Ionization of Air by γ-Rays as a Function of Pressure and Collecting Field II

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The γ-ray ionization current measurements in air at high pressures made by Erikson and by Clay and Van Tijn are shown to be largely modified by volume recombination at collecting fields below about 400 volts per cm. The Jaffé theory of columnar ionization does not explain the observed variation of ion current when it is applied over a wide range of collecting fields to data free from volume recombination.

IN 1932 one of the authors made ionization current measurements which were published under the above title.[1] Shortly after this Zanstra and Clay[2] called attention to earlier measurements made by Erikson[3] in 1908. Later Zanstra[4] applied the Jaffé theory of columnar ionization to explain the curves obtained by Erikson, and Clay[5] and Van Tijn made new measurements to which the formula developed by Zanstra was applied.

In the discussion of ion current measurements three types of recombination which prevent the collection of all ions formed are usually considered, namely: (a) preferential, i.e., recombination of the electron with the particular ion from which it was ejected, (b) columnar (called initial by some authors), i.e., recombination with a positive ion in the same β-ray track as the ion from which the electron was ejected, (c) volume, i.e., recombination with any positive ion. Obviously in processes (a) and (b) the probability of recombination of a given electron is independent of the number of tracks formed in the ionization chamber. Consequently if the pressure is kept constant, so that the number of ions per track does not vary, the fraction of ions collected is independent of the total ionization. On the other hand in process (c), i.e., volume recombination, the probability of recombination of a given electron is proportional to the number of positive ions in the gas. This type of recombination is therefore negligible at low rates of ionization, such as those found in measurements of cosmic-ray ionization, but becomes prominent at higher rates where it shows its presence by the variation in the fraction of the ions collected as the rate of ionization is changed.

The measurements made by Bowen were undertaken primarily to elucidate the behavior of cosmic-ray electrometers which use gases at high pressure. Consequently great care was taken to eliminate volume recombination. This was done by the use of a very weak source of radiation which produced a fairly uniform ionization of only 121 ions per cc per sec. per atmosphere. Furthermore at the two highest pressures used tests for the presence of volume recombination were made by taking a complete set of additional measurements when the ionization was reduced to 23.4 ions per cc per sec. per atmosphere. Similar precautions for the elimination of volume recombination were taken by Cox[6] in his studies of ionization in other gases than air.

On the other hand Erikson, who did not attempt to eliminate volume recombination, used ionization rates of from 2×10^5 ions per cc per sec. per atmosphere at points of the ionization chamber farthest from the radium to 10^7 ions for points nearest it. Clay and Van Tijn, according to a letter to one of the authors correcting their Table I, used an average of 2.7×10^4 ions per cc per sec. per atmosphere.

Neither Erikson nor Clay and Van Tijn tested for the presence of volume recombination by varying the average ionization used. Fortunately their collecting field and pressure ranges overlapped those of Bowen and consequently such a test can be made by superimposing their curves

[1] I. S. Bowen, Phys. Rev. **41**, 24 (1932).
[2] H. Zanstra and J. Clay, Phys. Rev. **41**, 679 (1932).
[3] H. A. Erikson, Phys. Rev. **27**, 473 (1908).
[4] H. Zanstra, Physica **2**, 817 (1935). See also, B. Gross, Zeits. f. Physik **78**, 271 (1932) and W. R. Harper, Proc. Camb. Phil. Soc. **28**, 219 (1932) and **29**, 149 (1933).
[5] J. Clay and M. A. Van Tijn, Physica **2**, 825 (1935).
[6] E. F. Cox, Phys. Rev. **45**, 503 (1934).

on Bowen's curves obtained at low rates of ionization. This is done in Fig. 1 where the number of ions collected is plotted against the logarithm of the collecting field for the pressures nearest 95 atmospheres used by each observer. All of the curves are reduced to the same scale by expressing the number of ions collected as the fraction of the number collected at 1000 volts per cm. Comparing first Bowen's curves at 23.4 ions and 121 ions it is seen that lack of superposition, indicating the presence of volume recombination at the higher ionization rate, sets in at a collecting field of 10 to 15 volts per cm. Likewise the curves obtained by the other observers using high rates of ionization definitely drop below the low ionization curves at 400 to 800 volts per cm, thus indicating the presence of volume recombination at all collecting fields below this. Similar results are obtained at other pressures although the collecting field at which volume recombination becomes negligible varies with the pressure.

The results of Erikson and Clay and Van Tijn are therefore not directly applicable to the problem of cosmic-ray ionization chambers which normally operate with collecting fields far below 400 volts per cm. Furthermore one is not justified in applying the Jaffé formula for columnar re-

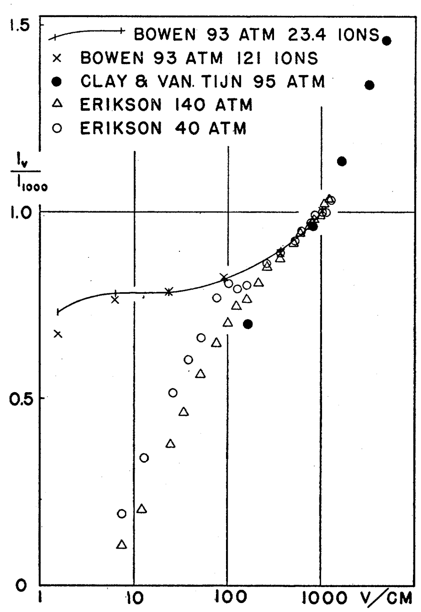

FIG. 1. Comparison of ionizations as a function of collecting field as obtained by various observers.

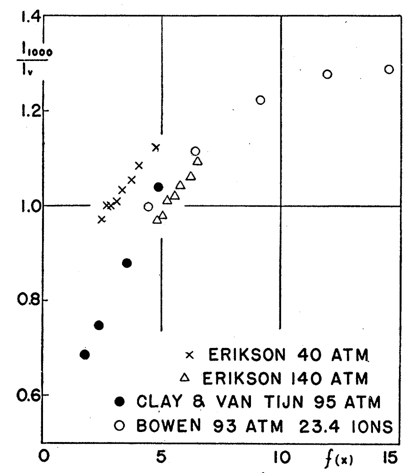

FIG. 2. Application of the Jaffé theory of columnar ionization using the graphical method suggested by Zanstra.

combination except to points that fall in the range which is free from volume recombination, i.e., in Erikson's data to points from 513 to 1223 volts per cm at 140 atmospheres and from 365 to 1288 volts per cm at 40 atmospheres, and in Clay and Van Tijn's data from 817 to 4917 volts per cm. On the other hand Bowen's ionization currents obtained at an ionization rate of 23.4 ions per cc per sec. per atmosphere are quite certainly free from volume recombination over the range from 6.2 to 1009 volts per cm. Fig. 2 represents the application of the Jaffé theory to these results in the above ranges. Following Zanstra the abscissa is his $f(x)$ while the ordinate is proportional to the reciprocal of the ion current collected. As in Fig. 1 the unit of current is taken as the current collected with a field of 1000 volts per cm. When plotted in this way all points obtained at a given pressure should fall on a straight line according to the Jaffé theory. The curves are apparently linear over the small ranges of the collecting fields available in Erikson's data where the field varies by a factor of about 3 and in Clay and Van Tijn's data where the range is a factor of 6. On the other hand the linearity breaks down completely in the range in the field of a factor of 160 available in Bowen's data. This breakdown is still more striking if Clay and Van Tijn's points are combined with those of Bowen at the same pressure thus extending the range to a factor of 800 in the collecting field. For values of $f(x)$ greater than 5, $f(x)$ may be represented by the equation $f(x) = A - 4.6 \log$ (collecting field/pressure) with an error of less than 1 percent. Consequently it is evident that the linearity cannot be improved by any reasonable shift of the constant A which is the only quantity not fully fixed by the Jaffé theory.

Another difficulty with the interpretation of these curves in terms of the Jaffé formula appears even in its application to the short linear sections of Clay and Van Tijn's curves. Thus they found from extrapolation by means of the Jaffé formula that the saturation currents, i.e., the number of ions originally formed, were less than half as great per atmosphere at 95 atmospheres as at one atmosphere. To explain this they assumed that at the lower pressure most of the secondary β-particles, that are the direct cause of the ionization, are ejected by the primary γ-rays from the walls of the vessel while at the higher pressure a large part of the β-rays are ejected from the air itself. The lower ionization per atmosphere at the higher pressure is then to be expected if the efficiency of the ejection of these secondary β-particles is greater from the walls, which are of relatively high atomic number, than from the air of low atomic number. However, Workman[7] found that the ionization was actually increased when the particles were ejected from an element of low atomic number such as carbon or aluminum rather than from steel or lead. Thus, if anything, more ions per atmosphere should be formed at the higher pressures.

[7] E. J. Workman, Phys. Rev. **43**, 859 (1933).

All of these considerations show, therefore, that the observed variation of ion current with collecting field cannot be explained by the Jaffé formula for columnar recombination.

In conclusion the authors wish to emphasize again the importance of using very low rates of ionization in measurements at high pressure in order to eliminate ordinary volume recombination. When volume recombination is present the current collected is not proportional to the intensity of the ionizing radiation. Furthermore the curves of ion current *vs.* collecting field become a function not only of the intensity of ionization as discussed above but of the dimensions of the collecting chamber as well. Consequently the significance of these curves is limited chiefly to that of a calibration of the ionization chamber used. The limiting ionization current that can be used before volume recombination becomes appreciable depends of course on the pressure, collecting field and dimensions of the apparatus used. In general, however, for pressures over 25 atmospheres and collecting fields below a few hundred volts per cm the ionization current should be made as low as is feasible without having it masked by the residual ionization caused by cosmic rays and local radioactivity. Finally, measurements should be made at different rates of ionization to determine whether volume recombination has really been eliminated.