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Plasma Diagnostics for Lyα and Satellite Lines from Laser-Produced Plasma

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Abstract

Recently soft x-ray line spectra of higher order satellite transitions near H-like Lyα of Mg ions in laser-produced plasma have been resolved with two dimensional curved Bragg crystals. A new plasma diagnostics for high temperature plasma is proposed which is based on satellite transitions of different orders. By this method, electron temperature as well as electron density can be determined only by satellite lines, which are opacity free. From the spectral distribution of the satellite lines, plasma electron temperature and density are estimated: T_e = 200 eV and $N_e = 5 \times 10^{20}$ cm^{-3}, respectively. The influence of optical depth to the Lyα lines is discussed using escape factor and Monte Carlo simulation methods.

Keywords:

plasma diagnostics, collisional-radiative model, satellite lines, Lyα line, radiation transfer

1. Introduction

In high temperature plasmas such as laser-produced plasmas, dielectronic recombination process is very important. This process strongly affects the ion abundances, and produces dielectronic satellite lines. The satellite lines appear near the resonance line through spontaneous radiative decay from the autoionizing states. Satellite line emissions from highly ionized ions are often used for plasma diagnostics which are important in various kinds of plasmas, *e.g.*, tokamak, inertial fusion, astrophysical and plasma sources, *etc*.

In this paper, the possibility of determining the electron temperature T_e and the density N_e using only satellite lines near H-like Lyα is studied. In standard diagnostics, the electron temperature is estimated by the intensity ratio of the satellite line (1s2p $^1P_1$-2p^2 $^1D_2$) to the Lyα line (1s-2p). This ratio drastically depends on electron temperature and is therefore suitable for electron temperature diagnostics. However, the Lyα line is often affected by opacity. Therefore we used the intensity ratios between only satellite lines which are optically thin. The electron density is also derived using only satellite lines [1].

Recently, X-ray spectra including satellite lines near Lyα lines of H-like Mg ions in laser-produced plasma, have been measured with high-resolution spectrograph [2]. We could identify not only satellite lines 1s2*l*-2*l*2*l*', but also 1s3*l*-2*l*3*l*' lines from the observed spectra. In order to analyze the spectra, we have constructed a collisional-radiative model including numerous doubly excited states [3]. We have analyzed satellite lines of the spectra and estimated plasma parameters using a new method for plasma diagnostics based on satellite lines only [4]. We also studied the influence of resonance scattering on Lyα by two methods, escape factor method and Monte Carlo simulation respectively.

2. Experimental setup

X-ray line spectra with high spectral resolution were measured at the nhelix-laser facility at GSI-Darmstadt [2,5]. Spectral resolution $\lambda/\Delta\lambda$ is about 5000. A Nd-Glass laser with wavelength, pulse width and energy of 1.046 μm, 15 ns and 17 J, respectively, was irradiated onto massive Mg target at normal incidence. Generated X-rays at the target have been observed with spherically bent mica crystals in the second order of refraction providing simultaneous high spatial and spectral resolution. Focal spot of the laser is 500 μm and the spatial resolution is 14 μm. Figure 1 shows the spectrum from the center in the focal spot.

2.1 Identification

The measured spectra include Lyα_1 (1s $^2S_{1/2}$-2p $^2P_{3/2}$) at 8.4192 Å, Lyα_2 (1s $^2S_{1/2}$-2p $^2P_{1/2}$) at 8.4246 Å and many

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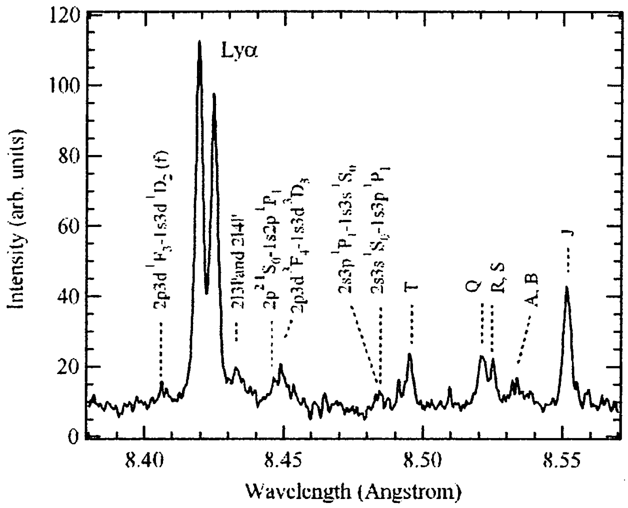

Fig. 1 The measured spectrum near H-like Mg Lyα lines together with the identification of satellite lines.

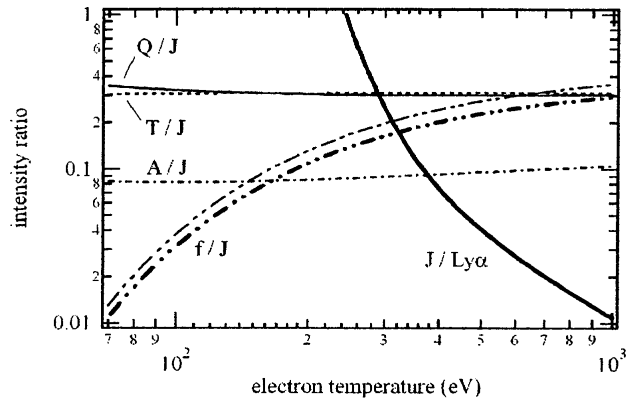

Fig. 2 Temperature dependence of theoretical line intensity ratios at N_e = 10^{20} cm^{-3} in an ionizing equilibrium plasma. Bold solid line is for I_J / $I_{Ly\alpha}$. Thin lines are intensity ratios employing MZ data for I_Q / I_J (solid line), I_T / I_J (dotted line), I_A / I_J (dot-dashed line) and I_f / I_J (dot-dot-dashed line). Bold dot-dot-dashed line is for I_f / I_J employing MBL data.

Table 1 Designations of satellite lines and comparison of wavelengths obtained from different methods, MZ and MBL respectively.

Symbol	Transition	λ_{MZ} (Å)	λ_{MBL} (Å)
A	1s2p $^3P_2 - 2p^2\ ^3P_2$	8.5327	8.532663
B	1s2p $^3P_1 - 2p^2\ ^3P_2$	8.5301	8.530058
Q	1s2s $^3S_1$ – 2s2p $^3P_2$	8.5208	8.520879
R	1s2s $^3S_1$ – 2s2p $^3P_1$	8.5243	8.524395
S	1s2s $^3S_1$ – 2s2p $^3P_0$	8.5259	8.525986
T	1s2s $^1S_0$ – 2s2p $^1P_1$	8.4956	8.495050
J	1s2p $^1P_1 - 2p^2\ ^1D_2$	8.5513	8.551344
f	1s3d $^1D_2$ – 2p3d $^1F_3$	8.4060	8.406039

dielectronic satellite lines 1s2*l*-2*lnl'* as shown in Fig. 1. We used atomic data by Vainshtein and Safronova [6,7] for identification of the satellite lines. Among the satellite lines the strongest is the line J (1s2p $^1P_1$-2p^2 $^1D_2$) at λ = 8.5513 Å. Most of the resolved lines are from 2*l*2*l'* states. Several resolved lines are from 2*l*3*l'* states. The lines from 2*l*4*l'* and 2*l*5*l'* states are overlapping with the Lyα lines. In this paper, we use symbols as listed in Table 1 [8].

3. Theory

3.1 Collisional-radiative model

Emission line intensity is calculated using a population density N_i of an upper level multiplied by a radiative transition rate. Population densities are calculated by rate equations as follows,

$$dN_i / dt = -\sum_j W_{ij} N_i + \sum_j W_{ji} N_j \,, \qquad (1)$$

where W_{ji} is a total transition rate from *j* state to *i* state. Our model includes singly excited states 1s*nl* (60 states), doubly excited states 2*lnl'* (230 states) and 3*lnl'* (70 states), 1s^2, 1s, 2*l*, and 3*l* states. In order to interpret the observed spectra, atomic data are very important. In this paper, we apply two different theoretical data in our model: i) Method by Z-expansion (MZ code) by Vainshtein and Safronova (MZ) [6,7], and ii) a code based on relativistic many-body perturbation theory combined with complex rotation by Lindroth (MBL) [9]. Comparisons between atomic data by MZ and MBL have been discussed in ref. [4]. As a line profile, a Voigt profile was used in our spectral analysis. Instrumental width *w* and ion temperature T_i are determined to be 0.5 mÅ and 200 eV from a line profile of J.

3.2 T_e-dependent intensity ratios

Electron temperature dependence of several line intensity ratios at N_e = 10^{20} cm^{-3} are shown in Fig. 2. The ratio I_J / $I_{Ly\alpha}$ drastically decreases with increase of temperature. However, in our case we do not use this ratio because Lyα might be affected by opacity as mentioned in the previous section. The intensity ratios, which have the same *n* quantum number as an upper state such as I_A / I_J, I_Q / I_J, and I_T / I_J, have no temperature dependence. The line intensity ratios with different quantum numbers *n* as upper states such as, I_f / I_J, depend on T_e in the range T_e < 1 keV and this effect can be used for temperature diagnostics. We derived electron temperatures mainly from the intensity ratio I_f / I_J.

3.3 N_e-dependent intensity ratios

The intensity ratios between satellite lines are shown in Fig. 3 as a function of electron density. The density dependence is strong for densities larger than about 10^{20} cm^{-3} for most of the intensity ratios. The density dependence of the ratio I_A / I_J is the strongest among other ratios. This dependence is caused by *l*-changing transition 2s2p $^3P_2$-2p^2 $^3P_2$ due to electron impact. With increasing electron density, the population density of 2p^2 $^3P_2$ increases by *l*-changing

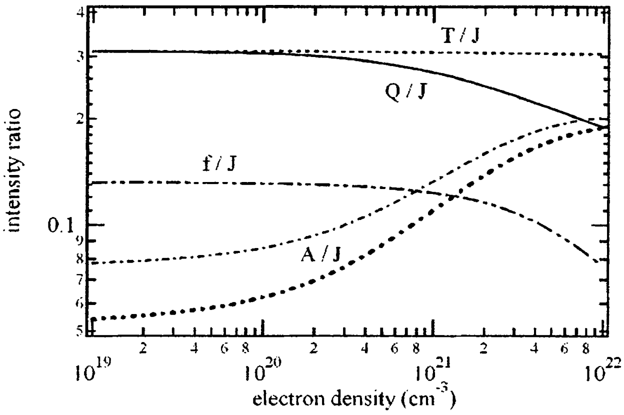

Fig. 3 Density dependence of theoretical line intensity ratio at T_e = 200 eV in an ionizing plasma. Thin lines are intensity ratios employing MZ data for I_Q / I_J (solid line), I_T / I_J (dotted line), I_A / I_J (dot-dashed line) and I_f / I_J (dot-dot-dashed line). Bold dot-dashed line is for I_A / I_J employing MBL data.

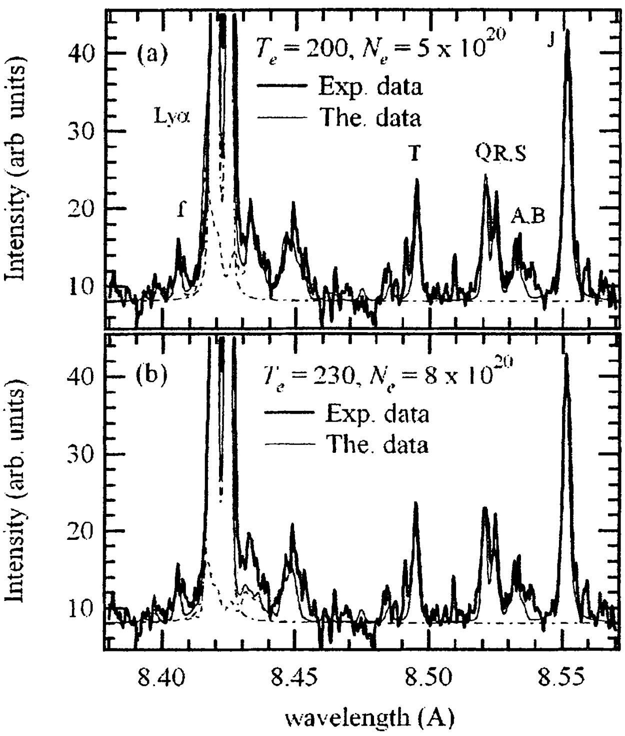

Fig. 4 Comparison with the measured spectra and theoretical spectra by best fit parameters T_e and N_e. Bold line is the measured spectra. Thin sold, dashed, and dot-dashed lines are the sum of satellite lines and Lyα line, single satellite line spectra, and Lyα line, respectively. (a) Theoretical spectra using MZ data at T_e = 200 eV and N_e = 5 × 10^{20} cm^{-3}, (b) using MBL data at T_e = 230 eV and N_e = 8 × 10^{20} cm^{-3}.

collisional excitation from 2s2p $^3P_2$. On the other hand the ratio I_T / I_J shows a constant value in all range of N_e.

4. Spectral fit

Theoretical spectra using the atomic data by MZ and MBL are shown with dashed lines in Figs. 4(a) and (b), respectively together with the measured spectrum indicated by the solid line. The electron density $N_e = 5 \times 10^{20}$ cm^{-3} is obtained from the measured spectra when MZ data are used. Comparing the simulations with the data we find that in the range of $N_e > 5 \times 10^{20}$ cm^{-3}, the intensity I_A and I_B are too weak, while the intensities I_Q, I_R and I_S are too large. The temperature T_e = 200 eV is derived from the intensity ratio I_f / I_J. When MBL data are used, the derived temperature is T_e = 230 eV and the density $N_e = 8 \times 10^{20}$ cm^{-3}. The disagreement of derived T_e and N_e using MZ data and MBL data is due to a difference of autoionization rates of the upper levels for lines A, B and f. The two broad peaks near 8.43–8.44 Å and 8.44–8.46 Å consist of a large number of weak satellite lines not only from 2*l*3*l'* but also from 2*l*4*l'*. They are in good agreement with the measured spectra when we used MZ data. However, near the blue wing of Lyα the calculated spectrum exceeds the measured spectrum as seen in Fig. 4(a). This excess comes mainly from the 1s4f-2p4f lines, which are much stronger with MZ data than with MBL data. Theoretical spectral feature near Lyα foot with MBL atomic data agrees with the measured spectra better than those with MZ data. Although the satellite lines in 8.44–8.46 Å are in good agreement, the theoretical values in 8.43–8.44 Å are too small when employing MBL data. The line intensity ratio I_T / I_J does not depend on T_e and N_e and should be constant for any condition as shown in Figs. 2 and 3. This intensity ratio can therefore be used to determine the background level. We derived the background level considering the intensity ratio I_T / I_J.

5. Radiation transfer

Lyα lines of H-like ion are often influenced by opacity. If the plasma is optically thin, the intensity ratio $I_{Ly\alpha 1}$ / $I_{Ly\alpha 2}$ is nearly equal to two. However, in optically thick plasmas, this ratio may be different. From the measured spectra, the line width σ are $\sigma_{Ly\alpha 1} < \sigma_{Ly\alpha 2}$ and the line intensity of Lyα_1 and Lyα_2 are $I_{Ly\alpha 1} \sim I_{Ly\alpha 2}$, respectively. In order to explain the observed ratio $I_{Ly\alpha 1}$ / $I_{Ly\alpha 2}$, we discuss the escape factor method and Monte Carlo method for the effect of opacity.

5.1 Escape factor

The intensity of Lyα_1 and Lyα_2 line is nearly equal in the measured spectra. For infinite cylindrical plasma, the escape factor g_0 can be expressed by

$$g_0 = \left\{1.92 - 1.3 \Big/ \left[1 + (\kappa_0 r)^{6/5}\right]\right\} \Big/ \left[(\kappa_0 r + 0.62)\sqrt{\pi \, ln(1.357 + \kappa_0 r)}\right], \quad (2)$$

where κ_0 is the absorption coefficients at the line center and r is the radius of infinite cylinder [10]. We assume the ion temperature T_i = 200 eV and the density $N_i = 2.8 \times 10^{18}$ cm^{-3} in our calculation. Assuming a Gaussian line profile, the coefficients κ_0 for 1s $^2S_{1/2}$-2p $^2P_{1/2}$ and 1s $^2S_{1/2}$-2p $^2P_{3/2}$ are about 4.40×10^{-17} N_i cm^{-1} and 8.78×10^{-17} N_i cm^{-1},

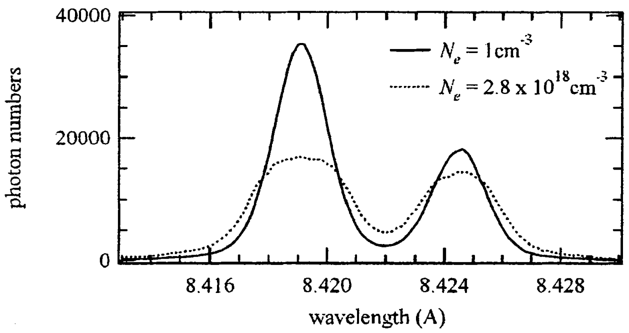

Fig. 5 The theoretical line profiles obtained by Monte Carlo simulation of the radiation transfer. Solid and dot lines are line profile of Lyα line in optically thin and thick plasma, respectively.

respectively. If the radius is the focal spot size, r = 250 μm, the escape factors g_0 are 0.2064 and 0.1050 for Lyα_1 and Lyα_2. Using this factors, the intensity ratio $I_{Ly\alpha 1}$ / $I_{Ly\alpha 2}$ is about unity.

5.2 Monte Carlo simulation

We constructed a model of resonance scattering by Monte Carlo method in order to analyze the line width of Lyα lines. The plasma geometry is assumed to be an infinite cylinder with radius r. Our model has 5 states, $1s^2\ ^2S_{1/2}$, $2s\ ^2S_{1/2}$, $2p\ ^2P_{1/2}$, $2p\ ^2P_{3/2}$, and continuum. Each step in the Monte Carlo simulation is approximately the same as in ref. [11]. Line profiles used for the emission and absorption coefficients are assumed to be the same Voigt profiles as we used for the spectral analysis. Figure 5 shows the results for line profiles of Lyα_1 and Lyα_2 for N_i = 1 cm^{-3} and $N_i = 2.8 \times 10^{18}$ cm^{-3} at r = 100 μm. In optically thin case (N_i = 1 cm^{-3}), the intensity ratio of Lyα_1 to Lyα_2 is two which is proportional to the statistical weight. In the optically thick case ($N_i = 2.8 \times 10^{18}$ cm^{-3}), we obtain the peak intensity ratio of Lyα_1 to Lyα_2 almost equal to the observed ratio. If the radius r is equal to the size of a focal spot, r = 250 μm, the intensity of Lyα is too weak comparing to those of satellite lines. With these parameters, our calculation can explain the ratio of peak intensity of Lyα_1 to Lyα_2. However, the observed difference of the line width between Lyα_1 and Lyα_2 cannot be explained.

6. Summary

We have demonstrated in test bed laser produced plasma experiments that the plasma parameters can be obtained employing satellite lines only: T_e = 200 eV and $N_e = 5 \times 10^{20}$ cm^{-3}, was obtained from the measured spectral distribution. Radiation transport effects of Lyα have been simulated employing the Monte Carlo method. We could explain the intensity ratio of Lyα_1 and Lyα_2 but the observed spectral width $\sigma_{Ly\alpha 1} < \sigma_{Ly\alpha 2}$ could not be explained by our simulation. This problem might be resolved by simulations including differential plasma motion.

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