Ionization of Gases by Collisions of Their Own Accelerated Atoms

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Neutral atom beans of noble gases of energies between 20 and 400 volts were produced by accelerating ionized atoms and then neutralizing the charges. The minimum energies which these neutral atom beams needed in order to ionize gas atoms by collision were determined. Neon, argon, krypton and xenon were found to ionize their own gases at energies about three times the actual ionization potentials. Attempts to observe ionization of one gas by neutrals of another have as yet given no results.

INVESTIGATION of the minimum energies necessary for ionization of noble gases by collisions of positive alkali ions[1] showed three significant results. If we remember that a singly charged positive alkali ion has identically the same number of electrons and electron structure as the noble gas atom next beneath it in the periodic table, the results were as follows: First, the experimentally observed ionizing energies had to be multiplied by a factor $m_a/(m_a+m_i)$, this factor being the fraction of the incident ion energy available for outside work after deduction of the amount necessary for the conservation of momentum (m_a and m_i are the masses of the gas atom and alkali ion, respectively). The reduced energy thus obtained for an ionizing collision between an ion having A electrons and an atom with B electrons was almost identical with that obtained when the ion had the B electrons and the atom had the A electrons. Secondly, the reduced ionizing energy was less when an ion and an atom had the same number of electrons than when they had different numbers. Thirdly, if other gases than the noble gases were ionized at all by positive alkali ions, the ionization could not have greatly exceeded one percent of the efficiency of K^+ in A.

The results of Beeck[2] and of Rostagni[3] on ionization efficiencies of noble gases by their own accelerated neutral atoms indicated that the determination of the actual inset energies for these processes might also yield valuable information, so the same method used for the alkali ion experiments was adapted to this problem.

The apparatus is illustrated in Fig. 1. Gas flows from a reservoir over the heated tungsten filament through a deep, narrow slit, 3 mm×0.5 mm (×4 mm depth), into a mercury pump. Electrons are accelerated from the filament toward the slit. If they produce any ions by collision in the field-free space inside the slit, these ions will be swept out at gas kinetic velocities by the flow through the slit. These ions are accelerated, as soon as they emerge from the slit, toward the negatively charged slit lying directly in line with slit one, and any electrons emerging from the first slit are stopped by this same potential.[4] Gas is allowed to stream out of slit number two into the pump orifice. The positive ions which were formed and accelerated before reaching slit two are now allowed to pass through the field-free space between slit two and aperture three. This region contains gas at about 10^{-2} mm Hg pressure. In these experiments, the same gas is used on both sides of the apparatus, so the positive ions are now traveling through their own gas. Kallmann and Rosen[5] first observed the fact that when ions, particularly noble gas ions, travel thus through their own gas, they are extremely efficient in picking off electrons from the relatively stationary neutral atoms, proceeding without change of velocity (speed or direction) as neutral atoms, and leaving behing a very slow positive ion which may be removed by a weak cross field. Beeck[6] has reported observing, under similar conditions to those described above, a beam of neutral atoms

[1] R. N. Varney, Phys. Rev. **47**, 483 (1935).
[2] O. Beeck, Ann. d. Physik **19**, 129 (1934).
[3] A. Rostagni, N. Cimento **11**, 34 (1934).

[4] This method appears to be due to Goldmann, Ann. d. Physik **10**, 460 (1931). It is obviously an excellent source of intense, monochromatic, positive gas ion beams. For details of the efficiency of this source see the reference above.
[5] Kallmann and Rosen, Zeits. f. Physik **61**, 61 (1930).
[6] O. Beeck, Ann. d. Physik **19**, 129 (1934).

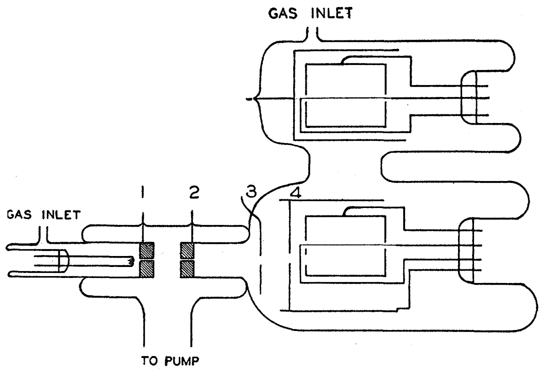

FIG. 1. Diagram of tube.

having 60 percent of the intensity of the original positive ion beam. No investigation was made in the present experiments to check the efficiency of neutralization, other than to observe that the intensity of positive ions emerging from the field-free space between slits two and three dropped off considerably when the gas was admitted. A final aperture number four having a large positive potential assured the stopping of any unneutralized positive ions emerging from aperture three, but this potential obviously has no effect on the neutral atom beam.

The neutral atoms, which are traveling with the energy they obtained as positive ions before neutralization, are now allowed to enter one of the space charge cylinders described at length in reference 1. Between this cylinder as anode and a heated tungsten filament as cathode flows a space-charge-limited electron current. If the neutral atom beam ionizes any gas atoms inside this cylinder, the positive ions thus produced are extremely effective in neutralizing the electron space charge, primarily because of their slower speed and more circuitous path. One positive ion has been observed to produce a space-charge effect equivalent to that of about 50,000 electrons.[1] The increased electron current reaching the anode as a result of this ionization by neutral atoms is measured by balancing out the ordinary electron current against that from a similar cylinder and filament arrangement outside of the path of the neutral atom beam.

The neon, krypton, and xenon used in these experiments were purchased in Pyrex flasks as 100 percent pure. The argon used was taken from a cylinder. Spectroscopic investigations at Berkeley indicated that impurities in argon from this tank did not exceed one percent, so aside from a liquid-air trap to remove water and mercury vapors, no further purification was attempted. In these experiments where the effect observed was large, traces of impurities are quite unimportant since the effects of impurities fall off directly with the pressure.

The ionization of each of these four gases by its own neutral atoms has been observed. The energies in electron volts at which ionization was observed to set in are given in column 1 of Table I.

These results are probably correct to within ± 2 volts except for Ne for which ± 4 volts is more accurate. Repeating the measurements under varying conditions, e.g., different pressures, different potential between filament and slit one, gave the same results usually well within the limits given above. The errors are only estimated and are based chiefly on possible doubts of the exact speed of the beam ions at the time of their neutralization.

Helium and nitrogen have been tried in this apparatus. Up to 400 volts no ionization was observed in either gas. Absolute measurements of ionization efficiency cannot be made with the space charge method, but it is estimated from the size of galvanometer readings that if the ionization of He in He had been five percent of that for A in A it could have been observed. In the case of N_2, it is possible that the experiments are confused by the fact that N^+ may have been formed rather than N_2^+ in the ion source, that N^+ might not neutralize very well in going through N_2 gas, and that barring the latter the N neutrals might not ionize N_2 by collision as well as N_2 neutrals might. A mass spectrograph is needed for further investigation of nitrogen ionization.

TABLE I. *Observed and reduced energies at which various gases are ionized by neutral atoms.*

	OBSERVED	REDUCED
Ne in Ne	74 volts	37 volts
A in A	48	24
Kr in Kr	40	20
Xe in Xe	35	17.5

The reduction factor mentioned above to correct the experimentally observed energies for energy losses in conserving momentum must also be applied in these cases. The factor is just one-half for all the cases in the table because the masses of the target and bullet atoms are equal. The resulting reduced values are given in column 2 of Table I.

These values are surprisingly low, being in each case only a few volts above the actual ionization potentials of the gases. The difference between these reduced potentials and the ionization potentials range from 16 volts for Ne to 6 volts for Xe. The results are almost half those for the alkali ions in the noble gases. This is not surprising because the previous results indicated the importance of electron configurations in this process. A collision, for example, between K^+ and A should be the same as between A and A except for the initially greater energy of the former combination with its positive charge which should make it more difficult to remove the electron.

The result for A in A agrees quite well with that obtained by Rostagni[7] at about 55 volts. Rostagni observed ionization of He by He neutrals, the efficiency being about ten percent that of A in A. Some doubt falls upon these results with helium, however, because ionization was indicated in the published curves at energies less than twice the electron ionization potential of He. Because of the conservation of momentum, which it seems certain must occur, only one-half of the energy of the incident atom at most is available in a collision between two such atoms of equal mass. Ionization by this mechanism should certainly cease therefore at a minimum value of twice the ionization potential. If the ordinates of Rostagni's He curve be multiplied by ten, the He curve coincides almost exactly with his A curve. This implies that the helium may have been contaminated with argon.

Further experiments have been conducted with a view to observing the ionization of one gas by the neutral atoms of another gas. Such experiments require one additional gas-filled chamber. In the present experiments the ions were neutralized in the same part of the tube in which they later ionized the gas. To observe the ionization of one gas by another, the ions must be neutralized in a chamber containing their own gas and then pass into one containing the different gas. Such an apparatus has been built and preliminary measurements made. So far, no ionization has been observed by argon neutrals in Kr or Xe up to 250 volts. The experiments are not final, however, because the complications in forming ions in one gas, accelerating them in vacuum, neutralizing them in more of the gas, and finally passing them into another gas result in such a drop in intensity as to cause some doubts over the sensitivity of the method. A in A was tested in the new arrangement and positive results were obtained. The efficiencies of A in Kr or Xe should thus not exceed 10 to 20 percent of those for A in A. Further experiments on ionization of one gas by accelerated neutral atoms of another may be reported at a later date.

[7] A. Rostagni, N. Cimento **11**, 34 (1934).