Variation of Range with Angle of the Disintegration Alpha-Particles of Li^7

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The range of the alpha-particles emitted from Li^7 under 200 and 240 kv proton bombardment was measured at various angles with respect to the incident beam of protons. The results are fully in accord with the predictions of the principles of conservation of energy and momentum when the straggling due to the penetration of the target by the proton beam is taken into account. The results show, furthermore, that if $_4Be^8$ is formed in this reaction, and subsequently disintegrates into two alpha-particles without the emission of a gamma-ray, it must have a mean life of not more than $3 \cdot 10^{-14}$ second.

Introduction

In nuclear disintegration experiments, when the amplifier-counter method is used, usually only those particles emitted in one particular direction are observed. When observations are made with a cloud chamber, particles given off at different angles can be observed, but the number of such observations is generally relatively small.

It was thought desirable to obtain some data by the amplifier-counter method concerning the ranges of alpha-particles given off at several different angles to the direction of the incident proton beam in the disintegration of Li^7 by protons. Such measurements offer a direct check on the conservation of momentum and energy in this nuclear reaction and also provide some information concerning the mean life of $_4Be^8$ if formed. $_4Be^8$ has been observed as a disintegration product in the bombardment of beryllium and boron[1] by protons; it is thus of interest to consider the possibility of its formation in this reaction, and to discuss its mean life if it is assumed to be unstable because of the very high energy release (17 MEV) of the reaction. Finally, information concerning the amount of straggling due to target penetration can be obtained from data of this type.

Some indirect evidence for the conservation of momentum in this reaction has been obtained by Cockcroft and Walton,[2] who found some of the alpha-particles to be emitted simultaneously in pairs in opposite directions, and by Kirchner,[3] who found the maximum angle between pairs of tracks in a cloud chamber to be consistent with the conservation of momentum. Dee and Gilbert[4] obtained consistent results in investigating the disintegration of deuterium by deuterons by assuming the conservation of momentum. Bothe[5] measured the ranges of the protons emitted by boron under alpha-particle bombardment at various angles to the incident beam by interposing absorption screens, and found agreement, within the relatively large error of this method, with the predictions of conservation of momentum.

Apparatus

The high voltage supply circuit, proton source, and accelerating tube used in this experiment were the same as those used by Giarratana and Brennecke,[6] and were described in detail in their article. The protons, after being accelerated, were separated magnetically and the beam was further defined by two 4 mm circular slits A, B, placed 17 cm apart (see Fig. 1). These served as an additional check on the voltage, since any appreciable change in the energy of the protons would cause the beam to be cut off.

The protons then struck a target T, consisting of a thick film of lithium fluoride, and the disintegration alpha-particles could issue from the chamber through the windows W, making various angles with the proton beam. The target was mounted on a stopcock and was always turned so that it made equal angles with the incident proton beam and the emerging alpha-

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[1] Oliphant, Kempton, and Rutherford, Proc. Roy. Soc. **A150**, 241 (1935).

[2] Cockcroft and Walton, Proc. Roy. Soc. **A137**, 229 (1932).

[3] Kirchner, Physik. Zeits. **23**, 777 (1933).

[4] Dee and Gilbert, Proc. Roy. Soc. **A149**, 200 (1935).

[5] Bothe, Zeits. f. Physik **63**, 381 (1930).

[6] Giarratana and Brennecke, Phys. Rev. **49**, 35 (1936).

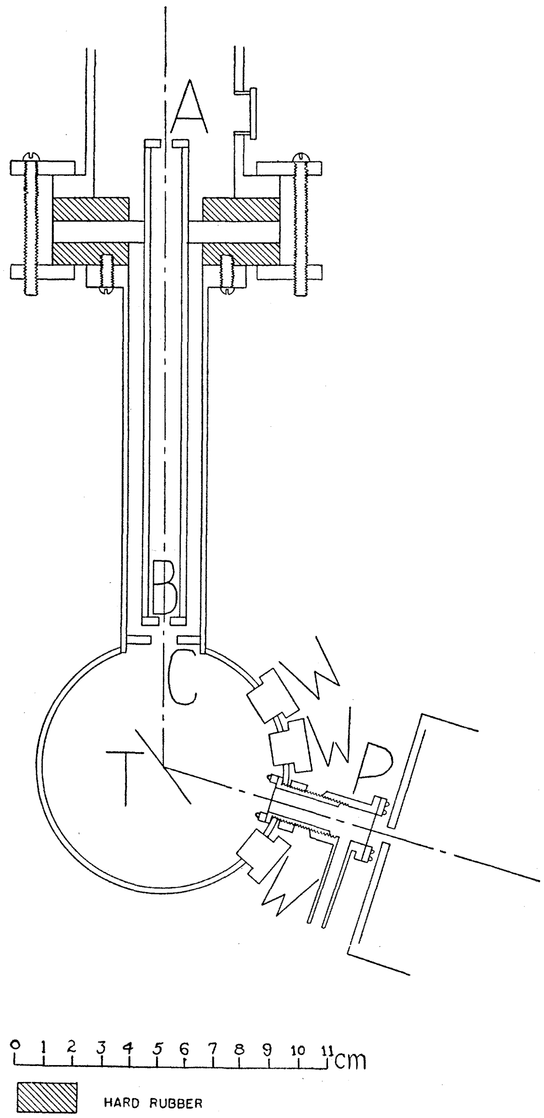

FIG. 1. Target chamber assembly.

particles. The auxiliary slit *C* served to reduce the escape of secondary electrons from the target chamber to a minimum.

The observed alpha-particles passed through a pressure chamber *P*, 3.8 cm long, sealed into one of the four windows *W*. A mercury manometer measured the air pressure in the chamber, which was sealed by mica windows, of which the inner had a stopping power of 3.5 cm air equivalent, the outer 1.5 cm. In addition the last 1.5 cm or more of the path of the alpha-particles was always in air; these precautions were necessary to secure equal stopping power of the mica for all ranges encountered.

The counting method formerly used was changed by replacing the recording oscillograph by a thyratron scale-of-four counter using RCA 885's. Visual observation of the pulses was provided by an RCA cathode-ray oscillograph in parallel with the counter.

The ranges of the alpha-particles were determined from the calibrated stopping power of the mica windows, the distance between the windows, the distance from the outer window to the ionization chamber, and the temperature and pressure of the air through which the alpha-particles travelled. A thermometer placed close to the pressure chamber was read at short intervals. The air pressure within the calibrated chamber was read to within one millimeter of mercury. The distance between the outer window and the ionization chamber was measured at the beginning and end of each run. In addition, the alpha-particles of thorium C′ were used to check the range measurements directly.

While counts were being recorded the proton current entering the insulated target chamber was permitted to charge a 1-mfd mica condenser. The total charge collected in a convenient interval of time was then determined by means of a ballistic galvanometer. Since the ranges were determined by plotting the counts per unit deflection of the galvanometer against the corresponding range, variations in the amount of the proton current did not affect the accuracy of the data and there was no necessity for maintaining a constant proton current. It was sufficient to adjust the hydrogen leak from time to time as the pressure in the supply tank decreased, in order to keep the proton current at a point where a convenient number of counts could be obtained. The actual currents used varied from 0.2 to 2.0 microamperes, averaging about 0.75 microampere.

The voltage across the accelerating tube was maintained constant by working just under sparking voltage of a 25-cm sphere gap adjusted to the correct distance.

CALCULATIONS

1. Conservation of momentum

From the equations expressing conservation of momentum and energy for the lithium-proton reaction, the following relationship can easily be derived between the momentum p of an emitted alpha-particle and the angle θ which its path makes with the direction of the incident proton beam:

$$p=\frac{p_0\cos\theta}{2}+\frac{1}{2}\left\{p_0^2\cos^2\theta+2\left[p_0^2\left(\frac{M-m}{m}\right)+2Mk\right]\right\}^{\frac{1}{2}},\quad (1)$$

where p_0 is the momentum of the proton, M the mass of the alpha-particle, m the mass of the proton, and k the energy released in the disintegration. Using this formula, the momentum, and hence the range of alpha-particles emitted in any direction can be calculated.

2. Mean life of ${}_4\mathrm{Be}^8$

If ${}_4\mathrm{Be}^8$ is formed in this reaction, the above formula will hold provided the ${}_4\mathrm{Be}^8$ nucleus disintegrates into two alpha-particles before losing appreciable energy by gamma-ray emission or by collision. Since the ${}_4\mathrm{Be}^8$ recoil nucleus loses appreciable momentum by collision in about $3\cdot10^{-14}$ second, its mean life must be less than this if the ranges of the alpha-particles are found to agree with formula (1), assuming that there is no gamma-ray emission. This figure is obtained by assuming that if the ${}_4\mathrm{Be}^8$ nucleus lost an appreciable portion of its momentum by any process, this would be easily observable in the range of the alpha-particles, which would then be emitted with different momenta. If the incident proton has an energy of 0.24 MEV, the range of the recoil ${}_4\mathrm{Be}^8$ particle, which has approximately one-eighth the velocity of the proton, can be interpolated from Blackett's data,[7] and turns out to be 0.2 mm in air, or not more than 0.0001 mm in the solid LiF target, whose density is 2.2. If we assume the Geiger range-velocity relation to hold, the average velocity of the particle will be three-fourths the initial velocity, which gives a time of $1.5\cdot10^{-13}$ second to completely stop the recoil. It seems reasonable to suppose that in the first 20 percent of the range enough momentum is lost to be measurable as a change of range of the alpha-particles in the forward and backward directions when the recoiling particle finally does disintegrate. This leads to the value of $3\cdot10^{-14}$ second as an upper limit for the mean life of ${}_4\mathrm{Be}^8$ if this nucleus is formed and subsequently disintegrates into two long-range alpha-particles.

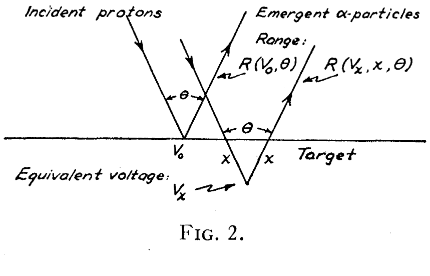

FIG. 2.

3. Thickness of target

Because of target penetration, the proton energy varies from a maximum at the surface of the target to zero at some point within. Since the yield of alpha-particles is a function of the proton energy, a calculation was made to determine the effect of target penetration on the mean range at different angles.

Experimentally, the target was always turned so that the distance traversed in the target was the same for both protons and alpha-particles. From Fig. 2 it appears that a proton whose initial voltage is V_0 and whose total range in the target is X penetrates the target to some distance x where it causes disintegration of a lithium nucleus. The range $R(x,\ V_x,\ \theta)$ of the alpha-particles emitted at this point will depend on the depth x, the equivalent voltage V_x at this depth of the proton, and the angle θ at which the alpha-particle is emitted. If we let $Y(V_x)$ represent the yield resulting from bombardment at the voltage V_x of a thin target, the mean range of all the alpha-particles emitted from a thick target will be

$$\bar{R}=\frac{\int_0^X Y(V_x)R(x,\ V_x,\ \theta)dx}{\int_0^X Y(V_x)dx}.\quad (2)$$

θ is a constant for any one window and $Y(V_x)$ can be obtained from a yield curve. In these calculations the yield data of Herb, Parkinson, and Kerst[8] were used.

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[7] Blackett, Proc. Roy. Soc. **A103**, 62 (1923).

[8] Herb, Parkinson and Kerst, Phys. Rev. **48**, 118 (1935).

TABLE I. *Summary of results.*

Equivalent Angle with Incident Proton Beam I	Voltage (kv) II	Mean Range (cm) at 76 cm, 15°C			Spread of Range Corresponding to Straight Portion of Range Curve (cm)	
		Observed III	Calculated *Thin Target* IV	Calculated *Thick Target* V	Observed VI	Calculated VII
46°	240	9.156±0.04	9.31	9.13	0.90±0.1	0.90
71°	240	8.859± .04	8.83	8.79	.85± .1	.68
96°	240	8.347± .04	8.32	8.32	.45± .075	.45
122°	240	7.839± .035	7.91	7.93	.35± .05	.37
46°	200	9.132± .08	9.14	9.09	.95± .15	.82
71°	200	8.624± .06	8.77	8.73	.65± .15	.58
96°	200	8.308± .06	8.29	8.30	.50± .1	.43
122°	200	7.856± .035	7.91	7.94	.30± .05	.37
		Extrapolated Range				
Thorium C′[13]		8.623± .025			.35± .05	

The integration is approximated numerically using for x the values given by Mano[9] and calculating $R(x, V_x, \theta)$ from formula (1). The results are shown in Table I.

A simple consideration of formula (1) shows that at the voltages used in this experiment the range of the alpha-particles increases as the proton energy increases when θ is less than a critical angle which is slightly over ninety degrees, while at angles larger than this the opposite is true. Hence the straggling effects due to target penetration should be counteracted to some extent in the backward direction and exaggerated in the forward direction.

RESULTS

The results of the experiment are given in Table I, and are shown graphically in Fig. 4. In the table, for convenience, the calculated mean ranges are listed, as found from formula (1) (listed as thin target) and as calculated from formula (2) (listed as thick target). It is well to note that, to the precision with which the results were obtained, the thick and thin target predictions are experimentally indistinguishable except in the direction closest to that of the incident beam, where the straggling is at a maximum. It is seen that where the results are unambiguously distinguishable (46°, 240 kv) the agreement is with the prediction for the thick target. As an additional check on the straggling calculations, the observed maximum spread in range of the alpha-particles, corresponding to the straight portion of the range curve, is given. The calculated spread shown in the table includes the straggling due to the thick target, the variation in range due to the fact that the particles were observed through an aperture covering a spread of 7.5° in angle with the incident beam, and the ordinary straggling to be expected from a homogeneous source; the last was observed directly, using Th C′. The agreement between observed and calculated quantities in this case is seen to be at least qualitatively correct, the straight portion of a range curve not being an extremely definite quantity.

In Fig. 3 the runs taken at the extreme angles at 240 kv are plotted, with Th C′ as a comparison on the same scale.

In Fig. 4 the results of the range measurements are plotted, the full line here representing the

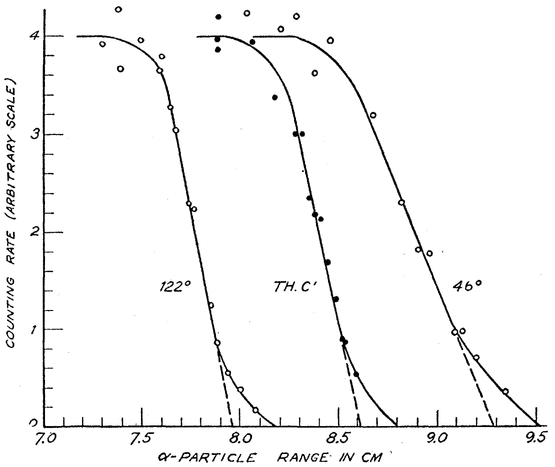

FIG. 3. α-particle range at 46° and 122°; 240 kv protons; Th C′ for comparison.

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[9] Mano, J. de phys. et rad. **5**, 628 (1934).

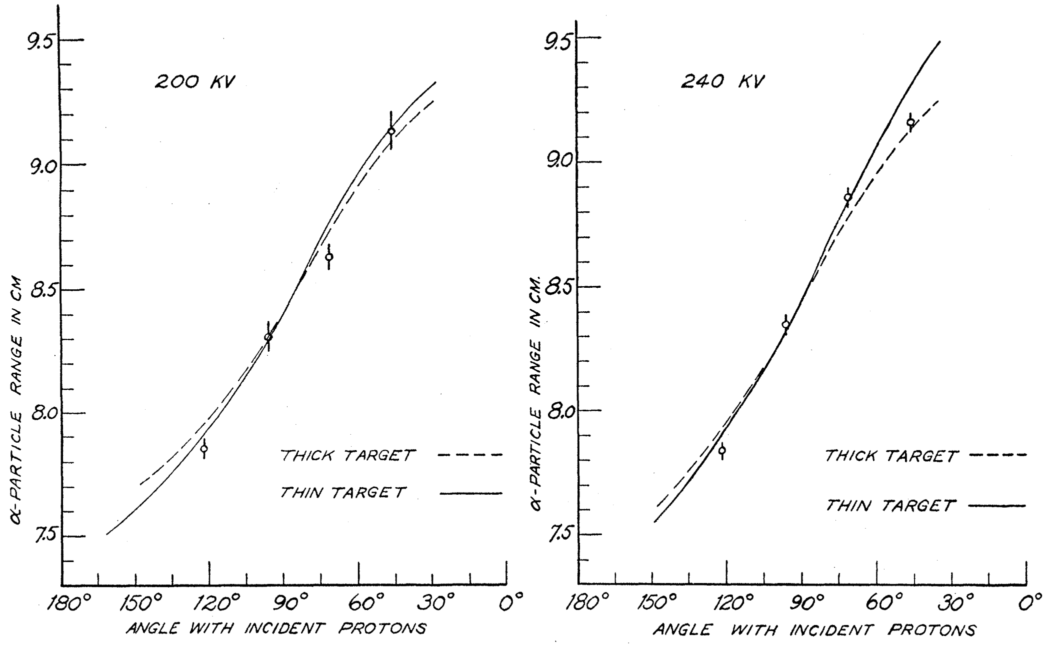

FIG. 4. α-particle range as a function of angle with incident protons.

range calculated for thin targets, the dotted line the range calculated for thick targets, and the circles experimental points. The range calculations are based on an energy release of 17.06 MEV, as found by Oliphant, Kempton and Rutherford,[10] and with which our results agreed.

The data for the range-velocity relations for alpha-particles were taken from the Cavendish laboratory curves.

PRECISION OF RESULTS

The most important uncertainty in determining the ranges arises from the extrapolation of the straight portion of the range curves. Taking into consideration this uncertainty and those mentioned in the discussion of the calibration of the stopping power of the apparatus, we estimate the total probable error to be that given in the table for each run. This includes the uncertainty in stopping power obtained from the thorium C′ measurements.

Since the circular opening of the ionization chamber subtended an angle of 7.5° at the target, a calculation was necessary to determine the angle corresponding to the effective range of the spectrum of particles obtained. An integration taking into account the change of range with angle and the varying area of the opening gives as a result for the equivalent angle the median angle minus three degrees.

The condenser circuit, including the insulated target chamber, was found to have a resistance to ground of more than 10^{10} ohms, which would introduce a negligible error in the galvanometer readings. Condenser polarization was also checked and found to have a negligible effect. The ballistic galvanometer could be read to within less than one millimeter in an average deflection of about 10 cm giving an error of less than one percent. The voltages can be considered as correct within five percent, and the voltage fluctuations were not greater than two percent.

CONCLUSIONS

It may be seen from the results that within the error of measurement and in the voltage range investigated, momentum is conserved in the lithium-proton reaction.

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[10] Oliphant, Kempton and Rutherford, Proc. Roy. Soc. **A149**, 406 (1935).

Since it has been shown by Alexopoulos[11] and Oliphant and Westcott[12] that no gamma-rays accompany the disintegration at the voltages used in this experiment, the variation in range with angle makes it appear that at these voltages, if $_4Be^8$ is formed and subsequently disintegrates into two 8.4-cm alpha-particles without the emission of a gamma-ray, it must have a mean life of not more than $3 \cdot 10^{-14}$ second.

The ranges calculated for a thick target at these voltages show no experimentally observable deviation from those for a thin target except in the extreme forward direction where the difference is observable and the observed range agrees with that calculated for the thick target. This agreement gives a separate additional check on the conservation of momentum, and, assuming that the theoretical data of Mano for the proton energy-range relation are correct, gives an approximate verification of the shape of the yield curves obtained by Herb, Parkinson and Kerst.[8] It must be noted, however, that the predicted mean range is not very sensitive to the shape of the yield curve, and a factor of 1.5 would not affect the calculations enough for the difference to exceed the experimental error.

We wish to acknowledge the valuable assistance of Drs. Giarratana and Brennecke in the construction of the apparatus used in this experiment.

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[11] Alexopoulos, Zeits. f. Physik **98**, 336 (1935).

[12] Oliphant and Westcott, London Conf. Rep. I, p. 152.

[13] Rutherford, Wynn-Williams, Lewis and Bowden, Proc. Roy. Soc. **A139**, 617 (1933).

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The Transmutation of Platinum by Deuterons

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The radioactivity induced in platinum by 5 MV deuterons is composite in character. Chemical separations of the active elements together with an analysis of the decay curves establish that at least two radioactive isotopes each of iridium and platinum are formed. The decay periods of the former are about 28 min. and 8.5 hrs. while the latter have periods in the neighborhood of 49 min. and 14.5 hrs. Inasmuch as the platinum activity emits both positrons and electrons it seems reasonable to ascribe the activities to the isotopes Pt^{193} and Pt^{197} resulting from neutron capture. The active iridium isotopes are probably formed in reactions involving deuteron capture and alpha-particle emission, and the likely radioactive isotopes are Ir^{194} and Ir^{196}. The transmutation functions for the reactions leading to iridium isotopes exhibit maxima indicative of resonance penetration of the platinum nucleus by the deuteron; the nature of the transmutation functions for the reactions giving platinum isotopes is not made certain by these experiments, because of the relative weakness of the platinum activities.

Introduction

One of the noteworthy results of investigations of artificial radioactivity induced by deuterons is that these nuclear reactions can be observed much farther up the periodic table than was expected on the basis of penetration of charged particles through nuclear barriers according to the theories of Gurney and Condon and Gamow. The theory of Oppenheimer and Phillips adequately accounts for the observations of reactions in which only the neutron of the deuteron enters the nucleus, but in the cases of some heavy elements investigated in our laboratory recently, the observations were not even in accord with this theory. Almost every heavy element that was bombarded with 5 MV deuterons exhibited evidences of induced radioactivity characteristic of the element. The yields of radioactivity, however, were small in comparison to those of lighter elements and accordingly the observations were suspected as being due possibly to contaminations.

Platinum, which was one of the heavy elements showing relatively strong radioactivity under deuteron bombardment, was selected for careful study as its chemical and physical proper-