Energy and Absorption of the Gamma-Radiation from Li^7+H^1

L. A. DELSASSO, W. A. FOWLER AND C. C. LAURITSEN
California Institute of Technology, Pasadena, California

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It is shown that a study of the pairs ejected from foils in a Wilson cloud chamber gives more reliable and useful information regarding gamma-radiation of very high energy than can be obtained from the recoil electrons. By this method the gamma-radiation from Li^7+H^1 is found to consist of a line at 17.1 ± 0.5 Mev of relative intensity 0.75 and probably one or more lines at about 14 Mev of relative intensity 0.25. No radiation is found between 2 and 10 Mev. The spectrum below 2 Mev has not been investigated. The distribution of recoil electrons is consistent with this and with the Klein-Nishina formula. The division of energy between members of pairs is in agreement with the predictions of Bethe and Heitler. It is shown that the usual method of measuring absorption coefficients leads to erroneous results for radiation much above 3 Mev and a method is described which depends on counting the number of high energy pairs observed in cloud chamber pictures taken alternately with and without 1 cm of lead in the beam. The results agree with theory within the experimental errors. The origin of the radiation is discussed and it is shown that the data can be accounted for if we assume that the proton is captured by the Li^7 nucleus producing a Be^8 nucleus in an odd state. According to Breit this should be a P state and the nucleus may drop to the ground state (^1S) with emission of 17 Mev radiation or to an even state at 3 Mev (^1D) and subsequently break up into two alpha-particles.

INTRODUCTION

IN an earlier attempt to investigate the gamma-ray spectrum from lithium bombarded with protons by means of the Wilson cloud chamber we[1] measured the tracks due to 1576 single electrons and 57 pairs. The single electrons were thought to be mostly recoil electrons from the chamber wall and seemed to suggest a line spectrum distributed more or less uniformly from 3 to 17 Mev. On the other hand, the 57 pairs were distributed mostly in the energy interval from 10 to 17 Mev, thus suggesting that most of the radiation was concentrated near the high energy end of the spectrum and giving no evidence for any radiation below 10 Mev.

Nevertheless, because the number of pairs observed was comparatively small we placed more emphasis on the single electrons. This we now realize was an unfortunate error, for subsequent work with better geometrical arrangement and improved technique has convinced us that most of the single electrons observed were of uncertain origin coming mainly from the field coils and from the top and bottom of the cloud chamber. On the other hand the origin of the pairs is in general unmistakable and they suffered in this early work only from the large energy loss in the thick wall of the chamber or the lead lining which served as scatterer.

For this and other reasons we decided to continue the work and to obtain a much greater number of pairs and at the same time learn more about the origin of the single tracks. To facilitate this a scatterer of low stopping power was placed within the cloud chamber and stereoscopic pic-

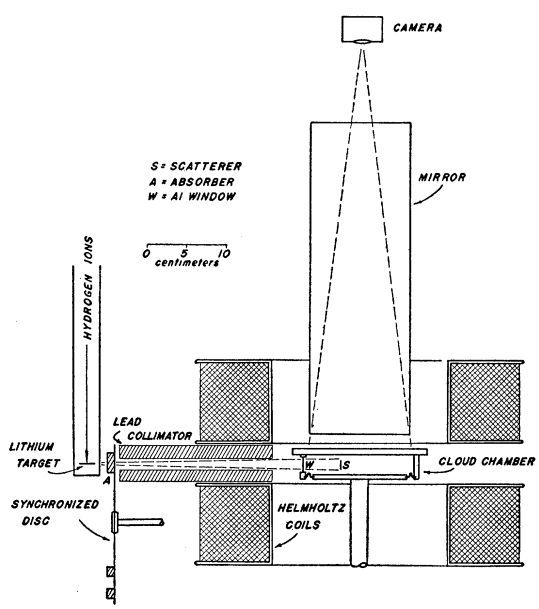

FIG. 1. Schematic diagram of the apparatus used in the determination of the energy and absorption of the gamma-radiation from Li^7+H^1.

[1] H. R. Crane, L. A. Delsasso, W. A. Fowler and C. C. Lauritsen, Phys. Rev. **48**, 125 (1935).

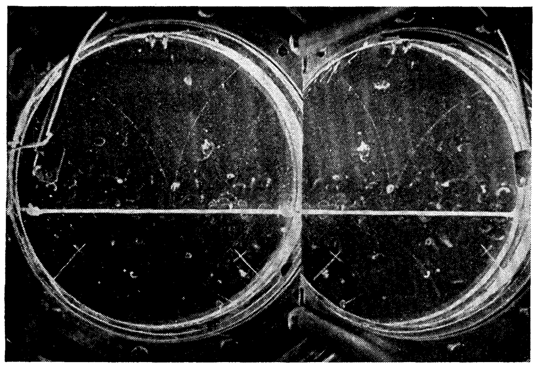

FIG. 2. Stereoscopic views of a 17.0 Mev pair ejected from a 0.012 cm lead scatterer by the gamma-radiation from Li^7+H^1. Magnetic field = 2580 gauss.

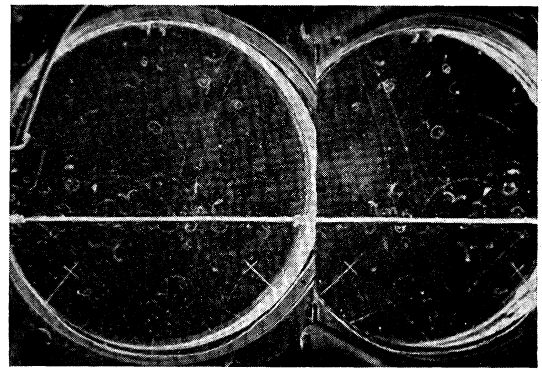

FIG. 3. Stereoscopic views of two pairs produced in a 0.012 cm lead scattered by the gamma-radiation from Li^7+H^1. In both pairs the greater portion of the energy has been given to the electrons. The total energies are 16.5 and 16.0 Mev. Magnetic field = 2580 gauss.

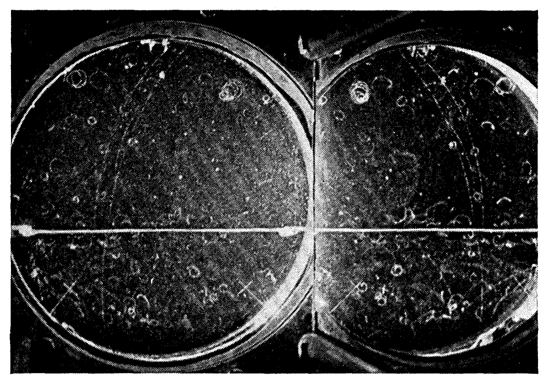

FIG. 4. Stereoscopic views of a single electron (9 Mev) ejected from a 0.012 cm lead scatterer and of an electron (11 Mev) traversing the scatterer. An electron of lower energy ejected from the bottom of the chamber is seen between the two. Magnetic field = 2580 gauss.

tures were taken. The results of a large series of exposures were reported at the Seattle meeting of the Physical Society in June, 1936. The principal conclusion reached was that most of the radiation is concentrated in a band or line at approximately 17 Mev.

When projected onto a model of the chamber and scatterer these stereoscopic pictures revealed the fact that most of the single tracks originated outside the cloud chamber and in the top and bottom of the chamber. In order to eliminate as many of these unwanted tracks as possible we have recently increased the distance between the target and the chamber and have interposed a lead collimator 18 cm thick with an aperture just large enough to illuminate the scatterer. A 1 mm aluminum window is provided in the wall of the chamber where the radiation enters, thus decreasing the number of electrons from the wall. In addition scatterers of lower stopping power were used in order to obtain better resolution. All of these improvements led to a considerable sacrifice in intensity but this was more than compensated for by certain improvements in operation and by the fact that the ratio of useful to unwanted tracks was very much increased.

The uniformity of photography has been much improved by replacing the carbon arc with four 300 watt lamps, two on each side. These lamps are standard 110 volt lamps flashed to about 190 volts. The magnetic field was 2580 gauss. The tube was operated continuously at 750 kv peak while the proton current was about 20 microamperes during the expansion. Metallic lithium was used for the target. The general experimental arrangement is indicated in Fig. 1 and sample pictures are shown in Figs. 2, 3 and 4.

We propose to present all of our measurements on pairs, but in addition we shall present separately our data on single tracks and pairs obtained most recently and with the thinnest scatterer because we consider them more reliable. In addition we shall present some data on the absorption of this radiation in 1 cm of lead.

RESULTS

Pairs

Fig. 5 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. Fig. 6 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 Fig. 5. 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 product of the reaction is unknown there is no direct experimental evidence against it.

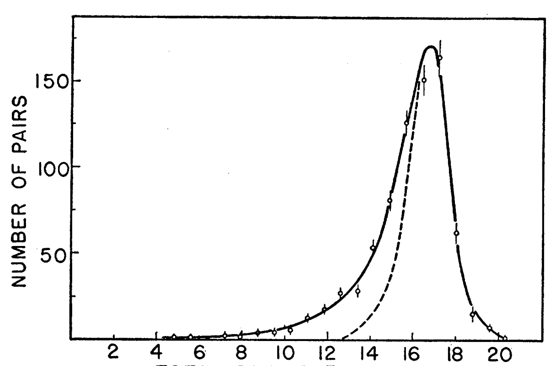

FIG. 5. The distribution in energy (kinetic plus 2 mc^2) of 513 pairs ejected from a 0.032 cm lead scatterer and 257 pairs ejected from a 0.012 cm lead scatterer. The dotted line is symmetrical about 16.7 Mev with the front portion of the curve.

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[1] the radiation in question is produced by resonance. The best measurements on the excitation as function of energy are those by Hafstad, Heydenberg and Tuve[2] 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 Fig. 5 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,[3] approximately

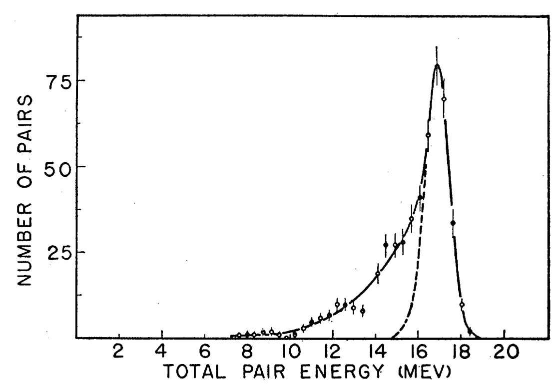

FIG. 6. The distribution in energy (kinetic plus 2 mc^2) of 257 pairs ejected from a 0.012 cm lead scatterer. Although no definite resolution of radiation between 10 and 17 Mev has been obtained the asymmetry of the curve is even more pronounced than in Fig. 5.

[2] L. R. Hafstad, M. T. Heydenberg and M. A. Tuve, Phys. Rev. **50**, 504 (1936).
[3] H. A. Bethe and W. Heitler, Proc. Roy. Soc. **146**, 83 (1934).

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 percent.

Fluctuations in the magnetic field amount to less than 2 percent, 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 Fig. 5 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 Fig. 5 is 190 or about 25 percent of the total. It seems likely that approximately one-fourth of these pairs, that is 10 percent 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 percent 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 the secondaries of a 17 Mev quantum and having energies between 10 and 17 Mev. This comes out to be less than 2 percent 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 percent 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 percent 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 percent of the total. We find no evidence for softer radiation but our present data do not definitely exclude radiation much below 2 Mev.

Recoil Electrons

It is much more difficult to obtain reliable data on the recoil electrons for clearly not all of the

Table I. *Reduction produced by collimation in relative number of single tracks.*

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

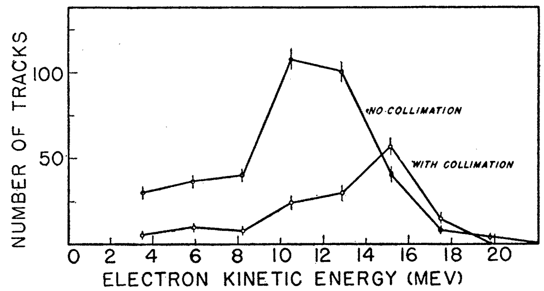

FIG. 7. The distribution in kinetic energy of the recoil electrons (observed electrons minus observed positrons) ejected from lead and aluminum scatterers with and without collimation of the gamma-ray beam. The curves are normalized to the same number of pairs. The large number of spurious tracks without collimation is apparent.

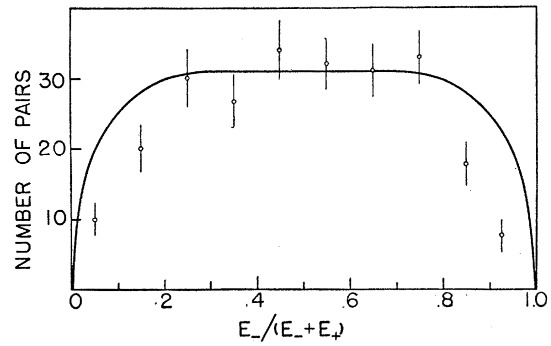

FIG. 8. Energy distribution of negative members of pairs with total energy between 15 and 18 Mev. The theoretical distribution (normalized to the average number within the central six intervals) is shown in the heavy line. The experimental points are shown.

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 I.

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 II 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 II. *Average energy of various particle groups, with and without collimation.*

	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

Fig. 7 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.

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 Fig. 8 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 because of 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.[4, 5] Unfortunately, such measurements are not reliable and cannot be taken as valid tests of the theory developed by

[4] E. McMillan, Phys. Rev. **46**, 868 (1934).
[5] H. R. Crane, L. A. Delsasso, W. A. Fowler and C. C. Lauritsen, Phys. Rev. **46**, 531 (1934).

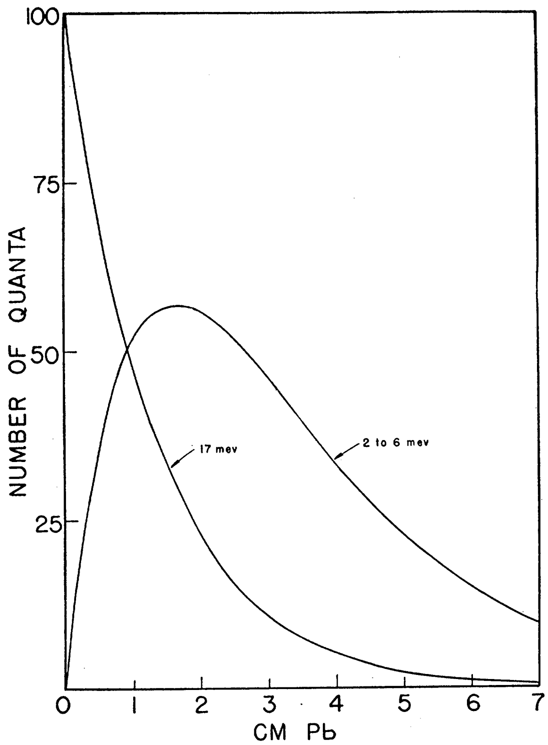

FIG. 9. The number of primary and penetrating secondary quanta as a function of absorber thickness.

Oppenheimer and Plesset[6] and by Bethe and Heitler.[3] 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 the measurement is made.

That this is so can be seen from a simple calculation. Let us consider an arrangement in which the target is comparatively close to the ionization chamber and the absorbers are interposed directly in front of the ionization chamber. Such an arrangement is far from ideal but is usually necessitated by the low intensity available.

We wish to determine approximately the composition of the radiation as a function of absorber thickness and from this the ionization to be expected. This gives the apparent absorption coefficient.

Let us assume that the primary radiation initially consists of N_0 quanta of 17 Mev. Then the number of primary quanta present at any depth x in the absorber is

$$N = N_0 e^{-\mu x},$$

μ being the total absorption coefficient for the material. The high energy quanta removed from the beam produce pairs and recoil electrons which in turn produce a continuous x-ray spectrum extending from zero to 17 Mev. If the absorber consists of a heavy element, say lead, a part of this continuous spectrum will have an average absorption coefficient μ' which is lower than μ. Let α be the number of such quanta produced for each primary quantum removed from the beam, then the change in the number N' of such quanta occurring in a layer Δx in the absorber is, if we neglect the range of the electrons in lead,

$$\Delta N' = \alpha \Delta N - N' \mu' \Delta x; \quad \text{or}$$

$$\Delta N' = \alpha N_0 \mu e^{-\mu x} \Delta x - N' \mu' \Delta x;$$

and hence the number of these secondary quanta present at any depth x in the absorber is

$$N' = \alpha N_0 (\mu / (\mu' - \mu)) (e^{-\mu x} - e^{-\mu' x}).$$

From the data given by Bethe and Heitler we can calculate α for any desired energy interval. We are particularly interested in the secondary quanta in the energy interval for which the absorption coefficient is near the minimum, that is roughly the interval from 2 to 6 Mev for which the average absorption coefficient is $\mu' = 0.50$ cm^{-1} in lead. For this interval α is equal to 1.3 and we can therefore calculate N' for any value

[6] J. R. Oppenheimer and M. S. Plesset, Phys. Rev. **44**, 53 (1933).

of x if we assume that the secondary quantum is produced at the point where the primary quantum is absorbed. This is of course not quite true but permissible in the approximation which we are attempting. Fig. 9 shows N and N' plotted against absorber thickness. It is seen that already at a depth of 1 cm the number of penetrating secondary quanta equals the number of primary quanta and they predominate more and more with increasing thickness of the absorber. In addition to these quanta there will be produced a considerable number of quanta of lower energy, partly belonging to the continuous x-ray spectrum just discussed and partly due to anihilation of pairs but these are comparatively rapidly absorbed and we shall neglect them.

The ionization to be expected in the ionization chamber is

$$I \sim N + \beta\gamma N',$$

where β is a factor smaller than 1 due to the fact that not all of the N' quanta are directed toward the chamber. They are, however, directed mostly in the forward direction and $\beta = 0.8$ seems a reasonable value. The factor γ is the ionization function which in this energy region is approximately proportional to the energy, hence $\gamma = 0.3$.

The calculated value of the logarithm of I is plotted in Fig. 10 giving an almost straight line with a constant slope corresponding to $\mu = 0.50$ cm^{-1} for all thicknesses of absorber. If the calculations were carried out exactly for still greater thicknesses 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 line $\mu = 0.73$ cm^{-1} is shown. This is the theoretical value of the absorption coefficient for 17 Mev radiation and it is worthy of note that the penetrating secondary radiation builds up so rapidly that the absorption

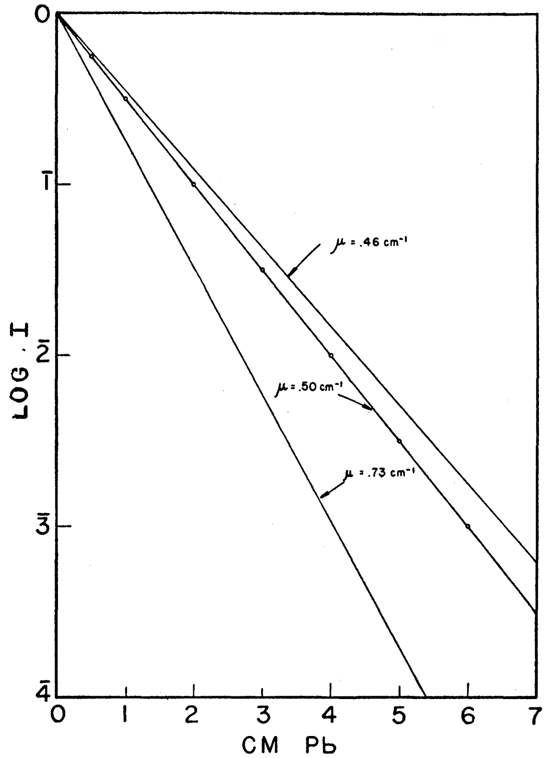

FIG. 10. The points on the curve marked $\mu = 0.50$ cm^{-1} are calculated neglecting the range of electrons in lead. This approximation is satisfactory except for the transition layer which is a few millimeters of lead.

curve as here calculated is straight, even for very thin absorbers, and at no point is the absorption coefficient for 17 Mev radiation approached. This is in agreement with the results of the experiments referred to above. It is clear, therefore, that this method is unsuited for determining the true absorption coefficient for radiation much in excess of 3 Mev.

TABLE III. *Numbers of pairs in three energy intervals, with and without absorber.*

	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

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 Fig. 5. In Table III we have listed the number of pairs observed in three energy intervals with and without absorber. The attenuation in 1 cm of lead of the radiation producing the high energy pairs is seen to be

$$(135\pm8)/(260\pm11)=0.52\pm0.04,$$

which gives a total absorption coefficient for this radiation of

$$\mu=-\log 0.52=0.66\pm0.07 \text{ cm}^{-1}.$$

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

which is in fair agreement with the observed value.

The data given in Table I permit us to determine the ratio σ/π for lead and for aluminum if we assume that the observed positrons as well as an equal number of electrons are members of pairs originating in the scatterer. The number of recoil electrons is then equal to the number of electrons minus the number of positrons and the true number of pairs is equal to the observed number of pairs plus the number of positrons plus an equal number of electrons. This gives for lead

$$(\sigma/\pi)_{\text{Pb}}=52/(257+98)=0.15$$

compared to the theoretical value of 0.142 and for aluminum

$$(\sigma/\pi)_{\text{Al}}=93/(71+24)=1.0,$$

for which the theory gives 0.90. The accuracy is not high and it is difficult to estimate the probable errors due to the uncertainty in the origin of some of the tracks.

Origin of the Gamma-Radiation

That the gamma-radiation here discussed is due to the Li^7 isotope is clear from energy considerations and this has recently been verified by Rumbaugh and Hafstad[7] 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.

Several suggestions regarding the possible mechanism of the radiation from Li^7+H^1 have been made but the discussions have usually been complicated or unsatisfactory owing to the uncertainty regarding the facts to be accounted for. In the article referred to above as (2) Breit gives a most excellent discussion of the several possibilities and the facts which we have just presented appear to fit well with certain of these and should prove helpful in excluding others. We enumerate our conclusions regarding the radiation to be accounted for:

(1) a line at 17 Mev of relative intensity 0.75,
(2) one or more lines between 10 and 17 Mev of total relative intensity 0.25,
(3) little or no radiation between 2 and 10 Mev. Relative intensity less than 0.05,
(4) radiation below 2 Mev not excluded by these experiments.

In particular it should be noted that we failed to find any radiation in the neighborhood of 8 Mev. If such radiation is emitted it is probably less than 2 percent of the total observed.

We have previously[1] discussed the following two possibilities for the mechanism responsible for the radiation.

(1) After capture of the proton by the Li^7 nucleus the resulting unstable (Be^8) nucleus breaks up into two alpha-particles, one or both of which may be in an excited state and subsequently drop to the normal state with emission of radiation.

(2) The (Be^8) nucleus is formed in a quasi stable state with a life time for alpha-particle disintegration which is long compared with the radiation time. It subsequently drops to the ground state in one or more jumps.

[7] L. H. Rumbaugh and L. R. Hafstad, Phys. Rev. **50**, 681 (1936).

The experimental data available at the time did not allow of a decision between these two alternatives but it seemed difficult to account for the long life time of the excited (Be^8) nucleus. This difficulty may, however, be resolved as Breit has pointed out and hence the second alternative now seems the more attractive, particularly since it is in complete analogy with the mechanism known to be responsible for the production of the gamma-radiation from Be^9 and B^{11} bombarded by protons.[1] In these two cases a mechanism analogous to (1) is ruled out by energy considerations. The mechanism which appears to account best for our observations is one of the several possibilities suggested by Breit and fully discussed by him. It 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 independently 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 Feenberg and Wigner.[8] 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.

This gives the following three possibilities for transition with gamma-ray emission.

$$Li^7+H^1\rightarrow(Be^8)\rightarrow Be^8+17 \text{ Mev } \gamma\text{-ray} \quad (1)$$

$$\rightarrow{}^*Be^8+14 \text{ Mev } \gamma\text{-ray} \quad (2)$$

$$\rightarrow{}^*Be^8+8 \text{ Mev } \gamma\text{-ray}. \quad (3)$$

[8] Now published, E. Feenberg and E. Wigner, Phys. Rev. **51**, 95 (1937). They give 3.8 mc^2 and 12.6 mc^2, respectively, for the ^1D and the ^1G level values. See also P. I. Dee and C. W. Gilbert, Proc. Roy. Soc. **154**, 279 (1936).

Our observations indicate that reactions (1) and (2) occur with a relative probability of at least 3 to 1, and (3) occurs rarely if at all. It is to be expected that the probability for reaction (3) would be very low since a transition between P G levels would be strongly forbidden. Since we find no radiation at 3 Mev it is most reasonable to suppose that $^*Be^8$ in reaction (2) breaks up into two alpha-particles each having an energy of approximately 1.5 Mev. This is consistent with an even ^1D level at 3 Mev. In reaction (1) Be^8 is presumably formed in the ground state which is even and it may or may not break up into two low energy alpha-particles depending on whether Be^8 is stable or not. The ^1D level here discussed may also be involved in the reactions

$$Li^7+H^2\rightarrow Li^8+H^1, \quad (4)$$

$$Li^8\rightarrow Be^8+\epsilon^-. \quad (5)$$

Rumbaugh and Hafstad[7] have shown that the protons from reaction (4) have a range of less than 8 cm which leaves some 3 or 4 Mev to be accounted for. It is not unlikely that Be^8 in reaction (5) is formed in the excited state ^1D and subsequently breaks up into two alpha-particles with approximately 1.5 Mev each.*

In conclusion we wish to express our appreciation to the Seeley W. Mudd Fund for financial support.

* *Note added in proof.* W. B. Lewis, W. E. Burcham and W. Y. Chang, Nature **139**, 24 (1937) have observed radioactive alpha-particles after bombarding lithium with 500 kv deuterons. The half-life of the alpha-particles as well as the beta-particles from (5) is given as 0.88±0.1 seconds. This is probably a more reliable value than the value 0.5±0.1 seconds observed for the beta-particles in this laboratory as the probable error was calculated only from the number of tracks observed and did not include possible systematic errors arising from the timing of the cloud chamber. We have confirmed the existence of these alpha-particles by cloud chamber observations and find a distribution extending from 5 cm range down to at least 0.5 cm with a maximum probability at 0.7 cm range or 1.5 Mev. Whether or not the spectrum is continuous or complex is as yet uncertain. Attempts to detect an instantaneous alpha-emission of similar distribution in the case of Li^7+H^1 are now in progress.

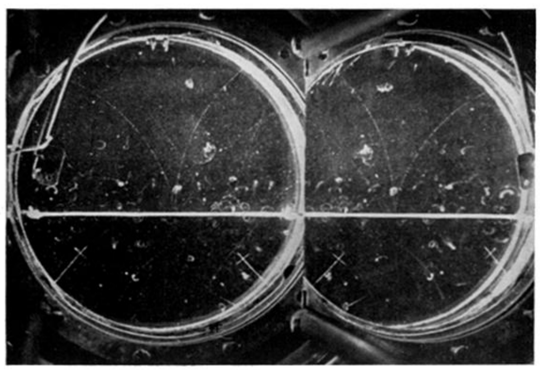

FIG. 2. Stereoscopic views of a 17.0 Mev pair ejected from a 0.012 cm lead scatterer by the gamma-radiation from Li^7+H^1. Magnetic field = 2580 gauss.

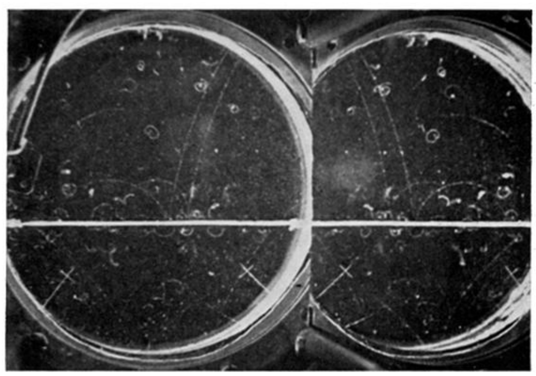

FIG. 3. Stereoscopic views of two pairs produced in a 0.012 cm lead scattered by the gamma-radiation from Li^7+H^1. In both pairs the greater portion of the energy has been given to the electrons. The total energies are 16.5 and 16.0 Mev. Magnetic field = 2580 gauss.

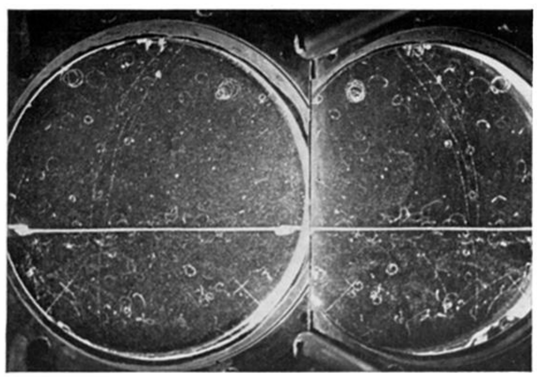

FIG. 4. Stereoscopic views of a single electron (9 Mev) ejected from a 0.012 cm lead scatterer and of an electron (11 Mev) traversing the scatterer. An electron of lower energy ejected from the bottom of the chamber is seen between the two. Magnetic field = 2580 gauss.