Second Series *May 1, 1932* *Vol. 40, No. 3*

THE

PHYSICAL REVIEW

Cosmic-Ray Energies and Their Bearing on the Photon and Neutron Hypotheses

BY ROBERT A. MILLIKAN AND CARL D. ANDERSON
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA

(Received April 12, 1932)

ON NOVEMBER 20, 1931, in a lecture before a large audience gathered at the Institut Poincaré in Paris, there were presented the first direct measurements taken by Carl D. Anderson of the energies of cosmic-ray tracks made with an apparatus capable of measuring, by the method of magnetic deflectibility in air, energies of the order of magnitude to be expected in cosmic-ray photon-encounters with electrons and nuclei, namely, from 27×10^6 volts up to at least 500×10^6 volts. These same photographs were also shown on November 23rd at a physical seminar at the Cavendish Laboratories. Cambridge, England. The eleven cosmic-ray-track photographs shown and discussed on these occasions[1] brought to light a certain number of new and important facts presented essentially as listed below in both of these lectures, and these facts have now been checked by three times as many successful exposures.

1.

The incident cosmic rays are absorbed *primarily* by the nucleus, rather than by extra-nuclear electrons, as heretofore generally assumed. This is shown by the new observation that the curvature of the tracks produced by a 17,000 gauss magnetic field corresponds more frequently to positive than to negative particles, though both appear. Positive particles can obviously come only from the nucleus. The length of the tracks available for the measurement of curvatures was here 6 inches, or 15 centimeters, in magnetic fields up to 20,000 gauss.

2.

In some 17 percent of the observed encounters between cosmic rays and the nucleus, the latter was disintegrated, both positive and negative particles being thrown out of it. Since a given photographic plate will often catch but

[1] One of the best of the photographs, showing a negative track of energy 140 million volts and an associated positive track of energy about 70 million volts, was published on December 18th, 1931, in Science Service, Washington, D. C., along with Dr. Anderson's photograph, under the title "Cosmic Rays Disrupt Atomic Hearts."

one of two or more associated tracks, a much larger percentage of the encounters is doubtless of this sort. Auger and Skobelzyn[2] had before observed double cosmic-ray tracks, but they had not been in position to differentiate between positives and negatives nor to measure their energies. Observations 1 and 2 show that formulae like the Klein-Nishina, which deal only with absorption by free electrons (negative or positive), can have no validity in the cosmic-ray field.

3.

The incident rays act like photons in two important particulars.

First, they appear to make occasional Compton encounters with electrons; showing in a 17,000 gauss field circular tracks just like those produced in check experiments made with gamma-rays, save that the cosmic-ray electrons show much larger circles—circles corresponding to energies up to 20 million volts.

Second, the fact that the incident rays give rise to more tracks that come from the nucleus than from extra-nuclear encounters is a definite photon-property. For, as is well known, x-rays and gamma-ray photons are always absorbed most copiously by those constituents of the absorbing atoms the binding energy of which is nearest the incident photon energy, provided only this latter exceeds the binding energy. Both of these properties might conceivably be possessed also by neutrons, recently suggested by Chadwick[3] to account for certain effects observed with highly penetrating rays produced by the impact of alpha-rays on beryllium, but this would be not only an *ad hoc* assumption, but an extremely unlikely one. The neutron-assumption seems, then, to be quite unnecessary for the interpretation of these observed cosmic-ray effects.

4.

Out of about 1000 exposures, 34 show measurable cosmic-ray tracks. Of these 34, 6, or 17 percent, represent associated tracks, as above stated, in which at least two particles—one a positive in four of the 6 cases—have come from one nucleus, the joint energy, assuming the positive to be a proton, the negative an electron—the most reasonable hypotheses—is in 4 cases about 200 million electron-volts, in one case but 21 million electron volts, and in the last of the 6 cases about 500 million electron volts.

Of the 34 tracks, 11 are single positive tracks of proton energy, as follows: 4 of around 150 million volts, 3 of around 100 million volts, 2 of 250 million volts, and 2 of 350 million volts.

There are also 2 single negatives of electron energy around 350 million volts.

There are 3 single low energy positives of proton energy from 16 to 40 million volts.

[2] Auger and Skobelzyn, C. R. **189,** 55 (1929). See also Skobelzyn, Zeits. f. Physik **54,** 686 (1929).

[3] Chadwick, Nature **129,** 312 (1932).

There are 5 beautifully circular single electron tracks that look like Compton encounters with extra-nuclear electrons, the electron-energies being from 7 to 18 million volts.

There are 3 single positives and 1 negative of energy around 500 million volts, and, finally, there are 3 positives and perhaps 1 negative, though its sign is doubtful, the curvatures of which seem to reveal energies of the order of 1000 million volts.

In a word, then, on the assumption that the tracks are due in all cases either to protons or to electrons, *nine-tenths of all the observed encounters yield energies which lie within the ranges computed from the Einstein equation and the atom-building hypothesis.* The helium-building rays of energy 27 million volts would all be absorbed before they get down to sea level, so that the incoming photons reaching the apparatus should be photons due to oxygen-building, by Einstein's equation of energy 116 million volts, or photons due to silicon-building of energy 216 million volts, or photons due to iron-building of energy about 500 million volts.

The other tenth of the tracks, however, appears to possess, with the foregoing assumptions, energies too high to be accounted for by this theory of origin. There is one observed fact, however, which seems to speak against the reality of these exceedingly high energies. It is that most, if not all, of the nearly straight, i.e., high energy tracks, show very small sudden changes in direction, such as both beta and alpha-rays from radium always reveal but which are not to be expected from the theory of scattering with the enormously high energies connected with the observed curvatures. There is, therefore, just a possibility that these few apparently very high energy tracks have been straightened by encounters, and are not actually of so great energy as they seem to be. In any case, the abundance of these sudden changes in direction speaks for a lower energy than is computed from the smallness of the apparent general curvature. Further study of these sudden changes in direction is needed before final conclusions can be drawn.

The fact herewith for the first time revealed of *the disintegration of the nucleus* definitely shown by the appearance of positive charges which, on account of the observed intensity of ionization, cannot be attributed to whole nuclei, these positives too often accompanied by high energy negatives, shows the illegitimacy of, in general, treating an encounter between a photon and a nucleus as a simple Compton encounter between a photon and one of the electrons or protons within the nucleus. The high energy of the negatives also eliminates the possibility, in view of the masses involved, that they have acquired their energy from encounters with high energy protons. Since the the whole energy of an incident photon may be absorbed within a nucleus which is disintegrated, without involving any violation either of the conservation of momentum or of the conservation of energy, the photon hypothesis as to the nature of the incident rays encounters no difficulty in explaining the observed energies; for practically the whole of the energy of the incident photon, or any fraction thereof, should be able to appear in a single ejected proton or electron, or in a number of such.

Some of the single high energy negatives may, however, represent simple Compton encounters of high energy photons with free negatives, for a high energy photon should be able even in a Compton encounter to transfer a large fraction of its energy to a free electron, while a neutron of rest-mass about that of the proton cannot possibly transfer more than one five-hundredth of its energy to a free electron, so that the photon hypothesis has greater flexibility in accounting for the observed high energy protons and electrons than has the neutron-hypothesis. The later seems to us quite impotent in the face of the herewith observed cosmic-ray energies, since no neutron of any energy whatever less that 10^9 volts can impart to a free electron as much as 3 million volts of energy, and yet our observed energies in what look like Compton encounters are nearly all from seven to twenty million volts. Only the photon hypothesis seems, then, to fit these facts.