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Satellite Line Spectra of H-Like Mg Ions for Plasma Diagnostics and Atomic Data

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Abstract

Electron temperatures have been determined using the ratio of satellite line intensities relative to the resonance line for various plasmas. In order to diagnose precisely, atomic data, wavelengths, radiative transition rates, and autoionization rates, have been calculated. In this paper we have developed a new method to infer plasma temperature and density using only satellite lines, since Ly_α lines are easily affected by opacity. Atomic data for satellite lines of H-like Mg are calculated using four different codes and all four data sets are compared with each other. We derived the electron temperature and density by analyzing spectra observed from a laser-produced plasma using a high resolution spectrometer and comparing the observed spectra with the theoretical spectra calculated with the four different atomic data sets.

Keywords:

Satellite line, H-like Mg ion, radiative transition, autoionization, laser-produced plasma

1. Introduction

Dielectronic satellite lines are produced through a dielectronic recombination process which strongly affects ion abundances of plasmas. The satellite lines produced by dielectronic recombination can be used to estimate the electron temperature and density of a plasma. Previously, we analyzed observed satellite line spectra measured with a high resolution spectrometer [1,2]. In Ref. [1,2], we showed a new method to estimate electron temperature and density by using only satellite lines which are opacity free. In this paper, we compare atomic data for satellite lines calculated by different four methods. We estimate the electron temperature and density from the measured spectra of laser-produced plasma by using four different data sets. The spectra were measured using a high resolution spectrometer.

2. Measured satellite line sapectra

High resolved X-ray spectra were measured at the nhelix-laser facility in GSI-Darmstadt. The laser used is a 100 J Nd-Glass Laser with a wavelength of 1.046 μm, a pulse width of 15 ns and energy of 17 J. Plasmas were produced by laser irradiated onto a massive Mg target at normal incidence with a focal spot diameter of 500 μm. X-ray spectra from the laser-produced plasma were spatially resolved using a high resolution spectrograph [3,4]. Figure 1 shows the measured X-ray spectra with Lyα and many satellite lines of H-like Mg. To identify the various satellite lines, we used data from the MZ code [5,6]. Most of the strong satellite lines are from $1s2l - 2l'2l''$ transitions. Satellite lines for $1s3l-2l'3l''$ and $1s4l-2l'4l''$ transitions were also measured. In this paper, we used following labels for the various satellite lines considered; A: 1s2p $^3P_2$–2p^2 $^3P_2$, B: 1s2p $^3P_1$–2p$^{2\,3}P_2$, T: 1s2s $^1S_0$–2s2p $^1P_1$, Q: 1s2s $^3S_1$–2s2p $^3P_2$, R: 1s2s $^3S_1$–2s2p $^3P_1$, S: 1s2s $^3S_1$–2s2p $^3P_0$, J: 1s2p $^1P_1$–2p^2 $^1D_2$, and f: 1s3d $^1D_2$–2p3d $^1F_3$ [7].

3. Comparison of intensity factor Q^d

In order to interpret the satellite line intensities in the measured spectra, the precise values of intensity factors Q^d are necessary. The Q^d_{ij} for satellite lines from state i to state j is defined by

$$Q^d_{ij} = \frac{g_i A^r_{ij} A^a_{ik}}{\sum_p A^r_{ip} + \sum_q A^q_{iq}}, \qquad (1)$$

where A^r_{ij} is radiative transition probability from state i to state j, A^a_{ik} is autoionization rate from state i to state k, and g_i is statistical weight of state i. The Q^d value is proportional to the intensity of the satellite line at the low density limit. We compared four different theoretical data sets for A^a and A^r; (1) MZ:

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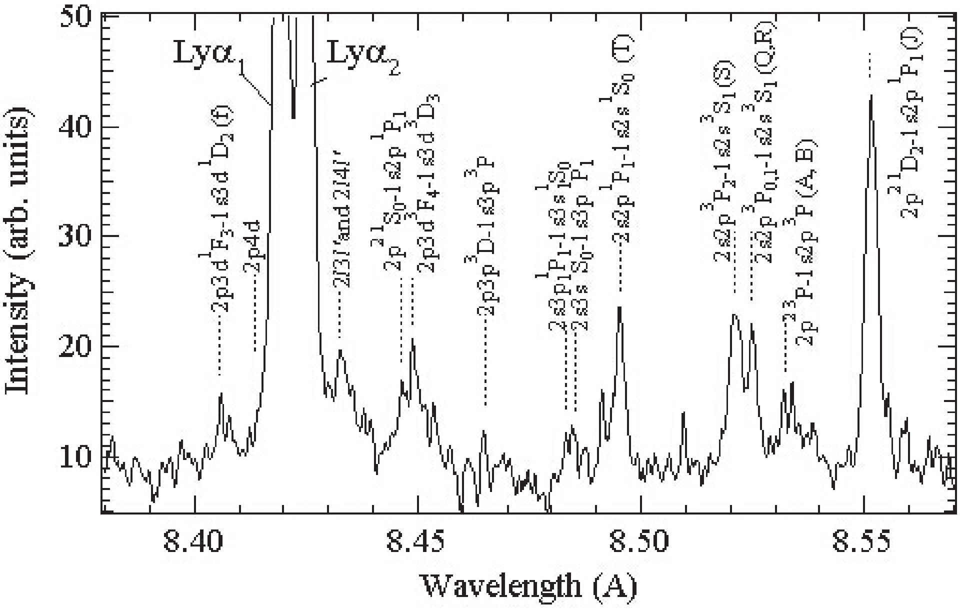

Fig. 1 The measured spectra from our laser-produced plasma observed with a high resolution spectrometer

MZ code by Vainshtein and Safronova [5,6], (2) MBS: RMBPT (Relativistic Many Body Perturbation Theory) code by Safronova [8], (3) MBL: data based on the many body theory by Lindroth [9], and (4) Hullac : Hullac code [10].

Figure 2 shows the comparison of $Q^d \times P(\lambda)$ calculated using different four data sets, where $P(\lambda)$ is the Voigt profile. Figures 2(a), (b), (c), and (d) are the $1s2l{-}2l'2l''$, $1s3l{-}2l'3l''$, $1s4l{-}2l'4l''$, and $1s5l{-}2l'5l''$ satellite lines, respectively. Almost all of the Q^d values for the $1s2l - 2l2l'$ satellite lines show good agreements each other. The Q^d values by MBS and MBL for line A, which is a useful line for estimating the electron density, are 30 % smaller than that of MZ. Hullac is 43 % smaller than that of MZ. The intensity ratio of line A to line J (A / J) increases strongly with increasing electron density. Therefore the electron density estimated using MBL data sets gives larger values than that using MZ data set. The various theoretical Q^d values for strong $1s3l{-}2l'3l''$ satellite lines agree to within 15 % with one another except for the Hullac results which are smaller that the other three calculation. This is because the Hullac A^a value for several of the Q^d values is smaller than the other calculations. Line f is useful for estimating the electron temperature. The MBS Q^d value for this line is 7 % larger than the MZ result, The MBL value is 13 % smaller than the MZ result, and the HULLAC value is 25 % smaller than the MZ result. A smaller Q^d value for line f results in higher inferred temperatures when the electron temperature is estimated using the intensity ratio of a line f to a line J (f / J). The differences between the MBS, MBL, and HULLAC results are small for Q^d for the $1s4l - 2l'4l''$ transitions. However, the MZ Q^d values are larger than that of the other calculations. The MZ A^a values for the 2p4f ^{3}P states are larger by 1-4 orders of magnitude than those from the other calculations. For the $1s5l - 2l'5l''$ transitions similar results to $n = 4$ are found.

4. Collisional-radiative model

We constructed a collisional-radiative model including doubly excited states for two-electron ions [11]. Our model includes singly excited 1s*nl* states and doubly excited 2s*nl*, 2p*nl*, 3s*nl*, 3p*nl*, and 3d*nl* states. In our model, excitation / de-excitation by electron impact, radiative transition, ionization / three-body recombination, radiative recombination, and autoionization / dielectronic capture are all included. We solved the following rate equations

$$\frac{dN_i}{dt} = -\sum_j W_{ij} N_i + \sum_j W_{ji} N_j, \qquad (2)$$

where W_{ij} is a total transition rate from i to j. The population density is calculated assuming quasi-steady state.

5. Estimation of T_e and N_e used four data sets

We compared the measured spectra shown in Fig. 1 with the theoretical spectra calculated with the four different atomic data sets and estimated the electron temperature and density of laser-produced plasma. The electron temperature is estimated by using the temperature dependence of the intensity ratio of line f to line J [1,2]. This method uses only satellite lines which are opacity free and can estimate the temperature more accurately than the method of using the intensity ratio of a satellite line to Ly_α. For estimation of the electron den-

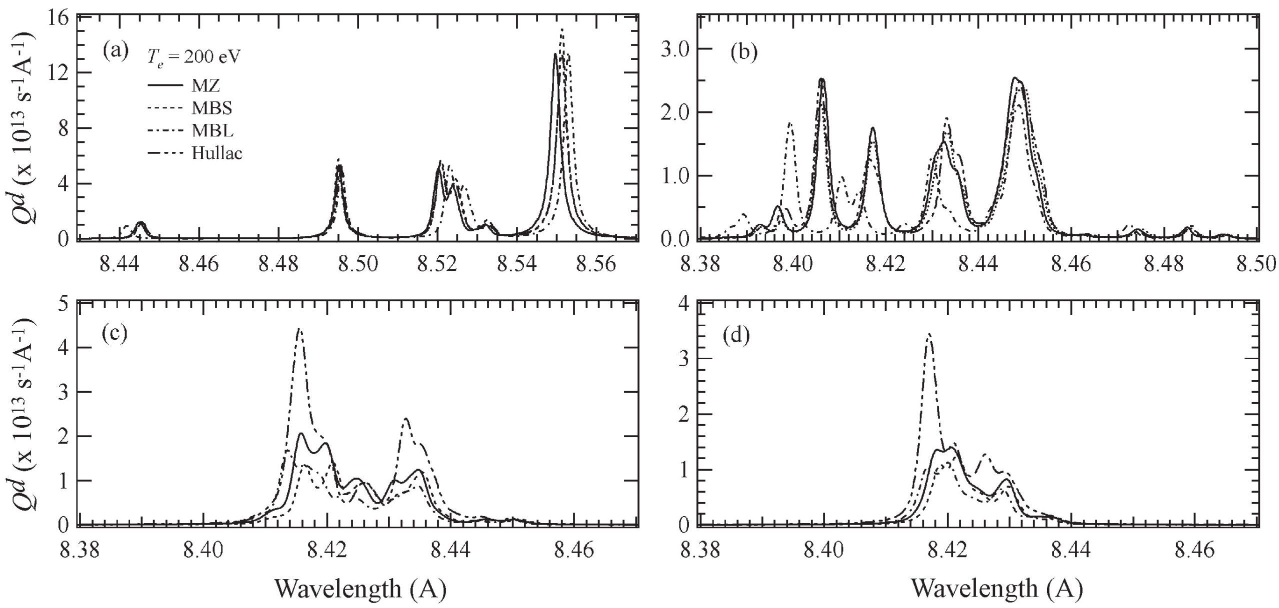

Fig. 2 Comparison of different four data sets for the predicted $Q^d \times P(\lambda)$ values for (a) 1s2*l*−2*l*'2*l*", (b) 1s3*l*−2*l*'3*l*", (c) 1s4*l*−2*l*'4*l*", (d) 1s5*l*−2*l*'5*l*". Solid, dotted, dot-dashed, and dot-dot-dashed line indicates those of MZ, MBS, MBL, and Hullac, respectively.

sity we use the density dependence of intensity ratio of line A to line J.

Figure 3 (a) shows the measured spectra and Fig. 3 (b) shows the theoretical spectra with best fit parameters T_e and N_e obtained using the MZ data set. The best fit parameters for T_e and N_e are 200 eV and 5×10^{20} cm^{-3}, respectively. The T_e and N_e derived by fitting spectra with the MZ data are lower than the value obtained by other atomic data sets. Figure 3 (c) shows the theoretical spectra with best fit parameter, T_e and N_e, obtained using MBS data set. Best fit parameters for T_e and N_e are 200 eV and 6×10^{20} cm^{-3}, respectively. The theoretical spectra with best fit parameters, T_e and N_e, obtained using the MBL data set are shown in Fig. 3 (d). Best fit parameters for T_e and N_e are 230 eV and 7×10^{20} cm^{-3}, respectively. These parameters are relatively higher than the results obtained using other different atomic data. Figure 3 (e) shows the theoretical spectra with best fit parameters, T_e and N_e, obtained using the Hullac data. Best fit parameters for T_e and N_e are 240 eV and 8×10^{20} cm^{-3}, respectively. We found a better spectral fit with MZ data than MBL, and MBS in 8.43 ~ 8.44 Å (2*l*4*l*′ lines). However MBL and MBS are better than MZ near 8.415 Å (2*l*4*l*′ and 2*l*5*l*′ lines).

6. Results

We have used a new method for plasma diagnostics involving intensity line ratios using only satellite lines. We have compared four different theoretical atomic data sets for satellite line spectra of H-like Mg ions. We estimated T_e and N_e from high resolution spectra of laser-produced plasma using our collisional-radiative model using four atomic data sets. When the measured spectra are fitted by the theoretical spectra by MBL and Hullac data, higher temperature and density are fitted using the theoretical spectrafrom the MBL and HULLAC data, higher temperatures and densities are obtained from the intensity ratios of line f to line J and from line A to line J than are those obtained using the MZ or MBS data. We find that the structure of the theoretical spectra in the wavelength range of 8.41 ~ 8.46 Å is different between the four data sets. This is due to the difference of the atomic data for the 2*l*4*l*′ and 2*l*5*l*′ satellite lines

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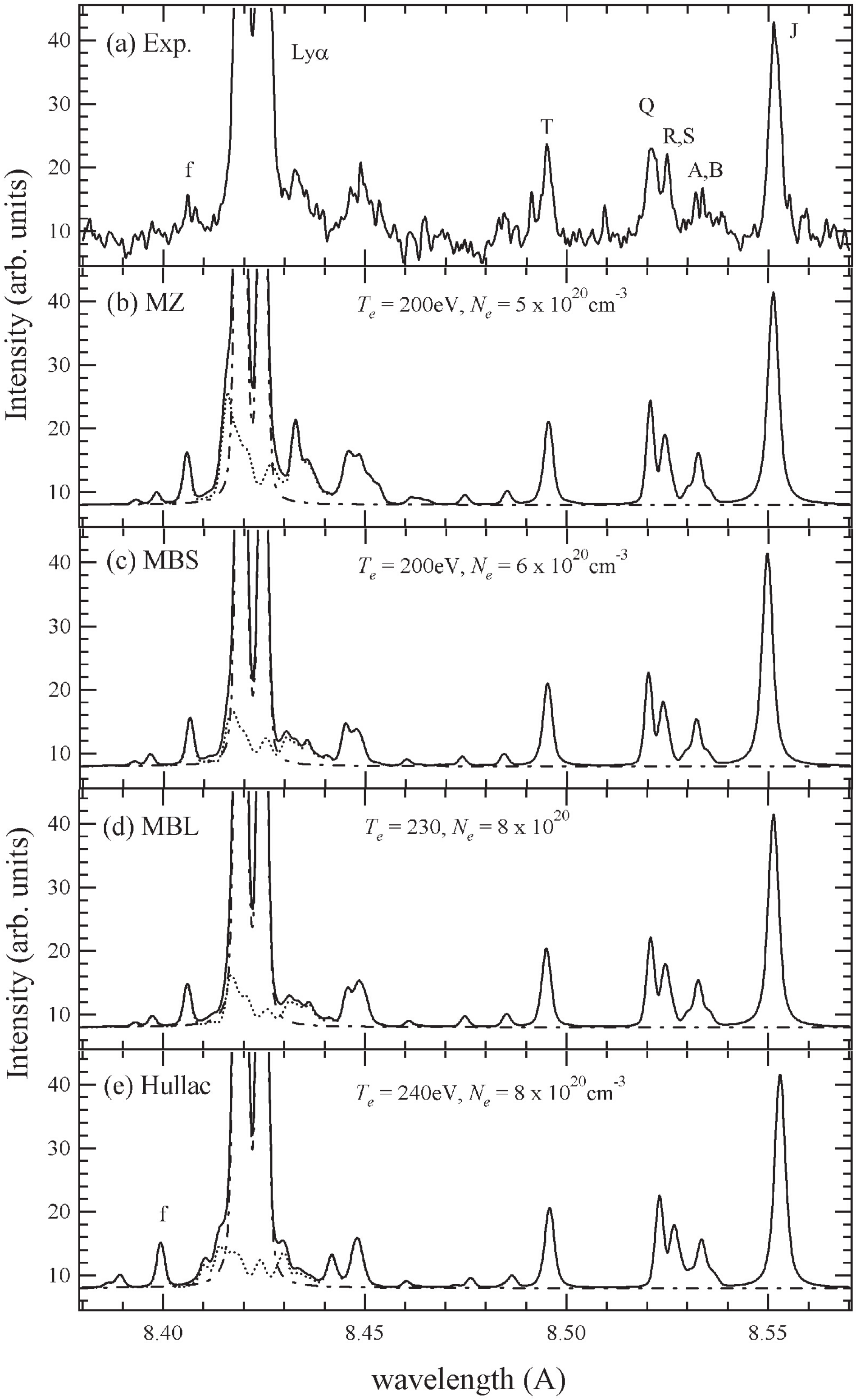

Fig. 3 The measured and theoretical spectra with best fit parameters using different data sets. (a) The measured spectra, (b) theoretical spectra with MZ atomic data, (c) with MBS, (d) with MBL, and (e) with Hullac. From (b) to (e), solid, dotted and dot-dashed are sum of all lines, only satellite lines, and Ly$_\alpha$, respectively.

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