*Second Series* *November, 1926* *Vol. 28, No. 5*

THE

PHYSICAL REVIEW

# HIGH FREQUENCY RAYS OF COSMIC ORIGIN III. MEASUREMENTS IN SNOW-FED LAKES AT HIGH ALTITUDES

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Abstract

1. **Absorption experiments in Muir Lake (alt. 11,800 feet).**—The sinking of sealed electroscope No. 3 in Muir Lake showed an ionization decreasing steadily with depth from 13.3 ions per cc per sec. at the surface to 3.6 ions at 50 feet below the surface, below which there was no further decrease. The absorption curve of electroscope No. 3 was in excellent agreement with that of No. 1.

2. **Absorption experiments in Arrowhead Lake (alt. 5,100 feet).**—The electroscope readings in Arrowhead Lake correspond uniformly to readings six feet deeper in Muir Lake. This difference is the exact water equivalent of the absorption of the atmosphere between the two elevations. All readings of both electroscopes fit satisfactorily upon a single curve relating ionization to depth beneath the surface of the atmosphere in equivalent meters of water.

3. **Rays of cosmic origin.**—1 and 2 combined with the failure to detect any systematic diurnal variation, in tests of a number of days duration at high altitudes, constitute new and quite unambiguous evidence for the existence of very hard etherial rays of cosmic origin entering the earth uniformly from all directions.

4. **Spectral distribution of cosmic rays.**—No single absorption coefficient is found to fit the absorption curve, the lower end of which requires a coefficient of .18 per meter of water; the upper end a coefficient, .30 per meter of water. These coefficients correspond, by Compton's equations, to wave-lengths $\lambda = .00038$A and $\lambda = .00063$A. These are fifty times the frequencies of ordinary gamma rays, $\lambda = .025$A, and the former corresponds to an energy of 32,000,000 volts.

5. **Number of pairs of ions due to cosmic rays.**—The observed number of pairs of ions in electroscope No. 1 due to cosmic rays is about 1.4 at sea level, 2.6 at 1600 meters, 4.8 at 3600 meters, 5.9 at 4300 meters.

6. **Stimulated secondary rays.**—Theoretically, cosmic rays of the foregoing energy should not stimulate ether waves of gamma ray hardness, but should produce beta rays capable of penetrating brass walls 5 mm thick. The observations present evidence of rays of about this hardness increasing systematically with altitude in rough proportionality to the intensity of the cosmic rays. This evidence is not completely convincing because of inability thus far to eliminate the effects of the gamma rays from the underlying rocks.

7. **Origin of cosmic rays.**—Evidence is presented that these rays do not result from the union of protons with negative electrons, but they are rather

due to nuclear changes of about one-thirtieth the energy corresponding to such union, taking place throughout the depths of the universe.

## I. Introduction

THE 1922, high altitude, sounding balloon flights reported in Part I[1] had shown that some sort of a penetrating radiation exists in the upper reaches of the atmosphere, though of not more than one fourth the intensity theretofore reported. Again, the 1923 absorption experiments on mountain peaks reported in Part II[2] had shown that there exists at such heights a new radiation of local origin and of something like gamma ray hardness, but they had seemed to prove conclusively that if rays of *cosmic origin* exist at all they must be of somewhat different characteristics from any as yet suggested.

Up to the time of the Pikes Peak observations (September, 1923) the only work which had appeared demanding an absorption coefficient smaller than $5\times10^{-3}\text{cm}^{-1}$ for cosmic rays, if they existed, was the aforementioned sounding balloon experiments of Millikan and Bowen performed in April, 1922.[1] However, at the sitting of December 20, 1923, of the Preussischen Akademie der Wissenschaften Dr. Werner Kolhörster presented the results of new experiments, the first of which consisted in sinking electroscopes in different bodies of water at about sea level and observing a slight decrease in the number of ions as compared with the surface value. He attributed the noticeable lack of concordance between the results in the different bodies of water experimented upon to the different influences of the banks, but even with a $CO_2$ filling of the electroscopes the maximum change produced by sinking in water amounted to 2.1 ions, which would presumably be about 10 percent of the normal surface reading (not recorded in the report).

Dr. Kolhörster's comments upon these observations are as follows. "From the lake-experiments there results the absorption coefficient $\mu=2\times10^{-3}\text{cm}^{-1}$, while my former balloon experiments gave $5\times10^{-3}\text{cm}^{-1}$, a satisfactory agreement in view of the small intensity, about 2 ions, with which the penetrating rays reach the earth," thus indicating that these measurements were not sufficiently certain, in his judgment, to differentiate between $\mu=5\times10^{-3}$ and $\mu=2\times10^{-3}$.

He next made observations in crevasses in glaciers at altitudes of 2300 m and 3500 m on the Jungfrau, and obtained in three experiments for $\mu$ $1.6\times10^{-3}\text{cm}^{-1}$, $2.6\times10^{-3}\text{cm}^{-1}$, and $2.7\times10^{-3}\text{cm}^{-1}$. Combining

[1] Millikan and Bowen, Carnegie Institution Year Book, No. 21, 386 (1922); also Phys. Rev. **22**, 198 (1923) and **27**, 353 (1926).

[2] Millikan and Otis, Phys. Rev. **27**, 645 (1926).

these three observations on equal footing with those made in water and reported above, he recorded as the rough mean of the four observations $\mu = 2.5 \times 10^{-3} \text{cm}^{-1}$, a figure, however, now so low as to be no longer incompatible with the Kelly Field sounding balloon experiments.[1]

Finally, after having quoted the value of $\mu$ for the hardest gamma rays from RaC as $3.9 \times 10^{-2} \text{cm}^{-1}$, and from ThD as $3.3 \times 10^{-2} \text{cm}^{-1}$, he summarizes his paper thus: "To resume, it is to be emphasized that the existence of a hard gamma ray with an absorption coefficient about 1/10 that of the hardest known gamma rays has been demonstrated." The final value chosen was thus about the linear mean of all the observations taken, from 1.6 up to 5.7, namely, about $3.3 \times 10^{-3} \text{cm}^{-1}$. Also, in a very recent paper[3] Dr. Kolhörster again holds that all his observations upon mountains have confirmed the results of his balloon observations, while Hess[4] also holds that the result obtained in Kolhörster's balloon-flights is more trustworthy than that given by Millikan and Bowen's 1922, sounding balloon observations.

The Pike's Peak work of Millikan and Otis[2] had shown, however, (1) that the *mean* absorption coefficient of the rays found on top of the peak was only about that of ThD, and (2) that cosmic rays producing 2 ions per cc at the earth's surface and having an absorption coefficient even as low as $\mu = 2.5 \times 10^{-3} \text{cm}^{-1}$, although no longer in conflict with the sounding balloon experiments would of necessity have produced a 50% larger change inside lead screens in going from sea level to Pikes Peak than that they observed. They concluded, therefore, that cosmic rays *of the assumed characteristics did not exist.* If any of the penetrating rays were of cosmic origin they had to be still harder. The whole of the Pikes Peak data could in fact be explained without them. Accordingly we planned for the summer of 1925 new experiments designed:

(1) To settle definitely the question of the existence or non-existence of a small, very penetrating radiation of cosmic origin—a radiation so hard as to be uninfluenced by, and hence unobservable with the aid of, such screens as we had taken to Pikes Peak; and

(2) To throw light on the cause of the variation with altitude of the radiation of about gamma-ray hardness which our absorption experiments on Pikes Peak showed to be more than twice as copious there as at Pasadena.

The only possible absorbing material obtainable in the immense quantities needed, and of homogeneous and non-radioactive constitution, were the waters of very deep snow-fed lakes—snow-fed because the

[3] Kolhörster, Die Naturwissenschaften **15**, 31, 426.

[4] Hess, Phys. Zeits. **27**, 405 (1926).

results of under-water experiments which we had previously carried on near Pasadena had been vitiated by our discovery that the waters were appreciably radioactive. We felt that there was much uncertainty as to how much this cause might have affected the European observations in and about glaciers. Further, since the Pikes Peak experiments had demonstrated that if any of the penetrating rays were of *cosmic origin*, the ionization due to them in our electroscope at sea level had to be less than the 2 ions, assumed above, out of the 11.6 observed, the experimental error being, say, half an ion, no crucial tests could possibly be made unless we could find very deep, non-radioactive lakes at very high altitudes where cosmic rays, if they existed, had two or three times the ionizing effect to be expected from them at sea level. We needed at the least three or four ions due to cosmic rays, to vary with absorbing materials, if we were to obtain *unambiguous* evidence.

## II. The Electroscopes

The two electroscopes used in these experiments are shown in Fig. 1. Electroscope No. 1 is the same as that used in the experiments described

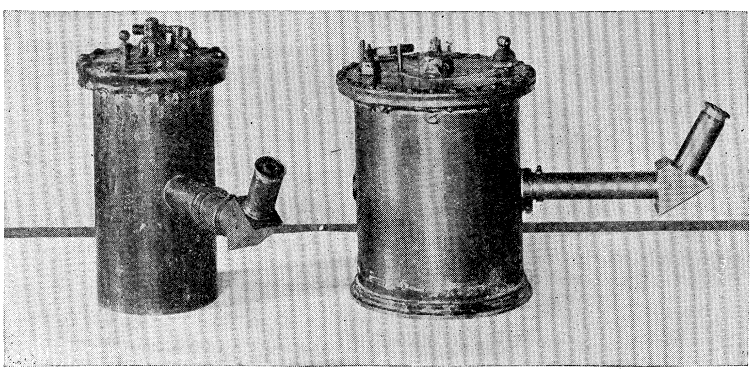

Fig. 1. Photograph of electroscopes 1 and 3.

in Part II,[2] but with new fibres inserted, while electroscope No. 3 is a new one very much like the first save that it had a greater sensitivity because of a larger volume and a smaller electrical capacity. It was 29.5 cm high and 15 cm in diameter. It was built entirely of brass, side walls 3 mm thick, and had a volume of 3211 cc, 1.69 times that of No. 1. The electrical capacity of No. 3 was 1.10 e.s. units, as measured by the method of mixed capacities, a small condenser the capacity of which (15.85 e.s. units) could be computed accurately from its dimensions being used as a standard. The capacity of No. 1, as remeasured for the purposes of

these experiments, was 1.41 electrostatic units. The method of measurement was precisely that described in Part II except that much longer periods of observation, from 5 to 14 hours, were generally used. As described in Part II a calibration curve was drawn for each reading to avoid errors due to changing characteristics of the instrument. That saturation was obtained was shown by the fact that for long observations in which the potential fell from say 200 volts to 50 volts the ionization was not appreciably less than when, with the same external radiation, the fall of potential was from 200 to 150 volts.

## III. Experiments in Muir Lake and Arrowhead Lake

The foregoing electroscopes were taken first to Muir Lake, 11,800 feet above sea level, just under the brow of Mount Whitney, the highest peak in the United States, a beautiful snow-fed lake hundreds of feet deep and some 2000 feet in diameter. Here we worked for the last ten days in August, 1925, sinking our electroscopes to various depths down to 67 feet. *Our experiments brought to light altogether unambiguously a radiation of such extraordinary penetrating power that the electroscope-readings kept decreasing down to a depth of 50 feet below the surface.* The atmosphere above the lake was equivalent in absorbing power to 23 feet of water, so that here were rays so penetrating that, if they came from outside the atmosphere, they had the power of passing through $50+23=73$ feet of water, or the equivalent of 6 feet of lead, before being completely absorbed. The most penetrating x-rays that we produce in our hospitals cannot go through half an inch of lead. Here were rays at least a hundred times more penetrating than these. This was in agreement qualitatively with Kolhörster's 1923 contention. The absorption coefficient however came out but one twentieth, instead of "about one-tenth of that of the hardest known gamma rays,"[5] and the number of ions at sea level was but 1.37 (see below).

How unambiguous was now the experimental evidence may be seen from the fact that with the aid of the new electroscope of high sensitivity (because of small capacity and large volume) the change in ions per cc per sec. in going from the surface of Muir Lake to the depth of 15 meters (50 feet) was from 13.3 ions to 3.6 ions, or a decrease to about a fourth value. Since the largest decrease below a surface reading reported by Kolhörster due to sinking electroscopes in water[5] was 2.1 ions, or a decrease of probably about 10%, we seem here to have obtained an altogether new precision of measurement and unambiguity of evidence.

[5] Kolhörster, Sitz.-Ber. Preuss. Akad. Wiss. **34**, 366 (1923).

To obtain definite evidence as to whether these very hard rays were however *of cosmic origin*, coming in wholly from above and using the atmosphere merely as an absorbing blanket, we next went to another very deep snow-fed lake, Lake Arrowhead in the San Bernardino mountains, 300 miles farther south and 6700 feet lower in altitude, where the Arrowhead Development Company kindly put all their facilities at our disposal. The atmosphere between the two altitudes has an absorbing power equivalent to about 6 feet of water. *Within the limits of observational error, every reading in Arrowhead Lake corresponded to a reading 6 feet farther down in Muir Lake, thus showing that the rays do come in definitely from above, and that their origin is entirely outside the layer of atmosphere between the levels of the two lakes.* This, taken together with the sounding-balloon data, appears to eliminate completely the idea that the penetrating rays may have their origins in thunder-storms, a possibility recently suggested by C. T. R. Wilson and repeated by Eddington.[6]

The procedure in taking these readings was to take the electroscopes out in a canvass army boat, carried part way up to the lake by pack animals and partly by ourselves, to sink both electroscopes side by side at the chosen depth, and leave them so immersed for a period of from 6 to 14 hours. We could usually obtain but two readings in 24 hours. The process of taking and of treating these readings was precisely that described in II. The elaborate precautions for eliminating leak over the supporting quartz rod were not used because they were found to make no change in the rate of discharge.

Table I

*Readings in Lakes Muir and Arrowhead*

Electroscope No. 3

| Muir Lake | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Depth below surface (m) | 0 | .45 | 1.0 | 2.8 | 3.0 | 5.0 | 10.0 | 15.0 | 20.0 |
| Ionization (ions/cc/sec) | 13.3 | 9.7 | 7.7 | 6.0 | 5.45 | 4.9 | 4.0 | 3.6 | 3.6 |
| | 13.2 | .... | 7.8 | 5.8 | .... | 4.6 | 4.0 | .... | 3.7 |
| Means | 13.25 | 9.7 | 7.75 | *5.9* ↙ | *5.45* ↙ | *4.75* ↙ | 4.0 | 3.6 | 3.65 |

| Arrowhead | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Depth below surface (m) | 0 | .7 | 1.0 | 1.1 | 3.0 | 5.0 | .... | 15.0 | .... |
| Ionization (ions/cc/sec) | 7.0 | 5.8 | 5.5 | 5.15 | 4.85 | 4.4 | .... | 3.7 | .... |
| | 7.2 | .... | .... | .... | 4.9 | .... | .... | .... | .... |
| | 7.5 | .... | .... | .... | .... | .... | .... | .... | .... |
| | 6.9 | .... | .... | .... | .... | .... | .... | .... | .... |
| | 7.2 | .... | .... | .... | .... | .... | .... | .... | .... |
| | | ↗ | ↗ | | ↗ | | | | |
| Means | 7.0 | *5.8* | *5.5* | 5.15 | *4.9* | 4.4 | .... | 3.7 | .... |

[6] Eddington, Nature Supplement, May 1, 1926, p. 32.

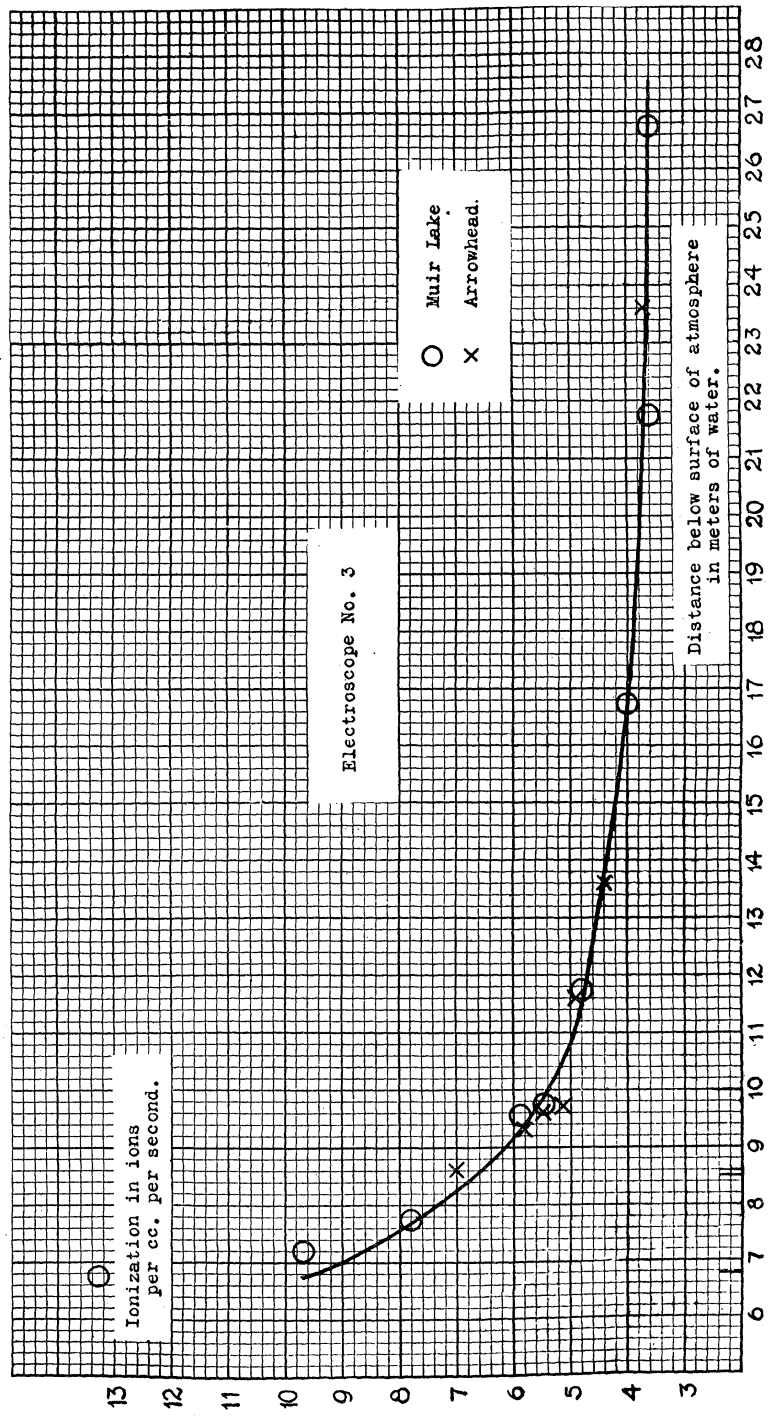


Fig. 2. Variation of the ionization in Electroscope No. 3 with depth below the surface of the atmosphere.

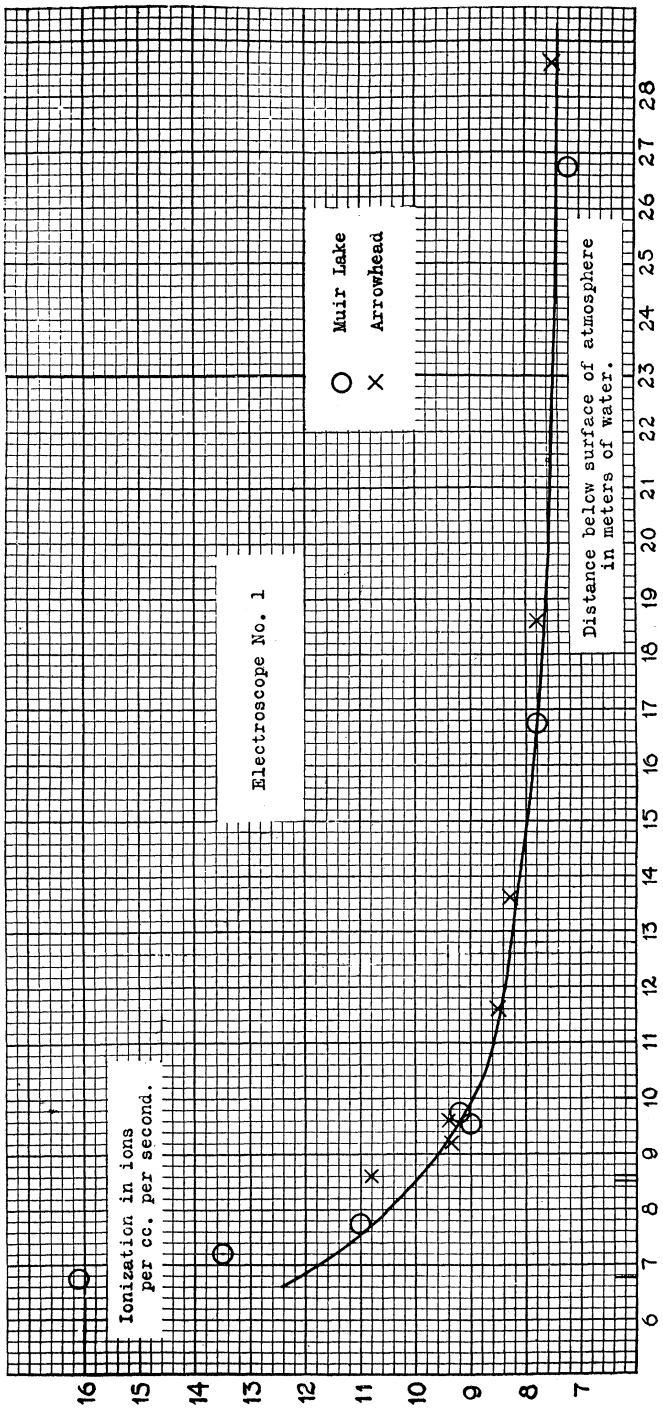


Fig. 3. Variation of the ionization in Electroscope No. 1 with depth below the surface of the atmosphere.

Electroscope No. 1
Muir Lake

| Depth below surface (m) | 0 | .45 | 1.0 | 2.8 | 3.0 | .... | 10.0 | .... | 20.0 |
|---|---|---|---|---|---|---|---|---|---|
| Ionization (ions/cc/sec) | 16.5 | 13.5 | 11.0 | 9.0 | 9.2 | .... | 7.8 | .... | 7.2 |
| | 15.8 | .... | .... | .... | .. | .... | .... | .... | .... |
| | 15.9 | .... | .... | .... | .... | .... | .... | .... | .... |
| Means | 16.1 | 13.5 | 11.0 | 9.0 | *9.2* ↙ | .... | 7.8 | .... | 7.2 |

Arrowhead

| Depth below surface (m) | 0 | .6 | 1.0 | .... | 3.0 | 5.0 | 10.0 | | 20.0 |
|---|---|---|---|---|---|---|---|---|---|
| Ionization (ions/cc/sec) | 10.5 | 9.35 | 9.6 | .... | 8.6 | 8.3 | 7.8 | .... | 7.5 |
| | 11.0 | .... | 9.2 | .... | 8.45 | .... | .... | .... | .... |
| Means | 10.75 | 9.35 | ↗ *9.4* | .... | 8.5 | 8.3 | 7.8 | .... | 7.5 |

Table I shows all of the readings taken in Lake Muir and Lake Arrowhead. The arrows connect or point toward readings taken at the same depth beneath the top of the atmosphere, and it will be seen that they are all the same within the limits of error whether taken in Lake Muir or Lake Arrowhead.

Figs. 2 and 3 show the curves obtained by plotting all the readings taken in the two lakes as ordinates, and as abscissas the depths in meters beneath the top surface of the atmosphere, reduced to the equivalent depth beneath water. These depths were computed with the aid of the mean temperatures, as a function of altitude, given in the Smithsonian Tables. On these graphs the "depth" beneath the top of the atmosphere of the surface of Muir Lake is 6.75 m, that of Arrowhead Lake 8.6 m, that of Lone Pine 8.5 m, and that of Pasadena 9.98 m. It will be seen that all of the readings corresponding to points more than half a meter beneath the surface of the water fall upon a smooth curve. The fact that readings taken above the surface are all above the curve is due to the presence above the surface in addition to the penetrating radiation of a local radiation of ordinary penetration. Since this latter radiation is all absorbed in a meter or less of water, the points corresponding to depths equal to half a meter are all on the smooth cosmic radiation curve, while those corresponding to readings at the surface are above this curve.

Analysis of these absorption curves shows that the rays are not homogeneous but are hardened as they go through the atmosphere, just as x-rays are hardened by being filtered through a lead screen. Our hardest observed rays have an absorption coefficient of 0.18 per meter of water, and the softest which get down to Muir Lake a coefficient of 0.3 per meter. The sounding balloon experiments of Millikan and Bowen make it improbable that they become very much softer than this at the top of the atmosphere, since otherwise these observers should have obtained larger readings in their very high flight.

Observations carried on by Millikan and Otis day and night for several days on Pikes Peak at an altitude of 14,100 feet, and for two consecutive days on Mount Whitney at an altitude of 13,500 feet had revealed no preferential direction in the heavens from which the rays come. These results were again checked in this work both on Mount Whitney and at Arrowhead Lake. One reading taken in a valley when the Milky Way was practically entirely behind the hills was not at all lower than when the Milky Way was overhead. *Within the limits of our uncertainty of measurement, then, these rays shoot through space equally in all directions.*

## IV. Method of Obtaining Absorption Coefficients

In making the foregoing analysis for absorption coefficients the rays were assumed, for the reasons just given, to enter the atmosphere equally from all directions. Then the differential equation for the intensity $I$ at a distance $H$ beneath the surface, in terms of the intensity $I_0$ coming into the atmosphere from all directions outside its upper surface is

$$dI = 2\pi I_0 \sin\theta d\theta e^{-\mu H \sec\theta} \tag{1}$$

Therefore

$$I/I_0 = 2\pi \int_0^{\pi/2} \sin\theta e^{-\mu H \sec\theta} d\theta. \tag{2}$$

Putting $x = \sec\theta$ this takes the form

$$I/I_0 = 2\pi \int_1^{\infty} \frac{1}{x^2} e^{-\mu H x} dx. \tag{3}$$

Now Gold[7] has published a table of values of an integral of the type in Eq. (3) so that from this table it was possible to obtain the absorption coefficients of rays coming in from all directions. The method of doing this was to select the most reliable observed value near the top of each curve and to see what value of $\mu$ in the Gold table best reproduced the portion of the curve near it.

As stated above, however, *no one coefficient would fit the whole curve.* This result is completely new, we think, even as a suggestion, for heretofore it has been the uncertainty of measurement which has made the reported values of $\mu$ fluctuate from say .16 up to .57. Here, however, the variation from .18 up to .30 *represents the discrimination of measurement, rather than the uncertainty of reading.* Indeed, no previous observers had worked with the foregoing Gold law for the evaluation of $\mu$ since the uncertainty of measurement had theretofore made it useless to attempt to discriminate between rays following a linear absorption law and rays

[7] Gold, Proc. Roy. Soc. **A82**, 152 (1909).

coming in from all directions. The radiations have clearly become more penetrating with depth. In other words, the radiation is not homogeneous but consists of a spectrum of wave-lengths. For electroscope No. 3 the upper portion of the curve gave, as stated, $\mu = .30$ per meter of water, and the lower end $\mu = .18$. Electroscope No. 1 gave the same result for the lower end of the graph and a value slightly less for the upper end. Electroscope No. 3 was the more dependable since it had about double the sensitivity of No. 1. These coefficients of course characterize the radiation only throughout the region studied. Somewhat softer components are to be expected at greater altitudes.

## V. Check Observations with Lead Screens

The same lead screens, 4.8 cm thick, used for making absorption experiments upon the radiations found about the granite rocks on top of Pikes Peak (see Part II) were taken to Muir Lake and observations similar to those there made repeated also upon granite rocks, both at Muir Lake (11,800 feet) and at Lone Pine (5500 feet). Then the instruments were brought back to Pasadena (759 feet) and similar observations made there on a soil consisting of decomposed granite. The lead was adapted for use with electroscope No. 1 alone and was the equivalent in absorbing power of 55 cm of water. The results of all these absorption experiments are collected in Table II.

Table II

*Cosmic rays inside* 4.8 *cm lead*

| | Pasadena altitude 305 m | Lone Pine altitude 1676 m | Muir Lake altitude 3590 m | Pikes Peak altitude 4298 m |
|---|---|---|---|---|
| Ions per cc per sec. unshielded | 13.0 | 16.7 | 20.0 | 23.7 |
| Shielded with 4.8 cm Pb | 9.0 | 10.1 | 11.8 | 12.6 |
| External radiations after screening | 1.6 | 2.7 | 4.4 | 5.2 |
| Cosmic rays (theoretical) | 1.3 | 2.4 | 4.1 | 4.9 |
| Cosmic rays (observed) | 1.32 | 2.21 | 4.08 | 5.0 |

In the first and second rows are given the readings without and with the lead shield, respectively. The figures in the third row are obtained by subtracting from those in the second row 7.4, which is seen from Fig. 3 to be the residual ionization in electroscope No. 1 when it is screened from all external radiation by being sunk to a depth of more than 50 feet in water. The third row, therefore, gives the total radiations of all kinds which penetrate at the various altitudes inside the lead screen.

A part of this radiation which gets through the lead is certainly due to the radioactive constituents of the surrounding rocks. Since these rocks were as nearly the same as possible in all the localities, a large variation

in the effect due to them is not to be expected. Kovarik and McKeehan[8] give the ionization on the earth due to $\gamma$ rays from igneous rocks as about 3 ions. We have therefore taken 3 ions as a probable mean value of the ionization within the unshielded electroscope due to the gamma ray activity of the rocks. About 10 percent of this is able to get through a screen of water 55 cm thick. The figures in the fourth row are therefore obtained by subtracting .3 ions from those in the third row, and what is left, if the assumption as to the constancy of the radioactivity of the rocks is correct, should be, theoretically, the amount of the cosmic rays (see fourth row labelled "cosmic rays (theoretical)" which get through the lead screen in the various localities.

But now we have the possibility of getting these values in another and quite independent way, namely, by taking the readings on the curve of Fig. 3 at each location, for this gives how much of the cosmic radiation actually is present at each elevation, all soft radiations having been screened out by the water. It is then easy to calculate how much of this cosmic radiation will penetrate 55 cm of water, using the coefficient .3 per meter of water (as we compute from our curve the absorption coefficient of the cosmic rays at this depth to be) and the formula $I=I_0e^{-\mu d}$. This should be the correct formula for this case, since here the shield completely surrounds the electroscope, and most of the radiation goes through it practically perpendicularly. The results are shown in the last row and are labeled "cosmic rays (observed)." The agreement between the observed and computed values in the fourth and fifth rows, respectively, is excellent and shows that after working out the characteristics of the cosmic rays from the observations in water we can actually compute accurately the amount of these cosmic rays which will be found inside a 4.8 cm lead screen with the aid of the assumption that the only other rays which get through the lead screen are the rays from the radioactive constituents found in granite rocks.

## VI. Soft Secondary (?) Rays

The agreement in Table II between the cosmic rays actually observed inside the lead (row 5) and those computed (row 4) on the assumption that the only other rays which can get inside the lead are the gamma rays due to the radioactivity of the granite rocks, assumed to be everywhere the same and equal to 3 ions, is apparently good evidence that the considerable amount of other soft radiations of local origin observed by Millikan and Otis on Pikes Peak is unable to penetrate appreciably 4.8

[8] Kovarik and McKeehan, Report of Committee on X-rays and Radioactivity, National Research Council, Washington, D. C., p. 141 (1925).

cm of lead. Before drawing inferences as to the nature and origin of these new soft rays, Table III is presented to show again their existence and distribution with altitude. The first row of this table repeats the total observed ionization inside the unshielded electroscope in the indicated localities, the second row the readings from the cosmic ray curve, Fig. 3. The differences between these two are found in the third row and represent all the rays which have passed through the walls of the unshielded electroscope No. 1 except the cosmic rays; i.e., all the rays of local origin which enter the electroscope from without.

Table III

*Soft secondary radiation*

| | Pasadena 305 m | Lone Pine 1676 m | Muir Lake 3590 m | Pikes Peak 4298 m |
|---|---|---|---|---|
| Direct observation | 13.0 | 16.7 | 20.0 | 23.7 |
| Cosmic rays (from curve) | 8.95 | 10.0 | 12.2 | 13.3 |
| Soft rays (observed) | 4.05 | 6.7 | 7.8 | 10.4 |
| Stimulated soft rays (assumed) | 1.05 | 3.7 | 4.8 | 7.4 |
| Stimulating cosmic rays (observed) | 1.55 | 2.6 | 4.8 | 5.9 |

Since we have just assumed the radioactive rays from the granite rocks to be responsible for 3 of these observed ions per cc per sec., the difference given in the fourth row represents other soft local rays. However, any error in the assumption of the uniform value 3 for the gamma rays of local origin would vitiate badly the fourth row of Table III, whereas it would have had but a small influence on the fourth row of Table II. The reason for this is that the total effect of these gamma rays inside the lead (fourth row, Table II) is but a few tenths of an ion at most, while in the fourth row of Table III it is ten times as much. The fifth row of Table III gives the actual values of the cosmic rays found within the unshielded electroscope. These are obtained from curve 4 for the various altitudes by subtracting the residual ionization, 7.4 ions, from the curve reading. It will be seen that there is a rough proportionality between the stimulating cosmic rays found in row 5 and the new soft rays shown in row 4. This is perhaps sufficiently good, in view of the aforementioned cause of uncertainty as to the values in the fourth row, to furnish evidence that the new soft rays of the fourth row are produced by the cosmic rays of row 5. Row 4 is therefore labeled "Stimulated soft rays." The argument here, however, is not one of certainty. The observed increase with altitude of the soft rays might be explained by making the unlikely assumption that quite accidentally we were observing on rocks of increasing gamma radiation as we progressed upward. Further experiments are needed to settle this point unambiguously.

## VII. The Spectral Distribution of the Observed Cosmic Rays

In order to obtain the spectral distribution of rays such as those here found for which the absorption coefficients are as low as 1/20 of those of RaC or ThD and vary from .3 per meter of water to .18 per meter of water there is as yet no altogether infallible guide. But the very recent experimental work of Ahmad[9] has shown that the gamma rays of radium in their absorption by matter obey the same general law as x-rays, and for these the relation between absorption coefficient and frequency is well known. Compton's theory of scattering predicts Ahmad's observational data very satisfactorily. According to the Compton-Ahmad formula the mass absorption coefficients may be calculated from the formula

$$\frac{\mu}{\rho}=\left\{\frac{\sigma_0}{1+2\alpha}+B\lambda^3Z^3\right\}\frac{ZN}{A} \tag{4}$$

the first term of which represents "Compton scattering" while the last is "true absorption" (ejection of photo-electrons). For absorption in water this last term is nearly negligible even for gamma-ray wave-lengths, so that it must certainly be negligible for the much harder rays here under consideration, so that for these rays

$$\frac{\mu}{\rho}=\left\{\frac{\sigma_0}{1+2\alpha}\right\}\frac{ZN}{A} \tag{5}$$

where

$$\alpha=\frac{.0242}{\lambda} \text{ and } \sigma_0=6.64\times10.^{-25} \tag{6}$$

Making the substitution of $Z/A=10/18$, its value for water, $N=6.06\times10^{23}$ and the observed range of absorption coefficients, namely, .0030 and .0018 we obtain $\lambda=.000634$A and $\lambda=.00038$A, respectively, or a spectral range of a little less than an octave in a region of frequencies about 50 times higher than that of the shortest measured gamma rays ($\lambda=.02$A). The foregoing reduction of absorption coefficients to wave-length has been given very considerable credentials by Ahmad's experimental proof of the ability of the Compton theory to predict fairly closely his observed results.[10] Also very nearly the same wave-lengths are obtained from Dirac's relativity-quantum-mechanics formula.[11] This yields about 30 percent lower wave-length values.

[9] N. Ahmad, Proc. Roy. Soc. **109**, 206 (1925).

[10] A paper has just appeared by Hoffman, Phys. Zeits. **36**, 25 (1926) which lends further support to the reliability of Compton's equations for the purpose in question.

[11] Dirac, Proc. Roy. Soc. **111**, 405 (1926).

## VIII. Nature of Soft Stimulated Radiations

We observe, first, that according to Compton's equations[12] the mean ratio of true scattering to true absorption—this is the ratio between the mean energy in the scattered quant and the energy in the recoil electron—is given by

$$\frac{\sigma_\sigma}{\sigma_\alpha} = \frac{1+\alpha}{\alpha} \tag{7}$$

Since, for the cosmic rays, $\lambda$ is of the order .0005 the quantity $\alpha$ is large compared to unity and therefore for this case

$$\frac{\sigma_\sigma}{\sigma_\alpha} = 1 \tag{8}$$

This means that on the average each particular act of scattering divides the energy of the original quant equally between the new quant and the recoil electron, and the scattered quant has therefore on the average twice the wave-length, or half the frequency of the original one.

Also, according to Compton's equations the average angle of scattering is given by

$$\lambda - \lambda_0 = .0242(1-\cos\theta)$$

and since for the cosmic ray, as just shown, $\lambda = 2\lambda_0$ we have

$$(1-\cos\theta) = .0005/.024 = .02$$

$$\cos\theta = .98 \text{ or } \theta = 11°$$

Further, since the original momentum in the direction of the ray is $h\nu_0/c$ and the momentum remaining in the scattered quant, namely $h\nu_0/c$ is very nearly $h\nu_0/2c$, since $\theta$ is small, it follows that the momentum imparted to the recoil electron in the direction of the original ray must also be exceedingly close to $h\nu_0/2c$. In other words, *the act of scattering of these very high frequency rays consists merely in taking half the energy of the light quant and transferring it to a recoil electron, both this new light-quant and the electron moving practically straight forward in the direction of the original beam, each with half the original energy.*

Altogether without reference to Compton's theory, the fact that the electrons do actually move more and more nearly straight forward as the frequency of the ray increases is shown directly by the C. T. R. Wilson photographs, so that the qualitative correctness of the foregoing conclusion can scarcely be doubted.

The foregoing equations show that contrary to Eddington's assumption[13] very high frequency cosmic rays do not degenerate in one scattering

[12] A. H. Compton, Phys. Rev. **21**, 494 (1923).
[13] Eddington, Nature **117**, 31 (1926).

act into rays of gamma-ray frequency as they would if, on the average $\theta$ were 90°, but instead, since $\theta$ is always very small, they soften to just one-half frequency at each act. Since further, in the process of the degeneration, the energy left in the ether-wave is always proportional to its frequency, when a cosmic ray of wave-length $\lambda = .0005$A has degenerated to an ordinary gamma-ray of wave-length $\lambda = .025$ it has left in it but 1/50th of the original energy. This shows, for example, *that if at a given altitude the cosmic rays produce say 5 ions per cc per sec. there is a wholly negligible ethereal radiation of gamma ray hardness mixed with them.* Indeed, until the radiation has become pretty well absorbed (reduced to less than half its original energy) the bulk of the ionization is due to the primary rays, a smaller part to the secondaries (of half the original frequency) a smaller part still to the tertiaries (of one-fourth the original frequency), and a very small part to all the other members of the series. In other words, while cosmic rays diminish in energy as they go through matter because some of the quanta are removed from the beam by scattering, they soften, or diminish in frequency, very little before the intensity of the beam has been reduced to a small fraction of the original value. Even then it is the secondaries and tertiaries which carry the bulk of the energy, so that the beam has not, on the average, degenerated to anything like gamma-ray hardness. Indeed, a more complete analysis on the basis of the Compton equation shows that *no matter how much the intensity of an originally monochromatic beam has been reduced by passage through matter, of whatever thickness, more than three-fourths of the resultant ether-wave energy is carried by the primaries, secondaries, and tertiaries whose frequencies are respectively 1, 1/2 and 1/4 times the original frequency.* We cannot, therefore, seek the source of the rays "of gamma-ray hardness" found on Pikes Peak in cosmic rays degenerated into actual gamma-rays by Compton scattering.

On the other hand, the following analysis shows that the observed soft rays are in part, at least, the $\beta$ rays produced by the cosmic rays. For one-half of the incident energy in each cosmic ray goes over in each scattering act into the recoil electron. The highest frequency cosmic ray observed ($\lambda = .00038$) has an energy-value corresponding to the fall of an electron through about 30,000,000 volts. Hence the beta-rays produced by the impact of these with electrons in Compton scattering have an energy of about 15,000,000 volts. The velocity of a 7,500,000 volt beta-ray, in terms of the velocity of light, is .998,[14] and since volts vary as $1/1-\theta^2$, which is proportional, for $\beta \doteq 1$, to $1/\sqrt{2(1-\beta)}$ for 15,000,000 volts rays $\beta = .9995$.

[14] National Research Council, Bulletin on Radioactivity, p. 92 (1925).

Now Bohr[15] has worked out the average range of $\beta$-rays as given in Table IV, finding the range proportional to $1/\sqrt{1-\beta^2}$ and Varder[16] has given Bohr's formula experimental verification. It will be seen from the formula and the table that for large velocities the range is proportional to the energy.

TABLE IV

*Showing variation of average range with velocity*

| Velocity of corpuscle / Velocity of light | Average range meters |
|---|---|
| 0.80 | 0.7 |
| 0.85 | 1.1 |
| 0.90 | 1.9 |
| 0.95 | 3.5 |
| 0.99 | 10.5 |
| 0.996 | 18.0 |
| 0.998 | 26.0 |
| 0.9995 | 52.0 |

We see, therefore, that beta rays having a range of 52 m in air, equivalent to 5.1 mm of brass, are produced by each act of scattering of the initial cosmic rays. *These are undoubtedly a part, at least, of the soft rays found on Pikes Peak.* In a preceding communication[17] these have been referred to merely as "rays of about gamma-ray hardness," not as actual gamma-rays, though various authors have so understood them.

## IX. Origin of the Cosmic Ray

It is altogether obvious that any rays of the hardness and distribution indicated, and of cosmic origin, must arise from nuclear changes of some sort going on all about the earth. The energy of the change involved is, however, four times that of any radioactive change thus far on record, being equivalent, for rays of wave-length $\lambda = .00038$ to the fall of an electron through a potential difference of 32,400,000 volts, and for rays of wave-length $\lambda = .000634$ to 19,500,000 volts. The fastest $\beta$-ray on record has an energy of 7,500,000 volts.

Both Eddington[18] and Jeans[19] wish to regard these observed cosmic rays as arising from the transmutation of the mass of the proton into radiation by the union of a proton with a negative electron. They regard this process as going on both in the nebulae and in the interior of stars. Such a process, however, would produce a ray of wave-length .000013A, which would be thirty times more energetic and more penetrating than the shortest wave-length which we have observed. This hypothesis does not seem to be tenable if the Compton equations are to be taken as guides,

[15] N. Bohr, Phil. Mag. **30,** 518 (1915).
[16] Varder, Phil. Mag. **29,** 731 (1915).
[17] Millikan, Proc. Natl. Acad. Sci., January (1926).
[18] Eddington, Nature **117,** 26 (1926).
[19] Jeans, Nature **116,** 861 (1925).

for, as already indicated, rays having that energy could not be softened to an average one-thirtieth of their original frequency by passage through any amount of matter. Their energy could all be dissipated in heat through the beta-rays, but such radiation as got out undissipated would have a considerable fraction of its energy in the original frequency.

Again, if rays thirty times the hardness of the rays observed were present we should not have found in two lakes our electroscopes reaching a constancy of reading at all depths below fifty feet. The reasons adduced by Eddington for assuming that this process is going on seem good, but its seat, if it exists, is presumably in the interiors of stars alone where the energy of the change is all frittered away into heat, through the medium of the beta-rays, before any appreciable part of it has found its way out into space. *The cosmic rays are probably, therefore, not degenerated waves of higher frequency, but are rather generated by nuclear changes having energy values not far from those recorded above.* These changes may be (1) the capture of an electron by the nucleus of a light atom, (2) the formation of helium out of hydrogen, or (3) some new type of nuclear change, such as the condensation of radiation into atoms. The changes are presumably going on not in the stars but in the nebulous matter in space, i.e., throughout the depths of the universe.

## Summary

The advances made in these researches seem to us to be

(1) The increased precision, definiteness, and unambiguity with which the properties of the penetrating rays have been brought to light.

(2) The definite proof that some of these rays come from above, the 6700 feet of atmosphere between 11,800 and 5,100 acting merely as a blanket equivalent to six feet of water. This is by far the best evidence found so far for the view that the penetrating rays are partially of cosmic origin.

(3) The bringing forth of evidence for the spectral distribution of cosmic rays and the rough determination of the frequency limits of the spectrum. This is altogether new.

(4) The bringing forth of evidence for the existence of a secondary very penetrating beta radiation stimulated by the primary cosmic rays.

(5) The fixing of the ionization at the earth's surface due to cosmic rays, as measured inside electroscope No. 1 at about 1.4 ions.

The whole of this cosmic ray work has been done with the aid of funds provided by the Carnegie Corporation of New York and administered by the Carnegie Institution of Washington.

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August 7, 1926.

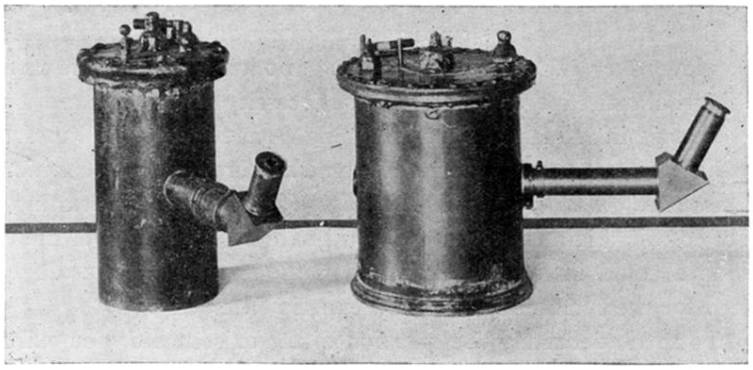

Fig. 1. Photograph of electroscopes 1 and 3.