PRAMANA — journal of physics Vol. 64, No. 1
January 2005
pp. 141–146

Effect of dielectronic recombination on the charge-state distribution and soft X-ray line intensity of laser-produced carbon plasma

A CHOWDHURY, G P GUPTA*, P A NAIK and P D GUPTA
Laser Plasma Division, Centre for Advanced Technology, Indore 452 013, India
*Laser and Plasma Technology Division, Bhabha Atomic Research Centre, Mumbai 400 085, India
E-mail: avijit@cat.ernet.in

MS received 29 August 2003; revised 13 July 2004; accepted 27 August 2004

Abstract. The effect of dielectronic recombination in determining charge-state distribution and radiative emission from a laser-produced carbon plasma has been investigated in the collisional radiative ionization equilibrium. It is observed that the relative abundances of different ions in the plasma, and soft X-ray emission intensity get significantly altered when dielectronic recombination is included. Theoretical estimates of the relative population of CVI to CV ions and ratio of line intensity emitted from them for two representative formulations of dielectronic recombination are presented.

Keywords. Recombination; soft X-ray; laser-produced plasmas.

PACS Nos 52.25.Jm; 52.50.Jm

The interest in laser-produced plasmas is of paramount importance for both basic research in laser-plasma interaction studies and technological applications [1–3]. X-ray emission from the plasma is used as a non-invasive diagnostic tool for determining the plasma parameters. The magnitude of radiative emission from an ion depends on its population density that is calculated using a suitable ionization equilibrium model. The accuracy of the prediction of plasma parameters depends on the description of the model and the rate coefficients used for various ionization and recombination processes included in that model [4]. Several different expressions of ionizations and recombination rate coefficients for laser-produced plasmas have been published in the literature, and have been used by many workers for calculating the ion populations [5]. However, these calculations are generally done either neglecting dielectronic recombination [6] or later is taken to be proportional to radiative recombination [7]. Since the theoretically calculated population density of an ionic charge state depends on the rate coefficients used, it is interesting to investigate their effect on the charge-state distribution and spectral line intensity ratio. The latter is also being used as a diagnostic tool for plasma temperature estimation.

In this brief report, we discuss the effect of dielectronic recombination on the charge-state distribution of ions in a laser-produced carbon plasma, considering two formulations of dielectronic recombination coefficients. Its effect is also calculated on the two strongest soft X-ray emission lines, namely Ly-α resonance (CVI: 1s $^2S_{1/2}$–2p $^2P_{1/2}$, at 33.7 Å) line and He-α resonance (CV: 1s^2 $^1S_0$–1s2p $^1P_1$, at 40.2 Å) line emitted from the carbon plasmas. These lines lie in the water window spectral range (23 Å to 44 Å corresponding to oxygen and carbon K-edge respectively) and have potential application in soft X-ray contact microscopy [3]. Further, the intensity ratio of these lines is used as a temperature diagnostics for the plasma.

Ion population densities in various ionization states can be best calculated using a collisional radiative model (CRE) where step-wise processes of excitation/de-excitation along with collisional and radiative ionization with recombination are considered. However, it has been shown by many authors [5,7,8], that for laser-produced plasmas, the ion populations can be determined by considering equilibrium between collisional ionization for the ground state and recombination (both radiative and three-body) from the continuum to the ground state. This is because, most of the ions are in the ground state, so that such an approximation holds true [9]. Under this condition, the steady state balance between the densities of any two consecutive charge states [5,7,8] is expressed as

$$n(Z)S(Z) = n(Z+1)[\alpha(Z+1) + \alpha^{\mathrm{DR}}(Z+1) + \beta(Z+1)], \tag{1}$$

where $n(Z)$ is the ion density in the charge state Z, and S, α, α^{DR} and β are the collisional ionization, radiative recombination, dielectronic recombination, and collisional three-body recombination rate coefficients respectively. It may be noted here that such an equilibrium is attained for laser pulses of the order of nanosecond duration. For very short duration pulses like femtosecond pulses, the plasma duration is much shorter compared to the ionization and recombination time-scales. Hence the plasma does not reach equilibrium and so such an equilibrium model is not applicable. From the above equation one can calculate the fractional densities $\delta(Z)(\delta(Z) = n(Z)/n_{\mathrm{i}}$, $n_{\mathrm{i}} = \sum_{Z=1}^{Z=Z_{\mathrm{a}}} n(Z)$ being the total ion density, Z_{a} being the atomic number of the target element) of the ions in different charge states Z and the average ionic charge state $\bar{Z}[\bar{Z} = \sum_{Z=1}^{Z=Z_{\mathrm{a}}} Zn(Z)/n_{\mathrm{i}}]$. We use the above equation for all our calculations.

For an ionic charge state Z, we have used the collisional ionization rate coefficient due to Landshoff and Perez (denoted here as S^{LP} [10]), radiative recombination due to Seaton (α^{S} [11]), and collisional recombination due to Salzmann and Krumbein (β^{SK} [8]) and are respectively given as

$$S^{\mathrm{LP}}(Z) = 1.24\times10^{-6}\xi_Z T_{\mathrm{eV}}^{-3/2}[\exp(-u)/u^2]F_1(u)\ \mathrm{cm}^3/\mathrm{s}, \tag{2}$$

$$\begin{aligned}\alpha^{\mathrm{S}}(Z+1) = {}& 5.2\times10^{-14}(Z+1)u^{1/2}\\ &\times(0.429 + 0.5\ln u + 0.469u^{-1/3})\ \mathrm{cm}^3/\mathrm{s},\end{aligned} \tag{3}$$

$$\begin{aligned}\beta^{\mathrm{SK}}(Z+1) = {}& \{3\times10^{21}[2g(Z+1)/g(Z)]T_{\mathrm{eV}}^{3/2}\\ &\times\exp(-u)\}^{-1} n_{\mathrm{e}} S(Z)\ \mathrm{cm}^3/\mathrm{s},\end{aligned} \tag{4}$$

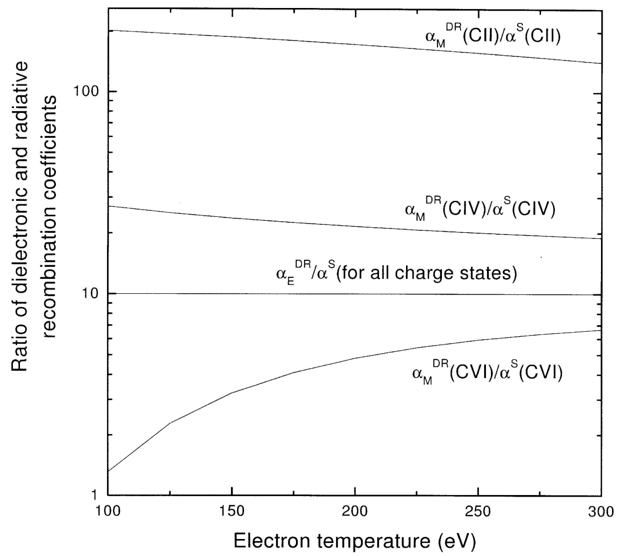

Figure 1. Variation of ratio of dielectronic and radiative recombination coefficients for CII, CIV and CVI ions with electron temperature.

where $F_1(u) = 0.915(1 + 0.64/u)^{-2} + 0.42(1 + 0.5/u)^{-2}, u = \chi_Z/T_{\mathrm{eV}}$, χ_Z is the ionization potential in eV, T_{eV} is the value of electron temperature in eV and ξ_Z is the number of electrons in the outermost (n,l) subshell with n the principal quantum number and l the azimuthal quantum number, n_{e} is the electron density, taken as 3×10^{20} cm^{-3} typical to laser (pulse width nano-second) produced carbon plasma and g is the statistical weight.

The dielectronic recombination is a multi-step process in which an electron undergoes radiationless capture into an autoionizing doubly excited state and subsequent stabilization by radiative decay or by some other atomic process. The final product of this stabilization may be a ground state or a singly excited state. We consider stabilization by radiative decay and the final product of the stabilization to be a ground state. The formulation of dielectronic recombination coefficient α^{DR} as suggested by Mazzotta *et al* [12], (α_M^{DR}) is as follows:

$$\alpha_M^{\mathrm{DR}} = \frac{1}{T_{\mathrm{eV}}^{3/2}} \sum_{i=1}^{4} c_{\mathrm{i}} \exp\left(\frac{-E_{\mathrm{i}}}{T_{\mathrm{eV}}}\right) \ \mathrm{cm}^3/\mathrm{s}, \tag{5}$$

where T_{eV} and E_{i} are in eV, c_{i} in cm^3 eV$^{3/2}$ s^{-1}. The coefficients c_{i} and E_{i} are taken from ref. [12]. Whereas Ma and Tan [6] have neglected the dielectronic recombination ($\alpha^{\mathrm{DR}} = 0$), Eidmann [7] has accounted for α^{DR} by using $\alpha^{\mathrm{DR}} = d \times \alpha$ with d as a free parameter. By comparing the estimates of the average ionic charge state of gold with those of the more accurate atomic model which treats α^{DR} in a consistent manner, it was concluded that α^{DR} is suitably taken into account with $d \approx 10$ for $T_{\mathrm{e}} < 1000$ eV. We consider α^{DR} in our calculations using these two representative formulations, viz. the expression given by eq. (5) and the one based

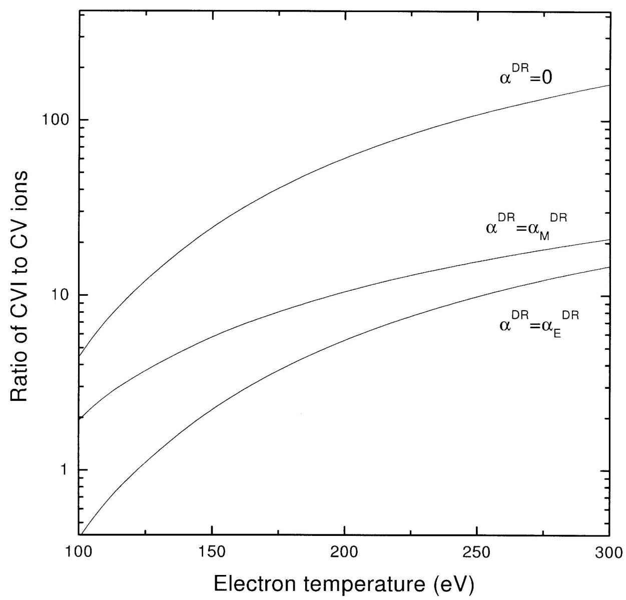

Figure 2. Ratio of CVI to CV ions as a function of electron temperature for different considerations of dielectronic recombination, viz. $\alpha^{\mathrm{DR}} = 0$, $\alpha^{\mathrm{DR}} = \alpha_M^{\mathrm{DR}}$ and $\alpha^{\mathrm{DR}} = \alpha_E^{\mathrm{DR}}$.

on $\alpha^{\mathrm{DR}} = 10 \times \alpha^{\mathrm{S}}$ and denote them by α_M^{DR} and α_E^{DR} respectively, and compare the result when dielectronic recombination is neglected, i.e. $\alpha^{\mathrm{DR}} = 0$ case.

To study the effect of dielectronic recombination on the ionic charge-state distribution, we have calculated the ratio of dielectronic and radiative recombination rate coefficients as a function of electron temperature for CII, CIV and CVI ions (see figure 1). The atomic data used for the calculation are taken from Kelly and Palumbo [13]. The ratio of α_E^{DR} and α^{S} for all the relevant charge states for the proportionality constant $d = 10$ is also shown for a ready comparison. It is seen from the figure that the ratio of dielectronic and radiative recombination rates are different for different ions. For instance, the ratio is 1.3, 27 and 201 at 100 eV for CVI, CIV and CII ions respectively. Thus the proportionality constant for the ratio of dielectronic and radiative recombination is not identical for all charge states of carbon. Further, for a given charge state, the ratio may not be constant. For example, at 100 eV the ratio of α_M^{DR} to α^{S} for CVI ions is 1.3 whereas it is 6.7 at 300 eV. Hence, it is worth studying the charge-state distribution with the various considerations of dielectronic recombination, e.g. dielectronic recombination proportional to radiative recombination, as per actual formulation and without dielectronic recombination as discussed below.

The effect of dielectronic recombination on the ratio of CVI to CV ions for different α^{DR} is shown in figure 2. The curves for $\alpha^{\mathrm{DR}} = 0$, $\alpha^{\mathrm{DR}} = \alpha_E^{\mathrm{DR}}$ and $\alpha^{\mathrm{DR}} = \alpha_M^{\mathrm{DR}}$ represent this ratio without dielectronic recombination consideration, with dielectronic recombination as ten times the radiative recombination due to Seaton [11], and with dielectronic recombination as per the detailed formulation of [12]. It is

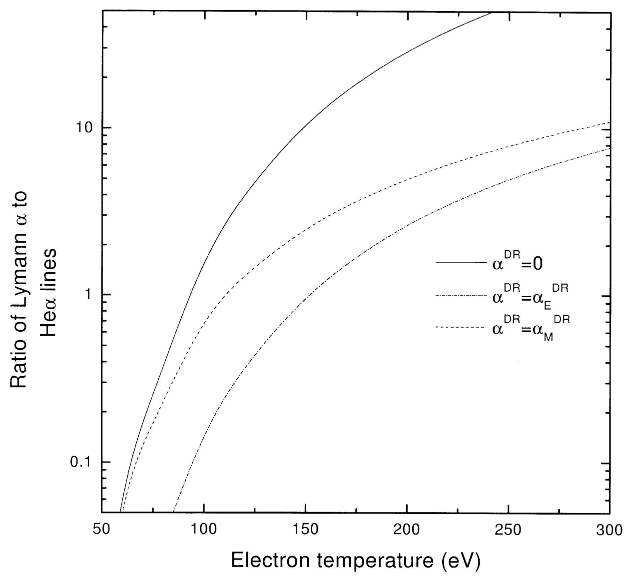

Figure 3. Ratio of intensities of Ly-α to He-α lines as a function of electron temperature for different considerations of dielectronic recombination.

seen that there is substantial difference in the calculated values of the ratio for different considerations of dielectronic recombination. For example, at 200 eV, the ratio is 61, 5.5 and 10.5 for $\alpha^{\rm DR} = 0$, $\alpha^{\rm DR} = \alpha_E^{\rm DR}$, and $\alpha^{\rm DR} = \alpha_M^{\rm DR}$, respectively.

Next, we determine the effect of dielectronic recombination on the Ly-α and He-α emission lines of a laser-produced carbon plasma. Details on the line intensity calculation is described in our earlier work [14]. Briefly, the expression for line intensity ($P_{\rm line}$) as given by Griem [15] and used extensively by Colombant and Tonon [16] is given by

$$P_{\rm line} = 7 \times 10^{-18} n_{\rm e} n_{\rm g} T_{\rm eV}^{-1/2} \sum_{\rm u} f_{\rm ug} \exp(-E_{\rm ug}/T_{\rm eV}), \tag{6}$$

where $n_{\rm e}$ is the electron density and is taken to be 3×10^{20} cm^{-3}, typical to a laser (pulse duration of nanosecond order) produced carbon plasma under consideration, $n_{\rm g}$ is the ion density in the ground state and is given by the product of fractional ion density with the total ion density, $f_{\rm ug}$ is the oscillator strength from upper level u to the ground state, and $E_{\rm ug}$ is the excitation energy from the ground state to level u. The atomic data tabulated by Wiese *et al* [17] are being used here. Figure 3 shows the ratio of Ly-α to He-α line intensities for the three different considerations of dielectronic recombination. From our experiments, carried out with a 2 GW, 4 ns Nd : glass laser, involving the measurement of line intensities from a laser-produced carbon plasma in the water window range using our flat field grating spectrograph [18], we obtained a line intensity ratio of Ly-α to He-α as 1.04 for a focussed laser intensity of 1.5×10^{12} W/cm^2. If this ratio of the line intensity is used as a diagnostic for electron temperature estimation, then as seen from the figure, the estimated temperature would be 93, 110 and 152 eV for $\alpha^{\rm DR} = 0$, $\alpha^{\rm DR} = \alpha_E^{\rm DR}$

and $\alpha^{\mathrm{DR}} = \alpha_M^{\mathrm{DR}}$, respectively, showing that there is a substantial variation in these three considerations.

In conclusion the effect of dielectronic recombination in determining the charge-state distribution of ions and X-ray emission intensity in a high density, high temperature plasma is studied. Quantitative estimates of relative abundances of ions in a laser-produced carbon plasma, and intensity ratio of soft X-ray emission corresponding to Ly-α and He-α lines using two representative formulations of dielectronic recombination are found to be quite different from the case when dielectronic recombination is neglected. This can have important implications as X-ray emission from laser-produced plasma is used for several practical applications as well as employed as a diagnostic tool for temperature measurement.

References

[1] J Lindl, *Phys. Plasmas* **2**, 3933 (1995)
[2] A Chowdhury, V Arora, P A Naik and P D Gupta, *J. Appl. Phys.* **93**, 3218 (2003)
[3] J A Chakera, V Arora, S R Kumbhare, P A Naik, V Ganesan and P D Gupta, *Rev. Sci. Instrum.* **72**, 1421 (2001)
[4] R Mewe, *Atomic physics of hot plasmas, Conference on X-ray Spectroscopy in Astrophys.* edited by J Van Pardijs and J A M Bleeker (Springer, Berlin, 1999) pp. 109–187
[5] G P Gupta and B K Sinha, *Phys. Rev.* **E56**, 2104 (1997)
[6] Gau-Bin Ma and Wei-Han Tan, *Phys. Plasmas* **3**, 2770 (1996)
[7] K Eidman, *Laser Part. Beams* **12**, 223 (1994)
[8] D Salzmann and A Krumbein, *J. Appl. Phys.* **49**, 3229 (1978)
[9] L A Gazzi, D Giulietti, A Giulietti, T Afshar-Red, V Biancalana, P Chess, E Schifano, S M Viana and O Willi, *Phys. Rev.* **E49**, 5628 (1994)
[10] R K Landshoff and J D Perez, *Phys. Rev.* **A13**, 1619 (1976)
[11] M J Seaton, *Mon. Not. R. Astron. Soc.* **119**, 81 (1959)
[12] P Mazzotta, G Mazzitelli, S Colafrancesco and N Vittorio, *Astron. Astrophys. Suppl. Ser.* **133**, 403 (1998)
[13] R L Kelly and L J Palumbo, *Atomic and ionic emission lines below 2000 Å* (Naval Research Laboratory, Washington DC, 1973) Report No. 7599
[14] A Chowdhury, R A Joshi, G P Gupta, P A Naik and P D Gupta, *Pramana – J. Phys.* **61**, 1121 (2003)
[15] H Griem, *Plasma spectroscopy* (McGraw Hill, New York, 1964) p. 167
[16] D Colombant and G F Tonon, *J. Appl. Phys.* **44**, 3524 (1973)
[17] W L Wiese, M W Smith and B M Glennon, *Atomic transition probabilities* (US Department of Commerce Publication, 1966) vol. 1, NSRDS-NBS-4
[18] A Chowdhury, R A Joshi, S R Kumbhare, P A Naik and P D Gupta, *Sadhana* **24**, 557 (1999)