II. MICROWAVE GASEOUS DISCHARGES

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A. COLLISION CROSS SECTION FOR SLOW ELECTRON IN HELIUM

Measurements of $(1/p_o)(\sigma_r/\sigma_i)$, the ratio of the real to the imaginary part of the electron conductivity, have been performed as a function of the average electron energy in the afterglow of a pulsed helium discharge. The average electron energy was varied over a range of 0.01 ev to 0.09 ev by varying the gas temperature from 95° K to 700°K. A variation of 0.04 ev to 2.5 ev was obtained by applying a microwave electric field in the afterglow. From these measurements the velocity dependence for P_m, the collision cross section for momentum transfer, was determined. A null method was used for measuring $(1/p_o)(\sigma_r/\sigma_i)$. The technique of this method is described in a paper by Gould and Brown (1).

The temperature measurements were taken in a copper vacuum cavity which was a rectangular parallelepiped in shape and was designed to be resonant in its three fundamental modes at wavelengths of 10.6 cm, 10.0 cm, and 9.6 cm. The 10.6-cm mode was used for measuring the electron conductivity, and the 9.6-cm mode was used for producing the pulsed discharge. Measurements of $(1/p_o)(\sigma_r/\sigma_i)$ were obtained at 77°K (liquid air), 195°K (dry ice), and temperatures up to 700°K. It is assumed that in the afterglow the electron distribution function is Maxwellian with a temperature that is the same as that of the gas. The results are shown in Fig. II-1. The solid line is the theoretical curve for the case where P_m is constant and equal to 18.3. The experimental points agree with this curve up to 400°K. Above 400°K, higher values of $(1/p_o)(\sigma_r/\sigma_i)$ were measured. In this region the values of $(1/p_o)(\sigma_r/\sigma_i)$ could be decreased by outgassing the cavity at higher temperatures for a long period of time. The following mechanism may explain this phenomenon. Photoionization of impurities by imprisoned resonance radiation of helium can produce high-energy electrons which would increase the average electron energy. At high temperatures an appreciable number of impurities are evolved from the walls of the cavity, and thereby give rise to the higher values of $(1/p_o)(\sigma_r/\sigma_i)$. It has also been found that $(1/p_o)(\sigma_r/\sigma_i)$ decreases with time in the afterglow. This is to be expected since the intensity of the imprisoned radiation is decreasing with time in the afterglow.

The measurements with the heating electric field were performed in a cubic quartz bottle enclosed in a microwave cavity. The center of this bottle coincides with the center of the microwave cavity. The modes are the same as those used for the copper vacuum cavity; in this case, the 10.0 mode is utilized for increasing the electron energy. Measurements of this type, performed in the copper cavity, were discussed in the Quarterly Progress Report of July 15, 1953. The nonuniformity in the spatial distribution of the

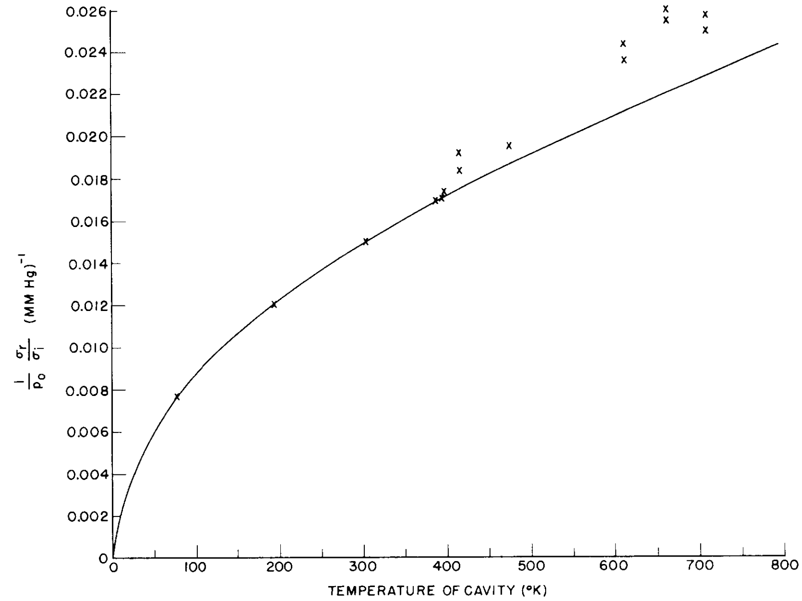

Fig. II-1

The ratio of the real to the imaginary part of the electron conductivity as a function of the gas temperature.

heating electric field makes it difficult to interpret the measurements of $(1/p_o)(\sigma_r/\sigma_i)$ because of the deviation in the electron density distribution from the cosine distribution and because of the influence of energy gradients on the average electron energy. With the quartz bottle, the nonuniformity of the heating field over the region of the bottle is small and the aforementioned effects are negligible.

$(1/p_o)(\sigma_r/\sigma_i)$ is related to P_m by the following expression (2)

$$(1/p_o)(\sigma_r/\sigma_i) = \frac{\int_V n\left[\int_0^\infty (P_m/\omega)\, v^4 (df/dv)\, dv\right] E_m^2\, dV}{\int_V n\left[\int_0^\infty v^3\, (df/dv)\, dv\right] E_m^2\, dV} \tag{1}$$

where n is the electron density, E_m is the measuring electric field, f is the electron distribution function, and V is the volume of the quartz bottle. When the heating field is applied, the distribution function is assumed to be Maxwellian with a temperature given by the relation

$$T_e = T_g + \frac{M}{6\omega^2 k}\left(\frac{e}{m}\right)^2 E_h^2$$

where T_g is the gas temperature and E_h is the heating field. The spatial distributions

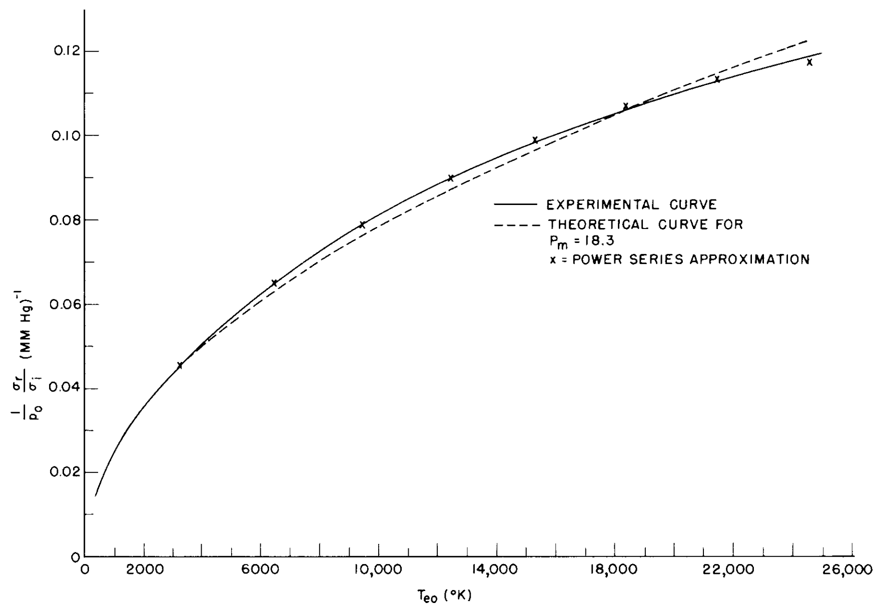

Fig. II-2

The ratio of the real to the imaginary part of the electron conductivity as a function of the electron temperature.

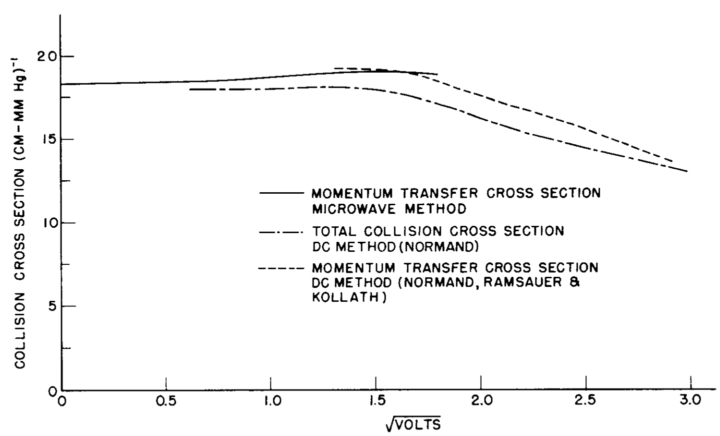

Fig. II-3

Comparison of various determinations of collision cross section as a function of electron energy.

for n, E_m, and E_h are

$$n = n_o \cos \frac{\pi x}{2.82} \cos \frac{\pi y}{2.82} \cos \frac{\pi z}{2.82}$$

$$E_h = E_{h_o} \cos \frac{\pi x}{7.55} \cos \frac{\pi y}{6.30}$$

$$E_m = E_{m_o} \cos \frac{\pi x}{7.55} \cos \frac{\pi z}{6.87}$$

A power series in v is assumed for P_m and the corresponding expression for $(1/p_o)(\sigma_r/\sigma_i)$ as a function of T_{eo}, the electron temperature at the center of the bottle, is obtained by using Eq. 1. The experimental curve for $(1/p_o)(\sigma_r/\sigma_i)$ as a function of T_{eo} is shown in Fig. II-2. A four-term power series in v is used for P_m. The coefficients are determined by comparing the theoretical expression for $(1/p_o)(\sigma_r/\sigma_i)$ with the experimental curve. The crosses in Fig. II-2 represent the power series approximation for $(1/p_o)(\sigma_r/\sigma_i)$. The following expression is obtained for P_m.

$$P_m = 18.3 - 7.38 \times 10^{-7} v + 3.96 \times 10^{-12} v^2 - 2.40 \times 10^{-18} v^3$$

This expression is valid up to an energy of 3.3 ev or a velocity of 1.1×10^6 cm/sec. Figure II-3 shows a comparison between the results obtained for P_m using the present method and the dc measurements for total collision cross section of Normand (3). Normand's data have been corrected for momentum transfer by using the angular distribution data obtained by Ramsauer and Kollath (4).

References

1. L. Gould, S. C. Brown: J. Appl. Phys. 24, 1053, 1953
2. A. V. Phelps, O. T. Fundingsland, S. C. Brown: Phys. Rev. 84, 559, 1951
3. C. S. Normand: Phys. Rev. 35, 1217, 1930
4. C. Ramsauer, R. Kollath: Ann. Physik 12, 537, 1932

B. HIGH-DENSITY MICROWAVE GASEOUS DISCHARGES

Since one of the most important phenomena encountered in high-density, high-frequency discharges is plasma resonance, the definition and significance of this phenomenon has been reinvestigated. There appear to be two principal definitions of plasma resonance. The first can conveniently be termed "impedance resonance," which is so defined that the E-field at a point has a relative maximum. The second can be termed "phase resonance" and is so defined that the dielectric constant is zero at the point considered.

The magnitude of the impedance at a point in a microwave discharge is

$$|E/J| = \frac{\left(\nu_c^2 + \omega^2\right)^{1/2}}{\omega\epsilon_o\left[(r-1)^2\omega^2 + \nu_c^2\right]^{1/2}}$$

where $r = (ne^2)/(m\omega^2\epsilon_o)$. This equation obviously has a maximum value when $r = 1$, which is the condition for impedance resonance. The value of the impedance is

$$|E/J| = \frac{1}{\epsilon_o}\left(\frac{1}{\nu_c^2} + \frac{1}{\omega^2}\right)^{1/2}$$

Thus, the lower the pressure and the longer the wavelength, the larger is the impedance at resonance.

Phase resonance occurs when the dielectric constant k_r is zero. Now

$$k_r = \sigma_i + \omega\epsilon_o = \frac{-ne^2\omega}{m\left(\nu_c^2 + \omega^2\right)} + \omega\epsilon_o$$

Hence the condition for phase resonance is

$$\frac{ne^2}{m\epsilon_o\left(\nu_c^2 + \omega^2\right)} = 1$$

The quantity on the left-hand side will be denoted by r_p and we have

$$|E/J| = \frac{1}{\epsilon_o\left[r_p^2\nu_c^2 + (1 - r_p)^2\omega^2\right]^{1/2}} = \frac{1}{\epsilon_o\nu_c}$$

at phase resonance. In this case the impedance is independent of wavelength but varies inversely as the pressure. At low pressure, when $\nu_c^2 \ll \omega^2$, the two types of resonance coincide; at high pressures, these resonances differ.

In Fig. II-4 are plotted the boundaries for impedance and phase resonance at the center of the cavity as functions of $p\lambda$ and $n_o\lambda^2$, where n_o is the density at the center of the cavity. A typical curve is also plotted for impedance resonance near the wall. A distance $\pi\Lambda/10$ from the wall was chosen, and the exponent a in the expression for ν_i was taken to be 2.

Impedance resonance (and maximum E-field), as might be expected, is related to the visual effects observed at plasma resonance. Phase resonance is principally important due to the fact that above it the transmitted electromagnetic waves are strongly attenuated and there is a reflected wave. The attenuation depends on the free-space wavelength and r_p. For example, with 10-cm waves and $r_p = 10$, the amplitude is reduced to $1/e$ in a distance of 5 mm. With $r_p = 2$, the distance is 1.5 cm. At low pressures

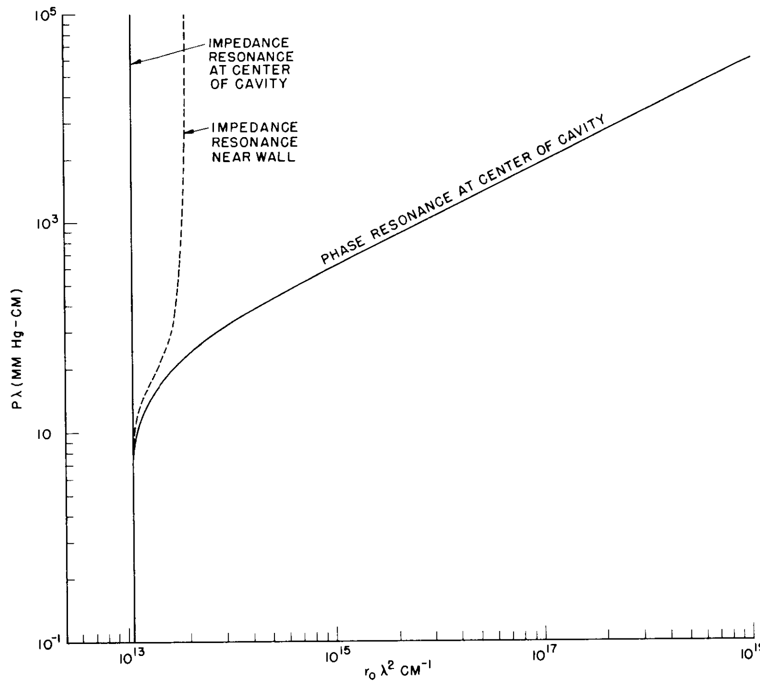

Fig. II-4

Plasma resonance boundaries in hydrogen. Phase resonance at the center of the cavity, $r_o = 1 + (\nu_c/\omega)^2$. Impedance resonance at the center of the cavity, $r_o = 1$. Impedance resonance near the walls (typical curve), $r_w = 1$. Point taken $(\pi\Lambda)/10$ from wall, $\alpha = 2$.

where $r_p = r$, attenuation is large at densities only a little above those for plasma resonance.

C. PROBE STUDIES

The investigation of a steady-state microwave gas discharge with movable probes in hydrogen was continued. A sketch of the rectangular cavity made of oxygen-free copper with the probe assembly (5-mil tungsten wires, 4 mm long) is shown in Fig. II-5. In the Quarterly Progress Report, July 15, 1953, it was reported that no electron saturation was observed when the single probe was operated at potentials positive with respect to the plasma potential. This occurs because the diffusive flow of electrons at pressures of approximately 1 mm Hg is too small to replenish the electrons taken by the probe. At pressures below 0.1 mm Hg the single probe curves tend to saturate.

The single probe behaves well when operated negatively with respect to plasma potential. In fact, the negative saturation part of the single-probe curve is identical

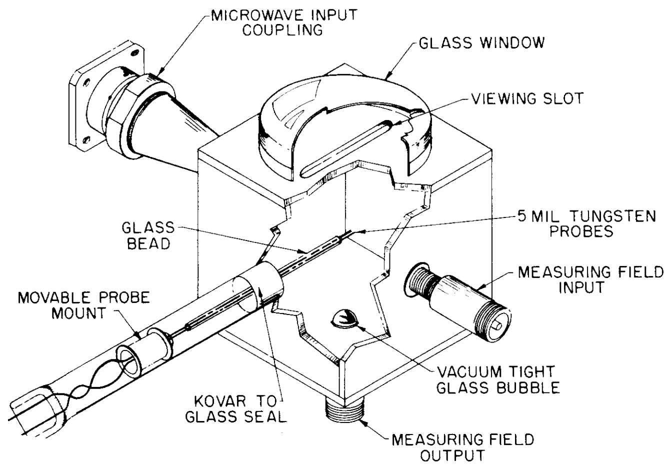

Fig. II-5

Microwave cavity with probe assembly.

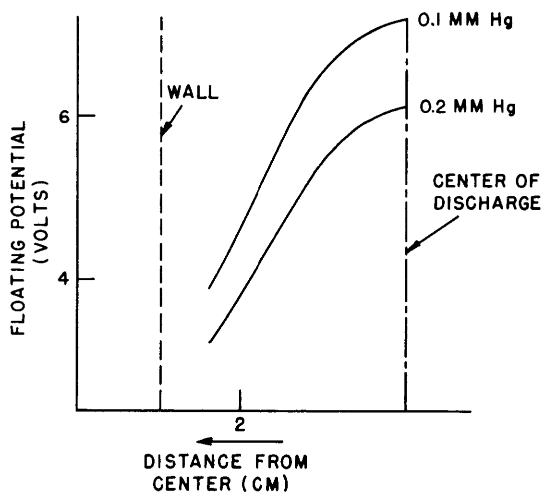

Fig. II-6

Floating potential as a function of position.

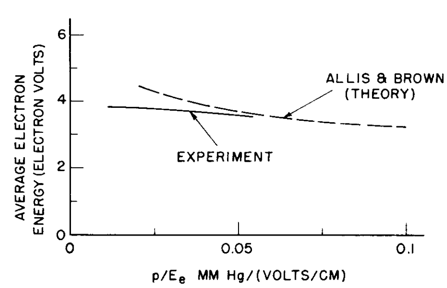

Fig. II-7

Average electron energy as a function of p/E_e.

with the corresponding portion of the double-probe curve, except that it is displaced on the voltage scale. This displacement is due to different reference points for measuring voltage. With the single probe, the wall is used as a reference; with the double probes, the voltage is applied between the two probes.

The single probe was used to determine potential variations in the ambipolar region of a microwave discharge. By measuring the floating potential of the probe with respect to the wall, the curves shown in Fig. II-6 were obtained. These potential variations cannot be measured near the wall because the potential gradient in the wall sheath is too large. The floating potential depends on the electron temperature. However, the temperature variation at low pressures is small, and Fig. II-6 need not be corrected.

The average electron energy at the center of the cavity was measured as a function of p/E_e, the ratio of the gas pressure to the effective microwave electric field. The electron temperature, T_e, was obtained from probe curves; E_e was determined by measuring the Q of the cavity with the discharge and the microwave power absorbed in the cavity. Figure II-7 shows a comparison between measured and theoretical values of average electron energy. (See W. P. Allis, S. C. Brown: Phys. Rev. 87, 419, 1952.)