have found the shape of the tail to be a sensitive function of surface impurity and only the cleanest surfaces show agreement with the Fermi factor. Once the Fermi tails are obtained however further precautions in outgassing procedure produce no further changes in the curve form.

In conclusion the author wishes to express his indebtedness to Professor L. A. DuBridge under whose direction this work was begun and to Dr. F. Seitz and Dr. M. S. Plesset for many helpful discussions of the theoretical aspects of this problem. Thanks are also due to the Bausch and Lomb Optical Company for the loan of a monochromator.

JANUARY 15, 1938 PHYSICAL REVIEW VOLUME 53

The Energy Flux of the Corpuscular Cosmic Radiation

C. G. Montgomery and D. D. Montgomery
Bartol Foundation of the Franklin Institute, Swarthmore, Pennsylvania
(Received November 26, 1937)

The recent advances in cloud chamber technique have made possible the measurement of such high energies of cosmic-ray corpuscles that one is led to inquire how much of the total energy of the cosmic radiation appears in a measurable form in the cloud chamber. It is possible to estimate the total flux of cosmic-ray energy across a unit surface, since all of this energy must eventually appear at points below the unit surface in the form of ionization and the excitation of atoms. Thus if we know the ionization at each point below our surface, we can integrate it and so obtain the total flux of energy through the surface. If we know also the number of corpuscular rays, we can obtain the mean energy per ray at any point. This can then be directly compared to the cloud chamber observations.

If we wish to consider only rays coming in near the vertical, as is the case in most counter controlled cloud chambers, we must know not the integral of the total ionization but the integral of the ionization produced by the vertical rays. For depths below the top of the atmosphere greater than four meters of water, where all the rays may be considered to travel straight paths,[1] the ionization produced by vertical rays, V, may be obtained by Gross' equation,[2] from the total ionization, I:

$$2\pi V = I - h dI/dh, \qquad (1)$$

where h is the depth below the top of the atmosphere. The mean energy is then

$$E_V = \frac{J}{n(h)}\int_h^\infty V dh, \qquad (2)$$

where $n(h)$ is the number of vertical rays per second per square centimeter per unit solid angle, and J the energy expended to form one ion. Substituting from Eq. (1) and integrating the second term by parts we have,

$$E_V = \frac{J}{2\pi n(h)}\left[2\int_h^\infty I dh + hI\right].$$

This we shall evaluate from the data of various observers. Since it may be of interest, in other connections, to obtain the mean energy of all the rays crossing a horizontal unit surface, we write also the expression for this mean energy:

$$E_T = J\frac{\int_h^\infty I dh}{2\pi\int_0^{\pi/2} n(h,\theta)\sin\theta\cos\theta d\theta}.$$

To evaluate these expressions, we have chosen for the values of the ionization below sea level

[1] W. F. G. Swann, G. L. Locher and W. E. Danforth, Phys. Rev. **51**, 389 (1937); Nat. Geog. Soc. Contributed Tech. Papers, Stratosphere Series, No. 2 (1936).
[2] B. Gross, Zeits. f. Physik **83**, 214 (1933).

the observations of Kramer[3] as corrected for residual ionization by Ehmert.[4] These observations were multiplied by a constant factor so that the ionization at sea level was 2.48 ion pairs/cc/second as given by Millikan.[5] The values of the ionization above sea level were taken from Millikan and Cameron, and Bowen, Millikan and Neher.[6] For the counting rate below sea level, the observations of Ehmert[4] were employed, and above sea level the results of Swann and Danforth[7] were used. The angular distribution of cosmic-ray particles counted at sea level was taken from Johnson and Stevenson.[8] The number of rays crossing a horizontal square centimeter 0.664 meters below the top of the atmosphere was obtained by integrating the results of Swann, Locher and Danforth.[1] All the counter observations were normalized to the value 1.33×10^{-2} per square centimeter per second per unit solid angle at sea level for the vertical direction.[9] The value of J was taken as 32 volts per ion pair. Table I gives the results of the calculations. For depths below the top of the atmosphere greater than 43 meters of water, Ehmert gives empirical formulae for the ionization and the number of rays. These result in the expressions in the last line of Table I. The values of the mean energy found in this way are illustrated in Fig. 1. Curve A gives the mean energy of the vertical rays, curve B the mean energy of all the rays crossing a horizontal square centimeter. It will be noted that the mean energy increases with increasing h. This is representative of the fact that there is a distribution of energies in the primary cosmic radiation, since the mean energy of the rays produced by a primary of a given energy must always decrease with increasing h. The mean energy at 0.664 meters below the top of the atmosphere is 1.46×10^9 volts, and since the earth's magnetic field excludes vertically incident rays of energy less than 6×10^9 volts, the mean energy must increase to some value of this order at the top of the atmosphere. This rise is indicated by the dotted portion of curve B.

We are now in a position to compare the results of the cloud chamber observations with those of these calculations. We choose for this purpose the observations of Blackett.[10] Blackett measures the energy distribution of the vertical rays up to energies of 2×10^{10} volts. Using his energy distribution, one finds that the total energy of the 1015 rays of energy less than 2×10^{10} volts is 2.44×10^{12} volts. He observes in addition 42 rays of energy greater than 2×10^{10} volts, which must have a total energy greater than 0.84×10^{12} volts. Therefore the mean energy will be somewhat greater than $(2.44+0.84)\times10^{12}/1057$, or 3.11×10^9 volts. This may be compared directly to the value calculated above for vertical rays at sea level, *viz.*: 3.04×10^9 volts.

[3] W. Kramer, Zeits. f. Physik **85**, 411 (1933).
[4] A. Ehmert, Zeits. f. Physik **106**, 757 (1937).
[5] R. A. Millikan, Phys. Rev. **39**, 397 (1932).
[6] R. A. Millikan and G. H. Cameron, Phys. Rev. **37**, 235 (1931); I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **52**, 80 (1937).
[7] W. F. G. Swann and W. E. Danforth, Phys. Rev. In process of publication.
[8] T. H. Johnson and E. C. Stevenson, Phys. Rev. **43**, 583 (1933).
[9] J. C. Street and R. H. Woodward, Phys. Rev. **46**, 1029 (1934).
[10] P. M. S. Blackett, Proc. Roy. Soc. **A159**, 1 (1937).

TABLE I. *Calculations of integrals for different values of h.*

h, METERS OF WATER	$J\int_h^\infty Idh$ 10^7 VOLTS CM^{-2} SEC.$^{-1}$	$J\int_h^\infty Vdh$ 10^7 VOLTS CM^{-2} SEC.$^{-1}$	$n(h)$ CM^{-2} SEC.$^{-1}$	$2\pi\int_0^{\pi/2} n(h,\theta)\sin\theta\cos\theta\,d\theta$ CM^{-2} SEC.$^{-1}$	E_V 10^9 VOLTS	E_T 10^9 VOLTS
0.664	217.	—	0.687	1.49	—	1.46
4.	32.6	21.2	0.172	0.241	1.23	1.35
6.	14.6	8.20	0.0593	0.0767	1.38	1.90
8.	11.1	5.09	0.0260	0.0364	1.96	3.05
10.3	9.53	4.03	0.0133	0.0194	3.04	4.91
12.	8.70	3.58	0.0101	—	3.55	—
18.	6.72	2.86	0.00596	—	4.80	—
25.	5.29	2.32	0.00345	—	6.73	—
43.	3.41	1.55	0.00149	0.00242	10.40	14.10
>43	$90/h^{0.87}$	$41/h^{0.87}$	$1.69/h^{1.87}$	$2.74/h^{1.87}$	$0.243h$	$0.328h$

These figures agree closely with each other, and we are led to the conclusion that, *at sea level, practically all of the energy in the cosmic-ray beam is carried by charged corpuscles.* These figures rule out the possibility of any appreciable contribution of energy by photons, neutrons, or other nonionizing entities.

The above conclusion is based on the assumption that all the energy of the cosmic radiation is eventually dissipated in ionizing and exciting atoms. If there are other means by which cosmic rays can lose energy, such as by the production of neutrinos,[11] then the energy lost in this way must be carried by nonionizing particles at sea level. The circumstance that, in the cloud chamber results, we are dealing with the penetrating component of the cosmic radiation which may consist of particles with higher rest masses than electrons, has only a very small effect on the measured energies, since the energies under consideration are high compared to the rest mass of the particles. The condition that most of the energy be carried by charged corpuscles would not obtain on the present theory[12] of the passage of a beam of high energy electrons and their secondaries through matter. In that case we should expect approximately equal amounts of energy to be carried by electrons and by photons. If suitable cloud chamber observations were available, taken at a high elevation, this point could be directly tested, as has been done above for sea level.

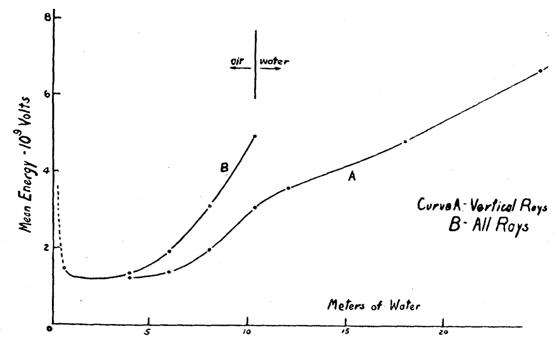

FIG. 1. The mean energies of cosmic-ray particles at various depths in the atmosphere.

[11] W. Heisenberg, Zeits. f. Physik **101**, 533 (1936).

[12] J. F. Carlson and J. R. Oppenheimer, Phys. Rev. **51**, 220 (1937); H. J. Bhabha and W. Heitler, Proc. Roy. Soc. **A159**, 432 (1937).