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Electron density determination from Stark broadening of high-*n* HeI lines

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Abstract. Calculations of Stark profiles of high-*n* lines (i.e., transitions from high-lying or Rydberg levels) emitted by neutral helium in a relatively dense plasma are presented. Stark broadening of HeI lines arising from Rydberg states are used here for the first time to determine the plasma electron density for densities corresponding to detached divertor plasmas or recombining regimes. In principle, this requires in addition to high-resolution spectroscopic measurements, the use of accurate atomic data which are not available at present time. However, since reliable data are not yet available, the results presented here have been obtained with a H-like approximation for the dipolar transition reduced matrix elements. The deduced electron density from Stark broadening is compared to its experimental value measured by a Langmuir probe.

I. Introduction

Introducing helium in a deuterium discharge or deuterium in a helium discharge through the periphery of a tokamak often results in the cooling of the divertor or edge plasma. Under such conditions the cold dense edge/divertor plasma allows the observation of line emission from high-lying levels (Rydberg states or high-*n*) of neutral helium. HeI triplet lines from high-*n* levels have been measured in the JET divertor (helium discharge with D_2 puffing) [1] and also in the linear divertor plasma simulator NAGDIS-II [2]. These spectral lines can be used to obtain the electron density from their Stark broadening and even the electron temperature from the line intensities if one uses a collisional-radiative model for the populations. However, density diagnostics based on Stark broadening require accurate atomic data for the considered transitions which unfortunately is not available presently. Therefore the results presented in this paper are based on two main approximations: the use of hydrogen dipole reduced matrix elements and the binary collision approximation for the radiator perturbation by electrons.

II. Atomic data and Stark profile calculation

Neutral helium emission lines of interest here involve transitions between triplet levels: $1snl\ ^3L$ (upper) and $1s2p\ ^3P$ (lower). Owing to computer limitations for the Stark profile calculations which manipulate matrices whose dimensions increase with increasing number of levels, we have limited ourselves to the following energy levels $1snl\ ^3L$ with $7 \leq n \leq 20$ and $0 \leq l \leq 3$, i.e., levels $1sns\ ^3S$, $1snp\ ^3P$, $1snd\ ^3D$ and $1snf\ ^3F$ with $1s2p\ ^3P$-$1sns\ ^3S$ and $1s2p\ ^3P$-$1snd\ ^3D$ as the allowed dipole transitions. Stark broadened line profiles are calculated using the PPP code [3] which requires, in addition to some plasma parameters, atomic data like level energies and populations as well as the reduced matrix elements of the radiative transitions. We have constructed an input file by taking the level energies from the NIST database [4] and using a hydrogen-like approximation to calculate the reduced matrix elements of all the allowed transitions between the considered energy levels including those within the upper levels group. The calculation of the Stark profiles presented here are based on the standard theory, i.e., the well known static approximation for the ions and the impact binary approximation for the electrons. For the plasma conditions considered here which are relevant to recombining plasma regimes, Stark broadening of lines from high-lying levels is dominated by the electron contribution while ion dynamics effect can be neglected.

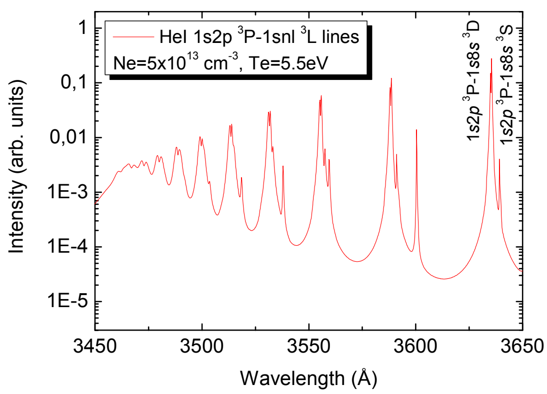

Fig. 1: A Calculated Stark profile of HeI $1s2p\ ^3P$-$1snl\ ^3L$ lines by the PPP code. Instrumental function and Doppler effect not included.

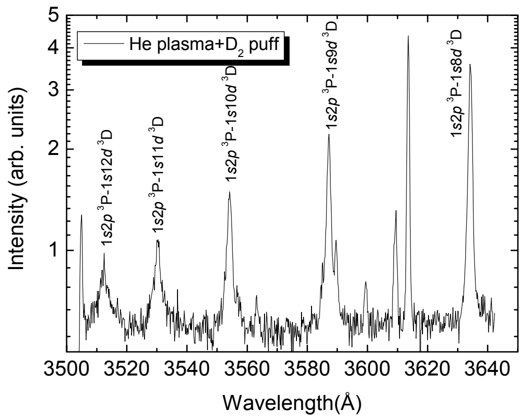

Fig. 2: An experimental JET spectrum measured in a helium discharge with D_2 puffing using the KT3A system.

For illustration purposes, a typical Stark profile of high members of the diffuse series calculated for neutral helium emitters embedded in a deuterium plasma with T_e=5.5 eV and N_e=5.5x10^{13} cm^{-3} is shown in Fig. 1. It has been obtained without the Doppler effect and the instrumental function. One clearly can see the expected increase of Stark broadening with increasing *n* leading eventually to a merging of very high-*n* lines (left of Fig. 1). Note that the sharp lines in Fig.1 represent $1s2p$ ^{3}P-$1sns$ ^{3}S transitions as indicated for the transition from level *n*=8.

III. Comparison to experimental data

In Fig. 2 we show an experimental spectrum measured in the JET divertor using the KT3A system with a 100 μ spectrometer slit entrance and a 0.18Å/pixel dispersion for the CCD camera corresponding to a Gaussian instrumental function having a FWHM of ~1.0 Å. The spectral range covered here (3500-3650 Å) allows the measurement of only 5 triplet lines (8≤*n*≤12) and a singlet line 1s2s ^{1}S-1s5p $^1P_1$ (second peak from the right of Fig. 2). Other weak peaks shown in Fig. 2 represent impurity lines. In Fig. 3 the HeI $1s2p$ ^{3}P-$1s12d$ ^{3}D line is fitted with a Lorentz line shape having a FWHM=3.7±0.3 Å. Being isolated and the most affected by Stark effect (its width > FWHM of the instrumental function), this line is the most convenient to deduce the divertor plasma electron density. The other 4 triplet lines of Fig. 2 were fitted with Lorentzians too. Their FWHM vary between 1.2 Å (for *n*=8) to 2.3 Å (for *n*=11).

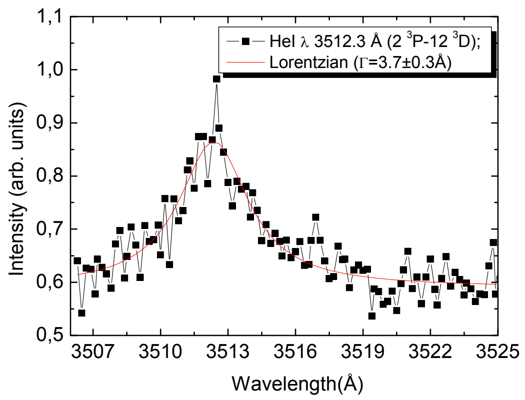

Fig. 3: Fit of the HeI λ 3512.3Å $1s2p$ ^{3}P-$1s12d$ ^{3}D triplet line with a Lorentzian having a FWHM=3.7±0.3 Å.

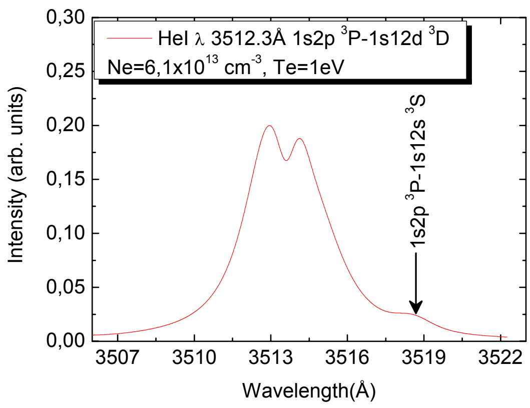

Fig. 4: A calculated profile of the HeI λ 3512.3Å $1s2p$ ^{3}P-$1s12d$ ^{3}D line obtained with the PPP code.

We have calculated Stark profiles for the HeI 1*s*2*p* ^{3}P-1*s*12*d* ^{3}D and 1*s*2*p* ^{3}P-1*s*11*d* ^{3}D lines. To account for the Doppler effect in addition to the apparatus function, a temperature of 10 eV has been assumed for the helium neutrals which slightly increase the total Gaussian FWHM. The calculations give for the HeI 1*s*2*p* ^{3}P-1*s*12*d* ^{3}D line, an electron density Ne~6.1±0.7x10^{13} cm^{-3}. Fig.4 shows the calculated profile for the above density. Note that electron temperature doesn't have a significant effect on the Stark broadening and that the line presents a structure which is not seen on the experimental spectral lines. The other comparison concerns the HeI λ 3531.7Å 1*s*2*p* ^{3}P-1*s*11*d* ^{3}D line. As the experimental line has a Lorentzian FWHM=2.3±0.2 Å, our calculations give an electron density Ne~4.2±0.7x10^{13} cm^{-3}. The two different deduced electron density values (40% difference) are nevertheless comparable to the value $Ne_{meas.}$~5.5x10^{13} cm^{-3} measured by a Langmuir probe located near the emitting zone.

IV. Conclusion

First results concerning the use of Stark broadening of neutral helium lines resulting from Rydberg states to determine the electron density of a divertor plasma have been presented for the first time. The electron density values deduced from two different lines, even different from each other by a factor of 40%, are of the same order of magnitude and close to the Langmuir probe measurement. This indicates some consistency of the calculations although obtained with approximate atomic data for the reduced matrix elements and consolidates probe measurements. However, the electron density uncertainty is thought to be due to the used atomic data and the binary collision approximation. Better results should be obtained with more accurate atomic data and high-resolution spectral measurements. It is projected to use in the future more accurate atomic data for high-*n* levels of neutral helium in order to improve the electron density diagnostic accuracy.

V. References

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