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UNIVERSITY OF ILLINOIS - URBANA, ILLINOIS

COLLISION CROSS SECTION OF SLOW ELECTRONS AND IONS WITH CESIUM ATOMS

Prepared by

C. L. CHEN AND M. RAETHER

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Abstract

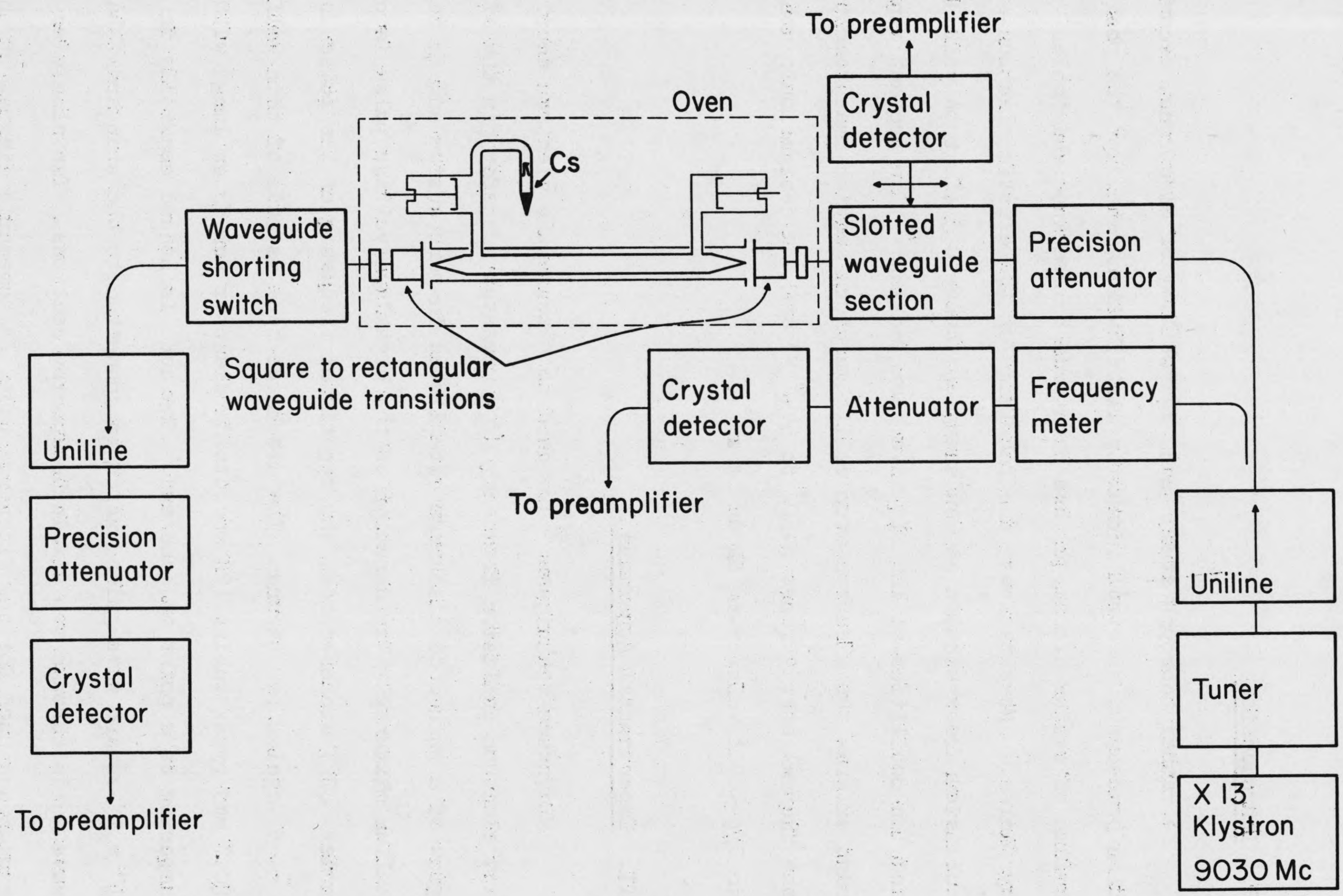
Microwave interferometry is adopted to measure the effective collision cross section for momentum transfer $\bar{Q}_m$ of thermal electrons (of mean energies of $\sim$0.06 to 0.071 eV) with cesium atoms in the afterglow of pure cesium and helium-cesium discharges. The momentum transfer cross section $\bar{Q}_m$ is found to be best represented by $1.61 \times 10^{-10}\ T_e^{-1} - 9.63 \times 10^{-12}\ T_e^{-1/2} + 2.03 \times 10^{-13}$ cm^2 in the temperature range of approximately 450° to 550° K. The energy dependence of the elastic electron-cesium-atom collision probability for momentum transfer is determined to be $P_m = 997\ u^{-1} - 4810\ u^{-1/2} + 7230$ cm^{-1} where u is the energy of the electrons in electron volts. This shows a smooth tendency to join Brode's data at higher electron energies. Mobilities of Cs^+ ions in helium and in cesium have been determined from the helium-cesium mixture experiments in the same temperature range. They are $\mu(Cs^+$ in He$)$ $= 18.5 \pm 0.5$ cm^2/volt-sec, and $\mu(Cs^+$ in Cs$) = 0.4 \pm 0.05$ cm^2/volt-sec referred to standard gas density (i.e., 2.69×10^{19}/cm^3).

I. Introduction

A rather thorough study (such as mobility of electrons, recombination processes, spectral intensity distribution, etc.) of the positive column of cesium discharges has been made by Boeckner and Mohler[1] and by Mohler.[2] Nevertheless, the knowledge of the elastic electron-atom collision cross section at low energies (below 0.3 electron volts)[3] and ion mobilities at low E/p have been lacking.[4] The present experiment extends the electron-atom collision cross section measurements to the thermal energy range (450° to 544° K) and the cesium ionic mobility to E/p $\sim$ 0.1 volt/cm-mm Hg or less.

II. Experimental Apparatus

Microwave techniques [5] are used to measure the electron density and electron collision frequency (for momentum transfer) in the afterglow of a pulsed dc discharge established in pure cesium and in cesium-helium mixtures. The duration of the breakdown voltage pulse is of the order of 7 microseconds, the repetition frequency of the pulse is $\sim$ 31 cycles per second. The discharge tube is made of thin wall (0.7 mm) pyrex tubing (22 mm outside diameter and 72 cm long) with 6 cm tapering to a point at each end. The tube is housed coaxially in a 1" x 1" square wave guide, which is connected to the standard X-band wave guide through two six-inch tapering sections. Tantalum electrodes are used for the discharge tube. A schematic diagram of the microwave circuitry used is shown in Figure 1. A five microsecond,



Microwave instrumentation for the experiment.

FIGURE 1. Schematic Diagram of the Microwave Circuitry

low power ($\sim$ 7 μ watt), 8647 MC probing signal is launched at times in the afterglow and measurements of phase shifts and attenuations are made.

The cesium used is obtained from the Bram Metallurgical Chemical Company claimed to be 99.9 °/o pure, the impurities being mainly sodium and potasium. Small capsules of cesium are made for the present experiments through vacuum distillation in a standard ultra-high vacuum system.[6] A capsule is then installed on the system in a side tube connected to the discharge tube. The system is then baked at 400° C for more than 24 hours. An ultimate vacuum of the order of 4×10^{-10} mm Hg is attained. The cesium capsule is opened by a breaker (a short soft steel bar sealed in an evacuated glass tubing) and the discharge tube is then sealed off. The temperature of the discharge tube is then brought up to the desired value by the oven control. The temperature of the cesium capsule and of the wave guide are monitored constantly by five copper-constantan thermocouples. The vapor pressure p(in mm Hg) of Cs is calculated from [7]

$$\log_{10} p = - \frac{4075}{T} + 11.38 - 1.45 \log_{10} T$$

where T is the temperature of the cesium reservoir in degree Kelvin. Two $\sim$ 1.5 mil mica sheets are placed on both sides of the discharge tube in the wave guide to cut down any convection and guarantee uniformity of temperature in the discharge tube. By this means, the temperature variation of the discharge tube is kept within 1° C.

III. Measurements in Pure Cesium

It can be shown[8] that the complex electrical conductivity, σ_c of a plasma is given by:

$$\sigma_c = -\frac{ne^2}{3m}\int \frac{v\,\frac{\partial f_o}{\partial v}}{\nu + j\omega}\, d^3 v \qquad (1)$$

where n is the electron density, e the electron charge, m the electron mass, and v the electron velocity. f_o is the zero-th order of a spherical harmonic expansion of the electron velocity distribution function and is assumed maxwellian. $\nu = NQ_m(v)v$ is the momentum transfer collision frequency of the electrons with the neutrals in the plasma. N is the neutral gas density and $Q_m(v)$ is the momentum transfer collision cross section defined as:

$$Q_m(v) = \int (1 - \cos\theta) \quad I(\theta, v)\ d\Omega \qquad (2)$$

where θ is the scattering angle of the electrons, and $I(\theta, v)$ is the differential scattering cross section.

For $\omega^2 \gg \nu^2$, (i.e.,low pressure and high frequency) Eq.(1) becomes:

$$\sigma_c = -\frac{ne^2}{3m\omega^2}\int (\nu - j\omega)v\ \frac{\partial f_o}{\partial v}\, d^3 v = \frac{ne^2}{m\omega^2}(\nu_{eff} - j\omega) \qquad (3)$$

where ν_{eff} is the effective electron collision frequency and can be shown to be

$$\nu_{eff} = \frac{4}{3}\ N\ \bar{Q}_m\ \langle v \rangle \qquad (4)$$

for f_o to be maxwellian.

The average velocity of the electrons $\langle v \rangle$ is given by

$$\langle v \rangle = \left(\frac{8kT}{\pi m} \right)^{1/2} \tag{5}$$

Here k is the Boltzmann constant and T is the electron temperature. $\bar{Q}_m$ is the effective collision cross section for momentum transfer of the electrons with the neutrals and is given by:

$$\bar{Q}_m = \frac{1}{8} \left(\frac{m}{kT} \right)^3 \int_0^\infty Q_m(v)\, v^5 \quad \exp \left(- \frac{mv^2}{2kT} \right) dv \tag{6}$$

$\bar{Q}_m$ as calculated from the measured ν_{eff} as a function of temperature is shown in Figure 2. Data were taken generally 1 ~ 2 milliseconds after termination of the excitation pulse (i.e., in the afterglow). The electrons are assumed to have relaxed back to the gas temperature at times the measurements were made. This is justified through comparison of the mobility data (Cs^+ ions in Cs) as calculated from the measured characteristic ambipolar diffusion time constants with those deduced from the helium-cesium mixture experiments (see Section V). Within experimental errors, they are generally the same. The fast cooling of the electrons in the afterglow of pure cesium discharge is attributed to the phenomenon of "diffusion cooling." [9]

The collision probability for momentum transfer is defined as:

$$P_m = N\, Q_m / p_o \tag{7}$$

where p_o is the gas pressure in mm Hg referred to 0^o C.

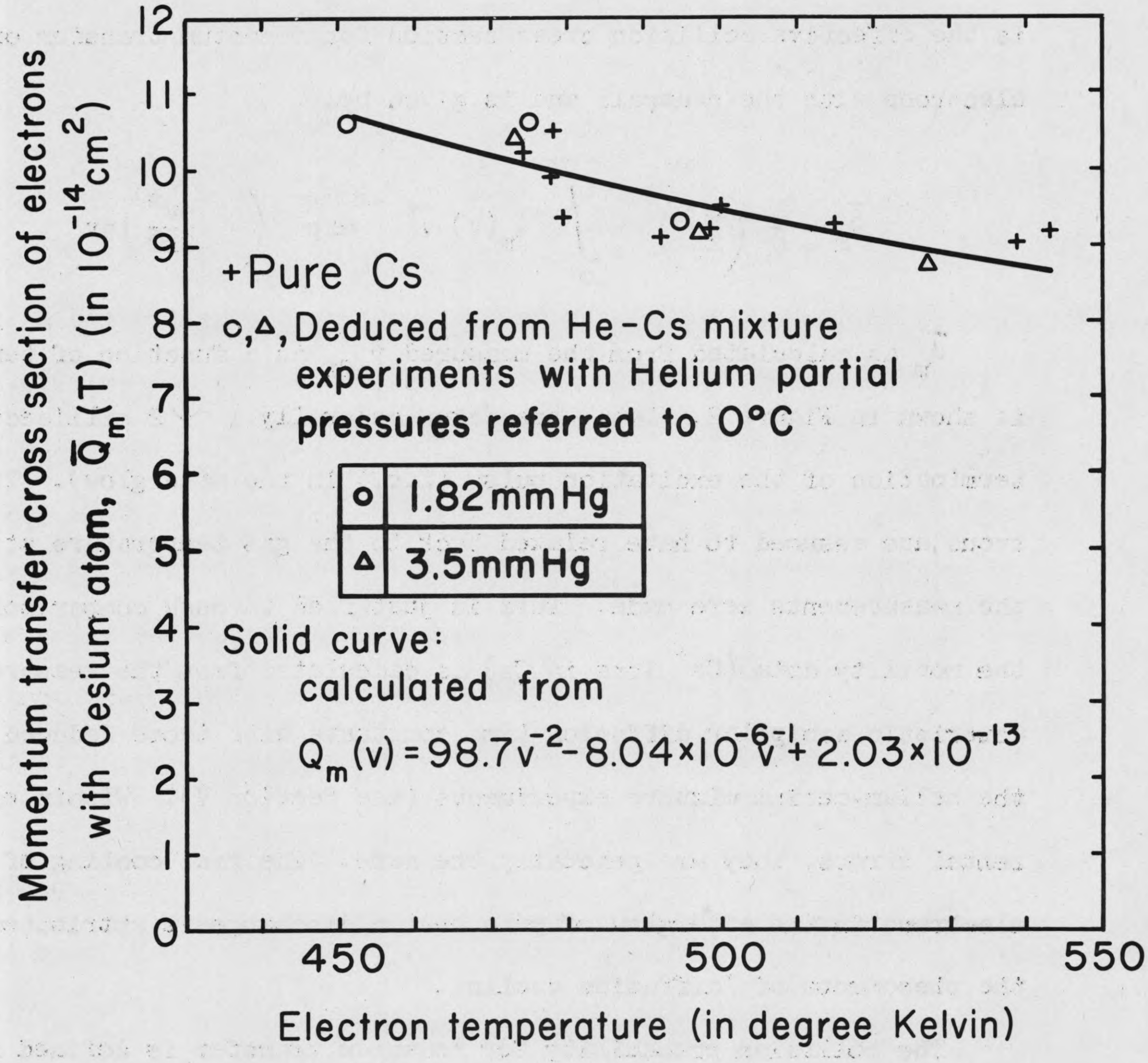


FIGURE 2. Momentum Transfer Cross Section of Electrons with Cesium Atoms

IV. Measurements in Cesium-Helium Mixtures

In order to insure that the electrons have relaxed back to the gas temperature at times in the afterglow the data were taken, helium gas of known density was admitted to the discharge tube. Since $\nu = \sum_i N_i Q_{m_i} v$ where i is the index representing different species of gas molecules in the discharge tube, it can easily be shown that:

$$\nu_{eff}' = \sum_i g_i \nu_{eff_i}' \qquad (8)$$

where the primes refer to the quantity per unit pressure and g_i is the fractional concentration of the i-th species of gas molecules provided $\omega^2 \gg \nu^2$. In our case, the effective electron-cesium collision frequency for momentum transfer is calculated from the measured ν_{eff}' by subtracting the electron-helium part using existing data.[10] $\bar{Q}_m$ for electron-cesium so calculated is shown in Figure 2. The value of $\bar{Q}_m$ for electron-helium is taken to be 5.3×10^{-16} cm^2 and has been shown to be independent of the electron energy from about 0.04 eV to about 2 eV.[10]

Theoretically, it is required to know the functional dependence of $Q_m(v)$ over the entire velocity spectrum in order to be able to calculate $\bar{Q}_m$ according to Eq. (6) and compare it with the experimentally determined one. This is not available at the present. Experimentally, $Q_m(v)$ could be determined if enough data of $\bar{Q}_m$ as a function of temperature were available. A least square fit to the present experimental points of $\bar{Q}_m$ by a polynomial of the form:

$$Q_m(v) = \frac{A}{v^2} + \frac{B}{v} + C \qquad (9)$$

gives

$$A = 98.7 \ \frac{cm^4}{sec^2}$$

$$B = -\ 8.04 \times 10^{-6} \ \frac{cm^3}{sec}$$

and

$$C = 2.3 \times 10^{-13} \ cm^2$$

Here v is the electron velocity in cm/sec. It is felt that this simple polynomial approximation is adequate because of the following reasons: 1) In the temperature range (450^o to 550^o K), the fraction of electrons possessing an energy higher than 0.5 eV is very small and the effect of these electrons on $\overline{Q}_m$ is negligible. 2) The fluctuation of the data (due mostly to the temperature drifts of the order of one degree in the experiment) prevents us from doing anything more meaningful.

The velocity dependence of the electron collision probability for momentum transfer P_m calculated according to Eq. (7) together with the existing data by Brode [3] is shown in Figure 3. The extrapolated curve beyond the thermal range (approximately 0.06 to 0.071 eV) of the present experiment according to Eqs. (9) and (7) exhibits a smooth tendency to join Brode's data at high energies.

To exhibit experimentally this strong velocity dependence of the electron-cesium-atom collision probability, we have performed microwave cross modulation [5,11] experiments in the decaying plasma established in

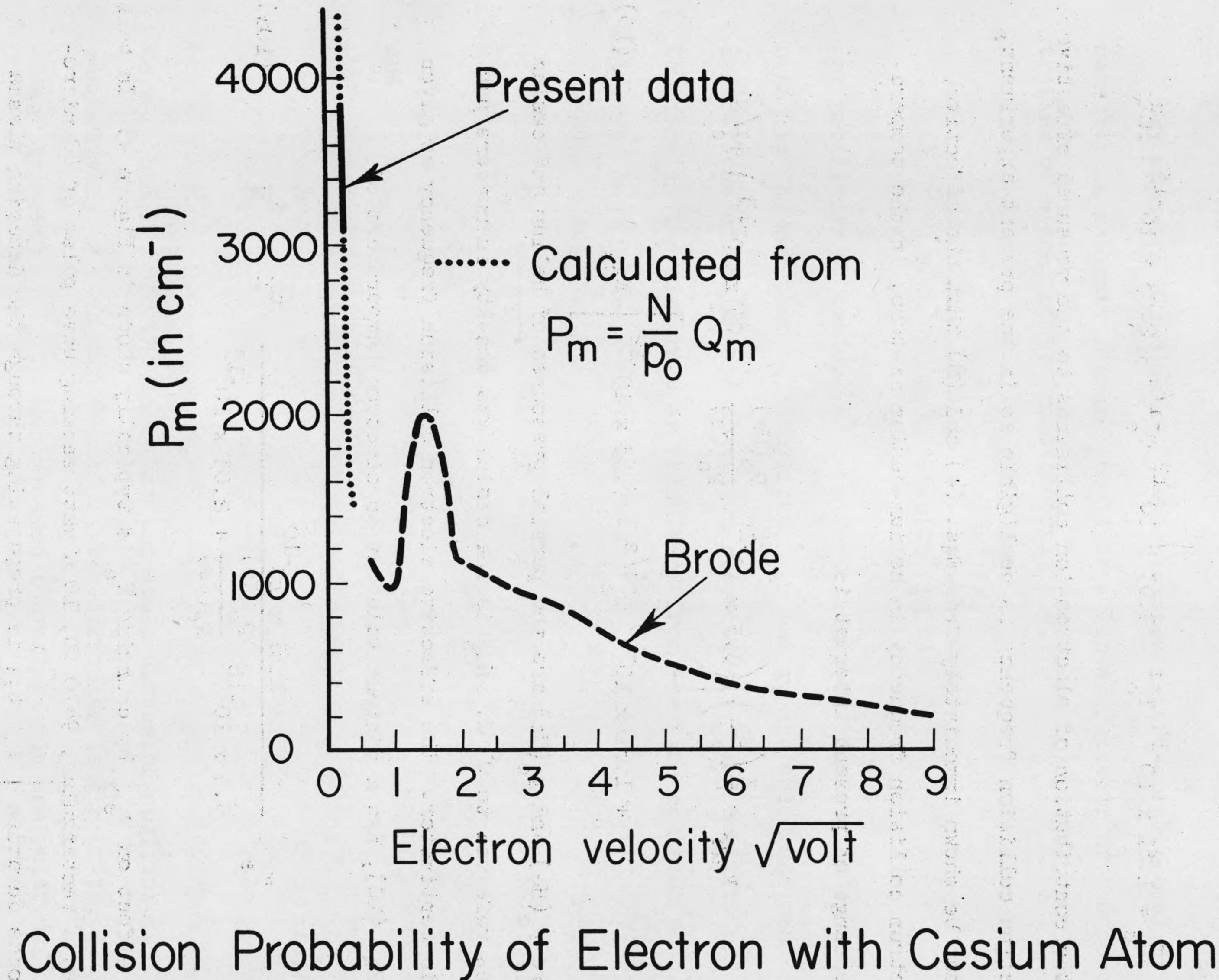


FIGURE 3. Collision Probability of Electrons with Cesium Atoms

helium-cesium mixture. The electron temperature dependence of $\bar{Q}_m$ for electron and cesium atoms as calculated from Eqs. (6) and (9) is

$$\bar{Q}_m = 1.61 \times 10^{-10}\, T_e^{-1} - 9.63 \times 10^{-12}\, T_e^{-1/2} + 2.03 \times 10^{-13} \quad cm^2$$

If the contribution of electron-ion collisions to the measured effective electron collision frequency is negligible as in the present experiment, it can be shown immediately from Eqs. (4) and (8) that the effective electron collision frequency in helium-cesium mixture, in the temperature range of present interest is

$$\nu_{eff} = \frac{3}{4}\left(\frac{8k}{\pi m}\right)\left[\left(5.3 \times 10^{-16}\ \frac{p_o(He)}{p_o(Cs)} + 2.03 \times 10^{-13}\right) T_e^{1/2} + 1.61 \times 10^{-10}\, T_e^{-1/2} - 9.63 \times 10^{-12}\right] N_{Cs} \qquad (10)$$

where $p_o(He)$ and $p_o(Cs)$ are the partial pressures of helium and cesium gases referred to 0^o C. N_{Cs} is the cesium gas density in numbers per cubic centimeter. The effective electron collision frequency as given by Eq. (10), has a minimum value at an electron temperature of

$$T_e = \frac{1.61 \times 10^{-10}}{5.3 \times 10^{-16}\ \frac{p_o(He)}{p_o(Cs)} + 2.03 \times 10^{-13}} \quad {}^oK \qquad (10a)$$

The effect on ν_{eff} by changing T_e is typically shown in Figure 4. In this case, a rectangular, 9410 MC, 10 μ watt sensing wave pulse of 60 microseconds duration $[t_o \ \ t_3]$ is propagating through the decaying plasma 700 microseconds after termination of the breakdown voltage pulse ($\sim$10 μsec). At times shortly after introducing the sensing wave

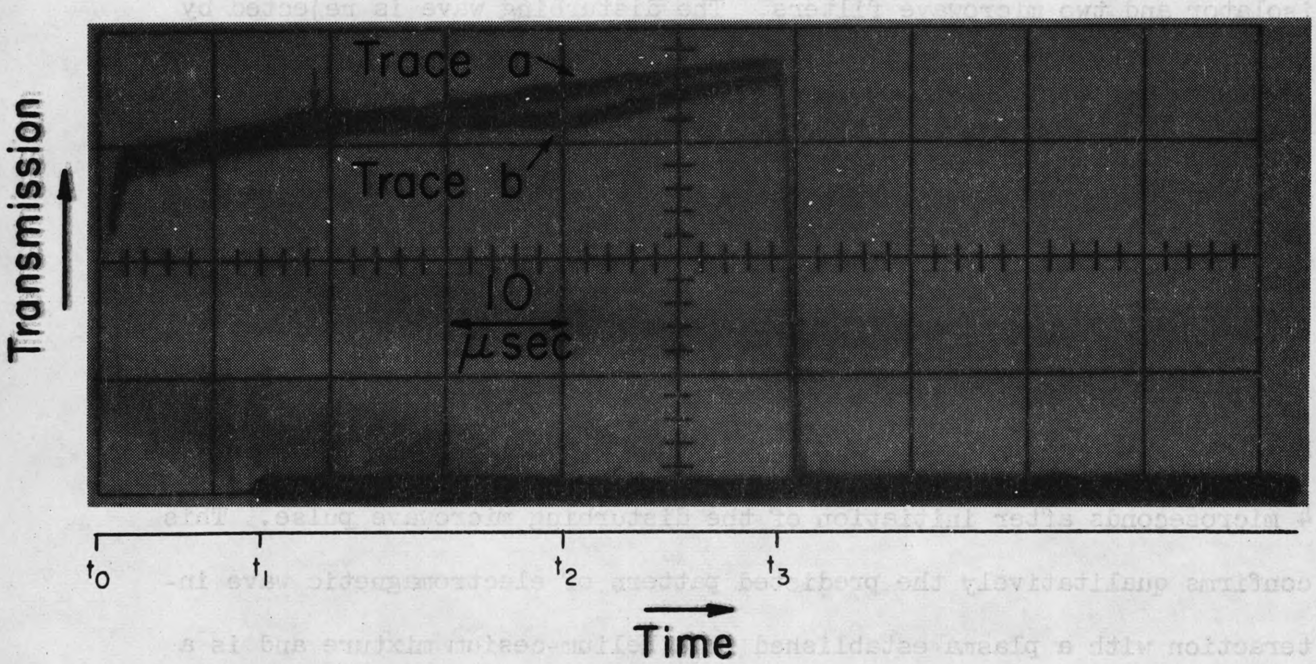


FIGURE 4. Effect (trace a) on the sensing wave pulse (60 microseconds) in the decaying plasma established in helium-cesium mixture with the presence of an $\sim$ 120 milliwatts disturbing wave pulse (20 microseconds). Here p_o(He) = 1.82 mm Hg and p_o(Cs) = 0.071 mm Hg. Trace b is the transmitted sensing wave pulse in the absence of the disturbing wave pulse.

(about 15 μsec), a rectangular 8650 MC, $\sim$ 120 m watt, 20 μsec duration disturbing wave pulse $\left[t_1 \; t_2 \right]$ is launched into the plasma. A fraction of this energy is absorbed by the electron gas and its temperature is hence increased. The change of ν_{eff} and hence the real part of the electrical conductivity of the plasma is then sensed by the sensing wave. The sensing wave is picked up at the far end of the discharge tube through a ferrite isolator and two microwave filters. The disturbing wave is rejected by the filters and is absorbed by the ferrite isolator. The traces shown in Figure 4 are double exposures of the oscilloscope traces. Traces "a" and "b" are the transmitted sensing wave without and with the disturbing wave present. It is predicted from Eq. (10a) for this particular case (p_o(He) = 1.82 mm Hg and p_o(Cs) = 0.071 mm Hg) that the minimum value of ν_{eff} should occur at $T_e = 745^o$ K while the background gas temperature is 495^o K. A bump is observed (as shown by an arrow in Figure 4) about 4 microseconds after initiation of the disturbing microwave pulse. This confirms qualitatively the predicted pattern of electromagnetic wave interaction with a plasma established in a helium-cesium mixture and is a further evidence that we do have a decaying plasma in which electrons have already been thermalized with the background gas at times in the afterglow studied.

V. Mobility of Cesium Ions

By applying Blanc's law [12] which states that the reciprocal of the mobility in a binary mixture should be a linear function of the concentration of either of its constituents, i.e.,

$$\frac{1}{\mu} = \frac{g_1}{\mu(Cs^+ \text{ in He})} + \frac{g_2}{\mu(Cs^+ \text{ in Cs})} \qquad (10)$$

the mobilities of cesium Cs^+ ions in helium $\mu(Cs^+$ in He) and in cesium $\mu(Cs^+$ in Cs) can then be determined. g_1 and g_2 are the fractional concentrations of helium and of cesium respectively. The mobility of Cs^+ ions in the mixture μ is calculated from the time constant of electron density decay curve by

$$D_a = \frac{\Lambda^2}{\tau_a} \simeq 2D_+ \qquad (11)$$

and

$$\frac{D_+}{\mu} = \frac{kT}{e} \qquad (12)$$

Here D_a and D_+ are the ambipolar and ionic diffusion coefficients, respectively. Λ is the characteristic diffusion length of the discharge tube and τ_a is the measured characteristic ambipolar diffusion time constant. From the best fit to the experimental points

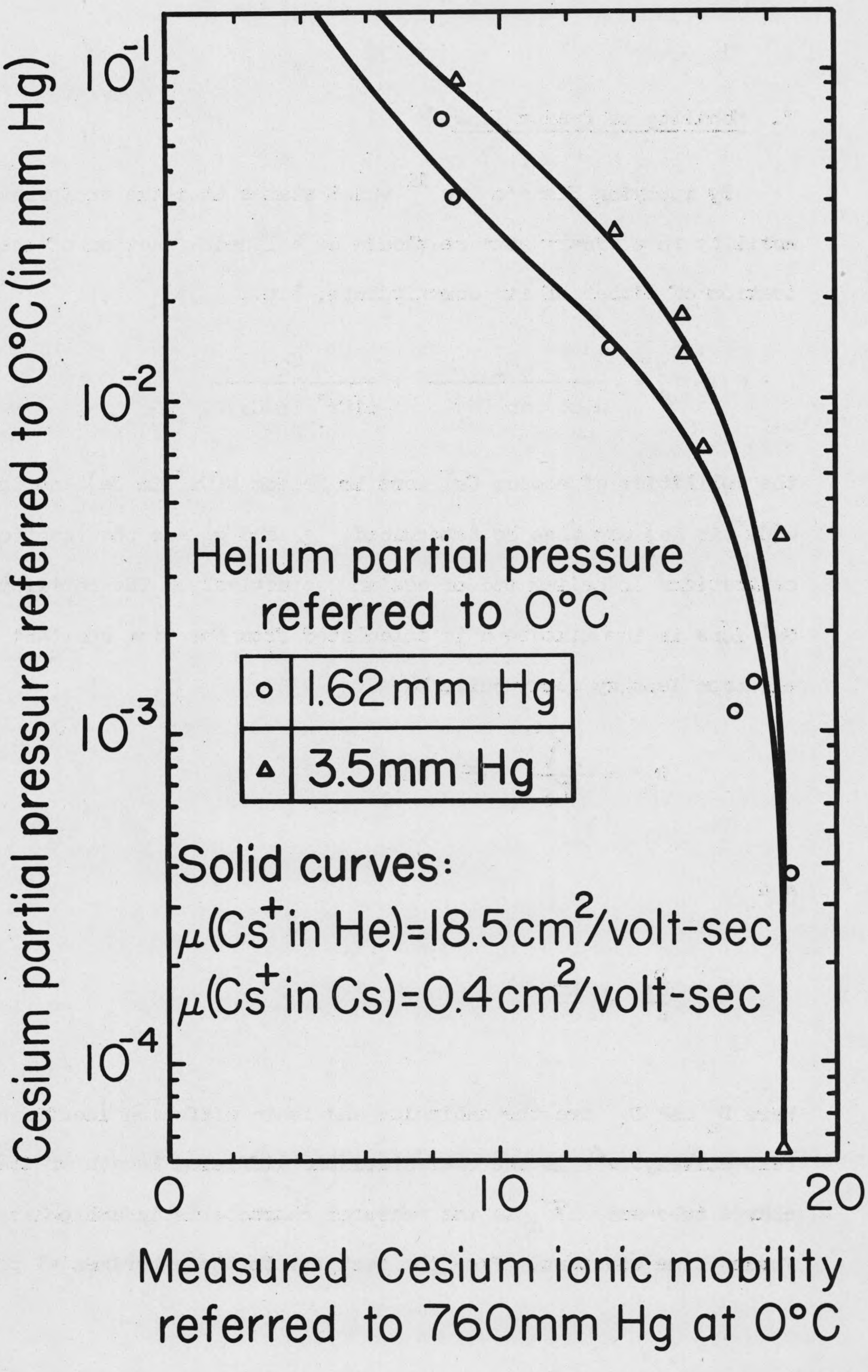


FIGURE 5. Cesium Ion Mobilities in Helium and in Cesium

(see Figure 5), we get $\mu(Cs^+ \text{ in He}) = 18.5 \pm 0.5$ cm²/volt-sec and $\mu(Cs^+ \text{ in Cs}) = 0.4 \pm 0.05$ cm²/volt-sec.

VI. Discussion

The elastic collision cross section of low energy electrons with heavy atoms is difficult to compute theoretically and only very few calculations have been performed.

Robinson [13] has calculated $Q_m(v)$ for cesium by using a polarization potential in addition to a scattering potential constructed from slater orbital type wave function. His preliminary analysis reproduces the shape of the cross section versus energy curves at high energies but disagree considerably with the present experiment at low energies. Recently, Phelps [14] has calculated the electron collision frequency with cesium atoms from Mohler's data[2] and found $\nu/N_{Cs} \simeq 1.6 \times 10^{-6}$ cm³/sec-atom for electrons of ~ 0.22 to 0.40 eV. We arrive at an expression

$$\nu/N_{Cs} = 1.34 \times 10^{-4}\, T_e^{-1/2} - 8 \times 10^{-6} + 1.66 \times 10^{-7}\, T^{1/2} \ \text{cm}^3/\text{sec-atom}$$

from Eq. (9). This yields $\nu/N_{Cs} = 1.95 \times 10^{-6}$, 1.76×10^{-6} and 1.66×10^{-6} cm³/sec-atom for electrons at 450° K, 500° K and 550° K, respectively, and in fair agreement with each other.

As to the mobility of Cs^+ ions in helium, the polarization force is believed to be the dominating interacting force at such low energies.

Langevin's theory [15] (to this limit) gives a value of 15.8 cm^2/volt-sec in contrast with 18.5 $\pm$ 0.5 cm^2/volt-sec determined by the present experiment. Tyndall et al.[16] used shutter methods to determine the mobilities of alkali ions in helium and found a value of 18.4 cm^2/volt-sec for Cs^+ ions in helium, in excellent agreement with the present experiment.

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