RECOMBINATION IN A HELIUM PLASMA*

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Experiments have shown that electron-ion recombination in gas discharges usually proceeds at a rate well in excess of the direct radiative rate. In weakly ionized discharges the experimental results appear to be moderately well explained by the process of recombination via the dissociation of molecular ions.[1] However, the rapid recombination observed in highly ionized discharges[2] appears difficult to explain by the molecular dissociation process. D'Angelo has recently suggested[3] that the dominant recombination mechanism in highly-ionized, low-temperature plasmas may be the inverse process of collisional ionization, i.e., the capture of an electron by an ion in a collision between the ion and two electrons. In this Letter we present experimental confirmation of the dominance of this three-body recombination in a low-temperature helium plasma.

Measurements were performed on magnetically confined plasmas in the B-1 stellarator,[4] the vacuum tube of which is 450 cm long and 4.8 cm in diameter. The plasmas were produced by ionizing helium gas with a 150-volt, 20-kc/sec electric field induced around the plasma loop. With this mode of excitation it was possible to achieve a high degree of ionization, from almost 100% to 2% as the helium pressure was varied from 0.25 to 100 microns. After removal of the breakdown voltage the following properties of the decaying helium plasma were measured: (1) the electron density, from the phase shifts of 8.6- and 4.3-mm microwaves propagated transverse to the plasma column; (2) spectroscopic measures of the absolute intensity of emission of each line in the visible neutral helium spectrum; (3) relative variations in the intensity of the total light; and (4) the electron temperature, from impedance measurements[5] with a low-power 60-kc/sec signal induced around the plasma loop.

After removal of the breakdown voltage the electron temperature drops rapidly below one volt; then ionization by electron impact becomes negligible and the plasma loss is governed by diffusion and recombination. The electron density was observed to fall exponentially between 5×10^{13} and 3×10^{11} electrons cm^{-3}. The intensities of the individual spectral lines and the total light intensity decayed exponentially at the same rate. The electron temperature fell at a somewhat slower rate. As shown by the experimental data in Fig. 1, the plasma loss rate is roughly proportional to the square root of the neutral

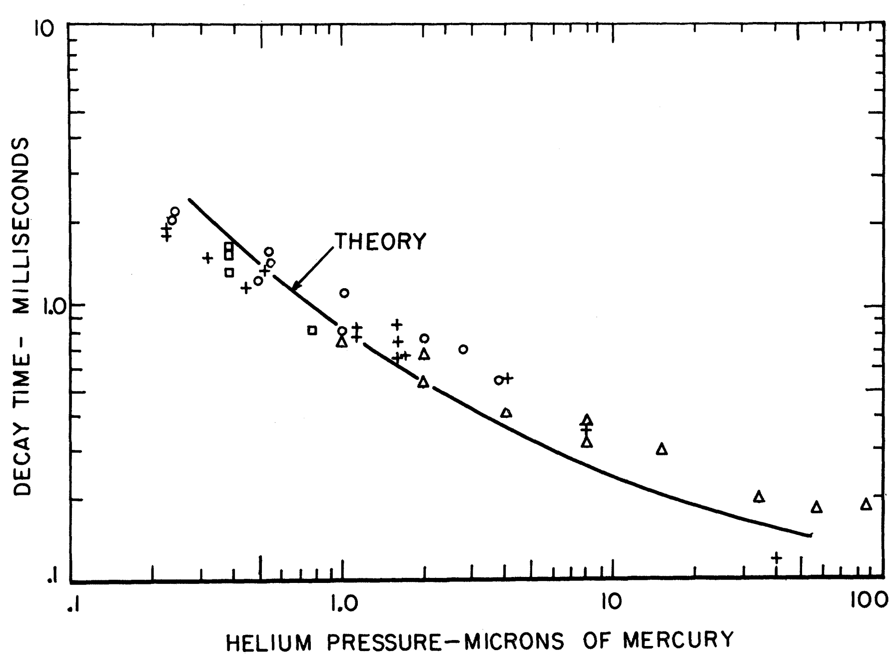

FIG. 1. Time constants for the initial decay of electron density in the stellarator following discharges in helium. The symbols represent experimental data obtained in a series of separate runs with the B-1 and B-3 stellarators.

pressure between 0.25 and 50 microns.

We believe that the plasma loss is caused primarily by recombination rather than by diffusion, because (1) the loss rate is independent of the confining magnetic field between 29 and 3.5 kilogauss; (2) the intensity of the light, which was shown by spectral analysis to originate from the recombining helium atoms, is proportional to the electron loss rate, independent of pressure and magnetic field; (3) the absolute intensity of the spectral lines accounts for substantially all of the electrons which disappear.

These basic features of the recombination process can be derived from the three-body recombination process. We have computed the capture rates for helium, taking into account all $\Delta l = -1$ radiative transitions. Collisional transitions between excited states have been neglected. The results show that the capture rate is a function only of the electron density, n, and the electron temperature, T, and can be approximately represented in the range of variables $10^{11} < n < 5\times10^{13}$ and $0.03 < kT < 0.3$ ev by the expression

$$dn/dt = 0.7\times10^{-19} n^{2.5}/(kT)^3, \qquad (1)$$

with n in $(\mathrm{cm})^{-3}$, t in sec, and kT in ev.

To predict the plasma loss rate one must know the time variation of the electron temperature. Since the electrons and the ions are almost in thermal equilibrium, the plasma temperature is determined by the interplay between two competing processes: energy loss via ion-neutral charge exchange and energy gain from metastable atoms formed by the recombination. The latter arises from the possibility that an atom in the $2\,^3S$ metastable level may undergo a superelastic collision with a plasma electron, returning 19.8 ev to the plasma. The time variation of the plasma energy can be written

$$3d(nkT)/dt = -n_0 n\sigma_i v_i \tfrac{3}{2}k(T - T_0) + n_m n\sigma_e v_e \epsilon, \qquad (2)$$

where n_0 and n_m are the neutral and the metastable densities, σ_i and σ_e are the cross sections for charge exchange[6] and metastable destruction,[7] v_e and v_i the electron and ion velocities, and ϵ the de-excitation energy of the helium metastable atom. If the gas pressure is low (<4 microns), the metastables flow freely to the walls, where they are destroyed. Under these conditions, if three-fourths of the electrons recombine to the $2\,^3S$ metastable level, the metastable density is given by

$$n_m = \tfrac{3}{4}\frac{dn}{dt}\frac{1}{n\sigma_e v_e + v_i/d}, \qquad (3)$$

where d is the average flight path, equal to the tube diameter. If the gas pressure is high (>15 microns), the metastables diffuse to the walls. Then

$$n_m = \tfrac{3}{4}\frac{dn}{dt}\frac{1}{n\sigma_e v_e + (0.48 v_0/d^2 n_0 \sigma_k)}, \qquad (4)$$

where σ_k is the metastable diffusion cross section.[8] The equations were integrated numerically, with the cross sections taken as $\sigma_i = 3\times10^{-15}$ cm^2, $\sigma_e = 8\times10^{-17}$ cm^2, $\sigma_k = 3.4\times10^{-15}$ cm^2. A comparison of the time dependence of the computed and measured electron density and temperature is given in Fig. 2. The analysis predicts successfully the initial exponential time variation of the electron density, the variation of this exponential with gas pressure (as shown in Fig. 1), and the break in the electron density curve when the electron temperature falls to room temperature. The absolute agreement must be considered fortuitous, since uncertainties in the cross sections, in the reflection of metastable atoms from the stainless steel walls,

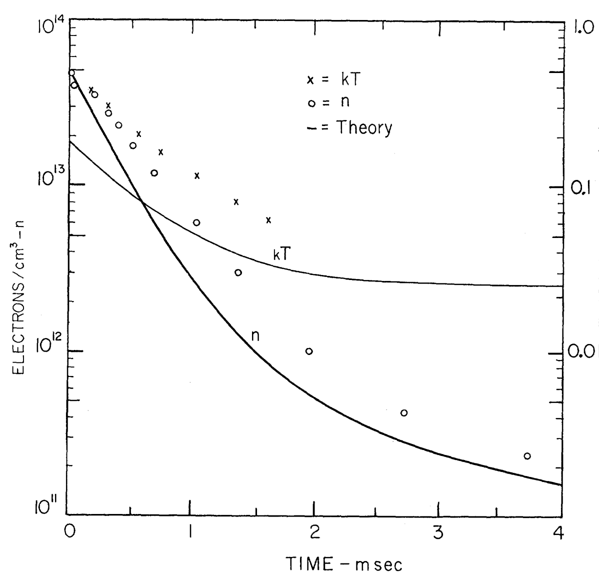

FIG. 2. Comparison of experimental (points) and theoretical (solid lines) time dependence of the electron density and electron temperature following discharges in helium. The helium pressure was 4 microns of mercury.

and in the absolute value of the three-body recombination coefficient give an estimated error of about a factor of three in the theoretical prediction of the electron decay rate. The theory predicts satisfactorily the time dependence of the electron temperature but not its absolute value. Whether this failure is related to the factors previously mentioned, to radial inhomogeneities in the plasma, or to the inapplicability of the standard conductivity-temperature relation is not known.

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ENERGY CONVERSION MECHANISM IN A BOUNDED MAGNETIZED CURRENT-CARRYING PLASMA*

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This Letter reports on an energy conversion mechanism in a bounded magnetized current-carrying plasma which supports the quasi-transverse electromagnetic waves and quasi-longitudinal space-charge waves of Hahn[1] and Ramo. These waves for a finite plasma are coupled. The coupling under certain circumstances can simulate a traveling-wave tube[2] type of interaction and thus can provide a means of transferring the kinetic energy of the drifting plasma to the electromagnetic energy, and vice versa. The essence of the analogy lies in the ability of the plasma to support slow electromagnetic waves. In a plasma composed of electrons and one kind of ion, analysis shows that for frequencies near electron or ion cyclotron frequencies the plasma indeed acts like a slow-wave structure.[3] In a drifting current-carrying plasma for frequencies in the vicinity of the ion cyclotron frequency, the ions will provide the slow-wave structure for circularly polarized transverse electromagnetic waves. This slow wave interacts with the longitudinal space-charge waves for electrons and thus grows at the expense of the drift energy of the electrons. The narrowness of the interaction region, which is indicative of the narrowness of velocity bandwidth for gain, forces one to choose the frequency of the electromagnetic wave close to and slightly below the ion cyclotron frequency. This choice consequently may permit the transfer of energy from the growing electromagnetic wave to the ions, and thus achieve plasma heating.[4] Thus, such a scheme, if efficient, can utilize the destructive energy of "runaway electrons" to heat the thermonuclear plasma. It is to be remembered that the critical temperature region for which the high-frequency plasma heating is efficient might be different from the temperature region for which runaway electrons appear; this scheme of energy conversion might act to prevent the instabilities due to runaway electrons even if not enhancing the plasma heating simultaneously. In addition, if such a traveling wave interaction between the streams of electrons and slow electromagnetic waves exists in the ionosphere, then it may explain certain types of very low frequency radio noise.

In order to understand this energy conversion mechanism quantitatively, a linear macroscopic harmonic analysis of the drifting plasma is carried out. For the sake of simplicity it is assumed that the circularly cylindrical plasma partially fills a perfectly conducting cylindrical waveguide and is subject to an axial static mag-