# Cloud Chamber Study of Cosmic-Ray Particles

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Contents

Abstract

In order to study the energy loss of cosmic-ray electrons in light materials where inelastic atomic collisions account for the main part of the loss, 10,000 cloud chamber photographs were taken in which a thin-walled copper counter or a combination of one or two counters with a 1/4 inch carbon plate was placed across the chamber as an absorber. The counter or counters was used at the same time to control the expansion. Only electrons of energy from 10 to 60 Mev are suitable for this purpose. These occur infrequently and only 36 particles in the case of a single counter absorber and 33 in the case of a counter-carbon absorber were found suitable for accurate measurement. The observed average values of energy loss in Mev/cm are compared with the theoretical average value. The result shows that in the energy range considered the theoretical formula for energy loss of electrons (no heavy tracks were included) by direct collisions are in approximate agreement with observation. The importance of an experimental test of these formulae lies in the fact that the mass estimates of the mesotron so far made have been based on the validity of these formulae.

Several heavily ionized tracks were discussed by considering their ionization and range relations. One of these was found to be probably a mesotron of negative charge. Two cases of abnormal energy loss which can not be accounted for by ionization and radiation alone were also discussed.

## Introduction

Many experiments have been made on the energy loss of cosmic-ray particles in heavy materials where radiation accounts for the major part of the loss. The results have been found in approximate agreement with the theory. The direct energy loss measurements of cosmic-ray particles in substances of low atomic number where the energy loss resulting from inelastic collisions plays the main part are meager. There appeared until now only the data of Anderson and Neddermeyer in 1934 and those of Turin and Crane in 1937 on the energy loss in carbon. The former have made five measurements on particles (presumably electrons) with a mean initial energy of 20 Mev, which gave a mean specific energy loss of 5 Mev/cm in a 1.5 cm plate[1]. The latter have made about 100 measurements on electrons with initial energies from 4 to 6 Mev (mean initial energy $\sim$ 5 Mev) and the mean specific energy loss to be 3.4 Mev/cm in a 0.5 cm plate[2]. The corresponding theoretical values calculated from Bloch's formula of collision loss are respectively 4.3 and 3.7 Mev/cm, which are just about within the limits of experimental uncertainty.

The present work has been aimed on the one hand to extend the energy loss measurements of cosmic-ray particles in carbon (and also in a glass-copper counter) up to 60 Mev and on the other to hope to catch some mesotrons near the end of their ranges as only then will the ionization shown by the particle be a marked function of its mass. Although we have obtained several cases of heavily ionizing tracks, the accuracy of the measurements was not high enough to ascertain them as mesotrons (see captions of Figs. 2 - 5 below). There was, however, one case reported by Neddermeyer and Anderson[3] in which it was certainly a mesotron stopped in the gas in the chamber after passing through the counter absorber. Its mass was estimated to be 220 ± 35 electron mass.

## Experimental details

Over 10,000 photographs were taken with the cloud chamber apparatus designed by Professor Anderson and Dr. Neddermeyer. The chamber, of dimensions 17 x 17 x 3 cms, was arranged with its long dimension vertical and incorporated into a powerful electromagnet capable of maintaining a uniform magnetic field of 7900 Gauss strength. The expansion of the chamber was controlled in the early arrangement by the discharge of a thin-walled copper counter sealed in a glass tube (referred to later as glass-Cu counter). The counter was placed across the middle of the chamber, serving at the same time as an absorber. In a later arrangement, this counter was coupled with an ordinary G-M counter placed immediately above the chamber and the coincident discharges of the two controlled the expansion. While the experiments were in progress, Dr. Y. K. Boggild had succeeded in making several bare thin-walled copper counters. In a later arrangement, one of these was combined with a carbon plate of about 1/4 inch thickness and the combination was used inside the chamber as an absorber. Later on, this was replaced by a combination of 2 Boggild counters and a 1/4 inch carbon plate. The top counter was dispensed with and the expansion was controlled by the coincident discharges of the two Boggild counters. The chamber was filled with argon at one atmospheric pressure throughout the experiment, save for some 10 early runs with a single counter inside, where a mixture of argon and helium in the ratio 1 :1 was used. Different thicknesses of lead from 1/4 to 6.5 inches were placed above the chamber throughout as a filter (except for the first 8 runs with a single counter inside). The 6.5 inch lead was used for the purpose of slowing down the mesotrons to increase the probability of observing a decay inside the chamber, according to the theory of decay of mesotrons as tested by several investigators in this field, but no noticeable difference has been observed.

The energy loss of cosmic-ray particles in the absorber was measured by measuring with ruled circles the curvatures of single tracks above and below the absorber. The particle was taken as a shower particle when its track was accompanied by one or more tracks in the chamber. Only those tracks were taken which exhibited in the magnetic field a radius of curvature of 45 cm or less, the limit for reasonably accurate measurements in this series of photographs. Although no accurate estimation of the error due to distortions of the tracks has been made, this was believed to be in general below the uncertainty of measurement at such low range because the selected tracks were all of uniform curvature as well as within the measuring limit. Except for several heavy tracks discussed below, the energy of the particles was calculated by assuming an electronic mass and using the ordinary energy - $H\rho$ relation for energies large compared with the rest energy $\mu = mc^2$, i.e. $E - \mu = 300\ H\rho$ ev. In calculating the specific energy loss $-\frac{dE}{dx}$, correction was made for the thickness traversed when the particle went through the counter in an inclined direction.

## Results

The results of measurements are divided into two groups:

(a) Those with the glass-Cu counter as an absorber. The normal thickness has a total surface density of 0.913 g/cm$^2$ which is equivalent in electron density to 0.825 g/cm$^2$ of air or 684.6 cm of air at one atmospheric pressure and 20° C. The electron thickness is calculated by assuming only NZ as the electron dependence in the stopping power of the absorber. The data are summarized in Table 1:

Table 1. Energy Loss in Glass-Cu Counter

| Initial energy in Mev | Specific energy loss in Mev/g | Initial energy in Mev | Specific energy loss in Mev/g | Initial energy in Mev | Specific energy loss in Mev/g |
|---|---|---|---|---|---|
| 7.3 | 2.0 | 27.6 | 0 | 44.2 | 7.4 |
| 11.2 | 1.1 | 28.5 | 4.8 | 45.0 | 1.8 |
| 14.2 | 0.6 | 30.4 | 2.4 | 45.8 | -3.1 |
| 15.0 | 2.9 | 32.4 | -3.9 | 49.0 | 3.8 |
| 15.0 | 1.6 | 32.4 | 4.6 | 52.1 | 3.0 |
| 15.2 | 0 | 34.0 | 2.9 | 56.8 | 5.5 |
| 15.5 | 3.4 | 34.0 | 2.6 | | |
| 15.8 | 4.6 | 34.8 | 5.4 | | |
| | | 36.3 | 1.7 | | |
| 19.7 | 3.1 | 37.1 | 5.9 | | |
| 19.7 | 2.6 | 37.2 | -1.9 | | |
| 20.5 | 1.6 | 37.2 | -7.3 | | |
| 22.9 | 3.6 | 37.9 | 6.5 | | |
| 24.5 | 0 | 37.9 | -6.2 | | |
| 24.5 | 3.8 | 38.7 | 5.6 | | |
| 25.6 | 18.3 | | | | |

In Table 1, 36 good measurements are entered. There are 4 particles in the low energy range, i.e. 7.3 Mev, 11.2 Mev, 14.2 Mev, 19.7 Mev, which show an apparent gain in energy if they are considered as going down the chamber, as is generally done with all other particles. The writer has, however, considered them as going upwards because these photographs were taken with only one counter inside the chamber and the tracks were so much curved that there is good reason to believe that they were going up. The other apparent energy gains in the higher energy ranges can be accounted for by errors. No heavy tracks were included. Particles of both signs are distributed over the whole group and the numbers of single and shower particles are about in the ratio 2:3. The data are not extensive enough to show any distinctive difference in the behavior of single and shower particles.

The particles are divided into 3 groups according to the initial energy, i.e. 0-20 Mev, 20-40 Mev, 40-60 Mev. The mean values of initial energy and specific energy loss in each group are computed and entered in Table 2:

Table 2. Mean Energy Loss in Glass-Cu Counter

| Mean initial energy in Mev | Observed mean specific energy loss in Mev/gm | Observed mean specific energy loss in Mev/cm | Calculated mean specific energy loss in Mev/cm |
|---|---|---|---|
| 14.9 | 2.18 | .00263 | .00241 |
| 31.7 | 2.51 | .00302 | .00262 |
| 48.8 | 3.06 | .00369 | .00273 |

The calculation of the mean specific energy loss will be explained below.

(b) Those with the counter-carbon combination as an absorber. The normal thickness is equivalent in electron density to .923 cm and 1.021 cm of carbon respectively in the two arrangements. In the first calculation, the density of carbon used was assumed to be 2.25 g/cm$^3$. But later a measurement of the density gave its value as 1.69 instead of 2.25. All the data were then corrected to those for 2.25 density (i.e. multiply by 1.33), since the theoretical curve was calculated for this value. The corrected data are summarized in Table 3:

Table 3. Energy Loss in Carbon

| Initial energy in Mev | Specific energy loss in Mev/cm | Initial energy in Mev | Specific energy loss in Mev/cm | Initial energy in Mev | Specific energy loss in Mev/cm |
|---|---|---|---|---|---|
| 10.9 | 1.3 | 28.4 | 3.9 | 44.2 | 5.0 |
| 13.4 | 4.6 | 29.2 | 14.6 | 45.8 | 6.7 |
| 15.5 | 3.1 | 31.6 | -3.1 | 47.4 | 13.5 |
| 18.5 | 4.2 | 32.4 | 5.9 | 50.6 | 10.4 |
| 19.7 | 7.6 | 34.0 | 4.4 | 60.6 | 9.4 |
| 19.7 | 4.9 | 35.5 | 32.1 | 61.6 | 19.5 |
| 19.7 | 14.1 | 37.1 | 4.8 | 79.0 | 10.3 |
| 20.5 | -1.0 | 37.9 | -1.1 | 110.0 | 19.8 |
| 20.5 | 6.1 | 37.9 | 2.3 | 111.0 | 20.7 |
| 21.3 | -1.4 | 38.7 | 4.6 | | |
| 22.9 | 0 | 42.6 | 0 | | |
| 26.8 | 2.5 | 44.2 | 2.0 | | |

In Table 3, 33 good measurements are entered in the same way as in Table 1. Three particles below 20 Mev, i.e. 10.9 Mev, 15.5 Mev, and 19.7 Mev (with energy loss 4.9) which showed an apparent gain in energy have been taken as going upwards, because the last two were taken with only 2 counters inside the chamber and the curvatures of the tracks were large enough to ascertain the upward motion. The first one was taken with one counter above and one inside the chamber, but the track above the absorber has a curvature of only 4.1 cm and apparently did not go through the top counter at all. No heavy tracks were included. Particles of both signs are distributed over the whole group and the numbers of single and shower particles are about 3 to 2. No distinctive difference in the behavior of single and shower particles has been observed.

The particles are divided into 3 groups according to the initial energy, i.e. 0-20 Mev, 20-40 Mev, 40-60 Mev. The mean values of initial energy and specific energy loss in each group are computed and entered in Table 4:

Table 4. Mean Energy Loss in Carbon

| Mean initial energy in Mev | Observed mean specific energy loss in Mev/cm | Calculated mean specific energy loss in Mev/cm |
|---|---|---|
| 16.8 | 4.27 | 4.27 |
| 30.3 | 4.97 | 4.57 |
| 47.8 | 6.72 | 4.78 |

## Comparison with theory

When a cosmic ray particle goes through an absorber it can lose its energy chiefly in two ways:

(a) It transfers its energy to an atom by exciting or ionizing the atom (collision loss).

(b) It loses its energy through nuclear collisions and the subsequent emission of Bremsstrahlung (radiation loss).

According to theory, the energy loss due to process (a) is very nearly proportional to NZ where N is the number of atoms per $cm^3$ and Z the atomic number of the atom struck, while that due to process (b) is proportional to $NZ^2$. In the energy range considered here (0 - 60 Mev) the collision loss increases with energy very slowly. The radiation loss is on the average small compared with collision loss in this range, because the absorber used is of low atomic number.

The mean energy loss of an electron of energy E due to inelastic collisions is given by the formula of Bloch as presented by Heitler:(4)

$$\left(-\frac{dE}{dx}\right)_{coll} = NZ\phi_0 mc^2 \frac{3}{4\beta^2}\left\{\log \frac{mc^2\beta^2(E - mc^2)}{2(1-\beta^2)I^2Z^2} + 1 - \beta^2 + \psi(0) - R\psi\left(i\frac{1}{137\beta}\right)\right\} \quad (1)$$

where $\phi_0$ is the cross section of scattering by a free electron = $6.57 \times 10^{-25}$ $cm^2$;

$\beta = v/c$;

IZ is the average ionization energy of an atom; I = 13.5 ev;

$\psi(x)$ is the logarithmic derivative of the Gamma function;

$R\psi(x)$ denotes the real part of $\psi(x)$.

For electrons of the energies concerned here, the two terms containing $\psi$ can be neglected. In air at 1 atmospheric pressure and 20° C, NZ = $3.62 \times 10^{20}$. Substituting all the numerical values into (1) and also

$$E = \frac{mc^2}{\sqrt{1-\beta^2}}, \qquad (2)$$

We have the mean energy loss of electrons due to collisions in air at 1 atmospheric pressure and 20° C,

$$\left(-\frac{dE}{dx}\right)_{coll} = \frac{0.913 \times 10^{-4}}{\beta^2}\left\{\log\left[\frac{\beta^2}{1-\beta^2}\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right)\right] + 1 - \beta^2 + 16.4\right\} \qquad (3)$$

expressed in Mev/cm.

From (2) and (3) a theoretical curve of the energy loss of electrons due to collisions in air can be plotted as a function of the initial kinetic energy $E - \mu$. The writer has had the privilege of taking the numerical calculations of Dr. Neddermeyer in plotting the curve (Fig. 1). For the energy loss of electrons due to collisions in carbon of density 2.25 g/cm$^3$, one has only to multiply the values for air by the factor 1750 (neglecting the $Z^2$ dependence in the log term).

In Tables 2 and 4, the calculated values of mean specific energy loss for the respective initial energies are found from the theoretical

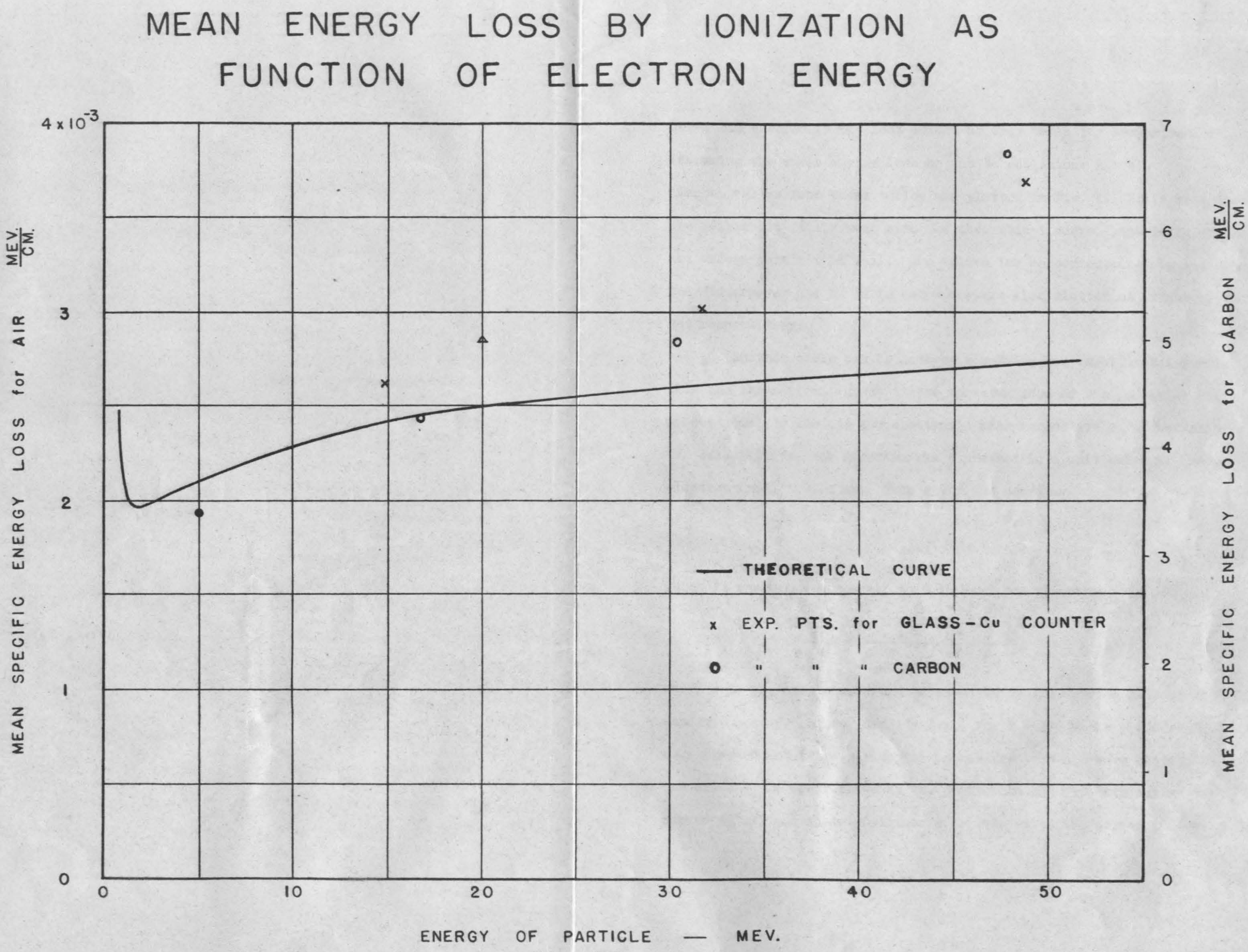
MEAN ENERGY LOSS BY IONIZATION AS FUNCTION OF ELECTRON ENERGY
4 x 10^-3
3
2
1
0
MEAN SPECIFIC ENERGY LOSS for AIR MEV./CM.
7
6
5
4
3
2
1
0
MEAN SPECIFIC ENERGY LOSS for CARBON MEV./CM.
0
10
20
30
40
50
ENERGY OF PARTICLE — MEV.
THEORETICAL CURVE
x EXP. PTS. for GLASS-Cu COUNTER
O " " " CARBON

FIG. I

curve and entered in the last column of each table for comparison (assuming the whole energy loss as due to collisions alone). The experimental values from these tables are plotted in Fig. 1. It is seen that the points fit fairly well with the theoretical curve, especially at the low energy part ( $\sim$ 15 Mev). The values for carbon obtained by Anderson and Neddermeyer and by Turin and Crane are also plotted as triangle and dot respectively.

Another check can be made by comparing the experimental points with the theoretical curves of the momentum loss of the particles for masses equal to 100 and 200 electronic mass respectively. To simplify the calculations, the momentum was expressed in a unit twice the natural electron unit, i.e. 2 mc. This gives the momentum

$$p = \frac{e}{2mc^2} H\rho, \tag{4}$$

which is approximately equal to E in Mev, for electrons (k = 1), and

$$\frac{dp}{dx} = \frac{\sqrt{k^2 + 4p^2}}{2p} \frac{dE}{dx} = \frac{1}{\beta} \frac{dE}{dx} \tag{5}$$

where k is the mass number and $\frac{dE}{dx}$ is given by (3). Two curves of the momentum loss in carbon (density 2.25) for k = 100 and k = 200 respectively were plotted and the experimental points from Table 4 were plotted for comparison. It was found that the points did not fit with any of the curves at all and their positions with respect to the curves indicate that the particles must be of a mass much lighter than 100 $m_e$. This gives another justification for assuming them as electrons.

The comparison between the curves of $\frac{dE}{dx}$ and the experimental points was made under the assumption that the energy loss was due to collisions alone. An estimate of the radiation loss in the counter-carbon combination can be made as follows. For a given thickness of absorber, the radiation loss is proportional to $NZ^2$ per $cm^2$. In the combination of a Boggild counter and a carbon plate, the relative $NZ^2$ of the two are $21.9 \times 10^{23}$ per $cm^2$ and $31.9 \times 10^{23}$ per $cm^2$ respectively. Hence the total $NZ^2$ is $52.8 \times 10^{23}$ per $cm^2$ for the given thickness. In the combination of two Boggild counters and a carbon plate, the relative $NZ^2$ of the counter and carbon are $43.7 \times 10^{23}$ per $cm^2$ and $30 \times 10^{23}$ per $cm^2$ respectively and the total $NZ^2$ is $73.7 \times 10^{23}$ per $cm^2$ for the given thickness. The average of the two, i.e., $63 \times 10^{23}$ per $cm^2$ was taken as the mean $NZ^2$ for the mean thickness. The radiation losses for the different initial energies were then computed by simple ratio from the corresponding losses in water whose $NZ^2$ for the same thickness is $21 \times 10^{23}$ per $cm^2$. The results of a closer comparison are summarized in Table 5:

Table 5. Mean Energy Loss in Carbon

| Initial energy in Mev | Observed $-\frac{dE}{dx}$ in $\frac{Mev}{cm}$ | Calculated $(-\frac{dE}{dx})_{coll}$ in $\frac{Mev}{cm}$ | Calculated $(-\frac{dE}{dx})_{rad}$ in $\frac{Mev}{cm}$ | Total calculated $-\frac{dE}{dx}$ in $\frac{Mev}{cm}$ |
|---|---|---|---|---|
| 16.8 | 4.3 | 4.3 | 0.8 | 5.1 |
| 30.3 | 5.0 | 4.6 | 1.6 | 6.2 |
| 47.8 | 6.7 | 4.8 | 2.8 | 7.6 |

It is seen from the table that the data are in approximate agreement with the theoretical formula of energy loss of electrons within the limits of experimental uncertainty.

## Conclusions

Several important conclusions can be drawn from the foregoing results:

(a) That most of the particles measured here are electrons except the few definitely heavy tracks discussed below (Figs. 2 - 4).

(b) That within the limits of experimental uncertainty, the observed results are in approximate agreement with the theoretical formula if the particles are taken to be electrons and if energy loss by ionization and radiation alone is considered.

(c) That except for the two cases discussed below (Fig. 5 - 6) there is no evidence for appreciable energy loss by any process other than ionization and radiation for most of the particles.

(d) That these results on absorption in an element as light as carbon where radiation energy losses are small show that in the energy range considered the theoretical formulae for ionization energy loss are valid within the limits of uncertainty of measurements. An experimental test of the formula for loss in energy by ionization (as contrasted with energy loss by radiation with which most of the previous experiments have been concerned since absorbers of high atomic number were used) is vital since all estimates so far given of the mass of mesotron have been based on the assumption of the validity of the theoretical formula for energy loss by ionization.

## Discussion of Heavy Tracks and Abnormal Energy Loss

Beside the electron tracks measured, there were several cases of heavily ionizing particles and abnormal energy loss. Pictures of these are reproduced in Figs. 2 - 6.

The $H\rho$ value of a particle measures its momentum p through the relation

$$p = \frac{e}{c} H\rho,$$

or

$$\mu \equiv \frac{p}{mc} = \frac{p}{mc^2} H\rho, \qquad (6)$$

where $\mu$ is the momentum expressed in natural electron unit mc. If the mass of the particle is Km where K is the mass number in terms of electron mass m, then $\mu$ and its energy are given by

$$\mu = \frac{K\beta}{\sqrt{1-\beta^2}} \qquad (7)$$

$$E = \frac{Kmc^2}{\sqrt{1-\beta^2}} = KE_0. \quad (E_0 = \text{energy of an electron of the same } \beta) \qquad (8)$$

Since the energy loss by collision is a function of $\beta$ only, it follows that the range of the particle is given by

$$R = \int_0^E \frac{dE}{-\frac{dE}{dx}} = K \int_0^E \frac{dE_0}{-\frac{dE_0}{dx}} \qquad (9)$$

where $\frac{dE_o}{dx}$ is given by (1). The change of R after it passed through the absorber is equal to the thickness traversed. Hence if $\mu_1$ and $\mu_2$ before and after passing through the absorber are known from the measurements, a value of K can be found by trial and error method from (7) and (9) which corresponds to the given change of R.

Examples of this method are discussed in the captions of the pictures below.

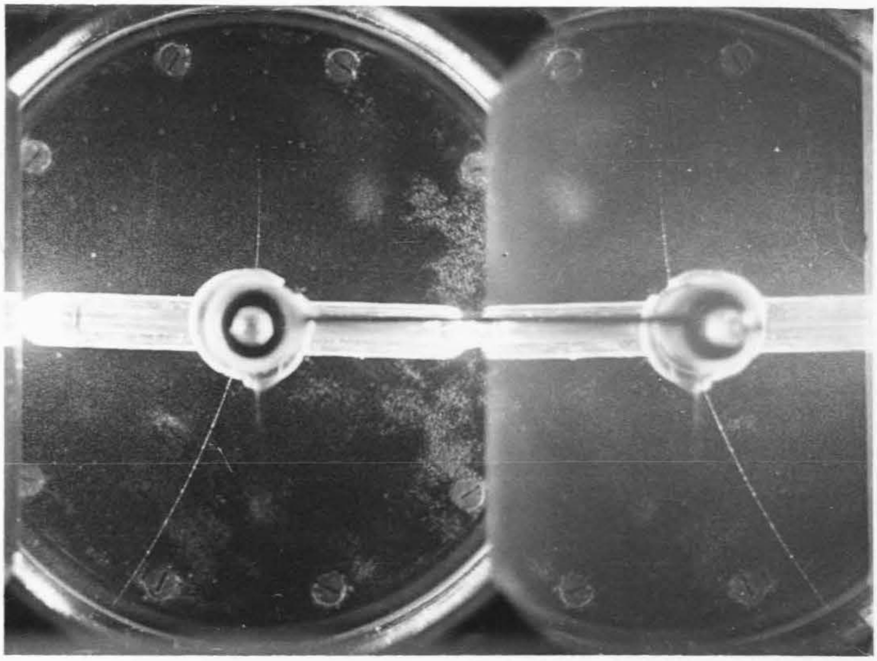

Fig. 2

A negative particle of $H\rho = 2.11 \times 10^5$ gauss cm passes through the glass-copper counter and emerges with an $H\rho = 1.68 \times 10^5$. Its momenta $\mu$ in natural electron unit mc calculated from the relation $\mu = \frac{e}{mc^2} H$ are $1.24 \times 10^2$ and $.99 \times 10^2$ above and below the counter respectively. If the whole energy loss is assumed to result from ionization alone this would correspond to a mass $\sim$ 220 electron mass, and ionizations above and below the counter of 2.7 and 3.5 times the minimum for a fast particle. The heaviness of the track below the counter seems consistent with the factor 3.5. The mass traversed is 0.825 g/cm² air equivalent. On assuming a mass 220, the value of $\rho_1$ calculated from $\rho_2$ and the actual thickness traversed is 26.1 cm which is in excellent agreement with the measured value (26.7 cm). Thus this particle is probably a mesotron of negative charge.

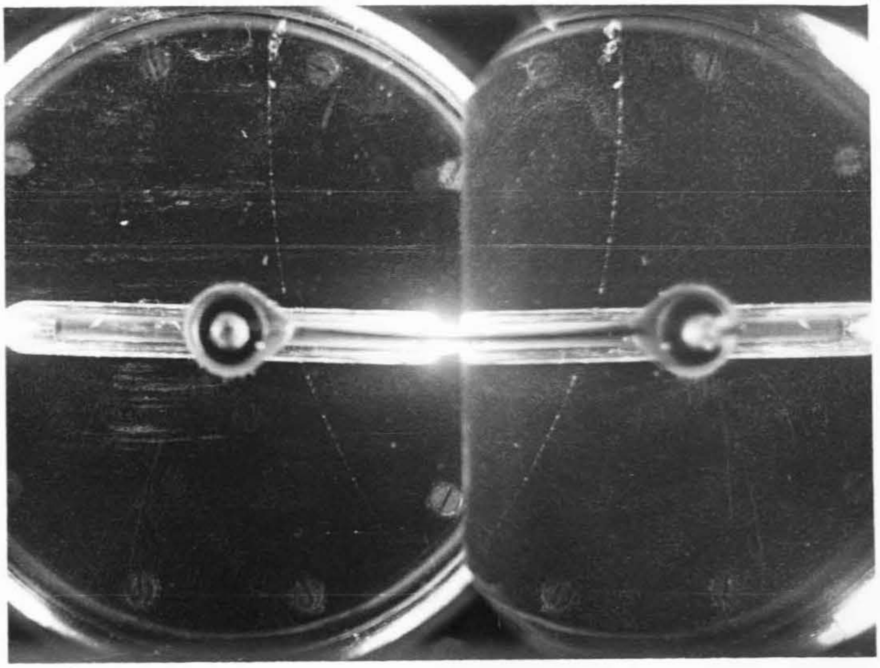

Fig. 3.

A positive particle enters with an $H\rho = 2.31 \times 10^5$ gauss cm and comes out with an $H\rho = 1.88 \times 10^5$ gauss cm. The corresponding momenta in natural electron units are $1.36 \times 10^2$ and $1.11 \times 10^2$ respectively. On assuming only energy loss due to ionization, this gives a mass of $\sim$ 260 electron masses and ionizations above and below the counter of 2.9 and 3.8 times the minimum for a fast particle. Although the mass estimation is not far from the value generally obtained, the ionization actually produced is not quite as much as the calculation requires.

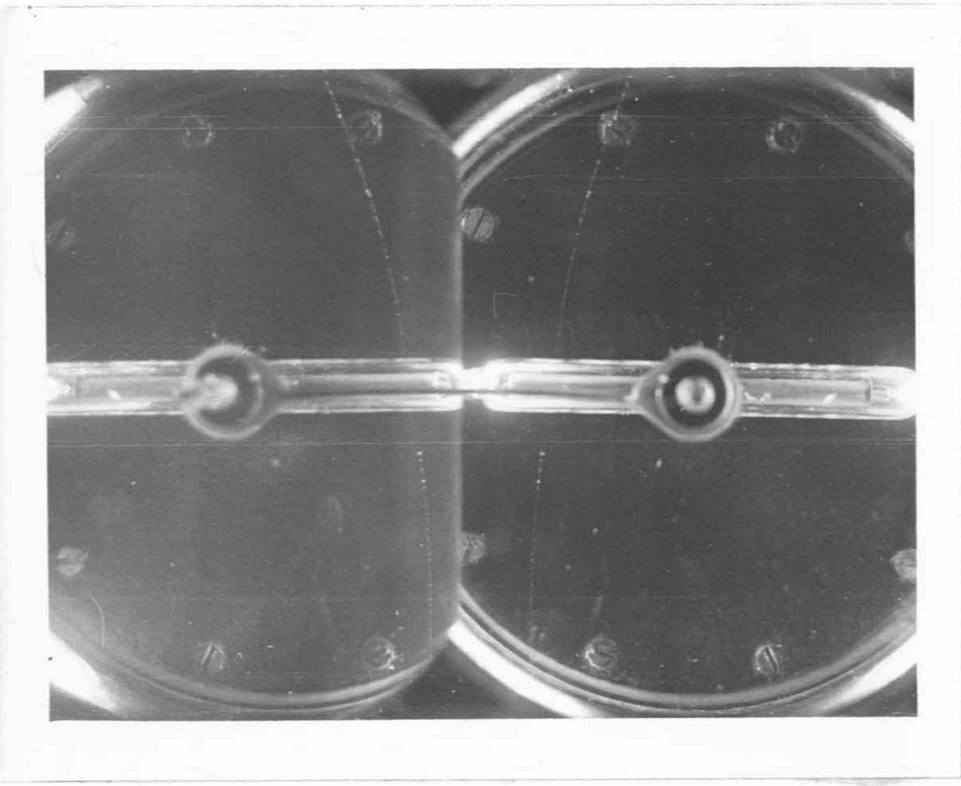

Fig. 4.

A negative particle enters with an $H\rho = 2.27 \times 10^5$ gauss cm and emerges with $H\rho = 1.79 \times 10^5$ gauss cm. The corresponding momenta in natural electron units are $1.34 \times 10^2$ and $1.06 \times 10^2$ respectively. On assuming the whole energy loss to result from ionization only, this gives a mass of $\sim$ 260 electron mass and ionizations above and below the counter of 3 and 4 times the minimum for a fast particle. Although the mass estimation is not far from the value generally obtained, the ionization actually produced is not quite as much as required.

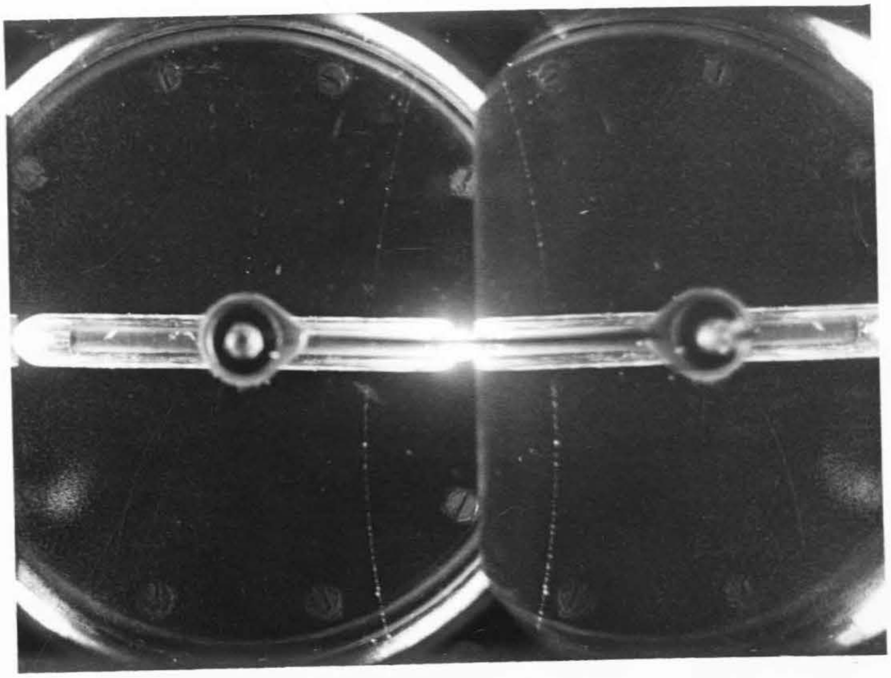

Fig. 5.

Photograph already published,(5) showing a positive particle entering with an $H\rho = 2.53 \times 10^5$ gauss cm and emerging with $H\rho = 1.74 \times 10^5$ gauss cm. The corresponding momenta in natural electron units are $1.49 \times 10^2$ and $1.03 \times 10^2$ respectively. If the whole energy loss is assumed to be due to ionization alone this would correspond to a mass of $\sim 360$ electron mass and ionizations above and below the counter of 4.1 and 7.6 times the minimum for a fast particle. The ionization as shown by the heaviness of the track is certainly greater than the minimum but not by so big a factor. On assuming a mass 220, the ionization factor should be 2.3 and 3.5 and the mass traversed should be 2.4 $g/cm^2$ air equivalent which is about three times the actual mass traversed. Taking into account the thickness of the tungsten wire in the counter, the chance of the traversal of which is rather small, the actual mass traversed could not be more than 1.5 $g/cm^2$. Hence it appears probable that the curvature change is to be explained in terms of an abnormal energy loss other than from ionization and radiation.

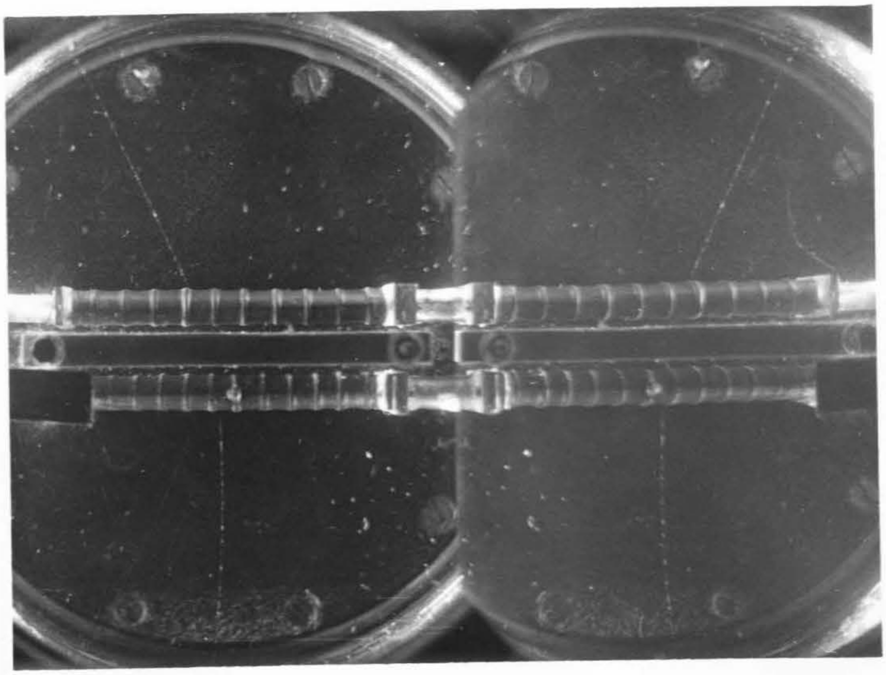

Fig. 6.

A negative particle enters with an $H\rho = 6.32 \times 10^5$ gauss cm and comes out with an $H\rho = 2.37 \times 10^5$ gauss cm. The corresponding momenta in natural electron units are $3.72 \times 10^2$ and $1.40 \times 10^2$ respectively. On assuming this tremendous momentum loss to be due to ionization only, the particle should have a mass of $\sim$ 100 times electron mass. This is obviously wrong, because a particle of this mass should have an ionization of 5 times the minimum of a fast particle and could not get through the absorber. It can not be easily interpreted either as an electron or as a mesotron, which loses energy only through direct ionization and radiation, because an electron with this momentum should not ionize as much as the picture shows and a mesotron with this momentum should go through a thickness of absorber about 11 times the actual thickness (1.073 cm of C, taking account of the inclination of the tracks to the normal) to lose that much of its momentum through ionization. The incident track was somewhat distorted near the top, but this is probably not big enough to account for the abnormal change of curvature. Hence this seems to be another case of abnormal energy loss which cannot be explained by collision and radiation alone.

In conclusion the writer wishes to express his gratitude to Professor Millikan for his continued interest in these researches and to Professor C. D. Anderson and Dr. S. H. Neddermeyer for their valuable directions and help from time to time which have greatly enlightened the work. The writer is also much obliged to Dr. J. K. Boggild for providing him with the bare copper counters and also assisting him in the operation of the apparatus. It is a pleasure to express my indebtedness to the Carnegie Institution of Washington from which has come all of the financial support.

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