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Ionization by Gamma-Rays and Cosmic Rays in Gases at High Pressure and High Collecting Fields

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Experimental test and theoretical considerations show that for the gamma-ray ionization measurements at high pressures by Clay and van Tijn at collecting fields of 5000−400 volt/cm there was no volume recombination. These measurements cannot be affected by criticism of Bowen and Cox founded on experiments with collecting fields of 1009−1.5 volt/cm. The theory advanced by the author that for all pressures the volume ionization is proportional to the pressure and that the wall ionization (produced by electrons ejected from the wall) is for high pressures independent of the pressure is verified by experiments in air and in argon for gamma-rays and for cosmic rays. This result removes the doubt expressed by Bowen and Cox on this point. For obtaining the saturation values at high pressures the Jaffé theory provides the only reliable method in existence.

I

THE ionization currents in gases at high pressure have been the object of observation and discussion by several investigators.[1, 2] Such investigations became necessary, when high pressures were used for getting enough ions from radiations of very small intensity, such as the cosmic radiations.

For every future theory it will be of principal interest to know the real number of ions produced by the radiation, the saturation value of the ionization current. To this end one has to eliminate the volume recombination and the columnar recombination. Now it is easy to eliminate the volume recombination by the use of even moderate fields. It will be shown in the following that we must have had less than 1 percent volume recombination in air at 95 atmos. when we used gamma-rays producing 7×10^5 ions per cm^3 per sec. and applied a collecting field of 100 volt per cm. (See III.)

While for the volume recombination the intensity of the radiations is of principal importance, the case is quite different for the columnar recombination. This kind of recombination is independent of the intensity because in this case only the processes in each individual column play a role. For this reason the weakness of the radiation is of no help in obtaining saturation.

Thus both experiment and theory show that it is very difficult not to say impossible to avoid the influence of columnar recombination at high pressures, even when using high fields, excluded for argon, and other noble gases.

For instance, Jongen and I found that cosmic radiation[3] gives 40 ions per cc per sec. in air at 37 atmos. pressure under a shield of 12 cm Fe at sea level and 50° ML but that with a field of 200 volt per cm only 70 percent of the ions were drawn from the columns. Even at 600 volt/cm there still remains a columnar recombination of 20 percent. Volume recombination does not pro-

[1] J. Clay and M. v. Tijn, Physica **2**, 825 (1935).
[2] I. S. Bowen and E. F. Cox, Phys. Rev. **51**, 232 (1937).
[3] J. Clay and H. F. Jongen, Physica **4**, 245 (1937).

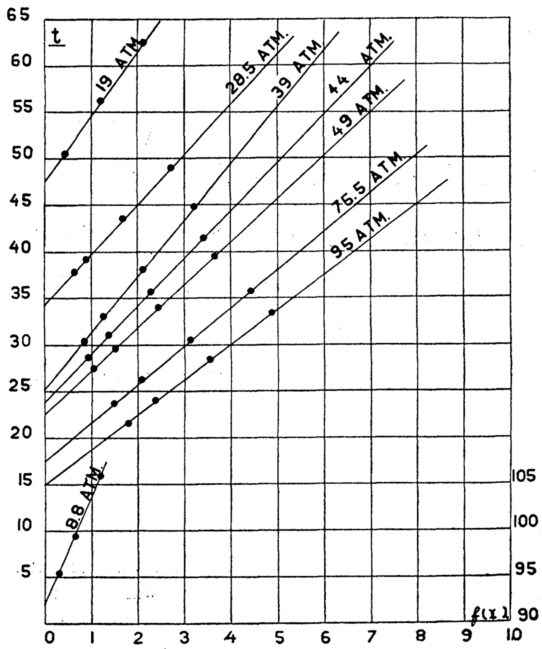

FIG. 1. Clay and v. Tijn. Measurements of ionization by gamma-rays in air between two flat plates at 0.6 cm distance at different pressures at different fields. According to formula 4 we may expect that the relation between I and $f(x)$ is linear for every pressure.

duce the slightest effect for such fields as we shall show further on.

II

It is of principal interest therefore to have a reliable way of finding the saturation value (that is, the ionization current produced by an infinite field), from the ionization found at finite fields. Now nearly every ionization (including that by gamma-rays and x-rays) takes place in columns as we see in Wilson photographs.

The theory of columnar ionization of Jaffé gives a good account of these phenomena, which have been proved in many cases. We think, therefore, the only way of reaching our aim is to follow this theory.

Zanstra,[4] using Erikson's measurements as an illustration, has found a very simple and useful way of so formulating Jaffé's theory, as to give the saturation currents. He found a linear relation between the inverse ionization and certain function of field and pressure, so that a linear extrapolation gives the saturation current I. The equation is

$$\frac{1}{i}=\frac{1}{I}+\frac{q}{I}f(x)(1)q=\frac{\alpha\cdot N_0}{8\pi D}. \qquad \text{(1a)}$$

In this equation
α is the recombination coeff. in the gas,
D is the diffusion coeff. in the gas,
N_0 is the number of ions per cm in the column and

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

where $$x=\left(\frac{\text{b.u. sin }\varphi X}{2D}\right)^2. \qquad \text{(2a)}$$

Further, u is the mobility of the ions, X the electric field, b the parameter of the column, and φ the angle between the axis of the column and X. As u and D are related to the pressure in the same way, and α is inversely proportional to p, Zanstra found it was possible to take for air

$$x=1,\ 24.10^{-4}\cdot(X/p)^2, \qquad (3)$$

when X is expressed in volt/cm and p in atmospheres. As for $X=\infty$, $f(x)=0$, the value for the saturation current is found by taking $f(x)=0$ in (1).

When we measure the time t necessary to collect a given ionization charge and T represents the time for the same charge if we had saturation Eq. (1) assumes the form

$$t=T+qTf(x). \qquad (4)$$

We have indeed shown in different series of experiments[1, 3, 5] that at a given pressure the values found are in the given linear proportion to $f(x)$ and in this way we have determined T (Figs. 1, 2 and 3). The linear relation (4) only holds for fairly homogeneous and fairly high fields. Needless to say the saturation value T can only be reliable when determined by an extrapolation from rather high fields where one is not too far from saturation.

III

We now come to the objection recently raised by Bowen and Cox[2] which is based on the work of the former. Bowen measured the ionization in air by gamma-rays but used a collecting field of

[4] H. Zanstra, Physica 2, 817 (1935).

[5] J. Clay and G. v. Kleef, Physica 4, Aug. (1937).

1009; 367; 230; 6.2 and 1.55 volt per cm. Only the field of 1009 volt in combination with higher fields would have been sufficient to test the formula of Jaffé, simplified by Zanstra and could be used to compare their values with ours which were at 5000, 3300, 1700 and 800 volt per cm.[6]

Bowen and Cox think that there was volume recombination in our case. There certainly was no appreciable volume recombination for the currents in the range between 800 and 5000 volt/cm which we used in our results, but also at the lower fields this recombination was much smaller than Bowen and Cox think. We can prove this theoretically and by experiment.

First we shall give an approximate theoretical argument. In the state of equilibrium let the number of ions present per cm³ be n, the velocity v, the area of the electrodes F. Then the ionization current will be

$$i = nFve.$$

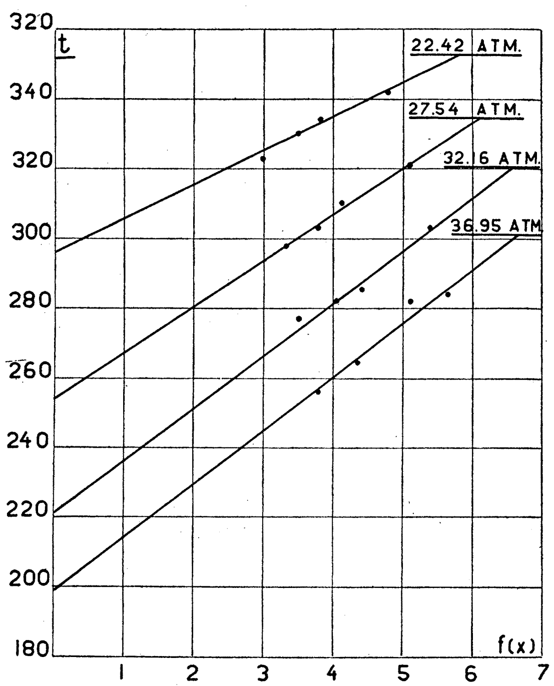

FIG. 2. Clay and Jongen. Measurement of ionization in air by cosmic rays between two coaxial cylinders at 3 cm distance at different pressures at different fields.

[6] It may be a question of taste that Bowen and Cox call the range 400–0 volt cm wide where the linear relation breaks down and is of no further use and that we are inclined to call the range infinity–400 volt/cm wide enough, where it holds and can be used successfully to find the saturation value.

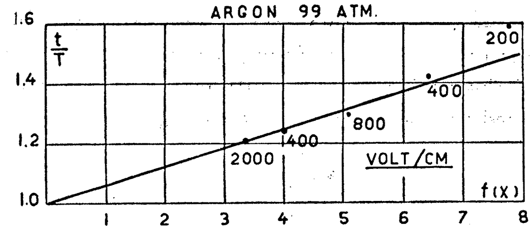

FIG. 3. Clay and v. Kleef. Measurements of ionization in argon by gamma-rays between two parallel grids at 0.5 cm distance. Between grids the deviation caused by volume recombination is readily noticed. Measurements are to be continued and published in *Physica* **4**, Aug. 1937.

When q pairs of ions are formed per cm³ per sec. the saturation current will be

$$I = qlFe,$$

where l is the distance between the electrodes. In our case the current i was a fraction a of I which was 0.33 at 95 atmos, and 166 volt/cm. From the above follows:

$$nFve = aqlFe,$$
$$n = aql/v$$

if u is the mobility of the ions at atmospheric pressure and V the potential

$$v = u_0 V/pl.$$

And when α is the recombination coefficient, which we suppose to have the same relation to pressure as u, we find for the fraction lost by volume recombination per sec.

$$\frac{\Delta n}{n} = \alpha n = \frac{\alpha_0}{p}\frac{aql^2p}{u_0V}$$
$$= \frac{1.4\times 10^{-6}\times 0.33\times 10^6\times 0.36}{1.2V} = \frac{0.14}{V},$$

so that for $V = 100$ volt we would have a volume recombination of less than 1 percent.

Mr. v. Kleef and I tried also the volume recombination experimentally in the same way as was done by Bowen and Cox. We made two series of current measurements in air at 60 atmos. ionized by gamma-rays of 0.14 mg Ra at the distances of 26.7 cm and 10.2 cm.

The ionization was in the second case 7.2 times the ionization in the first case. We put the relation in the form

$$t/T = 1 + qf(x), \qquad q = \alpha N_0/4\pi d.$$

We see that for two sets of measurements the same relation will be found if the theory is right and the volume recombination is absent. This is indeed the case as is seen from Fig. 4, also at 200

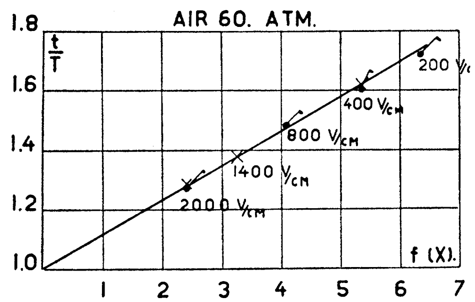

FIG. 4. Clay and v. Kleef. Measurements of ionization in air of 60 atmos. by two different gamma-radiations at different fields. ($\times I_1 = 7.9 \cdot 10^4$ e.s.u.; when possible the same sign as is given in the graph $\bullet I_2 = 5.7 \cdot 10^5$ e.s.u.).

volt/cm in the case of the strongest ionization ($5.7 \cdot 10^5$ I). Since, we have found the same evidence in argon of 100 atmos. In this case we had an ionization which was nearly 100 times as large, and we found a small volume recombination only for collecting fields smaller than 100 volt/cm.

We think we have now sufficiently replied to the first objections of Bowen and Cox since from a series of different experiments, as well as from theoretical arguments we have shown that we get the saturation values of ionization by the linear extrapolation method. Since the copy was sent to the *Physical Review*, Mr. v. Tijn and I found still another test by measuring Eve's constant, with a calibrated quantity of 23.16 mg Ra at 60 cm distance. From the saturation current found in air of 147.5 atmos. we found $4.30 \cdot 10^9$ I. (Physica **4**, Aug. (1937).)

IV

The second objection of Bowen and Cox is to the author's[7] theory of ionization as a function of pressure, the correctness of which they doubt.[8]

In this connection we can now discuss this theory of ionization which holds as far as our experiments show to pressures of 150 atmos. in air and in argon.

It was supposed by Bowen[9] and others that the ionization in a vessel should be directly proportional to the gas pressure only. But the experiments did not confirm this supposition, partly on account of lack of saturation.

Before this the opinion was put forward by Broxon[10] and others that the ionization was caused only by electrons projected from the atoms of the wall. In this case one has to expect that the ionization would be constant for pressures high enough, so that the whole energy of these electrons could be spent in ionization along their paths in the gas.

It was found by Broxon himself that this opinion could not explain the phenomena.

Then Bowen argued that if there were electrons that come from the wall, these electrons also would give an ionization proportional to the pressure so that the saturation ionization could only be proportional to the pressure but this opinion is not correct, as we will show on the basis of experiments.

The theory of ionization, proposed by the author,[7] takes into account the electrons of the gas and of the wall as principally different, so that the result was dependent on the pressure of the gas and the volume and the dimensions of the vessel.

The number of electrons ejected from the atoms of the gas will be proportional to the density of the gas.

The mean number of ion pairs given by one electron will be dependent on that part of the range of the electron that is enclosed in the ionization vessel, *viz.* on the dimensions of the vessel and the pressure of the gas. Let N_g be the average number of pairs that can be produced by one electron and p_0 the pressure which is necessary to limit the range in the vessel. Then the mean number of ion pairs for pressures below p_0 will be $N_g p/p_0$. If n_g is the number of electrons produced by the rays in one cc per sec. at one atmos., the total number of ions produced in the vessel of volume v, will be

$$I_g = Ap^2/p_0 \quad \text{for} \quad p < p_0 \quad A = n_g N_g v. \qquad (7a)$$

$$\text{and} \quad I_g = Ap \quad \text{for} \quad p > p_0.$$

[7] J. Clay, Physica **2**, 811 (1935).

[8] We are at a loss to follow their argument. Our theory does not presuppose that the efficiency of ejection of particles from the wall is larger than that from the gas, but rather that the range of the particles from the wall is much larger than of those from the gas.

[9] I. S. Bowen, Phys. Rev. **41**, 24 (1932).

[10] J. W. Broxon, Phys. Rev. **38**, 1704 (1931).

Now we consider the electrons from the wall. Let the number n_w of this kind be produced per cm^2 per sec. by the rays. If p_0' be the pressure for which the average range is just within the vessel and if the mean number of ion pairs for one electron is N_w, the mean number of pairs produced by one electron of the wall will be $N_w p/p_0'$.

The total number of pairs produced by the electrons from the wall, if we suppose that every part of the wall is on the same condition and its area F cm^2, is

$$I_w = Bp/p_0' \quad \text{for} \quad p < p_0' \quad B = Fn_wN_w.$$
$$\text{and} \quad I_w = B \quad \text{for} \quad p > p_0'.$$

In this simplified picture we have assumed that the wall particles ionize the gas in such a way that the ionization due to them is constant within a certain distance (the range) from the wall, and zero beyond this distance, not considering questions as to difference of directions and energy of the wall electrons.

The results of the experiments, where a flat condensor is used as ionization vessel, show that this assumption gives an approximation of the facts.

If the primary rays are photons, these will give pairs themselves. If the primary rays are charged particles which pass through the whole vessel as cosmic rays do, they will give a number of ions proportional to the pressure and proportional to the volume of the vessel. Adding the contributions (7), (8) and C_p we find for the total ionization

$$I = Ap^2/p_0 + Bp/p_0' + Cp \quad \text{for} \quad p < p_0, p_0',$$
$$I = Ap + Bp + Cp \quad \text{for} \quad p_0 < p < p_0',$$
$$I = Ap + B + Cp \quad \text{for} \quad p > p_0, p_0',$$

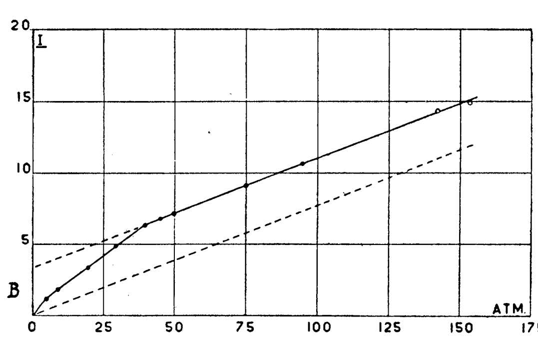

FIG. 5. Clay and v. Tijn. Measurements giving the relation between saturation current and pressure in air. Ionization by gamma-rays.

where A and B are given by (7a) and (8a) and C is zero if the primaries are photons. For high pressures we therefore expect that the relation of ionization to pressure is given by a straight line which does not pass through the origin, but intersects the I axis a distance B above it. This is

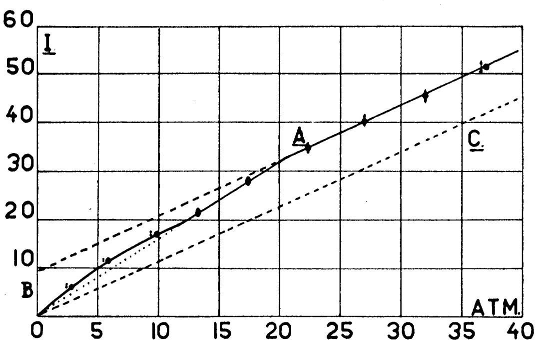

FIG. 6. Clay and Jongen. Measurements giving the relation between saturation current and pressure in air ionized by cosmic rays under a shield of 12.5 cm Fe.

proved by different experiments which we have already performed for gamma-rays in air (Fig. 5) and argon and for cosmic rays for argon and air.[11, 1, 3]

In order to find the ionization by cosmic rays in gas only the way we follow is the only way available at present. (Fig. 6.) This in reply to the criticism of Bowen and Cox who say that our method is not applicable to the problem of cosmic-ray ionization.

We have also realized experiments where the influence of the wall is eliminated by taking grid electrodes made of fixed wires. These experiments show a direct proportionality of the ionization to pressure, so that the factor B is negligible, as in this case it should be according to our theory (Fig. 8).

By taking grid electrodes and hydrogen we could also realize[7] the case for low pressures where

$$I = Ap^2/p_0 \quad \text{(formula (7) for } p < p_0).$$

All of these relations are only satisfied when we measure the saturation current of ionization and we know that it is difficult to get saturation in most of the gases when the pressure is high. Only in argon can approximate saturation be reached

[11] J. Clay, Physica 2, 111 (1935).

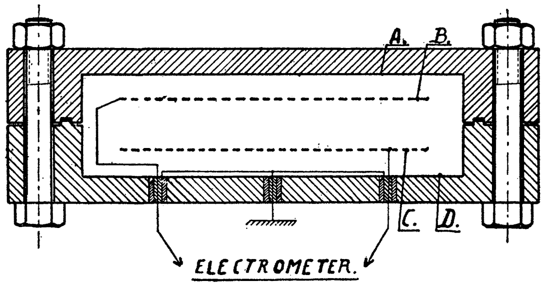

FIG. 7. Ionization vessel with two parallel grids.

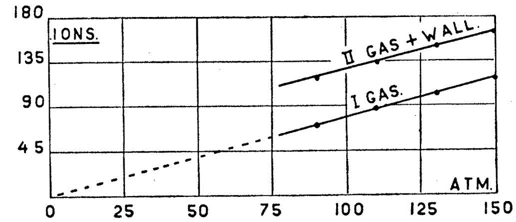

FIG. 8. Clay and de Bock. Saturation currents per cc in argon by cosmic rays under 16 cm Fe at different pressures. I. Between two grids. The ionization is proportional to pressure. II. The ionization between wall and grid $I=Ap+B$. The measurements are to be continued for the lower pressures and will be published in *Physica*.

at moderate fields. Therefore the criticism of Bowen and Cox about the linear relation

$$I=Ap+B$$

is shown to be groundless in the most direct way by experiments on ionization by cosmic rays in argon where we can find the approximate saturation values directly without the help of the Jaffé formula. This result was obtained first[11] in a vessel of the form given in Fig. 7. As long as the maximum range of the electrons is shorter than the distance, the ionization between the grids is directly proportional to the pressure, whereas the ionization between the wall and grid is increased by the ionization due to the electrons from the wall, which is constant above a pressure of 70 atmos.

Mr. de Bock and the author are now repeating this experiment with all possible precautions and have found that the ionization between the grids is accurately proportional to the pressure and that the ionization by the electrons between the wall and the grid is constant. (Fig. 8.) No objection can be raised to this result on account of eventual doubts regarding the Jaffé theory. Only we must have had a small lack of saturation which will not change this result. In our case we could not find a measurable difference between a collecting field of 200 and one of 650 volt/cm and we could not go higher.

V

It seems perhaps strange that there are such a small number of tracks of the electrons coming from the wall as seen on photographs of the Wilson chamber. To this we remark that the number of ion pairs produced by the electrons from the wall is for cosmic rays of the order of 100 per sec. per cm^2. When now the energy of one electron is 300,000 volt, one electron will make 10,000 ion pairs. We therefore need to have only one electron in 100 sec. per cm^2 to produce the ions. And, since a photograph takes about 1/25 sec., we have to look for one particle per 2500 cm^2 wall. Particles of this kind are certainly found. For particles from the wall ejected by gamma-rays we refer to the photographs of D. Skobelzyn.[12] He finds that these particles have generally a much greater energy than those ejected from the atoms of the gas. We hope to give in the near future a series of values of numbers of electrons ejected by the cosmic radiation from different materials.

[12] D. Skobelzyn, Zeits. f. Physik **28**, 278 (1924).