The Sensitivity of the Balanced Space Charge Positive Ion Detector

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Additional information is given on the reaction of the balanced space charge detector to fast positive ions in the presence of gas in the tube. The sensitivity of the detector is analyzed, primarily in terms of experimental observations. Further notes on the mechanism of the detector are added.

IN view of the questions raised by Rostagni[1] on the sensitivity of the balanced space charge method of observing ionization of gases, used by the writer in several recent experiments,[2, 3] it is necessary to describe more in detail the observations which led to the estimated sensitivities reported for the method.

The basic features of the detector may be summarized:

1. A hot filament cathode emits a space charge limited electron current to an almost completely enclosing cylindrical anode.
2. A positive ion in the space charge region has the effect of neutralizing part of the space charge and thus allowing an increased electron flow to the anode.
3. This increased flow is measured in the balanced space charge method by a sensitive galvanometer connected in a balanced bridge circuit.
4. The size of the increased electron current per positive ion depends on the mean length of time a positive ion remains in the space compared with the same time for an electron.
5. The time a positive ion spends in the space depends on:

(a) Slow movement of the ion.
(b) A long free path for the ion.

Rostagni points out very accurately that neither of the conditions 5 (a) or 5 (b) are satisfied in the writer's experiments. (a) The positive ions all had high speeds. (b) The gas pressure was so high that free paths were short.

On the other hand, the writer did observe large effects by positive ions on the electron current, and this paper describes some experiments which indicate how Rostagni's proposed mechanisms actually operate.

The direct effect on the space charge electron current produced by a beam of positive alkali ions of various speeds was first observed. Gas pressures (A, Ne, N_2, He) ranging from less than 10^{-5} up to 10^{-2} mm of Hg were used. The results are summarized here:

1. From 0 to 10 volts ion speed, the ordinary positive ion effect on the space charge was observed. As predicted, it fell off rapidly with increasing speed.
2. Above 10 volts, the beam had a very nearly constant effect on the space charge current.
3. The size of the effect in 2 depended on the gas pressure. In vacuum the effect was very small. With gas pressures from 5×10^{-3} to 10^{-2} mm, the increase in electron current reached 250 to 300 times the actual positive ion current.
4. Helium pressures had to be higher than argon pressures to produce a given size of effect.
5. No conspicuous differences were observed among Li^+, Na^+, K^+, Rb^+, and Cs^+.

It is concluded from these experiments that scattering of ions in the gas plays an important role. The exchange of charge between alkali ions and atoms of the gases used is very small so can hardly influence the results. That scattering of fast ions from the anode cylinder walls may under favorable conditions influence the space charge current considerably is indicated in recent results of R. Kienzle[4] who tried similar experiments in vacuum.

Further analysis of the detector resulted from the failure to observe ionization in some cases, chiefly neon and helium, where Beeck and

[1] A. Rostagni, Phys. Rev. **53**, 729 (1938).
[2] R. Varney, Phys. Rev. **47**, 483 (1935).
[3] R. Varney, Phys. Rev. **50**, 159 (1936).
[4] R. Kienzle, Ann. d. Physik **30**, 401 (1937).

Mouzon[5] and Rostagni[6] were more successful. The writer attempted to set an upper limit on the ionization efficiencies which might escape detection by the balanced space charge method. A discussion of the effect in helium as compared with argon is given, as an example, below.

About 1/150 of the deflection produced by ionization of argon by 100 volt argon atoms could have been observed. The published figure, namely, that 1/20 (or 5 percent) of the ionization in argon could have been observed was based on the following:

(a) Helium ions of a given energy have over 3 times the speed of argon ions of the same energy. Since slow ions are more effective in space charge neutralization, this factor of 3 goes against the sensitivity to helium.

(b) It is more difficult to produce a beam of helium neutral atoms, as the charge exchange cross section for (He^+-He) is much less than for (A^+-A). It is the opinion of the writer that this factor far outweighs any considerations of space charge insensitivity. It is inapplicable to the results on ionization by positive ions, of course. To offset the difficulty, the initial intensity of the helium beam was enlarged by increasing the intensity of the preneutralization ion beam[3] by a factor of 2 of 3. The pressure of helium in the apparatus was varied over a range from 5×10^{-3} to 5×10^{-2} mm of Hg. (This figure was unfortunately omitted in the original report.) No trace of ionization was ever observed. The combination of factors (a) and (b) was set at 7.5 as a result. The sensitivity of the detector to helium must be reduced by this factor in comparison with argon. 1/150 of the deflection in argon could have been observed, so in helium 7.5 times this amount or 1/20 of the deflection in argon should have been detectable.

It may be pointed out here that Rostagni[1] has given an argument which the writer overlooked showing that helium ions will be more effective than argon ions in one respect. Since the collision cross section of argon is much greater than of helium (factor of at least 3), helium ions will travel much farther between collisions than argon ions. The sensitivity of the space charge detector depends on this distance between impacts, so a factor of 3 or more in favor of the sensitivity to helium results.

One experimental result, however, is probably more significant than all the complex analysis. The result is the following: The relative efficiencies for ionization of Ne by Na^+, A by K^+, etc., as observed, uncorrected, by the space charge method were of the same order of magnitude as Beeck[7] had observed by an absolute method. In fact they agreed as closely as 10 percent. No attempt at accurate comparisons of ionizations was made with the balanced space charge method, but the ion beam intensity and the gas pressures were kept practically constant for all ion sources. The galvanometer deflections in the balanced space charge circuit were thus roughly an indication of the combined efficiency of ionization and efficiency of detection. The close agreement with Beeck's measurements of ionization efficiency led to the conclusion that the efficiency of detection must have been nearly constant for different gases all the way from neon to xenon. The decreased sensitivity factor of 7.5 in going from argon to helium was thus believed to be by no means an underestimate.

Rostagni[1] has suggested a masking of the ionization in helium by secondary electrons. The use of more than one gas pressure should automatically eliminate this possible error, for a surface and a gas phenomenon can only coincide at one particular gas pressure. It would furthermore require that the coefficient of ionization and the coefficient of electron liberation be identical functions of voltage, and Rostagni's[6] results do not indicate this to be true in the important region near the onset voltage.

An error particularly to be feared was that secondary electrons ejected from the back of a slit might in some manner be accelerated into the detector and actually ionize the gas. We ruled this out quite certainly by intentionally placing an electron accelerating voltage between the last slit and the detector. It not only did not alter previous results, but ionization of such gases as He, N_2, and H_2 still did not appear. This same technique was used in all experiments including those on ionization by neutral atoms. Rostagni's[1] suggestion that secondary electrons might enter

[5] O. Beeck and C. Mouzon, Ann. d. Physik **11**, 737, 858 (1931).

[6] A. Rostagni, Nuovo Cimento **11**, 34 (1934).

[7] O. Beeck, Ann. d. Physik **6**, 1001 (1930).

from the back of the last slit seems to be definitely outlawed. The effect could at best be only of the second order of small quantities.

Just what mechanisms are involved in the space charge detector containing gas and used for fast ions is still difficult to conclude. Scattering from the walls and from gas atoms has already been advanced. I am indebted however to Professor L. B. Loeb[8] for an additional and important suggestion concerning the operation of the detector. If the filament of the detector is run at a very high temperature and the applied voltage is small, the space charge may be so heavy that an actual positive ion trap or potential trough of appreciable size exists between the filament and cylinder. If as the result of collisions or any other process, a positive ion finds itself in this trough with insufficient energy to escape, it may be extremely effective in neutralizing electron space charges. That this does occur is indicated by the frequent observations of the writer of an apparent increase in sensitivity of considerable magnitude with increase of filament temperature. Neither the space charge limited current nor the applied voltage was allowed to vary as the temperature was raised. The filament was already far into the space charge controlled region of emission at the start. The slight increase in potential drop down the filament was readily shown to be inadequate explanation of the sensitivity increase, for the plain variation of the applied potential gave no such effect.

[8] Private correspondence.

Rostagni[1] has challenged the writer's negative results in some cases on the grounds that such results are surprising after all the positive ones with other noble gases. Without attempting to discuss what should or should not be expected, the writer feels obliged to point out that his statement that ionization efficiency in helium must be less than 5 percent of that in argon is hardly a denial of all ionization of helium by helium atoms. Rostagni's challenge could possibly be directed at the smallness of the result but not at its absence.

It has been pointed out previously, furthermore, that Beeck's data on the onset of ionization by positive ions fail to be even self-consistent in the cases (and only in those) where the writer has found no ionization by the balanced space charge method. Rostagni's[6] brilliant work on ionization by neutral atoms is clouded by a similar difficulty; the onset potential has been observed in every case to rise as the atomic weight decreases and as the ionization efficiency decreases. His result on He – He is the only one incompatible with this law.

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Quadrupole-Quadrupole Interatomic Forces

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Atoms the normal states of which are not S states experience quadrupole-quadrupole repulsive and attractive forces which vary as the inverse fifth power of the separation distance. At large distances, exchange being negligible, the expression for the interaction energy contains as factors two atomic coefficients and a root of a secular equation determined by the molecular state of the system. For a given atom the coefficient is determined by the nature of its lowest level. If one uses the Hartree-Fock approximation, it is proportional to the average of the square of the radial atomic distance for those electrons with orbital angular momentum not in complete shells. Atomic coefficients have been calculated for most of the atoms of the periodic table having incomplete p and d shells and the secular equations have been solved for a number of cases. At distances of twice the sum of the atomic radii, diatomic molecules resulting from the combination of such atoms of the first row of the periodic table have quadrupole-quadrupole energies of a few tenths of a volt, such energies becoming rapidly larger for smaller distances because of the inverse fifth power dependence.

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When two atoms are far enough apart that overlapping and consequent exchange effects are negligible, the interaction can be considered as being composed of mixed terms of different pole strengths. The terms are obtained from the expansion of the potential in a Taylor's