PHYSICAL REVIEW A VOLUME 24, NUMBER 2 AUGUST 1981

Density dependence of the intensity ratio of resonance and intercombination transitions in C V

H.-J. Kunze*
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 10 February 1981)

The intensity ratio of the resonance line and the intercombination line in heliumlike C V has been measured in plasmas produced in a theta-pinch discharge and is compared with theoretical models. Electron density and temperature were obtained from laser scattering measurements. The results suggest a weaker temperature dependence of the laboratory low-density ratio than now obtained theoretically.

The analysis of lines emitted from heliumlike ions in plasmas offers a rather powerful possibility for the diagnostics of astrophysical and laboratory plasmas. The high-lying metastable levels as well as doubly excited states give rise to a number of transitions displaying a temperature and density dependence different from transitions, for example, originating at levels of the singlet system. Selecting suitable lines thus allows the measurement of electron density and temperature, as well as of the departure from ionization equilibrium, simply from the observation of their intensity ratio. The almost equal wavelengths of the lines render, in addition, unnecessary absolute and even relative sensitivity calibrations of the complete optical detection system, making such measurements relatively straightforward.

These techniques have been increasingly applied in many investigations of solar flares and active regions of the sun,[1,2] as well as of tokamak plasmas[3,4] in the low-density regime; for high-density plasmas, they have become important in particular for the diagnostics of inertially confined plasmas or other laser-produced plasmas, where alternative techniques are not available.[5,6]

The analysis of the line emission essentially relies on various available theoretical atomic data which are constantly improved. Unfortunately, experimental verifications are nearly absent with the exception of very few measurements of relative and absolute electron-impact collision rates in theta-pinch plasmas.[7-10] In the following, we report measurements of the intensity ratio of resonance and the intercombination line emitted from C V ions in well-diagnosed plasmas produced in a theta-pinch device. These investigations are an extension of the early work,[8] where only very few values had been available. This ratio is of interest since in the high-density region it is practically a linear function of the electron density.

The dependence of this ratio over the complete density range has been discussed in detail by Gabriel and Jordan[1]:

$$R=\frac{I(2^1P_1-1^1S_0)}{I(2^3P_1-1^1S_0)}=\frac{A(2^1P_1-1^1S_0)}{A(2^3P_1-1^1S_0)}\frac{N(2^1P_1)}{N(2^3P_1)}. \quad (1)$$

Above some critical density N_e^{cr}, the 2^3S_1 and $2^3P_{0,1,2}$ levels as well as the 2^1S_0 and 2^1P_1 levels are collisionally coupled, and collisional transitions from the 2^3S and 2^3P levels to the continuum and to the singlet system become stronger than the radiative decay $2^3P_1-1^1S_0$. In this regime, one obtains a simple analytical expression for the ratio of the population densities, and R may be written as[1,8]

$$R=R_1+PN_e, \quad (2)$$

where

$$R_1=\frac{X(1^1S-2^1S)+X(1^1S-2^1P)}{X(1^1S-2^3S)+X(1^1S-2^3P)} \quad (3)$$

is the "laboratory low-density ratio" and

$$P=\frac{(R_1+1)X(2^3-2^1)+R_1S(2^3)}{\frac{1}{4}A(2^3P_1-1^1S_0)}. \quad (4)$$

P is independent of N_e and only a slow function of T_e. $S(2^3)$ is the ionization rate coefficient for the $n=2$ triplet levels, and the X's are "effective" rate coefficients for collisional transitions between the respective levels.

The ratio R was measured for heliumlike C V ions present as impurities in hot plasmas produced in a small theta-pinch device. The experimental techniques and the complete setup have been described in detail previously.[8] Electron density and temperature were obtained using Thomson scattering of a laser beam, the ion temperature was deduced from the Doppler profile of emission lines in the visible and uv spectral regions, and the length of the plasma column was obtained from the observation of the continuum intensity through small holes in the theta-pinch coil along its axis.

A 2.2-m grazing incidence monochromator (the grating had 1200 lines per mm) viewed the plasma column along its axis, and a diaphragm assured that only the center of the plasma was observed. After scanning the spectrum in the spectral region of interest, the ratio R was obtained by measuring the total line intensities at the peak of the C V emission and the background (entrance slit 20 μm, exit slit 30 μm). About ten discharges were averaged for each condition.

Different discharge conditions were adjusted by variation of the filling pressure, the filling gas, and the bias field. The low electron temperature, for example, was obtained with a filling pressure of 47-mTorr hydrogen, the low electron density in the third cycle of a discharge with 0.8-mTorr CH_4.

Table I shows the observed ratios in column R_{ex}, the first three columns giving electron density, electron temperature, and temperature of the C V ions. The calculated optical depth of the resonance line is shown in column τ_c, and finally, the column R_{ex}^{cor} contains the ratio corrected for radiative transfer as outlined in Ref. 7. The error of this corrected intensity ratio is estimated to be less than 20%; the experimental uncertainties of temperature and density are about 15%.

The question arises whether our ratio is influenced by satellite lines blended with the two observed transitions. Since all ratios were obtained time resolved in transient plasmas at a time when the concentration of the lithiumlike ionization stage was already very low, satellites caused by inner-shell ionization are certainly negligible. Also, while satellites resulting from dielectronic recombinations would be important for higher-Z elements, they are negligible for C V, as calculations by Bhalla *et al.* reveal.[11]

The lowest electron density obtained was 8×10^{14} cm^{-3}, and the ratio of $R = 2.2$ approaches the low-density value derived in Ref. 8 from corresponding measurements in O VII. This low-density limit corresponds to the ratio of effective collisional rate coefficients to the $n = 2$ singlet and triplet levels and is weakly temperature dependent. The effective rate coefficients X include contributions which result from excitation to higher levels followed by cascading.[1,12,13] This effect is practically negligible for the singlet system but rather considerable for the $n = 2$ triplet levels. In addition, it tends to reduce the dependence of R_1 on T_e. Computer calculations[13] show that the cascade effect for the total triplet excitation rate is $\simeq 0.4\exp(-0.21E_{13}/kT_e)$, where E_{13} is the excitation energy of the triplet levels. For $kT_e = \frac{1}{2}E_{13}$, this amounts to 26%.

The low-density ratio R_1 can be derived from the most recent calculations of Pradhan *et al.*[14] who included effects of resonances in their calculations. Column R_1 shows this ratio with the cascading contribution to the triplet levels included according to Ref. 13. (The same ratio derived from the close-coupling calculation of Wyngaarden *et al.*[15] is larger by less than 10%.)

The model [Eqs. (2)–(4)] contains the rate coefficient $X(2^3 \rightarrow 2^1)$ describing the excitation transfer from the $n = 2$ triplet levels to the $n = 2$ singlet levels. Following arguments of Bely,[16] which were supported by theoretical calculations for hydrogenic ions of infinite nuclear charge,[17] Gabriel and Jordan[1] (GJ) concluded that this rate coefficient indeed was negligible; however, in order to explain the experimental observations, they proposed as an additional process, collisional transfer from the $n = 2$ triplet levels to the singlet levels with $n \geq 3$ (rate coefficient $X_{3\geq}$) followed by cascade. This rate coefficient as well as the ionization rate coefficient $S(2^3)$ from Ref. 1 are shown in the table. Assuming that $\frac{2}{3}$ of the transfer collisions result in the emission of a resonance photon, the theoretical ratio thus calculated is given in column R_{GJ}. On the other hand, the calculations of Pradhan *et al.*[14] now reveal that resonances considerably enhance also the direct collisional transfer rates. Column $X(2^3 \rightarrow 2^1)$ shows their average rate coefficient, and R_{theor} the computed line intensity ratio with $X_{3\geq}$ now neglected.

Our experimental results confirm the earlier measurements where they overlap. The agree-

TABLE I. Comparison of experimental and theoretical line intensity ratios.

N_e (10^{15} cm^{-3})	kT_e (eV)	kT_i (eV)	R_{ex}	τ_c	R_{ex}^{cor}	R_1	$S(2^3)$ (10^{-10} $cm^3 s^{-1}$)	$X(2^3\rightarrow 2^1)$ (10^{-10} $cm^3 s^{-1}$)	$X_{3\geq}$ (10^{-10} $cm^3 s^{-1}$)	R_{GJ}	R_{theor}
0.8	190	2800	2.0	0.25	2.2	1.85	14.5	2.8	7.2	2.4	2.2
2.1	130	1000	2.24	1.11	3.2	1.4	11.4	4.2	7.6	2.3	2.2
2.5	170	1000	2.35	0.51	2.8	1.7	13.7	3.1	7.3	3.1	2.8
5.0	250	2200	4.9	0.14	5.1	2.4	16.3	2.1	6.7	6.6	5.7
5.3	250	2200	5.8	0.14	6.1	2.4	16.3	2.1	6.7	6.9	5.9
15	79	100	6.1	1.47	9.6	1.0	6.7	7.1	7.6	5.1	5.4

ment of R_{ex}^{cor} is somewhat better with R_{theor} than with R_{GJ} in the temperature range from 170 to 250 eV so that the proposed transfer $X_{3\geq}$ to $n \geq 3$ singlet levels becomes unnecessary. The experimental results, however, do not allow us to distinguish which transfer process dominates. The theoretical values are beyond the experimental uncertainty for the lower two temperatures. This suggests a much weaker temperature dependence of the low-density ratio R_1 than now obtained theoretically.

ACKNOWLEDGMENTS

It is a pleasure to thank A. H. Gabriel and H. R. Griem for valuable discussions. This work was supported by the U. S. Department of Energy.

---

*Present address: Institut für Experimentalphysik V, Ruhr-Universität, 4630 Bochum, West Germany.

[1]A. H. Gabriel and C. Jordan, in *Case Studies in Atomic Collision Physics*, edited by E. W. McDaniel and M. R. C. McDowell (North-Holland, Amsterdam, 1972), Vol. 2, Chap. 4.

[2]L. W. Acton and W. A. Brown, Astrophys. J. 225, 1065 (1978).

[3]M. Bitter, K. W. Hill, N. R. Sauthoff, P. C. Efthimion, E. Meservey, W. Roney, S. von Goeler, R. Horton, M. Goldman, and W. Stodiek, Phys. Rev. Lett. 43, 129 (1979).

[4]N. J. Peacock, M. H. Hughes, H. P. Summers, M. Hobby, M. W. D. Mansfield, and S. J. Fielding, in *Plasma Physics and Controlled Nuclear Fusion Research*, Proceedings of the VIIth International Conference, Innsbruck, 1978 (IAEA, Vienna, 1979).

[5]I. Yu Skobelev, A. V. Vinogradov, and E. A. Yukov, Phys. Scr. 18, 78 (1978).

[6]V. A. Boiko, S. A. Pikuz, and A. Ya Faenov, J. Phys. B 12, 1889 (1979).

[7]R. C. Elton and W. W. Köppendörfer, Phys. Rev. 160, 194 (1967).

[8]H.-J. Kunze, A. H. Gabriel, and H. R. Griem, Phys. Rev. 165, 267 (1968).

[9]W. Engelhardt, W. Köppendörfer, and J. Sommer, Phys. Rev. A 6, 1908 (1972).

[10]A. H. Gabriel and T. M. Paget, J. Phys. B 5, 673 (1972).

[11]C. P. Bhalla, A. H. Gabriel, and L. P. Presnyakov, Mon. Not. R. Astron. Soc. 172, 359 (1975).

[12]A. V. Vinogradov, I. Yu. Skobelev, and E. A. Yukov, Kvant. Elektron. (Moscow) 2, 1165 (1975) [Sov. J. Quantum. Electron. 5, 630 (1975)].

[13]R. Mewe and J. Schrijver, Astron. Astrophys. 65, 99 (1978).

[14]A. K. Pradhan, D. W. Norcross, and D. G. Hummer, Astrophys. J. (in press).

[15]W. L. van Wyngaarden, K. Bhadra, and R. J. W. Henry, Phys. Rev. A 20, 1409 (1979).

[16]O. Bely, Phys. Lett. 26A, 408 (1968).

[17]A. Burgess, D. G. Hummer, and J. A. Tully, Philos. Trans. R. Soc. London 266, 225 (1970).