COSMIC-RAY IONIZATION AND ELECTROSCOPE-CONSTANTS AS A FUNCTION OF PRESSURE

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(Received December 26, 1931)

Abstract

1. The residual ionization in an electroscope at infinite depth in water, that is, its zero reading, is found to be an inverse function of the pressure. Thus, in a particular electroscope the zero at 1 atmosphere was 5.13 ions cc/sec., while at 30.1 it had fallen to 1.2 ions cc/sec.

2. Also, when in this electroscope the pressure was changed from 1 atmosphere to 30.1 atmospheres the observed ionization current rose but 13.80 fold, which multiplying factor was found the same for gamma rays and for cosmic rays.

3. Both of these pressure effects are shown to be due to lack-of-saturation in high pressure electroscopes, as first explained in Nature of October 3, 1931, by Bowen and the author.

4. From the multiplying factor found in (2) in the measured ionization at Pasadena in this 30 atmosphere high-pressure electroscope, the number of cosmic-ray ions at 1 atmosphere (24° C 74 cm pressure) in this electroscope at Pasadena is found to be fairly accurately 2.63 ions cc/sec.

5. The sea level value of the ionization in this electroscope is 2.48 ions cc/sec.

I. Introduction

When in the fall of 1926 after our return from our experiments in Bolivia, Dr. Cameron and I set about increasing the sensibility of our cosmic-ray electroscopes through the use of high pressures we at first assumed that, at least up to the pressures we then wished to use, about 10 atmospheres, the ionization produced by rays of the enormous penetrating power of the cosmic rays would be proportional to pressure.

When, however, at Arrowhead Lake, we took ionization-depth curves down to depths of 200 feet with the same electroscope, first when filled to a pressure of one atmosphere, then to a pressure of from 6 to 8 atmospheres, and a little later to a pressure of 30 atmospheres, we found two unexpected results, first, a marked dependence of the zero of the electroscope, i.e., the reading which it asymptotically approached at great depths, upon pressure, and second, a markedly smaller ionization current at high pressures than corresponded to the expected linear relation between pressure and ionization. The chief purpose of the present paper is to present and explain these findings.

II. Electroscope Zero a Function of Pressure

With respect to the zero of the instrument the following data are illustrative. In effect three depth-ionization curves were first taken with the same electroscope at three different pressures, namely 1 atmosphere, 4.56 atmospheres, and 6.66 atmospheres. This particular electroscope will be called electroscope No. 1. It was spherical, capable of being completely encased in a spherical lead screen 7.6 cm thick, and had a volume of 1580 cc. The rate of discharge when completely evacuated was taken and found to be quite negligible, corresponding to a few tenths of a division per day or less than 0.2 ion per cc per second, so that although the leak of the supports is included in the zero anyway and is therefore eliminated, there is no possibility of its introducing appreciable uncertainty into the measurements by its variability. The zero of the instrument is then defined as the asymptotic value of the measured ionization current toward which the readings approach at infinite depth. It is due to traces of radioactive impurities in the walls. These asymptotic values were found in the case of electroscope No. 1 to be as follows:

At 1 atmosphere, zero reading = 3.50 ions cc/sec.
At 4.56 atmosphere, zero reading = 2.20 ions cc/sec.
At 6.66 atmosphere, zero reading = 1.97 ions cc/sec.

In the case of electroscope No. 2 (Vol. 1610 cc), which was made precisely as was No. 1 of steel hemispheres 0.66 mm thick, each carrying a flange at the equator for the sake of air-tight bolting, only zero pressure and atmospheric pressure were used, the former for seeing that the leaks of the supports were negligible and the latter for taking ionization readings. This electroscope, too, could be encased in lead 7.6 cm thick. The zero at one atmosphere of this electroscope was found by the foregoing method to be 3.73 ions cc/sec., and by a completely independent and more exact method (see below) to be 3.91 ions cc/sec. Although the difference is 5 percent I probably cannot claim a greater accuracy than this in this particular zero determination.

In the case of electroscope No. 3, which had a volume of 1622 cm and a wall thickness of 3 mm of steel, depth-ionization curves were taken at one atmosphere and at 30 atmospheres. The latter is the curve published in the Physical Review 37, 235 (1931). It is of course very much more dependable than any of the other curves since under the influence of the same radiation the currents are 13.8 times as great as at one atmosphere. This means that the asymptotic value can here be determined with relatively great precision, and in addition this zero value is so low (1.2 ions per cc/sec.) that a large percentage of error in it would affect but little the following computations or the conclusions drawn from them.

Let x be the zero value at 1 atmosphere, r_1 the reading in the electroscope at one atmosphere at any depth where the ionization is large enough so that the percentage error in it is small, say at 1 meter below the water surface, and let R_1 be the reading at this same depth where the pressure in the electroscope is 30 atmospheres. Also let R_{35} and r_{35} be the corresponding readings at a relatively large depth, say 35 meters. Then obviously

$$\frac{R_1 - 1.2}{r_1 - x} = \frac{R_{35} - 1.2}{r_{35} - x}.$$

Testing this equation to see whether x comes out constant when other readings than those at 1 m and 35 m are used is equivalent to proving that the actual cosmic-ray depth-ionization curve is independent of the type of electroscope used for testing it. When in one case the readings at 1 m and 20 m beneath the surface and in a second case at 0.85 cm and 35 m were substituted the zero of electroscope No. 3 at one atmosphere came out 5.13 ions cc/sec. and 5.12 ions cc/sec., respectively. The zero of electroscope No. 3 was then taken as 5.13 at one atmosphere and 1.2 at 30 atmospheres.

The foregoing method of comparing depth-ionization curves with different electroscopes was actually used in fixing all the above mentioned zero-values. A check-method on the foregoing determinations is as follows. After fixing the zero of No. 3 at 5.13 ions cc/sec., the three electroscopes 1, 2, and 3 were set up in the same spot on the campus at Pasadena all enclosed in the same lead shield. The mean ionization current in No. 1 was found to be 5.51 ions cc/sec., in No. 2 was 5.96 ions cc/sec., and in No. 3 it was 7.18 ions cc/sec. Then since the same external radiation is operating in all cases the zero of No. 1 must be the zero of No. 3 minus $(7.18-5.51)$ or $5.13—1.67=3.46$ ions cc/sec. as against 3.5 mentioned above as determined by the first method. Similarly the zero of No. 2 is $5.13-(7.18-5.96)=3.91$ as against 3.73 as determined from the under-water work at Arrowhead.

The foregoing data sufficiently establish the dependence of the electroscope-zero upon pressure. The reason for this dependence is obviously that increase in pressure reduces in much the same proportion the distance of separation of electrons detached from atoms by the radioactivity in the walls. And, since the forces pulling the detached electrons back to the parent atom vary inversely with a high power of the distance apart, ions which can get to the electrodes at low pressures cannot do so at high. In other words, *saturation becomes impossible at high pressures even though the applied potential is much increased, since the recombining forces increase enormously more rapidly.*

Although the foregoing explanation was seen at once to be satisfactory for the case of the relatively soft rays coming from radioactive constituents in the walls, it was not at once evident that it should also apply to the ionization produced by the extraordinarily penetrating cosmic rays. Indeed, the nature of the ionization produced by the cosmic rays was completely unknown so that the following facts were discovered purely experimentally.

III. Number of Cosmic-Ray Ions Produced in Electroscope No. 3 at Pasadena

For the sake of finding the ionization produced in electroscope No. 3 at one atmosphere by the cosmic rays the following procedure was adopted, Electroscope No. 3 was set out on a stand under a tree on the campus of the California Institute at Pasadena and a series of readings taken alternately with and without the lead envelope. These readings were

	Without Pb	With Pb
July 11, 1928	11.67	7.39
July 12, 1928	11.50	7.12
July 13, 1928	11.67	7.02
		7.20
Means	11.61	7.18

The zero of this electroscope having been determined as 5.13 by the under-water work at Arrowhead Lake (altitude 5,100 feet) it follows that $11.61 - 5.13 = 6.48$ = total ions formed per cc/sec. at Pasadena. (altitude 756 feet) and that $7.18 - 5.13 = 2.05$ = total ions inside Pb formed per cc/sec. at Pasadena.

But now from the general cosmic-ray curves in lead and in water already published by Cameron and myself[1] and taken with this same electroscope at 30.1 atmospheres it will be seen that the percentage of the cosmic rays getting through this identical lead screen at Pasadena is

$$(28.2 - 1.2) \div (37.5 - 1.2) = 74.4 \text{ percent}$$

Hence approximately $2.05 \div 0.744 = 2.75$ cosmic-ray ions per cc/sec. are formed at Pasadena (alt. 756 ft. above sea level) in electroscope No. 3 when it is not surrounded by lead. Hence, approximately of the 6.48 ions all told formed in electroscope No. 3 at Pasadena 2.75 are due to cosmic rays and $6.48 - 2.75 = 3.73$ are due to radioactivity in the earth and air. These figures need the following correction. Of these radioactive rays 2.4 percent get through the lead and there produce 0.09 ions so that of the 2.05 ions inside the lead only $(2.05 - 0.09) = 1.96$ are really of cosmic origin. Hence the ions due to cosmic rays in No. 3 electroscope when it is outside the lead are $1.96 \div 0.744 = 2.63$ and those due to local radioactive gamma-rays are $6.48 - 2.65 = 3.85$. The first of these numbers is constant within less than a percent[2] the second is of course variable in many localities, but in the dry summer months at Pasadena it was not found to vary by more than the limits of uncertainty of these measurements of it.

IV. Multiplying Factor for Cosmic Rays at 30 Atmospheres Same as for Gamma-Rays

Now in order to get the multiplying factor by which the ionization currents due to cosmic rays in electroscope No. 3 are increased when the pressure is raised from 1 atmosphere to 30 atmospheres it is only necessary to take as above from the general cosmic-ray curve obtained in water by Cameron and myself[1] with this electroscope at this pressure, the value of the ionization in it at the altitude of Pasadena. This is seen to be $(37.5 - 1.2) = 36.3$ ions. Dividing this by the number of ions formed by the same cosmic rays when the electroscope has a pressure of 1 atmosphere, namely 2.63, one obtains as *the cosmic-ray multiplying factor for 30 atmospheres 13.80.*

It is interesting to compare this with the multiplying factor for ordinary gamma-rays of radium and thorium. This can be obtained as follows: The difference between the ionization currents observed with electroscope No. 3 at 1 atmosphere has been given as $11.61 - 7.18 = 4.43$. This difference represents almost wholly the radioactive gamma-rays that are cut out by the lead. The same experiment was made in the same spot when the pressure was thirty atmospheres, the mean reading without lead being 90.75 ions cc/sec. and with

[1] Millikan and Cameron, Phys. Rev. **37**, 244 (1931).
[2] Millikan, Phys. Rev. **39**, 391 (1932).

lead 29.75 ions cc/sec. The ionization current now produced by these same rays is then.

$$90.75 - 29.75 = 61.00$$
$$61 \div 4.43 = 13.79$$

i.e., *the multiplying factor is the same for cosmic rays as for gamma-rays. This result is of no little importance since it means that the mechanism of ion formation with cosmic rays is essentially the same as with gamma-rays.*[3]

Since gamma-rays and cosmic rays show the same multiplying factor[4] it is of course unnecessary in order to get this factor to separate the ionization into the part due to cosmic rays and the part due to gamma-rays. Thus we had the total ionization at one atmosphere in No. 3 at Pasadena as $11.61 - 5.13 = 6.48$. Similarly at thirty atmospheres the total ionization is $90.75 - 1.02 = 89.55$. The multiplying factor for all the rays cosmic and gamma, is then $89.55 \div 64.8 = 13.82$. The beautiful agreement between these three different ways of getting the multiplying factor for 30.1 atmospheres leaves little uncertainty as to its accuracy. In the same way the multiplying factor of the same electroscope at 9.26 atmospheres was found to be 6.22.

V. Significance of Pressure-Ionization Relations

Bowen and I[3] have already pointed out that the significance of the foregoing pressure-ionization relations is simply that it is impossible to obtain saturation at high pressures. In the case of gamma-rays the immediate ionizing agent is a beta-ray and on the average the detached electrons are not thrown far away from the parent atom. When the pressure is increased thirtyfold this distance is greatly reduced and the powerful recombining forces cannot be entirely overcome by any ordinary increase in field strength. Indeed, changes in applied potential from one hundred to three hundred volts are found to cause at 30 atmospheres no appreciable increase in current, i.e., the currents appear saturated though in fact less than half the electrons actually detached are caught.

That the foregoing is the correct explanation of the pressure-ionization relations can be seen from the following considerations. The ionization produced within an electroscope by gamma-rays is always a little higher than that computed for free air by means of the so called Eve number because there is a small positive wall-effect. Now the mass absorption law is found to hold quite accurately for atoms of nearly the same atomic weight. When, therefore, the absorbing mass inside the electroscope is increased by crowding in say thirty times as many of the same molecules as are already there the absorption *must* be increased in the same proportion, and the absorption must manifest itself in the ions formed. If, then, we find by experiment that we get only half the expected number of ions it can only mean that we have not caught them all. That the cosmic rays behave in this respect just as do the

[3] Millikan and Bowen, Nature **128**, 582, (1931).

[4] This result was also found by Hoffmann, Zeits. f. Physik **69**, 704 (1931). See also Hoffmann and Lindholm, Gerlands Beiträge zur Geophysik **22**, 23 (1928).

gamma-rays must mean that in the case of cosmic rays the immediate ionizing agent is either a negative or a positive electron or both, for the general type of ionization is the same for electrons and for protons, as the Wilson tracks show.

VI. Cosmic-Ray Ionization at Sea Level

The result found above that the cosmic-ray ionization at Pasadena in Electroscope No. 3 is 2.63 cc/sec. is somewhat surprising because it is larger than our preceding estimate. Its accuracy, however, is very much greater than that obtained in any of our preceding work done with electroscopes at a pressure of one atmosphere, for the foregoing multiplying factor 13.80 is known with great certainty as the above data show, and the ionization at Pasadena taken from the Millikan-Cameron-30-atmosphere curve is a weighted mean of many observations, and its value is accurately 37.5 ions cc/sec. Now $(37.5-1.2)\div 13.80$ gives exactly 2.63, which is the ionization at Pasadena at 24° C, 74 cm pressure, the conditions at the time of filling the electroscope and in terms of which the pressure of 30.1 atmospheres was computed. As can be seen from the ionization-depth curve, 2.63 ions cc/sec. at Pasadena corresponds at sea level, i.e., at 10.33 meters of water, to 2.48 ions cc/sec. in place of the 1.4 or 1.6 ions cc/sec., which was published as a result of our early under-water work done in 1925 and 1926 before the technic of accurate cosmic-ray measurements had been developed.

The other two electroscopes here used, No. 1 and No. 2, when worked out in the same way give results in fair agreement, No. 1 giving cosmic-ray ions at Pasadena 5 percent lower than No. 3 and No 2 giving a value 7 percent higher. But the results with No. 3 are by far the most dependable. Not only the ionization-depth curve itself but the constants derived from it are so much more accurate than any of our previous results obtained with the earlier and much less sensitive electroscopes that although I can find no disagreements between the previous work and this that lie outside the older experimental uncertainties, this newer work should entirely replace the older at points at which they overlap. These former experimental uncertainties lay partly in the measurements of the electrical capacities of the fibers, then only roughly determined, but especially in the zeros of the electroscopes, insufficient depths and insufficient sensitivities having been used in determining them in the earlier work. This earlier work, too, was done with entirely different electroscopes which need not have the same wall-effects as has No. 3 here used, though I do not think this should make so large a difference. It is true that all measurements of the absolute value of the cosmic-ray ionization at sea level relate to the particular electroscope used and in general contain an unknown wall-effect. This effect, however, is probably rather small so that it is now highly probable that the absolute value of the cosmic-ray ionization in open air at Pasadena is somewhat over 2 ions. I hope to report later on the reduction of the values here found for electroscope No. 3 to absolute values in free air.