PRE-BREAKDOWN IONIZATION IN MOLECULAR NITROGEN IN $E \times B$ FIELDS

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Summary

Pre-breakdown ionization measurements in molecular nitrogen are examined to establish whether the influence of a transverse magnetic field is equivalent to an increase in the gas pressure from p to $p_e = p(1+\omega^2/\nu^2)^{\frac{1}{2}}$, where ω is the electron cyclotron frequency, and ν is a constant, effective, electron–molecule collision frequency. When the value of E/p_e lies within the range $150 < E/p_e < 250$ V cm^{-1} torr^{-1}, ν has a constant value equal to $8\cdot3 \times 10^9 p$ s^{-1}, but when $E/p_e < 150$, ν/p must decrease with decreasing E/p_e for satisfactory agreement to be maintained. The possibility of extending the concept to account for the changes in secondary ionization and the breakdown potential in nitrogen are also discussed.

I. INTRODUCTION

Investigations of the behaviour of electrons in the pre-breakdown ionization region in the presence of spatially uniform, time-independent $E \times B$ fields have been confined so far to the situation where it was believed that the mean free time $\tau = l/u$ between collisions of electrons and gas particles could be regarded as substantially constant. As far as many of the transport properties are concerned, the electrons then behave in the presence of a transverse magnetic field as though the actual gas pressure p has been increased to a value p_e given by

$$p_e = p(1+\omega^2\tau^2)^{\frac{1}{2}} = p(1+\omega^2/\nu^2)^{\frac{1}{2}}, \tag{1}$$

and the magnetic field B has been reduced to zero (Blevin and Haydon 195).8*a* $\omega = eB/m$ is the electron cyclotron frequency, and ν is the effective electron–molecule collision frequency. It should be noted that the term "*effective* collision frequency" is used for the parameter ν. The interpretation of this quantity is straightforward only for the special case when l/u is constant. In the general case when l/u is a function of electron energy, ν can only be regarded as an empirical quantity. Its precise interpretation in terms of the detailed properties of the electron collisions will be dealt with elsewhere.

The validity of the equivalent-pressure concept for molecular hydrogen has been tested by direct comparison of measured values of the primary ionization coefficient α/p in $E \times B$ fields with those values predicted on the basis of the increase in gas pressure mentioned above (Blevin and Haydon 1958*a*; Haydon and Robertson 1961*a*, 1963; Bernstein 1962). A constant value of $\nu = 2\cdot5 \times 10^9 p$ s^{-1} was found to fit the observations over the limited range of values of E/p and B/p examined (Haydon and Robertson 1963).

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Although the relevance and limitations of this particular equivalent-pressure concept in discussions of the wider problem of electrical breakdown in $E \times B$ fields have been discussed (Blevin and Haydon 1958*b*, 1963; Haydon 1961), the concept has nevertheless been invoked recently to interpret measurements of the breakdown characteristics of electrodeless discharges in $E \times B$ fields in air and nitrogen (Sen and Ghosh 1962, 1963). In these gases, however, it has never been tested experimentally whether or not an equivalent-pressure concept can be applied. As has already been done for hydrogen, it is the purpose of this paper to report the relevant measurements (Bagnall 1962) in molecular nitrogen, and also to discuss the results in terms of the problems of electrical breakdown.

II. Apparatus and Experimental Procedure

The essential prerequisite for any analysis of the influence of a transverse magnetic field on the behaviour of the electrons in these investigations is a knowledge of reliable values of the primary ionization coefficient $(\alpha/p)_{0,E/p}$ in static electric fields only. In nitrogen, as was the case in hydrogen (Haydon and Robertson 1961*b*), there is general agreement about the values when E/p is small, but discrepancies become more pronounced as E/p is increased to large values (greater than about 400 V cm^{-1} torr^{-1}). However, Heylen (1959) reports that impurities have little influence throughout a wide range of this parameter, and our own experience confirms that this is so. Consequently we have not found it necessary to take special precautions against contaminations, and over the range of values of E/p ($<$ 600 V cm^{-1} torr^{-1}) in which we are interested at present we have found no marked disagreement with the values reported earlier. We have nevertheless taken great care to maintain the cleanest possible conditions within the limitations imposed by a conventional vacuum system using oil diffusion pumps. The gas was a dry, oxygen-free grade obtained from a metal cylinder containing nitrogen at high pressure. Liquid air traps were used when storing the gas and when finally admitting the samples to the ionization chamber.

Also, by confining the present study to the influence of relatively small transverse magnetic fields it has not been necessary to use concentric cylindrical geometry in order to maintain the essential conditions of unrestricted $E \times B$ drift of electrons. All the measurements were made, therefore, with a plane-parallel electrode system, details of which, together with the experimental arrangements for measuring α/p in crossed fields, have been reported elsewhere (Haydon and Robertson 1963).

The important basic information about α/p in nitrogen measured with this system is shown in Figure 1, where a comparison is made with the results of Masch (1932), who also covered a similar range of E/p. Earlier measurements in hydrogen using the same apparatus are also shown for comparison. As with hydrogen, a saturation in the value of α/p also occurs in nitrogen, and, although the values of E/p ($\sim$ 1400 V cm^{-1} torr^{-1}) in this case are very much higher than in hydrogen ($\sim$ 350 V cm^{-1} torr^{-1}), the measurements in each case correspond to the same range of values of the gas pressure and the electrode separation, pd ($\lesssim 0 \cdot 5$ torr cm.) In these circumstances the growth of pre-breakdown ionization occurs under non-equilibrium conditions in which the electrons acquire beam-like characteristics because of the dominance of marked forward-scattering collision processes; this ionization growth is not fully understood, and in the present investigation we restrict our discussion of the crossed-field measurements to the equilibrium region corresponding to values of $E/p < 600$ V cm^{-1} torr^{-1}. For the purposes of the analysis referred to in Section V we note here that over the range $200 < E/p < 600$ the value of α/p satisfies the exponential form $\alpha/p = \mathscr{A}\exp(-\mathscr{B}p/E)$, where $\mathscr{A}$ and $\mathscr{B}$ have the values 14 cm^{-1} torr^{-1} and 380 V cm^{-1} torr^{-1} respectively.

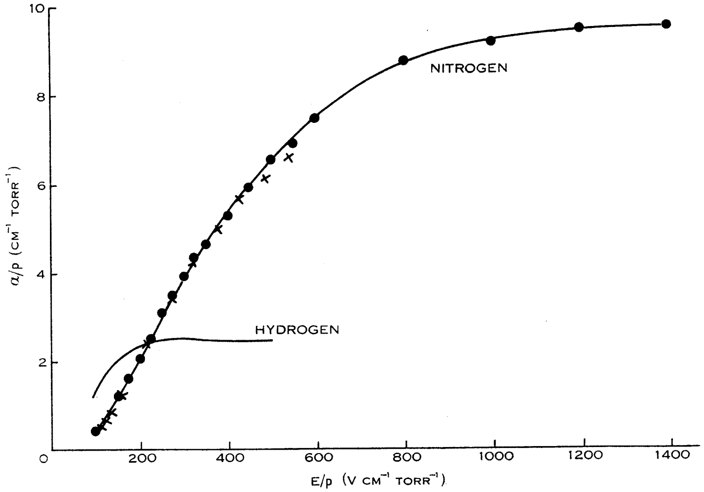

Fig. 1.—Values of α/p versus E/p for nitrogen. ● Present values. × Results of Masch (1932). Measurements in hydrogen are also shown for comparison.

III. The Equivalent-pressure Concept for $(\alpha/p)_{B/p,E/p}$ in Nitrogen

If the equivalent-pressure concept derived for molecular hydrogen can be extended to the case of nitrogen, then the crossed-field value for the ionization coefficient should be given by

$$(\alpha/p)_{B/p,E/p} = y(\alpha/p)_{0,E/py}, \tag{2}$$

where $y = p_e/p$. The values of α/p given in Figure 1 can then be used in conjunction with equation (2) to derive the values of $(\alpha/p)_{B/p,E/p}/(\alpha/p)_{0,E/p}$ ($\equiv \alpha_B/\alpha_0$) as a function of y to be expected for nitrogen. These values are shown in Figure 2.

To proceed further one can choose either of two alternative approaches.

(a) Convert the parameter y into B/p so that a direct comparison can be made with quantities which can be determined experimentally. This conversion requires the insertion into equation (1) of a value for the effective collision frequency ν/p.

(b) Make a direct comparison of the measured values of α_B/α_0 with those of Figure 2 in order to determine the values of y required in each case to give agreement at each value of B/p. These values of y can then be converted into values of ν/p using equation (1).

IV. Measurements of α/p in Crossed Fields

Measured values of α_B/α_0 versus B/p for values of $E/p = 250$, 400, and 600 respectively are given in Figure 3. Also included in this figure are the curves derived from Figure 2 on the basis of alternative (*a*) in Section III above for a value of $\nu/p = 8 \cdot 3 \times 10^9 \text{ s}^{-1} \text{ torr}^{-1}$. The agreement is seen to be good only over a limited range of values of E/p and B/p; in particular, for low values of E/p when B/p is small, and for high values of E/p when B/p is large. Now at the higher values of E/p non-equilibrium growth of ionization becomes increasingly evident and, because

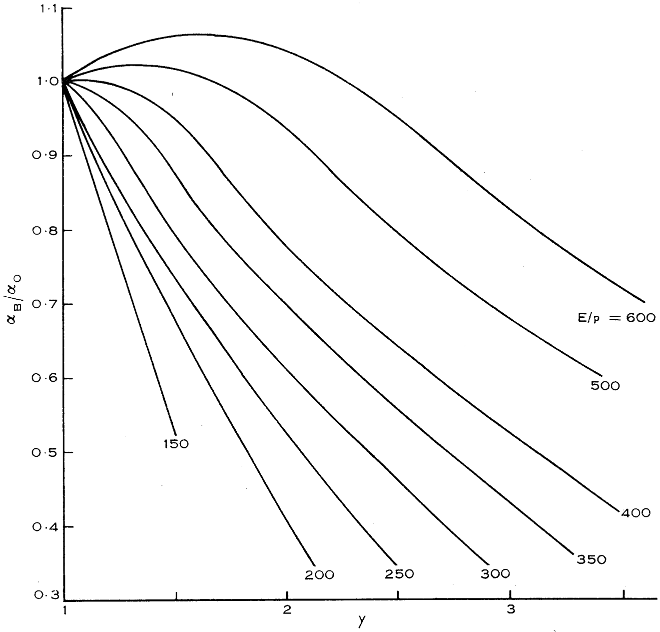

Fig. 2.—Values of $(\alpha/p)_{B/p,E/p}/(\alpha/p)_{0,E/p}$ $(\equiv \alpha_B/\alpha_0)$ for nitrogen derived from Figure 1 on the basis of the equivalent-pressure concept for $y = p_e/p = (1+\omega^2/\nu^2)^{\frac{1}{2}}$.

a small value of B/p corresponds to a small increase in the equivalent pressure and therefore to a small change in the effective E/p, the equivalent situation may still be a non-equilbrium one. This may account for the poor agreement in these circumstances. On the other hand, the lack of agreement at low E/p cannot be attributed to non-equilibrium conditions and the fact that the same value of ν/p cannot be used at low values of E/p needs further investigation.

We may examine the situation more satisfactorily by adopting the alternative (*b*) in Section III to see whether or not it is possible to obtain values of ν/p versus E/p_e which give good agreement over the whole range of experimental parameters.

V. The Effective Collision Frequency ν/p

The error involved in obtaining values for the effective collision frequency ν/p depends not only on the experimental error of α_B/α_0 but also on the particular

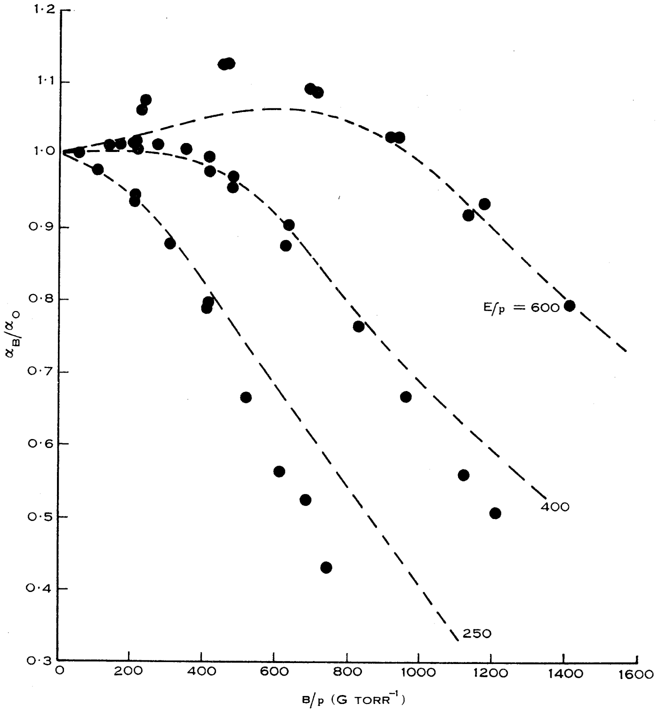

Fig. 3.—Measured values of α_B/α_0 versus B/p for various values of E/p. – – – Values derived from Figure 2 for $\nu = 8 \cdot 3 \times 10^9 p$ s^{-1}.

Table 1

VALUES OF THE EFFECTIVE COLLISION FREQUENCY OVER A RANGE OF EXPERIMENTAL PARAMETERS

E/p (V cm^{-1} torr^{-1})	B/p (G torr^{-1})	α_B/α_0	E/p_e (V cm^{-1} torr^{-1})	ν/p (10^9 s^{-1} torr^{-1})
250	800	0·36	103	6·3
250	700	0·48	119	6·6
250	600	0·60	138	7·0
300	800	0·61	149	8·1
250	500	0·72	160	7·8
300	700	0·69	170	8·5
400	900	0·72	182	8·2
600	1400	0·80	192	8·3
400	800	0·79	203	8·3
350	615	0·80	207	8·0
600	1100	0·95	225	8·5
350	530	0·88	233	8·4
400	594	0·91	244	8·1
400	570	0·92	250	8·1

value of the parameter y obtained from comparison with the curves of Figure 2. The experimental error $\Delta G/G$ in the ratio $G = \alpha_B/\alpha_0$ is $\pm 3\%$, and in terms of this quantity the error in collision frequency $\Delta\nu/\nu$ can be shown to be (Haydon and Robertson 1963)

$$\frac{\Delta\nu}{\nu}=\frac{\Delta B}{B}-\frac{y^2}{y^2-1}\left(1-\frac{\mathscr{B}py}{E}\right)^{-1}\frac{\Delta G}{G},$$

where $\mathscr{B}$ now has the value 380 V cm^{-1} torr^{-1} (see Section II).

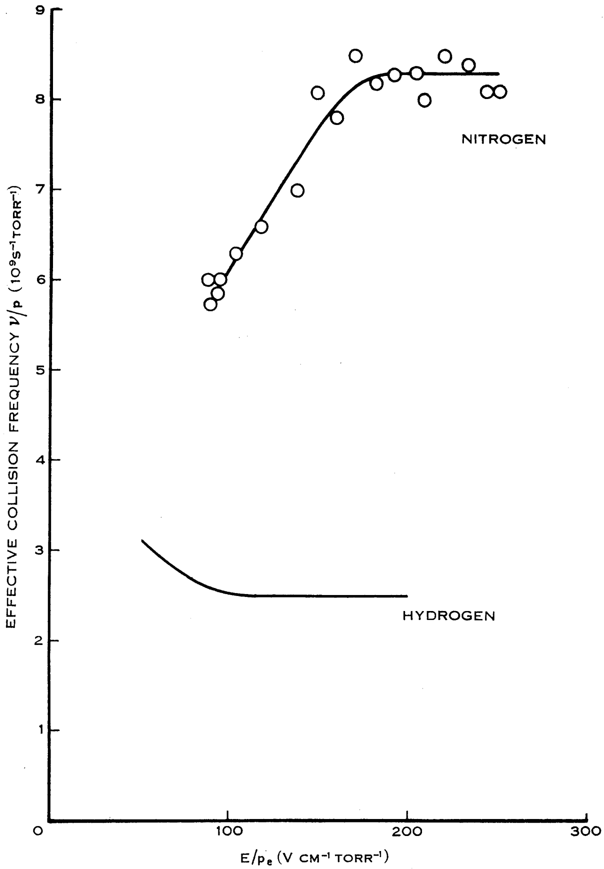

Fig. 4.—Comparison of values of ν/p versus E/p_e for hydrogen and nitrogen.

Using this equation, values of a_B/a_0 have been selected which yield values of ν/p within an acceptable error of less than $\pm5\%$. These values of a_B/a_0, E/p, and B/p are given in Table 1 together with the derived values of ν/p and E/p_e.

As can be seen, it is possible to apply the equivalent-pressure concept over the full range of values of E/p and B/p for which results are given in Table 1, provided that ν/p is made to vary with E/p_e in the manner shown. It should be noted that a constant value of $\nu/p = 8\cdot3\times10^9$ can only be used with confidence at present in the range $150 < E/p_e < 250$. A similar situation was observed in hydrogen (see Fig. 4). In this gas, however, the values of ν/p were found to increase as E/p_e was reduced, whereas, in order to obtain agreement between the measured and calculated values in nitrogen, the values of ν/p are required to decrease.

VI. Electrical Breakdown in Crossed Fields

The above discussions have been concerned only with measurements of the primary ionization coefficient α/p because the equivalent-pressure concept based on equation (1) may only be invoked to explain the behaviour of electrons in crossed fields. Electrical breakdown depends also on secondary effects which may involve a combination of positive-ion, metastable-atom, and photon interactions with the surfaces, and, in order to account for the influence of the transverse magnetic field on the breakdown potential V_s, some information is required about the relative proportions of the several possible effects. If, for instance, the dominant secondary mechanism were a positive-ion process then the equivalent-pressure concept underlying equation (1) would not adequately account for the influence of the transverse magnetic field on the breakdown potential. On the other hand, a dominant photon process, being dependent entirely on the behaviour of the electrons in the crossed-field situation, should lead to satisfactory agreement, provided, of course, there are no electron-recapture processes occurring at the cathode. For hydrogen, formative time-lag measurements have shown a predominance of photon effects at low values of E/p, with positive ions taking an increasingly important role as E/p is increased. For nitrogen, a sharp peak in the secondary coefficient for values of $E/p \sim 100$ has been attributed (Bowls 1938) to a dominant photoelectric effect, and the steady increase with increasing E/p at the larger values suggests again that the total secondary emission in this range is determined largely by the action of positive ions. In each of these gases, therefore, an equivalent-pressure approach to the secondary ionization, based on equation (1), ought to be more satisfactory at low values of E/p. The measurements carried out so far in nitrogen indicate that this is so. Figure 5(a) for instance shows that, whereas at high E/p there is little change in the secondary coefficient* Q/P for large changes in B/p, the corresponding changes are quite marked at low values of E/p. In order to show that this is probably associated with the predominance of a photoelectric effect at the cathode, these same values of Q/P are plotted in Figure 5(b) as a function of E/p_e and are compared with measurements made by Bowls (1938) in the absence of a magnetic field. Although it should be noted that the actual value of E/p_e assigned to each value of Q/P is subject to uncertainty because of the error in determining p_e, there is, nevertheless, a significant increase in values of Q/P as E/p_e is lowered.

The complex situation outlined above is, of course, not restricted to nitrogen, so that an approach to the problem of breakdown in terms of an equivalent increase in gas pressure is by no means simple. Furthermore, as far as the general problem of electrical breakdown in crossed fields is concerned the present investigation can only be regarded as of a preliminary nature. In particular, care must be taken to ensure that no restriction is placed on the $E\times B$ drift of electrons and detailed measurements

* $Q/P = \{(\omega/\alpha)\exp(-\alpha d_0)\}/(1+\omega/\alpha)$. d_0 is a measure of the distance that electrons released from the cathode must travel before acquiring the mean energy appropriate to the applied fields. For $\omega/\alpha \ll 1$, $Q/P \equiv \omega/\alpha$ as $d_0 \to 0$. (For further discussion see Haydon 1963.)

in a cylindrical system designed to reduce any lateral loss of electrons are necessary. Work is at present in progress to establish with greater accuracy the relation $\nu/p = f(E/p_e)$ and to extend the measurements for $B = 0$ to much lower values of E/p so that a more direct comparison can be made in the region of the photo-peak.

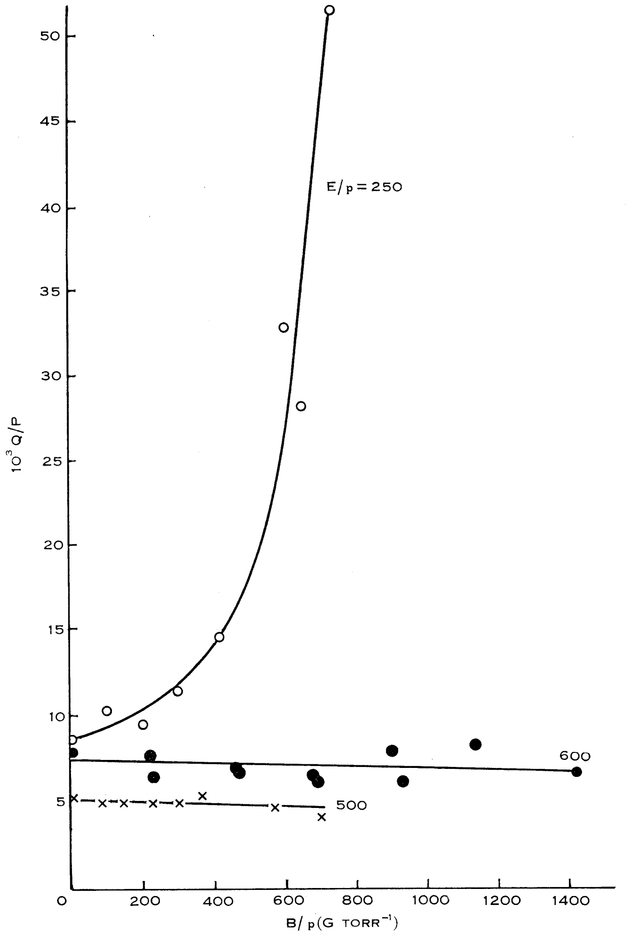

Fig. 5(a).—Variation of Q/P with B/p for various values of E/p in nitrogen.

VII. Conclusions

This investigation has shown that for nitrogen it is possible to apply the equivalent-pressure concept in which the influence of a transverse magnetic field may be regarded as equivalent to an increase in the gas pressure from p to p_e, where $p_e = p(1+\omega^2/\nu^2)^{\frac{1}{2}}$. Moreover, provided $150 < E/p_e < 250$, the formula for p_e may be applied with a constant value of $\nu = 8 \cdot 3 \times 10^9 p$.

Although this concept appears to some extent capable of accounting for the variations of the secondary ionization in the crossed-field experiments, this is only the case where a dominant photo-effect is present. In general a simple application of the concept to the problem of electrical breakdown is not possible because of the presence of both positive-ion and metastable interactions with the surfaces.

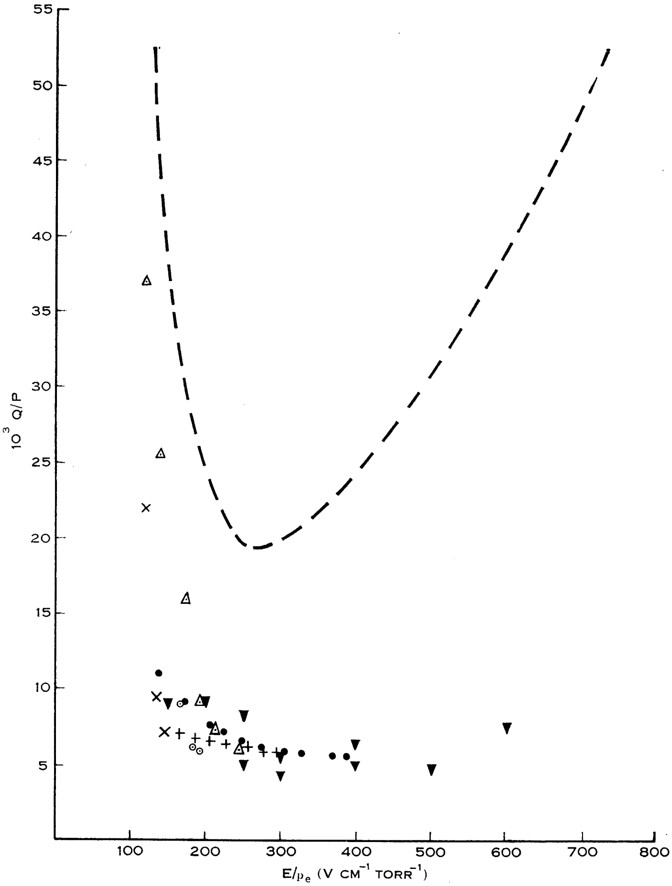

Fig. 5(*b*).—Q/P plotted as a function of E/p_e in nitrogen.
– – – Bowls's values of ω/α for platinum electrodes.
▼ $B/p = 0$, $p_e = p$.
× $E/p = 150$, $B/p > 0$
⊙ $E/p = 200$, $B/p > 0$
△ $E/p = 250$, $B/p > 0$
+ $E/p = 300$, $B/p > 0$
● $E/p = 400$, $B/p > 0$
copper electrodes; $p_e = p(1+\omega^2/\nu^2)^{\frac{1}{2}}$.

VIII. Acknowledgments

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