On the Sensitivity of the Balanced Space Charge Method for Detecting Ionization of Gases by Collision of Ions and Atoms

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Factors which influence the balanced space charge method of detecting ionization are discussed. These factors are (1) the velocities of the ions, (2) the distances traveled by the ions before they are neutralized, (3) the effect of secondary electrons on the space charge. It is concluded that the reduced sensitivity in some experiments may account for the failure to observe ionization.

ONSET potentials for the ionization of gases by positive ions and atoms have been investigated in several papers by R. N. Varney,[1] who used a balanced space charge method. Last year he reported experiments on noble gases bombarded by their own accelerated atoms. His results for A and Ne agree quite well with those obtained previously by me.[2] With He atoms in He he does not observe any ionization up to 400 volts primary energy, while I have found a positive effect between 60 and 460 volts, and have measured the ionization efficiency, which is about ten percent that for A in A.[3]

Varney estimates, merely from the size of galvanometer readings, that his method would have revealed an ionization effect five percent that for A in A. For this reason and on account of the similitude of A and He curves, he is inclined to regard my results on He as having been due to some A impurities. Varney must implicitly have made some assumption about the relative effects of He and A on space charge, but on this very essential point no specification is given in his paper, and I shall show that, whatever the assumption may be, it must necessarily contain much that is arbitrary.

Neither does Varney stop to consider the *a priori* rather surprising fact that helium will behave so differently from argon and neon as his experiments indicate. We may remark by the way that a similar anomaly is shown also by previous experiments with the same method; for example Varney[4] does not observe any ionization of noble gases by the lightest alkali ions Li^+ and Na^+, with the exception of Ne by Na^+, while he has positive results with any other alkali ion noble gas combination.

It appears a legitimate question to ask whether the sensitivity of the space charge method has not been overestimated, in respect to its adaptation to the problem of ionization by massive particles. Investigations of this matter have not been published. I think they are necessary, because, as we shall see, the mechanism involved is quite different from all previous applications of the method.

The enormous efficiencies of positive ions in neutralizing electron space charge observed by Kingdon,[5] Foote and Mohler[6] and others are the result of two factors:

(1) The velocities of the ions are, for the same kinetic energy, i.e., for a given potential difference, some 10^2 times smaller than those of electrons (in inverse proportion to the square root of masses).

(2) Positive ions produced inside the diode with a small initial velocity component transverse to the filament must travel many times to and fro

[1] R. N. Varney, Phys. Rev. **47**, 483 (1935); **50**, 159 (1936); **50**, 1095 (1936). Varney, Gardner and Cole, Phys. Rev. **52**, 526 (1937).

[2] A. Rostagni, Nuovo Cimento **11**, 621 (1934); **13**, 389 (1936); Ricerca Scient. **7**, 511 (1936).

[3] My lowest measured point for He corresponds in the published diagram to 62 volts on the abscissa, and 0.01 cm^2/cm^3 on the ordinate (cross section for ionization); which represents, as explicitly stated in my paper, the sensitivity limit of the method. Direct extrapolation from the traced curves would point to an onset potential ranging between 50 and 60 volts. I therefore question Varney's statement that my results indicated ionization energies less than twice the electron ionization potential of He.

[4] R. N. Varney, Phys. Rev. **47**, 483 (1935). This partially negative result contradicts also Beeck and Mouzon's experiments by another method: Beeck and Mouzon, Ann. d. Physik **11**, 737, 858 (1931).

[5] Kingdon, Phys. Rev. **21**, 408 (1923).

[6] Foote and Mohler, Phys. Rev. **26**, 195 (1925).

across the inner space before they discharge themselves.

Under Kingdon's experimental conditions the average distance which an ion travels before reaching the filament is of the same order of magnitude as the kinetic mean free path. This may be some 10^2 times the cathode-anode distance at sufficiently low pressure. We thus obtain amplification factors of 10^4 to 10^6 for electron current with regard to positive ions as observed by different authors. Now the experimental conditions of Varney seem to me not very different from those of Kingdon, as regards the discriminating factor $V(r/R)^2$; but the pressure being of 10^{-2} mm of Hg, we should expect amplification factors of 10^3 both for A^+ and He^+ ions, with a ratio of about $\frac{3}{2}$ in favor of A. Varney gives much greater values; it is possible that he has determined them directly, by some method equivalent to those used by Kingdon, although no mention of that is made in his papers.

But there is an essential remark to be made. A necessary condition in order that factor (2) may be effective at all is that the initial energies of the ions should be less than the applied potential, so that if they will not hit the cathode they will be also unable to reach the anode. That is of course verified with ions produced by photoelectric effect or by electron collision as in the experiments of Foote and Mohler, Kingdon, etc; but in the present case, where the masses of colliding particles are of the same order of magnitude as the gas molecules, we must expect most of the secondary ions to receive a finite fraction of primary velocities. That is shown directly by my own experiments. And as the applied potential ranges between 1 and 2 volts (it must be less than the resonance potential of the gas) most of the ions will therefore reach the anode. Factor (2) then becomes inefficient. As the energy of many of the ions is large compared with that of electrons, also factor (1) will be affected.

Now the sensitivity of the space charge method is actually greater than it would appear from this remark, or the method would not have yielded any valuable result. The sensitivity may only arise from the partial neutralization of the secondary ions on the way to the anode, giving rise to slow tertiary ions for which both sensitivity factors may be efficient. This fact seems not to have been taken into consideration; the neutralization plays an essential part in the working of the ion detector and the mechanism is more complicated than in usual applications.[7] The efficiency must depend on the following quantities: (1) cross sections for neutralization; (2) cross sections for scattering; (3) velocities of slow ions arising from neutralization; all as functions of the velocity of secondary and eventually of tertiary ions. These quantities should be known for every ion velocity between primary and thermal velocity, but they are not completely known:[8] and in any case the problem will be much too complicated to allow a calculation either of absolute or of relative efficiency. To determine it by experiment, the ions under question must be produced under proper conditions.

Another effect which has been totally neglected in the discussion because of the relatively low sensitivity of the ion detector to electrons, is the secondary electron emission from metal surfaces. As it has been shown that the amplification factor measuring the ratio of sensitivities may be less than expected it seems advisable to examine whether secondary electrons may not sometimes influence the measurements and perhaps in extreme cases counterbalance the effect of positive ions on space charge, thus putting a practical limitation to the efficiency of the method.

The principal source of secondary electrons in the space charge cylinder would be of course the metal surface hit by the primary beam in front of the entrance hole. As a discriminating factor to the relative efficiency of the method in the investigation of various colliding particles in differents gases, we may of course adopt the quotient q_i/k of the cross section for ionization of the gas by the coefficient of electron liberation from the metal surface by the particles under question. These quotients have been measured by me[9] for both systems A gas A atoms, He gas He

[7] The part of neutralization in the working of the ion detector also in previous applications is probably more important than hitherto supposed, and ought to be taken into account for a complete theory of it; however it is not so essential as here.

[8] A. Rostagni, Nuovo Cimento **12**, 134 (1935); Atti di Torino **70**, 472 (1935). F. Wolf, Ann. d. Physik **29**, 33 (1935). For anomalies presented by both cross sections for ion velocities under 30 volts see also A. Rostagni, Atti del Congresso Galvani (Bologna, October, 1937) in press.

[9] A. Rostagni, Nuovo Cimento **11**, 621 (1934).

atoms and copper surfaces. For energies of the particles between 60 and 460 volts they are always about fifty times larger with A than with He.

We are forced to conclude that if secondary electron emission really can exert any limiting effect on the sensitivity of the method, that will be much stronger in He than in A.

In order to calculate the magnitude of the effect we may consider a particular case. With 200 volt He atoms in He at a pressure of 10^{-2} mm Hg q_i/k is 0.006 ions per electron-cm. Since the beam length in the space charge cylinder was 2 cm, and since the effective cross section for collision of He atoms of 200 volts energy in He gas at 10^{-2} mm is less than 0.1 cm^{-1}, it follows that more than 80 percent of the primary atoms will hit the top of the cylinder with full energy, and liberate there about 70 electrons per positive ion produced in the gas. As the wall is positive with respect to inner space, not all the electrons will be able to travel far from it, but, since the field is small and concentrated near the filament, there is no doubt that a large fraction of them will contribute to increase the negative space charge.

Besides, in the special arrangement for investigating ionization by atoms,[10] we may look for another possible source of secondary electrons at the back of aperture 3, where practically all primary ions stopped by the field between 3 and 4 fall with their full energy. Unless the cylinder is negative with respect to aperture 3 (no mention of that is made in Varney's paper), a large fraction of these secondaries will be conveyed by the same field, through aperture 4, into the cylinder.

The proportion of secondary electrons to the ions inside the space charge cylinder should then be of the order of 100 to 1, in the case of helium. This result seems to justify our doubts on the legitimacy of neglect of secondary electrons. Moreover, the coefficient k for He atoms is rapidly increasing between 50 and 100 volt (from 0.01 to 0.1), at a rate which is comparable with that of ionization;[11] therefore it seems possible that the augmentation of secondary emission has masked the onset of ionization. Above 100 volts the quotient q_i/k for He remains practically constant. Any further increase of the velocities of the atoms therefore will be of no use in making ionization detectable.

By way of conclusion: while the positive results of the balanced space charge method in determining onset potential are certainly the most reliable, in order to secure reliability of negative results the sensitivity of the method needs to be more thoroughly investigated. As regards the particular case of the ionization of helium I am of the opinion that Varney's published results do not prove anything against the consistency of mine. These are confirmed on the one side by independent measurements with two quite different arrangements, on ions as well as on atoms, and by the perfect agreement of part of them with Varney's positive results, on the other side. I do not see any specific reason why if my results on A and Ne are correct, those on He should be completely wrong, since I reject the too simplifying hypothesis that my He had been contaminated, and since the principal disturbing effect of collecting field methods, the secondary electron emission, has been directly accounted for. I have, however, pointed out two independent reasons why Varney's result on He could be inconsistent.

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[10] See Fig. 1, in Phys. Rev. **50**, 159 (1935).

[11] A. Rostagni, Nuovo Cimento **11**, 99 (1934); Zeits. f. Physik **88**, 55 (1934).