Excitation of heliumlike B IV

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Measurements are reported for line-intensity ratios emitted from heliumlike B IV ions in a plasma with $N_e = 1.5\times10^{16}$ cm^{-3} and $kT_e = 175$ eV. The plasma was produced in a theta-pinch discharge. The analysis supports theoretical excitation rates calculated in the distorted-wave approximation, which include the effect of resonances.

Spectral lines emitted from heliumlike ions in plasmas are used rather commonly now for the diagnostics of laboratory[1-3] and astrophysical plasmas.[4] Earlier work is summarized specifically in Ref. 5. The characteristic features of the emission spectra have been described by Gabriel and Jordan[6] over a wide range of parameters from the low-density regime to high densities.

The interpretation of the spectral line intensities requires reliable excitation rate coefficients, and the data available as of 1980 have been reviewed by Henry.[7] It becomes evident that much theoretical work has been done to test these calculations, but only a few experiments.

Recently Fujimoto and Kato[8] constructed a collisional-radiative model for heliumlike ions considering 61 excited levels. In addition to excitation and deexcitation, ionization and recombination were included. It is obvious that in the most general case the emission coefficient ϵ of a line also depends on the density of the ionic species in the lithiumlike and hydrogenlike ionization stage. Introducing *effective* rate coefficients, we may write[9]

$$\epsilon = \frac{h\nu}{4\pi} N_e N_{\mathrm{He}} \left(X_{\mathrm{eff}} + \frac{N^{\mathrm{H}}}{N_{\mathrm{He}}} \alpha_{\mathrm{eff}} + \frac{N_{\mathrm{Li}}}{N_{\mathrm{He}}} S_{\mathrm{eff}} \right) \mathrm{W\,cm^{-3}\,s^{-1}} \ . \quad (1)$$

X_{eff} is the rate coefficient which, after all collisional losses, as well as cascading and emission into other lines from the same upper level, have been taken into account, gives the collisional-excitation rate leading to the emission of the specific line. Similarly, α_{eff} is the effective rate coefficient for recombination from the hydrogenlike ion, and S_{eff} is that for innershell ionization of ions in the lithiumlike stage, both contributing to this line. N_e, N_{H}, N_{He}, and N_{Li} are the densities of the free electrons and of the ions in the respective ionization stages.

In the following we report measurements of relative intensities of some lines emitted from B IV, and we compare the results with theoretical calculations.

The plasma was produced in a theta-pinch device, which has been described in detail previously, where measurements of ionization rates were reported.[10] Now small amounts of the gaseous compound B_2H_6 were added to the initial hydrogen filling of 1.6 Pa. The condition II of Ref. 10 resulted in a peak electron temperature of $kT_e = 235$ eV and an electron density of $N_e = 3.2\times10^{16}$ cm^{-3}. Both plasma parameters were obtained using Thomson scattering of a ruby laser beam. The length of the plasma column was derived from the continuum emission in the visible spectral region which was observed through small holes in the pinch coil.

The spectroscopic observations in the vacuum ultraviolet were carried out end-on using a 2.2-m grazing-incidence monochromator equipped with a p-terphenyl scintillator and a photomultiplier. A diaphragm assured that only the central part of the plasma column was viewed along the axis.

Through the other end of the discharge tube, a 1/4-m monochromator allowed the investigation of the emission in the visible and uv spectral region. The grazing-incidence instrument was calibrated *in situ* using the branching-ratio method as described in Ref. 11; the only additional line pair employed being the $2\,^3P_1 \rightarrow 1\,^1S_0$ and $2\,^3P_2 \rightarrow 2\,^3S_1$ transitions of B IV.

The temperature of the B IV ions was derived from the Doppler profile of the $2\,^3P_2 \rightarrow 2\,^3S_1$ transition at 282.17 nm, since the other two lines of the triplet were blended because of the Doppler broadening. A 1-m monochromator was available for this measurement. The temperature derived was 800 eV although a colder component of 330 eV was also present.

Preliminary estimates of the line intensities showed that the absolute experimental values were too low by about a factor of 4. The same result was obtained if other elements were added to the discharge for a cross check. This reveals that during the first implosion of the pinch discharge the added impurities are not swept along by the piston.[12] The total concentration of boron in the compressed plasma column is not known for this reason, and no absolute excitation rate coefficients can therefore be determined. Table I shows experimental line-intensity ratios at the peak of the B IV emission, which occurred at the time 2.4 μs after initiation of the main discharge. At this time, electron density and temperature were $N_e = 1.54\times10^{16}$ cm^{-3} and $kT_e = 175$ eV, respectively. The singlet lines were corrected for optical depth effects as described in Ref. 13. The reliability of this correction had been shown in Ref. 11.

The time development of the concentration of boron in the various ionization stages is very well known from the study of the ionization.[10] After $t = 6.5$ μs, 99% of the boron atoms have been completely ionized to the bare nucleus. With respect to the heliumlike ionization stage B IV, the plasma is in a rather rapidly ionizing regime. The time history of the line emission is strongly influenced by the rising electron density and temperature, and at the peak of the line emission the relative concentration of the B IV ions has already dropped from its maximum of 92% down to 49.3%. The relative concentration of the hydrogenlike ion has risen to 49% too, while that of the lithiumlike stage is negligible. Therefore, inner-shell ionization will certainly not contribute to the line intensities at their peak.

TABLE I. Experimental and theoretical line-intensity ratios for $N_e = 1.54\times 10^{16}$ cm^{-3} and $kT_e = 175$ eV.

	Experiment	Theory Ref. 17	Theory Refs. 20 and 21	Modified
$\frac{I(2^1P_1\to 1^1S_0)}{I(2^3P_1\to 1^1S_0)} = R$	106 ±30	124	148	125
$\frac{I(2^1P_1\to 1^1S_0)}{I(3^1P_1\to 1^1S_0)}$	5.8 ±0.9		7.3	6.2
$\frac{I(2^1P_1\to 1^1S_0)}{I(4^1P_1\to 1^1S_0)}$	17.1 ±3.4		22.6	19.2

On the other hand, with $N_H/N_{He} \simeq 1$, the effects of recombination have to be considered in Eq. (1). The dominant mechanism is dielectronic recombination. According to Burgess,[14] the total rate coefficient is $\alpha^d(175\text{ eV}) \simeq 2\times 10^{-13}$ cm^3 s^{-1}, which certainly is negligibly small in comparison with the rate coefficients for excitation, for example,

$$X(1^1S\to 2^1P) \simeq 2.2\times 10^{-10}\ \text{cm}^3\,\text{s}^{-1}$$

or

$$X(1^1S\to 4^1P) \simeq 1.2\times 10^{-11}\ \text{cm}^3\,\text{s}^{-1}\ .$$

For the analysis of our experimental data it is justified, therefore, to use a steady-state coronal model,[6] which connects the population densities of the upper levels only with the ground state of the heliumlike ion. The lifetimes of the upper states are the time constants for establishing population equilibrium.

We consider first the intensity ratio of resonance line to intercombination transition:

$$R = \frac{I(2^1P_1\to 1^1S_0)}{I(2^3P_1\to 1^1S_1)} = \frac{A(2^1P_1\to 1^1S_0)}{A(2^3P_1\to 1^1S_0)}\cdot\frac{N(2^1P_1)}{N(2^3P_1)}\ . \quad (2)$$

This ratio has been discussed in detail over a wide density range by Gabriel and Jordan.[6] Following the discussion of Refs. 6, 15, and 16, it may be written as

$$R = R_1 + PN_e\ , \quad (3)$$

where

$$R_1 = \frac{X(1^1S\to 2^1S) + X(1^1S\to 2^1P)}{X(1^1S\to 2^3S) + X(1^1S\to 2^3P)}\ , \quad (4)$$

and

$$P = \frac{(R_1+1)X(2^3\to 2^1) + R_1 S(2^3)}{\frac{1}{4}A(2^3P_1\to 1^1S_0)}\ , \quad (5)$$

since the $n=2$ triplet levels are indeed strongly coupled by electron collisions. Contributions due to cascading have to be included in the collisional-excitation rates. Previous experiments, as well as theoretical estimates, show, that the "laboratory low-density ratio" is about $R_1 \simeq 2$, which means that our measurements on B IV are in the high-density regime

$$R \simeq PN_e\ . \quad (6)$$

Thus, if R_1 is known, our experimental ratio is essentially a measurement of the factor P, i.e., a measurement of the collisional depopulation of the $n=2$ triplet levels by ionization $[S(2^3)]$ and collisional transfer to the $n=2$ singlet levels $[X(2^3\to 2^1)]$.

We calculate the ratio R using the theoretical excitation rates of Pradhan, Norcross, and Hummer[17] and the ionization rate coefficient $S(2^3)$ from the triplet levels as given by Ref. 6. The excitation to the $n=2$ levels was corrected for cascading contributions, which were estimated according to Mewe and Schrijver[18] and which amount to 32% for the present plasma condition. Cascading contributions to the $n=2$ singlet levels are negligible. The transition probability of the intercombination transition was taken from Ref. 19. The result is quoted in the third column of Table I, and our experimental value confirms the available theoretical data; this is consistent with the results obtained for C V at higher temperatures and lower densities,[16] where computer modeling revealed that the plasma is also in the ionizing regime for the C V ions. The process of collisional excitation from the $n=2$ triplet levels to the singlet levels with $n\geq 3$ followed by cascade, which was proposed in Ref. 6, is not necessary, therefore, to explain the experimental observation. The theoretical value of R would be further increased by such processes.

For comparison, the fourth column shows the ratio calculated using the excitation rate coefficients of Sampson, Goett, and Clark,[20,21] which were obtained in the Coulomb-Born-exchange approximation. This theoretical ratio is beyond the present experimental uncertainty. If we compare the individual rate coefficients we find that the total rates to the $n=2$ triplet levels of Refs. 17 and 20 are about equal, the total rate to the $n=2$ singlet level of Ref. 20, however, being a factor of 1.18 larger than that of Ref. 17, and the triplet-to-singlet rate coefficient of Ref. 21 even being 1.32 times that of Ref. 17.

The fourth column of Table I also displays the theoretical intensity of the resonance transitions from the $n=3$ and 4 levels relative to that from the $n=2$ level, the rate coefficients taken again from Sampson *et al.*[20] The intensity of the $2^1P\to 1^1S$ transition is given by direct excitation to $2^1S, 2^1P$ as well as excitation to the $n=2$ triplet levels and collisional transfer, which amounts to about $\beta \simeq 9\%$ of the total triplet excitation.

The collisional coupling between the $n=3$ levels is estimated using a rate coefficient given by Griem, Baranger, Kolb, and Oerte[22] for the high-temperature limit. The magnitude is such that collisional coupling can be neglected, and we may consider only excitation to the 3^1P_1 level. The intensity ratio thus is given by

$$\frac{I(2^1P_1 \rightarrow 1^1S_0)}{I(3^1P_1 \rightarrow 1^1S_0)} = \frac{\lambda(3^1P_1 \rightarrow 1^1S_0)}{\lambda(2^1P_1 \rightarrow 1^1S_0)} \frac{X(1^1S \rightarrow 2^1) + \beta X(1^1S \rightarrow 2^3)}{X(1^1S \rightarrow 3^1P)} , \quad (7)$$

where

$$\beta = \frac{X(2^3 \rightarrow 2^1)}{\frac{1}{4}A(2^3P_1 \rightarrow 1^1S_0) + N_e X(2^3 \rightarrow 1^1) + N_e S(2^3)} . \quad (8)$$

Similarly, we calculate the excitation to all $n=4$ levels but now have to assume collisional coupling between the $n=4$ levels.

All theoretical intensity ratios of this fourth column are larger than the experimental ratios and outside the estimated uncertainties. A comparison with the rate coefficients of Ref. 17 suggests that the total excitation rate to the $n=2$ singlet level is indeed too large, and a reduction of only this rate by the factor 1.18 results in good agreement for all observed intensity ratios. The last column (Modified) shows the corresponding ratios.

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