RECOMBINATION RADIATION OF CESIUM PLASMA IN A HOMOGENEOUS MAGNETIC FIELD

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The recombination radiation from cesium vapor plasma in a longitudinal magnetic field was investigated by spectrophotometric means. It was found that recombination emission is enhanced considerably with increasing field strength and diminishing gas pressure. This increase is due mainly to higher concentration of charge carriers near the column axis and, to a smaller degree, to decreasing electron temperature.

INTRODUCTION. STATEMENT OF THE PROBLEM

A homogeneous magnetic field H_z parallel to the positive column of a low-pressure gas discharge reduces the diffusion of charge carriers from the plasma to the walls.[1] The mean lifetime τ of free carriers in the plasma should thus be lengthened. Consequently, when the current strength i in the column is maintained unchanged, the average concentration of free electrons and ions n_e should increase, while the electron temperature T_e and the longitudinal electric field strength E_z should be reduced.[2] These conclusions are confirmed by probe measurements in helium.[3]

The longer lifetime τ in a field H_z should also increase the probability of volume recombination in the plasma,[4,5] which can then possibly exceed surface recombination on the walls. This effect should be manifested externally by enhanced intensity I of recombination radiation from the plasma. However, in investigations of recombination radiation from cesium plasma in a longitudinal magnetic field, Davies[6] found that, contrary to expectations, application of the field produces almost no changes in I and n_e, while T_e is increased slightly instead of being decreased.

We have performed a new investigation of recombination radiation from cesium plasma,* in order to check the foregoing hypotheses regarding the influence of a magnetic field on the probability of volume recombination. We aimed to determine the influence of the magnetic field on the intensity of electron recombination in an electropositive gas and also on the concentration and temperature of electrons in the plasma.

*E. Mikhalets assisted with some of the experimental work.

EXPERIMENTAL CONDITIONS AND TECHNIQUE

Spectrophotometric measurements were obtained for one of the recombination bands, the 6P "series limit continuum," in cesium vapor plasma. For a Maxwellian velocity distribution of the plasma electrons the spectral intensity distribution in the investigated band is given by Mohler and Boeckner[7,8] as

$$I(\nu) = \mathrm{const}\cdot n_e^2 T_e^{-3/2}\nu^{-1}\exp\left[-h(\nu-\nu_1)/kT_e\right],$$

where ν_1 is the frequency limit of the levels at which free electrons are captured. The electron temperature and concentration in the plasma were determined from this relation.

A stationary plasma was produced in a discharge tube 40 cm long and 2.5 cm in diameter. A cylindrical probe along the tube axis was used to measure plasma parameters, simultaneously with the optical measurements. The cesium vapor pressure varied from 2×10^{-3} to 0.13 mm Hg. The tube was placed in a homogeneous magnetic field generated by two solenoids that were separated by a gap through which the central portion of the tube was focused on a UM-2 monochromator. A photomultiplier was used to detect the radiation.

Photometric measurements were performed at several points of the recombination continuum, from its threshold at 4940 A to 4400 A. A standard temperature-calibrated tungsten lamp was used to record the spectral characteristic of the photomultiplier for this region.

The measured spectral distribution was appreciably distorted, especially at low pressures, by the bright Cs doublet $8P_{1/2,3/2}-6S_{1/2}$, which was scattered in the optical system and was superposed on the recombination band at the monochro-

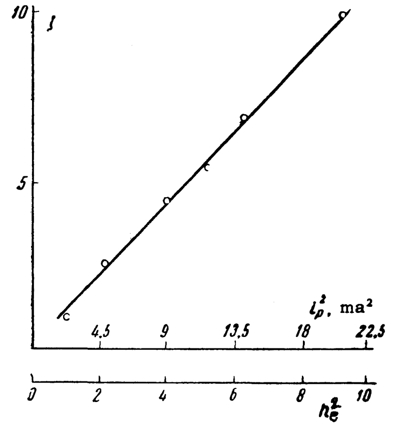

FIG. 1. Recombination radiation as a function of electron concentration. $p = 2.8 \times 10^{-2}$ mm Hg. H = 0.

mator exit. The doublet was excluded as follows. At the lowest values of the pressure and current density, when volume recombination in the plasma can practically be neglected, the intensity distribution was measured in the studied spectral interval; under these conditions the spectrum is determined completely by the scattered light. This distribution does not depend on the discharge conditions, which affect only the intensity of the doublet. Therefore the measured intensity of one of the cesium lines can be used under different discharge conditions to compute the scattered light intensity for any spectral region, thus permitting suitable correction of the recombination radiation measurements.

The spectral function $I(n_e)$ was recorded as a check to determine whether our measurements actually represented recombination radiation. The relative electron concentration was determined by measuring i_p, the ion current to the probe. n_e was varied by changing the discharge current i. Figure 1 shows the result $I \sim n_e^2$, as was to be expected for radiative recombination in two-body collisions.

BASIC EXPERIMENTAL RESULTS

1. The imposition of a magnetic field on a plasma enhances considerably the intensity I of recombination radiation (see the table), especially at low pressures. The simultaneous constriction of the positive column is observed; this effect is magnified, as expected,[9,10] with reduced cesium pressure and with growth of the factor $\omega_e\tau_e\omega_p\tau_p$ determining the effect of the magnetic field on the plasma.

2. The electron temperature T_e was determined from the slopes of the straight-line plots of $\ln[\nu I(\nu)]$ vs ν (Fig. 2). The straight line provide evidence of a Maxwellian electron distribution. The table gives values of T_e at different cesium pressures and in different magnetic fields. The table also includes values of T_e derived from probe measurements at H = 0, and the relative electron concentrations $n_e(H)/n_e(0)$ obtained from optical measurements. The last column gives the measured relative density of the ion current to the probe, $j_p(H)/j_p(0)$. A comparison of the fourth and fifth columns, and of the sixth

Pressure, 10^{-3} mm Hg	H, oe	$I(H)/I(0)$	T_e, °K From spectrum	T_e, °K From probe current	$n_e(H)/n_e(0)$	$i_p(H)/i_p(0)$
82	0	1		4200	1	1
	330	17			4.1	3.7
	660	38			6.0	5.7
	980	54			7.3	6.9
18	0	1	3700	3600	1	1
	330	2.6	3300		1.6	1.5
	660	4.8	3070		2.2	2.0
	980	7.3	3040		2.7	2.55
	1300	8.4	2550		2.9	3.08
36	0	1	3080	2900	1	1
	330	1.32	2850		1.14	1.18
	660	1.83	2800		1.33	1.35
	980	2.36	2670		1.49	1.53
	1300	2.64	2500		1.56	1.74
74	0	1	2640	2700	1	1
	330	1.19	2580		1.09	1.12
	660	1.28	2470		1.12	1.2
	980	1.37	2450		1.15	1.3
	1300	1.3	2370		1.12	1.35
130	0	1	2420	2100	1	1
	330	1.07	2440		1.03	1.07
	660	1.09	2410		1.04	1.08
	980	1.08	2400		1.04	1.08
	1300	0.98	2360		1.0	1.09

The data are given for the discharge current density j = 0.5 amp/cm².

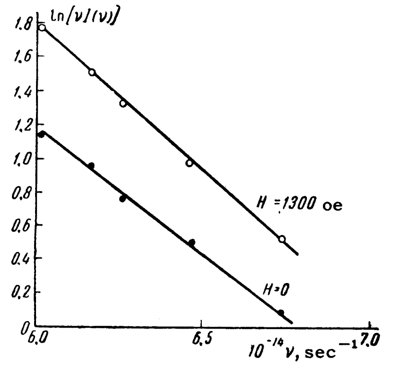

FIG. 2. Graphs used to determine the electron temperature T_e at $p = 36 \times 10^{-3}$ mm Hg.

and seventh columns, shows completely satisfactory agreement between the optical and probe measurements; the discrepancies lie within the limits of experimental error.

The table shows that the concentration n_e grows with increase of H_z for a given current strength; the effect becomes more pronounced as the gas pressure is reduced. On the other hand, the electron temperature T_e drops; this effect is also more pronounced as the pressure is reduced. When the pressure was raised to 0.13 mm we observed practically no influence of magnetic fields up to 1300 oe.

DISCUSSION OF RESULTS. CONTROL EXPERIMENTS

1. Our results agree with the previously derived[4,5] increase, in a magnetic field, of the fraction of charged particles disappearing from the plasma through volume recombination. The lowering of the temperature T_e and the enhanced axial concentration of charged particles in the magnetic field agrees with diffusion theory.

2. The enhancement of recombination radiation in a plasma subjected to a magnetic field is associated a) with the constriction of the positive column and the consequently increased concentration of charged particles along the discharge axis, and b) with the lowered electron temperature resulting in a larger recombination coefficient. A calculation shows that the second cause does not account for more than 10% of the observed enhancement of recombination radiation.

3. In analyzing the causes of the discrepancy between our results and those of Davies[6] obtained in the same range of cesium pressures, considerable differences in the diameter of the positive column and in the discharge current density must be noted. In Davies' investigation the diameter was one-fifth of ours, while the current density was one order of magnitude greater than in our experiments.

The effect of the latter circumstance was checked by performing measurements at different densities of the discharge current j. The measurements of T_e given in Fig. 3 show a diminishing

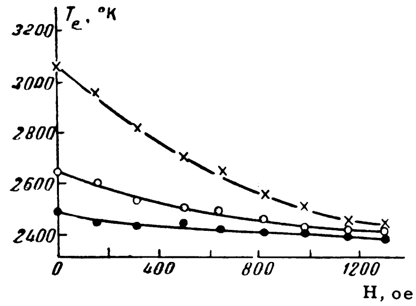

FIG. 3. Electron temperature vs magnetic field at different current densities. × – j = 0.2 amp/cm²; ○ – j = 0.3 amp/cm²; ● – j = 0.5 amp/cm². p = 0.13 mm Hg.

influence of the magnetic field on T_e as the current density increases. A similar conclusion follows from the data for the recombination radiation intensity and the charged particle concentration at $p = 0.2 \times 10^{-2}$ mm and H = 1300 oe:

j, amp/cm²	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0
$I(H)/I(0)$:	20	18.5	14.2	11.5	8.8	5.7	3.8	2.9
$n_e(H)/n_e(0)$	4.4	4.0	3.6	3.2	2.8	2.25	1.74	1.64

The high current density (5 amp/cm²) probably prevented Davies from observing the enhancement of recombination radiation and other effects induced by a magnetic field in a discharge with low current density. At the high degree of gas ionization (some tens percent) that characterized Davies' experiments, the electron and ion diffusion rates evidently depended on their Coulomb interaction rather than on collisions with neutral atoms. When electron-ion collisions are taken into account the flux of charged particles to the walls in directions normal to the magnetic field is given by[11]

$$\Gamma_{\perp} = -\frac{D_a^0 \nabla n}{1 + \omega_e \omega_p / \nu_{pa} (\nu_{ea} + \nu_{ep})},$$

where D_a^0 is the coefficient of ambipolar diffusion at H = 0, ω_e and ω_p are the Larmor frequencies of electrons and ions, and ν_{pa} etc. are the frequencies of collisions between ions and atoms, electrons and atoms etc. The frequency of electron-ion collisions is

$$\nu_{ep} = \frac{4}{3}\sqrt{2\pi}\,\Lambda n\,(e^2/kT_e)^2\,(kT_e/m)^{1/2},$$

where $\Lambda = {}^3\!/_2 \ln(3kT_e/2\sqrt{2}\,\pi^{1/3}e^2 n^{1/3})$ is the Coulomb logarithm. Calculations performed subject to the conditions obtaining in Davies' experiments, i.e., $p = 10^{-2}$ mm, $H = 1000$ oe, and $n = 10^{13}$ cm^{-3} (corresponding to ~ 10% cesium ionization) lead to a value of ν_{ep} that is one order of magnitude greater than ν_{ea}. This gives the ratio $\omega_e\omega_p/\nu_{pa}(\nu_{ea} + \nu_{ep}) \approx 0.1$, so that there is only a small reduction of charged particle flux to the walls in a magnetic field. Under the conditions of Davies' experiments we can therefore not expect any appreciable influence of the magnetic field on the electron parameters and recombination processes in a plasma.

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