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New calculations of Stark profiles of neutral helium lines

M. Koubiti[1], H. Capes[2], L. Godbert-Mouret[1], Y. Marandet[1], J. Rosato[1], R. Stamm[1]

[1] *PIIM, UMR 6633 CNRS/Université de Provence, centre St-Jérôme, service 232, F-13397 Marseille, France*

[2] *DRFC, Association Euratom-CEA, CEA Cadarache, 13108 St Paul lez Durance, France*

Abstract: New Stark broadening calculations of He I triplet lines 1s2p ^{3}P-1snd ^{3}D with n=8-20 are presented for electron densities and temperatures covering tokamak divertor conditions. The calculations are based on the standard broadening theory which consists on the use of the impact and the quasi-static approximations for the interactions of the emitter with the plasma electrons and ions respectively. More precisely, we have used for the electrons a binary model and for the ions the Holtsmark field distribution. An atomic physics data basis of neutral helium has been constructed using hydrogen wavefunctions to calculate the dipole transition matrix elements. The aim of these line profile calculations is to demonstrate their possible use for diagnostic purposes in divertor plasmas containing neutral helium.

1. Introduction

Spectroscopic plasma diagnostic methods are widely used in tokamaks to infer plasma parameters from the core and divertor/edge regions. For recombining deuterium plasmas leading usually to divertor detachment, high-members of the Lyman, Balmer or Paschen series of deuterium have been observed and used to deduce the electron density, the electron temperature or both in several tokamaks, e.g. JET [1], Alcator C-Mod [2] and ASDEX Upgrade [3]. In these experiments, the spectroscopic determination of the electron density relies on the use of either the profiles or the widths of transitions originating from highly-excited energy levels (high-n) which are subject to a linear Stark effect. On the other side, depending on the experimental data and plasma conditions, the electron temperature is obtained by one of the numerous spectroscopic methods such as the Boltzmann plot which is accurate when the level populations obey a statistical equilibrium. These spectroscopic techniques can be extended for the same purposes to the high-members of the triplet diffuse series of neutral helium, i.e. He I 1s2p ^{3}P-1snd ^{3}D (n≥8) lines observed in helium discharges or in plasmas containing helium. Such lines were already observed in a helium discharge with D_2 puffing in JET [4-5] and in several experiments performed on the linear divertor simulator NAGDIS-II [6-7]. A typical helium spectrum measured in the JET divertor has been previously analysed [4-5]. In this paper, two main points have been improved in comparison to the calculations reported in [4-5]. First, for all upper principal quantum numbers n=8-20, the 1sng ^{3}G levels have been included in the building of the atomic physics data basis. The other point concerns the use of a more appropriate cut-off for the strong collisions in the frame of the binary impact approximation applied to treat the emitter-electrons interactions. This cut-off which has been first introduced by Griem [8] for hydrogen lines is more convenient for neutral emitters immersed in plasmas of moderate electron densities and low temperatures.

2. Atomic physics data

The calculation of a Stark broadened line profile requires some atomic data like the energies and the reduced dipole matrix elements of the transitions between all the upper and lower levels. For the considered He I lines, the main difficulty concerns the reduced dipole matrix elements which are not all available in the literature. This lack of neutral helium data, especially for highly excited levels, has been overcome by constructing an approximate atomic data basis based on energies taken from the NIST [9] and reduced matrix elements calculated with hydrogen wavefunctions. The justification of this approximation is that the studied transitions involve only one optical electron occupying highly-excited levels, the other one being in the ground state. The excited electron sees a nucleus of charge +e. Moreover, as we are interested in transitions between 1snd ^{3}D and 1s2p ^{3}P levels with n in the range 8-20, we have retained only the closest levels for each, i.e. only levels with $0\leq l\leq 4$ for each upper energy level n. When the energy of 1sng ^{3}G level for a given n could not be found in [9], it has been set equal to that of the 1snf ^{3}F level.

3. Stark broadening calculations

The calculations presented here are based on the standard model of Stark broadening and were obtained with the PPP [10] line shape code. In this model, the interactions of the emitter with the plasma electrons and ions are respectively treated with the binary impact collision and quasi-static approximations. The electron broadening is represented by the following operator: $\Phi(\omega)=\frac{1}{3}\left(\frac{8\pi m_e}{kT_e}\right)^{1/2} N_e \frac{e^4}{\hbar^2}\vec{r}_n.\vec{r}_n\left(K_n+\int_{y_{\min}}^{\infty}\frac{e^{-y}}{y}dy\right)$, where $\vec{r}_n$ is the position operator of the bound electron and K_n is the n-dependent strong collision term. With $y=m_e \mathrm{v}_e^2/2kT_e$, the cut-off for the strong collisions corresponding to $\rho_W(\mathrm{v}_{\min})=\rho_D$ (Weisskopf and Debye radii) is given by $y_{\min}=\frac{\hbar^2 n^4}{3}\frac{\omega_p^2}{(kT_e)^2}$ [8]. The binary model is valid when $\rho_W/r_e<<1$, where $r_e=(3/4\pi N_e)^{1/3}$ represents the mean distance between electrons. Using the same Weisskopf radius as for hydrogen, i.e. $\rho_W=\hbar n^2/m_e \mathrm{v}_e$, we show in Fig.1 the limits of validity of the binary approach for n=8-12 and n=20 and plasma conditions relevant to divertors. Profiles calculated for plasma conditions similar to those measured in NAGDIS-II are shown in Fig. 2 in a semi-logarithmic scale. The plasma and the level populations are assumed to be respectively homogeneous and at a statistical equilibrium while all other broadening mechanisms (Zeeman and Doppler effects) are ignored.

Examination of validity criteria of the used approximations shows that the quasi-static approximation is good for plasma parameters corresponding to divertor conditions but the binary model becomes questionable for n>9 at high densities and low temperatures as can be seen from Fig.1. Therefore if the impact approximation is used, only lines with n=8 and 9 appear suitable for density diagnostics over almost the whole considered plasma parameter ranges ($N_e=10^{18}$-10^{21} m^{-3} and T_e=0.2-5 eV). Calculations of Stark broadening concerning the He I 1s2p ^{3}P-1s8d ^{3}D ($\lambda \approx 3634.2$ Å) line are summarized in Fig.3. In Fig.3 a), we show the different contributions to the line broadening at T_e=1 eV. The electron contribution w_e to the line FWHM is of the same order as the ion contribution w_i at $N_e=5x10^{19}$ m^{-3} but becomes dominant for higher densities, e.g. at $N_e=5x10^{20}$ m^{-3}, it is about twice the ion contribution (w_e~2 Å and w_i~1 Å). Note that features like line asymmetry and forbidden components are due to the ion contribution and that Doppler effect has a negligible contribution for the assumed neutral temperature of 10 eV. As Stark broadening depends on both the electron density and temperature, the electron temperature should be determined first using for instance the line intensities before using one of the He I lines for electron density determination by exploring the strong density dependence of Stark line broadening line.

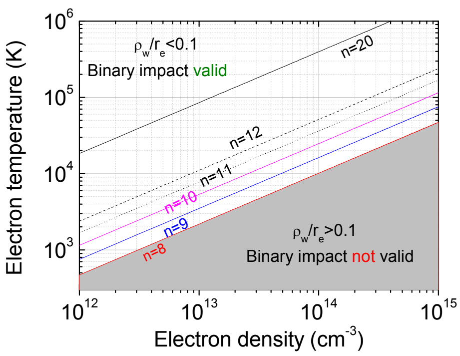

Fig.1. Validity of the binary impact approximation for n=8-12 and n=20 for plasma conditions relevant to Tokamak divertors.

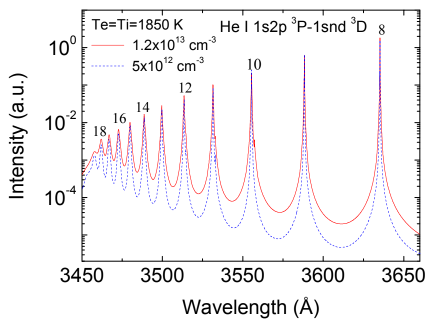

Fig. 2. He I 2p ^{3}P-nd ^{3}D line profiles calculated without Doppler effect for Te=1850 K, Ne=5x10^{12} cm^{-3} (dot) and Ne=1.2x10^{13} cm^{-3} (solid)

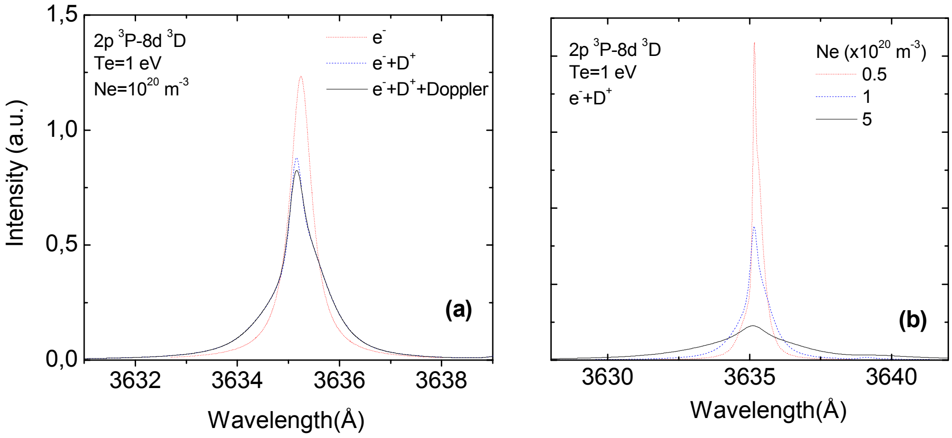

Fig. 3. Profiles of the He I 1s2p ^{3}P-1s8d ^{3}D line. a) the different contributions to the line broadening for Te=1eV and Ne=10^{14} cm^{-3}: electrons only, electrons and D^+ ions with and without Doppler effect (T_{He}=10 eV). b) Stark profiles for Te=1 eV and different electron densities.

4. Conclusion

Stark broadening of He I 2p ^{3}P-nd ^{3}D (n>7) lines perturbed by plasmas can serve as a diagnostic tool to characterise divertor plasmas of fusion devices. Several spectroscopic techniques exist for the electron temperature determination, e.g., the Boltzmann plot or the continuum spectral emission. In the opposite, only few spectroscopic techniques can be used for the electron density determination, the one based on Stark broadening being the most promising but requires highly-resolved spectra and an accurate modelling of both the electron and ion contributions to the line broadening. We have shown that in the frame of the standard theory, the only lines for which both the quasi-static and binary impact approximations hold over almost the whole plasma conditions relevant to divertors are the 2p ^{3}P-8d ^{3}D or 2p ^{3}P-9d ^{3}D. Aiming to provide theoretical Stark profiles of He I lines as accurate as possible, an atomic physics data basis has been built using a hydrogen approximation (H wavefunctions) to compute the dipole reduced matrix elements required by the modelling.

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