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Radiative Properties of High-n Neutral Helium Line Emission for Edge Plasma Conditions

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Abstract: Incomplete thermalization of singlet and triplet high n-levels results in a different response to diffusion processes under edge plasma conditions. The new collisional-radiative numerical code SOPHIA shows that intercombination transitions and radiation transport effects are extremely important to describe the line emission whereas in equilibrium plasmas, these transitions give only little corrections. Simulations relevant for edge plasma conditions of JET and the NAGDIS-II plasma simulator are presented.

I. Introduction

An important ITER design activity is the investigation of detached plasmas which provide a promising method for reducing the heat flux of plasma facing components. Recombination processes are made responsible for the plasma detachment and the spectroscopic investigation of the corresponding radiation emission is therefore of great importance [e.g., 1-3]. The analysis of the radiation emission originating from the various elements and ionisation stages is of great interest, because it provides the possibility for a wide and unique characterization of the plasma: e.g., temperature, density, diffusion, charge exchange, fields, temporal and spatial variations, turbulence and fluctuation analysis. Moreover, a large impact from the spectroscopic analysis stems from the fact, that it is based essentially on a collisional-radiative approach and therefore provides a plasma model independent information. However, the involved molecular recombination processes are very complex (e.g., vibrationally excited hydrogen molecules) and it is highly desirable to avoid them in diagnostic methods. For this reason the analysis of the neutral helium emission to probe edge plasma conditions is much more advantageous.

In order to study diffusion and radiation transport processes under detached plasma conditions through the perturbation of the neutral helium spectral distribution we have developed a new collisional-radiative numerical simulation code SOPHIA [4]. Simulations relevant for the interpretation of the neutral helium lines observed at JET [5] and the NAGDIS-II plasma simulator [1] are discussed.

II. Experimental Spectra of Neutral Helium Line Emission

Figure 1 shows the experimental spectra from the JET divertor [5] of neutral helium in the wavelength range 350-365 nm: the Rydberg-series of the triplet lines 1snd ^{3}D – 1s2p ^{3}P and the singlet line 1s5p^{1}P$_1$-1s2s^{1}S are identified and Fig. 2 shows the emission spectra [1] obtained from the NAGDIS-II plasma simulator [6] in the same spectral window. The arrows in Figures 1/2 indicate the large relative variation of the singlet line 1s5p^{1}P$_1$-1s2s^{1}S.

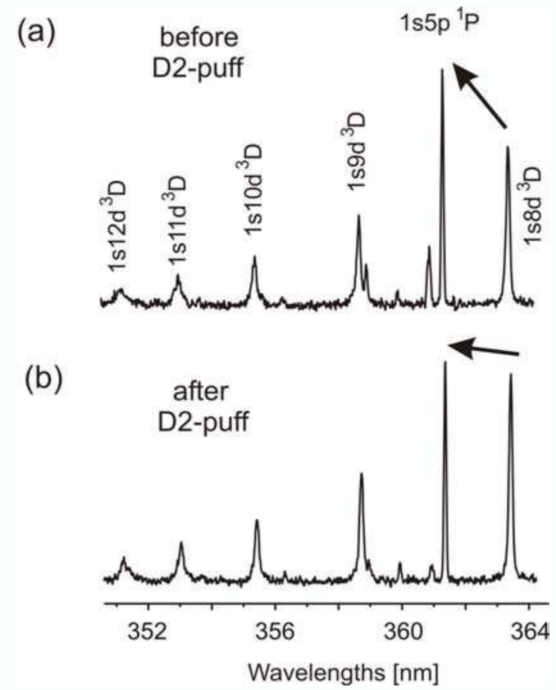

Figure 1: JET neutral helium spectra: triplet series 1snd ^{3}D – 1s2p ^{3}P and the singlet line 1s5p ^{1}P$_1$ – 1s2s ^{1}S$_0$, a) before D_2 gas puff, b) after D_2 gas puff. The strong relative variation of the singlet 1s5p ^{1}P$_1$ – 1s2s ^{1}S$_0$ line is indicated by arrows.

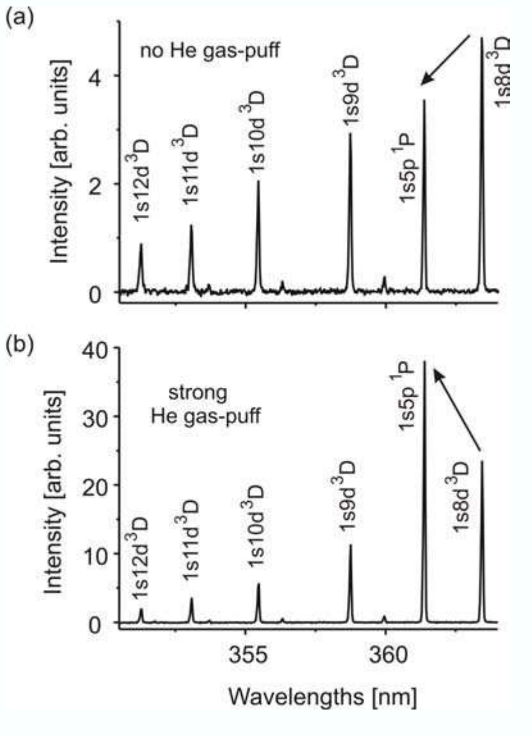

Figure 2: NAGDIS-II neutral helium spectra, a) He pressure of 4.3 mtorr without secondary He gas puffing, b) He pressure of 21.3 mtorr with He gas puffing.

The comparison of the data (Figs. 1 and 2) show a clear similarity, demonstrating that the NAGDIS-II experiment is able to simulate relevant regimes of magnetic fusion for edge plasma conditions discussed in the present paper.

Theoretical simulations with the SOPHIA-code show, that the observed singlet and triplet lines shown in Figures 1 and 2 are sensitive to diffusion processes [5]. It is therefore of great interest to study the line variations for the investigation of different plasma regimes like attached or detached plasmas.

III. Intercombination transitions and diffusion

The spectral distribution I(ω) of the line emission is calculated from the full set of level-population densities n_j, the Voigt-profile escape factors Λ_{ij}, and the normalized, optically-thick line-profile functions Φ_{ij} :

$$I(\omega) = \sum_{i,j} I_{ij}(\omega) = \sum_{i,j} \hbar\omega_{ij}\, n_j\, A_{ij}\, \Lambda_{ij}\, \Phi_{ij}(\omega). \tag{4}$$

Population densities are obtained from a collisional radiative system. Diffusion processes are calculated in τ-approximation, i.e., the flux divergence term $\nabla(n_j v)$ is replaced by n_j/τ, i.e., loss terms for the state $1s^2$, 1s and nucleus are included in eq. (1). At present, $\partial/\partial t = 0$ is assumed, the system is closed by normalization conditions (for more details see [4, 7, 8]).

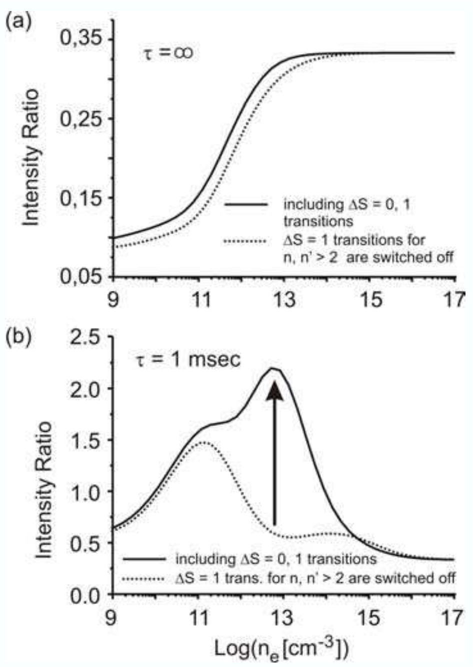

Figure 3 : SOPHIA simulation of the line intensity ratio I(1s5p $^1P_1$ – 1s2s $^1S_0$)/I(1s8d ^3D – 1s2p ^3P), a) no diffusion, b) diffusion time of τ = 1 msec. The arrow indicates the great influence of intercombination transitions.

Figures 3 shows the line intensity ratio I(1s5p $^1P_1$ – 1s2s $^1S_0$)/I(1s8d ^3D – 1s2p ^3P) as a function of n_e, kT_e = 5 eV. Fig. 3a: τ = ∞ (no diffusion), L_{eff} = 0 (no radiation transport). A strong dependence of the ratio for electron densities between 10^{11} cm^{-3} and 10^{13} cm^{-3} is seen. This is connected with the fact that levels with different n-quantum numbers equilibrate at different densities. The dashed curve is calculated by switching off all the intercombination transitions between the excited states n, n' > 2, while the solid curve shows the full calculations. The decrease of the dashed curve arises from radiative intercombination transitions.

Figure 3b shows the diffusive case τ = 1 ms, a large difference (see arrow) between the solid and the dashed curves is seen. The rise in the ratio is due to an effective collisional transfer from the triplet to the singlet levels and this process is much more important for diffusive plasmas: diffusion perturbs thermalization processes (perturbation of the relations established due to ionisation and 3-body recombination). Therefore, the difference of the singlet/triplet populations is larger in the diffusive than in the non-diffusive case. Comparison of the simulation results of Figs. 3 with the data of Figs. 1/2 shows, that the strong relative emission of the singlet line is obviously connected with non-equilibrium effects. For the data presented in Fig. 2, the additional gas-puff leads to a relative overpopulation of the He-like ground state $1s^2$ (compared to the 1s-state) resulting in a relative decrease of the 3-body contribution for the population of the triplet-levels (relative to the channels $1s^2 - 1snl\ ^{1,3}L$). Therefore the intensity of the triplet-series ($1snd\ ^3D - 1s2p\ ^3P$) decreases. In the simulation, this effect is taken into account by means of the diffusion time τ and the normalisation condition. The simulation is therefore able, to quantify the non-equilibrium situation of detached plasmas.

IV. Conclusion

We have shown that the intensity of transitions originating from the singlet and triplet system strongly depends on diffusion. The simulations indicate, that collisional and radiative intercombination transitions are very important for the description of the line emission in diffusive plasmas whereas in equilibrium plasmas the effects are much smaller.

V. References

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