Properties of OV Spectral Lines in Ionizing and Recombining Plasmas

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Abstract

A collisional-radiative model for Be-like oxygen ions has been constructed for OV plasma spectroscopy. The model takes into account recombination processes as well as collisional ionization, radiative transitions, and collisional excitation/deexcitation. Two sets of atomic data are used for comparison. We obtain OV line intensities as functions of electron temperature and density. The line intensity ratios of $2s3s\ ^3S - 2s3p\ ^3P_{J=0,1,2}$ are measured in LHD plasmas and are consistent with our models. The line intensity ratio of $2s2p\ ^3P - 2p^2\ ^3P$ and $2s^2\ ^1S - 2s2p\ ^1P$ in recombining plasma is an increasing function of temperature and one measured in the LHD plasma indicates electron temperature less than 7eV. The ratios measured in steady-state phase are larger than 1 and difficult to explain with the current model.

Keywords:

1. Introduction

OV spectral lines are often measured in laboratory plasmas and used for plasma diagnostics, since oxygen is one of popular impurity materials. In plasmas of the Large Helical Device (LHD) at National Institute for Fusion Science, Japan, the OV resonance line at 630 Å is used for monitoring plasma and some OV lines are measured with VUV and optical spectrometers. LHD plasmas seem to become recombining plasma at the later phase of shots. However, most theoretical study for OV lines did not include recombination processes for population kinetics and models were limited for lower excited states up to $2s3l$ levels [1-5].

We have constructed a collisional-radiative model (CRM) for OV (Be-like oxygen) ions with large number of excited states, including recombination processes for each excited states. The CRM calculates population densities of excited states and spectral line intensities with given electron density and temperature. Here we compare calculated line intensity ratios of OV lines with measurement of LHD plasmas and discuss properties of OV spectral lines.

2. Collisional-Radiative Model

Population densities of excited states are calculated by solving rate equations with assumption of steady state in the CRM. Electron temperature and density are given for each calculation. The rate equations take into account radiative transitions, collisional excitation/deexcitation, collisional ionization to Li-like ions, and dielectronic, radiative, and three-body recombination from Li-like ions.

The steady-state rate equations are linear functions

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of the Be-like ground state population n_1 and the Li-like ground state population n_+. We can obtain the excited state population densities $n(i)$ as a combination of a component proportional to n_1, and a component proportional to n_+:

$$n(i) = N_I(i)n_1 + N_R(i)n_+ . \qquad (1)$$

We call $N_I(i)$ the ionizing plasma component, and $N_R(i)$ the recombining plasma component, respectively. The ionizing plasma component originates from collisional excitation from the Be-like ground state, and the recombining plasma component originates from recombination from the Li-like ground state. The two components can be calculated separately.

In the CRM, we consider $2snl\ ^{2S+1}L_J$ and $2pnl\ ^{2S+1}L_J$ levels with $n \leq 6$, and $2snl$ levels up to $n = 50$ as l-bundled hydrogenic levels, where n is the principal quantum number and l is the orbital angular momentum quantum number. The $2pnl$ levels with $n > 6$ are autoionization states and we do not include them to the CRM. The energy levels and transition probabilities are calculated by Cowan code [6] for levels with $n \leq 6$, and by hydrogenic approximation [7] for higher levels.

For collisional excitation rate coefficients, we use data calculated by R-matrix method for transitions among $2s2l$, $2p2l$, and $2s3l$ from Kato *et al.* [1]. For other transitions among $n \leq 6$ levels, we use 2 data sets: Model 1 uses data by Sampson *et al.* [8] for $2lnl'-2p3l''$ transitions and Mewe's empirical formula [9] for other transitions. Model 2 uses collision strength calculated by Hullac code [10]. We use empirical formula for $n > 6$ levels in both models.

For recombination processes, dielectronic recombination rate coefficients are calculated with the use of Cowan code by Murakami *et al.* [11]. These are new data and we do not find a paper which describes the contribution of dielectronic recombination into separate excited states up to $n = 50$ precisely. Radiative recombination rate coefficients are estimated from photoionization cross section by Clark *et al.* [12] for $2snl$ states with $n < 5$ and from hydrogenic approximation for other $2snl$ levels, and three body recombination rate coefficients are calculated as an inverse process of collisional ionization. Collisional ionization rate coefficients are calculated with Lotz formula [13].

Spectral line intensity ratio of transitions from i to j and from p to q is obtained as $I(i \rightarrow j)/I(p \rightarrow q) = A_r(i,j)n(i)/(A_r(p,q)n(q))$, where $A_r(i,j)$ is radiative transition probability for transitions from i to j.

3. Spectral Line Intensity Ratios
3.1 Triplet transitions 2s3s ^{3}S – 2s3p ^{3}P

Here we examine the triplet transitions 2s3s ^{3}S – 2s3p ^{3}P$_J$ (J=0,1,2) at $\lambda\lambda$ 2781, 2787, 2790 Å. Figure 1 shows the spectra taken from the LHD experiment (shot no.10933) by the UV-visible spectrometer.

Figure 2 shows calculated line ratios as functions of electron density with given electron temperature in ionizing plasma (ionizing component only) for model 1 and model 2, respectively. The difference of atomic data (collisional excitation rate coefficients) causes prominent difference in the line ratios. The model 1 exhibits strong electron density and temperature
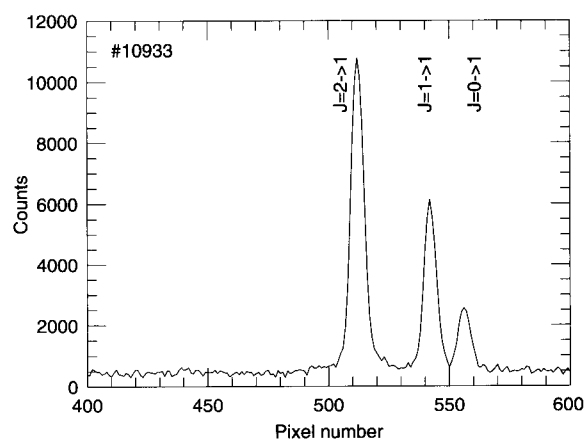

Fig. 1 OV Spectra of 2s3s ^{3}S$_1$ – 2s3p ^{3}P$_J$(J=0,1,2) transitions measured in the LHD experiments.
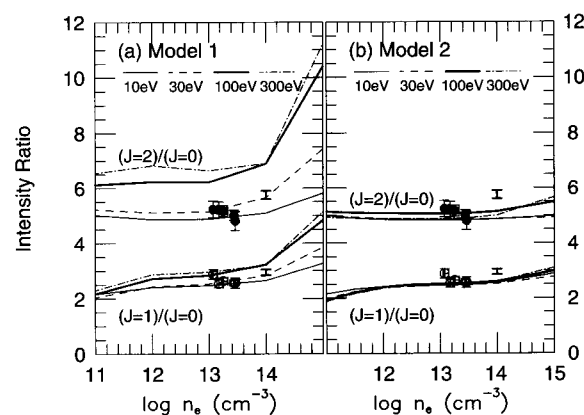

Figu. 2 Line intensity ratios, (J=2)/(J=0) and (J=1)/(J=0) of 2s3s ^{3}S – 2s3p ^{3}P transitions (see Sec. 3.1), as a function of electron density in ionizing plasma for model 1 (a) and model 2 (b). Circles with errors are measurements of the LHD and bar is of the Extrap.

172

dependence for both line ratios I(2s3s $^3S_1$ – 2s3p $^3P_2$)/ I(2s3s $^3S_1$ – 2s3p $^3P_0$) [shown as (J=2)/(J=0)] and I(2s3s $^3S_1$ – 2s3p $^3P_1$)/I(2s3s $^3S_1$ – 2s3p $^3P_0$) [shown as (J=1)/ (J=0)], but the model 2 shows smaller dependences. The ratios in recombining plasma (recombining component only) have larger dependences in model 1 than in model 2, similarly to ones in ionizing plasma.

Escape from 2s3p $^3P_0$ to upper levels such as 2s4*l* levels by several to orders of magnitude larger collisional excitation rates in model 1 than in model 2 causes anomalous population distribution for 2s3p ^3P J = 0,1,2 states, deviating from ratios determined by the statistical weights.

Experimental data measured from the LHD plasmas in the Third cycle (in 1999) (circles with error bars) and the Extrap T1 and T2 reversed field pinch experiments at KTH in Sweden (bar) [4] are shown in Fig. 2. For the LHD measurements, the electron density and temperature are nearly constant during exposure time (0.6–1 sec.) and plasmas are expected to be in steady state. The LHD measurements agree with both models within error bars. The model 1 indicates low electron temperature of 10–30 eV. Weak temperature dependence of the model 2 does not specify the temperature region. As for comparison with the Extrap measurement, the model 1 indicates ~30 eV which is lower than expected by Kato *et al.* [4]. On the other hand, the model 2 does not reproduce the ratios. There still remains a problem for explaining the Extrap measurement.

3.2 The resonance line and triplet transitions 2s2p ^3P – 2p ^3P

In this subsection we examine the line ratio of the resonance line $2s^2$ ^1S – 2s2p ^1P at λ 630 Å and the triplet transitions 2s2p ^3P – $2p^2$ ^3P at $\lambda\lambda$ 758–762 Å, which are unresolved in the LHD VUV spectra taken with the VUV multi-channel spectrometer (Fig. 3). Figure 4a shows the temporal distribution of the intensity ratio for the shot no.15078 in 1999. The exposure time was 0.184 sec. The LHD plasma was in nearly steady state with NBI injection after pellet injection was stopped and then changed into recombining phase after NBI injection was stopped.

Figure 4(b) shows the calculated ratios for the cases of ionizing plasma and recombining plasma as a function of electron temperature for model 2. Their density dependences are very small in the density region of 10^{12} cm^{-3} – 10^{15} cm^{-3}. The difference between models 1 and 2 for the ratio becomes larger at higher electron temperature.

In ionizing plasma, naively the resonance line is almost always stronger than the triplet transition line. The temperature dependence of the ratio is caused by different temperature dependences of the collisional excitation rates from the ground state to 2s2p ^1P and $2p^2$ ^3P states. In recombining plasma, the temperature dependence of the ratio at ~ 3–30 eV is caused by that of the dielectronic recombination to $2p^2$ ^3P states.

The observed ratios in recombining phase indicate low temperature less than 7 eV. We expect that OV lines would be emitted in a peripheral plasma, and such low temperature is not so surprising. However, during the
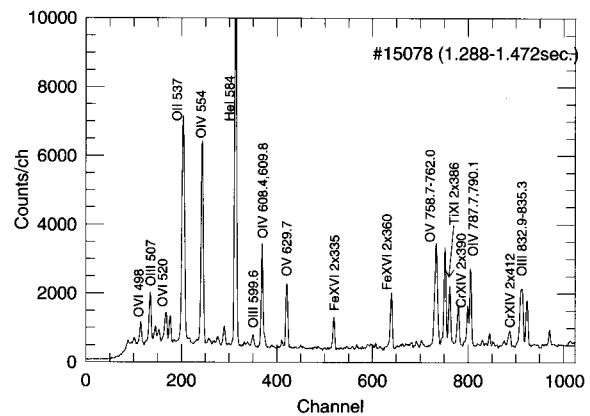

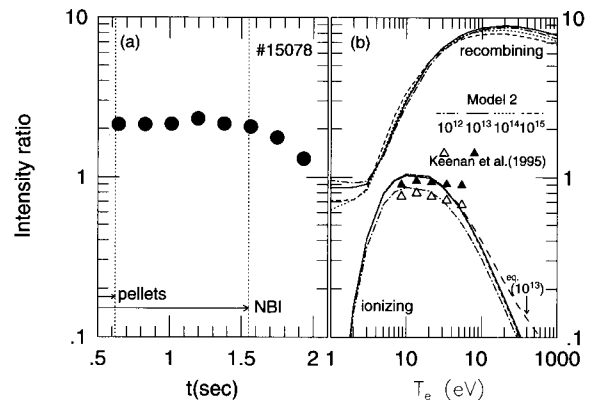Fig. 3 VUV Spectra measured in the LHD experiments.

Fig. 4 (a) Temporal distribution of intensity ratio I(2s2p ^3P – $2p^2$ ^3P)/I($2s^2$ ^1S – 2s2p ^1P) measured in the LHD experiments (shot no.15078). (b) The calculated intensity ratio of the same lines as in (a) for ionizing plasma (lower) and recombining plasma (upper) as a function of electron temperature for model 2. The ratio in equilibrium plasma (10^{13} cm^{-3}) is also plotted (dashed line). Triangles are obtained by Keenan et al. [3].

steady-state phase the ratios are larger than 1, which cannot be reproduced by our CRM for ionizing plasma or equilibrium plasma in which ionization equilibrium is assumed with ion abundance ratio n_+/n_1 calculated by the ADAS package [15]. We will discuss about the discrepancy in the next section.

4. Discussion

In the LHD experiments the triplet transition line $2s2p\ ^3P - 2p^2\ ^3P$ is stronger than the resonance line $2s^2\ ^1S - 2s2p\ ^1P$ even in steady phase. The current model seems too naive, since there would be a different channel to populate more at $2p^2\ ^3P$ levels. The inner-shell ionization from $2s^2 2p$ B-like ground state to $2s2p\ ^3P$ metastable states followed by collisional excitation to $2p^2\ ^3P$ levels could be non negligible at $T_e > 30$ eV in this electron density region.

The ion abundance of B-like oxygen ions in ionization equilibrium is comparable to that of Be-like oxygen ions at ~ 19 eV and is not so small at higher temperature than 19 eV [14]. OIV lines from B-like oxygen ions are observed at the same time in the LHD ̩UV spectra. We need to include the effect of B-like ions in the CRM with a model for ionization/recombination balance for all oxygen ions. Charge transfer process with neutral hydrogen in a peripheral plasma could also contribute to OV line intensities and we will need to estimate the effect as well.

The difference of atomic data causes significant effect to the line intensity ratios as seen in Sec. **3.1**. This result also indicates the importance of higher excited states in a CRM even in a ionizing plasma. In order to explain the Extrap measurements with large ratios, some mechanism to make population anomaly between $2s3p\ ^3P$ J=0,1,2 levels would be necessary. We need more accurate atomic data for excitation rate coefficients for higher excited states.

In summary, we have constructed a collisional-radiative model and calculated OV line intensity ratios for the resonance line and the triplet transitions. Comparing the model calculations with measurements of the LHD plasmas and the Extrap plasmas, we discussed the difference caused by atomic data and the line ratios in ionizing and recombing plasma phases. We need to improve the model with including the effect of B-like ions for a future plan.

References

[1] T. Kato *et al.*, At. Data Nucl. Data Tables **44**, 133 (1990).

[2] F.P. Keenan *et al.*, Astrophys. J. **382**, 349 (1991).

[3] F.P. Keenan *et al.*, Mon. Not. R. Astron. Soc. **276**, 915 (1995).

[4] T. Kato *et al.*, J. Phys. B **29**, 4241 (1996).

[5] E.E. Doschek *et al.*, Astrophys. J. **518**, 909 (1999).

[6] R.D. Cowan, *The theory of atomic structure and spectra*, University of California Press (1981).

[7] U.I. Safronova *et al.*, Physica Scripta **47**, 364 (1993).

[8] D.H. Sampson *et al.*, At. Data Nucl. Data Tables **30**, 125 (1984).

[9] R. Mewe, Astron. Astrophys. **20**, 215 (1972).

[10] A. Bar-Shalom *et al.*, Phys. Rev. A **38**, 1773 (1988).

[11] I. Murakami *et al.*, NIFS-DATA-66 (2001).

[12] R.E.H. Clark *et al.*, At. Data Nucl. Data Tables **34**, 415 (1986).

[13] W. Lotz, Astrophys. J. Suppl. **14**, 207 (1967).

[14] M. Arnaud and R.Rothenflug, Astron. Astrophys. Suppl. **60**, 425 (1985).

[15] URL=http://adas.phys.strath.ac.uk/