EFFICIENCY OF IONIZATION IN HYDROGEN BY POSITIVE-ION IMPACT AT 7000 VOLTS

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Abstract

Hydrogen at low pressure is bombarded with potassium positive ions of 7000 volts energy in a tube attached to a positive-ray box. Any hydrogen ions and scattered potassium ions passing into the latter are distinguished by mass analysis. The applicability of this method for measuring the efficiency of ionization is discussed. If the hydrogen molecules receive kinetic energy from the 7000-volt ions which ionize them, they will be scattered in all directions, and only those which happen to be projected towards the slit will enter the positive-ray box. But if ionization is unaccompanied by transfer of kinetic energy, the method is competent to compare the ionizing efficiency with that of electron-impact. With small positive-ion emissions no ionization was detected; with larger emissions a violent discharge took place through the tube. The conclusion reached is that either the ionizing efficiency is less than 1/150 of that of 50-volt electrons, or else that ionization is accompanied by transfer of kinetic energy.

IN EXPERIMENTS which have hitherto been made to study ionization of gases by positive-ion impact, the effect looked for seems always to have been masked by spurious effects. Although in bombarding a gas with electrons the presence of positively charged particles may be accepted as evidence of ionization, this method is of course excluded in the case of positive-ion impact, unless a method is provided for distinguishing the secondary ions from the primary. Horton and Davies,[1] and Hooper[2] who repeated the earlier work of Pawlow,[3] accordingly used the converse method, that of looking for the presence of electrons liberated from the gas by the positive ions. Unfortunately the liberation of electrons from the metal electrodes was found to mask completely the effect looked for, in helium up to 200 volts and in hydrogen up to 900 volts. Since vapor from stop-cock grease does not seem to have been excluded in either of these experiments it is possibile that this copious liberation of electrons came not from the metal but from an adsorbed layer.

If the gas bombarded is of different molecular weight from the ions of the primary beam, the presence of secondary ions can be shown by any method of mass analysis. In the experiments to be described a positive-ray box of the Dempster type was used together with the method of differential pumping employed by Smyth and others; a diagram will be found in a previous paper.[4] The source of positive ions was catalyst oxide, deposited on a platinum filament. An accelerating voltage applied between this filament and a nickel gauze directed a beam of ions down the axis of the tube, so that the

[1] Horton and Davies, Proc. Roy. Soc. **95**, 333 (1919).
[2] Hooper, J., Franklin Inst. **201**, 311 (1926).
[3] Pawlow, Proc. Roy. Soc. **90**, 348 (1914).
[4] Gurney, Phys. Rev. **32**, 467 (1928).

gas in the region above the slits was bombarded by the ions. The nickel parts were all outgassed by an induction furnace before assembling. The procedure for identifying any type of ion was that usually employed: the accelerating voltage between the two slits of the positive-ray box is varied over the range previously determined by calibration; on plotting the electrometer deflection against the applied voltage, the presence of a group of ions appears as a "peak." Before going into detail it will be well to consider the circumstance under which the method will be competent to measure the efficiency of ionization.

To pass through the second slit of the positive-ray box, an ion must have been travelling down nearly perpendicular to the upper slit. In the case of electron-impact this is easily achieved by drawing the ions down by a small collecting field; for the molecule ionized has a very small thermal velocity, and receives practically no kinetic energy from the electron which ionizes it. But from a positive ion possessing 7000 volts energy the molecule can receive a large amount of kinetic energy. If this occurs, the molecules will presumably be scattered over a hemisphere, and only those ions which happen to be projected nearly vertically downwards will be collected unless a huge collecting voltage be applied. But if a large collecting voltage were used, the ions formed at various distances from the slit would fall through very different amounts of potential, and would be spread out over a large range of velocity. On varying the field between the two slits of the positive-ray box no "peak" of secondary ions could be identified, especially if they have already received different amounts of energy from the positive ions which ionized them.

It is clear, therefore, that if the process of ionization resembles that by electron-impact in that no appreciable kinetic energy is transferred to the molecule ionized, then this method is competent to measure the ionizing efficiency. But in all other cases it is not competent.

Results

In the earlier experiments hydrogen at a pressure of 1.7×10^{-3} mm was maintained in the ionization chamber. It could be bombarded alternately with electrons of 50 volts or with potassium ions of 7000 volts energy. A fuse was inserted between the tube and the 7000-volt terminal of the constant-voltage kenetron set, which had been kindly loaned by the General Electric Company. The collecting voltage to draw the ions towards the slits was 50 volts.

First using electron bombardment with an emission of only 0.12 microampere, the H_2^+ peak was easily found and its height measured. Emission of positive ions was then started instead, and searches were made for hydrogen ions at various voltages of the primary beam up to 5000 volts, but without finding any peak outside the experimental error. A small emission of primary ions at 7000 volts was then used, and this emission was increased by steps. When the emission was raised to 0.65 microampere a discharge took place in the tube, and the fuse blew with a loud explosion. No hydrogen

ions had been detected at the lower emissions, and the ionizing efficiency must have been less than 1/60 of that of the 50-volt electrons used, as computed from the height of the smallest peak that would have been detected.

A lower pressure of hydrogen was then used, 8×10^{-4} mm. A positive ion emission of 1.1 microampere was maintained for some time at this pressure and 7000 volts. Search was made both for H_2^+ and H^+ ions, but none were found with certainty. When the readings of the electrometer were most consistent, it was found that the ionizing efficiency was certainly less than 1/150 of that of the 50-volt electrons. This value is again obtained by considering the height of the smallest peak that could be detected, and by assuming the width of the peak to be the same as that of the peak obtained by electron bombardment. But, as pointed out above, the peak may be many times wider. When larger emissions were tried at this voltage and pressure, a discharge always took place, and the fuse exploded.

This sudden discharge is presumably due to cumulative ionization. This may be caused by the liberation of electrons from the molecules of the gas by positive-ion impact, or may be due to electrons released from the electrodes either by the positive ions or by photoelectric action.

On the other hand, ionization may be taking place all the time but be undetected because of the transfer of momentum discussed above. In the apparatus described we were looking for ions drawn from the beam at a right angle, and there was the question whether it would be better to look for ions at some other angle. The source was therefore mounted so that the beam could be set at any angle, but the search for hydrogen ions was no more successful than before. This was to be expected, since if there were a considerable variation with angle this could only mean that the ions were being projected by the ionizing impact; and all the ions not actually projected through the second slit would be almost unaffected by the collecting field.

At the meeting of the American Physical Society, April 1927, a paper on ionization of HCl vapor by positive-ion impact was presented by W. M. Nielsen.[5] The method was the usual one of looking for negatively charged particles, which were said to have been found with impinging ions of only 34 volts energy. It was suggested that the HCl molecule was being dissociated into ionized components.

HCl vapor was accordingly substituted for the hydrogen, and a brief search was first made with the positive-ray box for H^+ ions and Cl^- ions, but without finding either. Then HCl^+ ions were looked for, but it was found that any such ions were being masked by the potassium ions from the primary beam, which were coming into the box in enormous quantities, after having been scattered around the walls of the nickel ionization chamber. When hydrogen was being studied this effect had been inappreciable because of the great difference in the atomic weight, and consequent difference in the value of the magnetic field required to bend the ions round the semicircle

[5] Nielsen, Phys. Rev. **29**, 907 (1927).

to the Faraday cylinder. But the scattered potassium ions (and ions of sodium which was present in the source as an impurity) made it impossible to study gases of higher molecular weight. An investigation into this intense scattering of ions from metal surfaces was therefore made, an account of which has recently been published.[4] The study of gases has not been carried further.

Discussion

Compton and Van Voorhis[6] measured the ionizing efficiency of electrons in gases, and correlated their results with the kinetic theory mean free path of electrons. They found that in hydrogen (and other gases) the number of ionizing collisions for electrons from 50 to 300 volts was about one-quarter of the number of kinetic theory collisions. The number of ionizing collisions for positive-ion impact seems to be a much smaller fraction of the number of kinetic theory collisions. It is of course doubtful what is the minimum transfer of energy or momentum which counts as a "collision" in the kinetic theory. But a simple calculation shows how small a fraction of 7000 volts transferred would suffice to account for the negative results obtained in the present experiments.

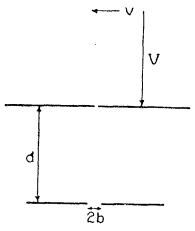

Fig. 1.

Let the half-width of the lower (wider) slit be b and the distance between the two slits be d. Let a molecule moving horizontally with a velocity v be ionized, and then acquire a velocity v' in falling through the collecting potential V. The condition for its getting through the second slit is approximately that v/v' be not greater than b/d. If E be the energy in volts corresponding to the velocity v, then $E/V=v^2/v'^2$ must not be greater than b^2/d^2. In the apparatus used $d=10$ mm, $b=0.2$ mm; so that $b^2/d^2=0.0004$. This means that the voltage applied must be 2,500 times the initial energy of the ion. This value may be halved to allow for the curvature of path produced by the other voltage applied between the two slits. This condition is just satisfied for thermal energies about 1/25 volt by applying 50 volts. But if the 7000 volt positive ions transfer as kinetic energy even less than one percent of their energy, i.e. less than 70 volts, it is clear that a very small yield could be obtained.

The conclusion reached then is that either the ionizing efficiency in hydrogen is less than 1/150 of that of 50-volt electrons, or that ionization is accompanied by transfer of kinetic energy.

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Palmer Physical Laboratory,
Princeton University,
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[6] Compton and Van Voorhis, Phys. Rev. **27**, 730 (1926).