Experiments on the Gamma-Radiation from Lithium and Fluorine Bombarded with Protons

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The recoil electrons ejected from a 2 mm carbon scatterer by the gamma-radiation from Li+H[1] have been investigated and indicate three lines of energies 17, 14.5, and 11.5 and possibly a fourth line of energy 8.5 Mev. Pairs ejected from the same scatterer were also observed. Most of these may be attributed to the 17 Mev line. Recoil electrons ejected from a 1.5 mm carbon scatterer by the gamma-radiation from F+H[1] have been observed, and indicate two lines of energies 5.7 and 4 Mev. Pairs produced by internal conversion of the gamma-radiation from F+H[1] were also observed, and indicate the same two lines. The cross section for this effect is in good agreement with the theoretical predictions. It is pointed out that a study of the pairs produced by internal conversion affords an excellent method of determining excitation levels in nuclei.

INTRODUCTION

Li+H[1]

THE question whether the gamma-radiation from lithium bombarded with protons is composed of a single line or a number of lines has not been clearly decided by the results of the experiments so far reported. The recoil electrons ejected from the glass wall of a cloud chamber by the radiation were studied by Crane, Delsasso, Fowler and Lauritsen[1] and were interpreted as indicating a complex spectrum extending up to about 16 Mev. During the same measurements a number of pairs was observed, which were grouped principally near the upper energy limit but extended down to 10 Mev. Subsequent measurements of a large number of pairs ejected from a thin sheet of lead were reported by Delsasso, Fowler and Lauritsen.[2] These pairs fell in a band or line at about 17 Mev and it was therefore concluded that there was little if any radiation below about 17 Mev. In a more recent report[3] these authors confirmed this distribution of pairs and suggested the possibility of one or more relatively weak lines of lower energy. The radiation studied in all cases is without doubt due predominantly to the first proton resonance level, the energy of which has been determined by Hafstad, Heydenburg, and Tuve[4] to be 440 kv.

In the experimental arrangement used by Crane, Delsasso, Fowler and Lauritsen for the observation of recoil electrons it was not possible to be sure that all tracks counted had their origin in the glass wall of the cloud chamber, rather than in material outside the wall. The spectrum obtained was therefore open to the objection that a considerable part of it may have been composed of electrons which were due to softened radiation or which originated in material outside the chamber. This objection seemed to be strengthened by the observations of Delsasso, Fowler and Lauritsen that nearly all the pairs fell in a band at about 17 Mev. Because of this disagreement between the results given by the recoil electrons and the pairs, we decided to make more refined measurements on the distribution of recoil electrons. A preliminary report of this work has already been published.[5]

F+H[1]

McMillan,[6] and Crane and Lauritsen[7] first determined the quantum energy of the fluorine radiation by the absorption method. They obtained an absorption coefficient which corresponded to radiation of about 6 Mev. At the same time Crane, Delsasso, Fowler and Lauritsen[7] studied the recoil electrons ejected into a cloud chamber from a thick sheet of lead. The distribution which they obtained extended up to about 6 Mev, and could be attributed to a

[1] Crane, Delsasso, Fowler, and Lauritsen, Phys. Rev. **48**, 125 (1935).
[2] Delsasso, Fowler, and Lauritsen, Phys. Rev. **50**, 389 (1936).
[3] Delsasso, Fowler, and Lauritsen, Phys. Rev. **51**, 391 (1937).
[4] Hafstad, Heydenburg, and Tuve, Phys. Rev. **50**, 504 (1936).
[5] Gaerttner and Crane, Chicago Meeting American Physical Society (1936); Phys. Rev. **51**, 49 (1937).
[6] McMillan, Berkeley Meeting American Physical Society (1934); Phys. Rev. **46**, 325 (1934).
[7] Crane and Lauritsen, Phys. Rev. **46**, 531 (1934).

single line at about this energy. Recently Delsasso, Fowler and Lauritsen[8] extended the cloud chamber method to the investigation of pairs and recoil electrons ejected from thin absorbers placed inside the cloud chamber. The pairs ejected from a thin lead sheet indicated a sharp line at 6 Mev and the recoils ejected from a thin aluminum sheet indicated a line of about the same energy. Using the same experimental arrangement initiated for the study of the lithium gamma-rays we have also investigated the radiation from fluorine. This particular experimental arrangement also made possible a study of the radiation which is internally converted in the target.

Apparatus

The apparatus used in producing the high speed protons necessary in these experiments consists of a one-million-volt transformer and vacuum tube apparatus.[9] A focused ion beam of about 250 microamperes can be obtained at the target. Since no provision is made to analyze the beam, it consists of both atomic and molecular ions. The cloud chamber is 15 cm in diameter and its depth can be varied from 2.5 cm to 3.8 cm. In the present investigation it is found convenient to use the shallower chamber when the chamber is used in the horizontal arrangement shown in Fig. 1, and the deeper chamber when used in the vertical arrangement shown in Fig. 2. The active depth of the chamber is determined by the depth which is illuminated. It is 1 cm in the horizontal arrangement and 2 cm in the vertical one. Nonstereoscopic photographs are taken by means of a Sept 35-mm motion picture camera having an f : 1.9 lens. The tracks are illuminated by a carbon arc light flashed at 300 amperes. Two water cooled, air core coils, one above and one below the chamber produce the required magnetic field. They are capable of producing a field of 4000 oersteds, when energized only for about 1 second at the time of the chamber expansion. The magnetic field intensity is regulated by varying the field current in a 50 kw generator which supplies the current for the field coils. The rheostat for this and also an accurately calibrated ammeter are located near the cloud chamber, and by means of these the mean deviation of the field current can be kept down to about 1 percent. A motor driven central contact system is used to operate the ion accelerating apparatus and the cloud chamber in synchronism. In this way it is necessary to energize the high voltage transformer and the ion source for only a fraction of a second at the time of the chamber expansion.

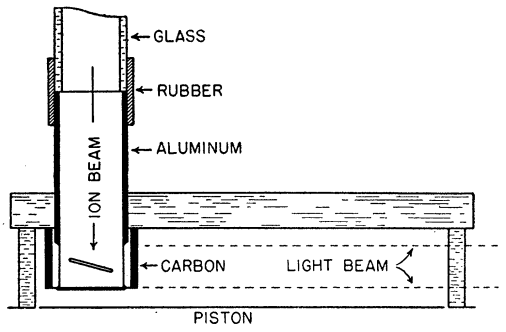

Fig. 1. Horizontal cloud chamber arrangement.

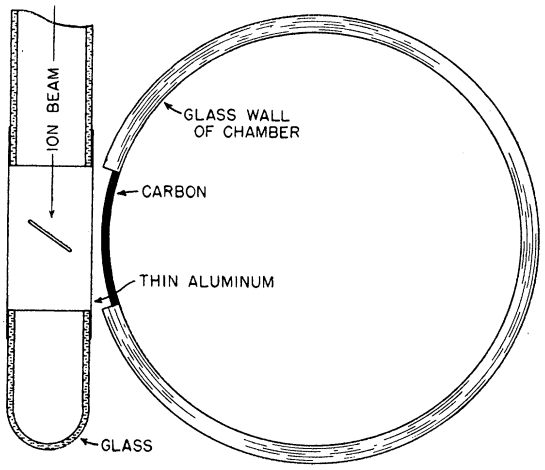

Fig. 2. Vertical cloud chamber arrangement.

The principal object in view in designing the present experimental arrangements was to eliminate doubt as to the origin of the tracks counted, and at the same time to obtain high resolving power by the use of thin scatterers. We accomplished this in our first arrangement, by placing the target in a well in a horizontal cloud chamber, and surrounding the target with a

[8] Delsasso, Fowler, and Lauritsen, Phys. Rev. **51**, 527 (1937).
[9] Crane, Phys. Rev. **52**, 11 (1937).

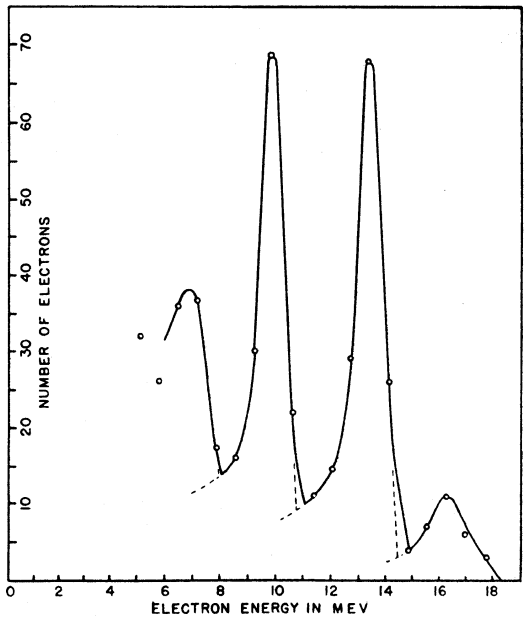

FIG. 3. Negative electrons ejected from 2 mm carbon by the gamma-radiation from $Li+H^1$. Horizontal arrangement. $H=2350$ oersteds.

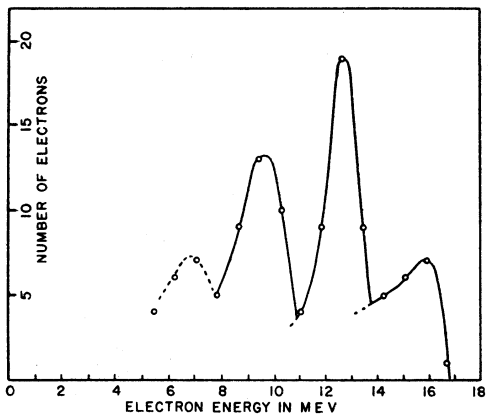

FIG. 4. Negative electrons ejected from 2 mm carbon by the gamma-radiation from $Li+H^1$. Horizontal arrangement. $H=2750$ oersteds.

thin-walled cylinder of scattering material, as sketched in Fig. 1. The large solid angle which the scattering material subtended to the target gave rise to a sufficient number of electrons even though the material had a stopping power of less than 1 Mev for electrons. The fact that the direction of the radiation from the target was everywhere *toward* the outside walls of the chamber, coupled with the fact that at high energies secondaries of all kinds travel predominantly in the direction of the radiation producing them, caused the chamber to be quite free from spurious tracks. We found by actual count that approximately five tracks came directly from the scattering material surrounding the source for every track which appeared elsewhere in the chamber. Thus the chance of a spurious track being situated so that it appears to come from the scatterer, and also to lie in the plane of the chamber is very small. As shown in Fig. 1, the ions were brought vertically downward to the target through a 2 cm brass pipe. The target was lithium metal and was placed at the angle indicated in the sketch, to prevent the gamma-rays from being absorbed in the target. The wall between the target and the scatterer was of thin aluminum (0.1 mm) and could therefore absorb very little of the radiation. The scatterer consisted of a cylinder of pure graphite 2 mm thick.

In an attempt to increase the number of recoil electrons ejected into the chamber from the thin scatterer and also to show that the results obtained were independent of the experimental setup, we made measurements with a second arrangement, using a vertical chamber. In this arrangement a 2 mm carbon scatterer was made part of the cloud chamber wall as shown in Fig. 2. The deeper chamber (3.8 cm), was used and a larger pipe was used to bring the ion beam to the target. Because it was possible to shield the chamber completely from soft x-rays from above, we were able to use considerably higher ion currents and to obtain a correspondingly larger yield of tracks from the lithium radiation. There was also the advantage that the tracks were longer, since the entire diameter of the chamber was available. On the other hand, more tracks due to scattered radiation appeared because the source was outside the chamber. Nevertheless by using a marker indicating the exact position of the scatterer it was possible to select and measure only those tracks which originated in the scatterer.

SELECTION AND MEASUREMENT OF TRACKS

The method generally used for determining the curvature of tracks is to project the full size image upon a white card on which circles of

various radii are drawn, and to determine which circle fits a given track. We have found that the following change in the procedure increases the accuracy of the measurement considerably: The image is projected upon a sheet of blank paper and the image of the track is traced, in full or in part, with a sharp pencil. The curvature of this

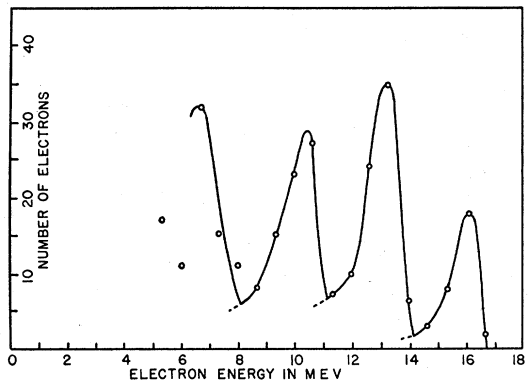

FIG. 5. Negative electrons ejected from 2 mm carbon by the gamma-radiation from Li+H[1]. Vertical arrangement. $H=2200$ oersteds.

arc is then measured by means of a piece of transparent celluloid on which circles are scratched. Parts of tracks which do not stand out with sufficient contrast against the background can easily be traced and measured to a high degree of accuracy.

It was also found that the quality of the tracks could be greatly improved by bombarding the target only for a very short time, 1/10 second, immediately before the photographic exposure. The exposure itself was only 1/10 second long. This rapid procedure accomplished much toward eliminating those changes in curvature of tracks which arise from the drifting and falling of the droplets. It had the further advantage that all tracks photographed were very sharp and narrow.

Before interpreting the present data it was desired to determine the actual amount of spreading of the lines which could be expected to arise from the human error in the measurement of tracks. The following experiment was therefore performed: A list of tracks was traced and measured separately by two observers and the results were later compared, track for track. It was found that the average amount by which the two observers disagreed was 0.3 Mev. This means that for a single observer the average error is somewhat less. The tracks used were of average quality and length and were a representative group having energies greater than 7 Mev.

In order to be selected and measured a track must satisfy the following conditions:

1. It must have its origin in the scatterer. This condition is satisfied if the track is visible to within 1 cm of the surface of the scatterer, and extends at least $\frac{2}{3}$ the distance across the chamber. Any track which starts in the top glass plate or in the floor of the chamber, and appears to come from the scatterer is necessarily short because the active depth of the chamber is only the narrow illuminated portion at the center.

2. A track must not be visibly scattered. The scattering to be expected in air for the high energies encountered here (10 Mev) is extremely small.

RESULTS

Negative electrons from Li+H[1]

In Figs. 3, 4 and 5 are shown the distribution curves of the negative electrons obtained from a

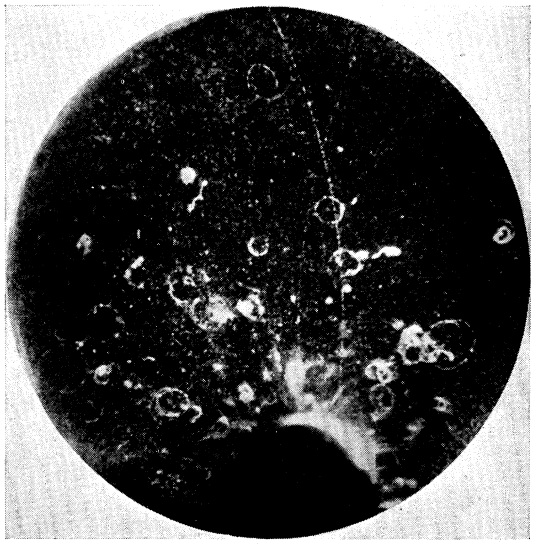

FIG. 6. Example of the pictures obtained with horizontal arrangement. The negative electron (curving to the left) satisfies the requirements for measurement. It is quite certain that the fainter positron track is not associated with this negative electron track.

carbon scatterer 2 mm thick, whose stopping power is about 0.8 Mev for high energy electrons. The electrons plotted in Figs. 3 and 4 were obtained with the horizontal arrangement, and those plotted in Fig. 5 were obtained with the vertical arrangement. Fig. 6 shows an example of the tracks obtained with the horizontal arrangement. Negative electrons which were visibly associated with positrons were not included in these plots. It was not possible, however, to exclude all negative members of pairs, but it is estimated that not more than 10 percent of the negative electrons in the above plots are members of pairs. The data obtained may be interpreted in several ways, as follows:

1. Assuming that the groups of electrons indicated are Compton recoil electrons, we can determine the gamma-ray energies by adding 0.25 Mev to the high energy cut-off of each of the peaks. This procedure gives very closely the same values in each of the sets of data: 17, 14.5, and 11.5 Mev, with the possibility of a fourth line at about 8.5 Mev. However, the data below about 10 Mev are not considered reliable because of the presence of some beta-rays from

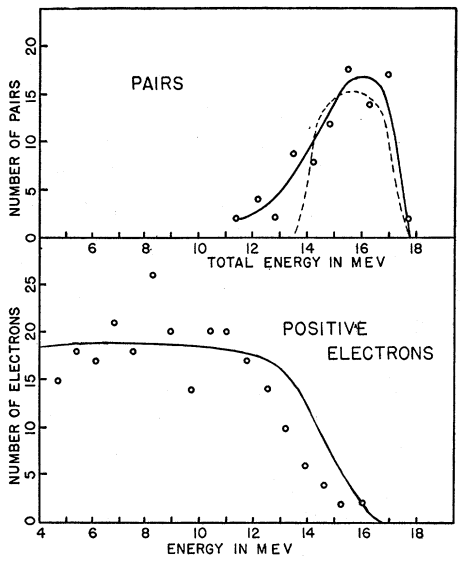

FIG. 7. Upper plot: Pairs ejected from 2 mm carbon by the Li+H[1] radiation, in the horizontal arrangement. $H=2350$ oersteds. The dotted curve is the theoretically expected distribution from a 17 Mev gamma-ray line and 2 mm carbon. Lower plot: Positrons which appear singly or as members of pairs. The curve shows the expected distribution from a 17 Mev gamma-ray line.

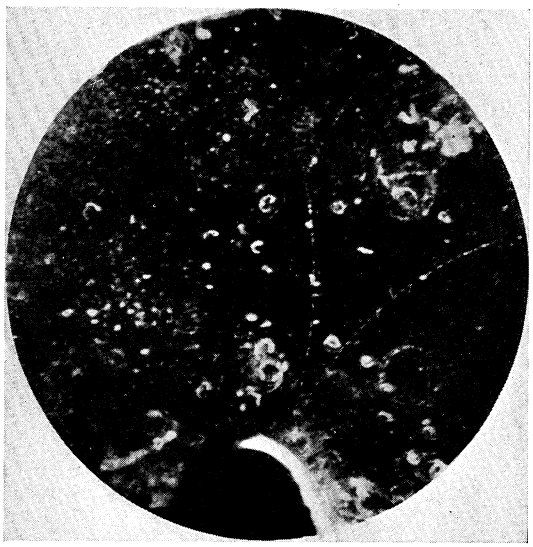

FIG. 8. Pair ejected from the 2 mm carbon scatterer in the horizontal arrangement. By extending the tracks until they intersect it can be shown that the pair originates in the carbon, rather than in the target. This indicates that it is not due to internal conversion.

Li^8, produced by deuteron contamination in the ion beam.

2. Internal conversion, giving rise to discrete beta-ray groups, can take place with very high efficiency, when only a particular kind of nuclear transition is available ($i=0$ to $i=0$). An example of this exists in the Ra C spectrum. In the present experiment such beta-rays from the target could pass through the carbon scatterer and enter the chamber with only about 0.8 Mev loss in energy. It seems unlikely that several lines could be due to this cause; nevertheless, an investigation of this possibility is being made.

3. It may be suggested that nearly all of the primary radiation has an energy of 17 Mev and that the electrons of lower energy are due to softened radiation, to *Bremsstrahlung*, or are electrons which have suffered large energy losses. It would be difficult to reconcile this hypothesis with (a) the sharpness of the peaks, (b) the fact that the same distribution is obtained with two quite different experimental arrangements, (c) the relatively small number of tracks (20 percent of the total) which do not appear to originate in the carbon scatterer, and (d) the fact that the ratio of positive to negative electrons changes roughly in the expected manner with the atomic

number of the scattering material used. This latter point was checked by replacing the carbon scatterer with a 0.7 mm brass scatterer. If the lower energy tracks were produced in the chamber walls the ratio of positives to negatives would not be sensitive to the material in the scatterer.

Pairs from Li+H[1]

Because of the low atomic number of carbon, which was the scattering material used, the amount of data obtained on pairs was smaller than that obtained on recoil electrons. A plot of 95 pairs obtained with the horizontal arrangement is shown in Fig. 7. Examples of the pairs obtained are shown in Figs. 8 and 9. In addition to pairs produced in carbon, there is the possibility that the plot includes some pairs produced by internal conversion in the target. The spreading in the distribution which results from the thickness of the scatterer and errors in measurement is expected to be roughly twice the spreading in the recoil electron plots, since two electron energies must be added. A dotted curve is shown in Fig. 7 to indicate the distribution of pairs which would be expected from a 17 Mev gamma-ray falling upon a 2 mm carbon scatterer, with an average error in measurement of 0.5 Mev. It is quite definite from this distribution that the majority of the pairs are produced in the carbon scatterer rather than by internal conversion in the lithium target, for if the distribution were due predominantly to internally converted pairs, one would expect the distribution to be an error curve with its center at 15 Mev. The dotted curve apparently accounts for the majority of the pairs observed. At most, about 20 percent of the pairs could be attributed to radiation below 17 Mev. These results are in good agreement with those obtained by Delsasso, Fowler and Lauritsen.[2, 3]

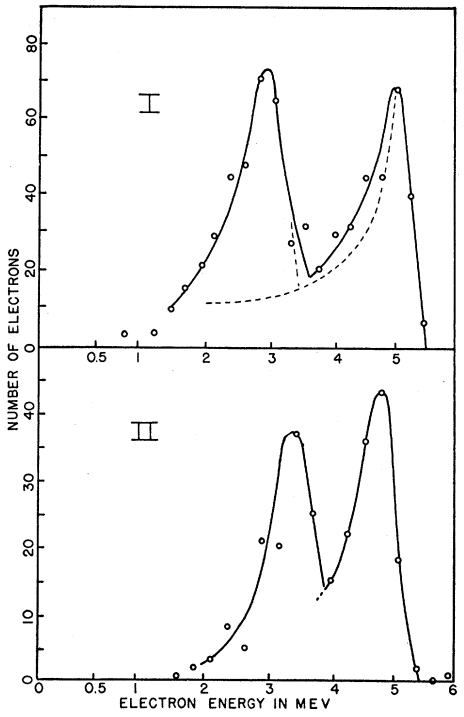

FIG. 10. Negative electrons produced by the gamma-radiation from F+H[1]. I: Horizontal arrangement of Fig. 1, 1.5 mm carbon scatterer. II: Collimated gamma-ray beam falling upon a 1.5 mm carbon sheet placed across the center of the chamber. $H=1850$ oersteds.

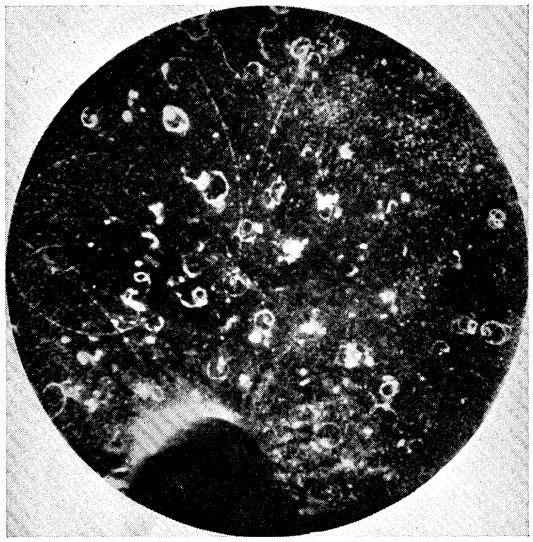

FIG. 9. A pair which originates in the gas in the cloud chamber. Its total energy is 17.1 Mev, with an uncertainty due to measurement and fluctuation in the magnetic field of at least ±0.5 Mev. One pair of this kind gives a good approximation to the quantum energy of one of the gamma-ray lines, because it suffers no absorption.

Positrons from Li+H[1]

In order to show that the distribution of electrons is not fortuitous, and also to get an independent check on the upper limit of the gamma-ray spectrum all the positives obtained in both arrangements were measured and plotted

on a common energy scale in Fig. 7. The criteria for selecting and measuring them were the same as for the electrons except that both associated and unassociated positives were counted. It is evident that the distribution shows no line structure and has a cutoff value of about 16 Mev. According to the theory of pair formation this places an upper limit of 17 Mev on the spectrum, a value in good accord with that obtained with pairs and recoil electrons.

Judging from the distribution of pairs, this distribution of positrons should be consistent with that expected from a 17 Mev line. To test this point we have plotted the theoretical distribution of positrons for 17 Mev gamma-radiation falling on 2 mm of carbon. This curve is also shown in Fig. 7. It appears that the experimental distribution is in fair agreement with this curve if allowance is made for the fact that there is some tendency to discriminate against the higher energy tracks. However, it is impossible to decide definitely from this data whether or not the positron distribution is due entirely to the 17 Mev line.

Negative electrons from $F+H^1$

The upper curve in Fig. 10 shows the distribution of negative electrons obtained by bombarding a crystal of calcium fluoride with 400 kv protons, using the horizontal chamber arrangement of Fig. 1. The scatterer in this case was 1.5 mm of carbon. The distribution indicates two gamma-ray lines, at 5.7 and 4.0 Mev. The energy of the higher line is in good agreement with the recent results of Delsasso, Fowler and Lauritsen,[8] who investigated both the pairs and the negative electrons ejected from sheets of material in the center of a cloud chamber. Their results do not, however, show the presence of the lower line. Because of this discrepancy we carried out an experiment using an arrangement similar to theirs; a sheet of carbon 2 mm thick was placed across the center of the cloud chamber, and gamma-radiation, collimated by a lead channel 15 cm long was allowed to fall upon the center of the carbon sheet. The negative electrons originating in the carbon gave the lower curve in Fig. 10. This is in substantial agreement with the curve obtained by the other method, although it falls off more rapidly at the low energies. The latter is undoubtedly due to the difference in the geometry involved in the two methods. The number of pairs obtained was too small, with either arrangement, to give any indication of the distribution of pairs.

Since the excitation curves of Herb, Kerst, and McKibben[10] indicate the possibility of a second resonance level at about 600 kv, we made a separate investigation of the spectrum of recoil electrons at a bombarding voltage of about 750 kv. The resulting distribution curve revealed the same two lines; consequently there appears to be no appreciable dependence of the spectrum upon bombarding voltage between 400 and 750 kv. However, it is possible that the molecular ions of 656 kv may completely mask the effect of a higher resonance level.

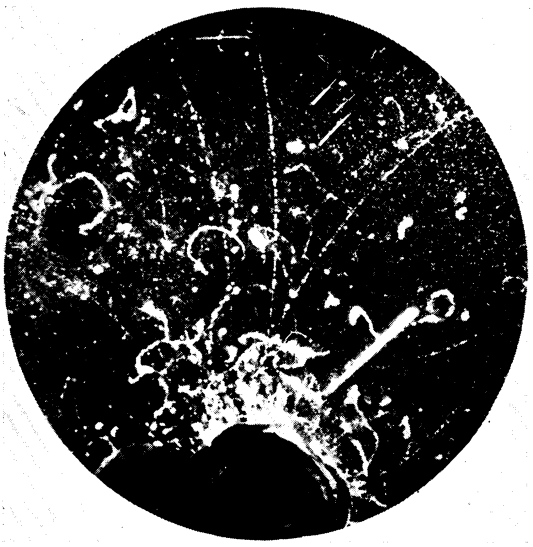

FIG. 11. Example of positive and negative electrons produced by internal conversion of the $F+H^1$ radiation into pairs. Negative electrons curve to the right. $H=820$ oersteds.

Internal conversion of the $F+H^1$ radiation

The well in the cloud chamber shown in Fig. 1 was replaced with a very thin aluminum tube (0.1 mm wall thickness). A thin target was made by depositing powdered CaF_2 upon a piece of 0.05 mm aluminum, and was sloped toward the chamber as shown in Fig. 1. An abundant emission of pairs was observed when the target

[10] Herb, Kerst, and McKibben, Phys. Rev. **51**, 691 (1937).

was bombarded with 400 kv protons. The ratio of negatives to positives, which was 15 to 1 in the previous experiment (carbon scatterer) now became 2 to 1. An example of the photographs obtained is shown in Fig. 11, and energy distributions of the pairs, positive electrons and negative electrons are shown in Fig. 12. The extreme sharpness of the peak in the pair distribution at 5.7 Mev should be noted. Because the pair receives the entire energy of excitation of the nucleus, and because there is practically no material in the path to reduce the energy of the pair, this proves an excellent means of measuring the energy levels in the excited nucleus. A second peak in the distribution, which may be somewhat doubtful, appears at 4 Mev. Those pairs which fall outside these two peaks most probably result from associating, in the measuring process, positive and negative electrons which are not members of the same pair. The average angle between the directions of emission of the members of a pair increases rapidly as the energy of the pair decreases. This makes it much more difficult to recognize pairs belonging to the lower line than to the upper line, and therefore the relative intensities in the plot are distorted.

The plot of negative electrons includes negative members of pairs and also recoil electrons from the small amount of aluminum surrounding the target. A part of the area under the curve is shaded to suggest what portion of the tracks might be negative members of pairs. The maximum at about 1.2 Mev is rather higher than expected. Judging from Fig. 10 there is probably no strong gamma-ray of this energy. There is, however, the possibility that this is a discrete beta-ray group from internal conversion. From a consideration of the ratio of the number of recoil electrons to the number of negative (or positive) members of pairs, it is estimated that the efficiency of production of internal conversion pairs is of the order of 1 pair per 10^3 gamma-rays. This is in good agreement with the theoretical predictions.[11]

It is worth pointing out here that the above experiments in which the carbon scatterer was removed furnish good proof that the origin of the tracks counted is not uncertain in the experimental method described.

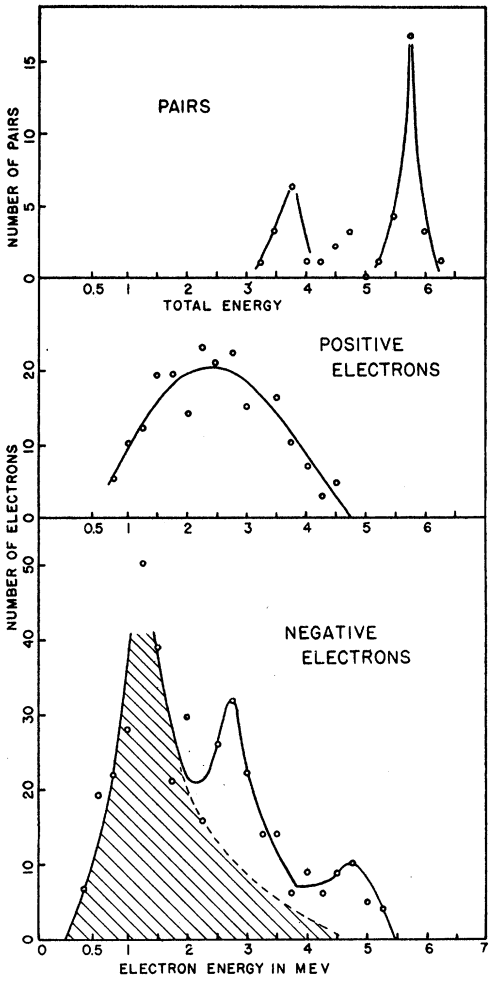

FIG. 12. Pairs, positive electrons and negative electrons obtained with only 0.1 mm aluminum between the target and the cloud chamber. The plots of single electrons include both associated and unassociated members of pairs. $H=820$ oersteds.

DISCUSSION

Origin of the radiation

Detailed discussions of the possibilities for the origin of the $Li+H^1$ radiation have been given by several authors.[12] It is agreed, from the standpoint of energy available, that one of the two reactions

[11] Oppenheimer and Nedelsky, Phys. Rev. **44**, 948 (1933); Uhlenbeck and Rose, Phys. Rev. **48**, 211 (1935); Jager and Hulme, Proc. Roy. Soc. **148**, 708 (1935).

[12] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **48**, 125 (1935); Hafstad, Heydenburg and Tuve, Phys. Rev. **50**, 510 (1936).

$$Li^7+H^1\rightarrow Be^{8*}\rightarrow Be^8+\gamma\rightarrow He^4+He^4+\gamma \quad (1)$$

$$Li^7+H^1\rightarrow He^{4*}+He^4\rightarrow He^4+He^4+\gamma \quad (2)$$

is responsible for the radiation; the only question is whether the radiation comes from Be^{8*} or He^{4*}. It is also clear that the radiation so far studied is associated with the first proton resonance level, 440 kv. The recent discovery by Lewis, Burcham and Chang[13] of a continuous alpha-particle group which is probably due to the reaction

$$Li^8\rightarrow Be^{8*}+e^-\rightarrow He^4+He^4+e^- \quad (3)$$

indicates that those levels in Be^8 which are permitted to disintegrate into two alpha-particles are extremely broad. If reaction 1 is responsible for the gamma-radiation, some lines might arise from transitions to lower states of Be^8 which are permitted to disintegrate into two alpha-particles. Such lines would be very broad. Since the 17, 14.5 and 11.5 Mev peaks in the negative electron distribution which we have obtained are almost exactly of the width expected from the Klein-Nishina scattering formula, it seems unlikely that these particular lines arise from transitions of this kind. Theory predicts[14] the existence of many levels in Be^8, and there is therefore no particular difficulty in accounting for all the observed radiation by means of reaction 1. Reaction 2 would give rise to sharp lines, but brings up at least two difficulties: First, the alpha-particle is not expected, on theoretical grounds, to possess more than one real excited level.[15] Second, unless the $He^{4*}+He^4$ were formed with an extremely small amount of kinetic energy, the peak in the excitation curve (proton energy) would be excessively broadened. This is known experimentally to be very narrow: its half-width is of the order of 10 kv.

Reactions analogous to those for $Li+H^1$ have been put forward to account for the gamma-radiation from $F+H^1$.

$$F^{19}+H^1\rightarrow Ne^{20*}\rightarrow O^{16}+He^4+\gamma, \quad (4)$$

$$F^{19}+H^1\rightarrow O^{16*}+He^4\rightarrow O^{16}+He^4+\gamma. \quad (5)$$

Here the question is whether the radiation comes from Ne^{20*}, O^{16*} or He^{4*}. He^4 may be eliminated tentatively on theoretical grounds because no levels of such low energy are expected. About 9 Mev is released in the over-all reaction, in both 4 and 5. If the energy of the highest line (5.7 Mev) is subtracted, more than 3 Mev is left to appear as kinetic energy of the $O^{16}+He^4$. The consequent short lifetime for separation of the O^{16} and He^4 would broaden the gamma-ray line in 4, and would broaden the peak in the excitation curve (proton energy) in 5, by 0.5 to 1 Mev. Such a breadth certainly does not exist in the excitation curve, and probably does not exist in the gamma-radiation. By subtracting the sum of the gamma-ray energies (5.7+4 Mev) from the total energy available, and allowing for some errors in the data, we find that the $O^{16}+He^4$ would have about zero kinetic energy, and the difficulty of the line breadth would disappear in both 1 and 2. A third possible reaction is that Ne^{20*} radiates to its ground state by several successive transitions. Here about 13 Mev is released, and it is not easy to see how the observed gamma-ray lines fit into such a scheme. One thing may be concluded with some confidence: The emission of a group of alpha-particles of any considerable energy, associated with the observed gamma-radiation is excluded because of the broadening effect it would necessarily have on the gamma-ray lines or on the peaks in the excitation curve.

Errors in the determination of energies

A summary of the errors involved in the present method can be given as follows:

1. The absolute value of the magnetic field intensity was determined both by means of a flip coil and by calculation from the geometry of the coils and the current. The error in this is not greater than 3 percent.

2. The average deviation of the magnetic field strength from the mean value during all the measurements was 1 percent.

3. The average error in the measurement of tracks was found by actual test to be not more than 2 percent.

4. No estimate of the error caused by scattering in the air has been made, but for electrons of such high energy this error is certainly much smaller than the other errors involved.

[13] Lewis, Burcham and Chang, Nature **139**, 24 (1937).
[14] Feenberg and Phillips, Phys. Rev. **51**, 597 (1937).
[15] Feenberg, Phys. Rev. **49**, 328 (1936).

5. Because nonstereoscopic pictures were used, a small error is involved due to the angle a track may make with the plane of the cloud chamber. From the criteria used in selecting tracks for measurement, the angle with the plane of the chamber is estimated to be less than 10°. Therefore, the maximum error introduced is 1.5 percent.

All of the errors mentioned, except the first, are of the kind which tend only to broaden the peaks. The first may introduce an error in the energy scale. For lithium, the most probable energies of the lines are 17, 14.5, 11.5 and possibly 8.5 Mev, with a maximum absolute error in the energy scale of about 1 Mev. For fluorine the most probable energies are 5.7 and 4 Mev, with a maximum absolute error of about 0.3 Mev.

Relative intensities

While the energies of the gamma-ray lines can be determined with some confidence from the recoil electron distributions, estimates of the relative intensities of the lines are less certain. The difficulty arises from a number of causes:

(1) Each line contributes some tracks to neighboring lines which lie at lower energy.

(2) There is some tendency to discriminate against tracks of large radius of curvature because they must be of greater length to afford accurate measurement. This is evidenced by the fact that the 17 Mev peak appears stronger in Fig. 4 than in Fig. 3. The magnetic field strength was greater in Fig. 4 than in Fig. 3.

(3) The angular distribution of recoil electrons emerging from the scattering material depends upon the energy of the gamma-ray line producing them, because of both the Klein-Nishina angular distribution, and scattering of the electrons in the material.

(4) An appreciable number of electrons fail to emerge at all from the scattering material, and this number is dependent upon the energy of the electrons. Whether this effect is due to multiple scattering or to a new process by which electrons are absorbed is not yet known, but it has been noticed by several investigators.[16]

It will be noticed, both in the case of lithium and of fluorine that the various sets of data do not show the same relative intensities. This is undoubtedly because of the difference in geometry in the various cases and, to some extent, because of the different magnetic field strengths used. The simplest method of estimating the relative intensities is to determine the relative numbers of tracks under the peaks (the average of all the data is used) and to apply a correcting factor for the variation in cross section for Klein-Nishina scattering as a function of energy. In this way we obtain the relative intensities 2 : 4 : 3 for the 17, 14.5 and 11.5 Mev lines of lithium, and 5 : 2 for the 5.7 and 4 Mev lines of fluorine.

Because of the fact that the cross section for pair formation increases with energy, while the cross section for Klein-Nishina scattering decreases with energy, the higher energy lines in the spectrum tend to appear relatively stronger in the pair distribution than in the negative electron distribution. The corrections of this kind which we are able to apply to the distributions at present do not seem to be sufficient to bring the pair and negative electron distributions into entire agreement. Although our data on pairs are not so extensive as those of Delsasso, Fowler and Lauritsen, they are in good agreement with theirs. It is our opinion at present that a further investigation of the number of electrons which are lost before emerging from the scattering material may be of help in explaining the apparent contradiction between the pair and the negative electron distributions.

The authors wish to express their gratitude to the Rackham Endowment Fund for the support of this work.

[16] Turin and Crane, Phys. Rev. **52**, 63 (1937).

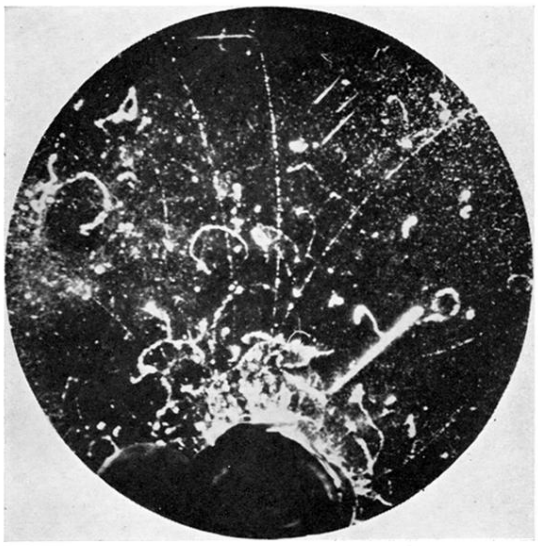

FIG. 11. Example of positive and negative electrons produced by internal conversion of the $F+H^1$ radiation into pairs. Negative electrons curve to the right. $H=820$ oersteds.

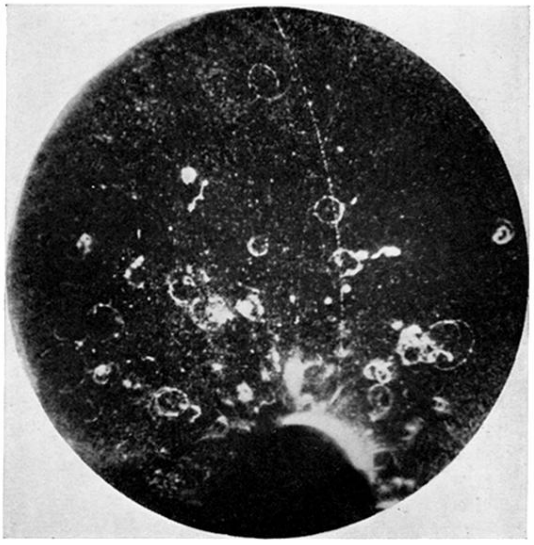

FIG. 6. Example of the pictures obtained with horizontal arrangement. The negative electron (curving to the left) satisfies the requirements for measurement. It is quite certain that the fainter positron track is not associated with this negative electron track.

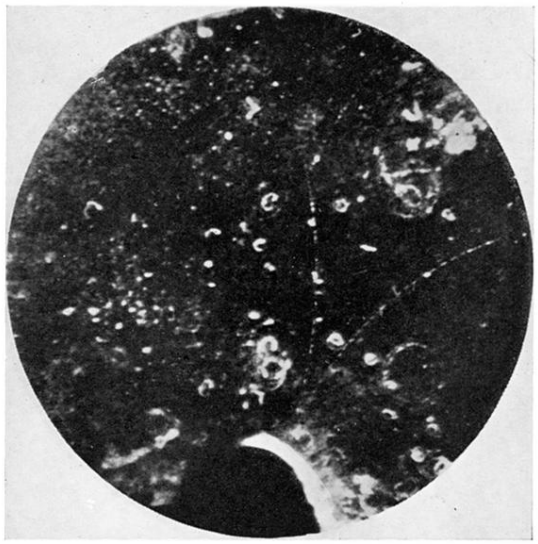

FIG. 8. Pair ejected from the 2 mm carbon scatterer in the horizontal arrangement. By extending the tracks until they intersect it can be shown that the pair originates in the carbon, rather than in the target. This indicates that it is not due to internal conversion.

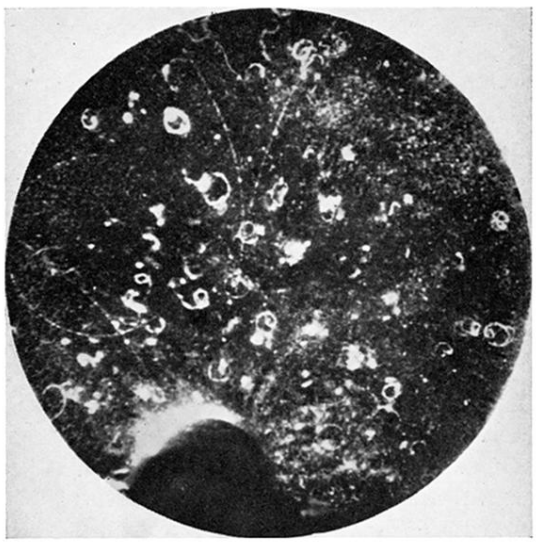

FIG. 9. A pair which originates in the gas in the cloud chamber. Its total energy is 17.1 Mev, with an uncertainty due to measurement and fluctuation in the magnetic field of at least ± 0.5 Mev. One pair of this kind gives a good approximation to the quantum energy of one of the gamma-ray lines, because it suffers no absorption.