

II. MICROWAVE GASEOUS DISCHARGES

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RESEARCH OBJECTIVES

Our general aim is to study the fundamentals of gas discharges by microwave techniques. Since 1946 we have been studying the microwave breakdown of gas discharges – an investigation that involves both measurements of the phenomena themselves and measurements of the electron collision and loss parameters. Through the years we have studied a number of these phenomena. At the present time measurements of high-pressure breakdown in hydrogen and the study of electron collision cross sections in neon fall into this general line of research.

The other main emphasis of this group has been on the study of the plasma resonance and plasma oscillation phenomena which fall in a convenient microwave frequency range. This is also a continuing interest. Several experiments are in progress to further our previous studies of the mechanism of plasma oscillations and the details of the interaction of microwaves with the ionized plasma.

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A. HIGH-DENSITY MICROWAVE GASEOUS DISCHARGES

Experimental work is being continued on the effect of plasma resonance on the transmission of microwaves through plasma(1). Preliminary experiments have shown that such an effect exists and that it is quite pronounced. A transmitting probe in the form of a coaxial line terminated by a disk was inserted in the plasma, 2.5 cm from a similar receiving probe. At resonance, transmission was minimum. A value for the electron density, n , could thus be obtained (1) from the formula, $\omega^2 = ne^2/m\epsilon_0$, where ω is the frequency of the probing signal and ϵ_0 is the permittivity of free space. A direct measure of n was also obtained by means of a double probe. There is general agreement between the two determinations.

With the type of apparatus described, we cannot hope to obtain more than qualitative results. It is impossible to match the probes to the line. It is also impossible to confine the waves to a small region of the plasma. It may be that this is the reason that the curves that show a minimum of resonance also exhibit unexplainable maxima and at times secondary minima.

To avoid these difficulties, we are now working on a different type of probe. It is planned to utilize the plasma itself as the outer conductor in a section of a coaxial line and to test the properties of such a line as a function of the density of electrons in the plasma. With this probe, maximum transmission would be expected at and above resonance, since in this region the plasma behaves essentially as a metal. This was, in fact, observed with the first probe built. The troublesome maxima and secondary minima of the disk type of probe were absent. However, the probe, because of its size, disturbed the plasma. Work is now being done on a coaxial probe 0.125 inch in

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diameter. It is hoped that with the much thinner probe the disturbance of the plasma will be negligible.

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

The purpose of these measurements was to determine the collision probability for momentum transfer of slow electrons in neon by the microwave method of Gould and Brown (1). The parameter $\rho = (1/p_0)(\sigma_r/\sigma_i)$ (p_0 is the pressure normalized to 0°C; $\sigma = \sigma_r + j\sigma_i$, the complex conductivity of the plasma) has therefore been measured in the afterglow of a neon discharge. All measurements were made at room temperature.

The value of ρ will be independent of the post-discharge time and of the pressure if the same is true for the distribution function of the electrons. The distribution function in a decaying neon plasma can change with time if one or more of the following conditions are present:

- a. The electrons have not yet reached thermal equilibrium with the gas;
- b. The fraction of the electrons leaving the plasma either because of diffusion or recombination with neon ions is a sufficiently fast varying function of the electron energy;
- c. The fraction of the electrons leaving the plasma either because of attachment or recombination with impurities (probably mostly O_2) is a sufficiently fast varying function of the electron energy;
- d. New fast electrons are entering the plasma from the ionization of neon metastables either because of metastable-metastable collisions or the Penning effect (probably with argon atoms).

In order to prevent case d, all measurements have been made at post-discharge times of more than 1 msec. To prevent case c, activated uranium has been used to reduce the content of impurities (except rare gases). The only way to prevent case d is to have enough argon atoms so that practically all neon metastables are ionized in the first millisecond of the afterglow. Case b is not present in helium (2), and we hope that it will not be in neon. (Biondi (3) found that the recombination coefficient in neon is independent of temperature in the range from 77°K to 410°K.)

Measurements were made at pressures of 12-14 mm Hg at post-discharge times varying from 1 msec to 3 msec; measurements of ρ cannot be made later in the

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afterglow, the inaccuracy being too large (more than 10 per cent). The value of ρ was independent of the post-discharge time for the bottled neon (spectroscopically pure Airco), and dependent on the time when the argon impurity content was reduced by using a discharge tube in which the cataphoresis effect was present (4). Values of ρ at the earliest post-discharge times increased with decreasing argon content. This increase is consistent with the expected behavior in case d and an expected increase of ρ with electron temperature. A preliminary value of ρ at room temperature is $1.7 \times 10^{-3} \text{ (mm Hg)}^{-1}$ when impurities and metastables are not present in an appreciable amount. Some measurements of ρ with mercury used as an impurity showed the same general behavior as that of argon but with a greater effect resulting from the larger difference between neon metastable level energy and impurity ionization potential. Some doubts still remain, however, concerning the previous explanation because no change was observed in the parameters of the electron density decay curve when the argon content was reduced. This result suggests that the number of fast electrons coming from metastable ionization is relatively small, and approximate calculations based on the average electron picture show that in such a case the observed changes in ρ cannot be easily explained. More investigation on this point is therefore necessary, and we need a better understanding of the phenomena which control the electron density decay.

The density decay curves obtained during the measurements show (a) no change after neon has been in the presence of activated uranium (this suggests that attachment to impurities is not an important factor here); (b) a change with breakdown pulsewidth, which cannot be understood if recombination is the only controlling factor; and (c) time decay constants that cannot be explained if only diffusion (also of higher modes) and metastable ionization are the controlling factors. Therefore, three processes are probably important: recombination, diffusion, and metastable ionization. To distinguish between the first two processes and the last one we propose to apply a pulsed sweeping field at a variable time in the afterglow, in order to sweep out most of the electrons of the plasma in a very short time; the pulse will not alter the metastable concentration, and the electron decay curve after the pulse will give information about the metastable decay. To distinguish between recombination and diffusion, criteria have been given by Persson (5).

A different criterion will now be discussed; it is based on using as a probing field the resonant modes of the microwave cavity higher than the fundamental one. We have a cubic quartz bottle of side d in the center of a microwave cavity of sides L_1, L_2, L_3 . We assume a set of corresponding orthogonal coordinates x_1, x_2, x_3 with the origin in the center of the cavity, and we suppose that the electron density at the post-discharge time t can be written as

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$$n(x_1, x_2, x_3, t) = n_1(x_1, t) \cdot n_2(x_2, t) \cdot n_3(x_3, t) \quad (1)$$

If we measure at the same t the frequency shift Δf for two different modes $TM_{k'\ell m}$ and $TM_{k''\ell m}$ (ℓ or m being equal to zero) we can show that

$$\frac{(\Delta f)_{k'}}{(\Delta f)_{k''}} = \frac{\sum_{h=1,3,5,\dots} g_{1hk'} n_{1h}(t)}{\sum_{h=1,3,5,\dots} g_{1hk''} n_{1h}(t)} \quad (2)$$

where $n_{1h}(t)$ are the coefficients of a Fourier series of the symmetric part (index s) of $n_1(x_1, t)$

$$n_1(x_1, t) = n_1^s(x_1, t) + n_1^d(x_1, t) \quad (3)$$

$$n_1^s(x_1, t) = \sum_{h=1,3,5,\dots} n_{1h}(t) \cos \frac{h\pi}{d} x_1 \quad (4)$$

and g_{1hk} are constants given by the formula

$$g_{1hk} = \frac{(-1)^{\frac{h-1}{2}}}{h} \left[1 + \frac{(-1)^k \cos k\pi \frac{d}{L_1}}{\left(\frac{2k}{h} \frac{d}{L_1}\right)^2 - 1} \right] \quad (5)$$

If Δf is measured as a function of time for a complete set of modes $TM_{k\ell m}$ with varying k , from Eq. 2 we can determine all the ratios $n_{1h'}(t)/n_{1h''}(t)$. Practically, if the series of Eq. 2 is rapidly converging, the measurements can be limited to just a few modes, and only the ratios of the important terms will be determined; this is particularly important because, for the higher modes, the errors caused by the finite thickness of the walls of the quartz bottle and by an off-center discharge will be a limiting factor in the use of the method. Using modes with different ℓ and m we could determine all of the functions $n_{ih}(t)$, where $i = 1, 2, 3, \dots$. From the differential decay equation when diffusion and any linear removing process (like attachment) are the only phenomena present

$$\frac{\partial n}{\partial t} = D \nabla^2 n - an \quad (6)$$

we have

$$\frac{\partial n_{ih}}{\partial t} = - \left[D \left(\frac{h\pi}{d} \right)^2 + a \right] n_{ih} \quad (7)$$

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$$\frac{n_{ih'}(t)}{n_{ih''}(t)} = \frac{n_{ih'}(0)}{n_{ih''}(0)} e^{-D \frac{\pi^2}{d^2} (h'^2 - h''^2)t} \quad (8)$$

Therefore, in this case, the measured ratios plotted in a logarithmic scale vs. time must be straight lines, and from all of them we must obtain the same D value. If this is not verified, some other process beside diffusion must be present, and we can compute from the measured values the symmetric parts of the functions $n_i(x_i, t)$. They can help in understanding the other processes that are involved in the decay.

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