The Significance of J. Clay's Ionization Depth Data in Relation to the Nature of the Primary Cosmic Radiation

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THE latitude and directional effects in cosmic radiation necessitate the existence of charged particles entering our atmosphere with energies greater than 10^{10} electron-volts. These particles, if of electron type, would, in passage through the atmosphere, lose but a fraction of their energy, so that they would arrive at the earth's surface with energies comparable with 10^{10} volts.

The latitude and directional effects necessitate the assumption that about 14 percent of the rays observed at sea-level are of energy greater than 10^{10} volts. On the other hand, it has been frequently asserted that cloud-chamber experiments show far fewer rays than this number with energies comparable with the amount in question.

In a former communication[1] the writer has pointed out that harmonization of the cloud-chamber experiments and the latitude and directional effects in these matters necessitates the assumption that corpuscular rays of sufficiently high energy (energy comparable to 10^{10} volts) do not ionize in the sense of producing ions at the rate of about 50 in each centimeter of their path at atmospheric pressure. It is inferred, however, that they do produce from time to time showers of secondary rays of lower energy. These showers perpetuate the directions of the non-ionizing primaries, and hand on these directional characteristics in Geiger counter experiments. They would hand them on even in cloud-chamber experiments, where, however, the secondary rays would reveal themselves only with the actual energies they possessed, i.e., with energies smaller than those of the primaries. The writer has further given theoretical reasons to substantiate the reasonableness of an absence of ordinary ionization in the case of very high energy primaries.[2] He has also pointed out[3] that the existence of such a state of affairs would result in a diminution of ionization in a vessel with increase of depth of the vessel below the surface of the medium (say water) until a depth was reached at which the primary rays had lost enough energy to bring them into the region of energy in which they could ionize. Below this depth, the observed ionization in the vessel should show an increase followed by a decrease to zero in a range comparable with that representative of the total range of ionization of the primary particles in the medium.

In a recent communication,[4] J. Clay has found, at great depths, an increase of ionization followed by a sharp decrease to zero, the whole phenomenon being in harmony with the predictions cited above. The object of the present note is to call attention to this fact and to trace its significance in somewhat greater detail. Fig. 1 represents a reproduction of Clay's curve. The ordinates represent relative values of the ionization at the depths given by the abscissae.

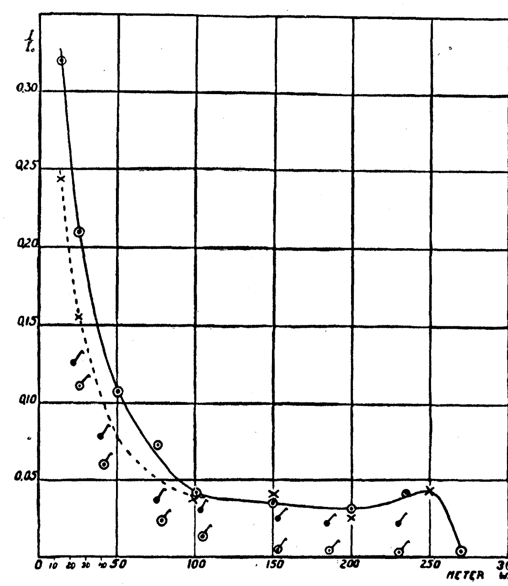

FIG. 1.

[1] W. F. G. Swann, Phys. Rev. **43**, 945 (1933).
[2] W. F. G. Swann, Phys. Rev. **44**, 943 (1933); J. Frank, Inst. **217**, 59 (1934). Also, W. F. G. Swann and A. Bramley. Phys. Rev. **41**, 393 (1932).
[3] W. F. G. Swann, Military Engineer, Vol. XXVI, No. 146, 116–120, March–April, 1934. See in particular p. 120.
[4] J. Clay, Physica **1**, 363 (1934).

It will be observed that there is a hump at 250 meters followed by a relatively sharp fall to zero at about 270 meters.

Statement of Hypothesis and Development of Consequences

For simplicity we shall consider the case of a corpuscular radiation of definite energy of such amount that the corpuscles can travel a distance L in the medium before their energy becomes reduced to the point at which ordinary ionization commences. After the energy has fallen to the region characterized by ionization, we shall suppose that the particle completes its range in a further distance l, in which distance it ionizes in the ordinary manner. For convenience we shall consider the atmosphere as compressed to a layer of the density of the medium under consideration (water), and shall picture it as lying on top of that medium, and forming part of it. We shall denote by h the distance below the surface and by θ the angle from the vertical. We shall suppose that the number of primary rays falling within the solid angle $\sin\theta d\theta d\varphi$ is

$$J = J_0 \cos^2\theta \sin\theta d\theta d\varphi,$$

$\cos^2\theta$ being the usually accepted empirical approximation to the result represented more exactly by the Gold formula, and φ being measured, of course, in the plane perpendicular to the vertical.

Consider an ionization chamber of volume V filled with gas at one atmosphere pressure. Then if q is the ionization per centimeter of path of the primary rays in the region of energy where they ionize, and if Q is the number of ions produced per second in the vessel by the primary rays, Q will be zero if $h > L+l$. Between the values of h given by $L+l$, and L the value of Q will be

$$Q_1 = 2\pi VqJ_0 \int_0^{\theta_1} \cos^2\theta \sin\theta d\theta,$$

where $\cos\theta_1 = h/(L+l)$. For $h<L$, the value of Q is

$$Q_2 = 2\pi VqJ_0 \int_{\theta_2}^{\theta_1} \cos^2\theta \sin\theta d\theta,$$

where $\cos\theta_1 = h/(L+l)$, $\cos\theta_2 = h/L$. Thus

$$Q=0 \quad \text{for } h > L+l, \tag{1}$$

$$Q = Q_1 = \frac{2\pi}{3} VqJ_0 \left[1 - \frac{h^3}{(L+l)^3}\right] \text{for } L<h<L+l, \tag{2}$$

$$Q = Q_2 = \frac{2\pi}{3} VqJ_0 \left[\frac{h^3}{L^3} - \frac{h^3}{(L+l)^3}\right] \quad \text{for } h<L. \tag{3}$$

We notice that for $h<L$, Q *increases* with increase of h, and proportionally to the cube. For $L<h<L+l$, Q decreases with increase of h, again in cubic fashion. The curve for Q plotted against h thus rises to a maximum (or rather to a highest value) at $h=L$, and then falls to zero at $h=L+l$. The general shape of the curve is such as is qualitatively indicated by the dotted curve of A, B, C of Fig. 2. To obtain the complete

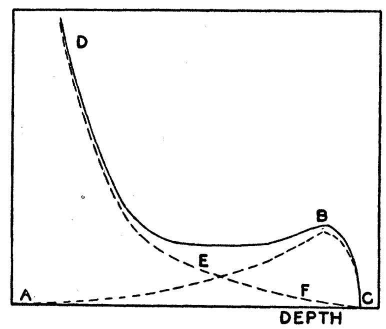

Fig. 2.

ionization in the vessel we must superpose upon this a curve which, according to our hypothesis would be produced by the showers generated by the primaries. If the rate of production of showers decreases with decrease of energy of the rays, attaining a sensibly zero value by the time the energy has reached the value at which ionization begins, we may expect to obtain a curve such as that qualitatively represented by the dotted curve D, E, F of Fig. 2. The combination of these two curves to the full curve thus gives a result similar to that shown by Clay's graph. On the basis of our hypothesis we should associate the point at 250 meters depth in Clay's curve with the point B of Fig. 2, and, the point where Clay's curve cuts the horizontal axis at 270 meters should be associated with the point C of Fig. 2. The total range of ionization would thus correspond to a path of 20 meters in water. Now according to the theoretical curves quoted by P. M. S. Blackett and G. P. S. Occhialini,[5] as obtained from the theoretical work of Bethe,[6] the energy loss, in ionization, per centimeter of path in water for rays of the order of 10^9 volts energy and of the electron type is about 2.5×10^6 volts per centimeter of path.[7] This gives 5×10^9 volts energy loss in 20 meters of water. Anderson's experimental data on absorption lead to an energy loss of 8×10^9 volts in 20 meters of water. It is a significant fact that the calculations of A. Bramley and the writer, based on the writer's theory already cited, suggests 10^{10} as the energy at which ionization should cease. The figures are not of course intended to give more than orders of magnitude; but, viewed in this light, it is of considerable interest to note that the magnitudes 5×10^9 to 8×10^9 volts found from Clay's curve on the basis of the present ideas represents approximately an upper limit to the energies of rays observed in appreciable numbers in cloud chamber measurements.

On the basis of the foregoing ideas the ionization at 250 meters depth is representative of the value given by (2) with h put equal to L. This value is, approximately, $2\pi VqJ_0l/L$. On the other hand, the ionization which would be obtained at the surface of the medium if all of the primary rays were capable of ionizing there would be $2\pi VqJ_0/3$. Since our interpretation combined with Clay's curve gives l/L of the order of 20/280, we see that if all of the primary rays ionized at the surface of the medium, or let us say at the earth's surface, with the normal ionization efficiency, they would produce $(1/3)\times(1/14)$, i.e., about 5 times the ionization observed at 250 meters. But the ionization observed at 250 meters is only about one-twentieth of that observed at the earth's surface. Hence, it is necessary to assume that, at the earth's surface there are 20/5, i.e., 4 times as many rays as there are primaries. In other words, each ray is responsible for 4 shower rays at the earth's surface, and this number would be still further reduced if some of the surface ionization were caused by other ionization agencies, such as photons or their secondaries. The foregoing considerations render it possible that the showers concerned involve only one or two secondaries. In conclusion it may be added that we would hesitate to extend the ideas here involved in too great detail to the higher regions of the atmosphere. However, as appears from the foregoing, the main relevant facts are discussable in terms of a comparison of the ionization at the earth's surface with that at great depths.

[5] P. M. S. Blackett and G. P. S. Occhialini, Proc. Roy. Soc. **A139**, 699 (1933).

[6] Bethe, Ann. d. Physik; Zeits. f. Physik **76**, 293 (1932).

[7] Bethe's theory would of course become invalid for energies higher than those where ionization ceases; but, it would represent an approximation of the truth for lower energies.