# The Absorption of High Energy Electrons

Thesis by

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# Abstract.

A study of about 10,000 photographs of cosmic ray electron tracks, taken by means of the counter controlled cloud chamber -magnet apparatus, has been made with the purpose of observing the interaction of these high energy particles with atomic nuclei and their external electrons. Four main types of interaction are known to occur, viz. (1) Ionization and excitation of atoms. (2) Large energy transfers to extranuclear electrons. (3) Production of positron-negatron pairs. (4) Radiation, presumably in nuclear encounters. Data obtained in the present investigation supply a means for making independent qualitative estimates of the contributions made by each of the above four processes to the energy lost per cm. in lead by cosmic ray electrons. It is found that the loss by ionization and production of high energy negatron secondaries, as well as the distribution in energy among these secondaries, are in rough agreement with existing theory, except that the ionization does not apparently increase with energy as the theory requires. 166 direct measurements of the loss of energy in a 0.35 cm. lead plate, undergone by electrons in the energy range below 150 mev. show that these losses are subject to very large fluctuations which must necessarily be attributed to radiation of high energy photons, and that these radiative losses constitute the major part of the energy loss in lead. The mean total loss per cm. for a group of electrons with a mean initial energy of 28 mev. turns out to be about 51 mev., and 90 mev. for a group with a mean initial energy of 124 mev. A comparison between these values and those computed theoretically by Bethe and Heitler, viz. 60 mev./cm. and 230 mev./cm. respectively,

indicates at least a qualitative agreement between theory and experiment in the low energy range, but a complete breakdown of theory in the range above a hundred mev.

## Introduction and Experimental Procedure.

A discussion of the processes involved in the absorption of cosmic ray electrons has been given at the London Conference (1934) by C.D. Anderson and the writer[1]. This paper contains a review of some of the results presented there, and the results of some further investigations which have been made jointly by Anderson and the writer. The new data consist of a set of about 10,000 photographs (about 7500 of which showed tracks), taken with the counter-controlled cloud chamber apparatus which was designed in its original form by Anderson and Millikan, and later adapted to counter control by Anderson with the assistance of Pickering and the writer. All of these new data were taken with a lead plate 0.35 cm. thick placed horizontally across the middle of the chamber, and with the magnetic field set at 46oo gauss, a value adequate to permit energy measurements to an accuracy of about 10 percent in the range below 50 mev. by the method of fitting ruled circles to track photographs while they are projected on a screen, and adequate to estimate energies to within 30 percent by the same method, up to about 200 mev. (mev. means million e-volts).

Four main types of interaction involving losses of energy are known to occur between high energy electrons ($E > 2mc^2$) and the matter they pass through, namely: (1) Excitation and ionization of atoms; (2) Transfers, by close encounters, of large amounts of energy to atomic electrons; (3) Production, in nuclear encounters, of positron-negatron pairs; (4) Radiation, presumably in nuclear encounters. The present set of data, containing 4577 traversals of electrons (with energies $>$ 200 mev.) through the 0.35 cm. lead plate, from which the incident particles occasionally eject secondaries, and 166 traversals (actually, 46 of these were apparently stopped by the Pb; see Section IV) of electrons with energies below 150 mev., whose losses of energy could be measured directly, permit independent estimates of the contributions to energy loss made by 1, 2, 3, above, and a determination of the total mean energy loss per cm. in Pb in the energy range below 150 mev., which then permits an estimate of the contribution made by (4). A discussion of the experimental data in relation to the above four processes follows in order.

## I. Excitation and Ionization.

When a rapidly moving charge passes close to an atom there is a certain probability that some energy will be transferred. This probability is zero for a transfer less than the lowest excitation potential of the atom; it becomes very high, depending upon the distance of closest approach to the atom, for transfers just sufficient to excite, or just sufficient to ionize the atom by removal of an electron. The probability then dies off rapidly, and for transfers whose magnitudes are two or three times the mean ionization potential of the atom, is very small, depending only on the closeness of approach to the individual atomic electrons. The energy loss per cm. due to atomic collisions can thus be divided with considerable sharpness into two parts: (1) Transfers which either excite the atom or ionize it, leaving the removed electron with an excess kinetic energy which, on the average, is not greater in order of magnitude than the mean ionization potential of the atom; (2) Transfers large compared to the mean ionization potential, in which the atomic electrons behave as if they were free. The amount contributed to energy loss in the transition region between (1) and (2) should be small compared to both (1) and (2). It is a process of the type (1) to which we shall refer loosely as ionization, or inelastic collisions; and a process of the type (2) as the formation of negatron secondaries, or simply elastic collisions. Both of these processes have been experimentally investigated by Williams and others[2], with both fast and slow beta-rays.

The number of ion (-pairs) per centimeter formed by direct action on atoms by the moving charge is generally referred to as primary specific ionization. Some of the primary negative ions (electrons) will have sufficient energy to form additional ions by collisions with atoms, and the totality of such secondary ions plus the primary ones will be referred to as total (specific) ionization. The primary ionization of high energy electrons may be observed directly on very sharp cloud tracks which have been formed before the ions have had time to diffuse away from the axis of the track. Each primary ion then appears as a single drop, or a very small unresolved cluster of drops. Total ionization may be observed on cloud tracks which have been formed after ( in standard air, about $\frac{1}{4}$ sec. ) the ions have diffused away from the axis.

There are two principal methods for estimating the contribution to specific energy loss which is made by ionization along cosmic ray electron tracks. The first consists in counting the total number of drops formed per cm. along a diffuse cloud track. A knowledge of the average energy expended per ion then enables one to estimate the energy loss per cm. A determination of the energy expended per ion (-pair) has been made by Eisl[3] for cathode rays with energies from 10 to 60 ekv., and he found that in this range of energy and in standard air, the total initial energy divided by the total number of ions produced was constant and equal to 32.2 volts per ion. Anderson and the writer have made counts of the total number of ions produced per cm. along diffuse tracks of cosmic ray electrons with energies in the range above about 30 mev. (See fig. 1) and have found a lower limit of 31 ion-pairs per cm., which apparently does not depend on the energy of the particle in the range considered. A determination of the actual number is subject to rather wide uncertainties because of the difficulty of counting the numbers of drops occurring in clusters due probably to fluctuations in the primary ionization. These clusters may add something like 50 percent to the above counts, and if we assume that Eisl's value of the mean energy loss per ion for cathode rays can be applied to electrons in this energy range (an enormous extrapolation, but one which has some theoretical justification, at least for approximation purposes) then we find as an estimate of the energy loss by ionization and excitation, $45 \times 32.2 \sim 1500$ ev./cm. in standard air. From this we can make a pseudo-experimental estimate of the energy loss by

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ionization in other heavier substances if we multiply by the ratio of the number of electrons per cm.$^3$ in the heavier substance to the number in air, and also by a theoretical factor, which is slightly less than unity, to take account of the tighter binding of the electrons in the heavier substance. In lead this factor is 0.87 for a 50 mev. electron, and 0.91 at 1000 mev. This leads to an estimate of 9 mev/cm. for the ionization energy loss in lead.

A second more direct method of determining the ionization loss in lead (applicable when the energy $\lesssim$ 50 mev.) is to make use of direct measurements of the energy loss in lead plates. It has been shown by Anderson and the writer that the total loss in lead is subject to large fluctuations due mainly to radiation losses (See Sec. IV), and partly to the occasional formation of high energy secondaries. The loss by ionization is however, a consequence of a very large number of collisions per centimeter, each collision contributing a small fraction of the total loss in a plate of the order of a millimeter or greater in thickness, and should therefore be a fairly definite quantity, not fluctuating widely from its mean value. If then, we observe a large number of individual cases of energy loss, the distribution of these observations, when plotted against energy loss per cm. should have an abrupt drop on the side of low losses, the cut-off region indicating approximately the magnitude of the ionization loss. Elastic collisions should produce on the average, in 0.35 cm. of lead, about 200 secondaries in the range from 1000 ev. to 10,000 ev. which contribute 1.5 mev./cm. to the mean specific energy loss (It is necessary here to anticipate some theoretical results given in Section II; see table 4), and 20 more in the range from $10^4$ to $10^5$ ev. contribute another 1.5 mev./cm. The contribution of the

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first group should be practically non-fluctuating; that of the second should fluctuate considerably. Even with a large number of observations then, we should expect the observed minimum specific energy loss in our lead plate to be about 2 mev./cm. higher than the ionization loss as it has been defined. This correction is only an approximate one and tacitly assumes the validity of the theory of elastic collisions for the above range of secondary energies.

With the 0.35 cm. lead plate there have been made 11 fairly accurate measurements on electrons in the range below 40 mev. which gave losses below 30 mev./cm. These are plotted as separate points in fig. 1a. The lowest measured value is 10 mev./cm., and there are three measurements between 10 and 13. The uncertainty in the lowest one is about 3 mev., so allowing 2 mev. for low energy secondaries we arrive at an estimated upper limit of 11 mev./cm. in lead for the ionization loss of a 20 mev. electron.

Nine cases of measurable energy loss in thick lead plates (~1 cm.) have been observed. These have already been published by Anderson and the writer, and are listed in table 1. The lowest value listed, 18 mev./cm., is subject to too great an uncertainty because of the high energy of the particle and the corresponding difficulty of measuring a small loss accurately, but we may take the first value in the table, 20 mev./cm. (±~8) as an upper limit to the ionization loss for a 100 mev. electron. This estimate is likely to be lowered by further measurements. A summary of the conclusions about energy loss by ionization, which can be drawn from data so far obtained is presented in table 2.

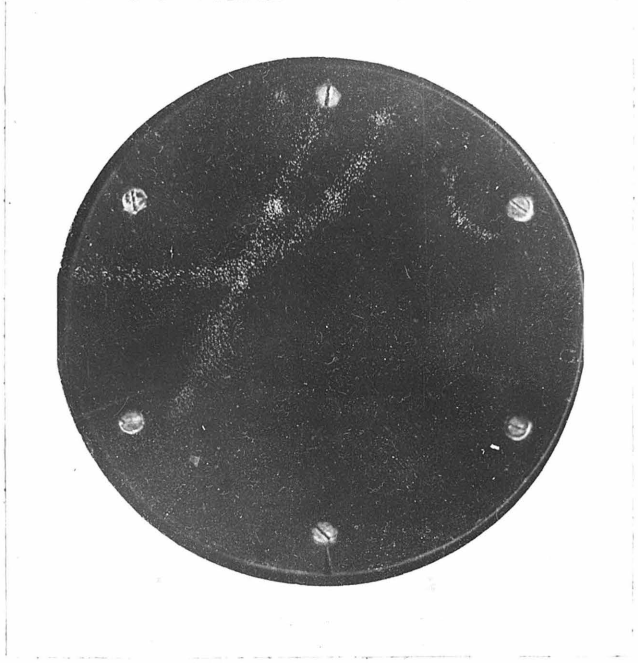

Fig. 1.

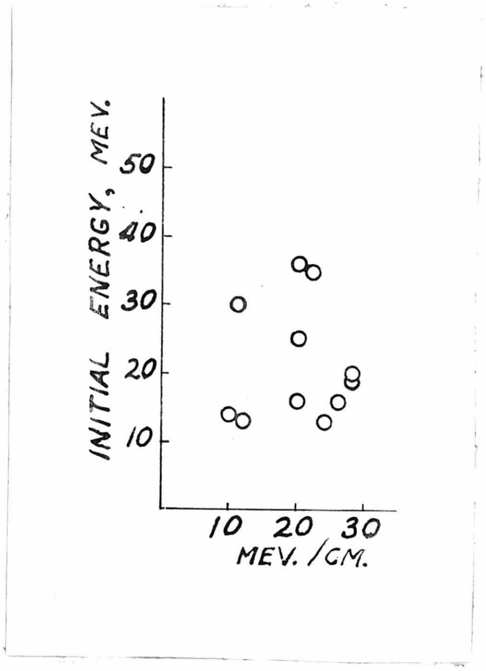

Fig. 1 a.

Fig. 1. Example of diffuse tracks suitable for counts of total ionization. The width of these tracks corresponds to a time of passage about $\frac{1}{4}$ sec. before the expansion took place. The electrons that are released by ionization quickly attach themselves to neutral molecules, so that both positive and negative ions have the same diffusion rate.

Fig. 1a. Measurements of small energy losses in 0.35 cm. of lead, by electrons with initial energies below 40 mev., used for estimating the minimum loss in lead. Initial energy is plotted against energy loss per cm. Five measurements in this range which were included in estimating over-all mean energy loss, have been left out of this group because the tracks were too short to be accurately measurable.

Table 1.

Energy loss per centimeter in lead. (Measured in plates ~1 cm. thick)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Initial energy | 113 | 240 | 220 | 38 | 63 | 200 | 140 | 106 | 110 | mev. |
| Loss/cm. | 20 | 18 | 55 | 29 | 57 | 68 | 120 | 80 | 65 | mev./cm. |

Table 2.

Energy loss by ionization.

| Energy of particle | Air N.T.P. | | Lead | | |
|---|---|---|---|---|---|
| | Ion counts | Theor. | Ion counts in air | Direct meas. in Pb | Theor. |
| 20 mev. | 1500 ev/cm | 1620 ev/cm | 9 mev/cm. | $\lesssim$ 11 mev/cm. | 9.3 mev/cm |
| 100 " | " | 1930 | " | $\lesssim$ 20 | 11.4 |
| 1000 " | " | 2370 | " | — | 14.4 |

The theoretical values have been computed from a formula given by Carlson and Oppenheimer[4] for the ionization loss:

$$\text{Loss/cm. (ion.)} = \frac{\pi e^4 n}{m^2 c^4} \log \frac{4\mathcal{E}_0^2}{\mathcal{E}_1}$$

where n is the number of electrons/cm.$^3$; $\mathcal{E}_1$ the mean ionization potential, and $\mathcal{E}_0$ the energy of the particle, both expressed in units of $2mc^2$, or about 1 mev. The value of $\mathcal{E}_1$ has been taken to be

$10^{-4}$ for air and 0.0011 for lead (See next section).

## II High energy negative secondaries.

The formation of a high energy negative secondary by an electron is a relatively rare event whose probability depends strongly on the energy of the primary particle when the secondary receives a large fraction of the initial primary energy. Attention has been confined therefore, to those primary particles whose energies lie in the range above about 200 mev., and that this provides a basis on which to make a partial comparison between the results of experiment and current theory will be seen below. In the present set of data there are 4577 traversals of such primary particles through 0.35 cm. of lead from which there have been observed:

101 single negative secondaries with energies > 1 mev.
4 double " " " "
2 single positive " " "
16 positron-negatron pairs (incl. 1 with (-) component < 1 mev.
1 shower of 2 positrons and 2 negatrons.

The rarity of single positive secondaries compared to single negative ones is considered justification for the assumption that practically all the single negatron secondaries arise from close encounters with atomic electrons. The expected number of double negatives, on the assumption that a single event can give rise to only one, is 1.3 per 4577 traversals, compared with the observed 4. The doubles have, however, been included in the negative secondary distribution, and it makes practically no difference in the result whether they are included or not. Examples of negative secondaries are given in figs. 2 and 2 a.

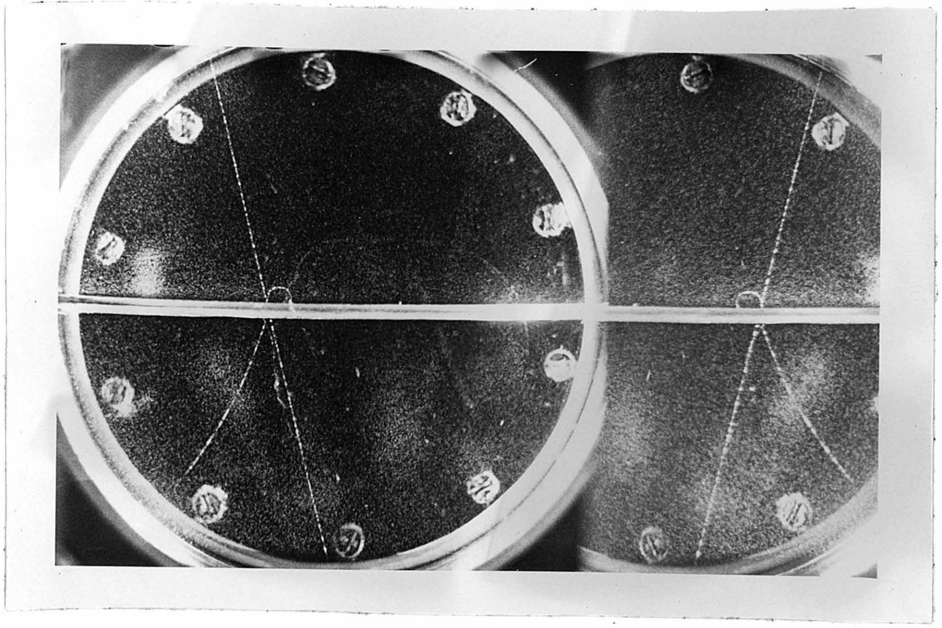

Fig. 2.

A high energy electron ejects a negatron secondary from a 0.35 cm. lead plate; energy, 16 mev. Another secondary with an energy of about 0.3 mev. is scattered backward from the top surface of the plate. The right hand view is a mirror image used for stereoscopic purposes.

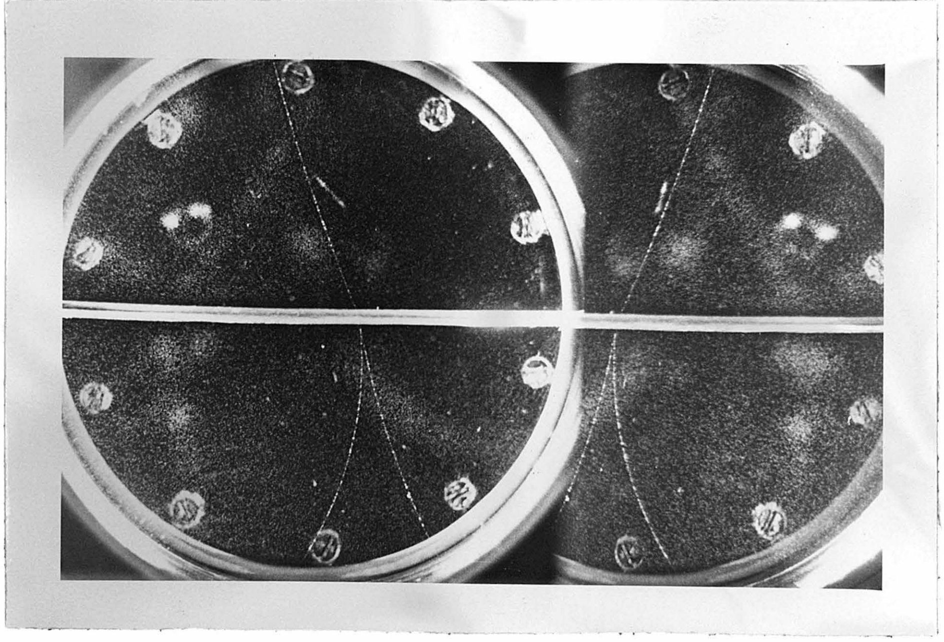

Fig. 2 a.

An 83 mev. positron loses 53 mev. in traversing 0.35 cm. of lead. Part of this is given to an extranuclear electron, which emerges with an energy of 14 mev. A large portion of the remaining loss was probably due to radiation.

The theoretical probability that a primary electron with energy $\varepsilon_0$ will produce a negative secondary with energy $\varepsilon$ in $d\varepsilon$, in traversing a (thin) plate of thickness t containing n atomic electrons/cm.$^3$, has been given by Carlson and Oppenheimer:

$$\underset{\times d\varepsilon}{p(\varepsilon,\varepsilon_0)} = \frac{\pi e^4 n t}{2m^2c^4}\cdot\frac{\varepsilon_0^4+\varepsilon^4+(\varepsilon_0-\varepsilon)^4}{\varepsilon_0^2\,\varepsilon^2(\varepsilon_0-\varepsilon)^2}\,d\varepsilon.$$

where e, m are the electronic charge and mass, and all energies are expressed in units of $2mc^2$, or about 1 mev.: e.g. $\varepsilon =$ energy of sec/$2mc^2$ In the present investigation we are considering only those primaries for which $\varepsilon_0 \gtrsim 200$, and since for most of these $\varepsilon_0 \gg 200$, the condition $\varepsilon_0 \gg \varepsilon$ is well satisfied in most cases, and the above formula reduces to

$$p(\varepsilon) = \frac{\pi e^4 n t}{m^2c^4}\cdot\frac{1}{\varepsilon^2}$$

in which form it is independent of the primary energy.

It is now necessary to compute the distribution that should theoretically be observed below a thick plate of material, taking account of the loss in energy of the secondaries before they emerge. The calculation is trivial if we make a few simplifying assumptions: (1) that the primaries traverse the plate normally; (2) that secondaries are ejected parallel to the primaries; (3) that scattering of the secondaries can be neglected; (4) that the range of a secondary can be expressed by the simple relation $R = \alpha\varepsilon$, where $\alpha$ is a constant.

Errors introduced by (1) have been made negligible by choosing only those primaries which traverse the plate at an angle less than 30° from the normal, and then introducing an effective thickness about 7 percent greater than that of the plate used. Assumption (2) introduces only a small amount of error for secondaries above about 10 mev. It can be shown by a simple calculation from the conservation laws for energy and momentum that the angle $\vartheta$ between primary and secondary is given to a close approximation by $\tan\vartheta = \sqrt{\frac{1}{\varepsilon}}$, so that $\cos\vartheta \sim 0.95$ for a 10 mev. secondary and $0.89$ for 5 mev, and the extra distances traversed by the secondaries amount to 5 percent and 12 percent respectively. Assumptions (3) and (4) produce negligible errors in a substance of low atomic number like carbon, but because of scattering and radiation losses, may produce very serious errors in the observed numbers of secondaries, of the order of 50 percent in a heavy material like lead, even for secondaries with energies as high as 25 mev. A complete analysis of these effects is very difficult.

If a secondary with energy $\varepsilon$ is produced at a distance $x$ from the lower surface of a plate of material, its energy on emerging will be $\varepsilon' = \varepsilon - x/\alpha$ ; and if $P(\varepsilon')$ be the probability distribution of secondaries emerging below the plate,

$$P(\varepsilon')\,d\varepsilon' = d\varepsilon'\int_{x=0}^{t} p(\varepsilon' + x/\alpha)\,dx = d\varepsilon'\,\frac{\pi e^4 n}{m^2 c^4}\int_0^t \frac{dx}{(\varepsilon' + x/\alpha)^2}$$

$$P(\varepsilon') = \frac{\pi e^4 n}{m^2 c^4}\cdot\frac{t}{\varepsilon'(\varepsilon' + t/\alpha)}.$$

The theoretical energy distribution $f(\varepsilon)$ of the secondaries observed when the plate is traversed by N primary electrons is them,

$$f(\varepsilon) = \frac{\pi e^4 n}{m^2 c^4}\cdot\frac{Nt}{\varepsilon(\varepsilon + t/\alpha)}.$$

In fig. 3 are shown the experimental data (already published[1]) from 587 traversals of a 1.5 cm. graphite plate (density 2.25), with

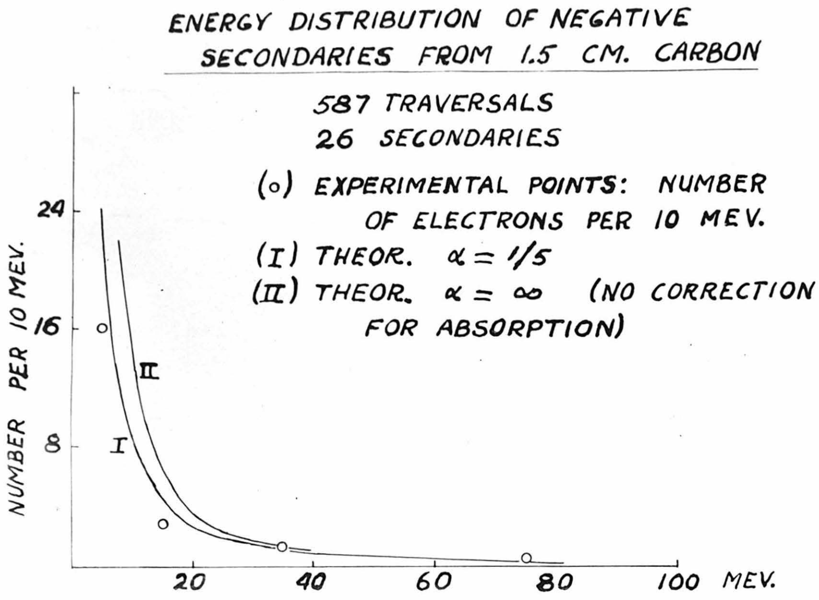
ENERGY DISTRIBUTION OF NEGATIVE SECONDARIES FROM 1.5 CM. CARBON
587 TRAVERSALS
26 SECONDARIES
(o) EXPERIMENTAL POINTS: NUMBER OF ELECTRONS PER 10 MEV.
(I) THEOR. α = 1/5
(II) THEOR. α = ∞ (NO CORRECTION FOR ABSORPTION)
NUMBER PER 10 MEV.
24
16
8
20
40
60
80
100 MEV.
I
II

FIG. 3

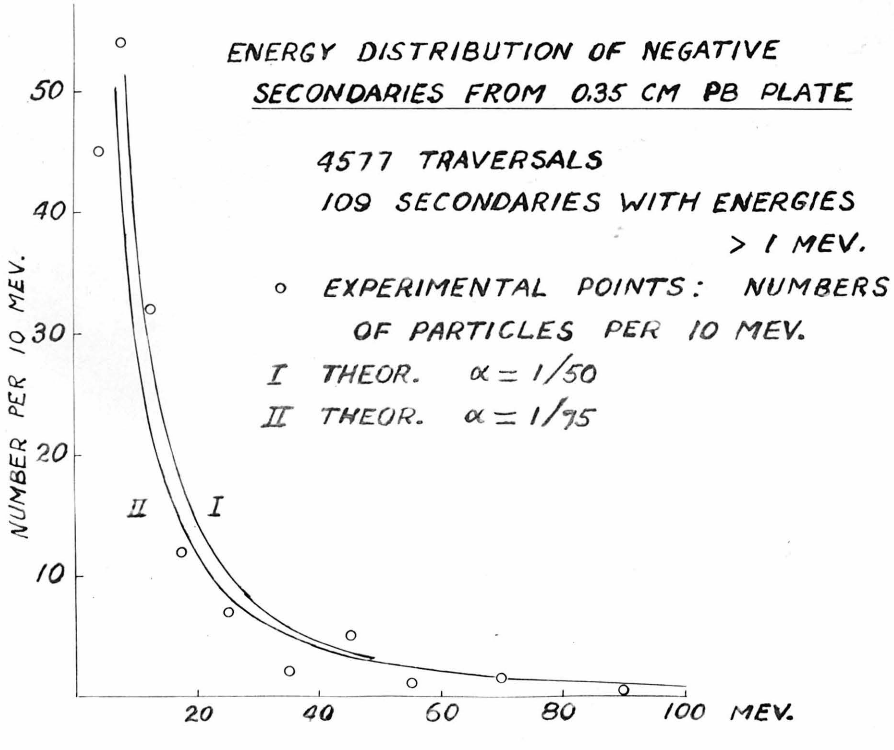
ENERGY DISTRIBUTION OF NEGATIVE SECONDARIES FROM 0.35 CM PB PLATE
4577 TRAVERSALS
109 SECONDARIES WITH ENERGIES > 1 MEV.
o EXPERIMENTAL POINTS: NUMBERS OF PARTICLES PER 10 MEV.
I THEOR. α = 1/50
II THEOR. α = 1/95
NUMBER PER 10 MEV.
50
40
30
20
10
20
40
60
80
100 MEV.
II
I

FIG. 4

the theoretical distribution calculated from the above formula represented by the lower curve; the upper curve is the theoretical distribution as it appears when uncorrected for energy loss. The value of $\alpha$ was estimated from the four available measurements of energy loss in carbon (viz. 6.8, 6.0, 3.5, 3.9 mev/cm.) by electrons with initial energies ranging from 12 to 34 mev. The mean of these is 5.0 mev/cm. and this has been taken as the value of $1/\alpha$ .

The present data from 4577 traversals through a 0.35 cm. lead plate are shown in fig. 4, with the theoretical curves for two values of $1/\alpha$ , viz. 50 mev/cm. for the upper curve and 75 for the lower. The latter value is probably about right for the part of the curve around 50 mev. (See section IV on direct measurements of energy loss in lead). The carbon data are represented by the theoretical distribution, within the uncertainty of experiment over the whole energy range above 5 mev., whereas the lead data are represented rather more closely by theory in the range below 50 mev. than should be expected offhand in view of the approximations that have been made. This can be understood in a qualitative way by observing that the errors introduced in the case of lead by scattering of the secondaries and by the variation of specific energy loss with energy are of like orders of magnitude and tend to cancel one another; that is, the scattering effect might be taken into account by adding a term to $1/\alpha$ which would increase as the energy decreases, whereas the actual energy loss per cm. along the path of the secondary decreases as the energy decreases (See section IV), in a way which is not yet accurately known.

For further comparison between experiment and theory there are given in table 3 the results of both observation and theory on the total numbers of secondaries and the sums of their energies. The first two columns apply to the 0.35 cm. lead data and the last two to the 1.5 cm. carbon data. In the former case only secondaries above 20 mev. have been considered, inasmuch as any comparison between theory and experiment for energies much lower than this must be regarded as completely meaningless because of the scattering and straggling effects already alluded to.

Table 3.

Observed and calculated numbers of secondaries, and their total energies.

| | 0.35 cm. Pb<br>$20 < \varepsilon \leq 120$ | | 1.5 cm. Carbon<br>$5 < \varepsilon \leq 50$. | |
|---|---|---|---|---|
| | Obs. | Calc. $(\alpha = \frac{1}{75})$ | Obs. | Calc. $(\alpha = \frac{1}{5})$ |
| Number of secondaries | 22 | 27 | 10 | 15 |
| Total energy of same secondaries (mev.) | 1085 | 1240 | 193 | 220 |

The data presented above indicate that the theory of the formation of high energy negative secondaries by close encounters with atomic electrons is not far from the truth, and we shall therefore assume it to be valid over the whole range and use it to estimate the contributions to mean energy loss/cm., which are made by secondaries lying in various energy intervals. The mean energy loss/cm. due to secondaries in the energy range $(\varepsilon_1, \varepsilon_2)$ is simply

$$\int_{\varepsilon_1}^{\varepsilon_2} \varepsilon\, p(\varepsilon)\, d\varepsilon = \frac{\pi e^4 n}{m^2 c^4} \int_{\varepsilon_1}^{\varepsilon_2} \frac{d\varepsilon}{\varepsilon} = A \log \frac{\varepsilon_2}{\varepsilon_1} \qquad (A).$$

with $A \equiv \frac{\pi e^4 n}{m^2 c^4}$.

n is, as before, the number of atomic electrons per $\text{cm.}^3$ The mean number of secondaries produced per cm. along the path of the primary, whose energies lie in the interval $(\varepsilon_1, \varepsilon_2)$ is

$$N_{(\varepsilon_1, \varepsilon_2)} = \int_{\varepsilon_1}^{\varepsilon_2} p(\varepsilon)\, d\varepsilon = A\left(\frac{1}{\varepsilon_1} - \frac{1}{\varepsilon_2}\right) \qquad \text{(B)}$$

$A = 0.65$ for Pb, and $0.16$ for graphite.

To obtain the total energy loss due to secondaries, we put in eq. (A) $\varepsilon_2 = \frac{\varepsilon_0}{2}$, where $\varepsilon_0$ is the primary energy ($\frac{1}{2}\varepsilon_0$ because the particle with the lower energy will always be called the secondary), and get

$$\text{Total loss/cm. (transfers} > \varepsilon_1) = A \log \frac{\varepsilon_0}{2\varepsilon_1}$$

If we use the theory of Carlson and Oppenheimer, which is presumably more accurate, and gives a slightly greater interaction when the energy transfer is not a very small fraction of the primary energy, we obtain instead of the above:

$$\text{Loss/cm. (trans.} > \varepsilon_1) = A\left(\log \frac{\varepsilon_0}{2\varepsilon_1} + 0.43\right) \qquad \text{(C)}$$

In table 4 are listed, for 1 cm. of lead, (1) the mean number of secondaries per primary traversal, produced in various energy intervals, and (2) the corresponding contribution to loss in primary energy.

Table 5 summarizes the total contributions to mean energy loss per cm. in lead and in air, as calculated from (C), for various values of primary energy, $\varepsilon_0$. The value which should be taken for $\varepsilon_1$ cannot be specified accurately, but no large mistake will be made by taking it equal to the mean ionization potential. This can be estimated theoretically from a formula due to Bloch,

$$I = 13.5\, Z \text{ volts}$$

where Z is the atomic number, and the constant has been determined semi-empirically by Bethe and Heitler[5]. This gives $\varepsilon_1 \sim 10^{-4}$ (100 volts) for air and $\varepsilon_1 \sim 0.0011$ (1100 volts) for lead.

Table 4.

Mean numbers of secondaries in various energy intervals, and the corresponding contributions to energy loss. Calculated theoretically for 1 cm. of Pb. $(\varepsilon_0 \gg \varepsilon)$

| Interval of secondary energy mev. | | Mean number of secondaries per cm. | Contribution to mean energy loss per cm. |
|---|---|---|---|
| 0.0011 to | 0.01 | 530. | 1.3 mev. |
| 0.01 | 0.1 | 60 | 1.5 |
| 0.1 | ~~10.~~ 1.0 | ~~0.6~~ 6.0 | " |
| 1.0 | 10. | 0.6 | " |
| 10. | 100. | 0.06 | " |

Table 5.

Total mean loss per cm. due to negative secondaries in lead and in air, for various primary energies. (Calculated theoretically from (C))

| $\varepsilon_0$ | Loss/cm. (air) | Loss/cm. (Pb) |
|---|---|---|
| 10. mev. | 1100 ev. | 5.7 mev. |
| 100. | 1320 | 7.2 |
| 1000. | 1540 | 8.7 |
| 10000. | 1760 | 10.2 |

An examination of table 4 indicates that secondaries in the interval from 0.1 to 10 mev. should introduce a high probability for a fluctuation of 1 to 3 mev. in the energy loss in a centimeter of lead. The study of these fluctuations by direct measurements of energy loss in thick plates of a substance of low atomic number like carbon, in which fluctuations of the above type would not be entirely masked by fluctuations due to radiative losses, should provide a means for checking up on the validity of the theoretical formula for secondaries in the interval from 0.1 to 5 mev., a region which has been out of reach in the present investigation.

## III. Formation of positron-negatron pairs by electrons.

From 4577 traversals of 0.35 cm. of lead by electrons with energies greater than 200 mev. there have been observed 2 single positron secondaries, 16 pairs, and one case of 2 positive and 2 negative secondaries generated by the same particle. A photograph of one of the pairs is shown in fig. 5. Traversals of 120 electrons in the range below 150 mev. have produced 2 pairs and 3 single positrons. The mean energy per pair, calling single positrons pairs, was 47 mev. in the former group, and 10 in the latter.

If we assume tentatively that the above pairs and single positives are produced by a direct process ( e.g. directly in a nuclear encounter, rather than by first forming a photon which is absorbed lower down in the plate), and make a reasonable correction (using data of section IV) for energy lost in the plate before the pairs emerge from it, then we find that the mean energy loss per cm. in lead contributed by pairs with energies greater than 5 mev. is about 0.8 mev/cm. for primary electrons with a mean energy $\gg$ 200 mev., and 2.5mev/cm for electrons with a mean energy of 75 mev.

Inasmuch as we have no direct means for determining whether the pairs arise largely from a direct or an indirect process, it is worth while to examine the consequences of the assumption that all of the observed pairs arise from the absorption of photons given off in radiative collisions. The mean energy lost per traversal by electrons in the lower energy group is 24 mev., and the mean observed pair energy is 10 mev. Taking 70 percent of the loss to be radiative (See data of next section) and assuming that most of that part of it results from large single losses, we get about 17 mev. for the average photon energy. If these are absorbed by pair formation, the observed mean pair energy, allowing an estimated 10 mev. per pair for absorption in the lead, would be about 7 mev., which is not far from the observed value. Using an absorption coefficient 0.6 for pair formation by the photons, and a mean distance traversed

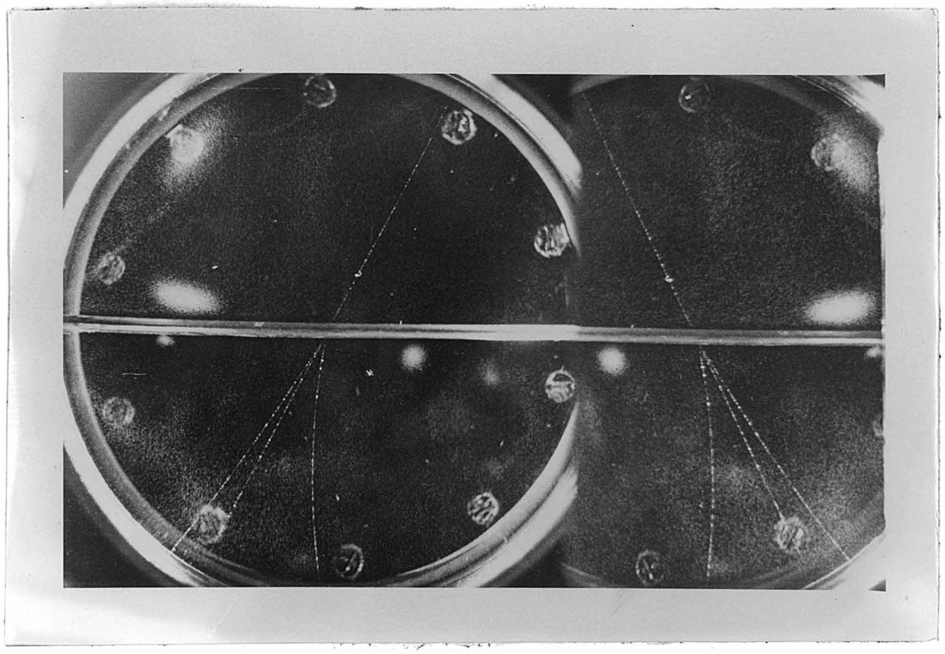

Fig. 5.

Example of pair formation by a high energy electron. The energies are 80 and 30 mev. respectively for the negatron and the positron.

equal to half the plate thickness, we can estimate that about 12 pairs should have been observed.

The observed number and the observed energies of pairs produced in lead by electrons with energies below 150 mev. are then roughly consistent with the conclusions given in the next section about losses of energy by radiation, and with the (approximately) known absorption coefficient for photons with energies around 20 mev., provided we assume a pair to result from the absorption of a photon given off in a radiative collision. It is therefore unnecessary to assume, for the interpretation of the data, that any of the pairs observed from low energy primaries resulted directly from the interaction of the incident particles with atomic nuclei; and there is no real experimental proof that the direct process occurs. Professor Oppenheimer has informed the writer that the theoretical integrated cross section for the direct process is small (of the order of a few percent) compared to the cross section for formation of a pair by a photon.

If the above interpretation is correct then the relative scarcity of pairs from the high energy electrons suggests, independently of the results of the next section, a breakdown of the radiation formula at high energies.

## IV. Radiative losses. Direct measurements of total energy loss in lead.

It has been shown by Anderson and the writer[1] that energy losses undergone by cosmic ray electrons in traversing plates of lead are subject to very wide fluctuations, whose magnitudes and frequency of occurrance are so great that they cannot possibly be accounted for by the formation of particle secondaries; these large losses have therefore

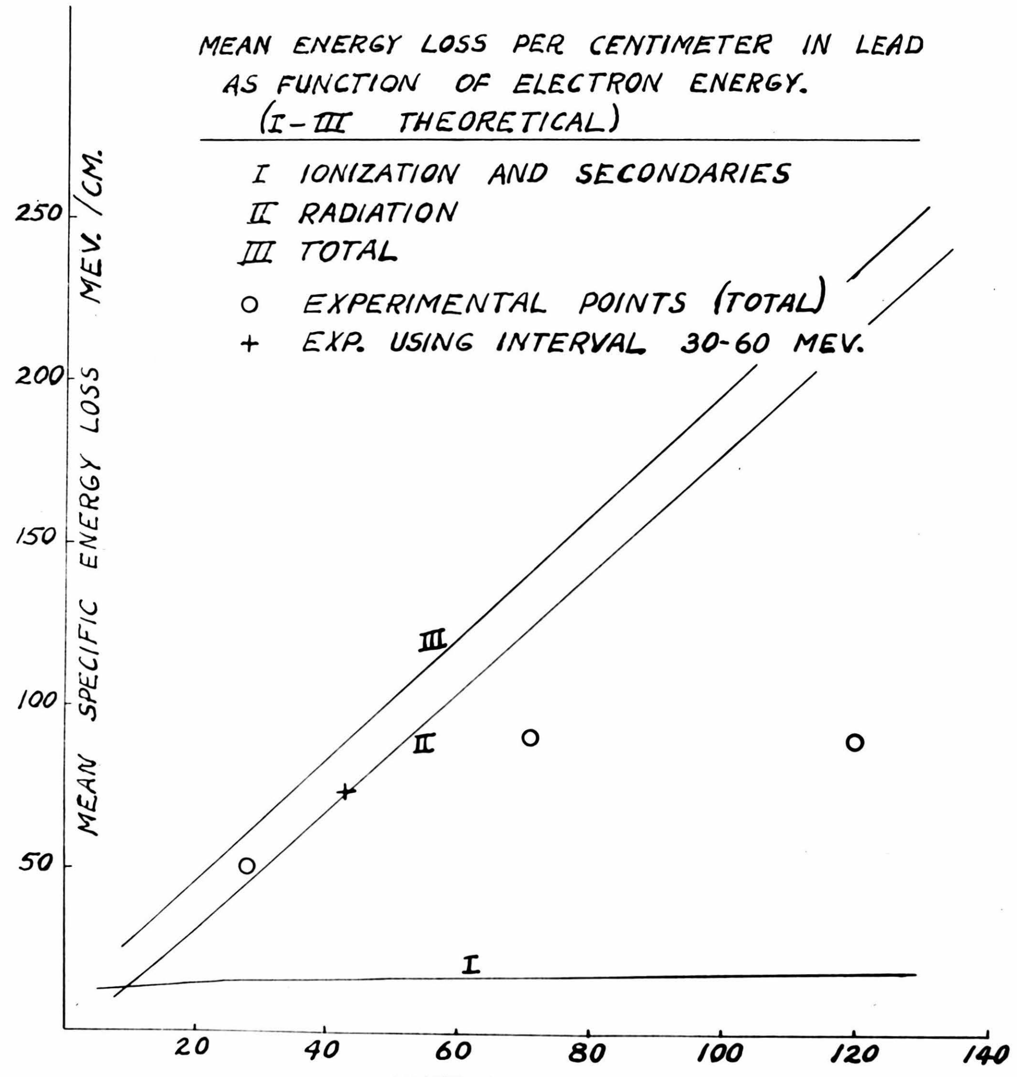
MEAN ENERGY LOSS PER CENTIMETER IN LEAD
AS FUNCTION OF ELECTRON ENERGY.
(I-III THEORETICAL)
I IONIZATION AND SECONDARIES
II RADIATION
III TOTAL
○ EXPERIMENTAL POINTS (TOTAL)
+ EXP. USING INTERVAL 30-60 MEV.
MEAN SPECIFIC ENERGY LOSS MEV./CM.
250
200
150
100
50
III
II
I
20
40
60
80
100
120
140
ENERGY OF PARTICLE MEV.

FIG. 6

been ascribed to the production, in nuclear encounters, of high energy photons. That they are responsible for a major part of the energy loss in lead has already been indicated by our earlier data and is made even more apparent by the results given below.

From the present set of data there have been made 166 determinations of the energy lost in 0.35 cm. of lead by electrons with energies in the range below 150 mev. To get some idea of the dependence of the mean specific energy loss on the energy of the particle, these electrons have been divided into three groups according to energy, each group lying in an interval 50 mev. wide. The mean initial energy and mean specific energy loss have then been determined for each group; the results are listed below in table 6, and plotted in fig. 6 along with theoretical curves constructed from data given by Bethe and Heitler[5] for the mean energy loss per cm. as a function of energy. An example of a large radiative loss is shown in fig. 7.

Table 6.

Energy loss measurements in 0.35 cm. of lead.

| Energy interval | $\varepsilon \leq 50$ | $50 < \varepsilon \leq 100$ | $100 < \varepsilon \leq 150$ |
|---|---|---|---|
| Number of tracks | 78 | 47 | 41 |
| Number stopped by lead | 40 | 4 | 2 |
| Mean initial energy | 28 mev. | 71 mev. | 124 mev. |
| Mean energy loss per cm. | 51 | 91 | 90 |
| Ditto, excluding those that stop | 40 | 86 | 80 |

There is some difficulty in estimating the accuracy of the experimental results. The most serious source of error in the energy range

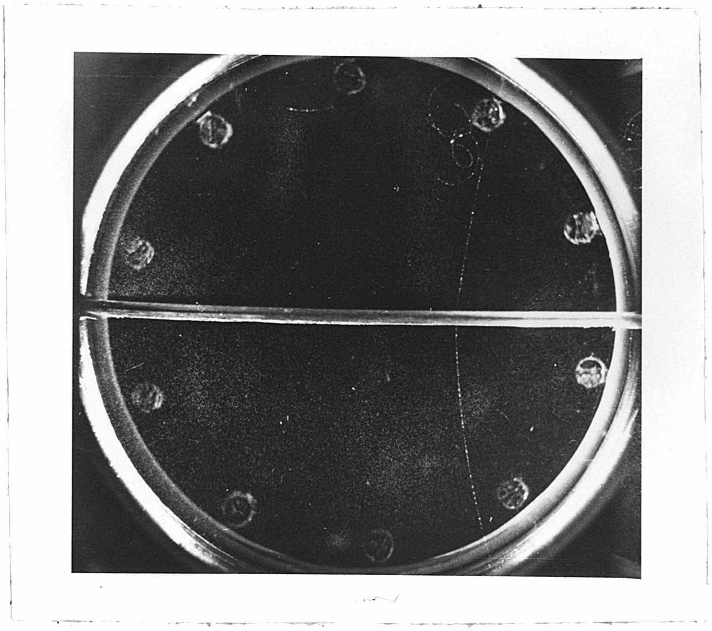

Fig. 7.

A 76 mev. positron goes through 0.35 cm. of lead and emerges with an energy of 35 mev. Scarcely a quarter of this loss is at all likely to be accounted for by ionization and close collisions, and the most reasonable assumption is that the excess was carried off by one or more photons.

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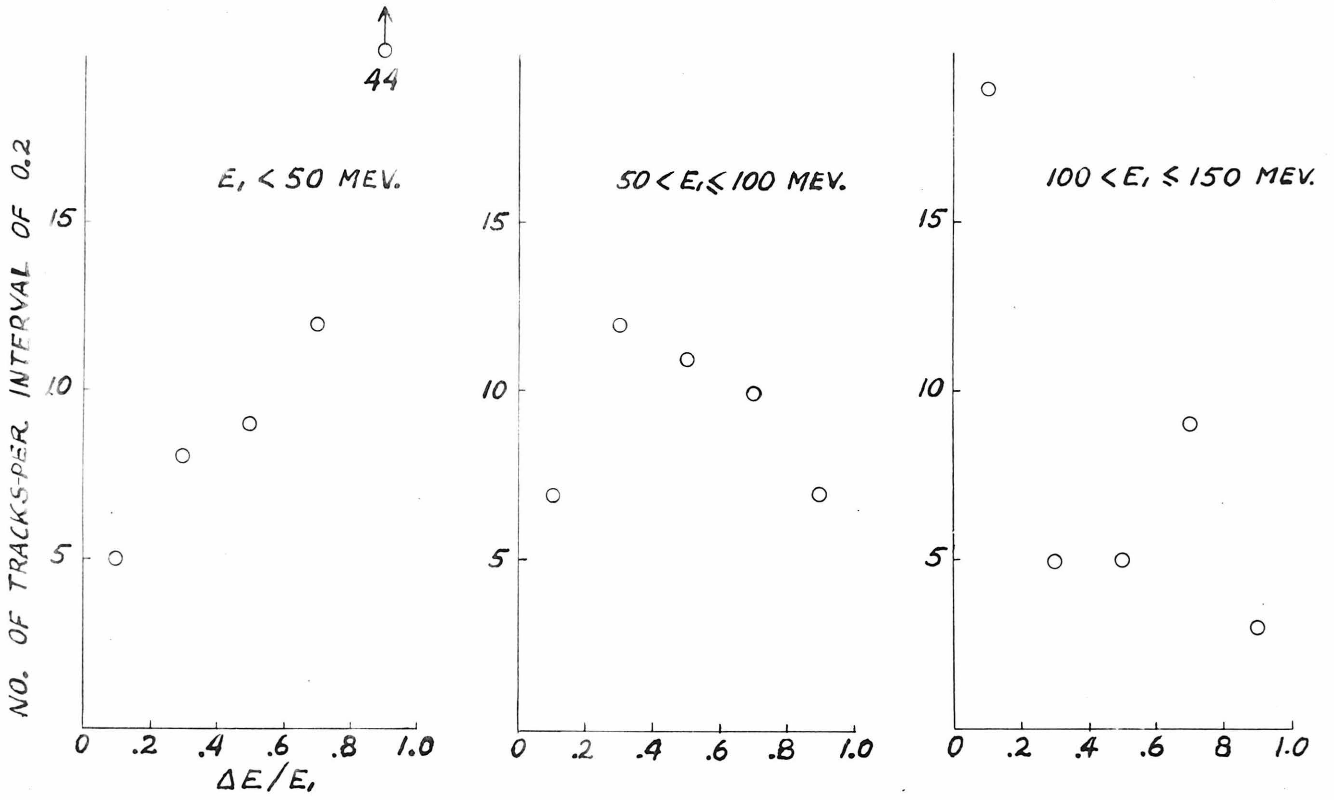
below 50 mev. arises from the occurrance of many cases in which the particles apparently stop in the lead plate, and the necessity for making a sound judgment in each case as to whether this actually happens. Even by stereoscopic examination it is often difficult to be sure that the particle has not merely been scattered out of view rather than stopped. There can be no doubt, however, that the particles do stop in many cases, and the uncertainty introduced in the final result should hardly exceed (±) the amount that these cases contribute, viz. about 20 percent, or 10 mev/cm. In the higher energy ranges the errors in curvature measurements are the predominating source of uncertainty, since a given error in the energy determinations produces a much greater



OBSERVED DISTRIBUTIONS OF FRACTIONAL ENERGY LOSS IN 0.35 CM. LEAD PLATE.

FIG. 8

(percentage of) error in the measurement of small energy losses. However, it has been found possible for two individuals (viz. Anderson and the writer) to check each other on energy measurements in the neighborhood of 100 mev., in practically all instances, to within 20 percent. Moreover, in the energy range from 100 to 150 mev., about three fourths of the measured mean loss is contributed by those particles which have lost more than half their initial energy in traversing the plate. The errors in measurement of energy loss, then, in those cases which contribute most of the final result, should not be more than about twice the errors in measurement of the particle energies themselves; and since the errors must partially cancel out in a large number of measurements, it appears that something like ± 30% should be a reasonable estimate of the limit of error in the final results for the energy range from 50 to 150 mev. Nine cases in this energy range which measure up to show an energy gain instead of a loss, if the particles were moving downward, have been included in the mean as negative losses, on the assumption that the negative results were a consequence of errors of measurement. If discarded entirely they raise the mean observed energy loss for this interval from 90 to 101 mev/cm. In the distributions of fractional losses shown in fig. 8. these cases were thrown into the interval 0--0.2.

It should be observed that the average specific energy loss, as measured above, does not mean quite the same thing as the definition used in the theory. This difference arises because some of the particles stop in the plate, and because of the dependence of the probability of a given energy loss on the electron energy. A decrease in this probability as the energy goes down must result in an observed decrease in the specific energy loss as the plate thickness is increased. Strictly, therefore, it is necessary in comparing experimental data with theory, to take into account the finite thickness of the plate. This correction is probably not very large for the thickness of plate used, and would not be of much significance for the present approximate data.

An examination of fig. 6 shows that the experimental value for mean total specific energy loss in lead is (with the foregoing reservations as to accuracy of the data) something like 2.5 times the total collision loss for particles with a mean initial energy equal to 30 mev., and about 4 times the collision loss in the range from 50 to 150 mev. The difference has necessarily to be attributed to losses by radiation. We may conclude that the theoretical result for total energy loss is not likely to be more than 25 percent too high in the neighborhood of 30 mev; but the experimental value at 120 mev., which is only 40 percent of the calculated value for this energy, indicates a definite breakdown of theory in the energy range above 100 mev.

The writer wishes to express his gratitude to Professor Millikan and to Professor C. D. Anderson, both for their interest and help, and for the privilege of assisting in the cosmic ray research program.

## References.

1. Anderson and Neddermeyer, Conference on Physics, London (1934).

2. E.J. Williams, Proc. Roy. Soc. A 130 328 (1931.

Williams' experimental results and those of other investigators are summarized in this paper.

3. Eisl, Ann. d. Phys. 3 277 (1929).

4. Carlson and Oppenheimer, Phys. Rev. 41 763 (1932).

5. Bethe and Heitler, Proc. Roy. Soc. A 146 83 (1934).