II. MICROWAVE GASEOUS DISCHARGES

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A. ELECTRON DENSITY MEASUREMENTS IN D-C DISCHARGES

The microwave signal can be used as a "probe" to determine the electron concentration in an operating discharge. The presence of free electrons in a microwave resonant cavity will result in a shift of the resonant frequency of the cavity, and if the collision frequency of the electrons is sufficiently large, in a change of the real conductance of the cavity. Either of these two effects may be utilized to determine the electron density existing in the cavity, but the latter is applicable only if the pressure of the filling gas is high. In either case the measurements must be performed upon the signal reflected from the cavity containing the discharge and thus the discharge must be sufficiently stable to permit a study of the reflected signal or a method of measurement must be used which is not disturbed by the instability.

A cylindrical cavity 3 inches in diameter and 1.5 inches in height was clamped around a cylindrical d-c discharge tube 5/8 inch in diameter, with the axis of the cylinder parallel to the axis of the discharge tube. The plasma filled the entire section of the tube covered by the cavity. The cavity was excited in the TM_{010}-mode by means of a 10-cm signal generator. The strength of this signal is small and has no detectable effect on the d-c discharge.

The most accurate method of measurement consists of determining the Q curve of the cavity with and without the discharge operating and then determining the resonant frequency shift from the two curves. A standing wave probe was placed in the coaxial line coupling the signal generator to the cavity, and the Q curve measured by determining the ratio of the standing wave maximum to the standing wave minimum as a function of wavelength. The electron concentration must be sufficiently constant to permit the location and measurement of the signal at the standing wave minimum.

A discharge tube formed with nickel electrodes and filled with hydrogen gas was operated as a glow discharge at pressures from 5.0 to 0.50 mm Hg and passing currents from 1.0 to 20.0 ma. In all measurements the reflected signal was very stable and permitted accurate density determinations to be made. Similarly the reflected signal from a tungsten filament arc discharge was stable and accurate measurements could be made. Two arc discharge tubes were used, one filled with hydrogen and the other with helium. These discharges ran at pressures down to 0.05 mm Hg.

Finally a mercury arc with a tungsten filament was studied by this method. In this case the standing wave minimum position was smeared out over a region of the coaxial line and no measurements were possible. The electron density and tube voltage were

oscillating with an approximately sinusoidal wave of a frequency in the range of 100 kc.
Two tubes of entirely different geometry were used and oscillations were present in
both. By sweeping the frequency of the incident signal and observing the response of
the reflected signal, rectified by a crystal, on an oscilloscope, the average resonant
frequency and hence the average electron density could be determined. There is no
apparent continuous correlation between electron density and frequency of oscillation
but there appear to be two modes of oscillation in the arc current range of 0 to 100 ma.
The frequency of these two modes varies as the current through the tube is changed.
An inductance comparable in impedance to the load resistor of the arc had little effect
on the frequency of the oscillation. The frequency of the oscillation increases as the
tube voltage is increased for a fixed value of filament heating current. The oscillations
are strong and stable when the mercury pressure is below 10^{-2} mm Hg but some insta-
bilities are present at higher pressures.

B.   ELECTRON COLLISION CROSS SECTIONS

The theoretical calculations of the normalized conductivity ratio, $(1/\gamma)(\sigma_r/\sigma_i)$, have
been extended to include a wider range of possible approximations to the collision proba-
bility curve. Calculations for the approximation $P_c = av^h$ have been extended to $h = +1$
by evaluating the conductivity integrals in terms of Lommel functions (Table of Laplace
Transforms, Admiralty Computing Service) and to $h = -2$ and -3 by evaluating the
integrals in terms of those for $h = 0$ and $+1$, respectively. Figure II-1 shows $(1/\gamma)(\sigma_r/\sigma_i)$
as a function of γ and h where

$$\gamma = \frac{ap_o}{\omega} \left(\frac{2kT}{m}\right)^{\frac{h+1}{2}} \quad .$$

If we require that $(\nu_c/\omega)^2 \ll 1$ for electron velocities in the thermal range, then

$$\frac{\sigma_r(\bar{u})}{\sigma_i} = \frac{4}{3\sqrt{\pi}} \frac{1}{(\bar{u})^{5/2}} \int_0^\infty \frac{\nu_c(u)}{\omega} u^{3/2} e^{-u/\bar{u}} du$$

where $\bar{u} = kT/e$ is the most probable energy of electrons in electron volts, u is the
electron energy, $\nu_c(u)/\omega = p_o P_c \sqrt{2eu/m}$ is the number of collisions per cycle. Although
this formulation of the problem suggests that the inverse Laplace transform can be used
to determine $P_c(u)$ from $\sigma_r(\bar{u})/\sigma_i$, the only solution obtained as yet is a polynomial
approximation whose coefficients can be evaluated most easily by direct integration.
The number of terms which can be used is equal to the number of measurements of
$\sigma_r(\bar{u})/\sigma_i$.

As an example of the application of these approximations consider the preliminary
data obtained with nitrogen. Figure II-2 shows the measured values of $(1/p_o)(\sigma_r/\sigma_i)$

NUMBER OF COLLISIONS PER CYCLE (γ)

100 10 1 0.1 0.01

COLLISION PROBABILITY PARAMETER (h)

NORMALIZED CONDUCTIVITY RATIO $\left(\frac{1}{\gamma}\frac{\sigma_r}{\sigma_i}\right)$

3.0
2.5
2.0
1.5
1.0
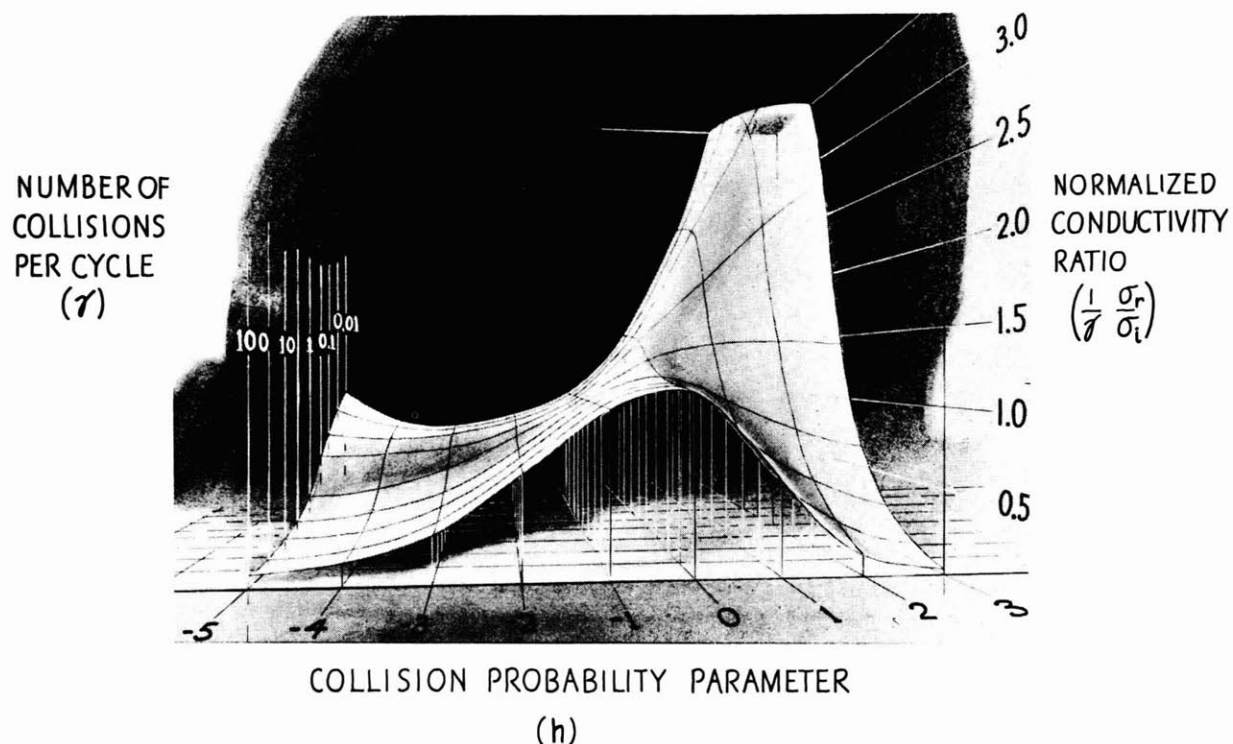0.5

-5   -4   -1   0   1   2   3

Fig. II-1

Normalized conductivity ratio surface as determined from conductivity integrals using the approximation $P_c = av^h$.

as a function of the square of the electric field at the center of the resonant cavity at three different gas temperatures. The values of $(1/p_0)(\sigma_r/\sigma_i)$ obtained by extrapolating these measurements to zero field are assumed to represent electrons in thermal equilibrium with the gas. Figure II-3(a) shows the zero field values of $(1/p_0)(\sigma_r/\sigma_i)$ as a function of their most probable energy, $\bar{u}$; the calculated curves of P_{co} vs. $\sqrt{u}$ are shown in Fig. II-3(b). The solid curve was obtained by using the $P_{co} = av^h$ ($h = +1$) approximation; the dotted curve was obtained by using a polynomial of the form, $P_{co} = a + bu + cu^2$. In this case the only advantage of the polynomial approximation is that it allows one to make the intercept at $u = 0$ finite and of zero slope as expected from theory.

Experiments are still being conducted to determine the optimum conditions for making conductivity measurements. Preliminary data obtained for Kr and Xe show that the probability of collisions rises rapidly as the electron energy decreases to thermal values. Rough values for P_c at about 1/40 ev are 55 (cm-mm Hg)$^{-1}$ for Kr, and 180 (cm-mm Hg)$^{-1}$ for Xe.
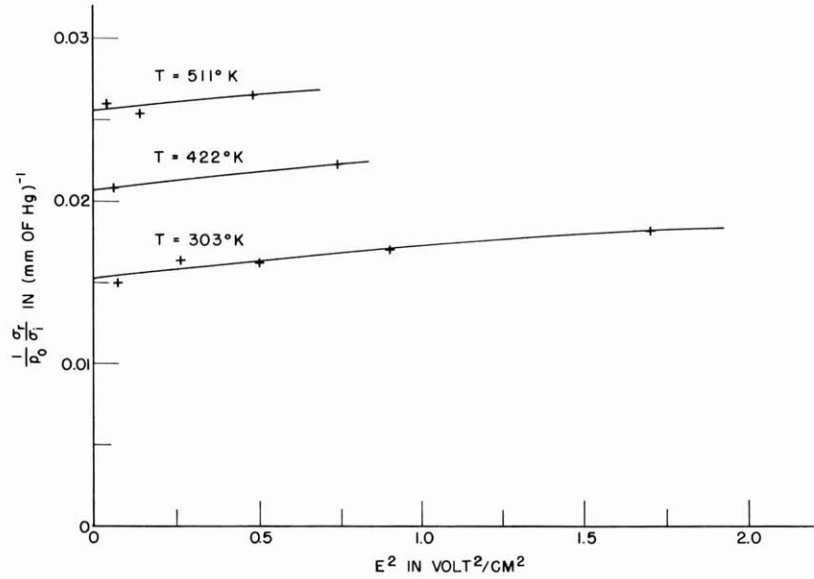
Fig. II-2 Determination of thermal values of $(1/p_o)(\sigma_r/\sigma_i)$ from measured values.
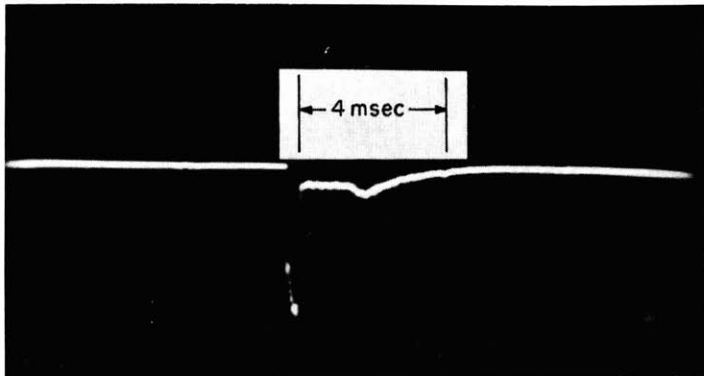

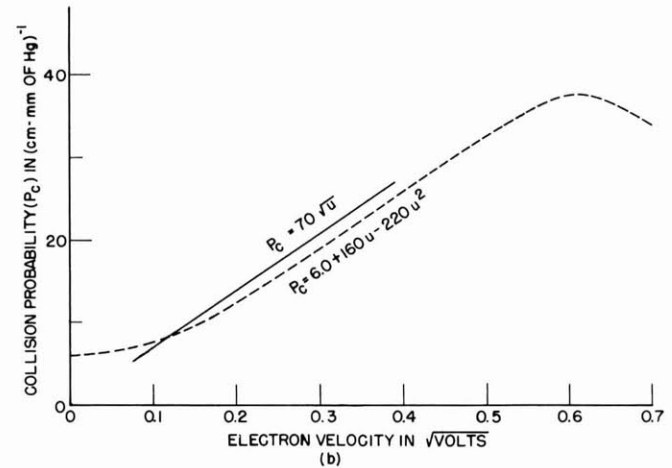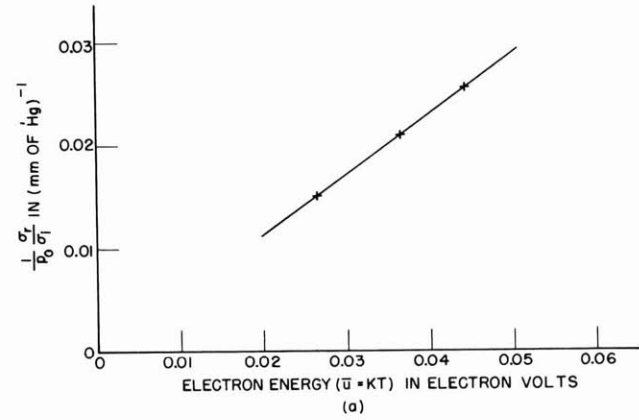Fig. II-4 He$^+$ ion current from pulsed discharge.

Fig. II-3 (a) Variation of zero field values of $(1/p_o)(\sigma_r/\sigma_i)$ with electron energy.

(b) Probability of collision from conductivity measurements.

C.   POSITIVE ION ANALYSIS

The construction of a mass spectrometer for the analysis of the positive ions present in the afterglow of a pulsed low pressure discharge has been completed. Exploratory observations have been made with helium. It has been possible to obtain satisfactory ion currents at the detector of the mass spectrometer with pressures in the discharge cavity as high as 4 mm of Hg.

The principal improvements over the previous apparatus are the use of an electrostatic gun to focus the ions leaving the cavity, the use of a 4-inch diffusion pump to remove the gas escaping from the cavity, and the use of lead wire gaskets so that the cavity can be baked at temperatures up to 300°C.

The first problem to be investigated is the identification of the ion or ions responsible for the low ambipolar diffusion coefficients reported by Biondi and Brown (Phys. Rev. $\underline{75}$, 1700, 1949). Present indications are that the ions are predominantly He^+ at pressures of the order of 1 mm Hg in a cavity with a diffusion length of 1 cm. Figure II-4 shows a typical oscillogram of the He^+ ion current taken with relatively impure He in the cavity. Since nearly all possible mass numbers are present it is not possible to draw any reliable conclusions from the observed ratio of He^+ to He_2^+.