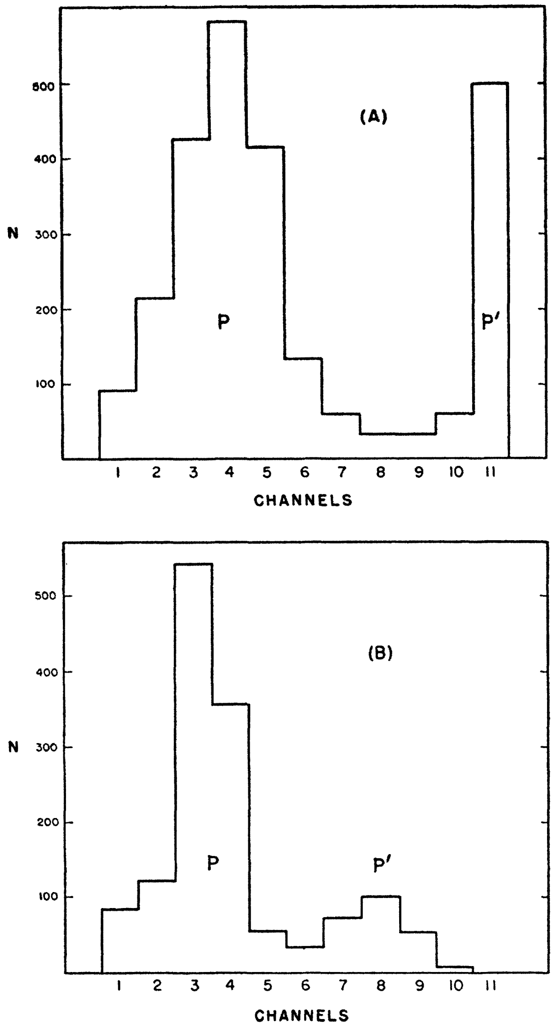

FIG. 3. Typical distributions of proton pulses obtained with the ten-channel discriminator. Pulse height increases with increasing channel number. Channel 11 represents the "overflow," i.e., all pulses larger than those in channel 10. These data were obtained with that setting of the proportional counter for which the short-range protons produced the larger pulses and therefore registered in the higher numbered channels. Distribution (A) was obtained with channels approximately 2 volts wide and most of the short-range protons were recorded in the overflow. The starting bias was approximately 50 volts. In distribution (B) the channels were over twice as wide and both groups were recorded within the ten channels. In these plots the numbers of counts in the various channels have been adjusted to compensate for inequalities in channel widths.

the channels of the discriminator, so that inequalities in channel width and slight overlapping of the two groups would not seriously affect the results. Since the proton energies depend on both bombarding energy and angle of observation, it was necessary to alter the range setting for each observation. This was accomplished by using appropriate aluminum absorbers as a coarse range adjustment, with variation of air path as a fine adjustment.

The counter was mounted on a carriage which provided a screw-driven radial motion, and the carriage in turn was attached to a radial arm which pivoted on the axis of the target chamber so that observation could be made at any one of seven thin windows of the target chamber. The latter was milled from a 4-in. solid aluminum cylinder. The complete assembly is shown in detail in Fig. 2.

TABLE I. Intensities in the center-of-mass system of the two ranges of protons from $Li^6(d,p)Li^7$. For each bombarding energy the yields have been normalized to one at 90° (in the laboratory system).

$\cos\theta$	400 kev	430 kev	540 kev	650 kev	780 kev
		Long range			
−0.95	0.88	0.92	0.95	1.04	0.99
−0.77	1.00	1.03	0.99	1.04	1.10
−0.48	0.98	0.98	0.95	1.01	1.05
−0.06	1	1	1	1	1
0.37	1.03	1.00	1.09	1.00	1.20
0.71	1.02	1.00	1.14	1.18	1.47
0.93	1.04	1.02	1.11	1.33	1.42
1.00	1.04	1.01			1.40
		Short range			
−0.95	0.67	0.62	0.72	0.93	0.60
−0.77	0.81	0.86	0.79	1.08	0.91
−0.48	0.98	1.06	1.00	1.08	1.04
−0.06	1	1	1	1	1
0.37	1.19	1.14	1.23	1.16	1.28
0.71	1.19	1.05	1.13	1.38	1.72
0.93	0.97	0.80	0.95	1.17	1.64
1.00	0.97	0.68			1.51

The target used for these measurements was a thin layer of ordinary lithium evaporated onto a thin silver foil by means of an oven introduced into the target chamber through a Wilson seal. Aside from the lowered intensity, the presence of Li^7 offers no difficulty in the present experiment. Observations at the backward angles were made with a target setting of 60° and at the forward angles with a setting of 120°, observation at 90° being included in each case for intercomparison.

Since angular yield measurements are critically dependent on reliable monitoring of the beam, two methods were employed. An electronic current integrator (Sands' design, Los Alamos) was used to measure the total integrated beam intensity during a run. In addition a small proportional counter was employed to observe the products of the reaction at a 90° window provided for this purpose on the free side of the target chamber. By accepting all the charged particles coming from the reaction, including the very numerous alphas from $Li^7(d,n\alpha)\alpha$, the statistical uncertainty introduced by the monitor was kept very small.

The general procedure followed in recording the angular yields was to traverse the windows in one direction and then to repeat the measurements in the reverse order. This precaution revealed the absence of any systematic drifts in the counting rate. Before each run the position of the proportional counter was adjusted so that the short-range protons gave maximum pulses. If this adjustment is made properly the pulse amplitudes are nearly independent of the angle of observation and the bombarding energy. In the course of the work, several settings of discriminator channel width and starting bias were tried. Results obtained with two different settings are shown in Fig. 3. The deuteron beam was obtained from the small horizontal statitron described elsewhere.[6]

IV. RESULTS

It is evident from Fig. 3 that the two groups of protons are not completely resolved, and it is therefore necessary to use some judgment in making a division between them. As mentioned above, an effort was made to produce similar distributions of pulses in the various channels over an entire angular run, so that, although a small absolute error could be made in dividing the groups, the relative error should be very small if the groups are divided in a consistent manner.

Table I gives a summary of the results in the center-of-mass system of coordinates. These data are the average of several runs. All the yields have been corrected by the inverse square law, and the results as observed in the laboratory coordinate system were transformed to the center-of-mass coordinate system by using the conversion tables compiled by Moskow.[7] To facilitate a comparison of the angular distributions at the five bombarding energies, the yields have been normalized to unity at 90°, and they are plotted against

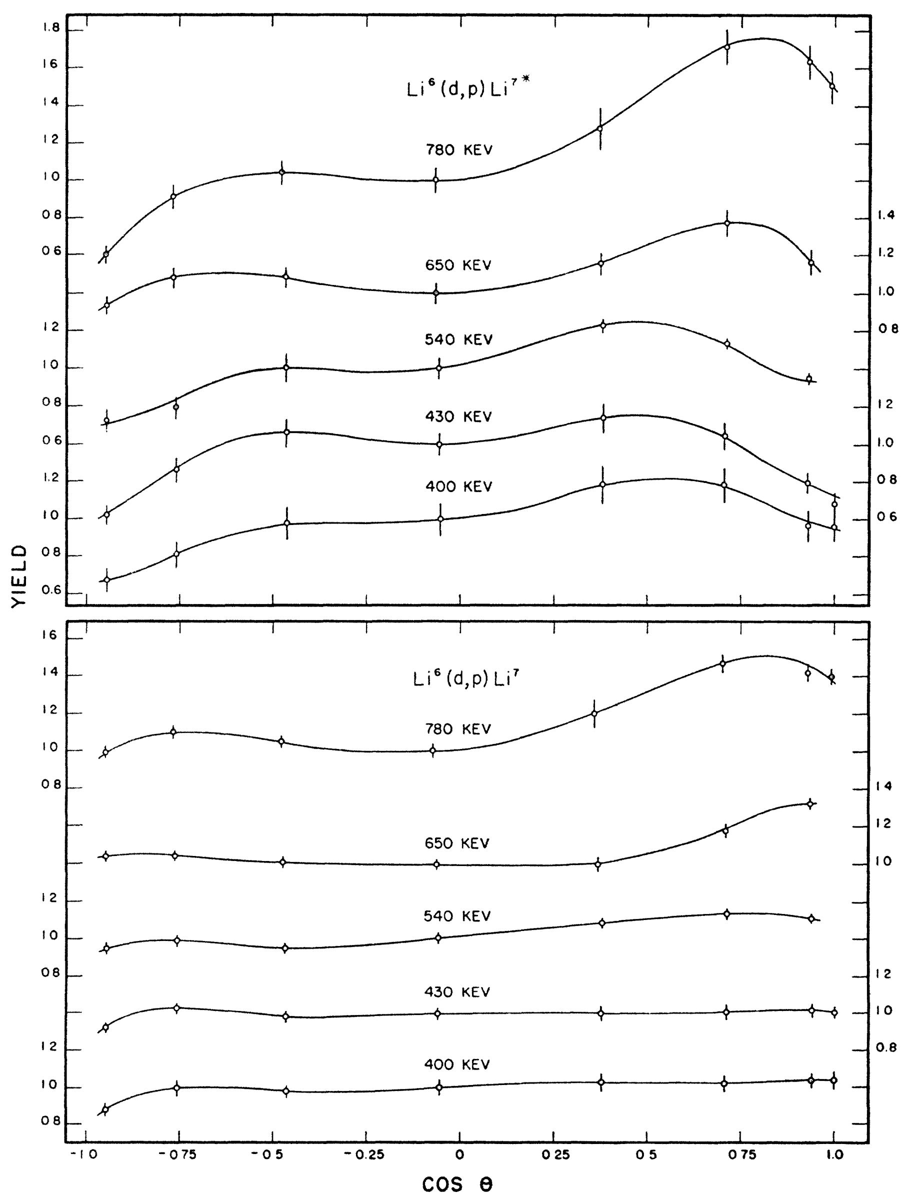

FIG. 4. Angular distributions in the center-of-mass system of the two proton ranges from $Li^6(d,p)Li^7$. Yields have been normalized to one at the 90° angle of the laboratory system. The curves are sixth-power polynomials in $\cos\theta$ obtained from an analysis using the seven points of observation (an average of the two forward measurements was used for the 400-, 430-, and 780-kev runs).

[6] Inglis, Krone, and Hanna, Rev. Sci. Inst. **20**, 834 (1949).
[7] M. Moskow, master's thesis, Johns Hopkins University (1948). (Copies available on request.)

TABLE II. Coefficients in the expansion,

$$Y(\cos\theta)=Y(0)\left(1+\sum_{n=1}^{6}A_n\cos^n\theta\right)$$

for both ranges of protons from $Li^6(d,p)Li^7$. The yields for $\cos\theta=0$ are expressed in arbitrary units which make the yield of long-range protons equal to one at 400 kev.

	400 kev	430 kev	540 kev	650 kev	780 kev
			Long range		
$Y(0)$	1	1.11	1.51	1.80	1.91
A_1	0.13	0.09	0.24	−0.07	0.25
A_2	−0.11	−0.26	−0.03	−0.03	0.78
A_3	−0.46	−0.40	−0.35	0.46	0.12
A_4	0.44	0.94	0.43	0.79	−0.28
A_5	0.46	0.41	0.21	−0.28	−0.13
A_6	−0.42	−0.77	−0.43	−0.61	−0.38
			Short range		
$Y(0)$	0.23	0.29	0.49	0.60	0.66
A_1	0.28	0.15	0.36	0.12	0.26
A_2	0.83	1.05	1.02	0.86	1.23
A_3	−0.12	−0.22	−0.52	0.36	0.88
A_4	−2.21	−2.94	−2.86	−0.65	−0.99
A_5	−0.20	0.15	0.28	−0.38	−0.61
A_6	1.20	1.54	1.63	−0.26	−0.26

$\cos\theta$ in Fig. 4. It is seen that at the highest energy recorded, the angular dependence is somewhat similar for the two groups. At the lower energies, on the other hand, there is a marked difference between the two distributions; the long-range distribution tends fairly rapidly toward spherical symmetry, while the short-range distribution retains most of the complexity displayed at the higher energy.[8] To investigate this more fully the results have been analyzed into polynomials in $\cos\theta$ up to the sixth power and the curves so obtained are plotted in Fig. 4. The analysis was made using seven observation points (a suitable average of the two forward angles was used in those runs in which an observation was made at 0°) so that the sixth power curves pass through all of these points. The coefficients A_n in the expansion:

$$Y(\cos\theta)=Y(0)\left(1+\sum_{n=1}^{6}A_n\cos^n\theta\right)$$

are given in Table II. An inspection of this table shows that all of the coefficients for the long-range distributions are less than unity, while some of those for the short-range group are considerably larger, especially at the lower energies. Because small uncertainties in the measured yields can lead to relatively large uncertainties in the expansion coefficients, it is questionable how much significance can be attached to these large values of the coefficients. In particular it seemed worth while to analyze the data into polynomials including terms only up to the fourth power. With such an analysis using a least-square criterion it is possible to fit the long- and short-range data to within about three and five percent, respectively. In view of the statistical uncertainty of the observations such a fit would seem to be entirely satisfactory were it not that the discrepancies so introduced are in general systematic and certain features of the distributions which seem reasonably well established from the observations are lost in the less complex analysis. Nevertheless, an inspection of the set of coefficients obtained from the less complex analysis given in Table III, shows that in general the coefficients are smaller, and it seems reasonable that at these low bombarding energies the analysis, which utilizes smaller powers of $\cos\theta$ and at the same time leads to smaller values of the coefficients, is more nearly correct.

TABLE III. Coefficients in the expansion,

$$Y(\cos\theta)=Y(0)\left(1+\sum_{n=1}^{4}A_n\cos^n\theta\right)$$

for both ranges of protons from $Li^6(d,p)Li^7$.

	400 kev	430 kev	540 kev	650 kev	780 kev
			Long range		
A_1	−0.00	−0.04	0.18	0.02	0.30
A_2	0.11	0.13	0.26	0.26	1.03
A_3	0.09	0.08	−0.11	0.15	−0.07
A_4	−0.17	−0.16	−0.25	−0.03	−0.87
			Short range		
A_1	0.30	0.09	0.28	0.23	0.43
A_2	0.27	0.30	0.16	1.03	1.43
A_3	−0.13	−0.02	−0.19	−0.12	0.12
A_4	−0.56	−0.77	−0.48	−1.08	−1.45

The angular measurements presented here do not conveniently give the variation of yield with energy. Since excitation curves have recently been obtained elsewhere,[8,9] it was thought advisable to make only a single check run with the present method. Only the relative change in yield with energy was measured and the data at the energies corresponding to the angular runs, included in Table II for completeness, have been normalized to make the yield of long-range protons equal to unity at the lowest energy.

[8] We note that the complexity that we find in the short-range group at the low energies disagrees with the result obtained by Whaling. In his method the intensity of the short-range group is obtained by subtracting the long-range plateau from the total-intensity plateau measured with a shallow counter and low bias. We are indebted to him for making his results available to us before publication. See W. Whaling and T. W. Bonner, Phys. Rev. **79**, 258 (1950).

[9] N. P. Heydenburg and D. R. Inglis, private communication.