# New Methods of Determining the Absolute Intensity of Cosmic Rays in the Atmosphere and the Residual Ionization in Ionization Chambers

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The portable Gish-Sherman ionization meter in connection with four geometrically similar cylindrical ionization chambers of different size was used for determining (1) the cosmic-ray intensity at sea level when the apparatus is completely shielded from local radiations by 10 cm of iron, and (2) at the same time a value for the residual ionization produced by spurious alpha-particles from the walls of the chambers. Two methods to obtain this end are described: one using all four chambers, and the other using the largest chamber and varying the pressure of the filling gas. Plotting the observed ionization *versus* the ratio of surface: volume gives a straight line which, when extrapolated for infinite volume leads to the value representing the ionization produced by cosmic rays without the secondaries from the wall.

THE "absolute intensity" of cosmic radiation at sea level (obtained in ionization chambers filled with air, reduced to normal temperature and pressure) reported by different authors varies within wide limits. For unshielded chambers at geomagnetic latitudes beyond the "knee" the values range from 1.9 to 2.8*I*. From the intensity *vs.* altitude curve a value of 2.08*I* was derived by Kolhoerster. In Holland J. Clay and P. H. Clay,[1] also using unscreened apparatus, found 1.63*I* for a vessel filled with air at atmospheric pressure and 15°C. This value is perhaps the most reliable one for the ionization by cosmic radiation at sea level, but even Clay did not take into account the increase of ionization by secondaries produced in the walls of the vessel. It is generally believed that the additional ion production by secondaries in a thin-walled brass chamber is quite small, perhaps only a few percent of the total effect. An experimental test for this contention would seem urgent.

The large discrepancies between the results of various authors may largely be due to the fact that the effects of local gamma-rays were not determined accurately enough. In some cases the residual ionization (due to radioactive impurities in the walls of the chamber) was over- or under-estimated; in other cases the reduction of observed ionization in high pressure chambers with argon or $CO_2$ to normal pressure in air may have been insufficiently accurate. In addition errors in the determination of small capacitances of some instruments or due to a lack of saturation in the ionization chambers may have been quite large.

One of us (V.F.H.) has made extensive studies of the ionization balance in the atmosphere at sea level[2] which is of fundamental importance for our knowledge of atmospheric electricity. The ionization of the atmosphere at sea level is produced by the alpha-, beta-, and gamma-rays from the radioactive products in the soil and in the atmosphere, and, to a lesser extent, by cosmic radiation. If we measure this ionization in a hermetically sealed vessel filled with a gas free of radon, the total ionization is due to: (1) occasional alpha-rays from radioactive impurities in the metal of the chamber (residual ionization, $q_O$), (2) gamma-rays from the radioactive substances in the soil ($q_E$), (3) gamma-rays from the radioactive decay products of radon, thoron, and actinon in the atmosphere ($q_A$), and (4) cosmic rays ($q_C$).

$$q=q_O+q_E+q_A+q_C.$$

If the ionization chamber is placed in an iron house with walls thick enough to absorb practically all gamma-rays (10 cm of iron) the total ionization is due to $q_O$ and $q_C$. In this case we observe the effect of cosmic rays filtered through 10 cm of iron. If the apparatus is set up outdoors and the top of the iron house is left open, the ionization is due to unfiltered cosmic radiation and to the small gamma-ray component $q_A$ which in most cases will not amount to more than 0.1*I*. The residual ionization ($q_O$) due to alpha-rays from the inner surface of the wall of the chamber can be kept at much less than 1*I* if the chamber walls are very carefully cleaned and the volume of the chamber is not too small. Since this residual ionization is proportional to the surface, while the other ionizing agencies are volume effects, it is advantageous to use chambers of fairly large size in which the ratio of surface area ($A$) to the volume ($W$) is rather small.

The total ionization as observed in the iron house (closed on top) is

$$q=q_O+q_C=Akn_\alpha+q_C, \quad (1)$$

TABLE I. Dimensions of the four chambers.

| Chamber | Volume ($W$) cm³ | Inner surface ($A=10r^2\pi$) cm² | Radius ($r$) cm | $A/W$ |
|---|---|---|---|---|
| I | 43680 | 7234 | 15.0 | 0.1656 |
| II | 13173 | 3247 | 10.16 | 0.249 |
| III | 4888 | 1675 | 7.30 | 0.348 |
| IV | 1645 | 811 | 5.08 | 0.504 |

[1] J. Clay and P. H. Clay, Physica **5**, 898 (1938).
[2] V. F. Hess, *Die Ionisierungsbilanz der Atmosphäre* (Akademische Verlagsgesellschaft, Leipzig, 1934). V. F. Hess, Terr. Mag. **46**, 409 (1941); Trans. Am. Geoph. Union **27**, 670 (1946); Phys. Rev. **72**, 609 (1947). V. F. Hess and J. D. Roll, Phys. Rev. **73**, 592 (1948); Phys. Rev. **73**, 916 (1948).

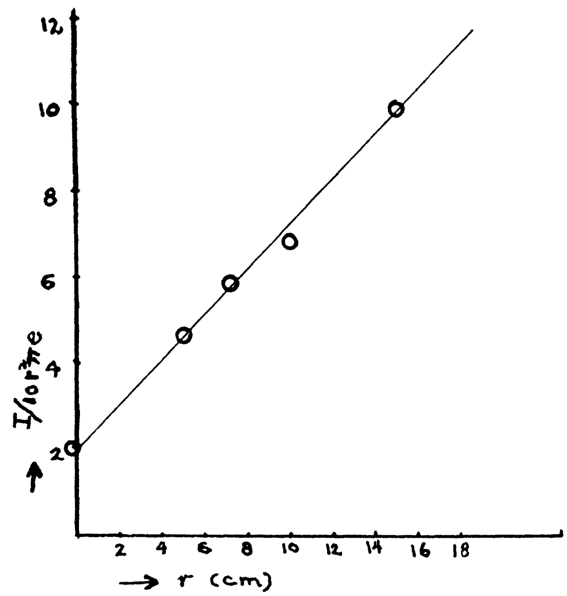


FIG. 1. Extrapolation of residual ionization from measurements of four chambers.

where $n_\alpha$ denotes the number of alpha-particles emitted from the wall per cm² per sec., $A$ the surface area of the chamber wall, and $k$ the average number of ion pairs produced by each alpha-particle.

The ionization produced by cosmic rays may also be considered partly as a surface effect since the secondaries produced in the walls of the chamber will increase (at constant thickness of the wall) with the area of the wall exposed to cosmic rays. Experiments to be discussed later will show that in thin-walled ionization chambers (as used by us) this effect of secondaries is very small. Therefore we can treat the cosmic-ray ionization as a volume effect, especially since the ranges of these secondaries are considerably longer than the diameter and height of our chambers.

We were using ionization chambers of cylindrical shape, made of yellow brass (wall thickness 2.5 mm) in conjunction with the ionization meter devised by O. Gish, K. L. Sherman and one of the authors which is described elsewhere.[3] The chambers were geometrically similar (height equal to twice the diameter of the chamber) with volumes 43.68, 13.17, 4.89, and 1.645 liters, and radii 15, 10.16, 7.30, and 5.08 cm respectively. All four cylinders were air-tight and could be evacuated or filled with any gas through a Hoke needle valve.

The amber-insulated inner electrode of each chamber is directly connected to the fiber system of a Lindemann electrometer which is mounted in a housing fitted exactly to the top of each of the chambers, which are used in a vertical position. The guard ring and the case of the electrometer are connected with a battery supplying 180 volts, and the center point of the quadrant battery is kept at the same potential. A needle contactor is used for connecting or disconnecting the fiber system from the battery with which the guard ring is permanently connected. The wall of each chamber is kept at ground potential. When the contactor is lifted the needle begins to float, and the rate of drift is a measure of the ionization in the vessel. We preferred to use the "null-method": a 3-volt auxiliary battery with a potentiometer and a precision voltmeter (range 3 volts) allowed us to add any voltage from 0 to $-3$ volts to the 180-volt sweep voltage, thus inducing an opposite charge on the floating system just enough to keep the electrometer needle always at or close to the zero point. When using this null-method, all corrections for insulation leakage of the electrometer are avoided. We found this method very reliable and practical even under very adverse atmospheric conditions. The reading of the compensating voltage at the end of each measurement (from 5 to 60 min. in duration) multiplied by a reduction factor, which is proportional to the induction coefficient between the guard ring system and the inner electrode for each chamber, gives the ionization ($q$) expressed in ion pairs per cm³ per sec.

The apparatus was built in the shop of the Department of Terrestrial Magnetism (Carnegie Institution), Washington, D. C. The fourth and largest chamber was constructed in 1947 and we are indebted to the Director, Dr. M. A. Tuve, for arranging this.

The capacitances and induction coefficients of all four chambers with the electrometer were redetermined in 1948 by means of a Wulf variable condenser calibrated with a G.E. capacitance bridge in the Department of Terrestrial Magnetism.

The residual ionization of the three smaller chambers was determined in 1947 by using them within the iron house in a subway tunnel under 210 ft. of solid rock where the cosmic-ray intensity is practically zero and local radiation was eliminated by the 10 cm iron wall around the apparatus. These direct measurements served as a control for determinations of the residual ionization with the two simpler methods to be described below.

We shall now first describe two methods used for the determination of the residual ionization and the intensity of cosmic rays in our brass chambers, and then proceed to the determination of the cosmic-ray intensity in the free atmosphere.

### A. METHOD I

The method is based on the successive use of all four chambers in the iron house at the location where a determination of the cosmic-ray intensity is desired. To test this method we tried it first indoors, in the basement laboratory of the physics building at Fordham University. The cosmic rays measured there are filtered through four floors and ceilings and the additional 10 cm of iron (the top of the iron house). The experiments will be continued outdoors by setting up the iron house in a tent.

[3] V. F. Hess, Trans. Am. Geoph. Union 27, 670 (1946).

The numerical values for the dimensions of the four chambers are listed in Table I.

The total ionization current in each chamber according to Eq. (1) is (in e.s.u.)

$$i = eAkn_\alpha + eWq_C. \quad (2)$$

Dividing by $eA$ and inserting $A = 10r^2\pi$ and $W = 4r^3\pi$ (radius $= \frac{1}{4}$ of the height of each cylinder), we get

$$(i/10er^2\pi) = kn_\alpha + 0.4rq_C. \quad (3)$$

This is a linear relationship between the total ionization observed and the radii of the chambers.

The experimental curve (Fig. 1) shows that such a relationship actually exists if all chambers show the same residual alpha-ray emission. Only chamber II shows a slight deviation. Extrapolation of the straight line to the value $r=0$ gives for $i/10er^2\pi$ the numerical value 2.00 which corresponds to our average value of ion production by alpha-ray emission from the walls of the brass chambers.

Taking for $k$ a mean value of $1.5\times10^5 I$ per alpha-particle, the number of alphas emitted per cm² would be $n_\alpha = (2/1.5\times10^5) = 1.33\times10^{-5}$ per sec., or 0.048 alpha-particles per hour for each cm² of brass. This figure may be a bit too low because some of the alpha-particles are coming not from the surface itself but from regions slightly below the surface. Taking $k = 1.0\times10^5$ would probably be a better estimate, giving $n_\alpha = 0.07$ alpha-particles per cm² per hour for our brass chambers. This shows that our chambers are practically free of radioactive impurities. The lowest alpha-ray emission reported so far is 0.03 per cm² per hour (for steel).*

We are now in a position to compute $q_C$. With nitrogen in the chambers at atmospheric pressure we got, for instance, for chamber I a total observed ionization $q = 1.602I$, from which it follows that $I/10er^2\pi = 9.89$. Inserting this value and the experimental value for $kn_\alpha$ (2.00) in Eq. (3)

$$0.4rq_C = 9.89 - 2.00 = 7.89$$
$$q_C = 1.315I.$$

This value of $q_C$ is, of course, the cosmic-ray ionization actually produced within the brass chamber. Similar values were obtained with chambers II, III, and IV.

The residual ionization computed for the largest chamber is, therefore, $q_O = 1.602 - 1.315 = 0.287I$. This value could not be checked directly by an underground experiment, because the underground station had to be discontinued before this particular chamber was constructed. For chambers III and IV such comparisons were made and gave satisfactory agreement within ±10 percent between experimental values (iron house in tunnel) and computed values of $q_O$.

* See J. A. Bearden Rev. Sci. Inst. 4, 271 (1933).

### B. METHOD II

This method is based on the observation of the change of ionization with pressure in the largest chamber. It is well known that ionization increases almost linearly with pressure, but the curve flattens out at higher pressures except when very pure argon is used.[4] For this reason it seemed more appropriate to work at lower pressures, as C. T. R. Wilson did in his early experiments on penetrating radiation. We measured the ionization in the largest chamber (43.7 liters in volume) filled with either commercial nitrogen or argon at atmospheric pressure and at lower pressures by reducing the pressure in steps of 5 or 10 cm Hg down to about 7 cm. It was to be expected that the ionization *vs.* pressure curve would be linear as long as the pressure ($p$) was not lower than that at which the range of the alpha-particles is equal to the diameter of the chamber (15 cm). At still lower pressure the curve was expected to deviate downward toward zero. The slope of the linear part of the curve then would represent the actual value of the ionization produced by cosmic rays in the chamber (including secondaries), while the extrapolation of the linear part of the curve for $p=0$ would give the approximate value of the residual ionization.

Theoretically, the observation of just two points on the linear part of the ionization *vs.* pressure curve at $p=1$ atmos. and about $p'=0.5$ atmos. would give these results. If the saturation currents, $i$ and $i'$, are measured in the iron house at the pressures $p$ and $p'$,

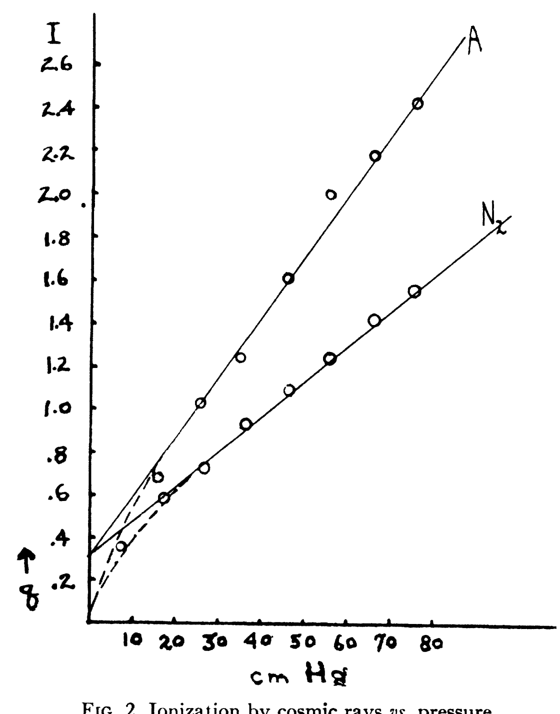


FIG. 2. Ionization by cosmic rays *vs.* pressure for argon and nitrogen.

[4] A. H. Compton and J. J. Hopfield, Rev. Sci. Inst. 4, 491 (1933).

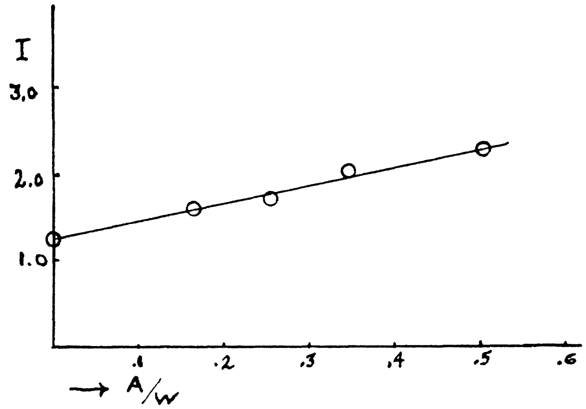


FIG. 3. Extrapolation of ionization by cosmic rays in the free atmosphere.

we have

$$i = Aekn_\alpha + Weq_C \cdot p$$

$$i' = Aekn_\alpha + Weq_C \cdot p'$$

$$i - i' = Weq_C(p - p')$$

$$q_C = \frac{1}{We} \cdot \frac{i-i'}{p-p'} = \frac{1}{We}\frac{di}{dp}.$$

For our cylindrical chambers (radius $= \frac{1}{4}$ of the height of the chamber)

$$i = 10r^2\pi ekn_\alpha + 4r^3\pi eq_C p,$$
$$i' = 10r^2\pi ekn_\alpha + 4r^3\pi eq_C p',$$

where $kn_\alpha$ and $q_C$ are the two unknown quantities. Since

$$q_C = \frac{1}{4r^3\pi e}\frac{i-i'}{p-p'} = \frac{dq}{dp} \quad (4)$$

we obtain the residual ion production per cm² per sec.

$$kn_\alpha = \frac{i}{10r^2\pi e} - \left(\frac{i-i'}{p-p'}\right)\frac{p}{10r^2\pi e},$$

and

$$q_O = \frac{Akn_\alpha}{W} = \frac{i}{4r^3\pi e} - \left(\frac{i-i'}{p-p'}\right)\frac{p}{4r^3\pi e},$$

$$q_O = q - \frac{q-q'}{p-p'} \cdot p.$$

It is, of course, more accurate to determine the slope of the curve $dq/dp$ from a number of points graphically and to obtain $q_O$ from the intercept of the straight line $dq/dp$ with the ordinate, as it is shown in Fig. 2.

We found it necessary always to begin with the readings at atmospheric pressure and to reduce pressure in steps instead of beginning at lower pressures, since filling the chamber with gas from a steel cylinder through a reduction valve is always accompanied by a spurious influx of ions, presumably Langevin ions, even when a cotton filter is inserted. It takes some time until this temporary ion cloud is removed. This effect is completely avoided when the readings are taken after each step of reduction in pressure.

Figure 2 gives two sample curves obtained with nitrogen and argon in the chamber. They show very clearly the linearity of the curves and the downward deviation of $q$ at the lowest pressures used. The extrapolated value of $q_O = 0.32I$ is in good agreement with the value obtained with method I.

The values of cosmic-ray ionization $q_C = dq/dp$ for argon ($2.10I$) and nitrogen ($1.24I$) at atmospheric pressure are also in good agreement with the accepted figures; their ratio (1.69) is practically the same as was found by Hopfield.[4] It is to be kept in mind that these values of $q_C$ represent the ionization by cosmic rays at sea level, geomagnetic latitude 51°N, in a large brass cylinder, after penetrating four ceilings and floors of our building and an additional screen of 10 cm of iron.

## C. DERIVATION OF THE VALUE OF THE TRUE IONIZATION BY COSMIC RAYS WITHOUT SECONDARIES

In order to obtain the ionization without secondaries from the walls of the chamber, one can proceed as follows: we plot the observed values of $q = Akn_\alpha + q_C$ (total ionization in the iron house) *vs.* $A/W$. The extrapolated value of $q$ for $A/W = 0$ (infinite volume) would indicate the ionization produced in a chamber of infinite volume filled with nitrogen at atmospheric pressure, at the point of observation. Figure 3 shows that the four chambers give a linear relationship $q$ *vs.* $A/W$ with an extrapolated value of $q_C = 1.23I$. This figure actually represents the true ion production in nitrogen without any secondaries emitted from the walls, since in a chamber of infinite volume any contribution of residual ionization (alpha-rays from the walls) as well as from electrons knocked out of the walls by cosmic rays would be negligible. If, therefore, similar experiments are performed outdoors, *we will be able to evaluate quite accurately the true ionizing effect of cosmic rays in the free atmosphere.*

The value obtained in a brass chamber, as derived in section $A$, $q_C = 1.315I$ is only 7 percent higher than the extrapolated value derived here. Therefore it is obvious that all measurements of cosmic-ray intensities with brass chambers are slightly too high. In other words, they do not represent the true ionization in the atmosphere at the point of observation. However, the difference is slight and certainly much smaller than many authors believed it would be sometime ago.

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