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I. The Intensity of Cosmic Rays

The Absolute Value of Cosmic-Ray Ionization at Sea Level in Different Gases

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THE value of the ionization produced by cosmic radiation under standard conditions has been a subject of discussion from the beginning of the study of this phenomenon. The values obtained by different observers in air at a pressure of 1 atmosphere in a vessel at sea level have been estimated between 0.5 and 3 I (ions per cc per sec.). The differences are due to uncertainty about the amount of residual ionization, about the lack of saturation, especially on account of small impurities in the gas, and about the influence of the wall of the vessel. We tried to measure and to eliminate the first factor, to find the real saturation value and to measure and eliminate the influence of the wall.

The theory of Jaffé on columnar ionization has helped us to find the saturation values. But in order to use this theory it is necessary to make measurements with high and homogeneous collecting fields. The application of the theory is facilitated when the form given by Zanstra[1] is used. We have verified this theory now for several gases, for Röntgen rays, gamma-rays and cosmic rays; and have only found deviations at extremely high fields with some gases (H and Xe). By ionizations higher than 10^8 ions per cc one must also take into account the volume ionization when the fields are below 100 volts/cm.

In Fig. 1 we see that there is a difference of saturation for gamma-rays and cosmic rays for the same fields. The experiments on gamma-rays were taken with Mr. Kwieser;[2] with cosmic rays together with Mr. Stammer.[3] Since the ionization currents depend on the specific ionizations, the lack of saturation is different for rays of different energy. Hence it is comprehensible that we found differences between gamma-rays and cosmic rays for the same fields. In Fig. 2 we see the results of the ionization measurements in krypton at different pressures in a vessel of 422 cc. The ionization was measured between two cylinders of 3 cm and 7.2 cm diameter (distance 2.1 cm), and the collecting fields were from 50 to 500 volts per centimeter. According to Jaffé-Zanstra we can find the time for collecting the charge from the relation,

$$t = T + qTf(x),$$

where $q = \alpha N_0/8\pi D, \quad x = c(X/p)^2,$

$$f(x) = e^x(i\pi/2)H_0^1(ix),$$

X is the field in volts/cm, and p the pressure in atmospheres. T is the time to collect the same charge for complete saturation, i.e., for field $X=\infty$, $f(x)=0$. α = recombination coefficient, N_0 = the specific ionization, D = the diffusion coefficient of the gas.

So far we have found in every gas a linear relation between t and $f(x)$ for a large range of collecting fields. In Figs. 3 and 4 we see the results in argon and nitrogen. In this way we obtained values of the ionization by cosmic rays for complete saturation in the same way as we did for Rontgen rays and gamma-rays. This method has still another advantage. It appears

[1] H. Zanstra, Physica 2, 817 (1935).
[2] J. Clay and M. Kwieser, Physica 5, 725 (1938).
[3] J. Clay and H. J. Stammer, Physica 6, 663 (1939).

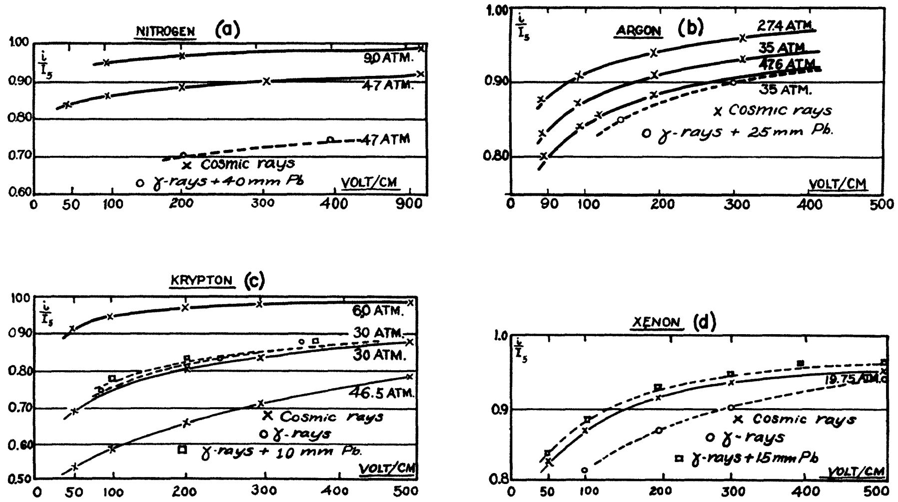

FIG. 1. J. Clay, M. Kwieser and H. J. Stammer. Ionization currents in relation to saturation in different gases for different fields by gamma-radiation and cosmic radiation.

that the lack of saturation in the ionization current is greatly increased by very small amounts of other gases. This is seen in the graph where we have given the results of a series of measurements with nearly pure argon in which we had introduced small pieces of metallic lithium. This metal binds chemically every non-noble gas and we see how the lack of saturation decreases with time, after the lithium is introduced. But what is very essential in our method, is that the saturation value itself is independent of the amount of impurities. We find by our extrapolation method the saturation value every day the same.

We have also to consider the relation between the ionization produced by rays traversing the chamber and the ionization arising from electrons from the wall.[4] We may expect that the first part is proportional to the density of the gas. The second part will be constant when the density of the gas is so high that the range of the electrons is smaller than the dimensions of the ionization chamber. By determining the value of the ionization at different pressures which are sufficiently high, it is possible to separate the volume ionization from the wall ionization, and it is also possible to find the ionization independent of the volume, the form of the vessel and the material of the wall. We[5] found the ionization in argon in a vessel of 4 L to be 1.58 I, the ionization from the iron wall being 36 I per cm^2. In another vessel of 0.422 L armored with 12 cm Fe and located in another building, we found 1.65 I for argon, the ionization from the iron wall being in this case 37 ions per cm^2. It was necessary to make measurements for at least three different pressures (sufficiently high) and for each pressure to use three or four homogeneous collecting fields of high value.

The saturation values of the ionization in different gases are found by extrapolation to the t axis in Figs. 2, 3 and 4. In Figs. 5 and 6 the saturation values for each pressure are given.

It can be seen from Fig. 7 that one gets a linear relation between I and density (pressure) for N_2, A and Kr. The line parallel to this line

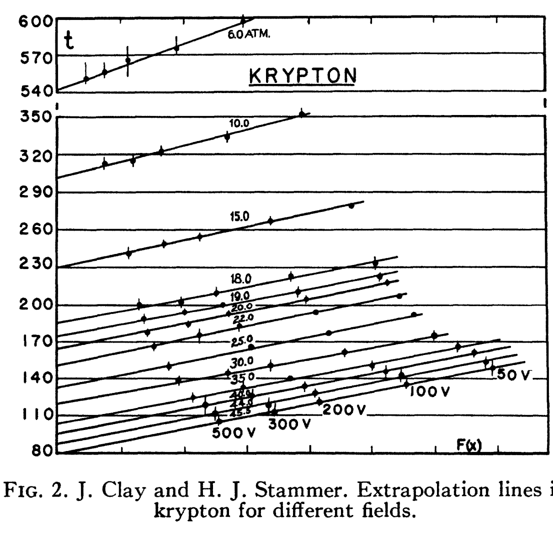

FIG. 2. J. Clay and H. J. Stammer. Extrapolation lines in krypton for different fields.

[4] J. Clay, Physica 2, 811 (1935).
[5] J. Clay and K. Oosthuizen, Physica 4, 527 (1937).

through the zero point gives the volume ionization in the gas only. Since we have given the direct value of the ions per cc we have also the ionization in relation to the pressure. The ordinate of the point of intersection of the total ionization line gives the ionization due to the electrons from the wall. From the known values of the surface and volume of our vessel (424 cm^2 and 422 cc, respectively) we obtain directly from this ordinate the number of ions produced per cm^2 surface. For this vessel we found in argon the above-mentioned value of 37 ion pairs per cm^2. Since the energy of the electrons from the wall is independent of the gas within the vessel, the number of ions formed will be inversely proportional to the mean ionization potential of the molecules of the gas; that is,[6]

$$N_{N_2}/N_A = 36/29 = 1.24.$$

Our measurements give a value of

$$N_{N_2}/N_A = 1.26.$$

This shows again that our measurements are in

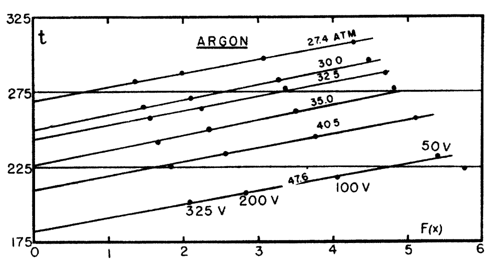

FIG. 3. J. Clay and H. J. Stammer. Extrapolation lines in argon for different fields.

agreement with our supposition about the volume ionization and wall ionization. The relative values of the ionization produced by cosmic rays in different gases are given in Table I.

In the same vessel we have started measurements in xenon. In this case we found for high collecting fields an extra current, the origin of which has not yet been cleared up. We give in the graph the preliminary values for xenon for which the extra current has been deducted.

There is still one point which may be mentioned. We have already pointed out in different publications that the lack of saturation for

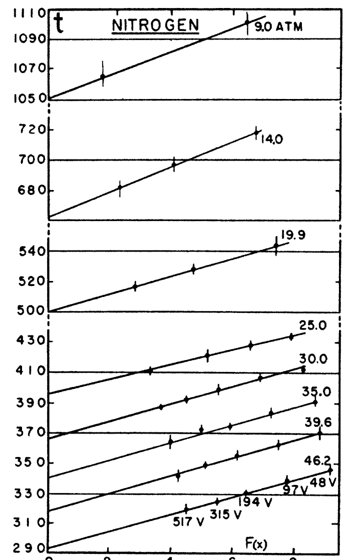

FIG. 4. J. Clay and H. J. Stammer. Extrapolation lines in nitrogen for different fields.

certain collecting fields is much higher for γ-rays than it is for cosmic rays, which shows that the specific ionization of the particles in the first case must be greater than it is for cosmic rays. The curves in Fig. 1(a) show this difference for nitrogen at 47 atmospheres for collecting fields up to 500 volts per cm. It should also be mentioned here that it makes a difference whether or not the gamma-rays are filtered. If they had not been filtered the lack of saturation would be still greater in N_2. Fig. 1(b) shows a similar comparison for the case of argon at 35 atmospheres. In Fig. 1(c) for krypton we find that at 30 atmospheres the lack of saturation for cosmic rays is a little greater than for gamma-rays. For xenon (Fig. 1(d)) one sees that the lack of saturation for cosmic rays is more than it is for gamma-radiation filtered by 15 mm Pb, but it is smaller than for unfiltered gamma-rays. This may be explained on the basis that for the curve which gives the relation between ionization and energy the minimum value shifts to a smaller energy for gases of higher atomic number, and perhaps also the form of the curve is not always the same. In every case there is always a difference between ionization by cosmic rays and gamma-rays.

Finally, we can compare the ionization by cosmic rays and gamma-rays for different gases. The values of the ionization in various gases produced by cosmic rays at sea level with a 12-cm

[6] A. v. Engel and M. Steenbeck, Elektrische Gasentladungen **1**, 41 (1932).

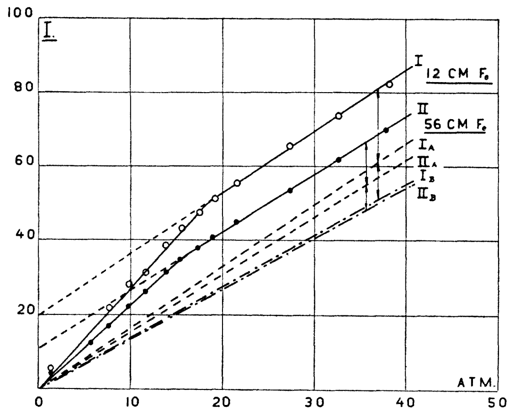

FIG. 5. J. Clay and K. Oosthuizen. Saturation values of ionization by cosmic rays in argon.

Fe shield are for N_2, 1.00 I; for A, 1.65 I; for Kr, 4.69 I and for Xe, 7.42 I.

For gamma-radiation the ionization depends on the screening of the rays, as we see in Fig. 8. The differences between the curves become smaller as the thickness of the shield increases. When we consider the ionization produced by hard gamma-rays (shielded with 8 mm Pb) and by cosmic rays (shielded with 12 cm Fe) in relation to the mass density and the electron density of the gases, we may conclude that not only does the ionization depend on the number of electrons (see Table I), but it also depends on the binding of the electrons in the atom. We find that the ionization by cosmic rays at sea level for a shield of 12 cm Fe can be expressed by a simple relation of the form

$$I = -0.80 + 1390\, d,$$

in which d is the density of the gas. The calculated and measured values are shown in Table II. In an open vessel the value would be 40 percent more.

When we now compare our values of the ionization in different gases with those of Juilfs and Masuch,[7] we find ours to be considerably smaller. For argon they find 2.45 I under 10 cm Pb, while our value under the same shield would be 1.41 I. Also, they find that cosmic rays filtered by 10 cm Pb give an ionization which is strictly proportional to the density, while we find that the ionization increases more rapidly than the density as shown in Fig. 7. The difference may be due to the fact that they did not separate the wall influence from the ionization of the gas itself, and we find that especially for light gases this part is much larger than is generally supposed. We have calculated the separate values of wall and gas ionization for the vessel used by Juilfs and Masuch, and we show the results in Table III. For nitrogen the influence of the wall is twice as great as that due to the gas itself. This is probably also the reason why such a high value was found by them for hydrogen. We believe that the difference between our value and that of Millikan[8] (2.48 I), in which case it does not seem that the influence of the wall can be as small as was supposed, can also be accounted for on the same basis. In the case of Compton, Wollan and Bennett[9] the relation between the ionization in argon and air taken from the experiments of Hopfield[10] (1.60 I) agrees quite well with the

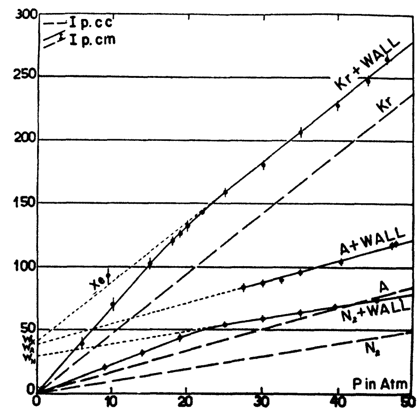

FIG. 6. J. Clay and H. J. Stammer. Saturation values of ionization by cosmic rays in krypton, argon, nitrogen and xenon at different pressures.

TABLE I. *Properties of gases and ratio of gamma-ray and cosmic-ray ionization to density.*

	N_2	A	Kr	Xe
Density	0.7	1	2.075	3.25
Electron density	0.78	1	2.00	3.00
Gamma-ray (ionization)	0.475	1	2.28	3.94
Cosmic ray (ionization)	0.608	1	2.80	4.50
Gamma-ray ionization / Density	0.68	1	1.10	1.21
Cosmic-ray ionization / Density	0.867	1	1.35	1.38

[7] J. Juilfs and V. Masuch, Zeits. f. Physik **104**, 458 (1937).

[8] R. Millikan, Phys. Rev. **39**, 391 (1931).

[9] A. H. Compton, E. O. Wollan and R. D. Bennett, Rev. Sci. Inst. **5**, 415 (1913).

[10] J. J. Hopfield, Phys. Rev. **43**, 675 (1933).

value 1.65 I found by us. For 50 atmospheres of argon one should have to take 82 I for saturation, but on account of the lack of saturation which I estimate from their data may be as much as 25 percent, one would expect a smaller measured value of I. The value so obtained would be 60 times the value in N_2 at atmospheric pressure. The value which they find for sea level is 1.22 I in air under 12 cm Pb, where we find 1.66 I, open, which would give 0.987 under 12 cm Pb. Also, in this case, the wall plays a rôle which acts in the opposite direction to that caused by the lack of saturation at high pressures for small collecting fields.

So far we have mentioned measurements taken on land with the ionization chamber shielded by iron to eliminate the gamma-radiation from the surroundings, but we could not be certain that this influence was eliminated without absorbing a part of the cosmic radiation. Therefore we used the opportunity to measure the ionization in a large vessel 28 L, 60 atmos. of argon, just above sea level in Bergen and afterwards placing this vessel at the same place and in the same shield as that for which we had measured the absolute ionization in air and in argon before. At sea level the mean value of 11 measurements of 4 minutes was 22.65 volt cm per minute with a mean deviation of 0.21 volt cm per minute. From the measurements at great depths we know that the residual ionization of our vessel is 0.20 volt cm per minute and the ionization of the radioactivity of the sea water is 0.11 volt cm per minute. The ionization of cosmic radiation at the surface of the sea is therefore 22.34 volt cm per minute (Bar. 770 mm Hg).

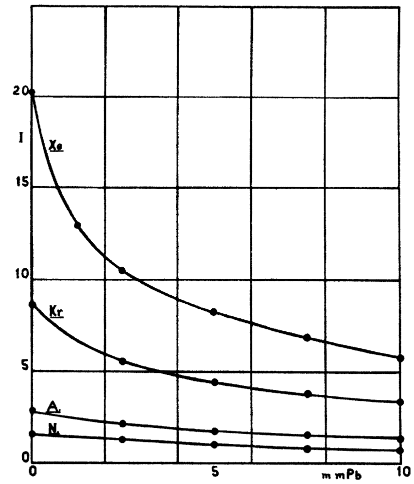

FIG. 8. J. Clay and M. Kwieser. Relation between gamma-rays in different gases and its dependence on the screening off of the rays.

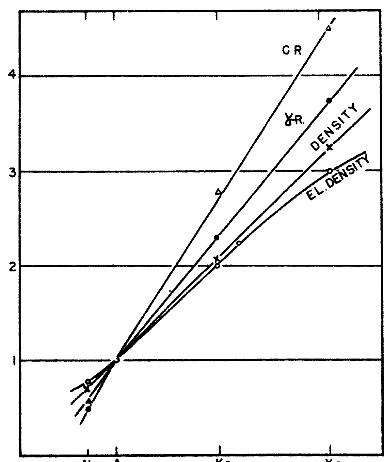

FIG. 7. J. Clay and H. J. Stammer. Relation of ionization by cosmic rays and gamma-rays and the density of different gases.

TABLE II. *Calculated and measured values of ionization.*

	I (CALCULATED)	I (EXP.)
N_2	0.92	1.00
A	1.67	1.60
Kr	4.34	4.69
Xe	7.26	(7.42)

TABLE III. *Influence of wall on ionization.*

	I (WALL)	I (GAS)
N_2	1.31	0.63
A	1.41	1.04
Kr	1.78	3.14
Xe	1.8	4.8

At Amsterdam the ionization in the iron shield of 12 cm Fe, the value was 16.37 volt cm per minute with a mean deviation of 0.3 percent. Correction for residual ionization gives 16.17 volt cm per minute (Bar. 767 mm Hg) or 16.05 volt cm per minute for 770 mm Hg. We find now for sea level the following values:

for argon $2.30 \pm 0.06\, I$ Bar. 770 mm Hg
for air $1.56 \pm 0.05\, I$

In open air this will give:

$1.63 \pm 0.05\, I$ Bar. 760 mm Hg

Formerly we found directly: 1.66 I.