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A MORE ACCURATE AND MORE EXTENDED COSMIC-RAY IONIZATION-DEPTH CURVE, AND THE PRESENT EVIDENCE FOR ATOM-BUILDING

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Abstract

The cosmic-ray *ionization-depth curve* has been extended at both its upper and lower ends and made more accurate throughout. The *absorption coefficients* obtained directly from the slope of the curve run from $\mu=0.35$ per m. of water at the top (Pike's Peak) to $\mu=0.028$ at the bottom (80 m. or 262 ft. of water below the top of the atmosphere, thus bringing to light both softer and harder components than the authors had before found. Strong quantitative evidence is presented, on the basis of the Klein-Nishina formula, that the strongest and most absorbable cosmic-ray band arises from the act of formation of helium out of hydrogen. Striking qualitative evidence is found that the three more penetrating bands are due to the formation out of hydrogen of the only other abundant elements oxygen (C, N, O) silicon (Mg, Al, Si, S) and iron (Iron group). Two independent proofs are given that the cosmic-rays enter the earth's atmosphere as photons, namely, (1) they are quite uninfluenced by the earth's magnetic field, and (2) the ionization produced by them in a closed vessel does not increase continually in going to the top of the atmosphere but passes through a maximum. It is shown to follow that the cosmic rays, in coming from their place of origin to the earth have not passed through an amount of matter that is appreciable in comparison with the thickness of the earth's atmosphere and that they must therefore originate in interstellar space rather than in the atmospheres of the stars. Some participation of the nucleus in the absorption of cosmic-rays is brought to light.

1. Objectives

The new series of measurements presented herewith on the relation between cosmic-ray ionization and depth in equivalent meters of water beneath the surface of the atmosphere was undertaken for two very specific reasons.

First.—Our preceding experiments, published in full in 1928,[1] had brought to light what seemed to us very striking evidence that the cosmic rays have their origin in the acts of formation "in the depths of space" of the atoms of the celestially common elements helium, oxygen (C, N, O), and silicon (Na, Mg, Al, Si, S) out of hydrogen. This evidence consisted:

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[1] Millikan and Cameron, Phys. Rev. **32**, 533 (1928).

(a) In our experimental proof that within the limits of our observational uncertainty these rays show a uniformity of distribution, i.e., an independence of both latitude and of sidereal time. Both of these conclusions had been established by our trip to the Bolivian High Andes[2] in 1926, the first point not having been previously tested at all by other observers, the second having been so tested but with opposite results, though subsequent more careful experimenting by Hoffmann and Lindholm,[3] Steinke,[4] Hess,[5] and by one of us[6] has confirmed our conclusion;

(b) In our proof shown unambiguously by the curve itself, of the *banded character* of the rays;

(c) In the general rough agreement between our observed sequence of band-absorption coefficients and intensities, and the sequence of energies released, in accordance with Einstein's equation and Aston's curve, when the celestially most abundant elements helium, oxygen, and silicon are formed out of hydrogen; and

(d) In the rough agreement between the observed absorption coefficients and those computed from Dirac's formula connecting ray-energy with ray-absorption.

If our interpretation of our cosmic-ray results is correct, rays of still higher penetrating power should exist corresponding to the formation of still heavier elements out of hydrogen. Iron, at least, is abundant enough so that our theory suggested that we might find a cosmic-ray band, or cosmic-ray bands, of higher penetrating power than any we had thus far definitely observed. Such rays could be brought to light only by working at still lower depths in snow-fed lakes with electroscopes still more sensitive than any we had thus far used, and this new series of experiments was started in the spring of 1928 in part to test this point.

Second.—Our 1927–8 ionization-depth curve[7] showed characteristics at its upper end, i.e., at the highest altitudes at which we had ionization-depth readings, which seemed to be a bit out of line with the theory. Thus, our analysis, by means of the Gold tables, of our curve into its "monochromatic" absorption coefficients yielded as the strongest and most absorbable component $\mu = 0.35$ per meter of water, while the Dirac formula gave for the coefficient of rays due to the formation of helium out of hydrogen $\mu = 0.30$. While this was of the right order of magnitude, indeed quite close in view of our accuracy, *the divergence was in the wrong direction*, for our computated value 0.30 had applied to a monochromatic beam, but the actual beam, even if it entered the atmosphere as monochromatic would, where observed, have secondary, tertiary, etc., components, due to Compton encounters with electrons, and all such encounters tend, *until the beam has got completely into equilibrium with its secondaries*, to push down the observed μ, i.e., the μ ob-

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[2] Millikan and Cameron, Phys. Rev. **31**, 163 (1928).

[3] Lindholm, Gerlands Beitrage zur Geophysik **22**, 141 (1929).

[4] E. Steinke, Zeits, f. Physik **42**, 570 (1927) and **48**, 647 (1928).

[5] Hess and Mathias, Wien. Ber. **137**, 327 (1928).

[6] R. A. Millikan, Phys. Rev. **36**, 1595 (1930).

[7] Millikan and Cameron, Phys. Rev. **31**, 925 (1928).

tained from the observed slope. The theory, then, shows no way by which the *computed* absorption coefficient of the pure radiation due to the formation of helium out of hydrogen can be *less than* the observed coefficient. It rather requires that the computed μ be at least as large as, and if equilibrium has not yet been obtained at the observation point, appreciably larger than the observed μ. We thought that our observations at high altitudes showed some slight indications that our uppermost lake-readings were accidentally high and we therefore wished to repeat these observations with more sensitive instruments and under better conditions, and to extend them, if possible, to still higher altitudes, hoping that a crucial test of our theory might come out of such more accurate high-altitude readings. In a word, then, we undertook the present series of observations to extend and improve our observational data at both the upper and the lower ends of the ionization-depth curve.

2. Technique

Our mode of procedure was precisely the same as that used in obtaining the last ionization-depth curve published in 1928, save that in order both to bring out weak effects at greater depths under water, and to obtain increased precision in high altitude observing, we were obliged to increase still further the sensitivity of our electroscope. To do this we built a new spherical instrument of steel, wall-thickness 3 mm, internal capacity 1622 cc, and filled it to a pressure of 30 atmospheres. (See Fig. 1.) This procedure, according to direct observational data to be presented later, multiplied our electroscope sensitivity 13.82 fold over that obtained under a pressure of one atmosphere. It represented, too, a sensitivity more than double that used in our published 1928 observations.[8] We determined the capacity of this electroscope with much precision by the method heretofore described,[8] finding it to be 0.979 absolute electrostatic units. Although we have not reached with this instrument the extreme limit of possible electroscope sensitivity, since increases in volume, slight decreases in fiber-capacity and still higher pressures are possible, yet, for the purposes for which it was to be used, this instrument came close to the limit of possible efficiency as a high frequency radiation detector.

In order to test the insulating properties of our quartz supports, before filling with air under pressure we pumped the chamber entirely free of air and found that it then leaked, to cite one particular test, from 226.5 volts to 226.0 volts *in four hours*. The support-leak was thus not as much as one-tenth of the slowest rate of discharge ever observed in this work, and a small fraction of a percent of the average rate. Further, it disappears entirely in our computations on rate of ion-formation because it is included in what we call the zero of our electroscope. Such minuteness of the leak of the supports, however, shows the completeness with which this source of error has been pushed into the background in these experiments.

As in all of our cosmic-ray work we followed here the procedure of reducing the fiber-deflection to volts at the instant at which it is read. This is done

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[8] Millikan and Cameron, Phys. Rev. **31**, 922—5 (1928).

by calibrating the scale in the eyepiece just before or after each reading. This procedure eliminates completely all temperature effects on the fibers or on any of the electroscope parts. Thus in under-water work our procedure is to calibrate the scale for the deflection to be used under quiet reading-conditions *at the surface*, then to sink the electroscope to the desired depth and leave it for say twelve hours, then to bring it quickly to the surface, read and calibrate again. A small correction is applied for the discharge during lowering and raising by going through the operation of lowering and at once raising and seeing whether an observable change is detectable, or by doing so repeatedly for the sake of magnification and then computing the correction for a single operation. These corrections are small and quite accurately obtainable. In some of our earlier work we used self-registering electroscopes, but for this work we considered them of no advantage.

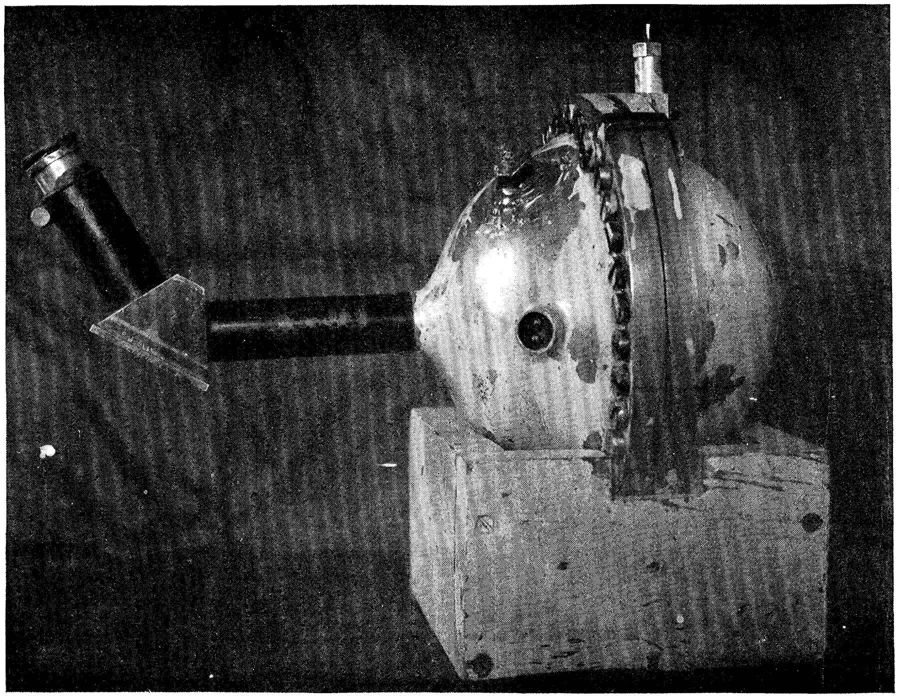

Fig. 1.

The electroscope with which all of the results herein reported were obtained is shown in Fig. 1. It was pumped up to a pressure of 30.14 atmospheres, one atmosphere being reckoned from the conditions existing in the Norman Bridge Laboratory at the time of filling, namely, 24°C, 74 cm pressure, and this pressure has held with no trace of leak for now two years since the time of filling.

The "electroscope constant" of this instrument in ions per cc per sec. is

$$I \text{ cc/sec} = \frac{\text{volts}}{\text{hours}} \times \frac{0.979}{300} \times \frac{10^{-10}}{4.770 \times 1622 \times 3600} = 1.172 \frac{\text{volts}}{\text{hours}}.$$

For observations on land this electroscope was provided with an accurately fitted, spherical lead shield 7.64 cm thick consisting of four layers of carefully shaped and fitted hemispherical shells, and two layers of shells divided into quadrants so as to fit closely the exterior electroscope wall, with its flange and bolts, and to facilitate the entrance of the necessary leading-in wires. The "water equivalent" of this lead shield as obtained by multiplying thickness by density was 85 cm. On account of the space occupied by the steel flange about which the inner layers of lead were fitted, the water equivalent was actually a trifle less than 85 cm, but in any case by careful experiments with radium and thorium in about the proportions in which they occur in surface rocks the percentage of local rays getting through this lead shield was found to be 2.4 percent, and save for this small correction-factor, always determined and applied to all readings, the rays inside the lead were pure cosmic rays and could be compared, as shown below, with readings at the same equivalent depth in water beneath the top of the atmosphere.

3. Readings in Snow-fed Lakes

The results reported in this section were taken partially during the summer of 1928 and partially during the summer of 1929 in the two different California lakes 250 miles apart, Arrowhead Lake (altitude 5100 feet) and Gem Lake (altitude 9120 feet). Since we showed in our first work in snow-fed lakes in 1925 that the measured intensity of the cosmic rays is a single valued function of the depth of the superincumbant atmosphere, it of course follows that it depends upon the barometric pressure, as has since that time been many times noted. Accordingly, in Table I the barometer height is given for each observation, or group of observations. At the higher levels, i.e., down to about sixteen meters beneath the top of the atmosphere, where readings at the same depth beneath the surface of the lake are made at different barometric pressures, the results are reduced to a common pressure by applying a small correction, which is computed from the Gold tables,[9] for the value of the absorption coefficient shown by the ionization-depth curve at the elevation considered. This computation, however, checks nicely with the observed slope of the curve and this slope is of course independent of any theory, so that these small barometric corrections may properly be said to be purely empirical, and hence free from any other than observational uncertainties. This correction is negligible below sixteen meters but amounts at Gem Lake to slightly more than 1% and at Pikes Peak to about 2% per tenth-inch of mercury. The under-water readings, taken in two lakes and over the period from August 1928 to September 1929, are all collected in Table I. It will be seen from columns 7 and 9 that these readings extend from a level equivalent to

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[9] Gold, Proc. Roy. Soc. **A82,** 43 (1909).

8.25 meters of water beneath the top of the atmosphere down to a level of 80 meters, or 262.5 feet, beneath the top, and that in that range of levels, or depths, the observed rate of discharge of the electroscope changes by more than thirty fold, namely, from a value represented by an intensity of ionization within the electroscope of 64.1 ions per cc per sec. down to 2 ions per cc per sec. The absorption coefficients as computed from the Gold tables at successive points along this curve are given in Table II.

TABLE I. *Ionization-depth readings in snow-fed lakes.*

Year	Date	Lake used	Depth in Water	Barometer Reading	Depth below Top of atmosphere	Ions per cc per second	Mean *I* cc/sec
1928	Sept. 11	Gem	.85 m	21.45	8.25	64.1	64.1
“	“ 9	“	1.00 “	21.48	8.42	59.8	60.1
“	“ 9	“	1.00 “	21.48	8.42	60.4	
“	“ 11	“	1.00 “	21.48	8.42	60.2	
“	“ 11	“	2.00 “	21.46	9.41	43.8	43.8
“	“ 11	“	2.00 “	21.41	9.40	43.8	
1929	Sept. 6	Arrowhead	.82 “	24.81	9.40	43.8	43.8
“	“ 7	“	1.50 “	24.77	10.06	37.5	37.5
“	“ 6	“	2.00 “	24.82	10.58	33.5	33.5
1928	“ 12	Gem	4.00 “	21.65	11.48	30.7	30.4
“	“ 13	“	4.00 “	21.65	11.48	30.2	
1929	“ 4	Arrowhead	3.00 “	24.94	11.59	29.6	29.5
“	“ 5	“	3.00 “	24.94	11.59	29.4	
“	“ 6	“	4.00 “	24.79	12.56	25.5	25.5
“	“ 5	“	5.00 “	24.87	13.56	23.0	23.1
“	“ 6	“	5.00 “	24.87	13.56	23.2	
“	“ 7	“	6.00 “	24.74	14.55	21.1	21.1
1928	Aug. 22	“	6.25 “	24.92	14.86	20.2	20.6
“	“ 23	“	6.25 “	24.93	14.86	20.8	
“	“ 25	“	6.25 “	24.81	14.82	20.9	
“	“ 23	“	8.25 “	24.92	16.85	17.10	17.33
“	“ 24	“	8.25 “	24.89	16.84	17.57	
“	“ 25	“	10.64 “	24.81	19.21	14.72	14.52
“	“ 27	“	10.64 “	24.89	19.24	14.33	
“	“ 25	“	15.90 “	24.81	24.47	10.22	10.23
“	“ 26	“	15.90 “	24.83	24.49	10.24	
“	“ 22	“	21.10 “	24.91	29.70	7.81	7.89
“	“ 23	“	21.10 “	24.93	29.71	7.96	
“	“ 20	“	26.25 “	24.81	34.82	6.07	6 .07
“	“ 21	“	26.25 “	24.81	34.82	6.08	
“	“ 19	“	30.35 “	24.79	38.91	5.34	5.21
“	“ 18	“	30.35 “	24.80	38.91	5.08	
“	“ 9	“	37.05 “	24.86	45.64	4.33	4.25
“	“ 10	“	37.05 “	24.86	45.64	4.09	
“	“ 11	“	37.05 “	24.86	45.64	4.34	
“	Sept. 9	Gem	43.00 “	21.48	50.42	3.68	3.62
“	“ 10	“	43.00 “	21.39	50.41	3.56	
“	Aug. 17	Arrowhead	42.78 “	24.91	51.38	3.90	3.79
“	“ 15	“	42.78 “	24.91	51.38	3.88	
“	“ 12	“	42.78 “	24.89	51.38	3.60	
“	Sept. 8	Gem	50.00 “	21.42	57.40	3.30	3.30
“	“ 12	“	60.00 “	21.36	67.38	2.49	2.49
“	“ 10	“	72.5 “	21.39	79.90	1.95	2.00
“	“ 11	“	72.6 “	21.45	80.00	2.05	

The curve starts a little higher up than does the 1928 curve, analyzed on page 927, Physical Review, Vol. 31, and it is significant that the absorption coefficient at the top is now a little higher than it was there, namely 0.27 instead of 0.22, i.e., it is *larger, not smaller,* then before. Also, in keeping with this fact the bend, or knee, at about 10 meters is sharper than ever, as shown by the change from $\mu=0.27$ to $\mu=0.16$ between 9.5 m and 10.5 m, when on the old curve we got $\mu=0.20$ between 9.5 and 10.5. *Of course this means that the most absorbable cosmic-ray band springs into view from these figures more insistently than before.*

TABLE II. *Absorption coefficients at various depths, in meters of water, below top of atmosphere.*

Depth in m. of water beneath top of atmos.	Absorption coef. μ	Depth in m. of water beneath top of atmos.	Absorption coef. μ
8.25– 9.5	0.27	20–30	0.045
9.5 –10.5	0.16	30–40	0.038
10.5–11.5	0.11	50–40	0.028
11.5–12.5	0.095	50–60	0.028
12.5–15.0	0.067	60–80	0.028
15.0–20.0	0.058		

4. LAND-READINGS UP TO GREAT ALTITUDES

The highest altitude snow-fed lake used for the foregoing readings was Gem Lake (altitude 9120 feet) and for the sake of being free from the possibility of effects due to the radioactive emanations of the atmosphere (though over large bodies of water these effects are actually very small) we used no reading nearer the surface of Gem Lake than 0.85 m, a level corresponding to 8.25 m of water beneath the top of the atmosphere. At this level, as indicated above, the curve was already beginning to show departures in the wrong direction for satisfactory explanation from the standpoint of the Dirac formula. However, in accordance with the second of the objectives discussed in §1, the most significant data were to be expected at still higher altitudes, and in order to obtain accurate data at least a meter of water higher up we arranged for a series of land observations as follows:

With the aid of the radiations emitted by known quantities of radium and thorium set up at suitably chosen points, from 2 to 10 meters away, and all around our 7.64 cm lead screen we took readings when the screen was in place and when it was removed from our electroscope, and thus found that about 2.4% of the local radioactive rays from surface rocks and soils get through the lead screen and produce ionization within our electroscope. We then took a series of land observations in various localities, situated in widely different latitudes and at varying elevations from sea level up to 14,100 feet (the top of Pike's Peak), half a dozen or more readings being in general taken at each locality over a period of several days, first, when the lead screen was in place, then when the screen was removed. By comparing these observations with those taken at the same levels beneath the surfaces of snow-fed lakes the water equivalent of the lead screen was quite accurately determined, as shown below, and in this way the depth-ionization curve was reliably extended upward the equivalent of about a meter of water above the highest point obtainable in Gem Lake. This last meter proves to be of great significance for

TABLE III. *Ionization-depth readings at various elevations with and without lead screens.*

Date	Locality	Elevation	Latitude	Barometer readings	Depth below top of atmosphere	Mean ions outside lead	cc/sec inside lead	% cos. rays getting through lead	Mean ions corrected for local rays
Sept. 23–24, '28	Pike's Peak	14,100 ft.	39⅓	17.94 in.	6.195 m. water	288.7	94.2	61%	90.9
Sept. 9–10, '30	Pike's Peak	" "	"	17.84	6.161 " "	290.0	96.4	61%	93.2
Sept. 24, '28	Windy Point	12,200 ft.	"	19.23	6.640 " "	247.4	77.9	62%	75.0
Sept. 10, '30	" "	" "	"	19.29	6.663 " "	245.6			
Sept. 25–26, '28	Mt. Manitou	8,590 "	"	21.97	7.595 " "	188.9	53.6	64%	51.1
Sept. 21–22, '28	Colorado Springs	6,035 "	"	24.13	8.333 " "	113.5	43.51	67%	42.3
Aug. 19–20, '30	Lake Louise Canada	5,670 "	51½	24.41	8.432 " "	81.14	41.80	68%	41.3
Aug. 18, '28	Arrowhead Lk. (in boat)	5,100 "	34	24.89	8.596 " "	63.3	39.96	69%	39.8 } 39.5
Aug. 19, '28	Arrowhead Lk. (on shore)	" "	"	"	" " "	124.8	40.97	69%	39.3
Sept. 22–23, '28	Pueblo, Colo.	4,651 "	38½	25.47	8.796 " "	107.1	37.9	70%	36.6
July 26 to Aug. 4, '30	Pasadena	756 "	34	29.14	10.06 " "	90.7	29.56	76%	28.30
Aug. 25 to Sept. 1, '30	Churchill Manitoba	20 "	59	29.44	10.16 " "	58.87	28.48	76%	27.90

the purposes of the second objective (§1) and in general for the interpretation of the cosmic radiations. Table III contains the record of these land-readings, which were taken during the summer and fall of three consecutive years, 1928, 1929, and 1930. The two readings on Pikes Peak taken two years apart are rather noteworthy. They differ by 2%, but in view of the difference in the barometer reading this difference is not only in the right direction but of the right amount.

The figures given in the last and the third from the last columns are in all cases the means of from three to nine different readings, the fluctuations in which are illustrated, for example, by the nine consecutive readings taken on Mt. Manitou at about two hour intervals beginning at 10:30 a.m. These nine readings, in ions per cc per sec, run 54.7, 52.8, 55.5, 54.3, 52.5, 53.7, 52.4, 52.2, 54.3. Mean = 53.6.

5. THE DEPTH-IONIZATION CURVE AND ITS SIGNIFICANCE

The graphical representation of the results in Tables I and III is given somewhat inadequately in Figs. 2 and 3,—inadequately because no small scale graph can reflect the consistency and precision of these readings. For this reason the readings themselves have been given in Tables I and III so that the reader may plot his own large-scale graph if he so desires. However, two important results stand out immediately and conspicuously from the graphs:

1. At great depths, i.e., between 40 m and 80 m (see Fig. 3) the readings are so consistent as to show that even a blanket of 80 m or 262 ft. of water is insufficient to absorb completely the cosmic rays. The curve has here reached a value of 2 ions per cc per sec., not a fiftieth of its value at Pike's Peak, *but it is still falling.* In order to find the zero of the instrument, or the ionization *when all external rays have become absorbed* and at the same time the absorption coefficient of these hardest rays, we analyzed the curve by the trial and error method between 40 m and 80 m with the aid of the Gold tables, and found that with a zero of 1.2 I per cc/sec. and an absorption coefficient of 0.028 per meter of water, *the whole long stretch of curve between 40 m and 80 m was very accurately reproduced. In a word, our curve shows at its lower end just such a band of hard rays as we had been looking for, and a single coefficient is adequate for the whole range between 40 m and 80 m.*

The significance of the value of this coefficient will be discussed presently, but the very existence of such a coefficient means that a hundred meters farther down, i.e., at 180 m, an ionization of about 0.03 I per cc/sec. should be observable by an instrument capable of detecting such an amount. We checked this conclusion qualitatively in 1928 by taking our electroscope and its lead shield down into a shaft 185 m deep, beside Lake Arrowhead, and finding, after allowing for the local rays, a fraction of an ion still left for the cosmic rays, though, on account of the location of the shaft *beside the lake* we could not reliably estimate the equivalent water depth.

However, Regener[10] has reported more dependable deep water observa-

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[10] E. Regener, Die Naturwissenschaften 15, 183 (1929).

tions which are in substantial agreement with the results here given. He reports his results in volts per hour, which is nearly the same as our ions per cc

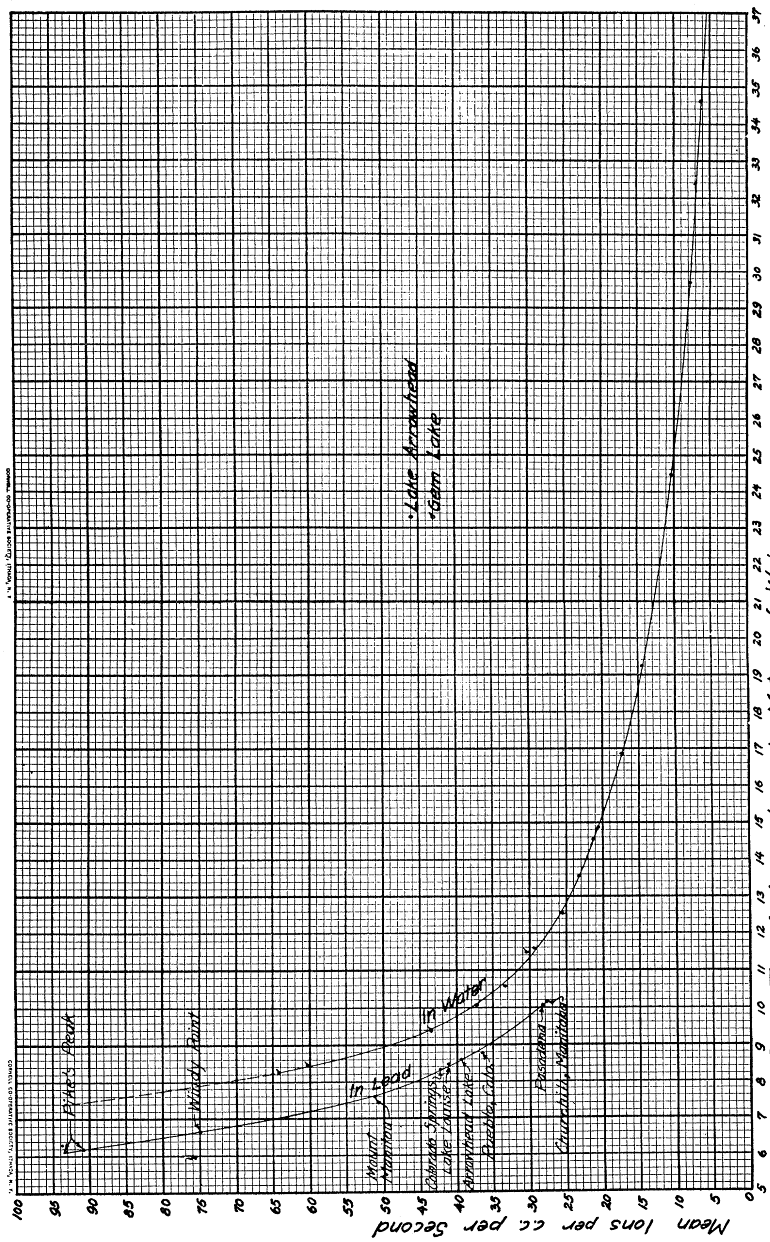

Fig. 2.

per sec., since the multiplying factor of 1.171 reduces in our case *I* volt/hour to *I* per cc/sec. His lowest really detectable reading is at 186 m, though he takes one observation at 230 m. He obtains both his zero and his absorption coefficient by essentially the same trial and error method that we use, and we take

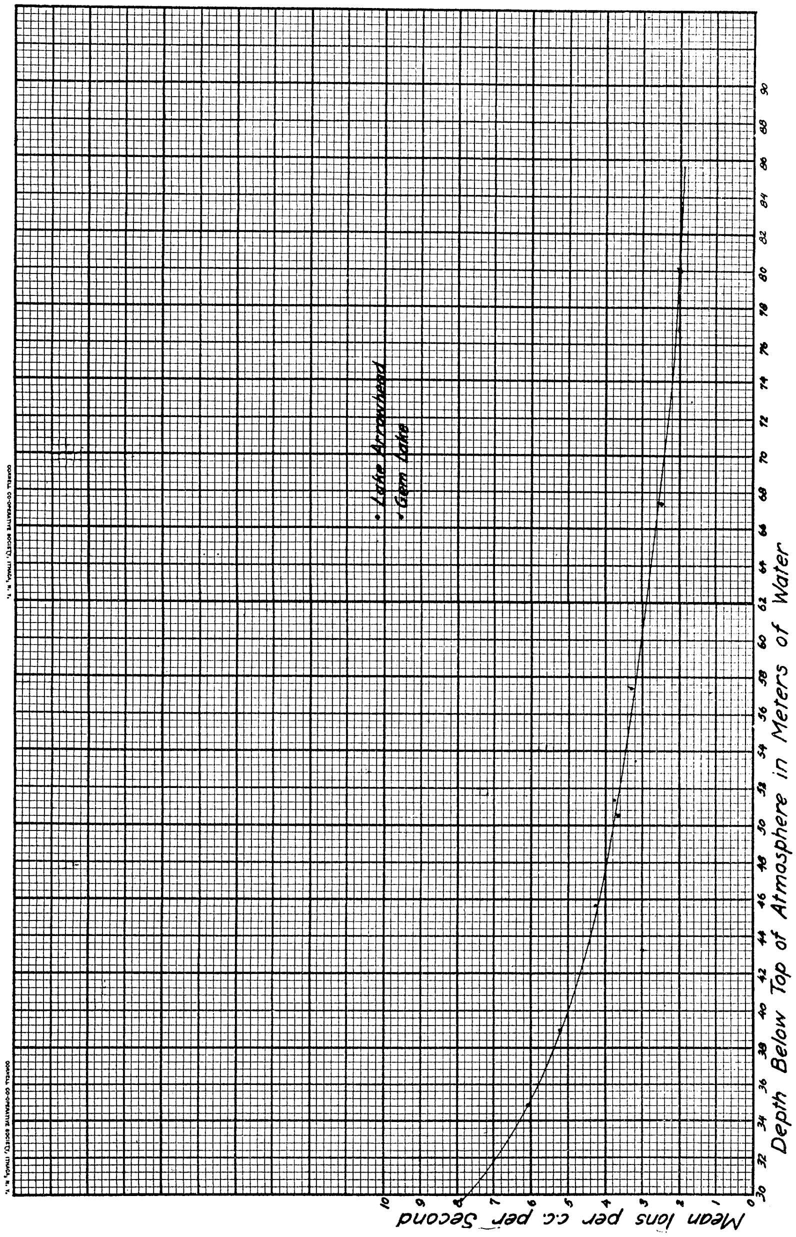

Fig. 3.

it that both he and we may have an uncertainty of as much as 0.2 I per cc/sec. in our zeros. Such a change in our zeros, if taken in the right direction for both of us, would bring our coefficients into fairly good agreement. His value is 0.018 per meter of water. However, for reasons which we shall presently detail, the precise value of the coefficient for this most penetrating cosmic radiation is not particularly significant. The important result that appears both from Regener's deep water work and from our own is merely that there exists a component of the cosmic rays which can penetrate as much as 180 meters of water and which is therefore approximately twice as hard as the hardest component we had before *directly observed* on our former curve namely, $\mu = 0.05$ per m of water.

2. The second immediately striking result that appears from our curves is that the quite accurate observations we have now taken *at high altitudes*—up to 14,100 feet, show that the absorption coefficient now rises *far above anything the Dirac formula will in any way permit.* The absorption coefficient shown at the top of our 1928 curve was 0.22 per m of water, that at the top of our present curve taken in water is 0.27 per m of water, and that at the top of the land-curve is 0.35 per m of water. This new curve then brings out more strikingly than ever the banded structure of the cosmic rays.

We have analyzed this new curve with the aid of the Gold tables precisely as we did the former one in our 1928 article. We at that time found that the peculiar sharp bend in the curve at between 10 and 12 meters could not be reproduced without invoking *three definite bands* having roughly the relative frequencies 1, 4, 8. The new curve revealed the same necessity through the shape of its upper and middle portion, while its shape at great depths requires the introduction of a fourth band, as indicated above. Fearing that we might have become special pleaders for our banded structure, we asked Dr. Bowen, who had not thus far helped in this kind of analysis, to start from first principles with our curve and see, without any suggestions from us, what kind of structure it demanded. He proceeded without reference to any theory to build up with the aid of the Gold tables our observed curve out of four components—no smaller number would do—and in such a way that the synthetic and the observed curve fitted exceedingly nicely from one end to the other.

The components from which the synthetic curve was thus built up to yield the ionization *observed in our electroscope* were as follows:

TABLE IV. *Assumed absorption coefficients and intensities of synthetic curve.*

Assumed absorption coefficients	Assumed I_0 at top of atmosphere	Total $I = I_0/\mu$
0.03	33	1100
.10	80	800
.20	130	650
.80	141,000	176,250

The foregoing of course assumes that the ionization has its maximum value I_0 at the surface of the atmosphere (see below, where this is shown to be incorrect), and the last column then shows that the total energy of formation of the iron group, the silicon group and the oxygen group is of the same general order of magnitude. This checks reasonably well with that we know of the relative abundance of these elements, and it would probably check better if suitable corrections could be made for the foregoing incorrect assumption. Table V then gives a comparison of the calculated and observed ionization.

TABLE V. *Comparison of synthetic and observed curves.*

Depth in meters	Calculated I	Observed I	Difference
7.5	89.7	90.8	−1.0
8.0	70.6	70.6	0
9.	48.2	48.1	− .1
10.	37.1	36.9	− .2
12.	26.4	26.5	+ .1
15.	19.1	19.1	.0
20.	12.53	12.55	+ .02
25.	8.87	8.75	− .12
30.	6.58	6.56	− .02
40.	3.93	3.83	− .10
50.	2.49	2.62	+ .13
60.	1.63	1.88	+ .25
70.	1.11	1.29	+ .18
80.	.74	.80	+ 0.6

Not only can the observed curve not be fitted accurately with less components than four, but also the four must be roughly of the foregoing type, though of course the lower bands can be split up into a finer structure if desired, i.e., 0.03 can easily be replaced by 0.02 and 0.04, for example. Not very much liberty, however, can be taken with the upper bands.

We shall now compare the results of this purely empirical study of our curve with the results computed by the Klein-Nishina formula,[11] the Einstein equation $mc^2=E$, and Aston's curve. This formula has the form

$$\mu = \frac{2\pi N e^4}{m^2c^4}\left\{\frac{1+\alpha}{\alpha^2}\left[\frac{2(1+\alpha)}{1+2\alpha}-\frac{1}{\alpha}\log(1+2\alpha)\right]\right.$$
$$\left.+\frac{1}{2\alpha}\log(1+2\alpha)-\frac{1+3\alpha}{(1+2\alpha)^2}\right\}.$$

Where $\alpha = h\nu/mc^2$, N = no. of electrons per cc. The values of α for the atom-building processes, according to Aston, are

$$H \rightarrow He = 0.029 \div 5.479 \times 10^{-4} = 52.9$$
$$H \rightarrow O = 0.1245 \div 5.479 \times 10^{-4} = 227$$
$$H \rightarrow Si = 0.232 \div 5.479 \times 10^{-4} = 423$$
$$H \rightarrow Fe = 0.48 \div 5.479 \times 10^{-4} = 876$$

5.479×10^{-4} is the atomic weight of an electron obtained from e/m spectroscropically determined. The numerical value of the constant factor is then

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[11] Nature **122,** 399 (1928).

$$\frac{2\pi N e^4}{m^2c^4} = \frac{2\pi N e^2}{c^4}\left(\frac{e}{m}\right)^2$$

$$= \frac{2 \times \pi \times 6.064 \times 10^{23} \times 10}{(2.998)^4 \times 10^{40} \times 18} \times (4.77 \times 10^{-10})^2 \times (5.279 \times 10^{17})^2$$

$$= 0.16614.$$

Then Table VI is the comparison of μ obtained from the Klein-Nishina formula and those of the synthetically obtained curves. The closeness of the agreement at the top is most significant. The progressive departures as the atoms become heavier look at first sight like a difficulty, but the next section goes into possible causes of this behavior.

TABLE VI. *μ in meters of water.*

	Computed	Observed
H→He	0.7957	0.80
H→O	.2409	.20
H→Si	.1418	.10
H→Fe	.0754	.028

6. CONDITIONS OF EQUILIBRIUM BETWEEN A BEAM OF PHOTONS AND ITS SECONDARIES PRODUCED BY THE COMPTON PROCESS

When a beam of photons strikes matter it is obvious that a certain thickness of matter must be traversed before the beam gets into equilibrium with its secondaries, tertiaries, etc., this condition of equilibrium being attained when as many of each kind of secondary is disappearing per second from the beam as is forming per second in it. While this process of getting into equilibrium is going on, the absorption coefficient of the beam, as measured by the rate of change with distance of the ionization produced per cc, is obviously smaller than it can be after equilibrium has been reached. Further, the absorption coefficient of the pure photon beam when it first strikes matter must be the same as that of the beam after it has got into equilibrium with its train of secondaries, provided the secondaries are more absorbable than the primaries,[12] for the reason that in this equilibrium condition the percentage of these secondaries is not changing at all as the beam moves on, the only element that is so changing being simply the number of primaries; but this is precisely the situation in which the beam found itself when it first entered matter.

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[12] The apparent absorption coefficient when equilibrium is reached is equal to the absorption coefficient of the primary or the secondary, depending upon which has the smaller coefficient, the general relation being

$$I = \frac{I_0\mu}{\mu_2 - \mu_1}(e^{-\mu_1 x} - e^{-\mu_2 x}).$$

Of the last two terms that having the larger coefficient will die out, leaving the effective coefficient the one having the smaller value. It is practically certain from Bothe and Kolhörster's work that the coefficient of the beta-rays at sufficiently high frequencies approaches that of the photons, and it is entirely possible that it may even fall below it for the hardest rays.

One of us[13] has recently shown that the cosmic rays enter the earth's atmosphere as streams of pure photons. This means that the ionization in a closed vessel should not be a maximum at the top of the atmosphere, but that there must be an optimum position somewhere beneath the top where this maximum ionization is reached This is precisely what the 1922 high balloon flights of Millikan and Bowen, when taken in conjunction with Hess and Kolhörster's earlier and lower ballon flights proved experimentally to be the case. For in the 1922 flights a recording electroscope rose to a hight of 15.5 kilometers, at which height 0.92 of the earth's atmosphere had been left behind, and the total ionization recorded by the self-registering mechanism proved to be only about one-fourth of that calculated from the absorption coefficient of 0.57 per meter of water, which had been found by Hess and Kolhörster in rising in manned balloons to from 5 to 9 kilometers. The discrepancy seemed to be eliminated in 1923 when Kolhörster in experiments in the Alps got a coefficient only about 0.25 per meter of water, a value not in conflict with Millikan and Bowen's high flight. But up to the present day, though the lower value has been accepted, it has remained a mystery why the earlier European flights yielded such high values. This is now quite clearly explained, for the completely reliable curve shown in Fig. 1 is at the top rising quite as fast as did the Hess-Kolhörster curves, *while the 1922 work shows unambiguously that it cannot continue to do so up to 15.5 kilometers.* In other words, the coefficient has passed through a maximum somewhere between these two levels, and at 15.5 kms. has fallen back again to low values. This is obviously what, from the foregoing considerations, it must do if the cosmic rays enter the atmosphere as pure ether waves.

It will be seen from the foregoing that the Klein-Nishina formula, combined with Aston's measurements and Einstein's equation, yields quite accurately the observed absorption coefficient of the most absorbable band, when it is assumed that that band arises from the synthesis of helium out of hydrogen. Also there is good reason to assume that at the level corresponding to the top of our curve this radiation has already reached a condition of equilibrium with its secondaries, so that the comparison is probably here legitimate. The less absorbable the radiation, however, the farther must it traverse matter thus to get into equilibrium with its secondaries, and it is most illuminating to see how the absorption coefficients computed by the Klein-Nishina formula (see Table VI) for the formation of oxygen, silicon, and iron out of hydrogen *are progressively higher than the observed coefficients* as obtained from the curve, thus indicating that these progressively harder rays are farther and farther removed from the situation in which they have traversed enough matter to get completely into equilibrium with their secondaries. Further, such attainment of equilibrium should become more and more difficult the nearer the absorption coefficient of the beta-rays released by Compton encounters with photons approaches that of the photons themselves, and Bothe and Kolhörster's recent experiments[14] show that this condi-

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[13] R. A. Millikan, Phys. Rev. **36**, 1595 (1930).

[14] Bothe and Kolhörster, Zeits. f. Physik **56**, 751 (1929).

tion is somewhat nearly approached for the harder rays, though it is probably not so for the softer components. It may be that for these very penetrating radiations the secondary electrons are more penetrating than the primary photons and consequently even when equilibrium is reached a lower absorption coefficient should be observed than that called for by the Klein-Nishina formula.[12]

7. Evidence for Atom Building

In a word, then, the general qualitative evidence that the cosmic rays are due to the formation out of hydrogen of the only four abundant groups of elements that there are, namely, helium, oxygen (C, N, O), silicon (Mg, Al, Si) and iron (the iron group), which elements, barring hydrogen, constitute more than 99 percent of all matter;[15] is quite extraordinarily good, but this evidence only becomes *quantitative* in the case of helium. That this band, however, which contains within itself probably more than 90 percent of all the cosmic-ray energy, has so closely the absorption coefficient predicted for it by the Klein-Nishina formula, taken in conjunction with Einstein's equation and Aston's curve, is exceedingly significant. By a process of exclusion we are well-nigh forced to adopt the synthesis of helium out of hydrogen as the origin of this cosmic-ray band; for the Einstein equation and Aston's curve leave us no other alternative, provided the Klein-Nishina formula yields a result of even the right order of magnitude for the relation between absorption coefficient and photon frequency or energy. The only other act that has been suggested, namely, the falling together of a positive and negative electron, *actually releases an energy 35 times that observed as obtained through the Klein-Nishina formula.* This formula has been proved by Millikan and Bowen,[16] by Chao,[17] by Tarrant[18] and by Meitner[19] to be approximately correct for the gamma rays from Th C′′ while the cosmic ray band under consideration, in accordance with our direct measurement, *is but five times* as penetrating as these gamma rays, so that wholly apart from its theoretical credentials, the extrapolation from Th C′′ up to the least penetrating cosmic-ray band is not a very long one. In other words, the Klein-Nishina formula ought to hold reasonably well for this softest cosmic-ray band.

8. Participation of the Nucleus in Cosmic-Ray Absorption

The Klein-Nishina formula, however, cannot be rigorously correct, for it makes the absorption proportional to the number of extra-nuclear electrons. We reported at the fall meeting of the National Academy in 1928 our definite evidence that the nucleus plays a role in cosmic-ray absorption. This evidence is found in the two curves of Fig. 2. If the mass absorption law held, the water equivalent of our lead screen would be 0.85 cm, this being obtained

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[15] H. N. Russell, Astro. Phys. Jr. **70,** 11 (1929). The enormous abundance of H and He is the most striking feature of this article.

[16] Millikan and Bowen, Proc. Nat. Acad. **16,** 421 (1930).

[17] Chao, Proc. Nat. Acad. Sci. **16,** 426 (1930) and Phys. Rev. **36,** 1519 (1930).

[18] Tarrant, Proc. Roy. Soc. **129,** 342 (1930).

[19] Meitner, Naturwissenschaften **18,** 534 (1930).

merely from the thickness of the screen (7.64 cm) and the relative densities of water and lead. The actual water equivalent of the lead screen for the softer cosmic rays is seen from the distance apart, on the x-axis, of the upper parts of the two curves, to be 122 cm. This distance would of course be expected to increase for harder rays, and the curves show that this is indeed the case, since for rays of the hardness that are found at sea level (10 m) the water equivalent of the lead has become 170 cm. Chao[17] has recently brought to light a similar behavior for gamma rays, though of less magnitude, thus suggesting again the identity in nature of the gamma rays and the cosmic rays. The existence of such nuclear influences on absorption means that the Klein-Nishina formula must itself be but an approximation.

9. THE UNIFORMITY OF DISTRIBUTION OF THE COSMIC RAYS

One of us has recently presented at length new evidence that the small fluctuations that have been reported in the intensity of the cosmic rays are due merely to changes in the thickness of the absorbing atmospheric blanket which surrounds the earth, and that the cosmic rays themselves are streaming into the earth with entire constancy and uniformity of distribution over the celestial sphere. The correctness of this conclusion with respect to latitude could scarcely be more beautifully attested than by the left-hand curve of Fig. 2. The observations there presented were taken with the same instrument under identical conditions as to observational technique, but at times extending over three different summers and in widely different altitudes and latitudes, the latter ranging from 34 to 59 degrees north. *Yet they fit with quite surprising exactness one single ionization-depth curve.* The observations at Lake Louise in Canada, latitude 51½, at Colorado Springs, latitude 39⅓, and at Lake Arrowhead, latitude 34, are especially comparable because taken at about the same heights, as are also the near sea-level observations at Pasadena (latitude 34) and Churchill, Manitoba (latitude 59).

This entire constancy in distribution of the cosmic rays is their most significant as well as most amazing property, and must mean, when taken in connection with their absorption coefficient, first, that the temperature existing even in the atmosphere of the sun, whence alone they could get to us from this star, and the same is true for other stars, is inimical to the union of hydrogen into the heavier elements, for hydrogen is present in enormous quantity in the sun's atmosphere. In the second place, these facts must mean that the cosmic rays do not originate in any places in the universe from which they are obliged to come to us *through any appreciable amount of matter whatever.* If they had done so they would on entering the earth be partly beta-rays and partly photons, and, on account of the earth's magnetic field, the beta-ray part would of necessity be stronger near the magnetic pole than at lower latitudes. *But no trace of such an influence can be discovered!* That, however, all about us "*in the depth of space*" hydrogen is somehow uniting into helium at least seems to us to be convincingly shown by the foregoing data, and that it is also uniting into the only other measurably abundant elements, the oxygen group, the silicon group, and the iron group, is strongly indicated, though precise quantitative proof becomes here impossible because of the change—always a decrease—in the absorption coefficient of a beam of highly penetrating photons while it is getting into equilibrium with its Compton secondaries. This phenomenon—the existence of which was demonstrated by the 1922 Millikan and Bowen experiments—renders futile a more precise analysis of our curve than we have given above.

10. SUMMARY

The foregoing results may be summarized as follows:

1. Much the most dependable ionization-depth curve which we have thus far presented, especially at very high and very low elevations, has been obtained and analyzed.
2. This curve shows, as did its predecessor, an unmistakable banded structure, and it further presents excellent quantitative evidence that the most intense and least penetrating band is due to the particular photon released when four hydrogen atoms unite to form an atom of helium.
3. Excellent evidence has been presented that these cosmic-ray bands enter the earth's atmosphere as ether waves and must penetrate far into it before getting into equilibrium with their secondaries; also, that until such equilibrium is attained the observed absorption coefficient is smaller than that of the initial monochromatic radiation. This means, as shown in the 1922 Millikan and Bowen experiments that there is a level beneath the top of the atmosphere at which the ionization due to a pure cosmic-ray beam is a maximum, this maximum moving rapidly farther down as the frequency of the initial photon increases.
4. The observed cosmic-ray curve has been shown to be consistent with the theory that it is made up of four bands due to the formation out of hydrogen of helium, oxygen, silicon, and iron the only atoms of sufficient abundance to render the radiation released by their formation detectable anyway, and it has been shown that the differences between the calculated and observed absorption coefficients of the photons produced by the formation out of hydrogen of oxygen, silicon, and iron are very nicely explained by the non-equilibrium theory given in (3), the departures all being in the right direction and increasing with frequency in the right way.
5. The constancy and the uniformity of distribution of the cosmic rays over the celestial sphere has been again brought strikingly to light, and the significance of this for the place and mode of origin of the cosmic rays has been again pointed out.
6. Some participation of the nucleus in the absorption of cosmic rays has been experimentally established.

We wish to express our appreciation to Professor Bowen for assisting, as indicated above, in the analysis of the curve.

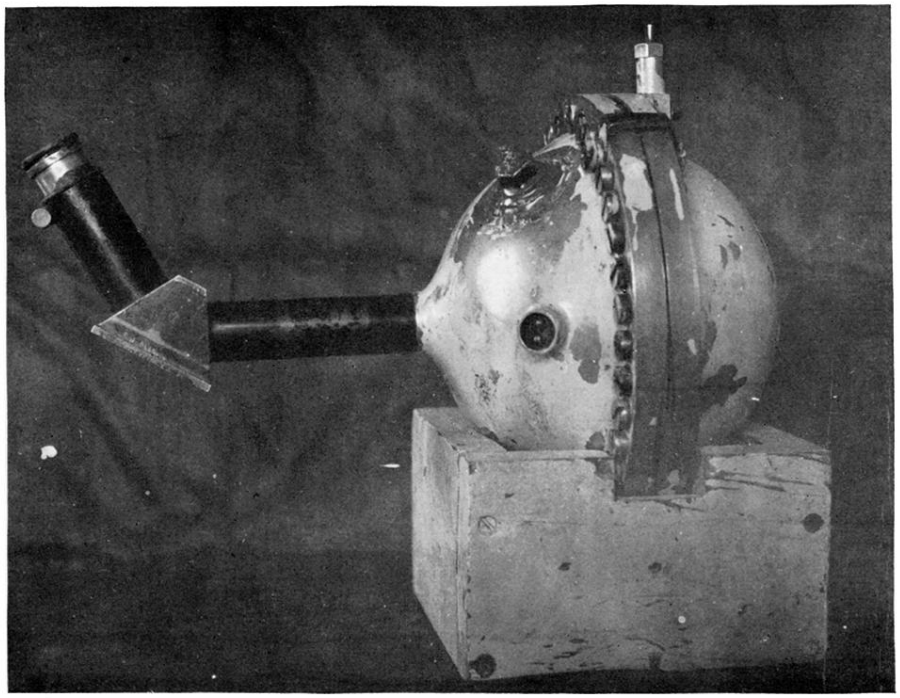

Fig. 1.