Electron Temperature Dependence of the Recombination Coefficient in Pure Helium*†

C. L. CHEN,‡ C. C. LEIBY, AND L. GOLDSTEIN
Department of Electrical Engineering, University of Illinois, Urbana, Illinois
(Received May 20, 1960; revised manuscript received November 21, 1960)

The phenomenon of "afterglow quenching" is employed to determine the electron temperature dependence of the electron-ion recombination coefficient in plasmas produced in purified helium (estimated impurity $1:10^9$). The total visible light intensity was studied as a function of electron temperature. By means of 1.5% bandwidth filters, the light intensity of two helium spectral lines (5876 A and 3888 A) were also investigated. It is found that the recombination coefficient for highly purified helium varies as the minus three-halves power of the electron temperature from 300° to ~1500°K at electron densities of $\sim 10^{11}$/cc, and gas pressures from 12.6 to 30.3 mm Hg. At 300°K (temperature determined from collision frequency measurements), the recombination coefficient in purified helium is found to be $(8.9\pm0.5)\times10^{-9}$ cm³/ion sec. It is found that both the recombination coefficient and its electron temperature dependence were strongly influenced by the addition of controlled amounts (2×10^{-4} to 1300×10^{-4} %) of neon impurities.

INTRODUCTION

THE electron-ion recombination processes in ionized gases have been studied both theoretically and experimentally in the past. In order to account for these phenomena, different mechanisms have been proposed which depend upon the nature of the ions involved. Electron recombination with atomic ions may be either radiative,[1] dielectronic,[2] or involve a third body. In addition, if the recombining ions are molecular, the recombination process may also be dissociative.[3] In all cases, the recombination coefficient (α_r) which characterizes this process in plasmas depends upon the electron and ion temperatures of the plasma.

In general, previous experimental determination of recombination coefficients have been made at fixed electron temperatures. Sayers,[4] using probe techniques in argon arc discharges, found a value of 1.12×10^{-9} cc/ion sec for α_r at an electron temperature (T_e) of 600°K and a value of 4.2×10^{-10} cc/ion sec for $T_e=1250$°K, at pressures from 0.1 to 1.0 mm Hg. Assuming a monotonic variation of α_r with T_e, these values indicate roughly a minus three-halves power electron temperature dependence. Biondi and Brown[5] have also studied the dependence of α_r upon electron temperature (presumed to be isothermal with the neutral gas temperatures) in hydrogen[6] and neon. They found a $T_e^{-0.8}$ to $T_e^{-0.9}$ dependence in hydrogen over several temperatures from 303° to 413°K, while no temperature dependence was found in neon for 195° and 300°K but an increase in α_r with increasing pressure was observed at 77°K. Anderson,[7] studying the recombination processes in the negative glow region of helium dc discharges by means of light quenching measurements, reported a $T_e^{-\frac{3}{2}}$ dependence.

In view of the sparsity of experimental results for the electron temperature dependence of the electron-positive ion recombination coefficients, it was felt that a study of this dependence should be undertaken over a wider range of electron temperatures. The present paper reports the results of such a study made in the afterglow of purified helium discharges.

The phenomenon of "afterglow quenching"[7,8] has been employed in determining the electron temperature dependence of the electron-positive ion recombination coefficient. At early times in a decaying (afterglow) plasma, a 20-μsec low-level microwave pulse was propagated through the ionized medium. As a result of the selective heating of the electron gas by this pulsed microwave, the electron-ion recombination probability is decreased. If the afterglow light intensity were the result of electron-ion recombination processes *within* the plasma, it should be "quenched" during microwave heating. Such is observed to be the case.[8] A photomultiplier was employed to study the variation of visible light intensity emitted from the plasma while the electron gas is heated. The correlation of the electron temperature and the electron-ion recombination rate (proportional to the afterglow light intensity) yields a

* This research was sponsored by the Air Force Cambridge Research Center.

† The principal results of this work were previously reported at the 12th Annual Gaseous Electronic Conference at the National Bureau of Standards, Washington, D. C., October 14–16, 1959 [Bull. Am. Phys. Soc. 5, 122 (1960)].

‡ Present Address: Coordinated Science Laboratory, University of Illinois, Urbana, Illinois.

[1] D. R. Bates, R. A. Buckingham, H. S. W. Massey, and J. J. Unwin, Proc. Roy. Soc. (London) A170, 322 (1939).

[2] H. S. W. Massey and D. R. Bates, Repts. Progr. Phys. 9, 62 (1943).

[3] D. R. Bates, Phys. Rev. Letters 78, 492 (1950).

[4] J. Sayers, Conference on the Physics of Ionized Gases, University College of London, Auspices Warren Research Foundation Royal Society, April, 1953 (unpublished).

[5] M. A. Biondi and S. C. Brown, Phys. Rev. 76, 1697 (1949).

[6] K. B. Person and S. C. Brown, Phys. Rev. 100, 729 (1955) concluded from their study of the afterglow of very pure hydrogen that the electron loss in such an afterglow is mainly due to diffusion. They also estimated that the recombination coefficient in the hydrogen afterglow is less than 3×10^{-8} cm³/ion sec at 300°K.

[7] J. M. Anderson, Phys. Rev. 108, 898 (1958).

[8] L. Goldstein, J. M. Anderson, and G. L. Clark, Phys. Rev. 90, 486 (1952); C. Kenty, Phys. Rev. 32, 624 (1928).

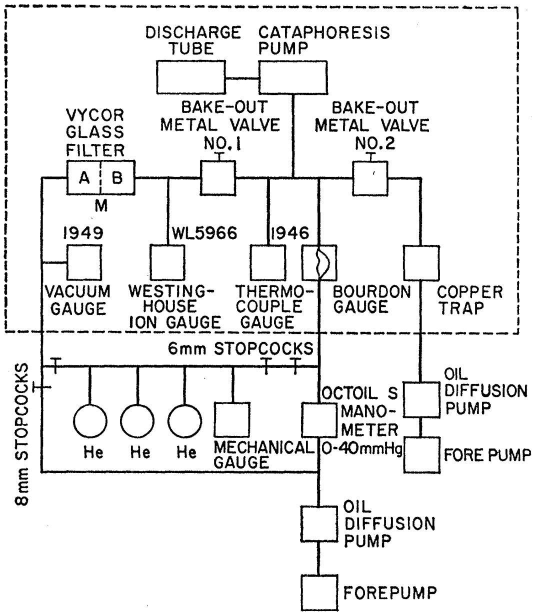

FIG. 1. Schematic diagram of the vacuum system and helium gas purification device. The "bakeable" portion of the system is enclosed in the dashed line.

measure of the electron temperature dependence of the recombination coefficient.

EXPERIMENTAL SETUP AND PROCEDURE

Since the nature of each recombination process taking place in a plasma depends upon the species of ion involved, it is necessary to know the types of ions present in the recombining plasma. Thus—in view of the fact that the ionization potential of helium is the highest of all gases—it is imperative that the helium used be of the highest possible purity.

To this end an ultrahigh vacuum system (Fig. 1), consisting of two sections separated by a Vycor glass membrane, was employed.[9] The system was baked out at 400°C for a period of twelve hours or more prior to each sequence of experiments. The residual gas pressure of the experimental region was of the order of 10^{-10} mm Hg and the rate of pressure rise in the system (when closed from the pumps) was about 2.2×10^{-9} mm Hg/hour at room temperature. This is approximately the rate at which atmospheric helium permeates through the pyrex walls of the system.[10] The Vycor glass membrane, which was enclosed in a separate oven, was then slowly raised to 400°C and "spectroscopic pure" helium gas (estimated impurity content approximately $1:10^6$—mostly neon) was admitted to the Vycor glass filter. The impurity content of *this* helium gas, after diffusing through the filter, was reduced by about two orders of magnitude.[9] In addition a cataphoresis pump[11] was employed for further continuous separation of any remaining impurities. Through this scheme, the impurity content of the helium gas in the discharge tube was estimated to be less than $1:10^9$.

The electrodes (Fig. 2) of the discharge tube are made of high-purity titanium sheet which continuously "getter" hydrogen, carbon dioxide, oxygen, and nitrogen impurity gases.[12] A simple keep-alive device was employed to provide a localized discharge behind the electrode so that electrons are available in abundance when the breakdown voltage is applied to the main discharge tube.

The gas pressure in the discharge tube was measured by means of a modified all glass Bourdon gauge.[13] A null-reading technique was used. This was achieved by introducing helium gas on the other (nonpurified) side of the Bourdon gauge until its pointer has returned to its zero-point, as viewed by a microscope. This balanced pressure, as read from an Octoil—S manometer, equalled the purified gas pressure in the discharge tube.

In addition, the effects of known impurities were investigated. Neon gas was used for this purpose. Small ampules of neon gas, equipped with break-seals, were attached to the system, permitting admission of known quantities of "spectroscopic pure" neon into the purified helium gas.

The gaseous discharge plasma was confined in a 52-cm over-all length, thin-wall (0.85 mm) Pyrex glass tube with inside diameter of 1.64 cm. The tube was housed coaxially in a 2.07 cm$\times$2.07 cm waveguide in which a low-level pulsed TE_{10} 9500-Mc electromagnetic wave was propagated (Fig. 3).

The inner surface of the square waveguide was gold plated to reduce light reflection and to provide good electrical conductivity. The square waveguide was coupled to standard X-band rectangular wave-guide through two 6-in. tapered sections. A slot, $\frac{3}{32}$-in. by 1 in., located near the front end of the discharge tube,

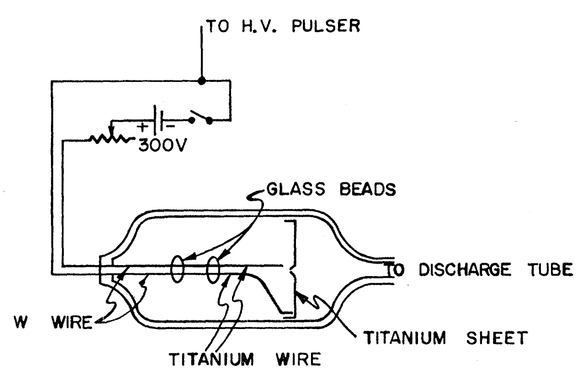

FIG. 2. Structure of the electrodes.

[9] C. C. Leiby and C. L. Chen, J. Appl. Phys. **31**, 268 (1960).
[10] W. A. Rogers, R. S. Buritz, and D. Alpert, J. Appl. Phys. **25**, 868 (1954).
[11] R. Riesz and G. H. Dieke, J. Appl. Phys. **25**, 196 (1954).
[12] V. L. Stout and M. D. Gibbons, J. Appl. Phys. **26**, 1488 (1955).
[13] W. E. Barr and V. J. Anhorn, *Scientific and Industrial Glass Blowing and Laboratory Techniques* (Instruments Publishing Company, Pittsburgh, Pennsylvania, 1949).

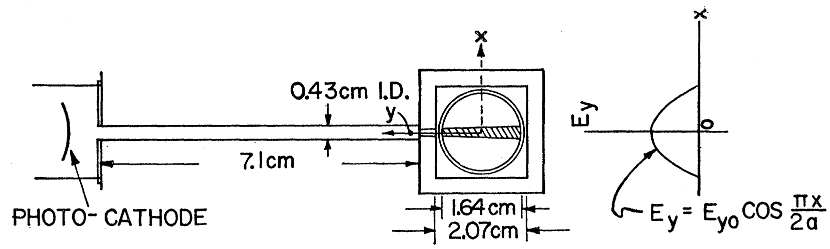

FIG. 3. A cross sectional view of the square waveguide, the discharge tube, the light-collimating tubing, and the photomultiplier.

was cut on the maximum E field side of the square waveguide to provide a port for observation of the variation of the luminous intensity of the afterglow. RCA6217 and 1P28 photomultipliers, appropriate to the spectral ranges studied, were pulsed on for 100 μsec approximately 30 μsec prior to the propagation of the microwave pulse. The photomultiplier output was terminated by a 560-ohm resistor, and coupled to a Tektronix type 121 preamplifier by means of a three-foot length of RA-62/U cable. Because of the low distributed capacitance (28.5 $\mu\mu$f per ft) of the cable, the time constant associated with this photoelectric detecting circuit is less than 0.05 μsec. Coupled with these photomultipliers, Baird-Atomic model $B1$, multilayer dielectric type interference filters of 1.5% bandwidth, centered at wavelengths 5890 A (74% transmission) and 3892 A (14% transmission) were employed to study the intensity variations of two helium lines, 5876 A ($3\,^3D-2\,^3P$) and 3888 A ($3\,^3P-2\,^3S$) as a function of the electron temperature in the decaying plasma. The total light intensity in the visible range of the spectrum was examined by means of the 6217 photomultiplier, with a viewing angle of 3.0 degrees (see Fig. 3), whereas the spectral lines (in view of their low intensities) had to be observed with a much larger viewing angle of 30°.

The plasmas were produced in helium (12.6 to 30.3 mm Hg) by an $\sim$14-μsec (maximum) duration high-voltage dc pulse at a repetition frequency of 50 per second. This short-duration dc pulse was employed in an attempt to minimize the production of metastable atoms which are believed to contribute significantly to the behavior of the plasma, especially in the late afterglow.[14] It is not unlikely that the results of helium afterglow studies are conditioned by the method used to create the plasma.

At appropriate times in the afterglow the pulsed low-level (maximum 440 mw) microwave heating signal was propagated through the plasma medium. The resulting variations in the afterglow light intensity (owing to microwave heating of the electron gas) were detected by the photomultiplier and displayed on an oscilloscope (Tektronix 531). Figure 4 is a block diagram of the microwave circuitry employed.

THEORY OF THE EXPERIMENT

As is known, both atomic and molecular helium ions are present in an active electrical discharge in helium. After termination of the active discharge, the plasmas disintegrate through electron-ion recombination and diffusion. In the course of this disintegration, atomic helium ions are continuously converted to molecular helium ions through triple collisions with two normal helium atoms ($He^+ + 2\,He \rightarrow He_2^+ + He$). Phelps and Brown[15] have found the conversion frequency for this reaction to be $\nu_{conv} = 65p^2$ at 300°K gas temperature (where p is the helium gas pressure in millimeters of mercury). In such a decaying plasma, the loss of electrons due to volume recombination alone is described by the relation

$$-dn/dt = \sum_j \alpha_{rj} n_{ij} n,$$

where $n = \sum_j Z_j n_{ij}$ is the electron density. The symbols Z_j and n_{ij} are the charge and number density of the jth species of ions, respectively. α_{rj} is the recombination coefficient of electrons with jth species of ions. In our experiments, however, the gas pressures (12.6–30.3 mm Hg) and the times in the afterglow ($\sim$500 μsec) were chosen so that the number density of molecular helium ions was essentially equal to that of the electrons. Thus, the loss of charged particles due to volume recombination alone is given by

$$-dn_i/dt = -dn/dt = \alpha_r n_i n. \qquad (1)$$

The recombination process of the molecular helium ions with slow electrons most probably is dissociative,[3] either directly or indirectly through the intermediary of a neutral electronically excited helium molecule (He_2^*). If these excited molecules do not radiate in the spectral region of excited helium atomic lines (He′) which are observed here, the recombination may be ascribed to the reaction

$$He_2^+ + e \rightarrow He + He', \qquad (2)$$

where He′ is a helium atom in one of its higher excited states. These excited atoms, in cascading to the ground state, emit photons in the visible spectrum. In any case, the light intensity of the afterglow, if arising from electron-ion recombinations, is expected to be proportional to the rate of loss of electrons.

$$I = -\xi dn/dt = \xi \alpha_r n_i n, \qquad (3)$$

where ξ is a proportionality constant. In the plasmas of interest here, $n_i \simeq n$, so that

$$I = \xi \alpha_r n^2. \qquad (3a)$$

[14] D. E. Kerr, Johns Hopkins University Report, Department of Physics, July 31, 1960 (unpublished).

[15] A. V. Phelps and S. C. Brown, Phys. Rev. 86, 102 (1952).

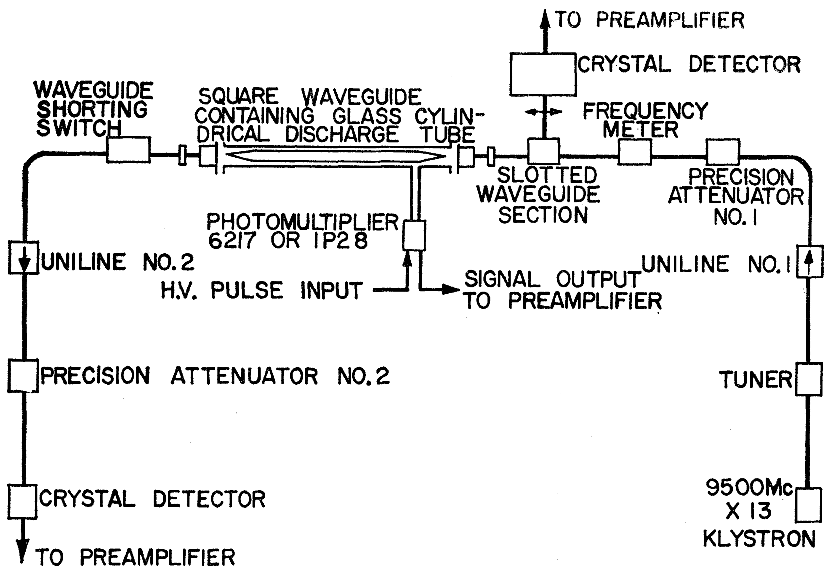

FIG. 4. Schematic diagram of the microwave instrumentation used in these experiments.

It is seen that

$$\frac{d\ln I}{d\ln T_e}=\frac{d\ln\alpha_r}{d\ln T_e}+2\frac{d\ln n}{d\ln T_e}, \tag{4}$$

where T_e is the electron-gas temperature.

We shall consider the case where the range of variation of electron temperatures is limited. In our experiment, temperatures ranged from approximately 300° to 1500°K, for which excitation and ionization of helium atoms by electron impacts, as well as enhancement of diffusion may be neglected. Therefore,

$$\frac{d\ln I}{d\ln T_e}=\frac{d\ln\alpha_r}{d\ln T_e}. \tag{5}$$

If α_r varies as $T_e^{-\zeta}$, the slope of $\ln I$ versus $\ln T_e$ plot should give the value of $-\zeta$.

The rate of energy absorption by the electron gas of the plasma per unit volume per unit time is $\sigma_r|E|^2$, where $|E|$ is the root mean square value of the electric field intensity. The symbol σ_r represents the real part of the complex conductivity of the ionized medium, and has the form

$$\sigma_c=\sigma_r+j\sigma_i=\frac{ne^2}{m}\left(\frac{\nu_{\rm eff}-j\omega}{\nu_{\rm eff}^2+\omega^2}\right), \tag{6}$$

where e is the electron charge, m is the electron mass, ω is the radian frequency of the microwave, and $\nu_{\rm eff}$ is the effective electron collision frequency for momentum transfer. In the case of the helium discharge plasmas of low degree of ionization ($<10^{-6}$) in the range of gas pressures used in our experiments, electron-molecule collisions predominate, and the momentum transfer cross section for electrons Q_m is practically constant for electrons with energies below 2 electron volts.[16] Thus

$$\nu_{\rm eff}=\tfrac{4}{3}Q_mN_m\langle v\rangle_{\rm av}, \tag{7}$$

for Maxwellian velocity distribution of the electron gas, which, in view of the high charge density and weak rf fields, is a good approximation. Here N_m is the number density of the gas molecules and $\langle v\rangle_{\rm av}$ is the average velocity of the electrons.

As a result of momentum transfer collisions with gas molecules and ions, the electrons gain thermal energy from the rf field. A fraction of this energy, however, is transferred to the gas molecules and ions in these collisions. The energy balance equation for the electron gas is

$$\frac{d}{dt}(\tfrac{3}{2}nkT_e)=\sigma_r|E|^2-G_{em}\nu_{em}[\tfrac{3}{2}nk(T_e-T_g)], \tag{8}$$

where k is Boltzmann's constant; T_g is the temperature of the background gas; G_{em} is the excess energy loss factor for the electrons colliding elastically with normal molecules and can be approximated by $2m/M$, where m is the mass of the electron and M that of the molecule. ν_{em} is the effective electron-molecule collision frequency. In Eq. (8), the effect of inelastic electron collisions with atoms has been neglected since the electron temperatures with which we are dealing are low (from 300° to $\sim$1500°K). The effects of electron-ion interactions also have been neglected inasmuch as $\nu_{em}\gg\nu_{ei}$ in our experiments. It is noted that the change of the electron density during the short period (20 μsec) of microwave heating is only a few percent at the most and therefore n can be considered to be constant. The solution of Eq. (8)

[16] S. C. Brown and W. P. Allis, Massachusetts Institute of Technology Technical Report MIT-283, Research Laboratory of Electronics, 1958 (unpublished); and J. M. Anderson and L. Goldstein, Phys. Rev. 102, 933 (1956).

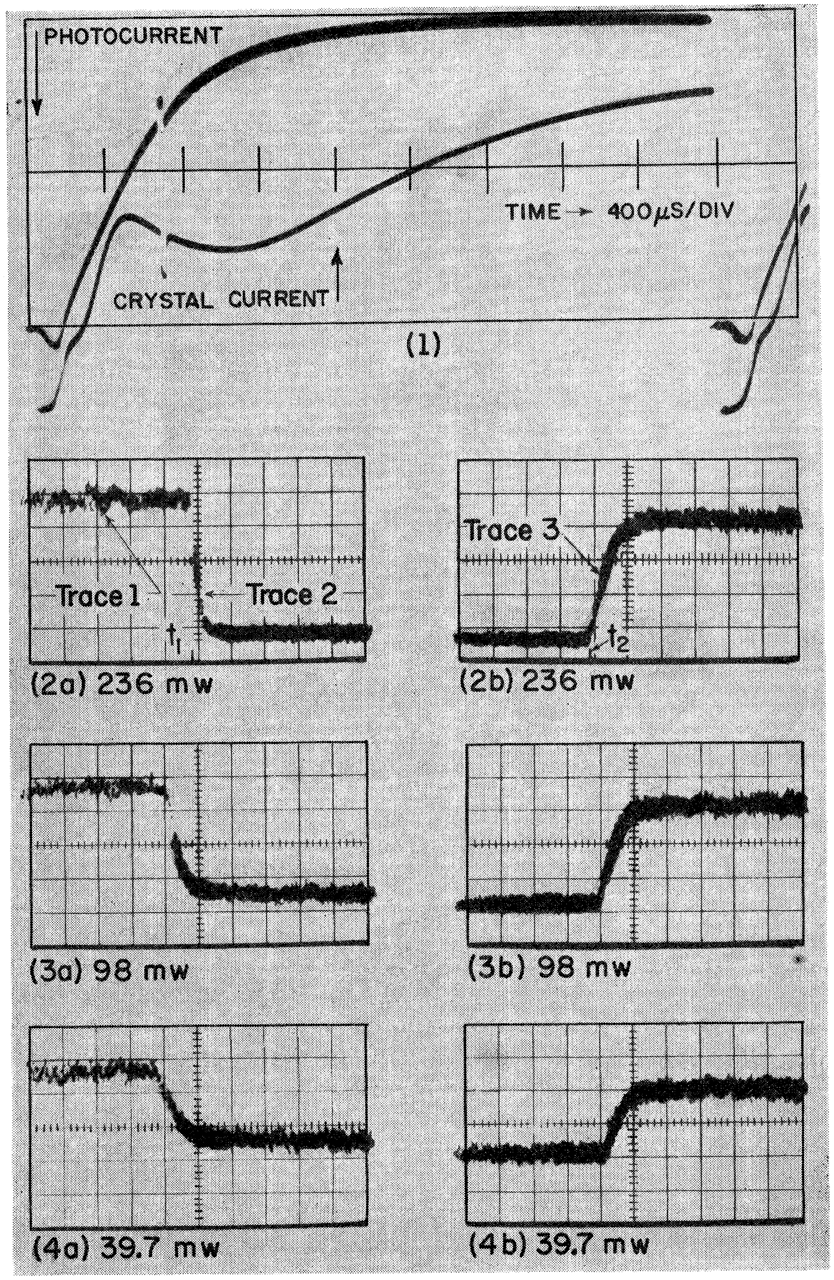

FIG. 5. The upper trace of (1) illustrates the phenomenon of afterglow light quenching which is produced by a pulsed microwave signal in a decaying helium plasma. The lower trace of (1) indicates the enhanced attenuation produced by this disturbing pulse on a low-level (~1 μw) cw microwave signal propagated through the same plasma. (2a), (3a), and (4a) are the leading transients of the afterglow light intensity in a helium room temperature plasma for three levels of incident pulsed microwave power; the time scale for these transients is 1 μsec per division. (2b), (3b), and (4b) are the corresponding relaxation transients of the afterglow light intensity of this plasma in the wake of the microwave pulse; the time scale for these transients is 2 μsecs per division. t_1 and t_2 are the times at which the pulse is switched on and off, respectively.

can be shown to be

$$T_e=(s-r)\left[\frac{1-A\exp(-t/\tau_1)}{1+A\exp(-t/\tau_1)}\right]^2,\quad \text{for}\quad t\geqslant 0, \tag{9}$$

where $t=0$ is when the microwave heating pulse begins, and

$$s=\left[r^2+\frac{1}{b}\left(T_g+\frac{d}{c}\right)\right]^{\frac{1}{2}}\quad {}^\circ\mathrm{K}, \tag{10a}$$

$$r=\frac{1}{2}\left(\frac{1}{b}-T_g\right)\quad {}^\circ\mathrm{K}, \tag{10b}$$

$$A=[(s-r)^{\frac{1}{2}}-T_g^{\frac{1}{2}}]/[(s-r)^{\frac{1}{2}}+T_g^{\frac{1}{2}}], \tag{10c}$$

$$\tau_1=[1+b(s-r)]/[2bcs(s-r)^{\frac{1}{2}}]\quad \mathrm{sec}, \tag{10d}$$

$$b=128Q_m^2N_m^2k/(9\pi\omega^2m)\quad {}^\circ\mathrm{K}^{-1}, \tag{10e}$$

$$c=8\sqrt{2}G_{em}Q_mN_mk^{\frac{1}{2}}/[3(\pi m)^{\frac{1}{2}}]\quad {}^\circ\mathrm{K}^{-\frac{1}{2}}\ \mathrm{sec}^{-1} \tag{10f}$$

and

$$d=16\sqrt{2}e^2Q_mN_m|E|^2/[9\omega^2(\pi k)^{\frac{1}{2}}m^{\frac{3}{2}}]\quad {}^\circ\mathrm{K}^{\frac{1}{2}}\ \mathrm{sec}^{-1}. \tag{10g}$$

In the steady state,

$$T_e=s-r. \tag{11}$$

The energy balance equation governing the relaxation phenomenon occuring immediately after removal of the microwave heating pulse is

$$\frac{d}{dt}(\tfrac{3}{2}nkT_e)=-G_{em}\nu_{em}[\tfrac{3}{2}nk(T_e-T_g)], \qquad (12)$$

whose solution is

$$T_e=T_g\left[\frac{1+A\exp(-t/\tau_2)}{1-A\exp(-t/\tau_2)}\right]^2, \quad \text{for} \quad t\geqslant 0, \qquad (13)$$

where

$$\tau_2=\frac{3(\pi m)^{\frac{1}{2}}}{8\sqrt{2}(kT_g)^{\frac{1}{2}}G_{em}Q_mN_m} \text{ sec.} \qquad (14)$$

It can be shown that $\tau_1\leqslant\tau_2$. The equal sign applies only when $E=0$.

The preceding analysis is suitable where the electric field intensity is uniform throughout the plasma. In the present experiments where the electric field intensity is not uniform over the cross section of the waveguide, a slight temperature gradient exists in a plasma of these dimensions and heat transport occurs owing to the thermal conductivity of the plasma. Furthermore, if density gradients are present, the effect of diffusion cooling should also be taken into account.

Taking these effects into consideration, the energy balance equation has the following form:

$$\frac{d}{dt}(\tfrac{3}{2}nkT_e)=\sigma_r|E|^2-G_{em}\nu_{em}[\tfrac{3}{2}nk(T_e-T_g)]-\nabla\cdot\mathbf{H}, \qquad (15)$$

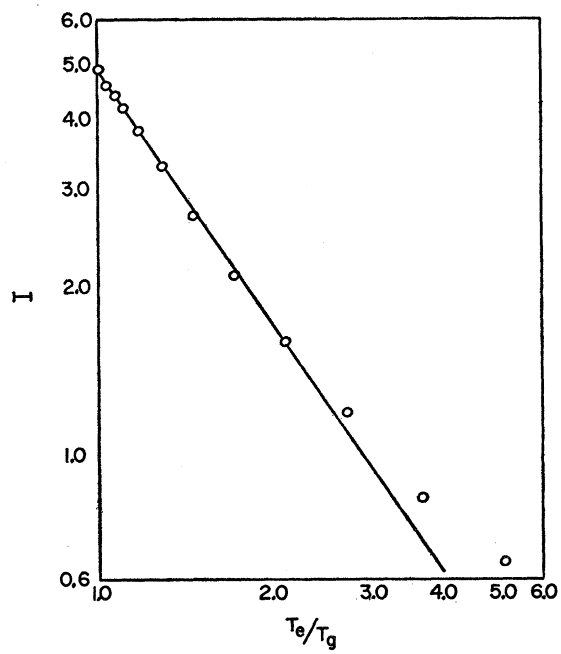

FIG. 6. Relative intensity of the afterglow light versus normalized electron temperature at gas pressure of 17.7 mm Hg and electron density of 1.62×10^{11} cm^{-3}.

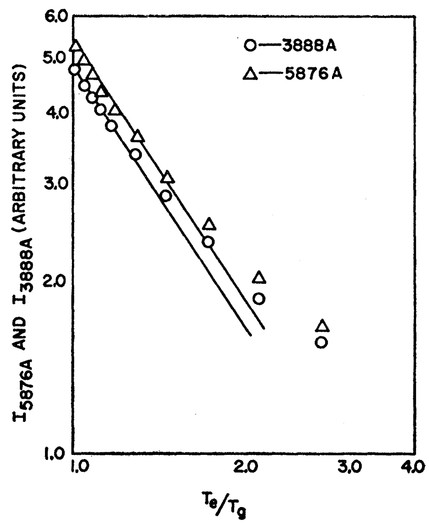

FIG. 7. Relative intensities of the 3888 A and 5876 A lines in helium afterglow versus normalized electron temperature at gas pressure of 17.7 mm Hg and electron density of 1.62×10^{11} cm^{-3}.

where $\mathbf{H}$ is the heat flux. It can be shown,[17] in the case of helium in the electron temperature range of interest,

$$\mathbf{H}=-\gamma_{\text{eff}}\nabla n-K_{\text{eff}}\nabla T_e, \qquad (16)$$

where γ_{eff} is the effective diffusion (ambipolar) cooling coefficient and K_{eff} is the effective thermal conductivity coefficient taking into account thermoelectric and gradient electric effects.

$$\gamma_{\text{eff}}=2kT_eD_a, \qquad (17)$$

and

$$K_{\text{eff}}=\frac{16}{3\pi}\frac{nk^2T_e}{m\nu}\left(1+\frac{\mu_i}{\mu_e}\right), \qquad (18)$$

where D_a is the ambipolar diffusion coefficient for the electrons and μ_i and μ_e are the mobilities of the positive ions and electrons in helium gas, respectively.[18]

From Eqs. (17) and (18), one can immediately show that

$$\frac{n\gamma_{\text{eff}}}{T_eK_{\text{eff}}}\simeq\frac{\mu_i}{\mu_e}\left(1+\frac{T_i}{T_e}\right), \qquad (19)$$

where T_i is the ion temperature. Therefore, in cases where $|\nabla n/n|$ and $|\nabla T_e/T_e|$ are of the same order

[17] C. L. Chen, Research Report, Coordinated Science Laboratory, University of Illinois (unpublished).

[18] In order to include the effect of electron-ion scattering, we generalize the effective electron collision frequencies to be $\nu=\nu_{em}+\nu_{ei}$, where

$$\nu_{ei}=\frac{e^4n_i\ln\{4\sqrt{2}\pi\epsilon_0^{\frac{3}{2}}k^{\frac{3}{2}}T_e^{\frac{3}{2}}/e^3n_i^{\frac{1}{2}}\}}{6\sqrt{2}\pi^{\frac{3}{2}}m^{\frac{1}{2}}\epsilon_0^2k^{\frac{3}{2}}T_e^{\frac{3}{2}}},$$

the expression of electron-ion collision frequency derived by Ginsburg [V. L. Ginsburg, J. Phys. U.S.S.R. 8, 253 (1944)]. It is interesting to note that, in the limit of $\nu=\nu_{ei}$, Eq. (18) gives the same expression as derived by Spitzer [L. Spitzer, Jr., *Physics of Fully Ionized Gases* (Interscience Publishers, Inc., New York, 1956)], except for a factor of approximately two.

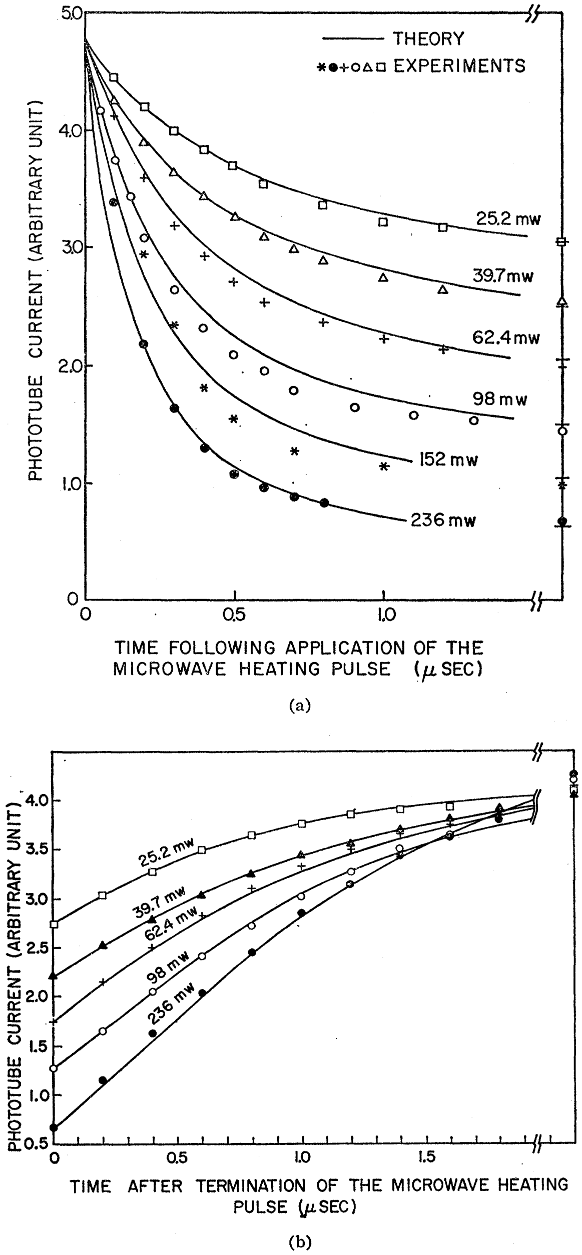

FIG. 8. (a) Transient response of the luminous intensity of the afterglow (at the time of initiation of the microwave pulse) versus time. The gas is purified helium of 17.7 mm Hg pressure and the electron density is 1.62×10^{11} cm^{-3}; (b) relaxation of the luminous intensity of the plasma (after termination of the microwave pulse) versus time. The gas is purified helium of 17.7 mm Hg and the electron density is 1.62×10^{11} cm^{-3}.

(valid approximately in the present experiments), the effect of diffusion cooling can be neglected.

An exact analytic solution of Eq. (15) is not available. However, in the present experiments, the third term on the right-hand side of Eq. (15) is about two orders of magnitude less than the first two terms, therefore one can treat the heat flow as a perturbation term. For the steady state,

$$T_e=T_g+\frac{2e^2|E_0|^2}{3km\omega^2G_{em}}\Delta C, \tag{20}$$

at $x=0$ (see Fig. 13), $\omega^2\gg\nu_{em}^2$ and assuming $K_{\text{eff}}/G_{em}\nu_{em}$ to be constant (this last assumption will be relaxed later by an iteration technique),

$$\Delta C=\left[\left(\frac{\pi}{a}\right)^2+\frac{3knG_{em}\nu_{em}}{4K_{\text{eff}}}\right]\Big/\left[2\left(\frac{\pi}{a}\right)^2+\frac{3knG_{em}\nu_{em}}{4K_{\text{eff}}}\right]. \tag{21}$$

Upon comparing Eq. (20) with Eq. (11), it is easily seen that, if a parameter s' is defined as

$$s'=\left[r^2+\frac{1}{b}\left(T_g+\frac{d}{c}\Delta C\right)\right]^{\frac{1}{2}}, \tag{22}$$

the corrected electron temperature (at steady state) will be

$$T_e=s'-r, \tag{23}$$

rather than $T_e=s-r$ which was obtained without considering thermal conduction effects. Therefore, in order to compute electron temperatures, including the effects of thermal conduction processes arising from nonuniform electric fields within the plasma, it is necessary to

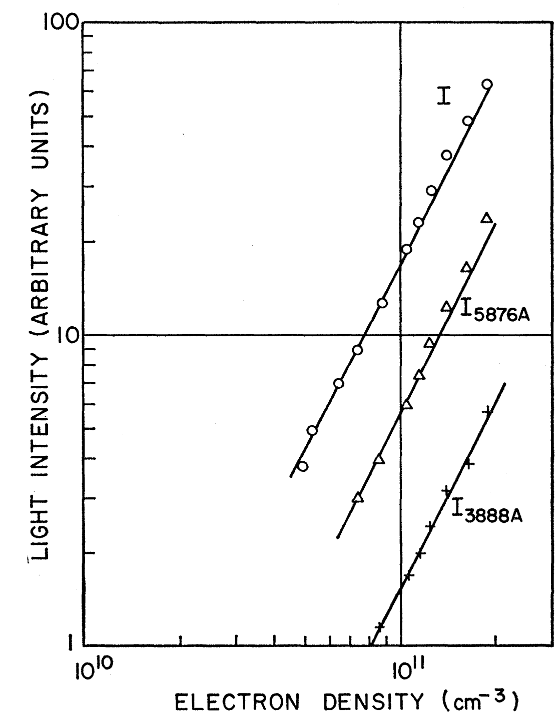

FIG. 9. Luminous intensity of the afterglow versus electron density at helium gas pressure of 17.7 mm Hg. The slopes of these curves are two.

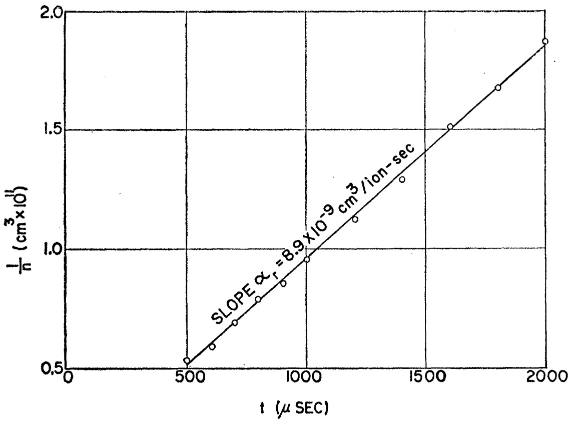

FIG. 10. Reciprocal of electron density versus time after termination of the discharge pulse. The helium gas at pressure 30.3 mm Hg.

substitute s' for s in all of the previously derived formulas.

The electric field intensity E_p in the plasma region where light intensity observations are made, is calculated in the following way. Let $z=0$ be the interface between plasma and free space in the square waveguide. Then at the interface,

$$P_i=P_r+P_t, \tag{24}$$

where P_i is the incident microwave power, P_r is the reflected power, and P_t is the transmitted power. In the present experiment, P_r/P_i was always less than 4×10^{-3}. Hence P_r can be neglected, and Eq. (24) gives

$$(E_p/E_0)^2=\beta_0/\beta_p=\lambda_g/\lambda_{g0}, \tag{25}$$

for a TE_{10} mode electromagnetic wave propagating in a homogeneous plasma medium. E_0 and E_p, β_0 and β_p, λ_{g0} and λ_g, are the electric field intensities, the phase constants and guide wavelengths in the air-filled and plasma-filled sections of the square waveguide, respectively. Assuming that the variation of the field in the direction of propagation is of the form $e^{-\gamma z}$ in the plasma section (where $\gamma=\alpha+j\beta_p$), the magnitude of the electric field intensity at a distance ρ from the interface

$$E_p=E_{p0}e^{-\alpha\rho}. \tag{26}$$

Since the attenuation constant $\alpha\propto\nu_{em}$ and $\nu_{em}\propto T_e^{\frac{1}{2}}$, the attenuation constant $\alpha\propto T_e^{\frac{1}{2}}$. The value of α for $T_e=300$°K (designated by α_0) is deduced from absorption loss measurements using very low microwave power probing signals ($<44\ \mu$w or $E\simeq0.033$ volt/cm maximum). For higher electron temperatures

$$\alpha=\alpha_0(T_e/300)^{\frac{1}{2}}\quad\text{nepers/cm}, \tag{27}$$

and the decibel power loss in the plasma section of length ρ is $A_d=8.7\rho\alpha_0(T_e/300)^{\frac{1}{2}}$ db. The square of the rms value of the electric field intensity at $z=\rho$ cm is then

$$E_p{}^2=P_t10^{-A_d/10}(\omega\mu_0\lambda_g/4\pi a^2). \tag{28}$$

(In the present experiment, $\rho=3$ cm.)

Equation (28) may be substituted into Eqs. (9) and (13) in order to compute the electron temperature by means of an iteration technique. This electron temperature may be then correlated with the corresponding light quenching measurements [via Eq. (5)] to yield the variation of the recombination coefficient as a function of electron temperature.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The phenomena of reduction of the recombination probability as a result of microwave heating of the electrons is demonstrated by a typical series of photographs of oscilloscope traces of the phototube current output (see Fig. 5). Each photograph in this figure shows the luminous intensity of the plasma at a temperature of 300°K as detected by the photomultiplier (trace 1) 600 μsec after termination of the gas discharge pulse. This T_e is determined from the measured electron-molecule collision frequency for momentum transfer. As a result of the introduction of the microwave pulse (not shown) at time t_1, the electrons are gradually heated. The transient response of the phototube current is shown by trace 2. Within a very short time interval (which, as has been shown, depends upon the gas pressure and the microwave power level), a steady state is reached at a somewhat elevated electron temperature (i.e., $T_e>T_g$). At time t_2, the microwave pulse is terminated and electrons, through collisions with neutral atoms and ions, gradually lose their excess energy and return to the neutral gas temperature. This relaxation is seen on the afterglow light intensity (trace 3). Electron temperatures are calculated from the incident microwave

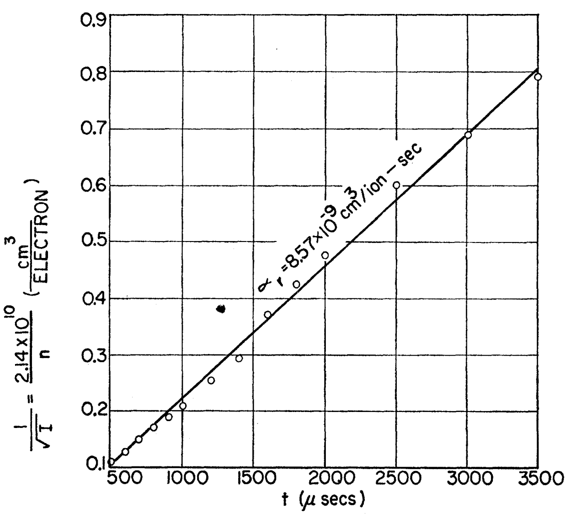

FIG. 11. Reciprocal of the *square root* of the phototube current versus time after termination of the discharge pulse. The helium gas pressure is 30.3 mm Hg.

power [using Eq. (23)] and normalized to the neutral gas temperature. A log-log plot of the measured luminous intensity I of the afterglow as a function of these normalized electron temperatures is shown in Fig. 6. Similar plots for the 5876 A and 3888 A lines (under the same experimental conditions) are shown in Fig. 7. The slopes of these curves are $-\frac{3}{2}$. According to Eq. (5), this implies that

$$\alpha_r \propto T_e^{-\frac{3}{2}}.$$

If, at a given time t in the afterglow, it is assumed that $I \propto T_e^{-\frac{3}{2}}$, Eqs. (9) and (13) will take the forms:

$$I(t)=I_1(0)\left(\frac{1-A}{1+A}\right)^3\left[\frac{1+A\exp(-t/\tau_1)}{1-A\exp(-t/\tau_1)}\right]^3, \quad t\geqslant 0 \quad (29)$$

and

$$I(t)=I_2(0)\left(\frac{1+A}{1-A}\right)^3\left[\frac{1-A\exp(-t/\tau_2)}{1+A\exp(-t/\tau_2)}\right]^3, \quad t\geqslant 0 \quad (30)$$

respectively, for the "leading" and the "trailing" transients of the light quenching. $I_1(0)$ and $I_2(0)$ are the initial values of the light intensity at the start of the transients.

Measurements of the transients are made from enlarged photographs of the quenched light intensity as a function of time. Typical results are shown in Figs. 8(a) and 8(b). These experimental observations are compared with corresponding values predicted by Eqs. (29) and (30). The close agreement of the observed and theoretically predicted quenched light intensities (as functions of time) further supports the $\alpha_r \propto T_e^{-\frac{3}{2}}$ relation governing the electron-ion recombination coefficient in a decaying pure helium plasma.

Equation (3) assumes that the afterglow light intensity of a plasma is proportional to its electron-ion volume recombination rate. Plots of the logarithm of observed electron densities (as measured by pulsed microwave techniques) vs the logarithm of observed luminous intensities (as measured by pulsed photomultipliers) during helium afterglows have slopes of two over a range of electron densities from 20×10^{10} to 4×10^{10} per cc (Fig. 9). Also measurements were made to determine the recombination coefficient in helium at $T_e=T_g=300°$K, both by microwave and optical means. Figure 10 is a plot of $1/n$ versus t for helium at a pressure of 30.3 mm Hg, whose slope has a value of 8.9×10^{-9} cm^3/ion sec for the electron-ion volume recombination coefficient. Figure 11 is a plot of $1/\sqrt{I}$ versus t for the same experiment. The value of α_r determined by these two methods differs by less than $\pm6\%$ and is independent of gas pressure in the pressure range studied (Fig. 12). The excellent agreement of the time behavior of the afterglow light intensity with that of n^2 seems to confirm our assumption that the light intensity is the result of an electron-ion volume recombination process.[19]

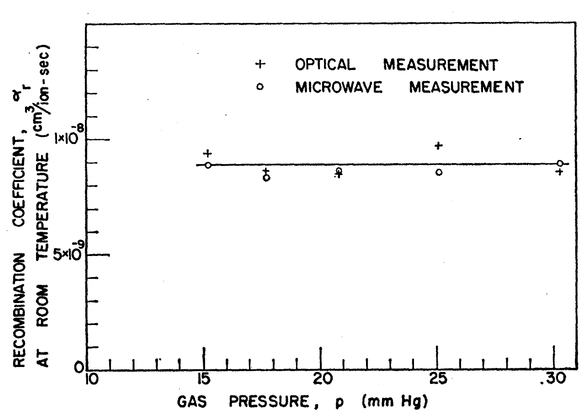

FIG. 12. Measured values of the room temperature effective recombination coefficient for plasmas established in pure helium as a function of gas pressure.

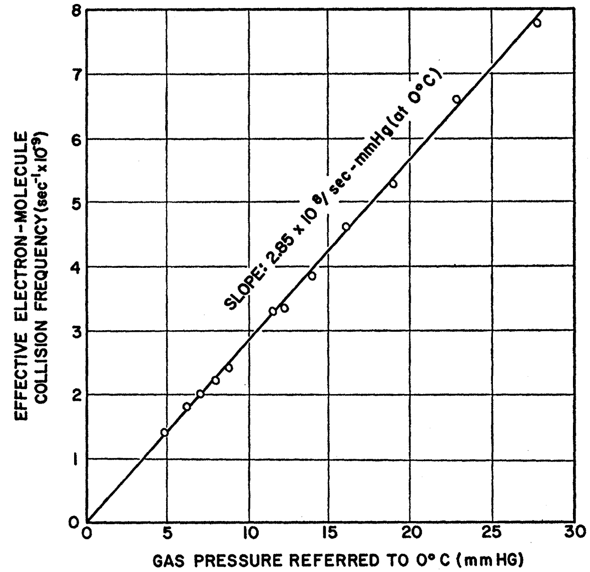

FIG. 13. Effective electron-molecule collision frequency as a function of pure helium gas pressure. This value of ν_{em} corresponds to a cross section of $(5.6+5\%)\times10^{-16}$ cm^2.

Further, it has been assumed that the observed "quenching" of the afterglow light intensity by pulsed microwaves was largely the result of a reduced electron-ion volume recombination rate brought about by microwave heating of the electron gas. However, two other mechanisms may contribute to this phenomenon, namely, ambipolar diffusion of electrons and ions and dissociation of helium molecular ions by electron impacts. Since the ambipolar diffusion coefficient $D_a \propto (1+T_e/T_i)$, increased electron temperature may result in enhanced diffusion of electrons and ions to the

[19] Donald E. Kerr and Claude S. Leffel, Jr., Bull. Am. Phys. Soc. 4, 113 (1959); and R. A. Johnson *et al.*, Phys. Rev. **80**, 376 (1950) have reported the existence of band spectra in helium afterglow plasma. However, our experimental arrangement did not permit us to determine whether or not such band spectra were present in significant intensities. Hence, correlation of the band spectra intensities with electron density and temperature could not be made.

plasma boundaries. If such an enhanced diffusion were responsible for the observed "quenching," the electron density at the conclusion of the microwave pulse should be appreciably reduced below its value at the beginning of the pulse. Since the light intensity is proportional to n^2, the afterglow light intensity also should not return to its initial value at the conclusion of the microwave pulse. Such a loss of electrons (or light intensity) was not observed experimentally.

"Quenching" can also be produced by the dissociation of molecular helium ions by electron impacts via the reaction

$$He_2^+ + e \rightarrow He + He^+ + e.$$

The electron energy required for this reaction is of the order of two electron volts.[20] Since the maximum electron temperature (generated by microwave heating of the electron gas) involved in these experiments was approximately 1500°K, the fraction of the plasma electrons possessing sufficient energy to cause the above reaction is far too small to be responsible for the observed "quenching."

A similar argument can be made concerning the possibility of exciting metastable helium atoms by electron impact (the nearest radiating state, the $2\,^3P$, lies 1.14 ev above the $2\,^3S$ metastable state). The principal loss mechanism for both singlet and triplet metastable helium atoms (in our geometry) is a diffusion mechanism.[21]

[20] L. Pauling, J. Chem. Phys. **1**, 56 (1933); S. Weinbaum, J. Chem. Phys. **3**, 547 (1935); W. Weizel, *Bandenspektron* (Akademische Verlagsgesellschaft, Leipzig, 1931), pp. 255–270; and G. Hersberg, *Spectra of Diatonic Molecules* (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1950).

[21] A. V. Phelps, Scientific paper 6-94439-6-P*s*, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania (unpublished).

The value of Q_m adopted in the present work was obtained from the microwave measurements of the effective electronatom collision frequency (Fig. 13). It gives a value of $(5.6\pm5\%)\times10^{-16}$ cm^2 for Q_m (the corresponding value of P_m—the electron collision probability for momentum transfer—is 20 ± 1 cm^{-1}−mm Hg^{-1}), which is in agreement with other authors.[16,22]

Admission of small amount of neon (as an impurity) into the purified helium gas radically changes the ionic constituents in the decaying plasma. The effective recombination coefficient, as well as its temperature dependence studied by light quenching, is strongly dependent on the neon impurity concentration. The observed values of Q_m were essentially unchanged, however.

In conclusion, the above-described afterglow light quenching experiments, as evidenced by both the percentage of quenching and the quenching transients, demonstrate that the electron-ion volume recombination coefficient in pure helium depends upon the plasma electron temperature to the minus three-halves power. This result appears to agree with Bates' theory[3] for a dissociative recombination process.

ACKNOWLEDGMENT

We wish to thank Professor D. E. Kerr of Johns Hopkins University for his report[14] in which a detailed study of problems associated with the work discussed here has been summarized.

[22] A. V. Phelps, O. T. Fundingsland, and S. C. Brown, Phys. Rev. **84**, 559 (1951); J. L. Hirshfield and S. C. Brown, J. Appl. Phys. **29**, 1749 (1958); D. Formato and A. Gilardini, Fourth Internation Conference on Ionization Phenomena in Gases, Uppsala, 1959 (unpublished); and A. V. Phelps, J. L. Park, and L. S. Frost, Phys. Rev. **117**, 470 (1960).

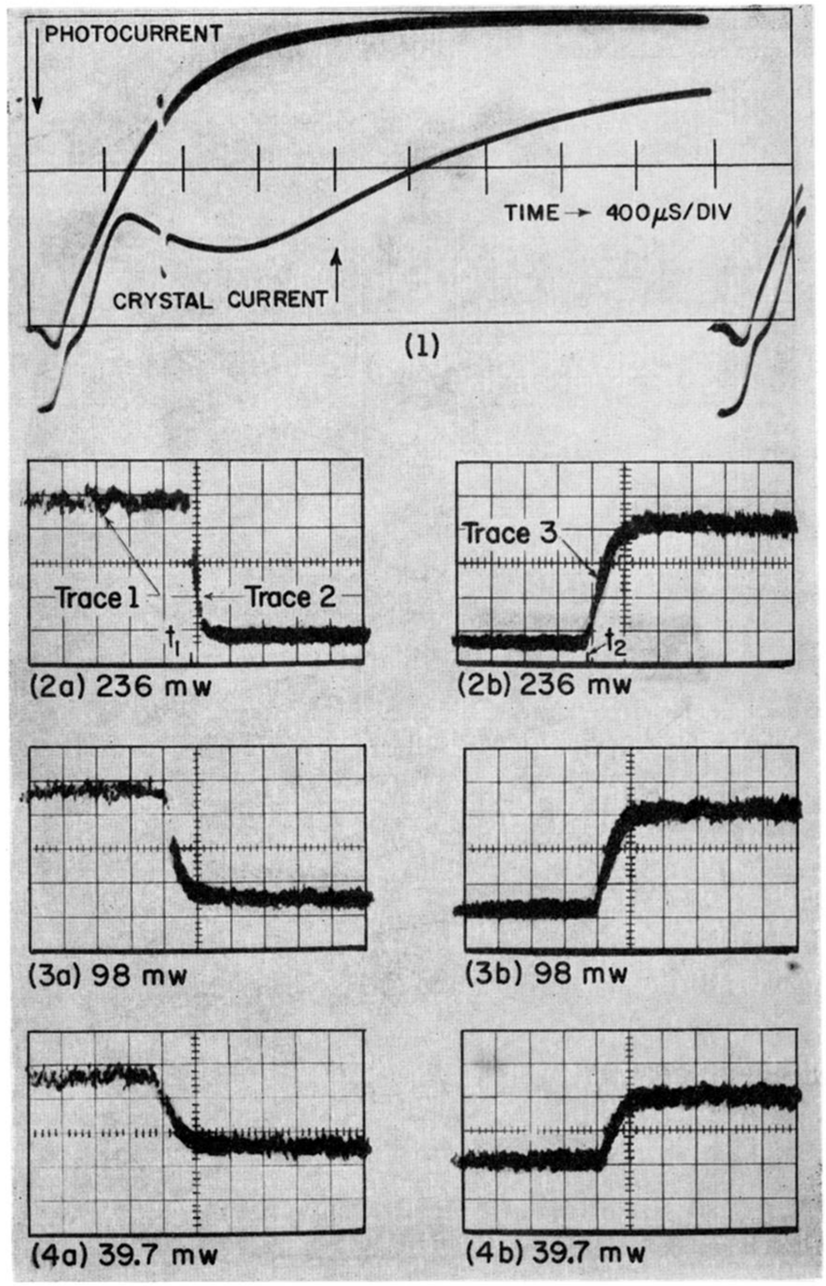

FIG. 5. The upper trace of (1) illustrates the phenomenon of afterglow light quenching which is produced by a pulsed microwave signal in a decaying helium plasma. The lower trace of (1) indicates the enhanced attenuation produced by this disturbing pulse on a low-level (~1 μw) cw microwave signal propagated through the same plasma. (2a), (3a), and (4a) are the leading transients of the afterglow light intensity in a helium room temperature plasma for three levels of incident pulsed microwave power; the time scale for these transients is 1 μsec per division. (2b), (3b), and (4b) are the corresponding relaxation transients of the afterglow light intensity of this plasma in the wake of the microwave pulse; the time scale for these transients is 2 μsecs per division. t_1 and t_2 are the times at which the pulse is switched on and off, respectively.