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# Dense plasma effects on atomic data and line emission of He I for divertor plasma conditions

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**Abstract**

Effects of collisions between autoionizing levels of helium on its dielectronic recombination rate coefficients are investigated for ionizing plasma conditions encountered in magnetic fusion devices. It is shown that the so-called density effects including collisions and level depression seriously affect dielectronic recombination rates and can alter the atomic/ionic fraction of helium which enters in several diagnostics employing population densities. On the other side, Stark broadening of the high members of the diffuse series of neutral helium is also examined for recombining plasma conditions relevant to divertor regions. It is shown that similarly to the Balmer lines of hydrogen isotopes, high-*n* helium lines can be used for electron temperature and density determination.
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## 1. Introduction

Atomic and plasma–material interaction processes play an important role in thermonuclear plasmas and their knowledge has a significant impact on fusion energy research and development. The analysis of the helium radiation emission plays an important role as recombining α-particles from the fusion reactions create He I and He II and ash transport, recycling and removal are key issues [1,2]. The fundamental understanding of the radiative properties and related atomic physics processes are therefore of great interest to independently characterize the various phenomena.

In this paper, we investigate the dielectronic recombination (DR) rate coefficients and the Stark line broadening of neutral helium for opposite plasma conditions met in magnetic fusion devices, i.e. ionizing and recombining plasmas respectively. A particular attention is granted here to dense plasma effects which have been traditionally ignored for magnetically confined plasmas. It will be shown that collisional redistribution effects between

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autoionizing levels as well as level depression seriously alter the dielectronic recombination rate. This in turn has a large impact for helium diagnostics. We present here spin-dependent calculations of helium DR rates up to principal quantum number $n = 10$ and scaling relations for larger quantum numbers $n > 10$. By means of collisional radiative calculations, carried out with the SOPHIA-code [3], we will show that dense plasma effects on DR enter strongly into the atomic/ionic fraction determination of He. This is important for all diagnostics employing atomic population densities like power loss and radiation cooling, diffusion and particle transport analysis.

On the other hand, neutral helium spectral emission especially triplet lines of the diffuse series 1s2p $^3$P-1snd $^3$D with $n \geqslant 8$ can exhibit a strong sensitivity to Stark effect and therefore can be used for plasma parameters determination. This diagnostic method, usually employed for hydrogen/deuterium emission (e.g., high-members of the Balmer series) in recombining plasmas [4–6] can be extended to neutral helium providing that the surrounding plasma is relatively dense and cold and contains helium atoms. Plasma conditions relevant to divertor regions ($N_e = 5 \times 10^{18}$–$5 \times 10^{20}\,\mathrm{m}^{-3}$, $T_e =$ 0.2–5 eV) have been investigated to find out how Stark broadening of He I 1s2p $^3$P-1snd $^3$D lines can be used for electron density diagnostics.

## 2. Dense plasma effects on helium DR rates

Dielectronic recombination is a fundamental electron–ion collision process of known importance in astrophysical and fusion plasmas [7]. It proceeds in two steps: a start with a dielectronic capture in a doubly excited state followed by autoionization or decay through photon emission. At low electron densities, each autoionizing level is considered to be independent from the other levels and provides its own contribution to the DR rate:

$$\langle \mathrm{DR} \rangle_{ji} = 1.656 \times 10^{-22} \frac{1}{g_s} Q_{\mathrm{isol},ji} \frac{\mathrm{e}^{-E_{s,j}/kT}}{(kT)^{3/2}} [\mathrm{cm}^3\mathrm{s}^{-1}], \tag{1}$$

where $E_{s,j}$ and $kT$ are respectively the capture energy for the $2lnl$ level and the electron temperature both in eV while $g_s$ is the statistical weight of the 1s-state. $Q_{\mathrm{isol},ji}$, the satellite intensity factor, is defined as:

$$Q_{\mathrm{isol},ji} = \frac{g_j \Gamma_j A_{ji}}{\Gamma_j + \sum_i A_{ji}}, \tag{2}$$

where $\Gamma_j$ and $g_j$ are respectively the autoionization rate and the statistical weight of state $j$, and $A_{ji}$ is the radiative decay rate coefficient for the transition between states $j$ and $i$.

The radiative and autoionization rates have been calculated with the Flexible Atomic Code, FAC [8]. After diagonalization operations of each 1s$nl$ and 2$lnl$ configurations, we have obtained intensity factors $Q_{\mathrm{isol}}(n)$ with $n$ up to 10. For higher $n$, we used a Genetic Algorithm (GA) [9] to generate a spin-dependent $Q_{\mathrm{isol}}(n)$ scaling laws for all kinds of transitions. The calculated total DR rate coefficients [10] agree well (within 20%) with the detailed calculations of Burgess and Tworkowski [11] and Wang et al. [12] while deviations by more than a factor of 2 are visible for other methods [10] for the considered electron temperature range 5–5000 eV.

At high densities where the collision rates exceed the autoionization and radiative decay rates (Boltzmann limit) the satellite intensity factor takes the form:

$$Q_{\mathrm{Boltz}} = \frac{\bar{g}\bar{\Gamma}(\bar{A}_{21} + \bar{A}_{n1})}{\bar{A}_{21} + \bar{A}_{n1} + \bar{\Gamma}} \tag{3}$$

with

$$\bar{g} = \sum\nolimits_j g_j, \quad \bar{\Gamma} = \frac{\sum_j g_j \Gamma_j}{\sum_j g_j} \quad \text{and} \quad \bar{A}_{21,n1} = \frac{\sum_{ij} g_j A_{ij}}{\sum_j g_j}.$$

The GA [9] was also used to obtain general formulas for the averaged autoionization and transition rates. Evaluation of $Q$-factors for large values of $n$ shows a slow convergence for both $Q_{\mathrm{isol}}$ and $Q_{\mathrm{Boltz}}$ ($Q_{\mathrm{isol}}(2l2l') = 0.16 \times 10^{12}$, $Q_{\mathrm{isol,scale}}$ $(2l15l') = 0.27 \times 10^{12}$ and $Q_{\mathrm{Boltz}}(2l3l') = 0.92 \times 10^{12}$, $Q_{\mathrm{Boltz,scale}}$ $(2l20l') = 0.11 \times 10^{13}$). Note that for highly charged impurities, e.g., argon, the dielectronic recombination rate converges rapidly (because of the large radiative decay rates) and high density corrections for configurations with large $n$ provide only a small correction for the total recombination rate. At an electron density $N_e = 10^{20}\,\mathrm{m}^{-3}$, the He I estimated [13] maximum quantum number $n_{\max}$ is 16. Therefore collisional redistribution effects between the autoionizing levels as well as level depression, which are preferentially important at large quantum numbers seriously alter the He I total dielectronic recombination rate.

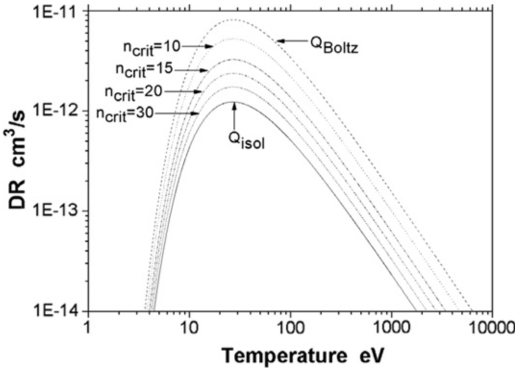

Fig. 1. Effects of electron density on the DR rate coefficients of helium for $T_e = 5$–$5000$ eV. Curves pointed by $Q_{\mathrm{isol}}$ and $Q_{\mathrm{Boltz}}$ represent respectively DR calculations obtained with intensity factors $Q$ calculated for low density (isolated levels) and high density (Boltzmann limit).

DR rate coefficients for $Q_{\mathrm{isol}}$ and $Q_{\mathrm{Boltz}}$ calculations are illustrated on Fig. 1. The DR rate obtained under the Boltzmann limit (high density) is larger than that calculated for isolated levels (low density) by a factor of 6.6 at the maximum DR rate coefficient. This demonstrates the importance of collisional processes between the doubly excited states. The intermediate electron density case was also investigated for several critical quantum numbers. As it can be seen from Fig. 1, the $Q$-factor following Eq. (4) depends extremely on the critical quantum number $n_{\mathrm{crit}}$. Therefore, collision effects increase largely the DR rate, e.g., from $n = 10$ it increases more than a factor of 4.

$$Q = \sum_{n=2}^{n_{\mathrm{crit}}} Q_{\mathrm{isol}} + \sum_{n>n_{\mathrm{crit}}}^{n_{\mathrm{max}}} Q_{\mathrm{Boltz}}. \tag{4}$$

Due to variation of the rate coefficients resulting from the use of different methods of atomic structure calculations, the SOPHIA-code [3] based on fully collisional-radiative model was used to investigate inaccuracies effects on the atomic/ionic balance. It has been shown [10] that the double ratio $R$ given by

$$R = \{n(1s^2)/n(1s)\}_{\mathrm{model}}/\{n(1s^2)/n(1s)\} \tag{5}$$

can be affected by a factor of 3 for a collisional ground state model where DR is coupled to the ground state of neutral helium, and by a factor of 10 for a channel collisional model where DR is coupled to the respective single excited singlet and triplet states after radiative decay. Therefore, high density effects influence largely the ionic/atomic fraction. This can cause anomaly in diagnostic interpretations employing atomic population densities.

## 3. Stark broadening of high-*n* lines emitted by neutral helium

The calculations discussed here concern Stark profiles of the high-$n$ triplet lines of the diffuse series 1s2p $^3$P-1snd $^3$D ($n = 8$–$20$) emitted by helium atoms contained in a plasma. They have been performed using the PPP line shape code [14,15]. The interaction of the radiating atom with the plasma electrons is treated within the frame of the impact theory assuming non-overlapping strong collisions (binary collision approximation). On the other hand, a quasi-static approximation [16] is used to represent the interactions between the emitter and the plasma ions. The quasi-static approximation is a good approach for the calculation of ion contribution to line broadening of all studied He I lines over the whole investigated domains of electron density and temperature, i.e. $N_e = 5 \times 10^{18} - 5 \times 10^{20}\ \mathrm{m}^{-3}$, $T_e = 0.2$–$5$ eV. On the opposite, the binary collision approximation validity criterion ($\rho_W/r_e \ll 1$, where the electron Weisskopf radius $\rho_W = n^2\hbar/m_e v_e$ and the mean inter-particle distance $r_e = (3/4\pi N_e)^{1/3}$) indicates that this approximation is good for $n = 8$–$9$ over the whole ranges of electron density and temperature but becomes questionable for higher $n$ especially at the highest density and lowest temperature values. In respect to our previously reported calculations [17,18], two main points have been improved. First, the 1sng $^3$G levels have been taken into account in the building of the He I atomic data basis. The second point concerns the cutoff for the strong electronic collisions, the former cutoff (more suitable for ionic emitters) has been replaced by the appropriate one originally proposed by Griem [16] for neutral emitters. Fig. 2 shows pure Stark profiles of high-$n$ ($n = 8$–$20$) He I lines calculated for plasma conditions similar to those of some experiments conducted on the linear divertor simulator NAGDIS-II [19–21], i.e. $T_e = 1850$ K and $N_e = 1.2 \times 10^{19}\ \mathrm{m}^{-3}$. To illustrate how the profiles are affected by the density at a given $T_e$, a calculation for a lower density $N_e = 5 \times 10^{18}\ \mathrm{m}^{-3}$ has been also added. In all these calculations, Zeeman and Doppler effects are ignored. From the above considerations, it appears that the best lines to use for plasma electron density determination are those involving $n = 8$ and 9 for the plasma conditions considered here. Fig. 3 shows how the density affects

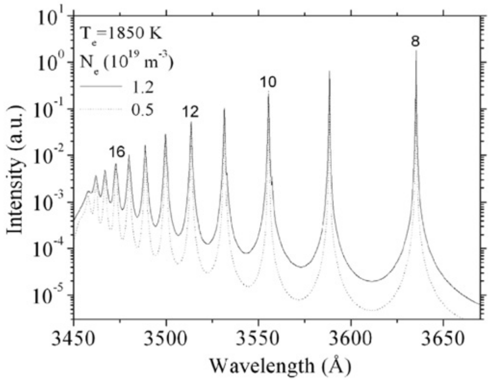

Fig. 2. Pure Stark line profiles of He I 1s2p $^3$P-1snd $^3$D lines with $n = 8$–20 calculated for a deuterium plasma with an electron temperature $T_e = 1850$ K and two electron density values $N_e = 5 \times 10^{18}$ m$^{-3}$ (dot) and $N_e = 1.2 \times 10^{19}$ m$^{-3}$ (solid). Note the use of a semi-logarithmic. Other broadening mechanisms and the Zeeman effect are not included.

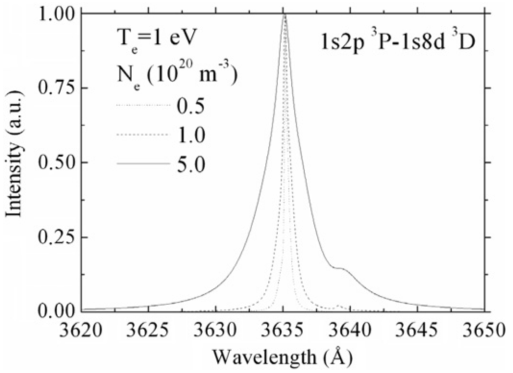

Fig. 3. Calculations of pure Stark profiles of the He 1s2p $^3$P-1s8d $^3$D line for a deuterium plasma with $T_e = 1$ eV and several densities $N_e = 0.5 \times 10^{20}$ m$^{-3}$ (dot), $1 \times 10^{20}$ m$^{-3}$ (dash) and $5 \times 10^{20}$ m$^{-3}$ (solid).

the shape of the 1s2p $^3$P-1s8d $^3$D line for a given electron temperature of 1 eV. As the density increases the line broadens, the forbidden components and the line asymmetry caused by ion broadening become more visible. Fig. 4 shows the effect of the electron temperature on the same line as in Fig. 3 for an electron density Ne of $5 \times 10^{19}$ m$^{-3}$. With decreasing temperatures, the electron broadening dominates the ion broadening and features due to forbidden transitions and ion broadening tend to disappear. This suggests that one should know the electron temperature in order to use Stark broadening of such a line for the electron density determination. Therefore, one has to determine first the electron temperature using for example the Boltzmann plot method (based on line intensities) before using one of the proposed He I lines for electron density determination.

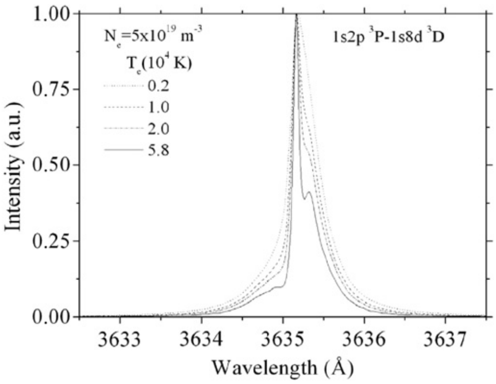

Fig. 4. Same as Fig. 3 but for $N_e = 5 \times 10^{19}$ m$^{-3}$ and several $T_e$ values (in $10^4$ K): 0.2 (dot), 1 (dash), 2 (dot-dash) and 5.8 (solid).

## 4. Conclusion

We have investigated, for ionizing plasma conditions ($T_e = 5$–5000 eV), the He I dielectronic recombination rate coefficients at electron densities ranging from the low density case (isolated autoinizing doubly excited levels) to the high density limit where collisions dominate (Boltzmann limit). We have shown, that dense plasma effects, like channeling and collisions (but also level depression) influence largely the atomic/ionic fraction determination of He I and consequently all the interpretations employing ionic/atomic abundances. On the other side, it has been shown that the He I spectral line emission especially 1s2p $^3$P-1snd $^3$D lines ($n = 8$–20) can be used for electron density and temperature diagnostics for conditions corresponding to recombining plasmas met in tokamak divertor regions. In particular, lines with $n = 8$ and 9 appear to be the most convenient for $N_e$ determination. However the electron temperature should first be obtained for instance using the relative line intensities (Boltzmann plot) before using Stark broadening of these lines for electron density determination.

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