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Note on the Nature of Cosmic-Ray Particles

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MEASUREMENTS[1] of the energy loss of particles occurring in the cosmic-ray showers have shown that this loss is proportional to the incident energy and within the range of the measurements, up to about 400 Mev, is in approximate agreement with values calculated theoretically for electrons by Bethe and Heitler. These measurements were taken using a thin plate of lead (0.35 cm), and the observed individual losses were found to vary from an amount below experimental detection up to the whole initial energy of the particle, with a mean fractional loss of about 0.5. If these measurements are correct it is evident that in a much thicker layer of heavy material multiple losses should become much more important, and the probability of observing a particle loss less than a large fraction of its initial energy should be very small. For the purpose of testing this inference and also for checking our previous measurements[2] which had shown the presence of some particles less massive than protons but more penetrating than electrons obeying the Bethe-Heitler theory, we have taken about 6000 counter-tripped photographs with a 1 cm plate of platinum placed across the center of the cloud chamber. This plate is equivalent in electron thickness to 1.96 cm of lead, and to 1.86 cm of lead for a Z^2 absorption. The results of 55 measurements on particles in the range below 500 Mev are given in Fig. 1, and in Fig. 2 the distribution of particles is shown as a function of the fraction of energy lost. The shaded part of the diagram represents particles which either enter the chamber accompanied by other particles or else themselves produce showers in the bar of platinum. It is clear that the particles separate themselves into two rather well-defined groups, the one consisting largely of shower particles and exhibiting a high absorbability, the other consisting of particles entering singly which in general lose a relatively small fraction of their initial energy, although there are four cases in which the loss is more than 60 percent. A considerable part of the spread on the negative abscissa can be accounted for by errors; it seems likely, however, that the case plotted at the extreme left represents a particle moving upward. Particles of both signs are distributed over the whole diagram, and moreover, the initial energies of the particles of each group are distributed over the whole measured range.

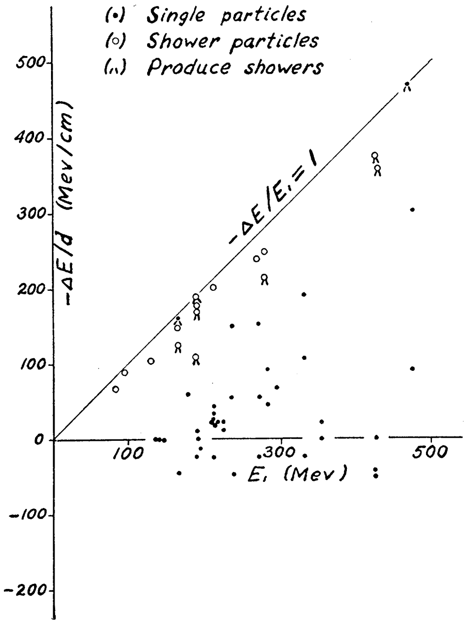

FIG. 1. Energy loss in 1 cm of platinum.

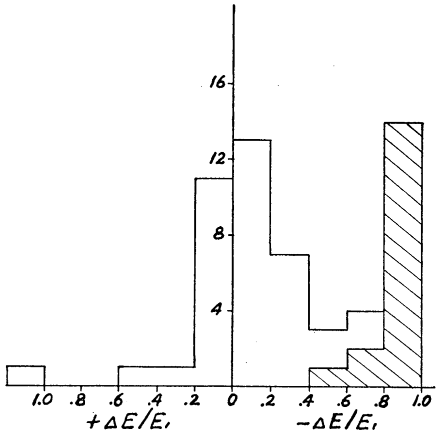

FIG. 2. Distribution of fractional losses in 1 cm of platinum.

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[1] Anderson and Neddermeyer, Phys. Rev. **50**, 263 (1936).
[2] Anderson and Neddermeyer, Report of London Conference, Vol. 1 (1934), p. 179.

The chief source of error in these experiments lies not in the curvature measurements themselves, but in the track distortions produced by irregular motions of the gas in the chamber. The distortions are much larger when a thick plate is inside the chamber than when it is left unobstructed. These distortions are not sufficient to alter essentially the distribution of observed losses for the nonpenetrating group, but they could have a very serious effect in the part of the distribution representing small losses. This is especially true inasmuch as this group represents a small percentage of the total number of tracks, selected solely on the basis that they should exhibit a measurable curvature and at the same time be free from obvious distortion. The problem of measuring small energy losses is then evidently an extremely difficult one compared to that of measuring energy distributions in an unobstructed chamber. While it is possible in many cases to distinguish a distortion as such when a magnetic field is present, it is necessary to obtain independent criteria as to the reliability of the measurements; it is not a satisfactory procedure to try to do this simply by measuring curvatures of tracks taken with no field and comparing the curvature distribution thus found with the one obtained when the field is present. Observations made with no magnetic field indicate that serious distortions occur on about 5 percent of the photographs, and show that they are by no means a uniform function of the orientation and position of the track in the chamber. It is therefore not possible to correct for distortion in individual cases. When large distortions do occur, however, they are likely to obey one or both of the following correlations: (*a*) a curvature concave upward when the track makes a considerable angle with the vertical; (*b*) a curvature concave toward the center of the chamber. The observed percentages of measured single tracks obeying the correlations (*a*) and (*b*) are compared in Table I with the percentages expected if the observed curvatures have no relation to the positions and orientations of the tracks. If the 11 cases of apparent gains in energy are left out of consideration the observed percentages are brought somewhat closer to the expected values as shown in the last column.

TABLE I. *Correlations between track curvatures and positions and orientations of tracks.*

Designation (See text)	Percentage correlation		
	Observed	Expected	Observed (excluding apparent gains)
(*a*)	52	50	55
(*b*)	67	50	55
(*a*) and (*b*)	33	25	27
neither	15	25	18

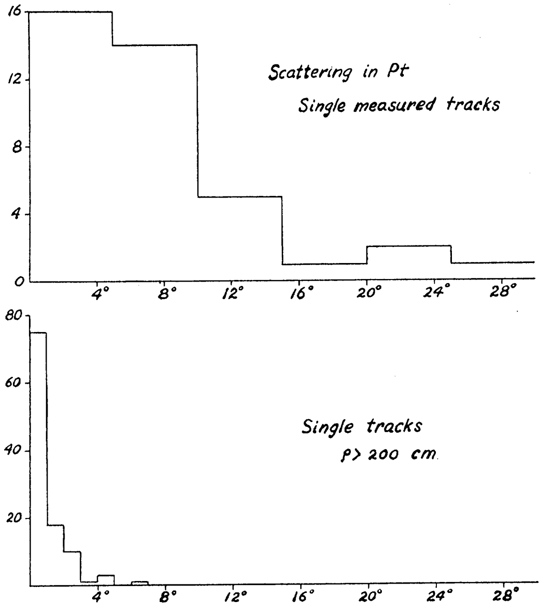

FIG. 3. Scattering distributions in 1 cm of platinum.

A second independent check on the validity of the measurements can be obtained by measuring the scattering of the particles which show apparent curvatures, and comparing this with the scattering exhibited by those single tracks whose curvatures are just outside the range of measurability. In Fig. 3 are shown the distributions of scattering angles (the angles projected on the plane of the chamber) for the measured single tracks and for single tracks with a radius of curvature, $\rho \gtrsim 200$ cm (475 Mev). As it is scarcely conceivable that distortions could influence the scattering measurements by as much as 5°, these distributions constitute strong independent evidence that the measured tracks actually lie in the energy range indicated by the curvature determinations.

It has been known for a long time that there exist particles of both penetrating and nonpenetrating types. Crussard and Leprince-Ringuet[3] have recently made measurements of

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[3] Crussard and Leprince-Ringuet, C. R. **204**, 240 (1937).

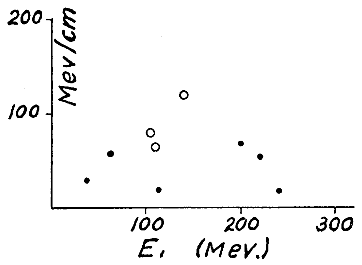

FIG. 4. Early measurements of energy loss in 0.7–1.5 cm of Pb. Dots indicate single particles; circles, shower particles.

energy loss in a range mainly above that covered in our experiments. They have concluded from their data that either the absorption law changes with energy or else that there is a difference in character among the particles. This same conclusion has already been twice stated by the writers.[4, 5] The present data appear to constitute the first experimental evidence for the existence of particles of both penetrating and nonpenetrating character in the energy range extending below 500 Mev. Moreover, the penetrating particles in this range do not ionize perceptibly more than the nonpenetrating ones, and cannot therefore be assumed to be of protonic mass. The lowest $H\rho$ among the penetrating group is 4.5×10^5 gauss cm. A proton of this curvature would ionize at least 25 times as strongly as a fast electron. It is interesting that our early measurements[2] of the energy loss in thicknesses of lead from 0.7 to 1.5 cm show a similar tendency to separate into two groups. They are reproduced in Fig. 4. If reinterpreted in the light of our present data they provide no evidence against high absorbability for electrons.

The nonpenetrating particles are readily interpreted as free positive and negative electrons. Interpretations of the penetrating ones encounter very great difficulties, but at present appear to be limited to the following hypotheses: (*a*) that an electron (+ or −) can possess some property other than its charge and mass which is capable of accounting for the absence of numerous large radiative losses in a heavy element; or (*b*) that there exist particles of unit charge, but with a mass (which may not have a unique value) larger than that of a normal free electron[6] and much smaller than that of a proton; this assumption would also account for the absence of numerous large radiative losses, as well as for the observed ionization. Inasmuch as charge and mass are the only parameters which characterize the electron in the quantum theory, assumption (*b*) seems to be the better working hypothesis. If the penetrating particles are to be distinguished from free electrons by a greater mass, and since no evidence for their existence in ordinary matter obtains, it seems likely that there must exist some very effective process for removing them.

The experimental fact that penetrating particles occur both with positive and negative charges suggests that they might be created in pairs by photons, and that they might be represented as higher mass states of ordinary electrons.

Independent evidence indicating the existence of particles of a new type has already been found, based on range, curvature and ionization relations; for example, Figs. 12 and 13 of our previous publication.[1] In particular the strongly ionizing particle of Fig. 13 cannot readily be explained except in terms of a particle of e/m greater than that of a proton. The large value of e/m apparently is not due to an e greater than the electronic charge since above the plate the particle ionizes imperceptibly differently from a fast electron, whereas below the plate its ionization definitely exceeds that of an electron of the same curvature in the magnetic field; the effects, however, are understandable on the assumption that the particle's mass is greater than that of a free electron. We should like to suggest, merely as a possibility, that the strongly ionizing particles of the type of Fig. 13, although they occur predominantly with positive charge, may be related with the penetrating group above.

We wish to express our gratitude to Professor Millikan for his helpful discussions and encouragement. These experiments have been made possible by the Baker Company, who very generously loaned us the bar of platinum; and by funds supplied by the Carnegie Institution of Washington.

Note added in proof: Excellent experimental evidence showing the existence of particles less massive than protons, but more penetrating than electrons obeying the Bethe-Heitler theory has just been reported by Street and Stevenson, Abstract no. 40, Meeting of American Physical Society, Apr. 29, 1937.

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[4] Reference 2, p. 182.

[5] Reference 1, p. 268.

[6] The energies referred to throughout are, of course, calculated on the assumption of electronic mass. For a mass $m \lesssim 50m_e$ the actual energy is very roughly $E = E_{el} - mc^2$ in the range of curvature here considered.