THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 53, NO. 10 MAY 15, 1938 SECOND SERIES

The Specific Ionization and Mass of Cosmic-Ray Particles

DALE R. CORSON AND ROBERT B. BRODE
Department of Physics, University of California, Berkeley, California
(Received March 25, 1938)

The specific ionization of 120 cosmic-ray tracks has been measured by counting droplets in photographs of delayed expansion cloud chamber tracks. For values of $H\rho$ between 10^3 and 2×10^5 the specific ionization as a function of $H\rho$ is found to be in good agreement with theory. The predicted minimum ionization for electrons of $H\rho\sim10^4$ ($\sim$2 Mev) is verified. These results are applied to the calculation of the mass of heavily ionizing cosmic-ray particles as observed by us and by others. The masses of all heavy cosmic-ray particles thus far reported, with one exception, do not seem to be in serious disagreement with a unique mass which lies in the limits $(200\pm50)m_0$.

TO obtain values for the specific ionization due to cosmic-ray particles several hundred cloud chamber photographs have been taken. The expansion was delayed to make possible the counting of the individual droplets in the tracks. The cloud chamber was 18 cm in diameter and was filled with nitrogen at about 1.5 atmospheres pressure. It was placed in a magnetic field of 800 gauss. The chamber was illuminated by a mercury arc lamp, operated with a fraction of an ohm series resistance and flashed on 220 volts d.c. for 0.1 second. The expansion was delayed for approximately 0.5 second by a cam mechanism set into operation by the tripping of a pair of Geiger counters.

The tracks were broadened by diffusion of the ions in the time between the passage of the ionizing particle and the expansion of the chamber (the clearing field was shorted out by the tripping of the Geiger counters). In spite of the breadth of the tracks it was possible to obtain quite accurate values for the curvature by measuring the coordinates of the estimated center of the band of droplets when observed with a measuring microscope.

The absence of turbulent distortions was checked by measuring tracks when the magnetic field was zero. These were found to be straight within the limits of experimental measurement except in the region less than two cm from the chamber walls. The droplets were easily counted as can be seen from the examples shown in Fig. 1. All results were reduced to 0°C and 760 mm of mercury pressure.

One hundred twenty tracks that were in sharp focus, so that the number of droplets per cm could be easily counted, were chosen for this preliminary survey. They were divided into seven $H\rho$ groups. In obtaining the mean number of droplets per cm in each group (plotted in Fig. 2) the mean number per cm in each track was weighted proportional to the total number of droplets in the track. The vertical lines represent the probable errors. In the lowest $H\rho$ group the radius of curvature is somewhat uncertain and the variation of ionization with

$H\rho$ is rapid. In this region large deviations from the mean are to be expected.

Discussion

The variation of the specific ionization in hydrogen is given theoretically by the formula[1]

$$I=\frac{A}{\beta^2}\left[\log k+\log\frac{\beta^2}{1-\beta^2}-\beta^2\right], \qquad (1)$$

where $k=1.6\times10^6$ for hydrogen. This is a function which varies nearly as $1/\beta^2$ for $\beta<0.9$, then passes through a minimum at $\beta\sim0.97$, and increases with increasing β. For electrons the value of $\beta=0.97$ corresponds to about 2 Mev. A smaller value of k must be used if this equation is to be applied to ionization in nitrogen. We have chosen $k=2\times10^4$ as an appropriate value. Since k enters only in the logarithmic term the choice of a value for k is not critical.

Our measurements do not give the primary ionization but the "probable" ionization,[2] i.e., the primary ionization plus the ionization produced by secondaries of energy lower than a certain critical energy. Secondaries of higher energies produce unresolvable clusters of ions. The manner in which the theoretical formula must be modified to be applicable to probable ionization is discussed by Oppenheimer.[3] Above the minimum point the probable ionization increases less rapidly than the primary ionization, but the changes in the shape of the curve below the minimum point are quite small.

The continuous curve in Fig. 2 is Eq. (1) with $k=2\times10^4$ and with the minimum ordinate arbitrarily adjusted to make the curve fit our observed points. The agreement of the theoretical curve with the experimental data is quite good. It is significant that our data differ from the classical $1/v^2$ variation of ionization with velocity, as shown by the dotted curve in Fig. 2. Our observations show the actual increase in ionization with $H\rho$, as predicted by theory.

A point of interest in connection with all our measurements is the ratio of probable to primary ionization. A number or observers[4–6] have measured the primary ionization of fast electrons by counting the number of distinct groups of droplets in sharp tracks, each group corresponding to one primary ion pair. For electrons with velocities comparable to those in the lower energy region of our observations all the observers report the number of primary ion pairs per cm (in air, nitrogen or oxygen at 0°C and 760 mm mercury pressure) to be about 20 or 25. By similar measurements on a few sharp tracks of energies in the minimum part of the curve we find between 14 and 18 primary ion pairs. Our total probable ionization is 50 ions or 25 ion pairs, which gives a ratio of probable to primary ionization of a little less than two. By counting the total number of droplets in diffuse tracks Wilson gives 1.8 for the same ratio. He says this value is low, however, because the larger groups of droplets were not resolved well enough to count. For lower energy electrons and more diffuse tracks he gives 3.5 for the ratio.

From the observed range of electrons, and the variation of range with $H\rho$ one can calculate the average energy loss per cm for an electron of given $H\rho$. If one takes the average energy per ion pair as 32 volts, this calculation indicates an average density of total ionization about twice that given by our droplet counts.

Calculation of Mass

In cloud chamber tracks of moving charged particles the observable quantities are ionization, range and radius of curvature (if in a magnetic field), and the rates of change of these quantities with distance. These quantities depend on the charge, mass and velocity of the particle. It is possible to represent very closely the relationships between these different quantities and their rates of change on a nomograph of straight parallel lines. Such a nomograph is shown in Fig. 3. m/m_0 is the ratio of rest mass to rest mass of the ordinary electron, D is the ratio of specific ionization to specific ionization at the minimum point, D' is the same ratio obtained by use of the $1/v^2$ law. R is the range in cm of

[1] Cf. Bethe, *Handbuch der Physik*, Vol. 24: 1.
[2] Williams, Proc. Roy. Soc. **A135**, 108 (1932).
[3] Oppenheimer, Phys. Rev. **47**, 44 (1935).
[4] C. T. R. Wilson, Proc. Roy. Soc. **A104**, 191 (1923).
[5] Williams and Terroux, Proc. Roy. Soc. **A126**, 289 (1930).
[6] Skramstad and Loughridge, Phys. Rev. **50**, 677 (1936).

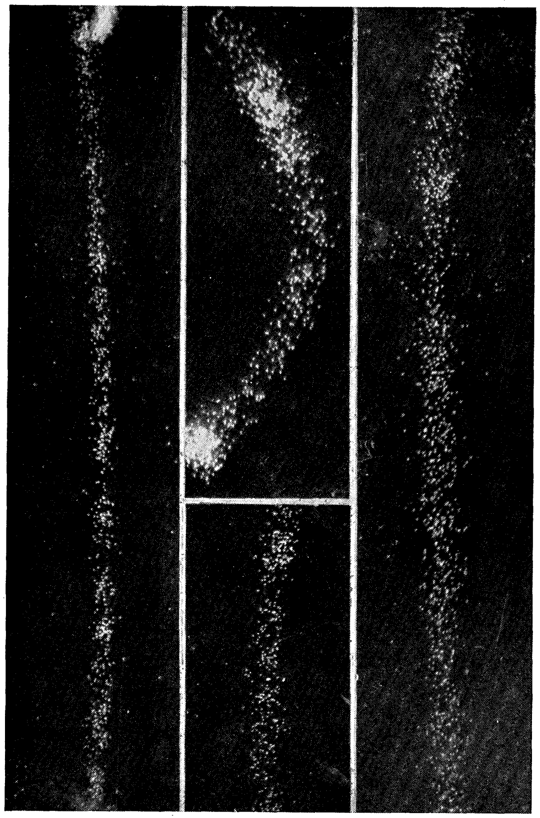

FIG. 1. Sections of electron tracks broadened by diffusion of the ions in delayed expansions.

air at 760 mm of mercury pressure and 15°C. $d(H\rho)/dR$ is the rate of change of $H\rho$ with distance. Any straight line drawn across the nomograph gives consistent values for all the quantities plotted. If the data include any two of the variables the mass of the particle in question is given at once.

From an inspection of the nomograph one sees that $H\rho$ and range afford the most accurate method of determining the mass, provided all the data are given with the same degree of precision. $H\rho$ and D also is a good way to determine the mass, for a relatively large change in D produces a relatively small change in m/m_0. D and range is a poor way to find m/m_0 for the value of D must be accurately given in order to determine m/m_0 within relatively small limits. This last method has the advantage that it does not involve a measurement of curvature, and so is free of distortions which may produce spurious curvatures. A significant fact is that a value of $H\rho$ and a minimum value for the range determine an upper limit on the mass.

The ionization is theoretically independent of the mass, is proportional to the square of the charge on the moving particle, and depends on the particle's velocity as given by Eq. (1). The fact that all particles with β near unity have approximately the same ionization indicates that all cosmic-ray particles carry the charge e. We have defined the relative specific ionization D as the ratio of the specific ionization at a given β to the ionization at the minimum, i.e. at $\beta \sim 0.97$. These values can be calculated from Eq. (1) when the specific ionization at the minimum is known. The experimental value of D is found by dividing the number of droplets per cm in the track by our observed minimum value of 50. In this way the value of β for any track can be found. Then the relationship between m, $H\rho$, and β for a charged particle moving in a magnetic field is given by the equation

$$m/m_0 = H\rho(e/m_0c)(1-\beta^2)^{\frac{1}{2}}/\beta,$$

where m_0 is the mass of the ordinary electron.

Since the loss of energy per cm of path of a charged particle depends only on its velocity one can write $R = kmf(v)$. R is the range in cm of air, m the particle's rest mass and $f(v)$ some function of velocity. This is true for relativistic as well as nonrelativistic energies. Then for all

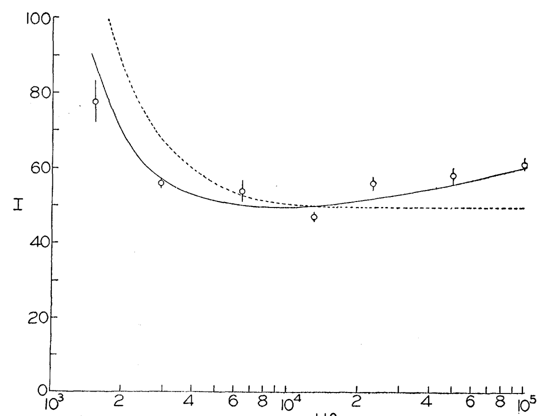

FIG. 2. Specific ionization *vs.* $H\rho$. I is the number of droplets per cm in nitrogen at 0°C and 760 mm pressure. The continuous curve is the theoretical equation (1). The dotted curve is the inverse square law. The vertical lines represent the probable errors of the measurements.

particles of the same velocity $R_1/R_2 = m_1/m_2$. When the velocities are the same we also have $(H\rho)_1/(H\rho)_2 = m_1/m_2$. Then we can use the known ranges of protons[7] to find the range R_1 of a particle of mass m_1 and $H\rho = (H\rho)_1$. Conversely, the range of a particle and its $H\rho$ determine its mass.

It is an experimental fact that the relation between range and velocity may be closely expressed as $R = kv^n$ or $R = k(H\rho)^n/m^{n-1}$. From this one gets

$$R = \rho/[n(d\rho/dR)].$$

Thus ρ and $d\rho/dR$ is sufficient information to determine the range and so the mass. The exponent "n" has a value varying from 3.45 to 3.70 for $10^4 < H\rho < 10^5$ and $80 < m/m_0 < 300$.

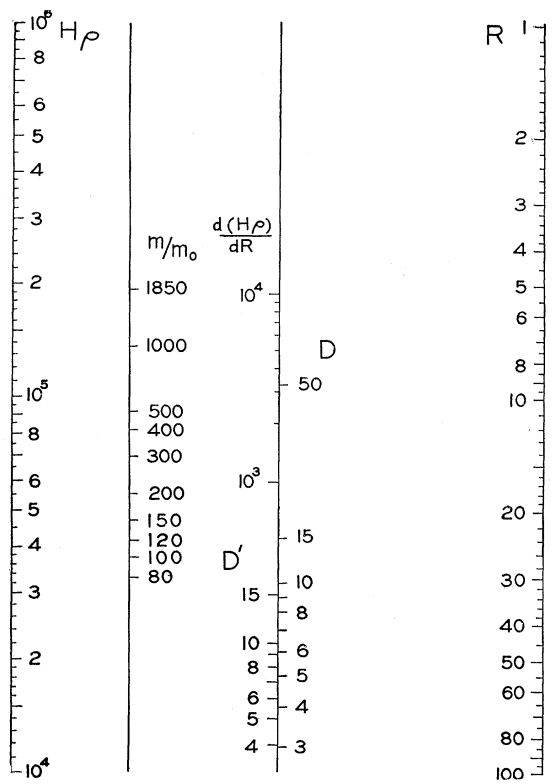

Fig. 3. Nomograph giving mass in terms of variables which can be determined from cloud chamber data. m/m_0 is the ratio of mass to the mass of the ordinary electron, D is the ratio of specific ionization to specific ionization at the minimum, D' is the same ratio from the $1/v^2$ law, R is the range in cm of air at 15°C and 750 mm pressure and $d(H\rho)dR$ is the rate of change of $H\rho$ with distance. Any straight line drawn across the nomograph gives consistent values for all the variables plotted.

[7] Cf. M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 269 (1937).

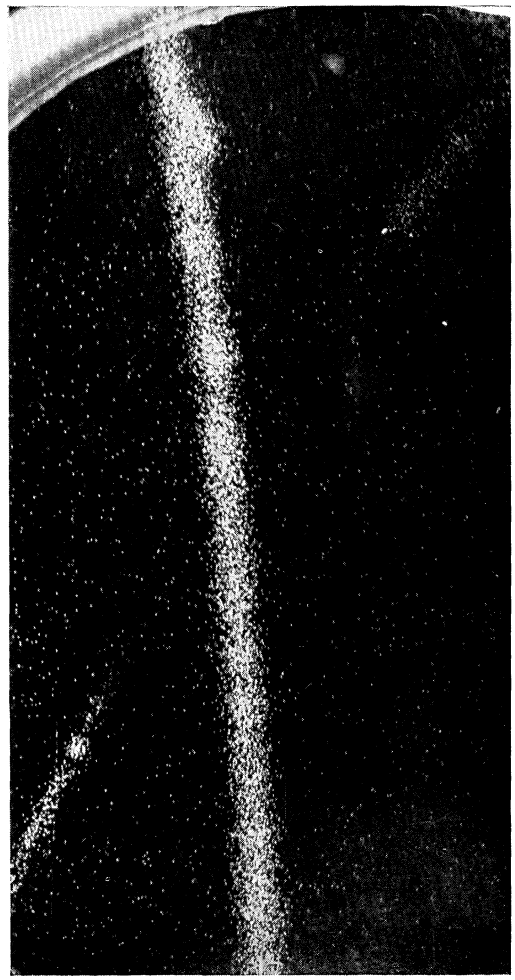

Fig. 4. A photograph of the heavy track previously reported by us. The density of ionization in this track is about 5.5 times that of an ordinary cosmic-ray track. The value of $H\rho = 1.5 \times 10^5$ gives a mass of 250 times the mass of an electron.

It is also possible to find m/m_0 in terms of range and ionization (i.e., in terms of range and velocity), and thus eliminate the necessity of measuring curvature. But, as was pointed out in connection with the nomograph, this is usually not a good way to determine m/m_0.

Application to Heavy Tracks

We have previously reported[8] a track of a heavily ionizing particle, reproduced here in Fig. 4. Because of an error in our calculations the $H\rho$ was incorrectly given. The correct value

[8] Corson and Brode, Phys. Rev. **53**, 215 (1938).

is $H\rho = 1.5\times 10^5$. The number of droplets per cm is 265, which is about 5.5 times the minimum density of normal tracks. By the use of this as the value of D on the nomograph a value of $m/m_0 = 250$ is found.

Another track of interest is one already published.[9] This track has an $H\rho = 5.5\times 10^4$ and an observable range of 18 cm (in nitrogen at 0°C and 760 mm of mercury pressure). These are sufficient data to place an upper limit of $200m_0$ on the mass. The track is out of focus slightly which makes a count of the specific ionization impossible. If the ion density were 10 times that of normal tracks the mass would be $125m_0$. The fact that undeflected tracks appear in the same region in the chamber makes it improbable that the curvature was produced by turbulence.

The track reported by Street and Stevenson[10] has an $H\rho = 9.6\times 10^4$ and an ion density six times that of normal thin tracks. Using the $1/v^2$ law for ionization, D' in Fig. 3, Street and Stevenson gave a mass of $130m_0$. When one uses, instead of D', the column D in Fig. 3 the mass is found to be $160m_0$.

Two unusual tracks have been reported by Anderson and Neddermeyer.[11] One of these tracks has an apparent $H\rho = 5.5\times 10^4$ and has a range of about four cm. This gives a mass of about $350m_0$. The other track has an apparent $H\rho = 1.4\times 10^5$ and a range greater than five cm (the particle apparently passed out of the illuminated part of the chamber). This puts an upper limit of about $1000m_0$ on the mass of the particle.

Ruhlig and Crane[12] reported a track with a curvature of nine cm in a magnetic field of 2850 gauss, and a rate of change of ρ with distance of 0.6 ± 0.4. This gives a mass of $(120\pm 30)m_0$. However, the track appears to have a range of at least five cm, which would place an upper limit of about $110m_0$ on the mass.

Nishina, Takeuchi and Ichimiya[13] reported a particle whose $H\rho$ changed from 7.4×10^5 to 4.9×10^5 in passing through 3.5 cm of Pb. If one assumes that this particle is losing energy only by ionization then the equivalent thickness of air[1] is about 1.8×10^5 cm, or a value of $d(H\rho)/dR = 1.4$. This gives a mass of about $200m_0$.

Discussion

Our measurements indicate that the variation of specific ionization with $H\rho$ (for $H\rho$'s between 10^3 and 2×10^5) is in good agreement with the theoretical equation (1). This agreement includes the verification of the minimum of ionization at $H\rho \sim 10^4$, as predicted by the theory. In determining the velocity (and so the mass) of heavily ionizing particles one should use, not the $1/v^2$ law, but Eq. (1). By use of Eq. (1), and consideration of the errors to which the experiments are subject, it seems that all the heavy tracks reported thus far, with the exception of Ruhlig's and Crane's, are not in serious disagreement with a unique mass lying within the limits $(200\pm 50)m_0$. The disagreement between the different values given for the mass of the heavy particle may be due to errors in determining the radius of curvature in the magnetic field. When the curvature is small it may be influenced considerably by scattering and turbulence. The range can be determined with a relatively high degree of accuracy. In nearly every case one observes a minimum range, thus placing an upper limit on the mass.

We are indebted to Professor J. R. Oppenheimer for his helpful discussions and suggestions.

[9] Brode and Starr, Phys. Rev. **53**, 3 (1938), Fig. 4.
[10] Street and Stevenson, Phys. Rev. **52**, 1003 (1937).
[11] Anderson and Neddermeyer, Phys. Rev. **50**, 263 (1936), Figs. 12 and 13.
[12] Ruhlig and Crane, Phys. Rev. **53**, 266 (1938).
[13] Nishina, Takeuchi and Ichimiya, Phys. Rev. **52**, 1198 (1937).

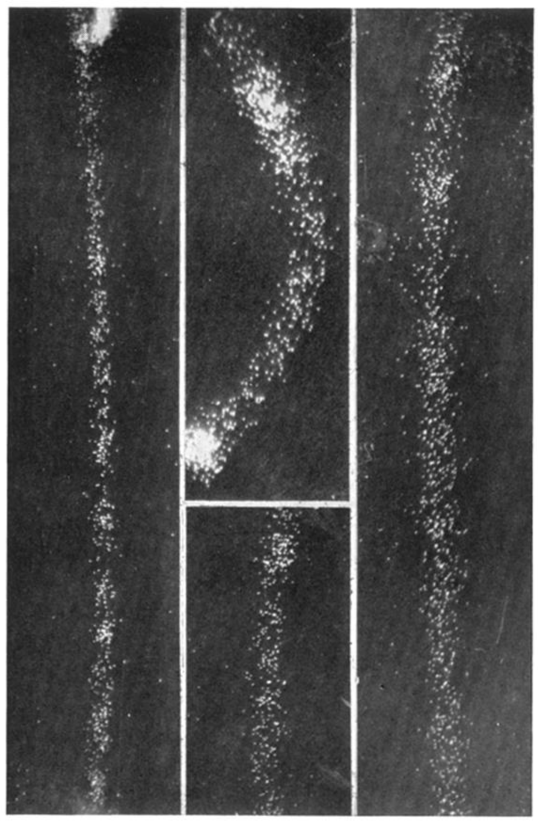

FIG. 1. Sections of electron tracks broadened by diffusion of the ions in delayed expansions.

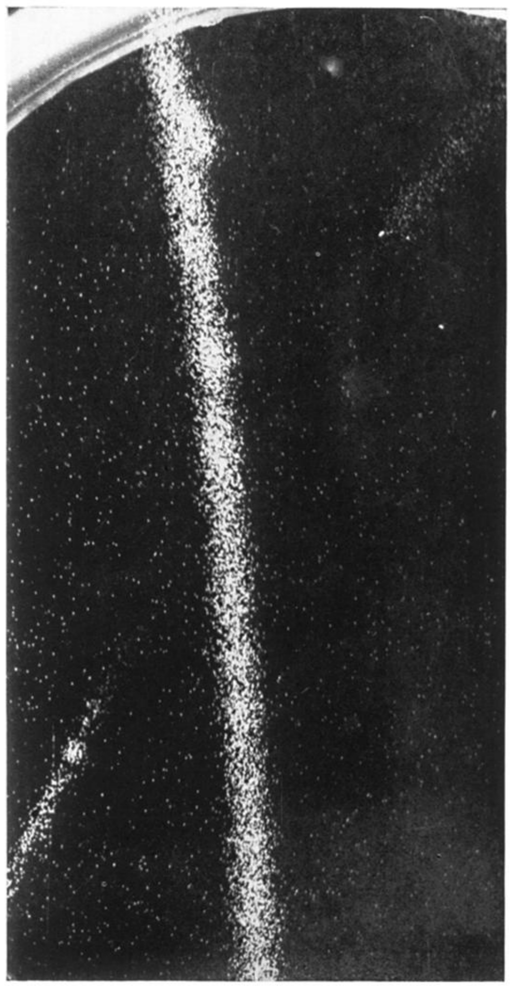

FIG. 4. A photograph of the heavy track previously reported by us. The density of ionization in this track is about 5.5 times that of an ordinary cosmic-ray track. The value of $H\rho = 1.5 \times 10^5$ gives a mass of 250 times the mass of an electron.