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Relative Intensities of the $3d$–$2p$ Lines Emitted by Ar^{13+} Ions after Impact Excitation by an Electron Beam

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The intensity ratio R of the dipole-allowed lines $3d\,^2D_{3/2,5/2} \to 2p\,^2P_{3/2}$ and $3d\,^2D_{3/2} \to 2p\,^2P_{1/2}$ emitted from highly charged boron-like Ar^{13+} ion collisionally excited by a monoenergetic electron beam has been theoretically studied versus electron densities from 10^9 to 5×10^{13} cm^{-3}. The calculations were performed at different angles θ of observation with respect to the electron beam direction and various incident-electron energies e_{i} from 0.65 to 3 keV. By taking into account all important transitions among 290 magnetic sublevels of the $2s^22p$, $2s2p^2$, $2p^3$, $2s^23l$, $2s2p3l$, $2p^23l$ ($l = 0{-}2$) configurations, a collisional-radiative model has been used for determining the populations of the upper magnetic sublevels of the lines. All required atomic data were computed with the Flexible Atomic Code. We find that the effect of anisotropy in the photon emission, due to the directionality of the incident electron beam, can lead to very significant differences between $R(0^\circ)$ and $R(90^\circ)$. Our results also indicate that the contribution from the $^2D_{3/2} \to {}^2P_{3/2}$ line which blends with the $^2D_{5/2} \to {}^2P_{3/2}$ line enhances the effect of anisotropy.

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1. Introduction

Relative intensities of lines arising from $3d \to 2p$ transitions in highly charged boron-like ions are often used to deduce the electron density of high-temperature astrophysical and laboratory plasmas. The ratio R of added intensities of the two blended lines $3d\,^2D_{3/2,5/2} \to 2p\,^2P_{3/2}$ over that of the resonance $3d\,^2D_{3/2} \to 2p\,^2P_{1/2}$ line is strongly sensitive to the electron density. This sensitivity arises from the metastability of the $2p\,^2P_{3/2}$ level from which there is collisional transfer of population to $3d\,^2D_{5/2}$ level. Most of the available studies on the R ratio have been devoted to plasmas with isotropic Maxwellian electron distributions [1]. There were also calculations of R for a monoenergetic electron beam relevant to EBIT experiments [2], but they ignored the anisotropy of the angular distribution of photon emission. This aspect needs to be considered to deduce a reliable value for the electron density of plasmas having cylindrically symmetric electron velocity distributions [3].

In this work, we have calculated the intensity ratio R for Ar^{13+} ions excited by a monoenergetic, unidirectional electron beam for a wide range of electron densities n_{e} from 10^9 to 5×10^{13} cm^{-3} and at different angles θ of photon emission with respect to the electron beam direction. The density dependence of R has been computed for several values of the incident-electron energy e_{i} from 0.65 to 3 keV.

In Sect. 2 of this paper there are provided some necessary formulae for the calculation of the line ratio R in a collisional-radiative model, taking into account the radiative emission anisotropy. In Sect. 3, we present our results for the intensity ratio R as a function of electron density for $e_{\mathrm{i}} = 1.1$ keV and two values of θ. Finally, conclusions are presented in Sect. 4.

2. Elements of theory

The intensity of a dipole line due to the transition from level $\alpha_{\mathrm{i}} \equiv \Delta_{\mathrm{i}} J_{\mathrm{i}}$ to level $\alpha_{\mathrm{f}} \equiv \Delta_{\mathrm{f}} J_{\mathrm{f}}$ at a photon emission angle θ with respect to the z-axis (along the incident electron beam) can be written in the form (see e.g. [4]):

$$I_{\alpha_{\mathrm{i}}\to\alpha_{\mathrm{f}}}(\theta) = \langle I_{\alpha_{\mathrm{i}}\to\alpha_{\mathrm{f}}}\rangle \left[1 + \beta_{2,\alpha_{\mathrm{i}}\to\alpha_{\mathrm{f}}} P_2(\cos\theta)\right], \quad (1)$$

where $P_2(\cos\theta) = \left(3\cos^2\theta - 1\right)/2$ is the Legendre polynomial of order two, $\beta_{2,\alpha_{\mathrm{i}}\to\alpha_{\mathrm{f}}}$ is the anisotropy parameter which is related to the populations of the upper magnetic sublevels $N_{\alpha_{\mathrm{i}} M_{\mathrm{i}}}$, and $\langle I_{\alpha_{\mathrm{i}}\to\alpha_{\mathrm{f}}}\rangle$ is the 4π-averaged intensity given by (see e.g. [5]):

$$\langle I_{\alpha_{\mathrm{i}}\to\alpha_{\mathrm{f}}}\rangle = N_{\alpha_{\mathrm{i}}} A\left(\alpha_{\mathrm{i}} \to \alpha_{\mathrm{f}}\right) \Delta E_{\mathrm{if}}. \quad (2)$$

In Eq. (2) $N_{\alpha_{\mathrm{i}}}$ is the total population of the upper level α_{i}, $A\left(\alpha_{\mathrm{i}} \to \alpha_{\mathrm{f}}\right)$ is the radiative transition probability and ΔE_{if} is the energy difference between α_{i} and α_{f}.

The line intensity ratio of interest here is defined as:

$$R(\theta) = \frac{I_{3d^2D_{5/2}\to 2p^2P_{3/2}}(\theta) + I_{3d^2D_{3/2}\to 2p^2P_{3/2}}(\theta)}{I_{3d^2D_{3/2}\to 2p^2P_{1/2}}(\theta)}. \quad (3)$$

To highlight the effects of anisotropy of line emission on the intensity ratio, it would be convenient to make comparison of $R(\theta)$ at some θ's values with the ratio of the 4π-averaged intensities

$$\langle R\rangle = \frac{\langle I_{3d^2D_{5/2}\to 2p^2P_{3/2}}\rangle + \langle I_{3d^2D_{3/2}\to 2p^2P_{3/2}}\rangle}{\langle I_{3d^2D_{3/2}\to 2p^2P_{1/2}}\rangle}. \quad (4)$$

3. Numerical results

All the required atomic data, including the radiative transition probabilities and the collision strengths for transitions between magnetic sublevels, were computed

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We have developed a Fortran program for determining the relative line intensities using a magnetic sublevel-to-magnetic sublevel collisional-radiative model [7], in which we have included the 290 sublevels belonging to the 9 configurations $2s^22p$, $2s2p^2$, $2p^3$, $2s^23l$ and $2s2p3l$ ($l = 0{-}2$).

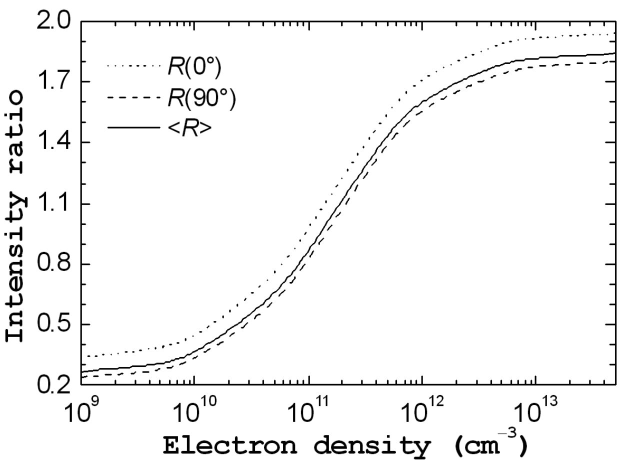

Fig. 1. Dependence of the ratios $R(0°)$, $R(90°)$ and $\langle R\rangle$ on the electron density for incident-electron energy 1.1 keV.

In Fig. 1 the calculated intensity ratios R at $\theta = 0°$ and $\theta = 90°$ are plotted as a function of the electron density n_e for the impact electron energy of 1.1 keV. To show the importance of the emission anisotropy, Fig. 1 also gives the results for the ratio $\langle R\rangle$ of the 4π-averaged intensities. We find that the ratio $R(0°)$ differs from the ratio $R(90°)$ by 42% in the low-density limit ($n_\mathrm{e} \le 10^9$ cm^{-3}) and by less than 10% for $n_\mathrm{e} \ge 9\times10^{11}$ cm^{-3}.

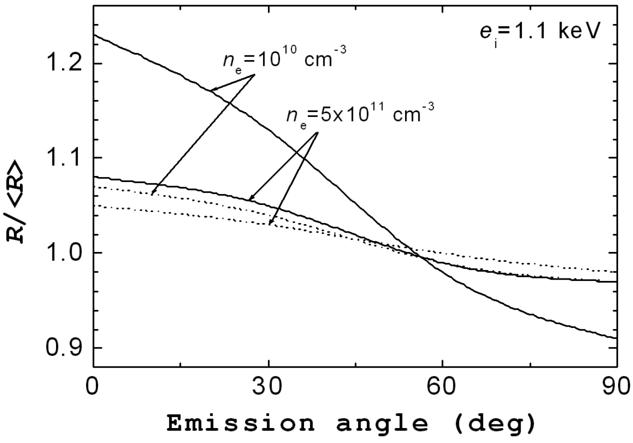

Fig. 2. Dependence of the ratios $R/\langle R\rangle$ on the observation angle θ shown for two values of electron density with (full curve) and without (dotted curve) including blend effect.

In Fig. 2 we have reported the results for the variation of the ratio $R(\theta)/\langle R\rangle$ with the observation angle θ obtained for $e_\mathrm{i} = 1.1$ keV and two values of electron density $n_\mathrm{e} = 10^{10}$ and 5×10^{11} cm^{-3} (full curve) together with the calculated $R(\theta)/\langle R\rangle$ obtained without allowing for the $3d\ {}^2D_{3/2} \to 2p\ {}^2P_{3/2}$ line contribution to the blend (dotted curve). Our calculations indicate that the contribution from the $3d\ {}^2D_{3/2} \to 2p\ {}^2P_{3/2}$ line which blends with the $3d\ {}^2D_{5/2} \to 2p\ {}^2P_{3/2}$ line has the effect to enhance the anisotropy of the angular distribution of the R ratio especially at low densities.

4. Conclusion

In this work we have studied theoretically the intensity ratio R of the summed intensities of the two blended lines $3d\ {}^2D_{3/2,5/2} \to 2p\ {}^2P_{3/2}$ to the intensity of the resonance line $3d\ {}^2D_{3/2} \to 2p\ {}^2P_{1/2}$ emitted from Ar^{13+} ion following impact excitation by monoenergetic and unidirectional electrons. The dependence of R on the electron-beam density ranging from 10^9 to 5×10^{13} cm^{-3} was calculated at different photon emission angles θ with respect to the electron beam direction. Our calculations show that at incident electron energy of 1.1 keV the ratios $R(0°)$ and $R(90°)$ can differ from each other by ≈42% at low densities. This difference decreases with increasing density and becomes less than 10% above $\approx 9\times10^{11}$ cm^{-3}. Also, the contribution from the $3d\ {}^2D_{3/2} \to 2p\ {}^2P_{3/2}$ line which blends with the $3d\ {}^2D_{5/2} \to 2p\ {}^2P_{3/2}$ line has the effect to enhance the anisotropy of the angular distribution of R.

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