II. MICROWAVE GASEOUS DISCHARGES

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A. PLASMA OSCILLATIONS

An investigation of the propagation properties of electromagnetic waves along an electron beam in a plasma is continuing. The feedback mechanism is provided by the secondary electrons coming off the nickel reflector which are formed into a return beam by the fields in the sheath surrounding the electrode. As previously described (1), the voltages which control the sheath thickness over the gun or reflector electrode are varied so as to maintain a given mode of oscillation. The transit time of a beam particle from one sheath edge to the next on the primary beam and back again on the secondary beam is calculated for each setting of sheath voltages.

The sheath spacing can be obtained by combining the space-charge law for an infinite parallel plate with a relation derived by Schulz and Brown (2) for the directed ion current into the sheath as a function of the electron temperature and density. This yields for the drift space, S, between the two sheaths

$$S = L - 5/f\,(15,000/Te)^{1/4}\left[V_{SG}^{3/4} + V_{SR}^{3/4}\right]$$

where L is the separation of the two electrodes, f is the frequency of oscillation, Te is the electron temperature as determined by probe measurements, and V_{SG} and V_{SR} are the sheath voltages over the gun and reflector. The transit time is then given by

$$t = S\left(\tfrac{1}{2}\, m/e\right)^{1/2}\left[(V_{acc} + V_{SG})^{-1/2} + (V_{SR})^{-1/2}\right]$$

where V_{acc} is the voltage through which the beam is accelerated before it is injected into the sheath.

A typical set of results for an oscillation frequency of 665 Mc, L = 1.84 cm, V_{acc} = 320 volts, Te = 16,500°K yields

V_{SG} (volts)	V_{SR} (volts)	t(sec)
130	96	3.42×10^{-9}
162	91	3.33×10^{-9}
187	85	3.33×10^{-9}
203	80.5	3.33×10^{-9}
228	76	3.33×10^{-9}
264	69	3.30×10^{-9}
291	65	3.30×10^{-9}

$$\frac{1}{f} = 1.5 \times 10^{-9} \text{ sec}$$

For this case $t \simeq 2\ 1/4\ f$, which is the condition for reflex klystron operation, namely, $t = (\ell + 1/4)\ 1/f$, considering bunching theory only. Wehner (3) has explained similar results in this manner.

However, this check seems to be accidental, since many similar experiments have shown that t takes on values which can be changed continuously as parameters such as L or V_{acc} are changed by small amounts. More careful measurements taking into account the plasma potential with respect to the anode, from which V_{SG} and V_{SR} are measured, have shown that the small spread, 3 per cent in this case, can be reduced to approximately 1 per cent.

The standing waves observed by Looney and Brown (4), and reproduced by the writer, as well as variations in the oscillation amplitude as a function of the distance from the cathode, observed by Merrill and Webb (5) and by Emeleus (6), must be explained. In addition to the variation along the beam, there is a decay of amplitude in the transverse direction indicating that the oscillatory energy is confined to the beam region only.

The starting point is Maxwell's equations plus the Lorentz force equation. First-order theory is assumed and $v_o^2/c^2 \ll 1$ is considered negligible. Inasmuch as the derivation is very lengthy it will be omitted. The result for beams of radius a moving in the $\pm$z-direction, with propagation constant α and frequency ω is

$$\left(1 - \frac{\omega_p^2}{\omega^2} - \frac{\omega_{o1}^2}{(\omega - \alpha v_{o1})^2} - \frac{\omega_{o2}^2}{(\omega + \alpha v_{o2})^2} - \frac{\omega_{o2}^2}{(\omega - \alpha v_{o2})^2}\right)\left(k_e^2 - \alpha^2\right)^{1/2} \cdot$$
$$\times J_1 \frac{\left(\left(k_e^2 - \alpha^2\right)^{1/2} a\right)}{J_o\left(\left(k_e^2 - \alpha^2\right)^{1/2} a\right)} = j\alpha \frac{H_1^1\,(j\alpha a)}{H_o^1\,(j\alpha a)} \tag{1}$$

where J and H^1 are Bessel and Hankel functions. There are four distinct groups of electrons, 1. plasma electrons with zero velocity and density parameter $\omega_p^2 = n_p e^2/\epsilon_o m$, 2. primary beam electrons with average velocity v_{o1} and density ω_{o1}^2, 3. secondary electrons with velocity v_{o2} in the -z-direction and density parameter ω_{o2}^2, and 4. secondaries reflected from the first sheath, moving in the +z-direction with parameters identical to the original secondaries. The density of the last two groups is at least larger than the density of the primary beam by a factor of the velocity ratio. It is possibly larger than that because the primary beam is continually contributing electrons which keep moving back and forth between the two sheaths until they collide. k_e^2 is a complicated function of all the parameters and is usually of order $k^2 = \omega^2/c^2 \ll \alpha^2$. However, there is an infinite set of solutions to Eq. 1 for which k_e^2 is of order α^2.

All of these solutions have the same dispersion relation, namely,

$$\left(1 - \frac{\omega_p^2}{\omega^2} - \frac{\omega_{o1}^2}{(\omega - av_{o1})^2} - \frac{\omega_{o2}^2}{(\omega + av_{o2})^2} - \frac{\omega_{o2}^2}{(\omega - av_{o2})^2}\right) = 0 \qquad (2)$$

The common property of all these solutions is that practically all the energy is confined within the beam, i.e., $J_o\left(\left(k_e^2 - a^2\right)^{1/2} a\right) \simeq 0$. Since the probe is usually a few millimeters away from the beam, these solutions are of interest in satisfying end boundary conditions, but do not contribute to the standing wave pattern.

It is of interest to note that this solution can be generalized to read

$$\sum_j \frac{\omega_{pj}^2}{\left(\omega - \vec{a} \cdot \vec{v}_{oj}\right)^2} = 1$$

independent of the beam radius. This is identical to the dispersion relation obtained in a very different manner by Bohm and Gross (7) for plasma waves in an infinite plasma.

It is an experimental fact that the frequency of oscillation is always close to the plasma frequency, ω_p corresponding to the density at the sheath edge. This is probably caused by the fact that the modulation of the beam takes place at the sheath edge in a region where the electrons of the plasma execute their largest motions. The density within the plasma is slightly larger than that at the edge. At any rate, the term $1 - \omega_p^2/\omega^2$ is negligible compared to 1 whereas the other terms in Eq. 1 can be shown to be larger than 1.

From Eq. 1, using this fact, we obtain the following dispersion relation

$$\frac{\omega_{o+}^2}{(\omega - av_{o1})^2} + \omega_{o-}^2\left(\frac{1}{(\omega + av_{o2})^2} + \frac{1}{(\omega - av_{o2})^2}\right) = 0 \qquad (3)$$

This is a quartic equation for av_o/ω and results in four roots, at least two of which must be complex conjugates in order to provide the growth in amplitude necessary to have sufficient feedback to maintain oscillations.

Preliminary results indicate that the phase velocities obtained in this way can explain the deviations in transit time from the required multiples of the period.

E. Gordon

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B. HIGH-DENSITY MICROWAVE GASEOUS DISCHARGE

Study of the high-density plasma by means of microwaves is being continued. An experiment is in progress in which the high-density plasma will be confined between two coaxial cylinders serving as a coaxial line for the probing microwave signal. For a successful experiment the plasma ought to be uniform in density in the radial direction. This is difficult to accomplish. There is some experimental evidence to show that a plasma produced in a very low frequency discharge between two coaxial cylinders may fulfill this requirement. More work is being done in this direction.

The origin of the bright sheaths formed between two parallel plates in a 3-Mc/sec discharge may be dc in nature. The bright sheaths are the cathode glow regions of a dc discharge, each plate acting as a cathode during its negative half-cycle.

S. J. Buchsbaum

C. MICROWAVE DETERMINATION OF THE PROBABILITY OF COLLISION OF SLOW ELECTRONS IN NEON

More measurements of the conductivity ratio ρ as a function of the electron temperature were performed in neon contaminated with argon (1). It was possible in this way to show a slight difference at the lower temperatures from the measurements in pure neon. Both cases are represented in Fig. II-1. The curves are plotted against the electron temperature T_{uc} which would be at the center of the cavity in the case of an infinite plasma in a uniform field. The theory shows that the difference is of the amount one would expect considering that the decay in pure neon is controlled by recombination (flat density distribution), and in neon contaminated with argon by ambipolar diffusion (cosinusoidal density distribution). At higher temperatures the two curves join, ambipolar diffusion becoming predominant, also, in pure neon. It was possible to perform measurements at high temperatures by using a pulsed heating field and to overcome the difficulty mentioned in the last report. The temperatures have been corrected by an experimentally determined factor to reduce the error in the measurement of the power incident on the cavity, which is the result of the finite directivity of the directional coupler.

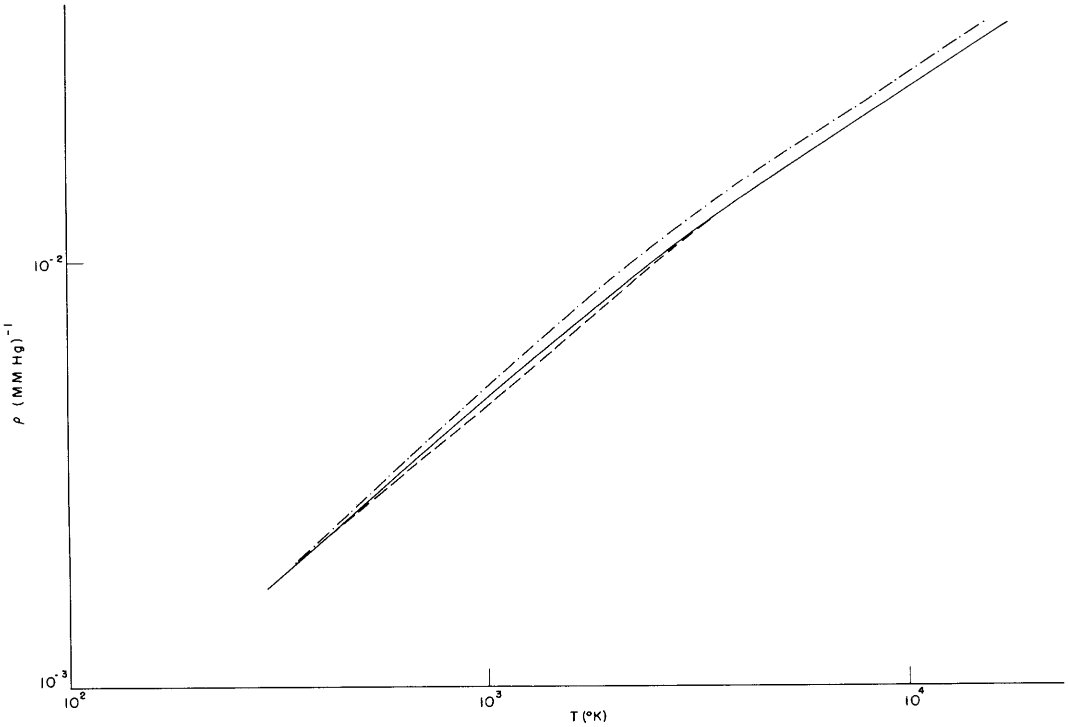

Fig. II-1. Conductivity ratio ρ as a function of electron temperature. Solid line: ρ versus T_{uc} for neon contaminated with argon. Short broken line: ρ versus T_{uc} for pure neon. Long dot and dash line: ρ versus T_o.

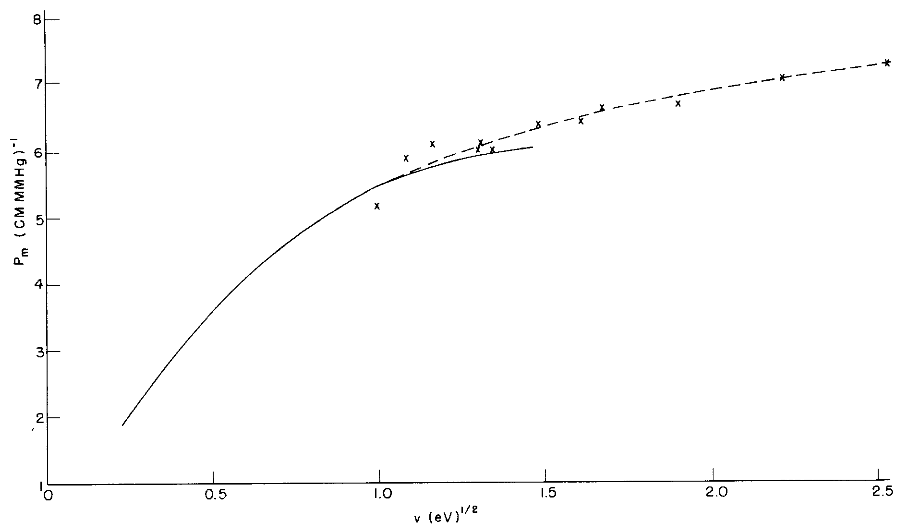

Fig. II-2. Electron collision probability versus velocity in neon

A theory was worked out to determine the collision probability from the measured curves; it will be discussed in a forthcoming paper. The theory shows that under our experimental conditions diffusion strongly reduces temperature nonuniformities and the measured ρ can be plotted as a function of a properly defined average temperature T_o. This temperature has the meaning of the temperature at which in an infinite plasma and uniform field we would measure that value of ρ. A small correction must be taken into account for the fact that in our case the distribution is not exactly Maxwellian. The curve of ρ versus T_o computed from that of ρ versus T_{uc} in neon contaminated with argon is shown also in Fig. II-1. The curve ends at $T_o = 15,500°K$, which theoretical analysis shows is the maximum temperature at which the effects of inelastic losses are not yet appreciable.

From this curve the collision probability for momentum transfer P_m versus the electron velocity in $(eV)^{1/2}$ was computed; it is shown as a solid line in Fig. II-2. The crosses represent measurements performed by Ramsauer and Kollath using a beam method (2) and reduced to P_m values by Barbiere (3); the broken line gives an average of their data. It is seen that there is good agreement between the microwave and the dc methods.

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D. TRANSITION FROM FREE TO AMBIPOLAR DIFFUSION

The transition from free to ambipolar diffusion has been investigated theoretically by Allis and Rose (1). They define an effective diffusion coefficient D_s, which in the case of a decaying plasma is given by the product of the decay rate γ and the square of the diffusion length Λ of the container. The ratio D_s/D_a, D_a being the ambipolar diffusion coefficient, is a function of the parameter $n\Lambda^2/T_e$, n being a characteristic electron density in the plasma (e.g., the density at the center), T_e the electron temperature. The general shape of the curve is shown in Fig. II-3. The actual theoretical values are slightly dependent on having an active or an isothermal plasma and on the shape of the container. The limit on the left is for free diffusion; the one on the right is for ambipolar diffusion.

In the measurements of afterglow decays we are almost always in the region of the last limit; but if we study the decay at electron temperatures higher than room temperature, in a container with a very small Λ, and at the smallest measurable electron

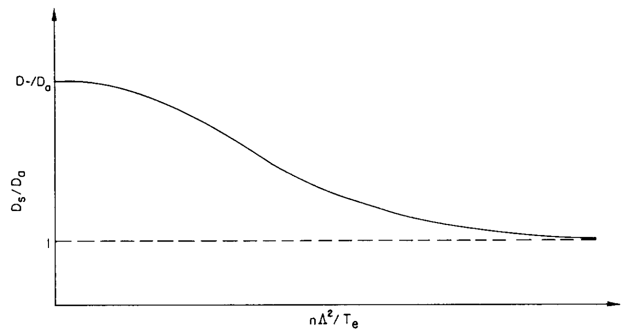

Fig. II-3. Effective diffusion coefficient versus $n\Lambda^2/T_e$

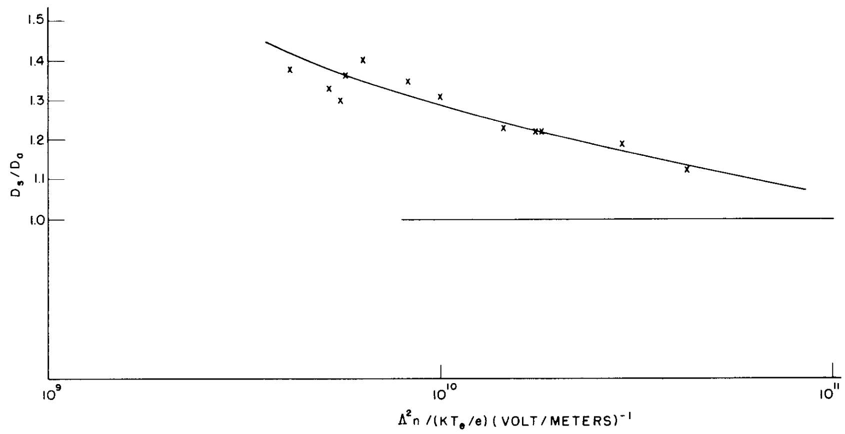

Fig. II-4. Diffusion coefficient versus $n\Lambda^2/T_e$ in neon contaminated with argon

densities, we can investigate the region in which the transition takes place. However, it can be shown that if we want to remain within the limits in which diffusion theory is correct and to satisfy the condition $\nu_c^2 \ll \omega^2$, so that the electron density is proportional to the frequency shift, there is a minimum value for the quantity Λ^2/T_e that we cannot pass.

With the same apparatus used for the determination of the collision probability of slow electrons some measurements have been performed in neon contaminated with argon. The results are shown in Fig. II-4. The container was a cubic quartz bottle with $\Lambda = 0.52$ cm; the electron density is an average value over the quartz bottle. The maximum temperature that can be reached is 15,500°K. In spite of the scattering of the results at the lowest electron densities, because of experimental conditions which were not the best for these types of measurements, it was clear that the parameter $n\Lambda^2/T_e$ was the proper one and that the effect is present at the expected order of magnitude. The ambipolar limit value is a measured one, and corresponds to a dc mobility of 7.6 cm^2 V^{-1} s^{-1}, in good agreement with the value for argon ions in neon to be expected from the curve of mobility in neon versus ion masses (2).

New measurements will be performed in an isothermal plasma at room temperature between parallel planes with a very small Λ, so that the quantity Λ^2/T_e is very near the minimum value previously discussed. We hope in this way to extend measurements to values of $n\Lambda^2/T_e$ about one order of magnitude less than those in Fig. II-4 and to avoid some of the causes of errors found in those measurements. To reduce Λ without decreasing the Q of the cavity, a cylindrical cavity has been designed with a height of 2.25 mm, partially filled with quartz so that the diffusion takes place between two planes only 0.25 mm apart.

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References

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E. MICROWAVE BREAKDOWN OF AMMONIA

The experimental investigation of the microwave breakdown of ammonia had two objectives: to find the microwave breakdown field as a function of the pressure of pure ammonia in a clean system and to learn how this breakdown field is affected by various contaminants such as water, air, and nitrogen. The criterion for microwave breakdown, given in many previous reports, is that the production of electrons by ionization in the gas should equal or just exceed the loss of electrons by the various mechanisms of diffusion, attachment, and recombination. The interesting facts about ammonia are that it has a very high electron attachment coefficient and a low ionization potential. These facts suggest that the breakdown of ammonia will be strongly influenced by the electron loss by attachment, especially at high pressures where this mechanism becomes more pronounced, and that the effect of the contaminants on the breakdown field will be small, since the ammonia molecule is more easily ionized and yet so effective in attaching electrons.

The experimental procedures for this investigation were similar to those used in the study of breakdown of other gases, with a slight modification in vacuum technique necessitated by the use of ammonia. A liquid air trap was installed between the forepump and the diffusion pump to serve as a reservoir of ammonia for the course of these experiments. Ammonia was introduced into the vacuum system from an external container of pure ammonia and promptly trapped in the reservoir. The usual cold trap in

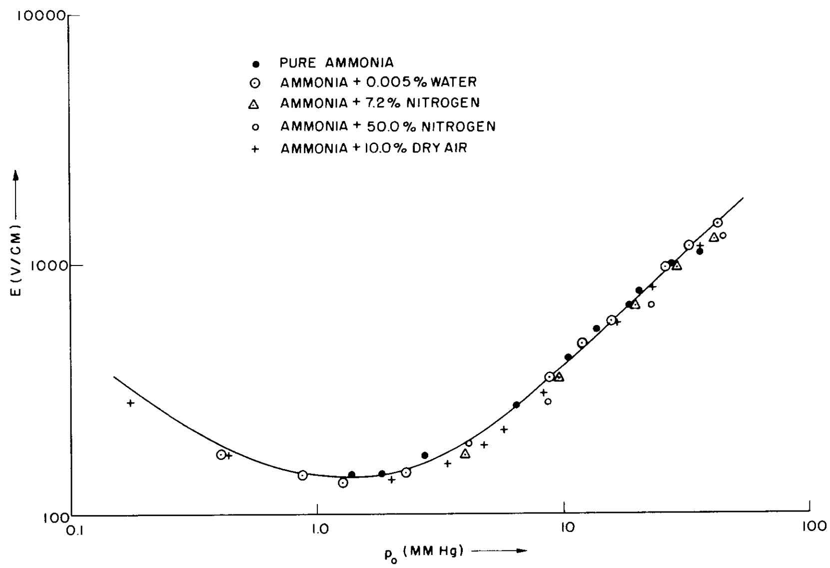

Fig. II-5. Breakdown electric field as a function of pressure for pure and contaminated ammonia

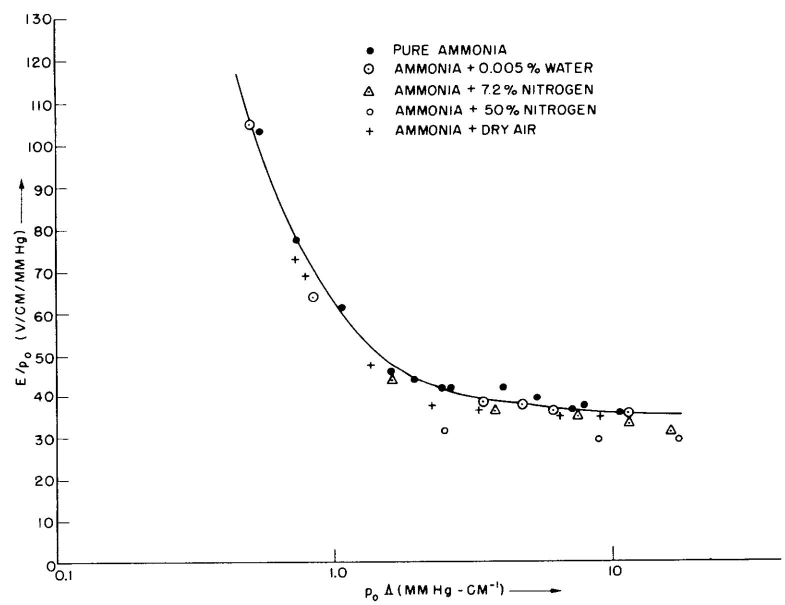

Fig. II-6. E/p_o as a function of $p_o\,\Lambda$ for pure and contaminated ammonia. Attachment is the controlling electron loss mechanism in the region where E/p_o becomes independent of $p_o\,\Lambda$.

the vacuum system required the use of an alcohol-dry ice mixture as a refrigerant to permit the use of ammonia up to pressures of 40 mm Hg. The microwave cavity used was an OFHC copper cavity, 0.5 inch high and resonant at 10.6 cm in the TM_{010}-mode. The vacuum system was subjected to the usual procedures of pumping, baking, outgassing, and so on, required to attain a vacuum better than 10^{-8} mm Hg. Samples of pure ammonia were introduced into the cavity by removing the liquid air bottle from the ammonia reservoir until sufficient gas had accumulated; the metal valve between the cavity and the remainder of the system was then closed and the liquid air bottle replaced.

In the second part of the experiment, in which contaminants were used, no effort was made to obtain a vacuum better than could be obtained with a forepump alone. The contaminants and ammonia were mixed in the desired concentrations external to the vacuum system and introduced into the system through stopcocks. The first contaminant was a slight trace of water amounting to 50 parts per million, such as is present in commercial grade ammonia. The second contaminant was dry nitrogen, first, in a 7.2 per cent concentration and later in a 50 per cent concentration. The third contaminant was a 10 per cent concentration of air, dried by passing it through a tube of Drierite.

The results of this experiment are shown in Figs. II-5 and II-6. Figure II-5 is a plot of the breakdown electric field, E, in volts/cm versus p_o, the pressure of the sample normalized to 0°C. From this figure, it can be seen that, in general, the effect of contaminants is only to lower slightly the breakdown field for pure ammonia and that an extremely large concentration of N_2 was required to lower it by a significant amount. Figure II-6 is a plot of E/p_o versus $p_o \Lambda$, where E/p_o is related to the energy per mean free path, Λ is the characteristic diffusion length, and $p_o \Lambda$ is a variable related to the number of collisions for electron escape. This figure indicates that at pressures greater than 5 mm Hg the breakdown becomes predominantly controlled by electron attachment.

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