COSMIC-RAY PARTICLES

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(Received January 28, 1932)

Abstract

Specific Ionization. In a previous experiment, a number of thin straight tracks formed in a Wilson cloud-apparatus were identified as cosmic-ray particle tracks, by means of a Geiger-counter. The specific ionization along these has now been determined and is found not to exceed 36 ion-pairs per cm, in air at 1 atmosphere. This is less than one third the ionization calculated by Kolhörster and Tuwim, whose value is believed to be erroneous, at least for individual tracks, for reasons set forth in this paper.

"Group Phenomenon". On 148 stereopictures of tracks attributed to cosmic-ray particles, 20 groups of 2 or more such tracks were found. The tracks of a group usually converge to a point near at hand, which suggests that they have a common source. Each group is believed to be made by secondary electrons ejected by one photon. Possible explanations of the origin of the groups have been considered; the one that seems most favorable supposes that a cosmic-ray photon may interact with an atomic nucleus and eject one or more fast β-particles from it; the convergent groups are, then, formed when 2 or more particles are ejected from one nucleus. The production of groups may affect the interpretation of various ionization and Geiger-counter experiments with cosmic-rays. Some energy calculations have been made on the basis of the measured specific ionization of the cosmic-ray particles; for example, a minimum of 5×10^8 *e*-volts energy are required to send an electron through the earth's atmosphere. An ionization experiment is proposed, by which it should be possible to tell whether or not cosmic-rays produce groups of tracks by nuclear disruption.

The Specific Ionization

THE specific ionization of cosmic-ray particles may be calculated by determining the rate of their influx with a Geiger-Müller counter of known dimensions and getting the corresponding ionization produced in an ionization chamber whose dimensions are also known, or more directly, by counting the number of ions in a Wilson cloud-chamber along tracks that are identified to be due to these particles.

Using the former method, Kolhörster and Tuwim[1] have recently calculated that the average specific ionization is 135 ion-pairs per cm ± 10 percent, in air at normal pressure, or about the same as that of β-particles of velocity 0.6 C. In order for β-particles of cosmic origin to have the necessary penetration and still produce the observed ionization, they calculated that the energy must be $E > 2\times10^9$ electron-volts. On the other hand, an ordinary β-particle of velocity 0.6 C has only 127,000 volts energy, so it is very hard to reconcile the high energy of a cosmic-ray corpuscle with its high rate of ionization, since the ionization of a β-particle is thought to approach a minimum of about 40 ion-pairs per cm as the velocity approaches that of light. Assum-

[1] W. Kolhörster and L. Tuwim, Zeits. f. Physik **73**, 130 (1931).

ing that 135 ion-pairs per cm is correct, 2×10^9 volts is of the right order to allow the cosmic-rays to penetrate the whole atmosphere and still have enough energy to eject 2×10^8-volt electrons, independently of whether the cosmic-rays, themselves, are photons or swift β-particles.

The present paper proposes, first, that the specific ionization along *individual* cosmic-ray particle tracks is very much less than 135 per cm, and, second, that the particles arrive in *groups*, which may explain the high average ionization got by Kolhörster and Tuwim.

In a recent experiment,[2] L. M. Mott-Smith and the writer obtained ion-tracks in a Wilson cloud-apparatus simultaneously with discharges of a Geiger-Müller counter arranged above the chamber. Then, from stereoscopic reconstruction of the tracks formed under such conditions, it was found that they were usually in line with the counting-tube. The evident conclusion was that a cosmic-ray particle had, in each case, set off the counter discharge and proceeded through the chamber, making the observed ion-track.

Fig. 1. Cosmic-ray particle tracks in air at 68 cm pressure. Magnification $\times 4.03$.

All of the good pictures of tracks that were identified in that way have been photographed again under a low-power microscope, in order to count the ions, with results such as are shown in Fig. 1. This could only be done with the denser tracks, for some were so faint, either due to their small ionization or to weak illumination, that it was previously found necessary to mark the positions of their images by scratching fine lines on the negatives before using them in the stereo-reconstruction outfit. For this reason, also because of the evident difficulty of resolving individual droplets in the tracks, it is only possible to fix an approximate upper limit to the ionization along them. In all cases a liberal allowance was made for the bunching of ions, which results in a diminution of the number of drops. The specific ionization thus determined does not exceed 32 ion-pairs per cm, in water-saturated air at 68 cm pressure, or $32\times76/68=36$ pairs per cm at normal pressure. This is less than one third of the value calculated by Kolhörster and Tuwim, but is in agreement with the 40 pairs per cm estimated by Skobelzyn[3] for similar tracks that he found to be undeflected by a magnetic field of 1500 gauss.

The problem is, then, to explain the discrepancy between the values obtained on Kolhörster and Tuwim's calculation and the cloud-chamber deter-

[2] L. M. Mott-Smith and G. L. Locher, Phys. Rev. **38**, 1399 (1931).

[3] D. Skobelzyn, Zeits. f. Physik **54**, 686 (1929).

minations, since it seems especially desirable that the specific ionization should be known with some certainty, because of its bearing on the interpretation of ionization experiments and for determining the energy (so perhaps deducing the origin) of cosmic-rays.

Very heavy tracks were produced in the cloud-chamber by α-particles and x-ray photoelectrons, under conditions exactly similar to those existing during the formation of the cosmic-ray particle tracks. This leads to the belief that every ion-pair in these relatively thin tracks was the nucleus of a droplet, since there was always an abundance of super-saturated water vapor available for condensation. The present count is based on the assumption that every drop represents an ion-pair, and that every ion-pair gave a drop, the separation of the ions of any pair being too small to be detected by the means used, at 68 cm pressure.* Concerning the electrical method, it seems quite certain that not every cosmic-ray particle passing through a counter will give an impulse in it, especially because of the "group phenomenon" described in the next section, and if the number counted is less than the number penetrating the tube, the specific ionization calculated on this basis will be too large. On the other hand, there is a possibility that some of the ions in the cloud-tracks recombine before condensation can occur on them, resulting in an apparent reduction of the specific ionization; but the same argument would apply even more strongly to recombination in the ionization chambers, because of their higher pressure, thus emphasizing the present disagreement, instead of removing it.

The "Group Phenomenon"

By the "group phenomenon" is meant the practically simultaneous arrival of two or more penetrating particles, in a given small region, more often than can be explained by accidental coincidence. It was first noticed by Auger and Skobelzyn,[4] who found, on 27 cloud-pictures of tracks that were undeflected

Series Number		Pictures with thin, straight tracks	Groups of these tracks
1		74	13
2		11	1
3		63	6
	Totals:	148	20

"Track-pictures" showing groups: 20/148 = 13.5 percent (If the count is not restricted to thin straight tracks, the ratio becomes: 33/177 = 18.6 percent).

by a field of 1500 gauss, 4 cases in which there were groups of these tracks. It was thought that the particles were recoil electrons due, in each case, to repeated Compton scattering of one of the hardest components of "ultra-gamma" radiation. They calculated that such electrons would have sufficient

* Another effect might tend to reduce the number of drops photographed: one drop may screen off the light from another, while the picture is being taken. But the sparseness of the ionization in these thin tracks makes it unlikely that this is important, even with the worst orientation of the track with respect to the line of illumination.

[4] P. Auger and D. Skobelzyn, Comptes Rendues **189**, 55 (1929).

penetrating power to follow the quantum through the chamber, making a group of tracks.

The 1770 pairs of pictures collected in the present experiment[2] show the results, (see table on preceding page) with regard to groups.

A significant observation was made: *the tracks of a group usually converge to a point near at hand.* Fig. 2, *a*, *b*, *d*, and *f*, shows some groups of this type. The agreement of the 13.5 percent of groups with Auger and Skobelzyn's 4/27 = 14.8 percent may be accidental, but the high percentage (especially of 3), and the convergence of the tracks, is believed to be important. In one case, there were 5 straight tracks on one picture, 3 of which converged at the wall of the chamber; in 5 cases there were groups of 3 tracks, while the other 14 were pairs. One member of one group was aligned with the counting-tube above the chamber; also, a discharge of the counter was recorded simultaneously

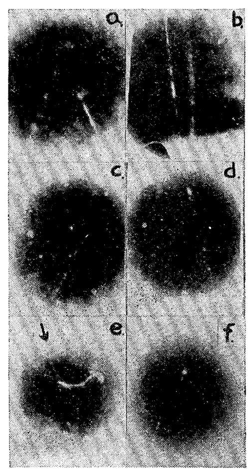

Fig. 2. *a*, *b*, *d*, and *f*, groups of tracks emanating from a common point; *c*, a bent track; *e*, track with a 22,000-volt branch. Magnification ×1.21.

with the formation of the track, indicating that the particle had passed through it, hence was of the type previously discussed. Examination of the tracks of the groups with a microscope shows that the specific ionization along them is about the same as for tracks identified by means of the counter, so the velocities of the particles must exceed 0.9 C.

The convergence of the tracks shows that the particles could not have been liberated at great distances from the apparatus, and indicates that they were produced by one cause and are not merely due to chance arrival of several particles at nearly the same time (within 0.06 sec.). In view of the existence of these groups, as well as their convergence, it is difficult to support the view of Bothe and Kolhörster, that cosmic-rays are only swift β-particles coming from inter-stellar space; it is more probable that the observed particles are secondary electrons ejected from atoms near at hand, by high energy photons. These electrons may come either from inside or outside the nuclei of the atoms, since the cosmic-ray energies so greatly exceed those of

γ-rays. If the tracks of each group converge to a point, approximately, it is difficult to explain them as being made by recoil electrons due to Compton scattering, because of the low probability of getting more than one scattering within so small a thickness of matter as the wall of the cloud-chamber (5mm of glass). The same difficulty would apply to the ejection of electrons from the nuclei, unless more than one electron is ejected when a cosmic-ray photon collides with a nucleus. It may be, however, that the constituents of the nucleus are so closely packed as to allow a considerable probability of the simultaneous ejection of two or more particles, due to a collision of this type; or the ejection of even one such electron may destroy the equilibrium of the nucleus and cause it to eject additional corpuscles, within a very short time. These processes would constitute atomic disintegration, brought about by cosmic rays, instead of beginning spontaneously as in ordinary radioactivity.

Clearly, a group of particles passing simultaneously through a Geiger-counter, or any arrangement of counters, will cause only a single impulse; hence the number of impulses recorded will be less than the number of particles passing through. This will affect ionization determinations, and perhaps other measurements, involving the use of counters. For example, Kolhörster and Tuwim's value of the specific ionization of cosmic-ray particles is about 3.7 times as great as the author's. To explain the discrepancy on the basis of this effect alone, it would only be necessary to assume that Tuwim's counter gave, on the average, one impulse for every 3 or 4 electrons traversing an equivalent volume of Kolhörster's ionization chamber. It will be further noticed that the divergence of the tracks of the groups increases the effective size of any counting-tube or other device arranged to intercept them.

Another point to consider is the effect of the secondary electrons liberated from the walls of an ionization chamber, on the ionization measured therein. In this connection, suppose a beam of very penetrating rays produces secondary electrons as it passes through successive layers of matter of different densities, but undergoes little total absorption. A simple calculation shows that the number of secondary electrons in any cross-section of the beam is constant, hence independent of the density of the material traversed, even at a boundary, provided that the number ejected per cm varies directly with the density of the material, and the length of track varies inversely with the density. These conditions are approximately satisfied by γ-rays, and may even apply to cosmic-rays, if these latter only eject recoil electrons from outside the nucleus and *single* electrons from inside. But if there is a finite probability that more than one electron will be ejected from a nucleus by a single photon, this probability must be a function of the atomic number of the element under bombardment, so that the mass law will not hold. For example, the number of cosmic-ray particles crossing a section would be the same for gaseous oxygen as for liquid oxygen, but the number would be different for oxygen and iron, on this supposition, because the nuclei are different. To test this experimentally, one could compare the cosmic-ray ionization in a series of ionization chambers that have the same dimensions and gas content, but have walls of metals of different atomic numbers (with the same mass per unit area). This might well be done by comparing the ionization in pairs of the chambers, using a differential method. (Evidently Geiger-counters could not be used, because the effect investigated is due to simultaneous groups of particles.) The ionization produced in the same chambers by radioactive γ-rays could be used as a check, in case the experiment gave positive results; this should be the same in all the chambers. The author believes that this experiment would lead to positive results, because of the groups of tracks observed in cloud-chambers. The absorption anomalies found by Geiger, Steinke, and others[5] are also thought to be connected with the group phenomenon.

Some Energy Considerations

Some simple deductions about the order of magnitude of the energy of cosmic rays have been made from the value of the specific ionization. These calculations are mostly speculative, because of the uncertainty of the hypotheses on which they are based, but they may be of interest.

A β-particle of energy $E > 7 \times 10^8$ volts, and specific ionization 36, could pass through the atmosphere and still have residual energy $> 2 \times 10^8$ volts, which is sufficient to allow it to penetrate about 40 cm of lead. (A specific ionization of 135 in air would require $E > 2 \times 10^9$ volts.)

The path of an electron of 2×10^8 volts energy is $\geqq 3500$ meters in air at normal pressure; this corresponds to about 4.6 meters in water, or 42 cm in lead. If a photon of 2×10^9 volts energy produces, on the average, one 2×20^8 volt electron at every 950 meters of its path through the atmosphere, then any cross-section of the photon's path should have 3.7 electrons in it, if they are ejected in the forward direction. This would account for the high value of the specific ionization calculated by Kolhörster and Tuwim. Such photons would undergo about 10 scatterings in traversing the atmosphere, so that homogeneous incident radiation would be degraded into a spectrum with energy between 2×10^9 and zero, at the earth's surface. This is suggested as a possible process, rather than a probable one. Elaboration and test of a good theory of nuclear absorption seems especially desirable.

Fig. 2, *c*, and *e*, shows two interesting tracks, probably of recoil electrons from radioactive γ-rays, that were found among the pictures collected in this work. A sharp bend in the first (43° deflection) indicates close approach of the particle to a nucleus. In the case of the track shown in *e*, a 22,000 -volt branch was produced, causing a deflection of only 5.7° in the path of the β-particle. Assuming that both were electrons, and that momentum was conserved at the impact, the velocity of the impinging one was 0.92 C (energy 7.8×10^5 volts). Evidently an electron of 10^8 volts energy would undergo no appreciable deflection in producing a similar branch.

The author is indebted to the National Research Council for a grant which met part of the expense of the experimental work herein described.

Professor H. A. Wilson has very kindly criticized this paper and has suggested part of the ideas and calculations incorporated in it, for which the author wishes to express his appreciation.

[5] Discussion of Ultra-Penetrating Rays, Proc. Roy. Soc. **A132**, 331 (1931).

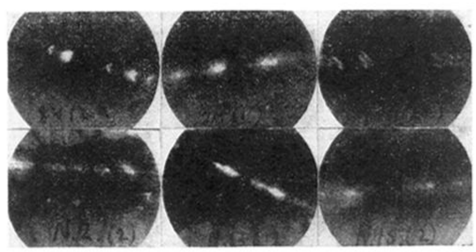

Fig. 1. Cosmic-ray particle tracks in air at 68 cm pressure. Magnification $\times 4.03$.

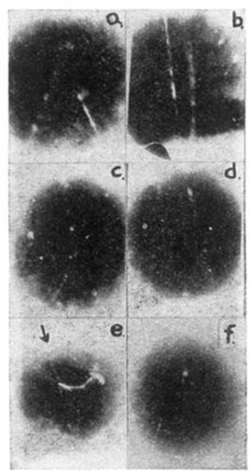

Fig. 2. *a*, *b*, *d*, and *f*, groups of tracks emanating from a common point; *c*, a bent track; *e*, track with a 22,000-volt branch. Magnification ×1.21.