Recombination rates, Resonance Strengths and Line Profiles of Dielectronic Satellite Lines of He-like Ca, Fe, Ni

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Summary. Dielectronic satellite (DES) lines arising from the radiative decay of ions with excited cores are used as diagnostics of the plasma conditions found in astronomical objects. In collisional plasmas, the most common DES lines are due to an electron being dielectronically captured by a He-like ion, forming a 3-electron, Li-like ion in a doubly excited, autoionizing state (i.e. 1s2l2l' (KLL), 1s2l3l' (KLM), etc). These states can decay to bound levels by emitting a photon, completing a process known as dielectronic recombination (DR). The autoionizing KLL complex gives rise to 22 DES lines, labeled 'a' through 'v', via transitions of the type $1s2l2l' \rightarrow 1s^2 2l$. These lines are seen at energies lower than the He-like resonance line ($1s2p(^1P^0_1) \rightarrow 1s^2(^1S_0)$ - which is also referred to as the 'w' line). The unified recombination method, which treats photoionization and electron-ion recombination in a manner which couples autoionizing states to the continuum, has been extended to study the DES lines of the highly charged ions Ca XVIII, Fe XXIV, and Ni XXVI. In contrast to obtaining a single energy point for a DES line (as is the case for existing theoretical approaches based on the isolated resonance approximation - IRA), the unified method: (i) provides detailed profiles of DES lines, including the blending of lines which occurs in nature, (ii) includes the background contribution of radiative recombination (RR), and (iii) provides a simple relation between the resonance strengths and recombination rates of narrow lines which is useful for astrophysical modeling.

1 Introduction and Theory

There are two ways of measuring DES lines: (i) the related quantities of satellite line intensity (I_s) and the intensity ratio ($\frac{I_s}{I_w}$), and (ii) the resonance strength, S. These are defined as follows:

$$I_s \approx \alpha_s \frac{n_i}{n_e} \quad , \quad \frac{I_s}{I_w} \approx \frac{\alpha_s}{q_w} \; , \; \text{and} \;\; S = \int_{E_i}^{E_f} \sigma_{RC} \, d\epsilon \tag{1}$$

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where α_s is the recombination rate coefficient through the DES line, n_i is the ion density, q_w is the collisional excitation rate coefficient of the w-line, E_i and E_f are the lower an upper bounds of the line shape, and σ_{RC} the recombination cross section (e.g. Beiersdorfer et al. 1992).

The earlier theoretical treatments, initiated by Gabriel (1972), are based on the IRA. For a continuum electron that is captured into autoionizing state i by an ion in state m which then decays to state j the recombination rate coefficient (Bates & Dalgarno 1962) is calculated as

$$\alpha_s^{DR}(T) = \frac{g_i}{2g_m} \frac{h^3 e^{\frac{-\epsilon_s}{kT}}}{(2\pi m_e kT)^{\frac{3}{2}}} \frac{A_a(i \to m) A_r(i \to j)}{\sum_l A_r(i \to l) + \sum_k A_a(i \to k)} , \qquad (2)$$

where A_r is the radiative decay rate, and A_a the autoionization rate. The IRA does not include the background RR contribution or interference effects, although these may be small.

The unified method (Nahar & Pradhan 1994; Zhang et al. 1999) calculates σ_{RC} from detailed photoionization cross sections (σ_{PI}) that include autoionizing resonances:

$$\sigma_{RC} = \sigma_{PI} \frac{g_i}{g_j} \frac{h^2 \omega^2}{4\pi^2 m^2 c^2 v^2} . \qquad (3)$$

The satellite lines are the resonances in σ_{RC} and their structures provide the energy profile of DES lines and include the contribution of the background and interference effects. Thus the entire DES spectrum is generated naturally.

The needed cross sections are calculated using the relativistic Breit-Pauli R-matrix (BPRM) method which includes coupling between channels (Nahar & Pradhan 2006). The recombination rate coefficient of a DES line is obtained from the above using the following expression:

$$\alpha_R(T) = \frac{4}{\sqrt{2\pi m}} \frac{1}{(kT)^{3/2}} \int_{E_i}^{E_f} \epsilon \, e^{-\frac{\epsilon}{kT}} \sigma_{RC} d\epsilon \, . \qquad (4)$$

For a narrow resonance line we can approximate the electron distribution as a constant over the line's width. Taking ϵ_s to be the line's peak energy, we can write

$$\alpha_s(T) = \frac{4}{\sqrt{2\pi m}} \frac{e^{-\frac{\epsilon_s}{kT}}}{(kT)^{3/2}} \int_{E_i}^{E_f} \epsilon \, \sigma_{RC} d\epsilon = f(T) S_{RC} \qquad (5)$$

where

$$S_{RC}(s) = \int_{E_i}^{E_f} \epsilon \, \sigma_{RC} d\epsilon \;\; \text{and} \;\; f(T) = \frac{4}{\sqrt{2\pi m}} \frac{e^{-\frac{\epsilon_s}{kT}}}{(kT)^{3/2}} = 0.015484 \frac{e^{-\frac{\epsilon_s}{kT}}}{T^{3/2}} . \qquad (6)$$

Hence, the recombination rate coefficient of the DES line s can be written as