II. MICROWAVE GASEOUS DISCHARGES

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A. POSITIVE ION ANALYSIS

The studies of the positive ions in the afterglow of a low pressure helium discharge have been completed. The principal result of this work is that the ambipolar diffusion coefficient for the atomic helium ion, as determined from the microwave measurements of the decay of the electron density, is in good agreement with the value predicted from quantum mechanical calculations. In terms of the more familiar mobility coefficient, the present and previous (1) microwave measurements give a value of $\mu_0 = 12.8 \text{ cm}^2/\text{volt-sec}$ at 760 mm Hg (pressure at 0°C) whereas the theory (2) predicts a value of 11.2 cm$^2$/volt-sec. The ions were identified with a mass spectrometer so as to remove the element of confusion which has accompanied previous measurements of the mobility of helium ions.

The dominant processes in the helium afterglow are expected to be the production of ions and electrons by collisions between pairs of metastable atoms, the conversion of the He$^+$ ion into the He$_2^+$ ion upon collision with two neutral atoms, and the ambipolar diffusion of the ions and electrons to the cavity walls. A detailed analysis of these processes allows a prediction of the time dependence of the average electron density in the microwave cavity and the positive ion current reaching the cavity wall. Figure II-1 shows the results of such a theory using the reaction rates from previous experiments (3) and from theory (4). Figure II-2 shows a typical set of experimental electron density and ion current curves. The general features of the theory are observed in the experimental results. The theory shows that the time constant, $T$, for the final decay of the He$^+$ and electron concentration at low pressures is given by

$$\frac{p}{T} = \frac{D_{a_p} p}{\Lambda^2} + \zeta p^3.$$  

Figure II-3 shows the experimental data in the form of $p/T$ vs. $p^3$ for cavities with $\Lambda^2 = 0.85 \text{ cm}^2$ and 0.31 cm$^2$. The average coefficients determined from these curves are $D_{a_p} = 555 \text{ cm}^2\cdot\text{mm Hg/sec}$ and $\zeta p^2 = 65 \text{ p}^2\text{sec}^{-1}$. Biondi and Brown reported an ambipolar diffusion coefficient of $D_{a_p} = 540 \pm 10 \text{ cm}^2\cdot\text{mm Hg/sec}$. Bates predicted a value for the frequency of conversion of He$^+$ ions into He$_2^+$ ions of 160 p$^2$sec$^{-1}$.

B. THE STEADY STATE DISCHARGE IN HYDROGEN

A perturbation solution for the electron energy distribution has made possible a simple treatment of the theory of the maintaining fields of a microwave gas discharge.
Predicted electron and ion densities for $p = 0.3 \text{ cm}^2$ and $\Lambda^2 = 0.85 \text{ cm}^2$.

Measured electron density and ion currents for $p = 2.9 \text{ mm}$ and $\Lambda^2 = 0.85 \text{ cm}^2$.

$p/T$ vs. $p^3$ plot for determination of He$^+$ diffusion and ion conversion rates.
This type of solution has been reported previously in a Quarterly Progress Report (5).

A further development of the theory is concerned with the calculation of the ratio of the diffusion coefficient of electrons in the presence of space charge to that in the absence of space charge, \( \frac{D_s}{D_-} \). There are four equations which must be solved simultaneously to determine \( \frac{D_s}{D_-} \). They are

\[
\begin{align*}
\Gamma_- &= -D_- \nabla n_- - \mu_- E_s n_- \quad (1) \\
\Gamma_+ &= -D_+ \nabla n_+ + \mu_+ E_s n_+ \\
\nabla \cdot \Gamma &= \frac{\nabla n_-}{n_-} \quad (3)
\end{align*}
\]

and

\[
\nabla \cdot E_s = \frac{e}{\epsilon_0} (n_+ - n_-) \quad (4)
\]

Equation 1 states that the electron particle current must be equal to a diffusion current \( D_- \) times the gradient of the electron concentration, and a mobility current proportional to the space charge field. Equation 2 is a similar expression for the positive ion current. Equation 3 states that the divergence of the current, in the absence of other production terms, must equal the rate of ionization by electrons. Equation 4 is Poisson's equation.

The boundary conditions require that the electron density go to zero at the walls and that the flow and electric field and their divergences be zero at the center of the resonant cavity.

A satisfactory solution to Eqs. 1-4, and one that is consistent with the boundary conditions, has been worked out. This solution gives the ratio \( \frac{D_s}{D_-} \) as a function of \( n_0 \Lambda^2 \), the electron density at the center of the cavity times the square of the diffusion length. Figure II-4 shows this relationship.

Measurements of \( \frac{D_s}{D_-} \) in three different cavities fall well within 5 percent of the expected values over a region of density from \( 10^8 \) electrons per cubic centimeter to \( 5 \times 10^{10} \) electrons per cubic centimeter. The discharge is unstable and cannot be operated below densities less than \( 10^8 \) and for this reason further work is proceeding in the high density region where the power available is the only limitation. A thousand-watt magnetron is being set up with the
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hope of getting densities greater than $10^{11}$ electrons per cubic centimeter.

C. OSCILLATIONS IN D-C DISCHARGES

A low pressure mercury arc discharge tube, similar to that used by Merrill and Webb (6), has been prepared to study high frequency oscillations. The anode, cathode, and probe structures duplicate those of the tube used in the earlier experiments. However, a vacuum tight stainless steel bellows forms the support for the probe rod. The motion of the upper end of the probe rod is controlled by a micrometer head. The combination of a flexible bellows and the micrometer control allows the probe to be moved rapidly and precisely through the discharge. A sketch of this tube is shown in Fig. II-5.

The results of Merrill and Webb indicate that a beam of electrons emerges from the cathode fall region of the arc and proceeds into the plasma. The beam shows a sudden spread in velocity at extremely sharp regions of the discharge and high frequency oscillations are detected in regions just beyond these scattering layers. Since both the scattering layer and the oscillating region are very narrow it is desirable to have a device which locates the scattering layer rapidly. For this purpose we have designed an electronic circuit which applies a sweep voltage to the probe and differentiates the probe current drawn. For a beam of electrons, the derivative of the probe current with respect to the probe voltage gives the velocity distribution of the beam of electrons. Thus it is possible to observe the form of the beam of electrons, as the probe is moved through the discharge, and to locate any sudden changes in the distribution of the beam of electrons. In addition, probe curves can be taken at any point by the usual technique and correlated to the form of the electron beam obtained from the differentiator.

Preliminary results verify the conclusions of Merrill and Webb concerning the scattering of the electron beam. The scattering layers appear very suddenly and move toward the cathode as the pressure or arc current is increased. Methods of detecting high frequency oscillations, if any exist, are being investigated.
D. BREAKDOWN IN HYDROGEN AT 100 MC/SEC

The experiments on breakdown in hydrogen reported in a previous progress report (7) were continued. The cavity described in that report (with a diffusion length of \( \Lambda = 0.7 \) cm) suffered from the fact that the discharge occurred at the edges of the re-entrant post where the field cannot be easily computed. A new cavity of brass with a diffusion length of 0.4 cm and a measured Q of 3300 was built. The construction of this cavity is similar to the one shown in Fig. II-2, p. 10 of reference 7. Great care was exercised in designing the bottom of the re-entrant post and in rounding the edges so that breakdown would occur at the center where the field can be computed accurately from known parameters of the cavity. The inside of the cavity was copper plated. A vacuum of \( 5 \times 10^{-8} \) mm Hg to \( 1 \times 10^{-7} \) mm Hg was obtained after baking the cavity in an oven at 130°C for several days. Hydrogen was admitted to the cavity through a palladium leak. The data obtained from this cavity are shown in Fig. II-6.

Many experiments were performed and it was found that the data are very sensitive to impurities. It can be seen from Fig. II-6 that the experimental curve follows the theoretical curve at low pressures but rises sharply at high pressures. Also, there seems to be a limit to the value of \( p/E \). Theoretical considerations based on diffusion alone do not show such a limit. It seems, therefore, that an additional loss mechanism has to be considered at high pressure. It should be noted that the theoretical calculations give only the shape of the theoretical curve and not its exact position because the excitation function is not reliably known.

In order to investigate the unexpected behavior at high pressures, further experiments were necessary. A cavity of diffusion length \( \Lambda = 0.2 \) cm was constructed similar to the previous cavity and the amount of oxygen in the hydrogen atmosphere within the cavity was varied from 0.1 percent to 2.75 percent. It can be seen from Fig. II-7 that the curves bend up at a lower pressure when the amount of oxygen is increased. The curve for the least impurities (0.1 percent \( O_2 \)) is very similar to that of the cavity with \( \Lambda = 0.4 \) cm. It is suggested, therefore, that the sharp increase at high pressure is independent of the diffusion length of the cavity. This fact would exclude recombination as the cause for the loss mechanism at high pressure.

From these experiments it is felt that the sharp increase of the curves is a result of the attachment of electrons to oxygen molecules. Also, water vapor could have been involved in the process. In water vapor, no attachment occurs up to \( E/p = 8 \) volts/cm-mm Hg and then attachment begins. The curves in Figs. II-6 and II-7 show that the limiting value of the curve is in the neighborhood of \( E/p = 8 \) (\( p/E = 0.125 \)).

Theoretical calculations on the variation of breakdown with oxygen content are made difficult by the fact that the variation of the coefficient of attachment with \( E/p \) is unknown; however, the trend of the curves is in agreement with theory.
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Fig. II-6
100-Mc breakdown in hydrogen.

Fig. II-7
100-Mc breakdown in H₂ as a function of oxygen content.

References

5. Quarterly Progress Report, Research Laboratory of Electronics, M.I.T. p. 10, July 15, 1951
7. Quarterly Progress Report, Research Laboratory of Electronics, M.I.T. p. 9, January 15, 1951