

IONIZATION IN GASES BY IONS AND ATOMS

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It has been assumed for a long time that the ionization of atoms by ions must in one form or another play an important rôle in the phenomena of gas discharges. This assumption found its mathematical expression in the well-known theory of Townsend. Only recently, however, have the elementary effects of the ionization by ions been experimentally investigated. The ionization of noble gas atoms by alkali ions was studied in particular and a number of important results have been arrived at by R. M. Sutton,¹ R. M. Sutton and J. C. Mouzon² and O. Beeck.³

The points which are essential for our considerations may be stated roughly as follows. Denote the masses of the impinging ion and the target gas atom by m and M , respectively. With the auxiliary condition that the energy of the impinging ion be kept constant

$$mv^2/2 = K = eV \quad (1)$$

we obtain these results:

(1) The efficiency of ionization has a maximum for the ion whose mass comes nearest to satisfying the relation

$$m = M. \quad (2)$$

(2) For $m \geq M$ the efficiency γ of ionization falls off both sides. It is significant, moreover, that it falls off much more rapidly for $m < M$ than for $m > M$, i.e., that

$$\gamma_{M+m_1} > \gamma_{M-m_1}. \quad (3)$$

(3) The efficiency of ionization has a general tendency to increase both with the masses of the impinging ion and the atom which is to be ionized.

(4) The potential V_i at which the ionization first sets in is lowest for $m = M$.

We try now to find an interpretation for the observations (1) to (4). It is known that the ionization of atoms by not too slow electrons ($V > 100$ volts) can be accounted for by calculating the momentum J which is directly transferred from the impinging electron to an electron of the atom which is hit. If ϵ_P is the ionization potential of the target atom, an electron will be ejected from this atom if the momentum transferred to it satisfies the inequality

$$J^2/2\mu > \epsilon_P \quad (4)$$

where μ is the mass of an electron.

Such a procedure is legitimate in this case because a not too slow electron traverses the atom in a time which is considerably shorter than the period of revolution of the bound electrons.

In the case of an ion impinging on the gas atom, however, the duration of the impact is much greater than the period of the bound electron. Indeed, we may picture the interpenetration of the two particles as a perfectly elastic process. The duration τ of the impact then is independent of the relative velocity of the two particles, as τ may in the first approximation be looked upon as the period of an elastic oscillation which is independent of the amplitude. We may put approximately

$$\tau = \pi \left[\frac{mM}{f(m+M)} \right]^{1/2}. \quad (5)$$

The elastic constant f (force for a displacement of 1 cm.) will be of the same order of magnitude as the elastic constant which characterizes the binding of the two atoms in a diatomic molecule, HCl for instance. We thus will have this order of magnitude

$$\tau = 10^{-12} \text{ seconds} \quad (6)$$

whereas the period of revolution of an electron is of the order 10^{-16} sec.

The impinging ion therefore causes an adiabatic disturbance in the gas atom in the form of an elastic wave, which is similar to the elastic waves which are set up in colliding billiard balls. The ionization of the atom then might be compared to the rupture of one of the billiard balls. On this simple picture the efficiency of ionization evidently will depend on the following two conditions:

(α) The elastic wave set up in the atom will transfer a certain maximum effective momentum J_{eff} to one of the atom's bound electrons. If

$$J_{\text{eff}}/2\mu > \epsilon_P \quad (7)$$

the electron will be ejected.

(β) The ionization potential ϵ_P in this case will be characteristic for the "freak" molecule formed for an instance by the two colliding particles at the time of closest approach or at the time of reversal of that component of the relative velocity which lies in the connecting line of centers of the two particles.

We now ask how the essential quantities J_{eff} and ϵ_P might be determined.

The elastic wave set up in the atom will be determined by the hardness of the impact (maximum force of repulsion F) and its duration τ . We shall have roughly

$$J_{\text{eff}} \propto \tau F \propto J \quad (8)$$

It was known to me from the experiments of F. M. Penning⁴ and others that neutral argon atoms up to speeds corresponding to several hundred volts may be obtained by shooting A^+ ions through argon gas. Some of the A^+ are neutralized by an exchange of electrons taking place with the argon atoms of the bombarded gas. Those particles which are neutralized without being deflected also retain their original energy. As it seemed possible in this manner to produce beams of neutral A atoms with speeds corresponding to several hundred volts I proposed about a year ago⁵ to try the experiment of ionizing argon by fast argon particles. Dr. O. Beeck of our Institute, who was well equipped to carry out this investigation, very kindly took up my suggestion and successfully accomplished the difficult experiment. The preliminary results which he has obtained check very well with the predictions which I based on the above considerations. For the details of the experimental arrangement and the results obtained so far I refer the reader to Dr. Beeck's paper in this same issue of the PROCEEDINGS.

It is desirable of course to investigate the ionizing power of doubly charged ions also and to bombard noble gas atoms other than argon in order to establish more firmly the correctness of the theoretical considerations given here. So far these conceptions have well served their purpose as a guiding viewpoint for furthering our knowledge of ionization phenomena. There is no doubt, however, that they will have to be refined and that a more complete theory must be worked out in order to account for all the details of the phenomena in question. Indeed the statement of the experimental results given in the points (1) to (4) represents only a crude approximation to the really observed phenomena which have been described in detail in previous publications by Dr. Beeck.

A few remarks concerning the weak points of the considerations given may not be out of place.

In the first place it seems fairly clear that J_{eff} will not depend merely on the momentum J transferred from the impinging particle to the gas atom. J_{eff} in fact is the product of the time of duration of the impact multiplied by a certain average of the force \bar{F} acting during the impact.

$$J_{\text{eff}} = \tau \bar{F} \quad (10)$$

Now τ is maximum for $m = \infty$ as appears from (5). On the other hand \bar{F} is maximum for $m = 0$ whereas the product J is maximum for $m = M$. It is to be anticipated that J_{eff} will depend not only on J in a wholesale fashion but will also be affected somehow or other by τ and \bar{F} individually. Such effects have here not been considered.

In the second place it is to be expected that the charge will have some effect in the formation of J and J_{eff} . Indeed due to its polarizing power

the atom hit by an ion will not only be distorted by the impact but also by electric polarization. Furthermore, the resulting relative speed will not be exactly given by the initial speed v , but instead there will be an additional velocity due to the attraction which results from the energy of polarization

$$-\alpha e^2/r^4 \quad (11)$$

where α is the polarizability of the atom which is hit and r the distance between the two particles.

Thirdly, as mentioned before, we have neglected the elastic wave inside of the atom in calculating the momentum transferred.

Finally the effective ionization potential will not depend simply on the ionization potentials of the two particles involved. A more exact theory will have to take into account the more characteristic properties of the outer shells of the colliding particles and their dynamic behavior during the impact.

It seems probable that the above considerations can be generalized to ionization and dissociation processes produced by collisions of ions and atoms with molecules.

The results obtained so far promise to be of the greatest importance for our understanding of many phenomena in gas discharges, thermal ionization, etc., possibilities which have been pointed out by Dr. Beeck in his paper.

I am indebted to Drs. Sutton, Mouzon and Beeck for having called my attention to the problem of ionization by ions and for the first-hand information which I obtained from Dr. Beeck during many mutual discussions.

¹ R. M. Sutton, *Phys. Rev.*, **33**, 364 (1929).

² R. M. Sutton and J. C. Mouzon, *Phys. Rev.*, **35**, 695 (1930).

³ O. Beeck, *Ann. Physik*, **6**, 1001 (1930); O. Beeck and J. C. Mouzon, *Ann. Physik*, **11**, 737 (1931).

⁴ F. M. Penning and C. F. Veenemans, *Zeitschr. Physik*, **62**, 746.

⁵ The essential points of this paper were presented during a discussion at the American Physical Society meeting at the University of California at Los Angeles, December 12-13, 1930.