THE DISINTEGRATION OF LITHIUM

Thesis
In Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy.

Submitted By
LEWIS ALEXANDER DELSASSO

CALIFORNIA INSTITUTE OF TECHNOLOGY

Pasadena, California

May 19, 1937.

SUMMARY

An attempt is made to summarize the reasonably well established experimental results on the disintegration of lithium with particular reference to the work done by the author in this field. The reactions discussed are classified according to the disintegration products. Particular emphasis is placed on the work on the gamma radiation produced from lithium under proton bombardment, including a detailed description of the experimental set-up and methods used, and a discussion of the probable origin of this gamma radiation.

The subject is summarized in a table comparing the experimental values of the reaction energies and the corresponding energies obtained from the masses involved.

THE DISINTEGRATION OF LITHIUM

INTRODUCTION

The first successful attempts at artificial disintegration were those of Rutherford in 1919. He was able to observe the disintegration protons from nitrogen when bombarded with alpha particles. Similar experiments on lithium by Rutherford and Chadwick(38, 39, 40) and by Kirsh and Petterson(23) proved unsuccessful.

Rutherford and Chadwick, using a right angle method of observation that permitted them to observe protons down to 3 cm. range found no effect when lithium was bombarded with alpha particles of 7 cm. range, and concluded that disintegrations of this kind did not take place. This conclusion has not been contradicted up to the present time, although as we shall later see, disintegrations of lithium with products other than protons do occur under alpha particle bombardment.

The first disintegration by artificially accelerated particles was that by Cockcroft and Walton(8) in 1932. Their disintegration of lithium by protons accelerated up to about 500 K.V. marked the beginning of a period of intensive work in nuclear reactions which has continued unabated to the present. In their first experiments they bombarded a target of lithium placed at 45° to the direction of the beam, and observed the products of disintegration at right angles by means of a scintillating screen and microscope. With this arrangement they were able to observe disintegrations down to about 70 K.V. bombarding energy. Later Oliphant and Rutherford(33) using a Wynn Williams counter detected disintegration down to 30 K.V. and finally Traubenberg(44) reported positive observations at 13 K. V.

Cockcroft and Walton supposed that the scintillations were due to alpha-particles. They suggested the reaction ${}_3Li^7 + {}_1H^1 \longrightarrow {}_2He^4 + {}_2He^4 + Q$ as their origin. They also measured their ranges and checked the simultaneity of the emission of the two particles. They took cloud chamber pictures and used an oscillograph in connection with a Wynn Williams chamber to check the nature of the particles. From these data and energy considerations they were able to conclude that their hypothesis for the production of the particles was correct.

Since Cockcroft's original report, much experimental work has been done on the disintegration of lithium by alpha-particles, neutrons, and by artificially accelerated particles. Much of this work has been done in this laboratory. This and also the work done elsewhere will be discussed now.

DISINTEGRATION ALPHA PARTICLES

1) ${}_3Li^6 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^3 + Q_1$

2) ${}_3Li^7 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^4 + Q_2$

3) ${}_3Li^6 + {}_1H^2 \rightarrow {}_2He^4 + {}_2He^4 + Q_3$

4) ${}_3Li^7 + {}_1H^2 \rightarrow {}_2He^4 + {}_2He^4 + {}_0n^1 + Q_4$

5) ${}_3Li^6 + {}_0n^1 \rightarrow {}_2He^4 + {}_1H^3 + Q_5$

REACTION 1)

The short range particles from this reaction were first reported by Walton & Cockcroft(47). Dee(16) showed from cloud chamber work that the particles were emitted simultaneously and in opposite directions. Oliphant, Kinsey and Rutherford(32) studied this reaction in detail and obtained the values of 6 - 8 mm and 11.5 mm for the ranges of ${}_2He^4$ and ${}_2He^3$ respectively. They also found that the efficiency of production of the short range particles is 30 times greater than that for the long range particles from reaction (2) and the variation of number with voltage is the same as that for (2).

Finally, Oliphant, Shire and Crowther(34) using separated isotopes were able to show conclusively that the short range particles are produced in reaction (1).

REACTION 2)

This is the reaction first studied by Cockcroft and Walton. Their measurement of the range of the alpha particles gave 8.4 cm. Oliphant(32) and collaborators showed by means of separated isotopes that as previously assumed by Cockcroft the source of the 8.4 cm. particles is reaction (2). A precise measurement of the range of these particles was made by Oliphant, Kempton and Rutherford(31). Using air as an absorber and comparing with the alpha particles from Th C^1 (8.6 cm.), which in turn have been measured very precisely in a magnetic field, they found the range to be 8.29 ± .03 cm. after the correction was made for the bombarding voltages.

REACTION 3)

This reaction was first reported by Lawrence(25). Due to his high bombarding voltages he reported 14.0 cm. as the range. Precise measurements by Oliphant, Kempton and Rutherford(31) using the method of comparison already described, gave 12.6 ± .05 cm. for the range of these particles. Finally, Oliphant, Shire & Crowther(34) showed by separated isotopes the correctness of the assumption as to the source of these particles.

REACTION 4)

In this case there is a continuous distribution for the alpha particles, since there are three disintegration products. Oliphant, Kinsey and Rutherford(32) found the upper limit to be 7.3 cm. The neutrons from this reaction will be discussed later.

REACTION 5)

This reaction is reported for slow neutrons by Chadwick & Goldhaber(6). They found the singly charged particles and doubly charged particles to have ranges of 5.5 cm. and less than 1.5 cm. respectively. Taylor(43) has found tracks of 6.64 ± .06 cm. equivalent length in photographic plates. According to Chadwick and Goldhaber, the cross-section for this reaction is 10^{-21} cm.^{2} and was, therefore, suggested by them as a means of detecting slow neutrons.

DISINTEGRATION NEUTRONS

(6) $_3\mathrm{Li}^7 + {}_1\mathrm{H}^2 \rightarrow {}_2\mathrm{He}^4 + {}_2\mathrm{He}^4 + {}_0\mathrm{n}^1 + Q_6$

(7) $_3\mathrm{Li}^7 + {}_1\mathrm{H}^2 \rightarrow {}_4\mathrm{Be}^8 + {}_0\mathrm{n}^1 + Q_8$

(8) $_3\mathrm{Li}^6 + {}_1\mathrm{H}^2 \rightarrow {}_2\mathrm{He}^4 + {}_2\mathrm{He}^3 + {}_0\mathrm{n}^1 + Q_7$

(9) $_3\mathrm{Li}^7 + {}_2\mathrm{He}^4 \rightarrow {}_5\mathrm{B}^{10} + {}_0\mathrm{n}^1 + Q_9$

REACTIONS (6) AND (7)

The emission of neutrons from lithium under deuteron bombardment was first reported by Crane, Lauritsen and Solton(14). They attributed the neutrons to reaction (6). The energies of these neutrons and those of reaction (7) have been determined by Bonner and Brubaker(2). For these measurements they employed a high pressure cloud chamber which could be operated at pressures up to 15 atmospheres of methane.* The results are shown in figure (1). The upper curve is the distribution of recoil protons, the

---

* For the higher energies a mica absorber had to be placed in the chamber.

dotted curve the distribution of the primary neutron after correcting for the variation in neutron-proton collision area. We see in this curve a continuous distribution of energy (three body problem) with a most probable energy at 2.1 Mev. and a mean energy at about 3.9 Mev. There is a pronounced hump at approximately 13.0 Mev. superimposed on the continuous distribution. This has been interpreted by Bonner and Brubaker as due to the formation of ${}_4Be^8$ as given by reaction (7). The area under this hump is about 5% of the total area under the curve, indicating the reaction (7) occurs about 5% of the time. Calculations from these data give the mass of ${}_4Be^8$ as 0.3 ± 0.75 Mev. greater than that of two alpha particles.

REACTION 8)

Although Oliphant, Shire and Crowther$^{(34)}$ have reported negative results for reaction (8), Rumbaugh and Hafstad have shown that this reaction does occur. No measurements have been made on the energy of these neutrons. This reaction is exothermic by only 1.3 Mev. so that we would not expect to find it appearing in Bonner & Brubaker's work on the unseparated isotopes.*

REACTION 9)

The emission of neutrons under alpha particle bombardment was first observed by Bothe and Becker$^{(4)}$. Snetzler$^{(42)}$ has shown that the energy of the alpha particles at which this reaction begins is very close to 4.7 Mev. This value is in good agreement with the

---

* The neutrons from this reaction would be buried under the maximum of the reaction (6) curve unless reaction (8) occurred much more frequently than (6).

findings of Savel(41)# of approximately 5.0 Mev. Meitner(30) has reported additional reactions with both $_3Li^6$ and $_3Li^7$ in which $_5B^9$ and $_4Be^{10}$ are formed, these latter having positron and beta activity respectively. However, careful work by Snetzler has failed to detect such activity, and one must conclude for the present that Meitner's report is in error. The energies of the neutrons from reaction (9) are not well known, values are given from 0.2 to 0.9 Mev.

DISINTEGRATION PROTONS

10) $_3Li + _1H \rightarrow _3Li + _1H + Q_{10}$

11) $_3Li^6 + _1H^2 \rightarrow (_3Li^7)^* + _1H^1 + Q_{11}$

The disintegration protons from lithium were first reported by Lawrence(26) and later by Cockcroft & Walton(9). Reaction (10) was offered for their formation. Cockcroft found, using a mixed beam and ordinary lithium target, only one group at 30.5 ± 1.0 cm. Later Oliphant, Shire & Crowther(34) proved by the use of separated isotopes that this group came as postulated from $_3Li^6$. They were unable to find any proton group from Li^7.

In an effort to find the protons emitted in the presumed reaction producing the radioactive $_3Li^8$ (which will be discussed later) it was decided to investigate carefully in this laboratory(18) the protons from Li under $_1H^2$ bombardment. These experiments were done in a cloud chamber in which the pressure could be varied to make the particles stop in the chamber. The setup was essentially

---

\# These results will be further discussed in connection with the gamma rays.

as shown in figure (2), the only difference was the addition of baffles to confine the protons to within 5° of the plane of the chamber. The stopping power of the foil, separating the target from the cloud chamber, was determined by two methods: by weighing, and by measuring the residual range in the cloud chamber of the alpha particles from $_3Li^7$ bombarded by protons. This range, as has been described, has been carefully determined. The stopping power of the foil (of approximately one-half mill copper) was found to be 4.7 cm. The stopping power of the mixture of Ethyl alcohol vapor and air was determined by two methods: (1) by determining the pressure and temperature and computing the stopping power; and (2) by measuring the range of polonium alpha particles in the chamber, which is well known. The stopping power for alpha particles and protons of other energies was computed from data given by Mano (29). An example of the photographs obtained is shown in figure (3). The distribution in range of the particles resulting from the disintegration of lithium by 700 K.V. (peak) deuterons is shown in figure (4). The extrapolated ranges of 31.7 ± 0.5 cm. 13.8 ± 0.7 cm. and 8.9 ± 0.1 cm. respectively, for the longer range protons and two alpha particle groups are in good agreement with the ranges which have been measured at Cambridge (7). The group at 26 ± 1 cm. from reaction (11) was not reported previously. The energy of the protons of this group is 4.3 ± 0.1 Mev. This group was attributed at the time to reaction (12) forming $_3Li^8$. This has since been proven not to be correct. Efforts were made at the time to obtain separated isotope targets to check this conclusion, but these proved unsuccessful.

Recently, L. H. Rumbaugh and L. R. Hafstad(37) have repeated the measurements of the proton groups, using separated isotopes. They found that both these groups come from the Li^6 reaction. From Li^7 they found no protons of ranges greater than 8 cm.* which could not be accounted for by contaminations. The possible implications of the two groups of protons from ${}_3Li^6$ will be discussed later.

DISINTEGRATION ELECTRONS

(12) ${}_3Li^7 + {}_1H^2 \rightarrow {}_3Li^8 + {}_1H^1 + Q_{12}$

(12a) ${}_3Li^7 + {}_0n^1 \rightarrow {}_3Li^8 + Q_{(12a)}$

(13) ${}_3Li^8 \rightarrow {}_4Be^{8*} + e^- + \nu + Q_{13}$

(14) ${}_4Be^{8*} \rightarrow {}_2He^4 + {}_2He^4 + Q_{14}$

Artificial radioactivity of lithium under deuteron bombardment was first reported by Crane, Delsasso, Fowler and Lauritsen(11). The radioactive element is assumed to be ${}_3Li^8$ formed in reaction (12) and disintegrating according to reaction (13) and finally (14). (ν here stands for the neutrino). The experimental setup for observing the electrons is shown in figure (2). The target was placed at 45° to the plane of the chamber. The electrons entered the chamber through a thin copper foil soldered over a window cut in the target holder. A quartz ring, visible through a glass section in the ion tube, fluoresced under bombardment and made it possible to direct the beam on to the target. Movement of the chamber necessary to line up the beam was made possible by a sylphon in the ion tube. The magnetically operated shutter in the ion beam permitted the beam to be cut off at any time desired in relation to the expan-

---

* It is extremely difficult to measure shorter ranges because of the continuous alpha particles produced.

sion of the chamber.* A description of the chamber proper and the coils for producing the magnetic field will be found under the section on gamma rays. Photographs were taken at right angles to the plane of the chamber. The photographs were re-projected through the same optical systems to actual size and the curvature of the tracks measured by comparison with arcs of known radii. A typical cloud chamber photograph is shown in figure (5). A careful discussion on the errors of measurement will be found in the article on "Radioactive Elements of Low Atomic Number," by Fowler, Delsasso and Lauritsen(20).

From the masses we obtain for the sum $(Q_{12} + Q_{13} + Q_{14})$ 15.6 ± .2 Mev. Rumbaugh & Hafstad(37) have shown that the range of the protons in reaction (12) must be less than 8 cm. or $Q_{12} < 1.8$ Mev. From the experimentally observed end point of the beta spectrum Q_{13} is found to approximate 10.5 Mev. These data make Q_{14} approximately 3.3 Mev. From this it was concluded that ${}_3Li^8$ did not go directly to the ground state of ${}_4Be^8$ in the beta transition, but rather to an excited state of ${}_4Be^8$ which then could disintegrate to two alpha particles. On the assumption that the end point of the beta spectrum is a constant, the data were plotted in two different forms, corresponding to two ways of expressing the Konopinski-Ulenbeck modification of the Fermi theory, based on Pauli's neutrino assumption(20) and are shown in figure (6) and figure (7). The radioactive alpha particles from reaction (14) have recently been reported by Lewis, Burchain and Chang(27) who reported an energy distribution up to approximately 6 Mev., with most of the particles below 2.5 Mev. From their limited data they were not able to say whether the particles represented a line structure or a continuous distribution. This distribution has

---

* Essentially the same setup has recently been used to study the alpha particles from reaction (14). The copper foil in this case is replaced by an aluminum foil of 4 mm. air equivalent.

been carefully investigated in this laboratory(50). The distribution in energy has a maximum at 1.3 Mev. and falls sharply to less than half the maximum at 1.0 Mev. The width at half maximum is very close to 0.5 Mev. The high energy portion of the distribution decreases rapidly with increasing energy extending to at least 6.0 Mev. The average energy of the alpha particles is found to be 2.0 Mev. No evidence was found for line structure. With this distribution of alpha particles, one then will not have the beta transition with a single maximum energy point, that is Q_{13} and Q_{14} constants, but rather the sum of Q_{13} and Q_{14} only is a constant.

Under these circumstances, the application of the unmodified theory to the experimental results is not justified, and the only reason one obtains a reasonable agreement is because the distribution of the alpha particles is such that most of them come within a small range of energy.

Knol and Veldkamp(24) have reported the formation of radioactive $_3Li^8$ from $_3Li^7$ by slow neutrons. They have recently repeated this work(51). By using a target of $LiNO_3$ solution which they circulated through a closed system past two thin walled counters spaced along the system they can determine the half life of the beta activity, knowing the time for a given part of the solution to pass from one counter to the next. In this manner they obtain a value of 0.8 ± 0.2 sec. No measurements on the energy of the beta rays are reported. They conclude that according to reaction (12a) $_3Li^8$ is formed in an excited state, losing its excess energy as gamma radiation. Such radiation has not been observed so far.

DISINTEGRATION GAMMA RAYS

(15) $_3Li^7 + {}_1H^1 \longrightarrow ({}_4Be^8)' \longrightarrow {}_4Be^8 + 17\text{ Mev.} + Q_{15}$

(16) $_3Li^7 + {}_1H^1 \longrightarrow ({}_4Be^8)' \longrightarrow ({}_4Be^8)'' + 14\text{ Mev.} + Q_{16}$

The gamma rays from lithium under proton bombardment have been the source of controversy ever since their discovery was reported. In fact, the controversy has ranged from the complete denial of their existence by Oliphant and Westcott(35) to reports by Traubenberg and collaborators(45,46) of their existence at 45 to 60 k.v. bombarding voltage; later work explains Oliphant's failure to find gamma rays at bombarding voltages below 200 k.v. and shows that whatever Traubenberg found, it was not gamma rays from lithium. Crane and Lauritsen(13) reported gamma rays from a LiF target under 600 k.v. bombardment. Although their existence has no longer been a point of controversy for some time, the nature and origin of these gamma rays have up to the present been a matter of concern for the workers in this field. Much experimental work has been done in this laboratory and elsewhere. This work will now be discussed.

The absorption method was first used in an effort to determine the energy of these gamma rays as reported by Crane, Delsasso, Fowler and Lauritsen(12). The value obtained by this method (6.3 Mev.) was interpreted as the average value of a complex spectrum. This conclusion as later experimental work has shown was incorrect. The explanation for the absorption values obtained will be given later. It was next decided to use the recoil electrons as observed in a cloud chamber in a magnetic field to determine the energy of this radiation. This work was reported by Crane, Delsasso, Fowler and Lauritsen(12). The glass wall of the cloud chamber was used as a scatterer. Single photographs were taken, but it was believed that one could be reasonably sure of the origin of the tracks. The energies of 1576 single electrons and 57 pairs were measured. The single electrons, which were considered as being mostly recoil electrons from the glass wall were interpreted as a line structure extending from 3 to 17 Mev. The 57 pairs on the other hand were distributed in the energy interval from 10 to 17 Mev., indicating the radiation to be distributed mostly in the higher energy region. Because of the small number of pairs and because the behavior of recoil electrons was considered better known, more emphasis was placed on the single electrons. This choice of quantity over quality as we shall see was unfortunately a poor one. Because of this discrepancy between the recoil electrons and pairs, it was decided to obtain more data on this problem under better experimental conditions.

EXPERIMENTAL ARRANGEMENT

The arrangement of apparatus is shown in figure (8). The cloud chamber used is the same as shown in figure (9), with the exception that a "knee" has been added between the piston rod and the operating sylphon to make it possible to "disconnect" the chamber from the operating mechanism, and thus secure a more rapid expansion. The more rapid expansion permitted the tracks to be photographed closer to the scatterer, and, therefore, made their identification easier. The Helmholtz coils are capable of producing a field of about 3000 gauss without undue heating when operated intermittently, that is, energized about 1 second out of fifteen. Stereoscopic pictures were taken by means of a single mirror. When re-projected into a model chamber and scatterer, the pictures revealed the fact that most of the single tracks originated outside and in the top and bottom of the chamber. In order to reduce the number of these unwanted tracks, the distance between the chamber and target was increased and a lead colimator, 18 cm. thick, with an opening just large enough to illuminate the scatterer, was interposed. A 1 mm. aluminum window was introduced in the wall of the chamber, where the radiation enters, in order to reduce the number of electrons from the chamber wall. Scatterers of small stopping power were used to increase the resolution. These changes lead to a considerable sacrifice in intensity, but this sacrifice, as the data obtained has proved, was well worth while.

The carbon arc used in previous work for illumination was replaced by four 300 watt lamps, two on each side. The 110 volt lamps were flashed at approximately 190 volts. This change improved the uniformity of the photography greatly, and also released one D. C. generator for other work.

The synchronized disc carrying the lead absorber was so arranged that alternate pictures were taken with the absorber in the beam. A marker operated from the shaft of the disc was photographed at each exposure, thus insuring later certainty as to whether the lead was in or out for any photograph. The high voltage equipment for accelerating the ions for this and all other experiments performed in this laboratory and considered here has been carefully described.(15)

An automatic contact system provided proper timing for the magnetic field, the filament and anode of the discharge tube, flashing the lamps, the chamber expansion and the exposure. Figures (10,11) show examples of photographs obtained with this arrangement.

RESULTS

Pairs. Figure (12) shows the distribution in energy of a total of 770 pairs obtained from stereoscopic pictures. 513 of these were obtained with 0.032 cm. lead scatterer and 257 with 0.012 cm. Figure (13) represents the 257 pairs plotted separately. These were obtained most recently and under the best conditions. It is seen that the two curves are in good agreement as far as the distribution in energy is concerned, but the width at half maximum is considerably greater in figure (12). This is to be attributed mostly to greater experimental errors as indicated by the displacement of the high energy side of the curve. The still greater displacement of the low energy side is presumably due to the somewhat greater energy loss in the thicker scatterer used in most of the pictures.

These curves indicate clearly a gamma radiation with a strong maximum near 17 Mev. To account for the observed distribution of pairs we must consider the following possibilities for the gamma ray spectrum:

(1) a continuous spectrum beginning at about 10 Mev. and ending above 17 Mev. and having a strong maximum at or near the upper limit;

(2) a single line at about 17 Mev.

(3) a line at 17 and one or more weaker lines between 10 and 17 Mev.

Of these the first seems the least likely for no mechanism is known which might produce such a continuous spectrum and there is no evidence for such a spectrum in any nuclear reaction so far observed. Nevertheless, it cannot be ruled out from our data and since the final produce of the reaction is unknown, there is no direct experimental evidence against it.

It does not seem possible to account for the observed distribution of pairs as being due to a single line. The observed width of the distribution in energy of the pairs produced by such a line would be due to the following causes:

(1) natural line breadth;
(2) ionization losses in the scatterer;
(3) radiation losses in the scatterer;
(4) fluctuations in the magnetic field;
(5) scattering of the electrons in the gas;
(6) errors in reprojection and measurement of curvature of the tracks.

According to Crane, Delsasso, Fowler and Lauritsen(12) the radiation in question is produced by resonance. The best measurements on the excitation as function of energy are those by Hafstad, Heydenburg and Tuve(22) who find strong resonance at 0.440 Mev. with a half width of 0.011 Mev. From this we conclude that the half width of the gamma ray line is not much more than 0.011 Mev.

The scatterer used for obtaining most of the data in figure (12) was 0.032 cm. of lead and the ionization losses for 17 Mev. pairs are, therefore, uniformly distributed between zero and 0.800 Mev. The effect of this is to broaden the line uniformly toward lower energy by this amount. The radiation losses for electrons in this energy range are, according to Bethe and Heitler$^{(1)}$ approximately equal to the losses by ionization, but the number of electrons which would suffer a radiative collision in 0.032 cm. of lead comes out to be rather small. Radiation losses will not produce a uniform broadening of the line but only a tailing off toward lower energy. The number of pairs contained in this tail may be calculated from data given by Bethe and Heitler and is about 10%.

Fluctuations in the magnetic field amount to less than 2%, causing a symmetrical broadening of not more than 0.340 Mev.

The scattering of these high energy electrons in air at a pressure of one atmosphere is extremely small and we prefer to include this in the errors of measurement of curvature.

The measurement of curvature is usually reproducible to 1 Mev. for any pair and we consider the probable error due to scattering, reprojection and measurement less than this amount.

The total effect of all these factors would be a nearly symmetrical broadening of the line but with a shift of the center of gravity amounting to about half of the ionization loss in the scatterer. We have indicated such a symmetrical distribution in figure (12) and it is seen that most of the pairs observed lie within this distribution and may be attributed to a line at 17.1 ± 0.5

Mev., but it is clear that a considerable fraction of the pairs of lower energy cannot be attributed to this line directly.

Analyzing the data in this manner, we obtain the following results: The average energy of 580 pairs lying within the symmetrical high energy region is 16.7 ± 0.5 Mev. To this must be added 0.4 Mev. for the mean loss due to ionization in the scatterer, giving as the most probable value of the energy of the high energy gamma ray 17.1 ± 0.5 Mev. The number of pairs lying below the symmetrical distribution in figure (13) is 190 or about 25% of the total. It seems likely that approximately one-fourth of these pairs, that is 10% of 580, can be accounted for as being pairs which have lost from 1 to 10 Mev. in escaping from the scatterer. The remaining pairs, amounting to some 15 to 20% of the total, can apparently not be accounted for in this manner and must then be due to radiation of energy less than 17 Mev. falling on the scatterer. This radiation may be due to one or more of the following causes:

(1) one or more lines or bands of gamma radiation from $Li^7 + H^1$ in addition to the 17 Mev. radiation;

(2) secondary radiation produced by the 17 Mev. line in the material surrounding the cloud chamber and scattered into the chamber;

(3) radiation due to contamination in the beam or target, or both.

From the work of Bethe and Heitler we can calculate the number of quanta produced by a 17 Mev. quantum and having energies between 10 and 17 Mev. This comes out to be less than 2% even for lead, and can, therefore, not account for the low energy pairs observed.

The only reaction known which might give radiation of sufficient energy to account for the observed pairs is $B^{11} + H^1$, but it has an excitation efficiency of the same order as $Li^7 + H^1$ and hence the contamination would have to amount to some 20 to 30%, which is obviously out of the question.

Thus we seem forced to the conclusion that $Li^7 + H^1$ emits some radiation between 10 and 17 Mev. in addition to the radiation at 17 Mev.

It seems highly probable that this radiation consists of a line in the neighborhood of 14 Mev. and that the intensity amounts to some 20% of the total, but it is possible that it is distributed among two or more lines between 10 and 17 Mev. From our measurements we may further conclude that there is no radiation between 2 and 10 Mev. amounting to more than 5% of the total. Softer radiation (down to a million volts) was looked for, using a weaker magnetic field, but none was found.

RECOIL ELECTRONS

It is much more difficult to obtain reliable data on the recoil electrons for clearly not all of the single tracks observed belong to this category. This is particularly true in the pictures taken without collimation. The reduction due to collimation in the relative numbers of single tracks is best seen from Table 1.

Table 1

	Scatterer	Pairs	Electrons	Positrons	Recoil Electrons
no collimation	Pb	513	381	155	
collimation (	Pb	257	101	49	52
(	Al	71	105	12	93

It seems most reasonable to assume that the single positrons observed when collimation is used are in reality members of pairs originating in the scatterer and that an equal number of the single electrons are of the same origin. Presumably the corresponding pair members have escaped detection either due to large energy loss and scattering or to imperfect photography. To obtain the approximate number of recoil electrons we have, therefore, subtracted the number of single positrons observed from the number of single electrons.

The effect of collimation is also apparent from Table 2 in which we have shown the average energies of the several groups with and without collimation. The average energy of recoil electrons obtained with collimation and determined as indicated above is 12.7 ± 0.7 Mev. which is in satisfactory agreement with the value 12.2 Mev. predicted by the Klein-Nishina formula for 17.1 Mev. radiation.

Table 2

	With Collimation	Without Collimation
Average energy of pairs	15.7 ± 0.7	15.7 ± 0.5
Average energy of electrons	12.2 ± 0.6	10.7 ± 0.3
Average energy of positrons	11.1 ± 1.0	10.8 ± 0.6
Average energy of recoil electrons	12.7 ± 0.7	10.7 ± 0.4

Figure (14) shows the distribution in energy of apparent recoil electrons with and without collimation. The distribution obtained with collimation probably represents quite accurately the true recoil electrons and is in satisfactory agreement with expectations based on the Klein-Nishina theory and the radiation indicated by the pairs.

From the data presented above, it seems that no contradiction exists between the results given by the pairs and the recoil electrons, at least at these energies, and, therefore, such an explanation as proposed by Crane(10) to account for such a discrepancy seems unnecessary.

Energy Division Between Pair Members:

Bethe and Heitler have calculated the probability for the energy division between the two members of pairs of various energies. The curve in figure (15) shows this probability for 17 Mev. pairs and the points represent the number of electrons observed having a given fraction of the total energy of the pairs. The deviation at the low and high end are to be expected due to the great probability that a pair is not measured as such if the energy division is very unequal. This systematic error is not included in the probable errors indicated. The agreement with the theory is entirely satisfactory.

Absorption in 1 cm. of Lead: Up to the present time the only measurements of absorption coefficients for radiation in this energy range have been made in the usual way by means of ionization chambers. Unfortunately, such measurements are not reliable and cannot be taken as valid tests of the theory developed by Oppenheimer and Plesset(36) and by Bethe and Heitler(1). This is evident from an examination of cloud chamber pictures taken under similar conditions for they show that most of the ionization is produced by electrons which cannot be attributed to the direct beam. With the low intensity available the geometrical arrangement is necessarily such that stray and scattered radiation contributes a large part of the ionization and because the absorption coefficient for much of this radiation is lower than that for the primary radiation this part becomes relatively greater with increasing absorber thickness.

With such an arrangement we should, therefore, expect to obtain a value of the absorption coefficient which lies below the true value and approaches the minimum of the absorption curve as the thickness of absorber is increased. For lead this minimum occurs at about 3 Mev. and the measured absorption coefficient may, therefore, correspond to any value of the gamma ray energy between 3 and 17 Mev., depending on how this measurement is made.

Calculations have been made to show this(19). Figure (16) shows the number of primary quanta and quanta from 2 to 6 Mev. as a function of thickness of the lead absorber. It is seen that already at a depth of one cm. the number of penetrating quanta (around 3 Mev.) equals the number of primary quanta, and they predominate more and more with thickness of the absorber.

The calculated value of the logarithm of I (the ionization expected in the ionization chamber) is plotted in figure (17), giving an almost straight line with a constant slope corresponding to $\mu = 0.50$ cm.$^{-1}$, the average total absorption coefficient corresponding to radiation in the interval from 2 to 6 Mev. If calculations were carried out for still greater thickness, the slope would gradually decrease, ultimately approaching the value $\mu = 0.46$ cm.$^{-1}$, which is the minimum absorption coefficient in lead and corresponds to radiation of approximately 3 Mev. For comparison, the theoretical value of the absorption coefficient, $\mu = 0.74$ cm.$^{-1}$ for 17 Mev. radiation is also shown. It should be noted that the penetrating secondary radiation builds up so rapidly that the absorption curve as here calculated is straight even for very thin absorbers, and at no point is the absorption coefficient of 17 Mev. radiation approached. This shows clearly the absorption method is unsuited for determing the true absorption coefficient for radiation above 3 Mev.

To circumvent this difficulty, we have taken cloud chamber pictures alternately with and without 1 cm. of lead interposed between the target and the cloud chamber. By comparing the number of pairs obtained with lead in the beam with the number obtained without lead we have a true measure of the total attenuation in 1 cm. of lead of the radiation which produces these pairs.

It seems likely that some pairs of low energy are produced by radiation which is scattered into the chamber from the lead absorber, hence it would be reasonable to consider only pairs having energies near the maximum, say within the symmetrical distribution indicated in figure (13). In Table 3 we have listed the number of pairs observed in three energy intervals with and without absorber.

Table 3

	Number of pairs in symmetrical high energy region	Remainder above 10 Mev	Pairs below 10 Mev	Total
No absorber	260 ± 11	66 ± 6	2	328
With 1 cm. lead absorber	135 ± 8	51 ± 5	8	194

The attenuation in 1 cm. of lead of the radiation producing the high energy pairs is seen to be $\frac{135 \pm 8}{260 \pm 11} = 0.52 \pm 0.04$

which gives a total absorption coefficient for this radiation of

$$\mu = -\log 0.52 = 0.66 \pm 0.07 \text{ cm}^{-1}$$

The Klein-Nishina formula gives for 17.1 Mev radiation

$$\sigma = 0.09 \text{ cm}^{-1}$$

while Bethe and Heitler give for the absorption due to pair formation

$$\pi = 0.64 \text{ cm}^{-1}$$

Hence

$$\mu = \sigma + \pi \quad = 0.73 \text{ cm}^{-1}$$

which is in fair agreement with the observed value.

Origin of the Gamma Radiation: That the gamma radiation here discussed is due to the Li^7 isotope is clear from energy consideration and this has recently been verified by Rumbaugh and Hafstad(37) who, using the separated isotopes of lithium, observed gamma radiation from Li^7 and confirmed the resonance at 0.44 Mev. but found no gamma radiation from Li^6. The energy available may be calculated from the masses and is

$$7.0182 + 1.0081 - 8.0080 = 0.0183$$

or 17.0 Mev. To this must be added 7/8 of the kinetic energy of the bombarding proton. Hence the total energy available is 17.4 Mev. In the article by Hafstad, Heydenberg and Tuve(22), Breit gives a discussion of several possible mechanisms to account for the radiation under discussion. The one which best accounts for the observations is based on the assumption that the proton is captured on a virtual level forming a Be^8 nucleus in an excited state which is supposed to be odd in order to exclude disintegration into two alpha particles. This was first suggested to us by Dr. Elsasser, his assumption being that only protons having the correct combination of angular momentum and spin could be captured on this level. The model of the Be^8 nucleus used by Breit is based on unpublished calculations by Wigner and Feenberg. The ground state of Be^8 is a ^1S level which is even and there is an even ^1D level at approximately 3 Mev. The next even level would be a ^1G at about 8 Mev. The virtual level at 17 Mev. is supposed to be an odd P level.

The data presented here indicate that the transition between P to G levels occurs rarely if at all. This is to be expected, since this is a strongly forbidden transition. This leaves reactions (15) and (16) as the probable source of the radiation observed, these occurring with a relative probability of 3 to 1. Since no radiation at 3 Mev. was found, it is reasonable to suppose the Be^8 in reaction (15) breaks up into two alpha particles, each having an energy of approximately 1.5 Mev.

It must be mentioned that results of experiments recently presented by Gaerttner and Crane(21) agree with the results presented above as far as the pair data are concerned, but disagree in results obtained from the single electron data. The fact that in the setup used by Gaerttner and Crane, it is not possible to determine the starting point of the electrons and that they may also have electrons due to radioactivity induced by the deuteron contamination in the proton beam, may explain this discrepancy.

The above explanation of the origin of gamma rays seems to account for the facts reasonably well. It is, however, based on the assumption that all the gamma radiation observed is due to the 440 K.V. resonance level. Recent work by Bothe & Gentner(49) shows an additional resonance at approximately 200 K.V. A possible source of this resonance could be Boron contamination, for which they find a resonance at 180 K.V. However, from the relative intensities given by them the contamination would have to be at least 20%, and possibly 50%, which seems too large to be probable. It is impossible to say from the work of Tuve and his collaborators whether this lower resonance does exist or not. Their published data do not extend in any detail to these low voltages. Neither can one draw any conclusions from the fact that Oliphant was not able to observe gamma radiation in the work reported at the International Conference of Physics in 1934, his maximum voltage being 187 K.V. On theoretical grounds such a resonance can not be excluded either. This might be the excitation of another member of the triplet state, the separation of approximately 200 K.V. is not unreasonable.

Bothe & Gentner also report measurements on the energy of the gamma radiation produced at 300 K.V. and 520 K.V.. For both of these they obtain the same result of 18.0 Mev. However, their method of measuring would not be able to resolve lines only 200 K.V. apart, so that they do not contradict the preceding discussion. They do show, however, that the 14 Mev. component observed in this laboratory is not produced exclusively by the 200 K.V. resonance.

Finally, one must say that before any definite conclusion about this resonance is reached, more work is necessary.

Gamma radiation from Lithium under alpha particle bombardment was first reported by Bothe & Becker(4). Snetzler(42) finds that production of this gamma radiation begins with 2.3 Mev. alpha particles as compared to 4.7 Mev. for the minimum energy for producing neutrons. These results corroborate the results of Savel(41), who found approximately 2.8 Mev. necessary for the production of gamma radiation, compared to 5.0 Mev. from the neutron reaction. From these results the conclusion is drawn that this gamma radiation is produced by inelastic impact. Webster's(48) attempts to show that the energy lost by the alpha particles corresponds to the energy of the gamma radiation are not very conclusive in the case of lithium. Bothe(5) has given the energies of this gamma radiation as .39 Mev. and .59 Mev. From the difference in the proton ranges previously discussed, we might expect a gamma ray of approximately .4 Mev. This is in fairly good agreement with the value 0.39 Mev. obtained by Bothe, although it does not explain the 0.59 Mev. value.

CONCLUSION

Table (4)

	Q's in Mev.	
Reaction	Experimental	From Masses$^{(x)}$
1. $_3Li^6 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^3$	3.8 ± 0.3	3.7
2. $_3Li^7 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^4$	17.06 ± .04	17.0
3. $_3Li^6 + {}_1H^2 \rightarrow {}_2He^4 + {}_2He^4$	22.06 + .04	22.0
4. $_3Li^7 + {}_1H^2 \rightarrow {}_2He^4 + {}_2He^4 + {}_0n^1$	14.6 + 0.3$^{(a)}$	14.8
5. $_3Li^6 + {}_0n^1 \rightarrow {}_2He^4 + {}_1H^3$	4.3 ± .5	4.7
6. $_3Li^7 + {}_1H^2 \rightarrow {}_2He^4 + {}_2He^4 + {}_0n^1$	14.3 ± .5$^{(b)}$	14.8
7. $_3Li^7 + {}_1H^2 \rightarrow {}_4Be^8 + {}_0n^1$	14.8 ± 0.3	14.8
8. $_3Li^6 + {}_1H^2 \rightarrow {}_2He^4 + {}_2He^3 + {}_0n^1$	Not known	1.5
9. $_3Li^7 + {}_2He^4 \rightarrow {}_5B^{10} + {}_0n^1$	Not known	-2.6
10. $_3Li^6 + {}_1H^2 \rightarrow {}_3Li^7 + {}_1H^1$	4.8 ± 0.1	5.0
11. $_3Li^6 + {}_1H^2 \rightarrow {}_3Li^{7*} + {}_1H^1$	4.4 ± 0.1	See Note (c)
12. $_3Li^7 + {}_1H^2 \rightarrow {}_3Li^8 + {}_1H^1$	$<$ 1.8	See note (d)
12a. $_3Li^7 + {}_0n^1 \rightarrow {}_3Li^{8*}$	Not known	See note (e)
13. $_3Li^8 \rightarrow {}_4Be^{8*} + e^- + \nu$	See note (f)	
14. $_4Be^{8*} \rightarrow {}_2He^4 + {}_2He^4$		
15. $_3Li^7 + {}_1H^1 \rightarrow {}_4Be^{8*'}\ {}_4Be^8 + 17$ Mev.	17.1 + .05	17.4 $^{(g)}$
16. $_3Li^7 + {}_1H^1 \rightarrow {}_4Be^{8*'} \rightarrow {}_4Be^{8*''} - 14$ Mev.	See note (h)	

Table (4) shows the values of the Q's obtained from the experimental data and those obtained from mass considerations (appropriate corrections for bombarding energies have been included).

(x) The masses used here are those given by Bonner & Brubaker$^{(3)}$. They were obtained from mass spectrographic data and from disintegration data, including some of the above reactions.

(a) Obtained from maximum range of the alpha particles.

(b) Obtained by using mean energies of alpha particles and neutrons.

(c) $_3Li^7$ is left in an excited state.

(d) Mass of $_3Li^8$ not known.

(e) Mass of $_3Li^8$ not known; also it is left in excited state.

(f) Approximate estimates only can be made at present which do not disagree with the values obtained from the imperfectly known masses.

(g) To the mass energy 0.4 Mev. of the bombarding energy must be added.

(h) $_4Be^8$ left in excited state.

From the material presented here and summarized in Table (4) it is seen that so far as energy balances are concerned, the known reactions from lithium are in a reasonably satisfactory state and probably no great amount of new knowledge can be obtained from further experimental study of these balances.

The work on the excitation functions and cross-sections for these reactions is, unfortunately, with the exception of isolated cases, very poor and has for this reason not been included here.

ACKNOWLEDGMENTS

I take this occasion to express my gratitude to Professor Lauritsen for his guidance and constant interest in my work. I thank Dr. W. A. Fowler, who with Professor Lauritsen collaborated with me in the work referred to herein under our names. Finally, I wish to acknowledge the financial assistance of the Seeley W. Mudd Fund.

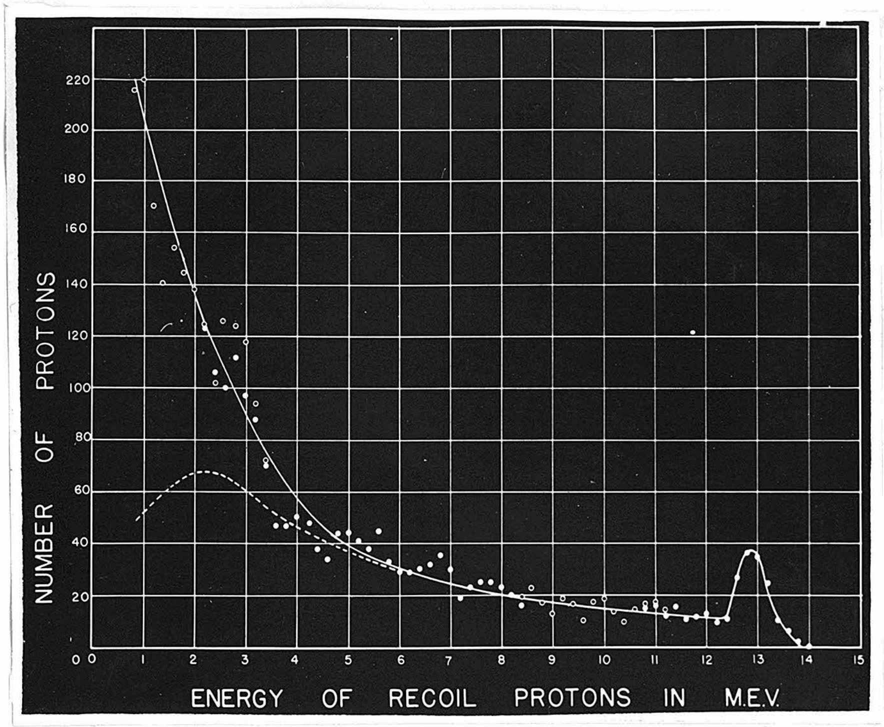

Fig. 1. Energy distribution of recoil protons (upper curve) and primary neutron (dotted curve).

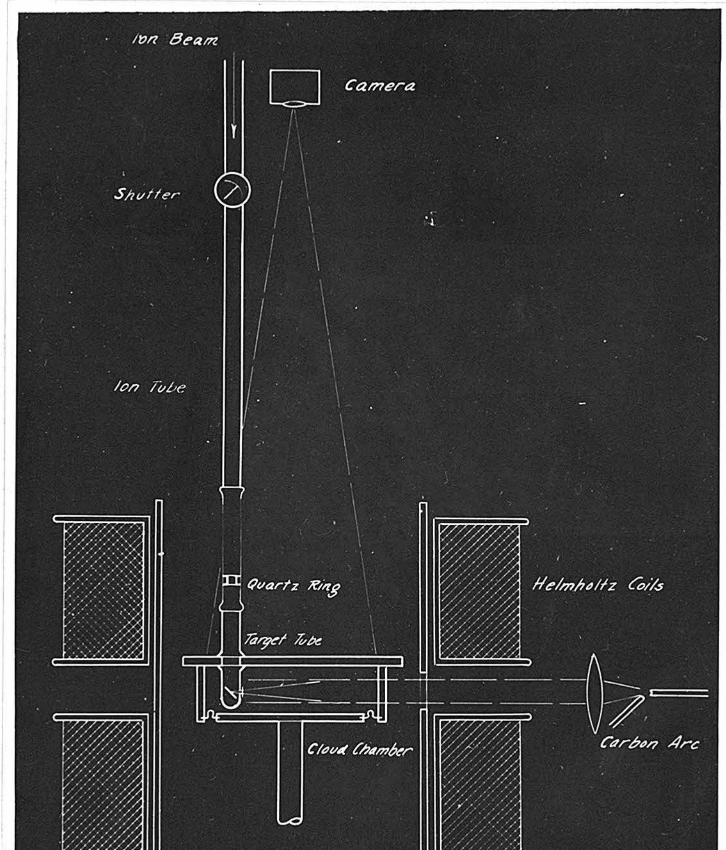

Fig. 2. Arrangement of apparatus for determination of electron distribution in energy.

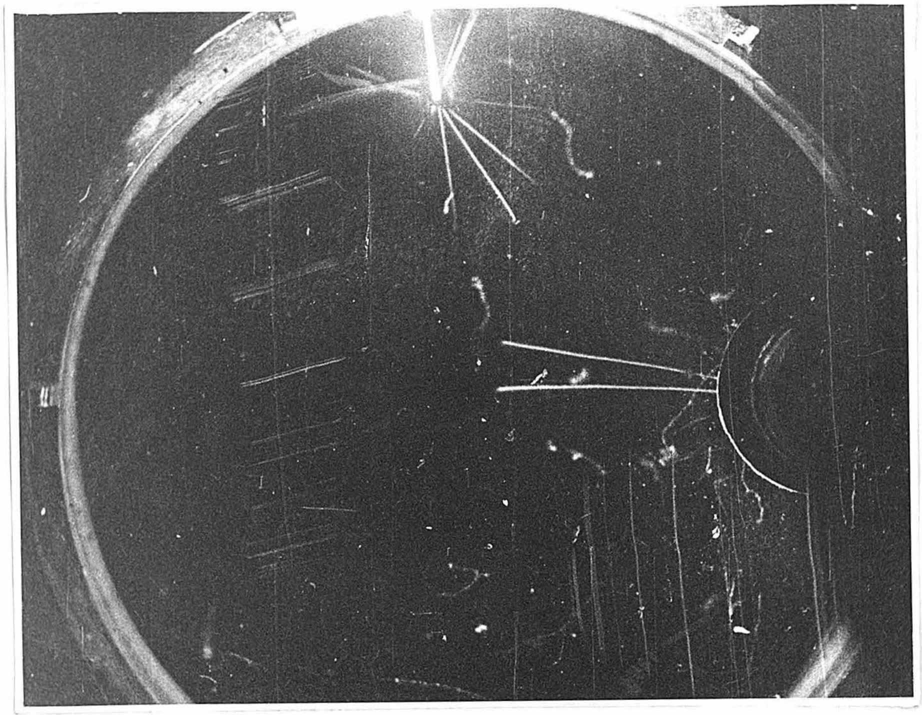

Fig. 3. Example of proton tracks

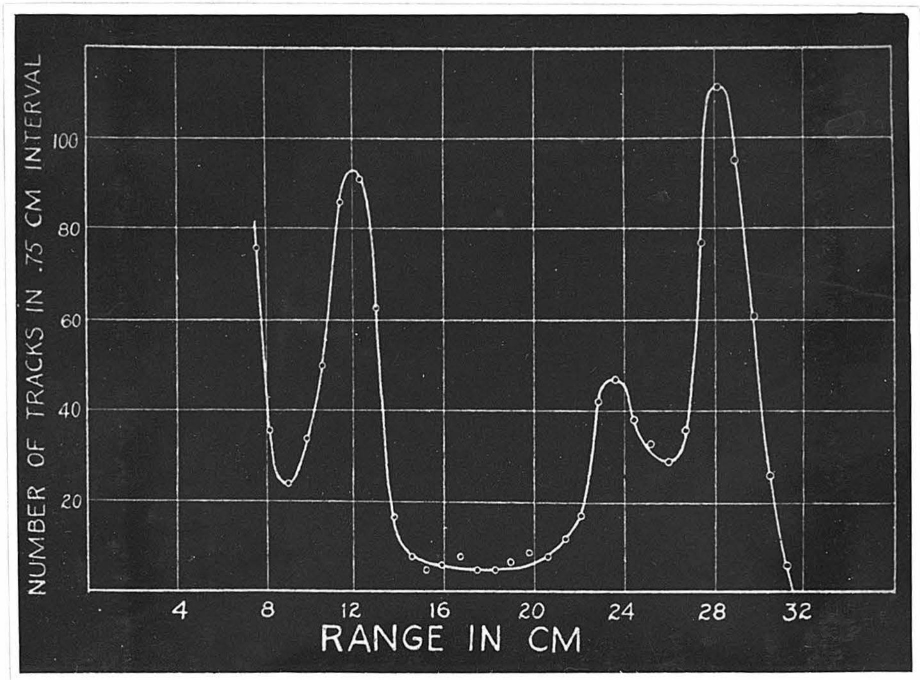

Fig. 4. Distribution in range of alpha particles (short range groups) and proton (long range groups)

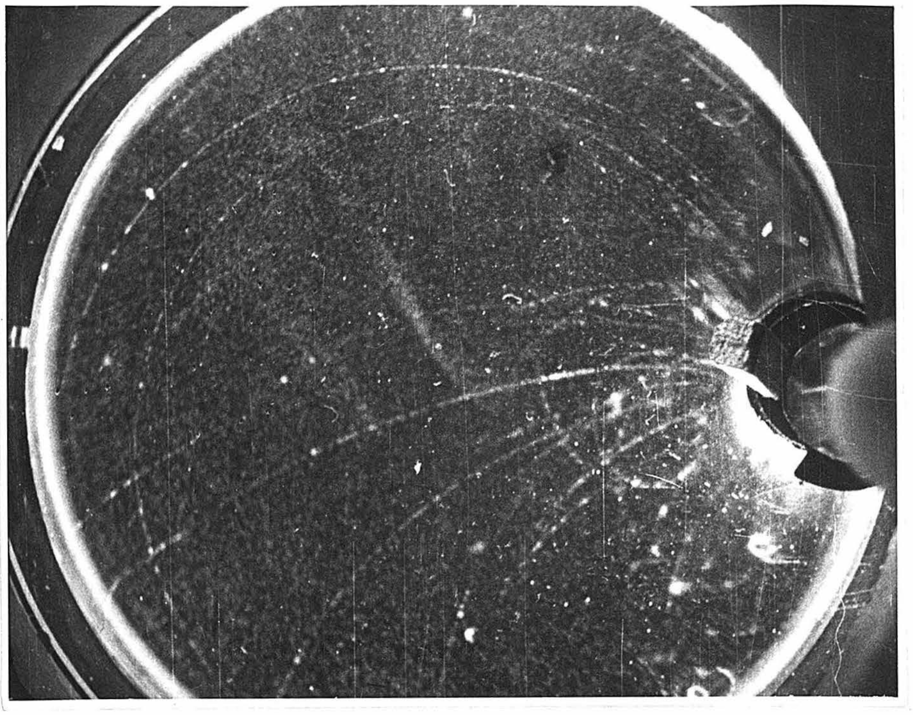

Fig. 5. Example of electron tracks

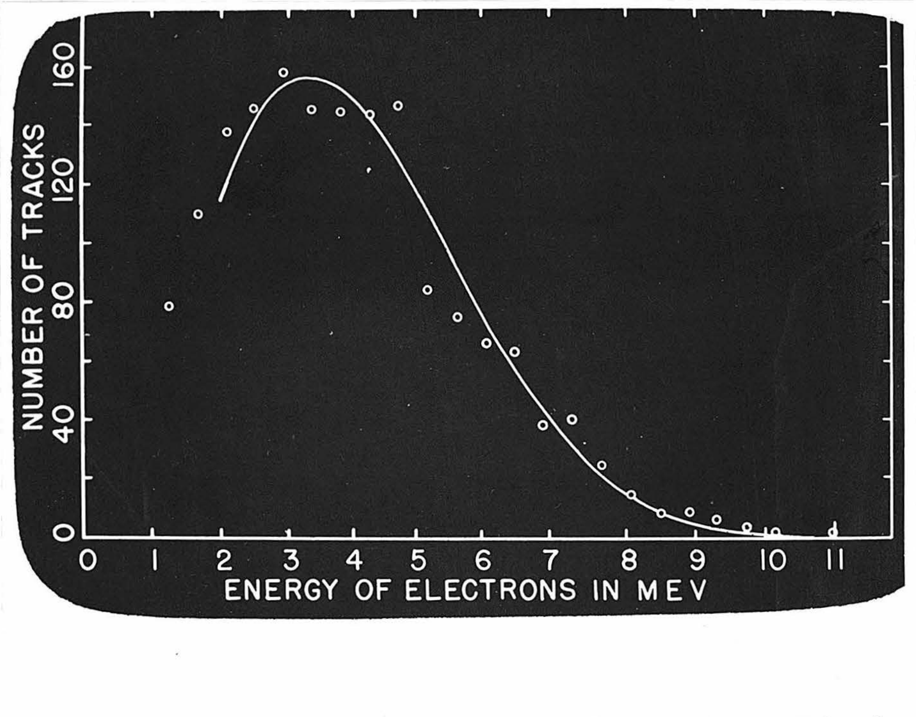

Fig. 6. Energy Distribution of electron omitted from Li. bombarded by deuterons.

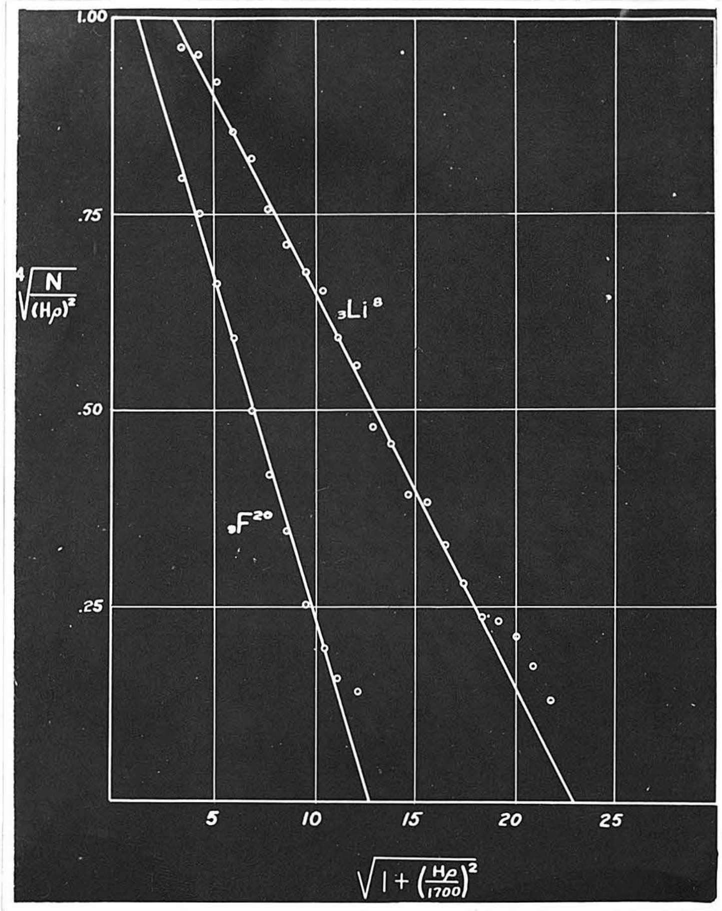

Fig. 7. K. V. plots for $_3Li^8$ and $_9F^{20}$

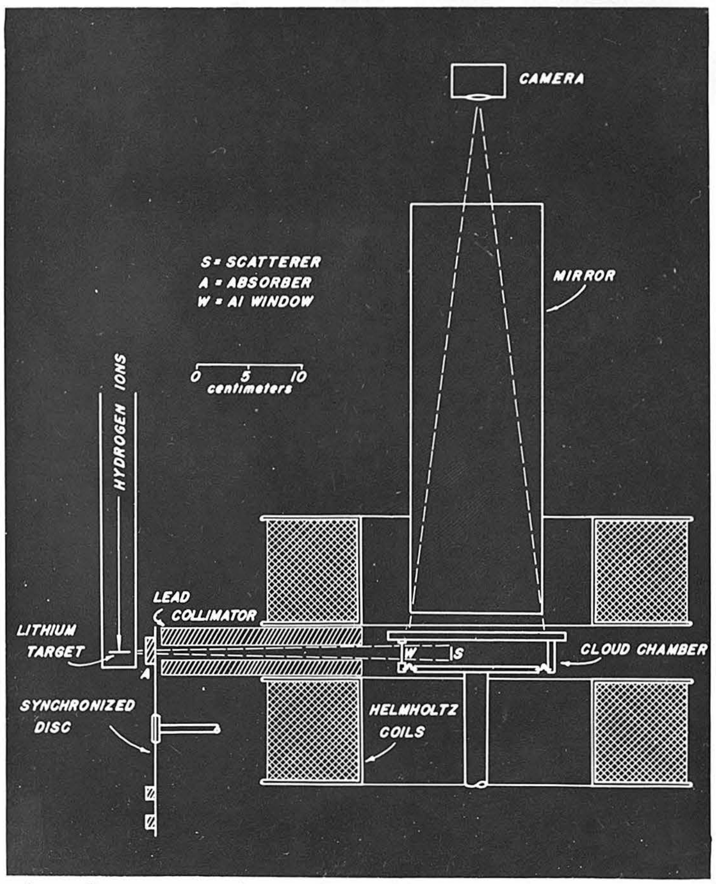

Fig. 8. Arrangement of apparatus for the determination of gamma ray energies

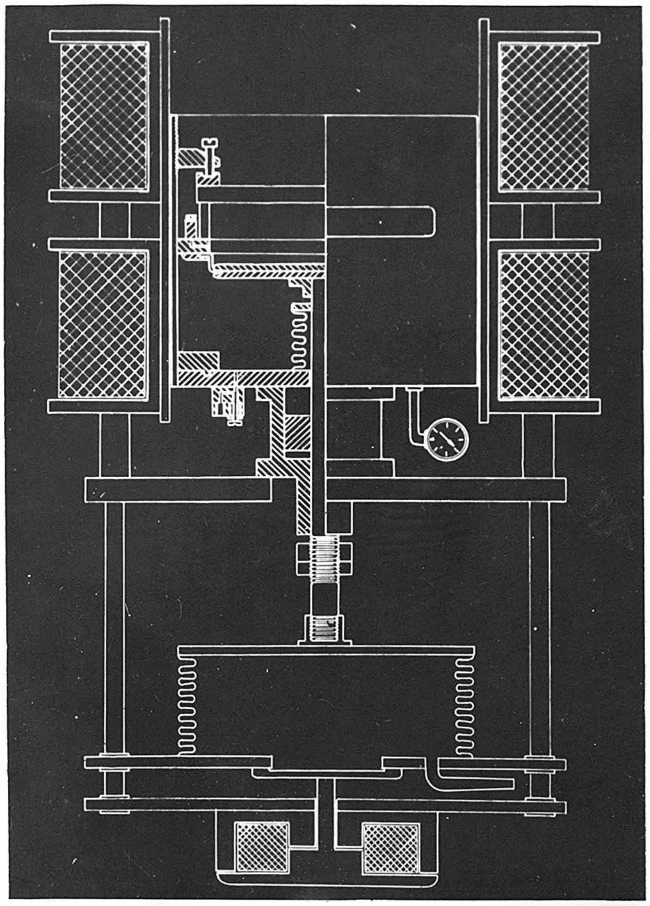

Fig. 9. Cross-section of cloud chamber.

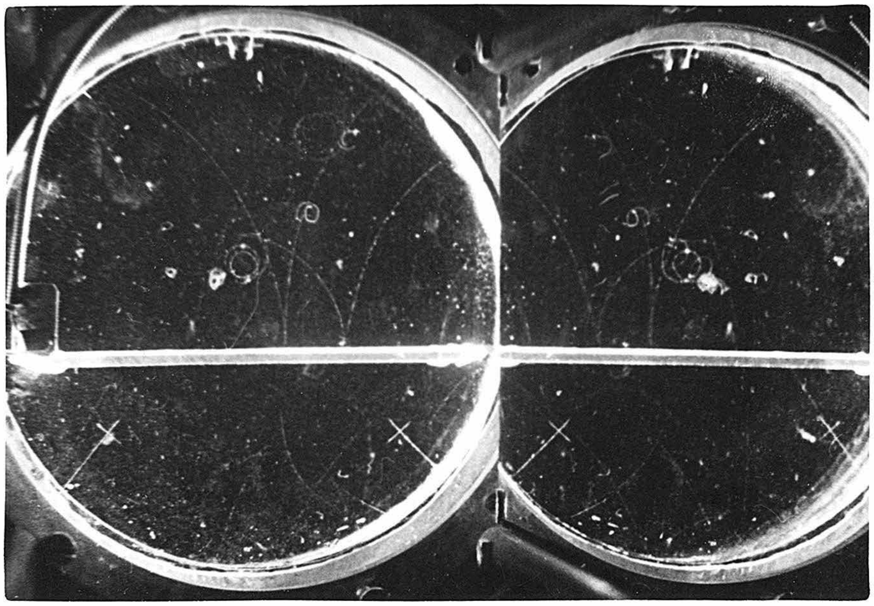

Fig. 10. Examples of pairs from lead scatterers.

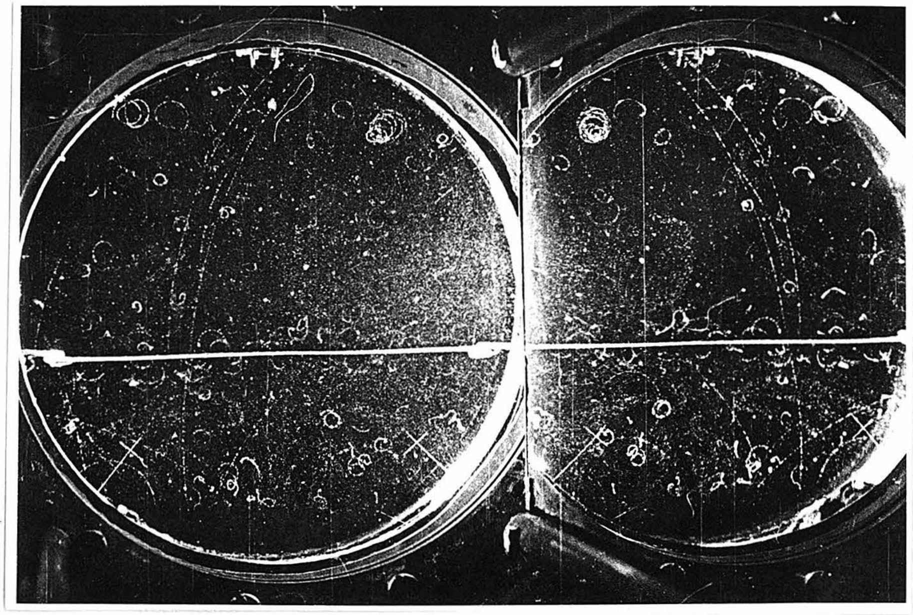

Fig. 11. Example of recoil electron starting in the scatterer and one passing through.

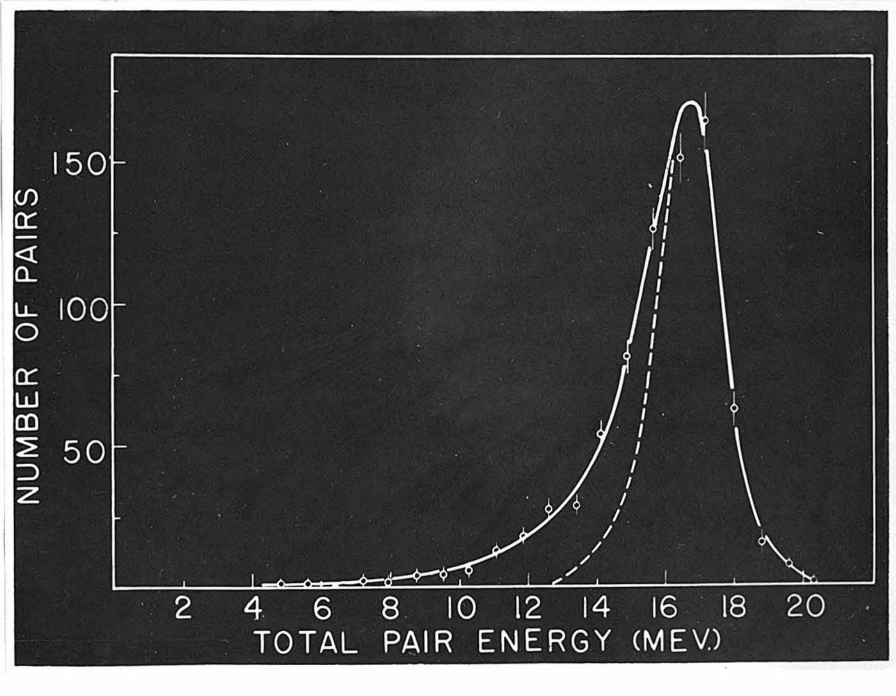

Fig. 12. Distribution in energy of a total of 770 pairs. Obtained from a 0.032 cm. lead scatterer and a .012 cm. lead scatterer.

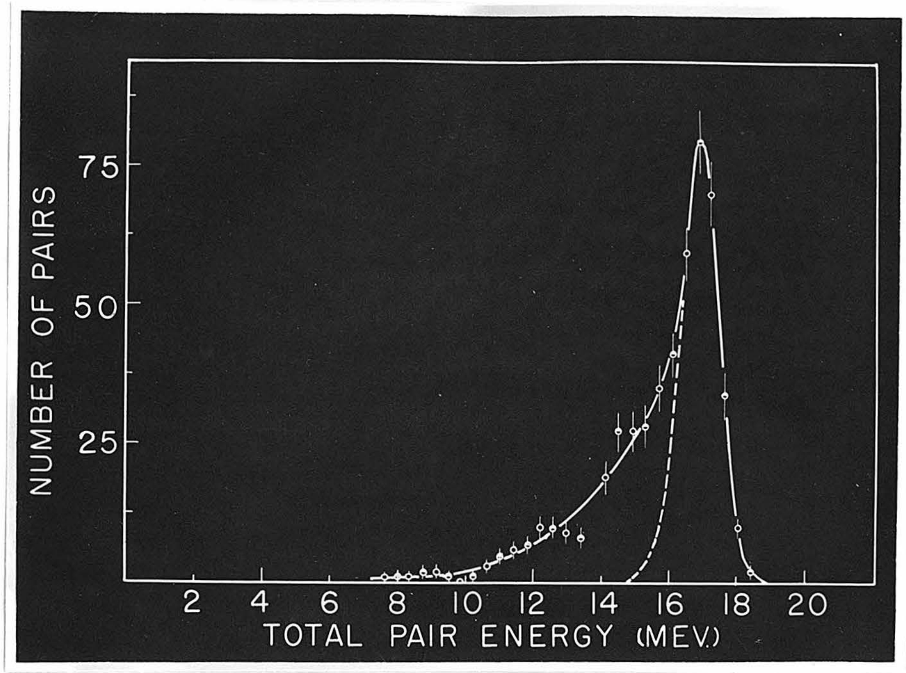

Fig. 13. Distribution in energy of 257 pairs from a 0.012 cm. lead scatterer.

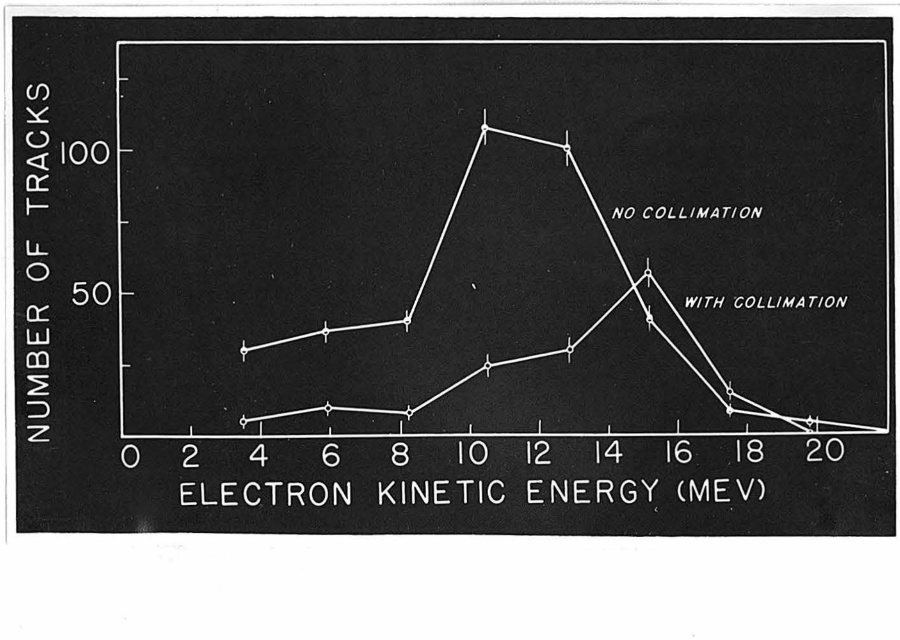

Fig. 14. Distribution of apparent recoil electron with and without collimation.

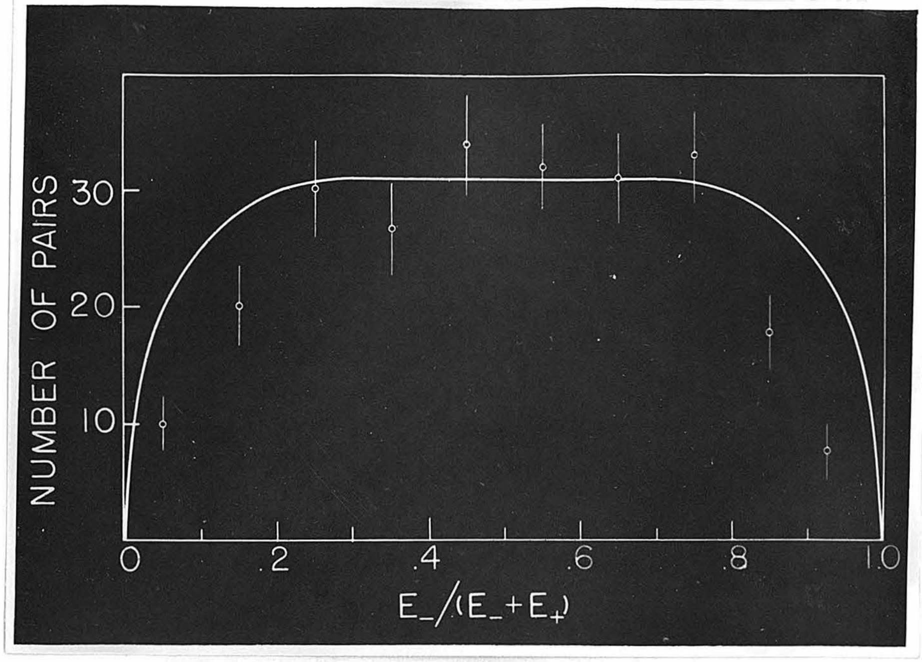

Fig. 15. Energy division between members of 17 Mev. pairs.

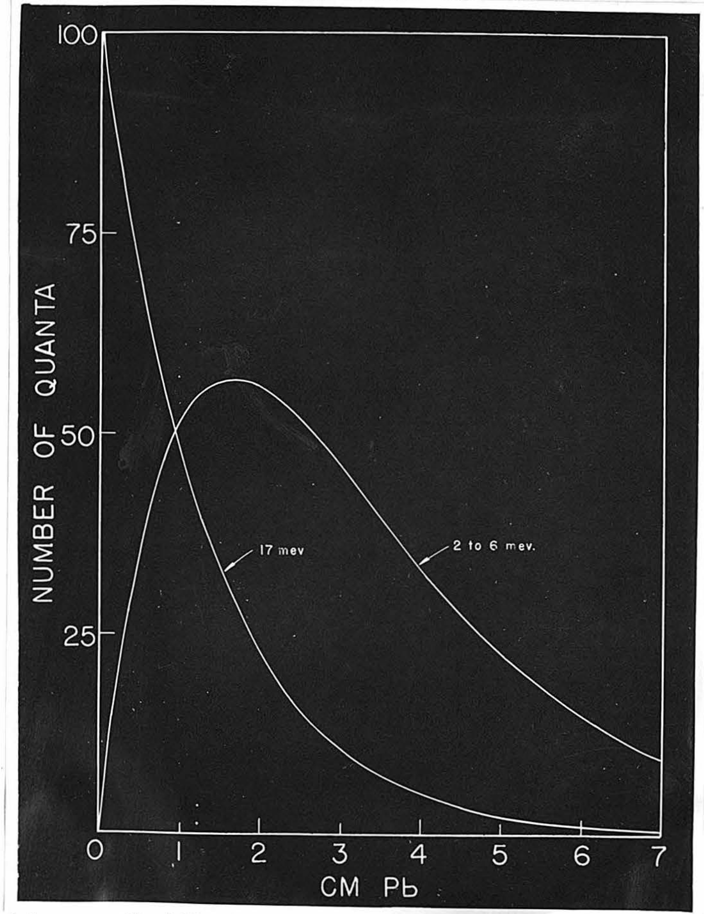

Fig. 16. Distribution of 17 Mev. primary radiation and 2 to 6 Mev. radiation as a function of absorber thickness.

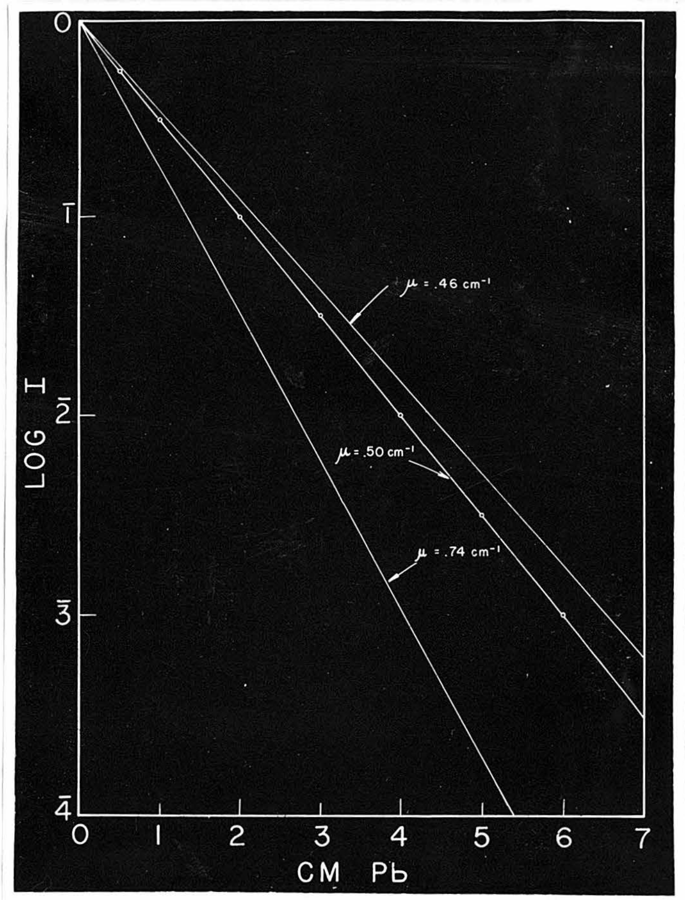

Fig. 17. Log of ionization as a function absorber thickness for

= 0.46 cm.$^{-1}$ (3 Mev. radiation)

= 0.50 cm.$^{-1}$ (2-6 Mev. radiation)

= 0.74 cm.$^{-1}$ (17 Mev. radiation)

BIBLIOGRAPHY

(1) Bethe, H., Heitler W. Proc. Roy. Soc. 146, 83 (1934).

(2) Bonner, T. W., Brubaker, W. M. Phys. Rev. 48, 742, (1935).

(3) Bonner, T. W., Brubaker, W. M. Phys. Rev. 50, 308, (1936).

(4) Bothe, W. v., Becker, H. Zeit. f. Phys. 66, 289, (1930).

(5) Bothe, W. v. Zeit. f. Phys. 100, 273, (1936).

(6) Chadwick, J. Goldhaber, M. Nature, 135, 65, (1935).

(7) Cockcroft, J. D. Int. Conf. on Physics, (1934).

(8) Cockcroft, J. D. Walton, E. T. S. Proc. R. S. A. 137, 229, (1932).

(9) Cockcroft, J. D. Walton, E. T. S. Proc. R. S. A. 144, 704, (1934).

(10) Crane, H. R. Phys. Rev. 51, 50, (1937).

(11) Crane, H. R., Delsasso, L.A., Fowler, W.A., Lauritsen, C.C. Phys. Rev. 47, 971, (1935).

(12) Crane, H. R., Delsasso, L.A. Fowler, W.W., Lauritsen, C.C. Phys. Rev. 48, 125, (1935).

(13) Crane, H. R., Lauritsen, C.C. Phys. Rev. 45, 64, (1934).

(14) Crane, H.R., Lauritsen, C.C. Solton, A. Phys. Rev. 44, 692, (1933).

(15) Crane, H.R. Lauritsen, C.C. Solton, A. Phys. Rev. 45, 507 (1934).

(16) Dee, P. I. Nature, 132, 819, (1934).

(17) Dee, P.I., Gilbert, C.W. Proc. R. S. A., 154, 279, (1936).

(18) Delsasso, L.A., Fowler, W.A. Lauritsen, C.C. Phys. Rev. 48, 848, (1935).

(19) Delsasso, L.A., Fowler, W.A. Lauritsen, C.C. in publication.

(20) Fowler, W. A., Delsasso, L.A. Lauritsen, C. C. Phys. Rev. 49, 561, (1936).

(21) Gaerttner, Crane, H. R. Phys. Rev. 51, 49, (1937).

(22) Hafstad, L. R., Heydenburg, N. P., Tuve, M. A. Phys. Rev. 50, 504, (1936).

(23) Kirsh, G. Atomzertrümmerung, Akademishe Verlagsgesellschaft m.b.H. Leipzig, (1926).

(24) Knol, K. S., Veldkamp, J. Physica 3, 145, 1936.

(25) Lawrence, E. O., Livingston, M. S., Lewis, G. N. Phys. Rev. 44, 56, (1933).

(26) Lewis, G. N., Livingston, M. S., Lawrence, E. O. Phys. Rev. 44, 55, (1933).

(27) Lewis, W. B., Burchain, W.E., Chang, W. Y. Nature, 139, 24, (1937).

(28) Lyman, E. M. Phys. Rev. 51, 1, (1937).

(29) Mano, G. J. de Phys. et Rad. 5, 628, (1934).

(30) Meitner, L. Naturwissensch. 22, 420, (1934).

(31) Oliphant, M. L. E., Kempton, A. R., Rutherford, E. Proc. R. S. A. 149, 406, (1935).

(32) Oliphant, M.L.E., Kinsey, B. B., Rutherford, E. Proc. R. S. A., 141, 722, (1933).

(33) Oliphant, M.L.E., Rutherford, E. Proc. R. S. A. 141, 259, (1933).

(34) Oliphant, M. L. E., Shire, E. S., Crowther, B. M. Proc. R.S.A. 146, 922, (1934).

(35) Oliphant, M.L.E., Westcott, International Conf.of Physics, (1934).

(36) Oppenheimer, R. J., Plesset, Phys. Rev. 44, 53, (1933).

(37) Rumbaugh, L. H., Hafstad, L.R. Phys. Rev. 50, 681, (1936).

(38) Rutherford, E., Chadwick, J. Phil. Mag. 42, 809, (1921).

(39) Rutherford, E., Chadwick, J. Nature, 113, 457, (1924).

(40) Rutherford, E., Chadwick, J. Proc. Phys. Soc. Long. 36, 4117, (1924).

(41) Savel, P. Compt. Rendu, 198, 368, (1934).

(42) Snetzler, K. v. Zeits f. Phys. 95, 302, (1935).

(43) Taylor, H. J., Dabholkar, V. D. Phys. Soc. Proc. 48, 285, (1936).

(44) Traubenberg, R. H. v., Eckardt, A., Gebaur, R. Naturwissenschaften, 21, 26, (1933).

(45) Traubenberg, R. H. v. Zeit. f. Phys. 80, 557, (1933).

(46) Traubenberg, R. H. v. Zeit. f. Phys. 89, 582, (1934).

(47) Walton, E. T. S., Cockcroft, J. D. Nature, 131, 23, (1933).

(48) Webster, H. C. Proc.R.S.A. 136, 428, (1932).

(49) Bothe, W., Gentner, W. Zeit. f. Phys. 104, 685, (1937).

(50) Lauritsen, C. C. Fowler, W.A. In publication.

(51) Veldkamp, J., Knol, K. S. Physica, 4, 2, 166, (1937).