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LIF measurements for validation of collisional-radiative modelling of atomic helium in the edge of a fusion plasma

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Abstract. Local values of the electron density and temperature in the edge of a fusion plasma can be derived with high space and time resolution by the use of line radiation of atomic helium beams. The accuracy of this method is mainly limited by the uncertainties in the collisional-radiative (CR) model which is needed in order to obtain both plasma parameters from the measured relative intensities of atomic helium lines. Laser-induced fluorescence spectroscopy on a thermal helium beam in the edge plasma of the tokamak TEXTOR in Jülich was applied to validate the CR model of helium. By use of a high-power, pulsed laser system (a dye laser pumped by an excimer laser) several laser excitation schemes starting from the n=2 levels have been tried. The fluorescence light was observed at the laser wavelength and elsewhere in the spectrum providing information on population densities of initial levels as well as on collisional population transfer between excited levels. This paper summarises the results of the measurements, showing principal limits and possible improvements of this experimental validation method of the CR model of the diagnostic helium beam.

1. Introduction

Line radiation of atomic helium is widely used for the determination of spatially and temporally resolved electron density and temperature in the plasma. One way of diagnosing the edge region of fusion plasmas is to use radial gas injection into the plasma in the form of thermal [1] or supersonic beams [2][3][4]. The method is based on the intensity measurement of three spectral lines of atomic helium. Electron density and temperature are obtained by comparing two line intensity ratios, with the main dependence on either n_e or T_e, with those calculated using a collisional–radiative (CR) model for helium. Hence, a reliable model is crucial for the accuracy of derived plasma parameters. The model contains a large number of rate coefficients for electron collisional excitation and ionization [2][5][6][7][10] which are in most cases known only from calculations. An earlier work of Brix showing some deviations between the calculated line intensities and corresponding measurements performed on the tokamak TEXTOR in Jülich [2] suggested the need of further improvement of the CR model. Similar conclusion is drawn in a recent study by Schmitz [8].

In this paper we describe our investigations towards a validation of some parameters of the CR model for electron temperatures $T_e \approx 50$ eV, as relevant for the edge of fusion plasmas. The laser-induced fluorescence (LIF) spectroscopy was applied on a thermal helium beam on TEXTOR using a dye laser pumped by an excimer laser. In [9] we describe the details of the experimental set-up (including the laser system, the gas injection and calibration issues) as well as refer to earlier work in this field. In [9] we also derive particle densities in a selected quantum level from LIF signals. In this paper we concentrate on the determination of rate coefficients for collisional population transfer between levels of similar excitation energy from the shells n=3 and n=4. The rate coefficients of our standard CR model we refer to throughout the paper are taken from the ADAS 2002 preferred data set based on the compilation of Ralchenko et al. [10].

2. Rate coefficients for population transfer between levels of the shells n=3 and n=4

Laser excitation between a level of the shells n=2 and n=3-4 of atomic helium is possible in the visible and near UV spectral range. The (saturated) excitation results in a quick population increase of the upper level and thus an enhanced radiation from this level. Due to high enough electron densities, collision-induced population transfer from the upper level to other levels of the shells n=3-4 is in competition to the radiative decay making the detection of collision-induced fluorescence signals originating from those levels possible. Analysis of all those signals provides access to the rate coefficients relevant for the transfer of the excess population to the other levels, some of them being of direct importance for the accuracy of n_e and T_e derivation from intensity ratios.

In Figure 1 the most successful pumping schema is shown with laser excitation at λ = 388.9 nm ($2^3S \rightarrow 3^3P^o$) and fluorescence detection at the laser wavelength and three other ones resulting from collision-induced population transfer. Example time traces of signals originating from the levels of the shell n=3 (at T_e = 50 eV) are shown in Figure 2. In the following, three possible methods of derivation of rate coefficients are described, including experimental and theoretical difficulties affecting the uncertainty of resulting rate coefficients.

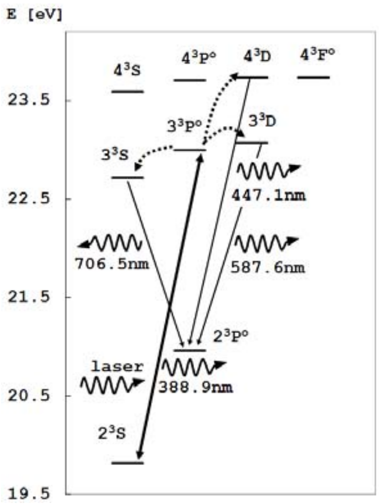

Figure 1: Example pumping channel in triplet helium.

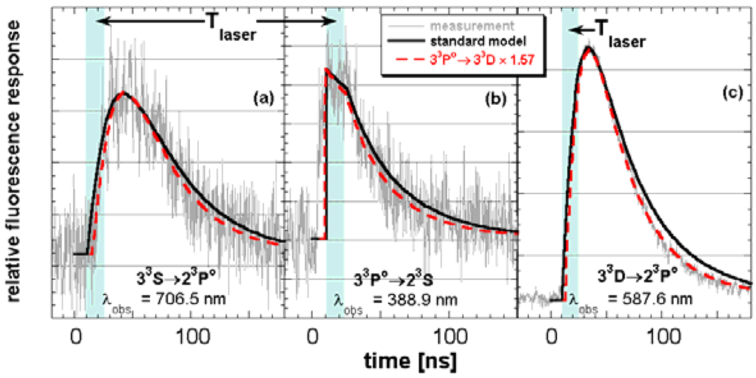

Figure 2: Time traces of fluorescence signals induced by laser excitation at λ = 388.9 nm originating from three different n=3 levels.

2.1. Derivation of a rate coefficient from a time trace of collision-induced fluorescence

Consider Figure 2 c) with the purest signal. The shape of the decaying signal depends mostly on the well known radiative transition probabilities and on the collisional population transfer rate from the upper level to the level 3^3D. As we see, the best fit is achieved upon enlarging the rate coefficient $3^3P^o \rightarrow 3^3D$ by a factor of 1.57. The rate coefficient in question can be derived in this way with an accuracy of 15% which could be further improved by averaging over more laser pulses (in the case of

TEXTOR discharges this means repetition of plasma discharges of same parameters). Since the only quantity, the rate coefficient is retrieved from, is the shape of the decaying part of the signal, the (absolute) calibration of the detection system, the properties of the laser and of the helium beam are not of concern. The only measures needed are a linear detector response as well as a good knowledge of T_e and mostly of n_e since the collisional transition rate is the product of n_e and the rate coefficient. In our experiments we relied on temperatures and densities obtained with a diagnostic thermal helium beam located at a different position (at the equatorial plane at the low field side) complemented by density measurements of a thermal lithium beam at the same position. The accuracy of the plasma parameters obtained in this way is believed to amount to 10% (n_e) and 30% (T_e) [8]. However, the plasma parameters obtained at a different position in the plasma must be mapped to our position being a source of additional uncertainty. Unresolved scattering of the same rate coefficients obtained from different plasma discharges or from different methods suggest a problem with correct mapping of n_e and T_e to our measurement position. To resolve this problem, plasma parameters have to be sampled at the position of the LIF measurements.

2.2. Derivation of a ratio of rate coefficients from a ratio of collision-induced fluorescence

A possibility to obtain ratios of rate coefficients is given by analysis of ratios of signal maxima, e.g. the signals in Figure 2 a) and c) for $<\sigma v>(3^3P^o \rightarrow 3^3D)/<\sigma v>(3^3P^o \rightarrow 3^3S)$, as this signal ratio mostly depends on the ratio of the rate coefficients. The main source of uncertainty in this measurement is the (relative) intensity calibration of the detection system at both wavelengths: application of different gain factors of the photomultipliers in calibration and TEXTOR measurements as well as progressive transmission losses due to contamination of the first, in-vessel mirror limited the measurement accuracy to 20-50%.

2.3. Derivation of a rate coefficient from a ratio of collision- and laser-induced fluorescence

The ratio of signal maxima in Figure 2 c) and b) can be used to determine the rate coefficient of population transfer between both radiating levels. This method, providing rate coefficients and not their ratios, is, however, suffering from several additional uncertainties. We have to cope with the strong laser stray light when detecting the fluorescence from the upper level (the fluorescence signals amounted in many cases only to a fraction of a few percent of the total signal). This deteriorates the signal-to-noise ratio and can lead to a non-linear detector response. Furthermore, very low light intensity of the Ulbricht sphere for wavelengths $\lambda < 400$ nm (detection of the fluorescence at $\lambda = 388.9$ nm) enlarged the error bar of the intensity calibration by up to 20%. An additional issue is the dependence of the pumping efficiency on the collisional population redistribution between the magnetic sublevels of the upper level: it influences the collision-induced fluorescence (e.g. from the level 3^3D) stronger as the fluorescence from the upper level. In the extreme case of very rapid (on the time scale of the laser pulse length) redistribution this would mean in some cases an overestimation of the rate coefficient by up to 50%. This issue could be examined experimentally by measurement of time-resolved traces of both π and σ components of the resonant fluorescence light in the case of exciting e.g. only a π component of the Zeeman-split line.

3. Results and suggestions for future experiments

In triplet helium we deduced the rate coefficient $<\sigma v>(3^3P^o \rightarrow 3^3D)$ from different discharges at the laser excitation at $\lambda_L = 338.9$ nm and $\lambda_L = 587.6$ nm at $T_e \approx 50$ eV to be larger by a factor 1.5 than in our standard model with a relative uncertainty of 40% (unresolved level of scattering of the data). For the rate coefficient $<\sigma v>(3^3P^o \rightarrow 3^3S)$ we obtain a factor 1.3 with relative error of 50% and for $<\sigma v>(3^3P^o \rightarrow 4^3D)$, obtained as a relative value to $<\sigma v>(3^3P^o \rightarrow 3^3D)$, the rate coefficient of our standard model was confirmed with a relative error of 50%. In singlet helium, being a much higher challenge due to very quick radiative decays to the ground state, we were only able to detect collision-induced fluorescence at $\lambda = 667.8$ nm ($3^1D \rightarrow 2^1P^o$, laser excitation at $\lambda_L = 501.6$ nm, according to $2^1S \rightarrow 3^1P^o$) and at $\lambda = 492.2$ nm ($4^1D \rightarrow 2^1P^o$, laser excitation at $\lambda_L = 396.5$ nm, according to $2^1S \rightarrow 4^1P^o$). Owing to the lack of signal detection at the laser wavelengths we are not able to give final statements about the rate coefficients. However, if we assume an overestimation of the model prediction of the 2^1S population by 30% (which could be suggested by our measurements of absolute population densities of the triplet n=2 levels [9]), we can conclude the rate coefficient $<\sigma v>(3^1P^o \rightarrow 3^1D)$ to be higher by a factor 1.9 (relative error 50%) at T_e = 45 eV than the one used in our standard model and to match the one obtained by Brix with the ATOM code using the Born approximation [2]. A further conclusion of the assumption is the confirmation of the rate coefficient $<\sigma v>(4^1P^o \rightarrow 4^1D)$ as used in our standard model (relative error 50%).

The enhanced values of the triplet rate coefficients affect only the line intensity ratio for the T_e derivation: its application (at T_e = 50 eV) in our model would lower T_e values by up to 7%, depending on n_e. On the other hand, the enhanced value of the singlet rate coefficient affects only the density sensitive line intensity ratio and results in lowering of derived n_e values by 10-20%, depending on n_e. However, we were not able to get any insights to one more rate coefficient ($<\sigma v>(3^1P^o \rightarrow 3^1S)$) of a similar importance for both the n_e and T_e derivation, which would complement our investigations. In this sense several improvements are suggested for future experiments, which, applied collectively would allow to suppress the uncertainties by up to a factor of two.

Laser stray radiation: suppressing it by avoiding to hit the nozzle by the laser beam is of utmost importance for better signal-to-noise ratios, avoiding signal distortion by onset of nonlinear response of the photomultipliers as well as to allow signal detection at the laser wavelength in singlet helium (at least for laser excitation of the level 2^1S at λ_L = 501.6 nm). Reproducibility: signal fluctuations of unknown source enlarged the error bars in some cases by up to a factor of two - more experimental time could help to reach satisfactory signal reproducibility. Machine access: more flexible access to the machine to check transmission losses due to build up of coatings on in-vessel optics and for more frequent calibrations. Simultaneous measurement at all relevant wavelengths: getting rid of differing n_e and T_e values at measurement position, more robust intensity calibration. In-situ n_e and T_e measurement: avoiding of mapping uncertainties from other positions in plasma. Use of supersonic helium beam: extending the measurement range towards smaller minor radii, i.e. higher n_e and T_e values. Investigation of collisional population redistribution between the magnetic sublevels of the n=3 levels: more accurate values of the pumping efficiency. In case of using a thermal helium beam: systematic study of the density distribution in the beam by spatial scans of laser-induced fluorescence signals over the beam and by density measurements using a neutral gas manometer for more accurate measurements of absolute densities of the n=2 levels.

References

[1] Schweer B, Mank G, Pospieszczyk A, Brosda B and Pohlmeyer B, *J. Nucl. Mater.* **196–198** (1992) 174–8.
[2] Brix M, *Jülicher Report* **Jül-3638** (1998).
[3] Hidalgo A, Tafalla D, Brañas B and Tabarés F L, *Rev. Sci. Instrum.* **75** (2004) 3478–80.
[4] Andruczyk D, Namba S, James B W, Takiyama K and Oda T, *Plasma Devices Oper.* **14** (2006) 81–9.
[5] Fujimoto T, *J. Quant.Spectrosc. Radiat. Transfer* **21** (1979) 439–55.
[6] Goto M and Fujimoto T, Report NIFS-DATA-43, NIFS, Nagoya (1997).
[7] Brix M and Schweer B, *Proc. 24th EPS Conf. on Controlled Fusion and Plasma Physics* (Berchtesgarden) **21A** (1997) 1837–40.
[8] O Schmitz, I L Beigman, L A Vainshtein, B Schweer, M Kantor, A Pospieszczyk, Y Xu, M Krychowiak, M Lehnen, U Samm, B Unterberg and the TEXTOR team, *Plasma Phys. Control. Fusion* **50** (2008) 115004.
[9] M Krychowiak, Ph Mertens, R König, B Schweer, S Brezinsek, O Schmitz, M Brix, U Samm and T Klinger, *Plasma Phys. Control. Fusion* **50** (2008) 065015.
[10] Yu.V. Ralchenko et. al., Report NIFS-DATA-59, NIFS, Nagoya (2000).