Energy Release from $Be^9(d,\alpha)Li^7$ and the Production of Li^7*

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The α-particles from $Be^9(d,\alpha)Li^7$ have been investigated with a variable air pressure absorption cell, ionization chamber and linear amplifier. It has been established that there are two groups of α-particles differing at 760 mm pressure and 15°C by 3.08 ± 0.10 mm range reduced to zero bombarding voltage. The groups have been shown to be associated with the production of Li^7 in the ground state and in an excited state. At 239 kv bombarding voltage, the excited state is formed 1.7 times as often as the ground state. The energy balance, Q, associated with the production of the ground state has been determined to be 7.093 ± 0.022 Mev. The energy of the excited level has been determined to be 494 ± 16 kev. The total yield curve for α-particles has been investigated from 235 kv to 390 kv bombarding voltage. The measured value for the energy of the excited level in Li^7 is discussed in connection with values from other reactions in which Li^7 is an end product and with γ-ray measurements of the level.

INTRODUCTION

It has been shown that Li^7 is formed partially in an excited state of relatively low energy in the reactions

$$Li^6+H^2\rightarrow Li^7+H^1+Q_1,^{1-3} \quad (1)$$

$$B^{10}+n\rightarrow Li^7+He^4+Q_2.^{4-7} \quad (2)$$

The estimates of the energy of the excitation level, however, have diverged widely. It is to be expected that Li^7 might also be formed in an excited state in the process

$$Be^9+H^2\rightarrow Li^7+He^4+Q_3, \quad (3)$$

particularly since the intermediate nucleus, B^{11}, and the end products, Li^7+He^4, are identical with those of (2). Reaction (3) has been investigated by Williams, Haxby and Shepherd[8] with thick targets. They found only a single group of α-particles giving a value for Q_3 of 6.95 Mev. Since the most recent energy release measurements on other reactions performed in this laboratory[9] predict a value of 7.04 ± 0.06 Mev, it seemed appropriate to perform a similar investigation with thin targets to redetermine Q_3 and to ascertain whether any structure might appear in the α-particle spectrum indicating the formation of Li^{7*}.

APPARATUS

The Cockcroft Walton circuit previously described[10] was used to accelerate deuterons pulled by a probe from a low voltage arc source to energies of from 200 to 350 kev. The beam was magnetically analyzed and collimated through 0.794-cm apertures by an aluminum tube 16.5 cm long. The target was mounted to allow for preheating by a platinum filament. A negative potential of 300 volts to prevent entrance of secondaries from the collimating tube was applied to the target chamber which was insulated as a Faraday cage. Beams which measured from 15 to 20 microamperes at the target were used. The current integrator which tripped the counter was adjusted so that about 75 to 100 counts were included in the counting period. The disintegration products emitted at $90°\pm2°\ 15'$ were counted after passage through the variable air pressure absorption cell described by Smith.[9] Thin windows (about 2 mm air equivalent) of

[1] L. H. Rumbaugh and L. R. Hafstad, Phys. Rev. **50**, 681 (1936).
[2] J. H. Williams, W. G. Shepherd and R. O. Haxby, Phys. Rev. **52**, 390 (1937).
[3] L. H. Rumbaugh, R. B. Roberts and L. R. Hafstad, Phys. Rev. **54**, 657 (1938).
[4] O. Haxel, Zeits. f. Physik **104**, 7–8, 540 (1937).
[5] C. O'Ceallaigh and W. T. Davies, Proc. Roy. Soc. London **A167**, 81 (1938).
[6] M. S. Livingston and J. G. Hoffman, Phys. Rev. **53**, 227 (1938).
[7] W. Maurer and J. B. Fisk, Zeits. f. Physik **112**, 7–8 436 (1939).
[8] J. H. Williams, R. O. Haxby and W. G. Shepherd, Phys. Rev. **52**, 1031 (1937).
[9] N. M. Smith, Jr., Phys. Rev. **56**, 548 (1939); S. K. Allison, L. S. Skaggs and N. M. Smith, Jr., Phys. Rev. **57**, 550 (1940), a correction to previously published Q_3 for $Be^9(p,\alpha)Li^6$.
[10] G. T. Hatch, Phys. Rev. **54**, 165 (1938).

Newskin were mounted at each end of the cell on copper microphone screening of transmission coefficient 0.315. In order to use the cell at less than atmospheric pressures, the window facing the ionization chamber was mounted on the outside of the cell. The entire cell, insulated from the target chamber by a Bakelite bushing, was raised by batteries to a potential of 225 volts and formed the front cap of an ionization chamber 3 mm deep. The collecting button of the ionization chamber connected directly to the grid of a 954 acorn tube in the first stage of a linear amplifier.

The pulses from the linear amplifier were recorded through a scale-of-sixteen dividing circuit by a Cenco mechanical counter. The bias voltage on the scaling circuit was read with a voltmeter and frequently checked and adjusted if necessary. The output of the amplifier was also fed into a 5-inch cathode-ray oscillograph so that conditions could be checked visually. It was found that with these large beams, secondaries from the target striking the front of the absorption cell caused a bad disturbance in the background. This was eliminated by deflecting the secondaries with a small electromagnet.

Thin targets were made by vaporizing BeF_2 from a platinum wire in an oxygen flame. The BeF_2 vapor was condensed on a cold nickel button placed in the tip of the flame for a few seconds. This process was repeated many times in order to obtain targets of sufficient strength. Two thin targets were used for the data reported. One was roughly three or four times as strong as the other, but both yielded thin target curves as judged by comparison with curves from a thin Po source.

Experimental Procedure

The type of number-*vs.*-range curve which is obtained from the bombardment of a thin target depends upon the bias voltage used to select the threshold of ionization which shall be recorded as a count. If the bias is set at a low voltage so that small amounts of ionization will be recorded, a plateau curve which falls to zero in several mm of range is obtained for a single group of α-particles. The point of steepest slope differs from the mean range of the group by a small constant equal to the depth of penetration into the chamber necessary to produce a count. If there are two groups of α-particles separated by a small range difference, the front of the curve will have a hump in it and two points of maximum slope corresponding to the two mean ranges. Also if, as in this reaction, longer range particles whose ionization is fairly constant over the part of the curve in question are present, they will produce a background which is subject to statistical fluctuations which add to the fluctuations of the shorter range groups. Thus, it may become impossible under such conditions of bias to resolve two groups of α-particles whose ranges differ by only a small amount. The bias voltage may be increased until a peaked curve is obtained which runs fairly constant at some low value, then rises rapidly to a maximum and falls to zero with a half-width at half-maximum of about 1 mm. Under these conditions, fluctuations from the lower ionization groups are eliminated and the resolving power is greatly increased. Two distinct α-particle groups then produce a curve which is the sum of two such peaked curves of similar shape. Since range is directly proportional in our experiment to cell pressure, the number *vs.* cell pressure curve corresponds to the number *vs.* range curve.

In making these measurements, a series of curves (number-*vs.*-cell pressure) were taken at various bias voltages with a thin Po source. That voltage was selected which gave the narrowest peaked curve without too great a sacrifice of maximum height. With higher bias voltage, the height was cut down and the half-width of the curve was hardly changed at all. This bias voltage was then used for the Be+D run. Since the amplification changed from day to day with charging of batteries etc., the correspondence of bias voltage with threshold of ionization could only be relied upon during the few hours consumed in a particular run. Consequently, this selection of bias voltage had to be made anew for each run. For two of the determinations of Q_3, the Po run and the Be target run were made consecutively. For the other two, the Be curves were compared with Po curves of corresponding threshold of ionization taken through identical cell windows but obtained on

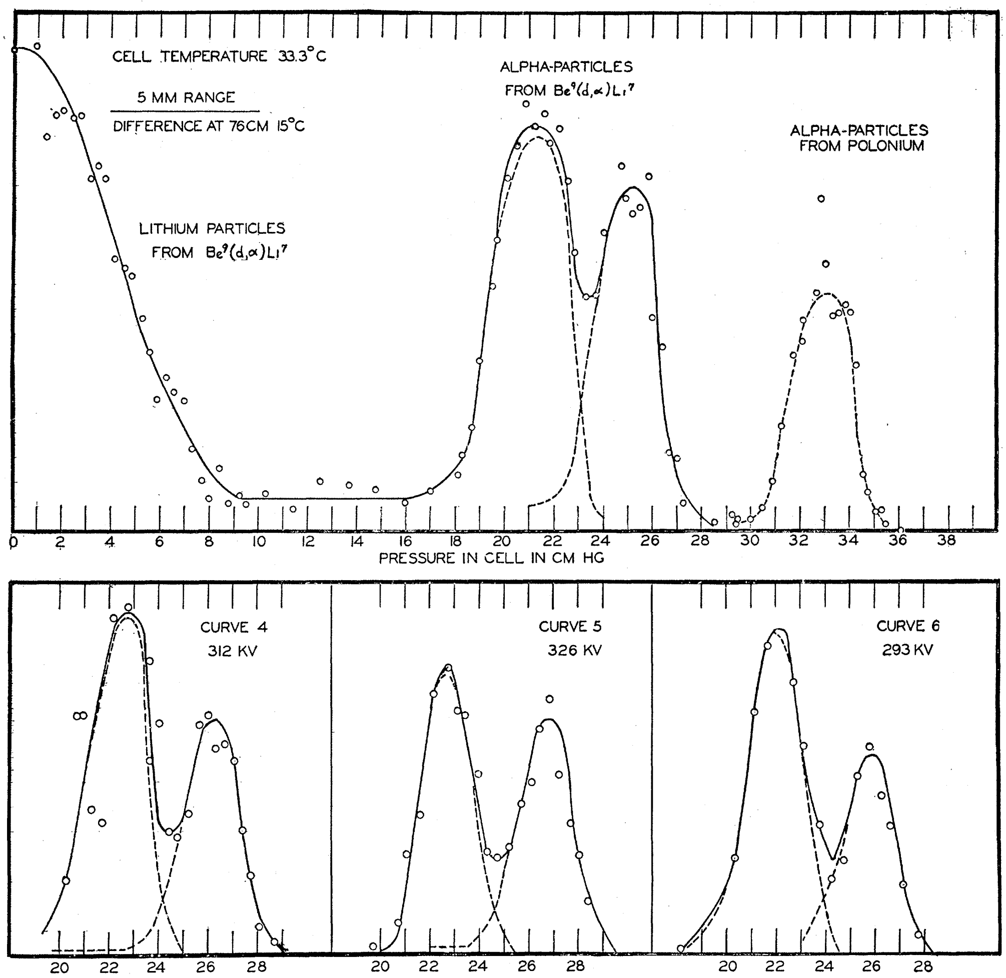

FIG. 1. Analysis of disintegration products from beryllium under deuteron bombardment, showing particles of ranges under 4 cm. The points at the peak of the longest range artificial alpha-particle group represent the counting of about 150 particles.

different days. Consequently, weights of 10 and 5, respectively, have been used in averaging. The BeF_2 targets were heated before and during bombardment to prevent deposition and carbonization of oil, and the Po source was also heated. In every case the cell temperature was read frequently, and the barometer was watched for change. Cell pressure was read on an open end manometer connected directly to the cell. The reading after the cell had been pumped out thoroughly with a Cenco Hyvac pump was taken as the zero of pressure. CO_2 and H_2O were removed from room air before it was admitted to the cell. Sample curves are shown in Fig. 1.

Eleven curves are used for the determination of the energy difference between the two groups of α-particles. Po curves were not taken to establish the bias for all of them because after a little experience it was easy to select the proper bias by quickly running over the curve and adjusting for the heights of the maxima and minimum. Then a run was made with the bias voltage carefully kept constant throughout. Runs were taken with NaF and C targets to eliminate the possibility that α-particle groups from F or from carbon contamination might account for either of the groups in the doublet.

Resolution of the Doublet and Results

Each doublet curve was resolved in the following manner. The Po curves for various biases were reduced to the height of the high energy peak, and the Po curve which best fitted it with regard to front slope and width was drawn as the high energy component. Where consecutive Be and Po runs were made, the best curve was, of course, the corresponding Po curve. The curve representing the complete doublet joined the high energy component somewhere between the minimum and the second maximum. The low energy component was then derived by subtraction. This procedure gave components whose half-widths at half-maximum agreed in seven cases to within 0.1 mm range in about 1.1 mm. Now let P = critical pressure in cm Hg corresponding to center of peak measured at half-maximum, L = length of path in air in cell in cm, T = temperature of cell in degrees absolute, R = mean range in cm at 76.0 cm pressure, 15 degrees centigrade.

Then $R=L\times P/76.0\times 288/T+c$

where c is the sum of the air equivalents of the windows (about 2 mm each) and the penetration depth for counting which is a function of the threshold of ionization. Hence, the difference in range between two groups whose critical pressures, P_1 and P_2, have been measured is

$$\Delta R=R_1-R_2 = L\times 288/76.0\times(P_1/T_1-P_2/T_2)+c_1-c_2.$$

Table I. Q_3 and ΔQ_3 from experimental data. (± values are root mean square deviations.) Weighted average $Q_3=7.093\pm0.022$ Mev; weighted average $\Delta Q_3=0.494\pm0.016$ Mev; range difference between two groups at $E_d=0$, (760 mm; 15°C), $\Delta R=3.08\pm0.10$ mm.

E_d Mev	Curve No.	$R_{Po}-R_\alpha$ 15°C; 760 mm	Q_3 (Mev)	Wt.	ΔQ_3 (Mev)	Wt.	Av. I_{Li^*}/I_{Li}
0.351	1	0.658 cm	7.105	10	0.501	8	1.15
0.326	2	0.695	7.067	5	0.473	10	
	5				0.514	6	1.40
	11				0.509	10	
0.312	3	0.675	7.108	5	0.490	4	1.39
	4	0.699	7.066	10	0.487	9	
	6				0.500	4	
	7				0.531	2	1.69
	8				0.471	8	
	9				0.520	5	
0.254	10				0.487	8	1.72

If the same windows and threshold of ionization have been used in measuring P for each group, then $c_1-c_2=0$. Since both windows bulge in the same direction by the same amount, L is the length of the cell = 6.699 cm. Because of the method of biasing and the proximity of the Po range and the artificial α-particle ranges, no significant corrections have to be applied.

From curves 1, 2, 3, 4, range differences between Po and the artificially produced α-particles are calculated for each of the two groups, and the corresponding energy differences, are taken from the 1938 Cornell range-energy curve for α-particles. The absolute energy for Po is taken to be 5.298 Mev from Lewis and Bowden[11] corrected according to Briggs'[12] new determination of $H\rho$ for RaC′ which was used as a standard for the Po energy determination. E_α is 5.298 Mev minus the measured energy difference. From the derived values of E_α, and the values of the deuteron energies E_d, the reaction energy Q_3 for the reaction

$$Be^9+H^2\rightarrow Li^7+He^4+Q_3$$

may be determined from the expression

$$Q_3=\left(1+\frac{4.00386}{7.01814}\right)E_\alpha-\left(1-\frac{2.01473}{7.01814}\right)E_d.$$

The numerical values in this expression are the masses of He^4, H^2, and Li^7, and the expression assumes conservation of energy and momentum at right angles to the deuteron beam.

If ΔE_α is the energy difference between the two alpha-particle groups, the decrement ΔQ_3 in the reaction energy corresponding to the production of the excited state of Li^7 is given with sufficient accuracy by

$$\Delta Q_3=(11/7)\Delta E_\alpha.$$

No polonium curves were taken with curves 5 to 11 to establish the absolute energy of either group. For these curves ΔR was computed by the method of resolution into components outlined above. The energy of the ground state group was computed theoretically using the ob-

[11] W. B. Lewis and B. V. Bowden, Proc. Roy. Soc. London **A145**, 235 (1934).

[12] G. H. Briggs, Proc. Roy. Soc. London **A157**, 183 (1936).

served Q_3 from curves 1, 2, 3, 4 and the bombarding voltage. This value was used as a reference point on the range energy curve from which to read the ΔE_α corresponding to ΔR.

The values obtained for Q_3 and ΔQ_3 are summarized in Table I. The weighted average for Q_3 of 7.093 ± 0.022 Mev lies within the range of predicted values, which is 7.04 ± 0.06 Mev, and establishes the higher energy group as the ground state group. The average intensity ratio I_{Li^*}/I_{Li} decreases gradually with increasing bombarding voltage.

The total yield curve from a thick target was investigated from 235 kv to 390 kv and is shown in Fig. 2. The plot $\log_{10} N$ against E_d gives a straight line which, if extrapolated to 210 kv, gives a yield of about 1×10^{-9} alpha-particle per deuteron. Since certain auxiliary experiments showed that the mass 2 spot of the deuteron beam contained over 90 percent deuterium, no correction for beam composition was made. The yield at 210 kv agrees with the experiments of Williams, Haxby and Shepherd[8] who found 1×10^{-9} alpha-particle per deuteron at 212 kv.

It is possible to derive Q_2 for

$$B^{10}+n\rightarrow Li^7+He^4+Q_2 \quad (2)$$

from fundamental measurements considering the following chain of reactions in conjunction with (2):

$$Be^9+H^2\rightarrow Li^7+He^4+Q_3, \quad (3)$$

$$B^{10}+H^2\rightarrow Be^8+He^4+Q_4, \quad (4)$$

$$Be^9+h\nu\rightarrow Be^8+n+Q_5, \quad (5)$$

where

$Q_3=7.093\pm0.022$ Mev,
$Q_4=17.80\pm0.15$ Mev,[13,14]
$Q_5=-1.63\pm0.02$ Mev.[15]

Thus

$$Q_2=-(2H^2-He^4)+Q_3+Q_4-Q_5.$$

Bainbridge and Aston have independently measured the doublet $(2H^2-He^4)$ with comparable results.[16] Using Bainbridge's value, 0.02561 ±0.00004 mass unit, we calculate

$$Q_2=2.68\pm0.17 \text{ Mev}.$$

Aston's value for the doublet, 0.02551 ± 0.00008 mass unit, gives

$$Q_2=2.78\pm0.17 \text{ Mev}$$

($\pm$ value is $[\Sigma\ (\text{r.m.s. deviation})^2]^{\frac{1}{2}}$). A weak point in the chain of reactions is $Q_4=17.80$ Mev with an uncertainty of 0.15 Mev. As pointed out by Allison,[14] however, any error in Q_4 is likely to be such as to reduce its value. Therefore, any error in Q_2 introduced by Q_4 will be more likely to cause a lower value than a higher one.

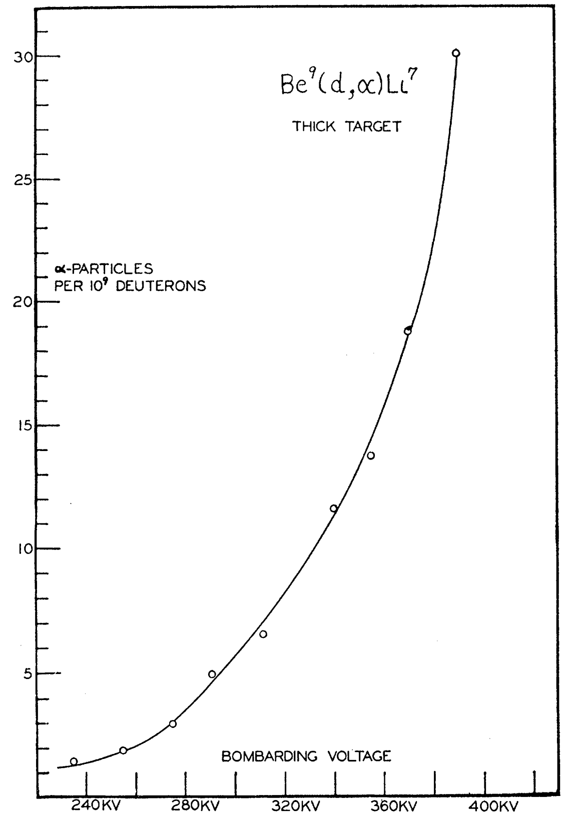

FIG. 2. Total yield of alpha-particles from bombardment of a thick target of metallic beryllium with deuterons.

Discussion

Evidence for the production of an excited state of Li^7 has now been found in connection with

[13] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. London **A154**, 246 (1936).
[14] S. K. Allison, Phys. Rev. **55**, 626 (1939).
[15] L. S. Skaggs, Phys. Rev. **56**, 24 (1939). By considering a correction to the calculations on the electrostatic analyzer (see S. K. Allison, L. S. Skaggs and N. M. Smith, reference 9) the value -1.62 ± 0.02 Mev given in this reference has been lowered to -1.63 ± 0.02 Mev.
[16] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 370 (1937).

TABLE II. *Summary of measurements on* $B^{10}(n, \alpha)Li^7$. *Where only one range group has been found, it is tabulated under* $Range_1$. *Where an additional group has been found, it is tabulated under* $Range_2$. *In rows 1 to 7, column 5 contains* Q_2 *calculated from* $Range_1$, *and column 6 contains* ΔQ_2 *calculated from* $Range_1$–$Range_2$. *In row 8, column 5 contains the five energy groups reported by Maurer and Fisk, and column 6 contains the corresponding* ΔQ*s.*

Author	Method	$Range_1$	$Range_2$	Q_2 (Mev)	ΔQ_2
Walen[17]	R_α by ioniz. ch.	8.5 mm		2.54	
Rotblat[18]	R_α by ioniz. ch. + Hoffman electrometer	8.18 mm		2.44	
Fünfer[19]	R_α by prop. counter + linear amplifier	8.6 mm		2.57	
Haxel[4]	R_α by variable pressure counter	9.4 mm	6.4 mm	2.80	0.92
Bower, Bretscher and Gilbert[20]	Total $R_\alpha + R_{Li}$ from Boric acid methyl ester in cloud ch.	7.0 mm		2.08	
O'Ceallaigh and Davies[5]	R_α from amorphous *B* on foil in cloud ch.	8.9 mm	7.15 mm	2.66	0.54
Livingston and Hoffman[6]	R_α by ioniz. ch. + linear amplifier	8.5 mm	7.15 mm	2.53	0.47
Maurer and Fisk[7]	Total *E* by ioniz. ch. + linear amplifier and oscillograph			$Q=2.90$ $Q'=2.70$ $Q''=2.49$ $Q'''=2.26$ $Q''''=2.06$	 0.200 0.410 0.640 0.840

the following reactions:

$$Li^6+H^2\rightarrow Li^7+H^1, \quad (1)$$

$$B^{10}+n\rightarrow Li^7+He^4, \quad (2)$$

$$Be^9+H^2\rightarrow Li^7+He^4, \quad (3)$$

$$Li^7+He^4\rightarrow Li^{7*}+He^4, \quad (6)$$

$$Li^7+H^1\rightarrow Li^{7*}+H^1, \quad (7)$$

$$Be^7\rightarrow Li^7. \quad (8)$$

Reaction (1), investigated by Williams *et al.*[2] and by Rumbaugh *et al.*,[3] has been shown to yield two groups of protons separated by about 4.3 cm range. The energy level in Li^7 is computed to be 455 ± 15 kev. This is to be compared with our value of 494 ± 16 kev corresponding to an α-particle group separation at zero bombarding voltage of 3.08 ± 0.10 mm. However accurate the range difference measurements may be in each case, the energy level must be derived from the range energy curves for protons and α-particles. The energy correction necessary to bring the α-particle range difference into agreement with the proton range difference is $-7/11\times40$ kev $=-25$ kev, or that to bring the proton difference into agreement with the α-particle difference is $7/8\times40$ kev $=35$ kev. A correction of this type necessitates a change in slope of the range energy curve. According to Holloway and Livingston,[21] the 1938 Cornell curve for α-particles is fitted experimentally between 2.5 cm and 2.8 cm range where it is known with good accuracy and again at the Po point of 3.840 cm range. If the curve is revised by connecting the 2.8-cm point and the 3.840-cm point by a straight line, this change is sufficient to reduce ΔQ_3 to 477 kev and changes Q_3 to 7.067 ± 0.020 Mev. It may be pointed out, however, that to reduce ΔQ_3 further by adjusting the range energy curve is not consistent with a constantly decreasing slope but would require putting a hump in the curve. Reducing ΔQ_3 to 477 kev in this manner would leave only a correction of $7/8\times20$ kev to be made in the proton difference. Since the data of Rumbaugh *et al.* extend over a bombarding voltage range of 200 kv, the slope change would

[17] R. J. Walen, Comptes rendus **202**, 1500 (1936).
[18] J. Rotblat, Nature **138**, 202 (1936).
[19] E. Fünfer, Ann. d. Physik **29**, 1 (1937).
[20] J. C. Bower, E. Bretscher and C. W. Gilbert, Proc. Camb. Phil. Soc. **34**, 290 (1938).
[21] M. G. Holloway and M. S. Livingston, Phys. Rev. **54**, 30, 37 (1938).

have to extend from about 24 cm to 32 cm range. It is fairly obvious that no such change can be made. Hence, it must be concluded that the value 455 kev from the proton difference cannot be changed appreciably by adjusting the range energy curve. Since agreement cannot be reached between the two values in this manner, we leave the value from the α-particle range difference at 494 kev and the corresponding Q_3 at 7.093 Mev. Either some unseen correction must be applied or the levels represented are not the same.

An excellent summary of the methods used and the results obtained up to 1938 for reaction (2) has been made by O'Ceallaigh and Davies[5] using the 1937 Cornell range energy curve for α-particles and its revision according to Blewett and Blewett. In Table II we have summarized the recent work, recalculating Q_2 from the published ranges by means of the revised 1938 Cornell curve which supersedes the others. The ranges published by Livingston and Hoffman[6] have been raised slightly by a recalculation of the ionization chamber penetration depth from the new range energy curve. Because the older mass values predicted $Q_2=2.99$ Mev, it was previously suggested that Walen,[17] Rotblat[18] and Fünfer[19] were probably observing the α-particles associated with the production of Li^{7*}. Estimates of the energy level were made on this basis. We have derived $Q_2=2.68\pm0.17$ Mev using Bainbridge's doublet measurement, and $Q_2=2.78\pm0.17$ Mev using Aston's doublet measurement. In view of this derived Q_2 and the work of O'Ceallaigh and Davies and of Livingston and Hoffman, Walen, Rotblat and Fünfer were probably observing the ground state group. If the range energy curve in the low energy region is reliable, the lower value $Q_2=2.68$ Mev is in better agreement with experiment.

Maurer and Fisk interpret their results as indicating four excitation levels in Li^7. We find, as shown in curve 1, no evidence for any other α-particle groups of comparable intensity between 1.9-cm range and the full range group. We can, therefore, say that no other excited states of comparable intensity are evident up to 1.8 Mev. Using the partition ratio found by Bower, Bretscher and Gilbert[20] for shorter range Li^7+He^4, $R_\alpha/R_{Li}=1.62$, we calculate roughly that the Li particles should have a range of about 1.6 cm. This range is represented on curve 1 by 5.6 cm cell pressure. The wider peak from 0 to 9 cm pressure is then ascribed to Li particles and its greater width is probably due to higher ionization in the chamber, to variation of charge, and to lack of resolution of the two range groups.

Because of the difficulty in making measurements on short range α-particles, the results from the $B^{10}(n,\alpha)Li^7$ reaction are more uncertain than the results from the $Li^6(d,p)Li^7$ and the $Be^9(d,\alpha)Li^7$ reactions. Therefore, comparison can be made only in a general way.

Li^{7*} should revert to the ground state with the emission of a γ-ray. Table III summarizes the most recent work on γ-rays in the low energy region from the bombardment of Li and the decay of Be^7. $Be+H^2$ bombardment has been investigated[22,23] for γ-rays of higher energy arising from excited states of B^{10}, but measurements have not been carried to a sufficiently low energy region to detect the γ-ray expected from Li^{7*}. The γ-ray measurements in general are not reliable enough to compare critically with the energy differences from particle range differ-

TABLE III. *Summary of related γ-ray measurements.*

Source	Author	Method of E_γ Meas.	E_γ(Mev.)
Li^6+d	Williams *et al.*[2]	Abs'n coeff. in Pb	0.400 ± 0.025
$Li^7+\alpha$	Webster[24]	Abs'n coeff. in Pb	0.600 ± 0.100
	Savel[25]	Abs'n coeff. in Pb	0.500
	Bothe[26]	β-ray spectrograph	0.390 and 0.590
	Speh[27]	Abs'n coeff. in Pb	0.700 ± 0.070
Li^7+p	Fowler and Lauritsen[28]	Abs'n coeff. compared with N^{13} rad'n	0.495 ± 0.025
$Be^7\rightarrow Li^7$	Rumbaugh *et al.*[3]	Abs'n coeff. compared with N^{13} rad'n	0.425 ± 0.025

[22] H. R. Crane, L. A. Delsasso and W. A. Fowler, Phys. Rev. **47**, 782 (1935).
[23] H. R. Crane, J. Halpern and N. C. Oleson, Phys. Rev. **57**, 13 (1940).
[24] H. C. Webster, Proc. Roy. Soc. London **A136**, 428 (1932).
[25] P. Savel, Ann. de physique II **4**, 88 (1935).
[26] W. Bothe, Zeits. f. Physik **100**, 273 (1936).
[27] K. C. Speh, Phys. Rev. **50**, 689 (1936).
[28] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **56**, 840 (1939).

ences. A direct comparison of the γ-rays from $Li^6(d,p)Li^7$ and $Be^9(d,\alpha)Li^7$ in the low energy region would be of interest.

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Internal Scattering of Gamma-Rays

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If an element is irradiated with gamma-rays of sufficiently high energy, the upper limit of the Compton recoils is less than the minimum energy of photo- or conversion electrons from any shell. But electrons of energy between these two limits may be ejected in processes in which the momentum condition can be relaxed. Such processes are (1) the scattering of an external gamma-ray by a bound electron, where momentum can be taken up by the nucleus, (2) the internal scattering by the electrons of the radioactive atom itself, where the radiation field of the near-by nucleus can fulfill momentum conditions impossible for a plane wave. We consider the second case, for scattering of an electric dipole gamma-ray by s electrons. We use Dirac electron theory with Born approximation. The process is of order α compared to the internal conversion, as expected. Our small result indicates that most of the electrons observed in such a region—for instance from the 2.62-Mev gamma-ray of Th C″—are of instrumental origin. This is in agreement with the results of the latest experiments.

I. Introduction

In the study of the electron energy spectrum of radioactive elements with the magnetic spectrograph, certain observers[1] found an unexpectedly large number of electrons in energy regions just below strong K-conversion lines. A particularly clear-cut case in point was that of the region 2.39–2.52 Mev in the spectrum of the thorium elements, in which really no electrons were expected. This is below the 2.62-Mev gamma-ray of ThC″, but near no other strong gamma-ray. Any electrons near 2.62 Mev and above the upper limit of the beta-ray spectrum at 2.25 Mev, must be indirectly produced by this gamma-ray.

The ordinary processes by which a gamma-ray can produce electrons are internal conversion, and photo-effect and Compton scattering in the material of the source. There is an upper limit to the energy that can be given a recoil electron in Compton scattering. In general this is $E_c = h\nu/(1+mc^2/2h\nu)$. The sharp K-conversion line sets a lower limit for both of the absorption processes: $E_K = h\nu - mc^2[1-(\alpha Z)^2]^{\frac{1}{2}}$. For any element E_K will be greater than E_c if only the gamma-ray energy, $h\nu$, is large enough. In the case mentioned this condition is fulfilled. In fact $E_K = 2.52$ Mev and $E_c = 2.39$ Mev. Thus, between 2.39 and 2.52 Mev, no electrons from these processes can appear. The problem was whether it was necessary to attribute the many electrons observed in the excluded region to unknown instrumental difficulties, or whether some other process for their production was actually involved.

Now, internal conversion and photo-effect are the only processes of first order in the interaction of matter and radiation; i.e., with a probability proportional to α, the fine structure constant. Any other process will be proportional to a higher power of α. Only one process seemed important here. This is internal scattering, which we shall

[1] Reported by Professor C. D. Ellis and F. Oppenheimer in discussion. Also W. J. Henderson, Proc. Roy. Soc. **A147**, 572 (1934).