Interplay between D^0 and D_2 in front of a graphite surface in the plasma edge of TEXTOR

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Introduction

Hydrogen isotopes will be the fuelling gases in future fusion devices. The knowledge of the behaviour of H in front of **P**lasma **F**acing **C**omponents (PFC) like walls, limiters and divertors is of main interest. Contrary to noble gases like He, H can also form stable molecules. As an additional complication, these molecules are not only produced by different hydrogen isotopes (isotopomers), but also by interaction with carbon (hydrocarbons) as the present main PFC material. The fluxes of the different species released from PFC, as their velocity distributions, relative concentrations and life times, are of special interest. These quantities are covered by the term "hydrogen recycling" [1]. For molecules, the vibrational ground state population is of supplementary importance for release mechanisms and can vitally influence the recycling.

Passive spectroscopy of atomic lines, e.g. H_α, is a standard method for the determination of atomic quantities [2] like the atomic flux. The velocity distribution and the density of atoms can be measured by laser-induced fluorescence (LIF) on L_α [3, 4]. The rotational and the vibrational population of molecules and the molecular flux are deduced from Fulcher-α spectroscopy [4, 5]. The mapping from the electronically excited state into the electronic ground state requires collisional-radiative models [6, 7].

In TEXTOR measurements in deuterium discharges at constant plasma conditions have been performed in front of an electrically pre-heated graphite test limiter (Fig. 1).

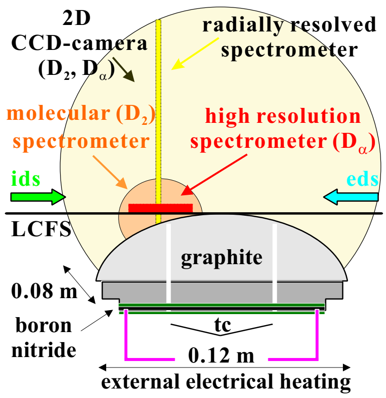

Figure 1: *Spectroscopic observation volumes*

In dependence on the surface temperature T_s, a change of the molecular to atomic deuterium flux ratio has been observed. A correction of the atomic flux, measured by D_α, or equivalently, a correction of the conversion factor S/XB due to molecules, is presented.

Experimental setup and plasma conditions

The measurements have been performed in front of a graphite test limiter positioned at the Last Closed Flux Surface (LCFS) and located in a limiter lock at the medium size tokamak TEXTOR ($R =$ 1.75 m, $a = 0.46$ m). The liner of the tokamak is actively heated to a temperature of about 620 K. The graphite test limiter itself can in addition be electrically pre-heated up to $T_s = 1500$ K ($P_h \geq 3.5$ KW). The external preheating guarantees a homogeneous surface and bulk temperature of the graphite PFC. The temperature is measured by two thermocouples (tc) located just below the surface. The plasma conditions were held constant for a series of high density ohmic discharges. The electron temperature T_e and density n_e at the LCFS, measured by the Helium beam diagnostic [8] in the midplane, amount to $kT_e = 42$ eV and $n_e = 5.5 \times 10^{18}$ m^{-3} during the flat-top phase. The limiter lock allows multiple spectroscopic access to the limiter [4]. A horizontal observation port, with a tangential view on the test limiter was used for the measurement. Simultaneously, the line shape of D_α ($\Delta\lambda < 8$ pm), the penetration depth of D_γ ($\Delta r = 0.2$ mm) and the Q(0-0)-branch of the Fulcher-band ($3p\ ^3\Pi_u \rightarrow 2s\ ^3\Sigma_g^+$) ($\Delta\lambda = 50$ pm) were observed by different spectrometer systems. A 2D CCD camera with a D_α interference filter observes the full limiter and was used for atomic flux measurements. The observation volumes located around the strike zone on the ion drift side (*ids*) in front of the limiter are depicted in Fig. 1.

Experimental results

A variation of the test limiter surface temperature, generated by external electrical heating, was performed for two series of 15 identical plasma discharges (Fig. 2).

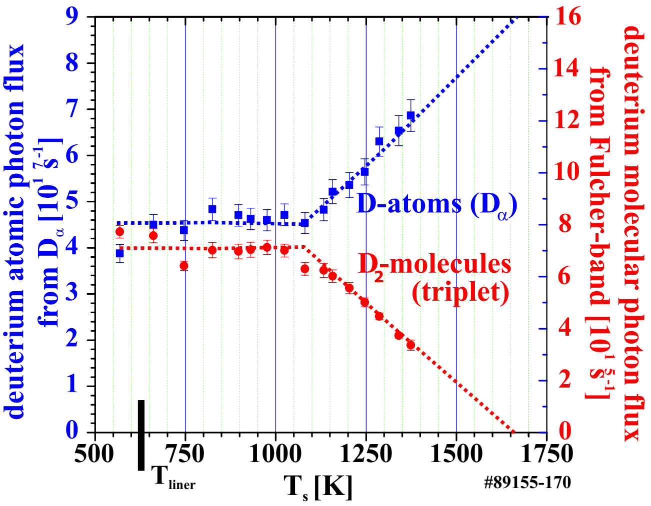

Figure 2: *Variation of Φ_D and Φ_{D_2} with T_s*

The photon flux of atomic deuterium Φ_D measured by means of the D_α-light shows a nearly constant value up to a temperature of 1100 K. For temperatures higher than 1100 K, a significant increase of the intensity is perceived: an increase of Φ_D of more than 30% at the maximal measured T_s. Similar results were also achieved with D_γ line intensity (5). The molecular photon flux Φ_{D_2}, measured simultaneously via the line intensities of the Fulcher-α spectrum, shows an inverse behaviour for high T_s: a decrease of the light emission of about 50% in the temperature range between 1100 and 1400 K. An extrapolation of the curve to higher T_s shows a full disappearance of the molecular intensity for $T_s > 1700$ K. For technical reasons, such a high T_s could not be reached during the campaign. The change in Φ_{D_2} at $T_s = 1100$ K is thus just as sharp as for the atoms. Up to this value the variation of the flux is negligible. Similar results were also obtained from deuterium ion beam experiments on carbon surfaces [9]. It is also necessary to determine the vibrational and rotational populations of the molecules in the electronic ground state, because of a possible re-distribution of the initial vibrational and rotational population. Therefore, it was necessary to derive from the measurements also the vibrational temperature of the ground state (T_{vib}) and the rotational temperature of the excited state (T_{rot}).

Molecular properties

The rotational population was determined by a Boltzmann-fit of the diagonal Q$(0-0)$-branch. Six lines were included into the fitting procedure. The dependence of the rotational population of the $3p\ ^3\Pi_u$ on T_s is depicted in Fig. 3. T_{rot} increases nearly linearly with T_s. The behaviour of the vibrational population was verified for high and low T_s at similar plasma conditions. From the measurement of the vibrational population of the upper state, the ground state population was recalculated by means of the CRMOL-code [7]. Since the deviation between both measurements was within experimental error, a variation of the vibrational population of the ground state during the heating can be excluded. From previous measurements [4], where density scans in front of the same type, but unheated, test limiter were performed, a factor for the conversion from the number of photons of the (0-0)-branch to all visible branches ($v' = v'' = 5$) was determined. The total number of Fulcher-band photons and finally Φ_{D_2}, the photon flux of surface released molecules, can be calculated. For the conversion of photon into molecular particle fluxes Γ_{D_2}, the conversion factor D/XB, which represents the number of molecular losses per Fulcher-band photon, or equivalently, the number of Fulcher-band photons emitted per dissociation, ionisation etc. of a molecule, in comparison to S/XB for atoms, has to be known. This factor can be both measured by gas injection experiments and calculated by collisional-radiative models. D/XB also depends on plasma edge parameters, and amounts approximately to 2×10^3 for the plasma used.

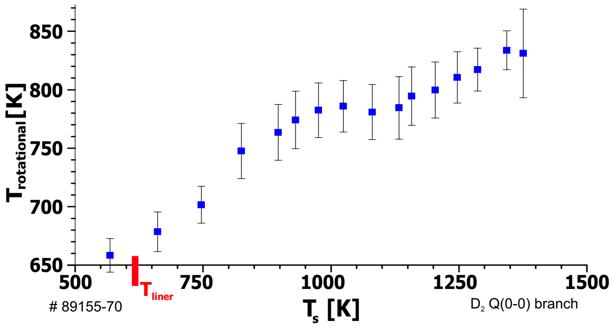

Figure 3: *Variation of T_{rot} with T_s*

Atomic properties

By means of the Zeeman-splitting analysis of the D_α-line profile [10], measured by the high resolution system, three temperature components were identified. For cold limiter conditions ($T_s = 570$ K), at first a background component, caused by reflected and charge exchange particles, can be set fixed. Then a cold component $kT_c = 0.25$ eV and a lukewarm component $kT_l = 3.5$ eV were fitted by two gaussian curves (Fig. 4). The absolute energy value of the cold component varies in a similar way to the variation of the molecular intensity depicted in Fig. 2. Up to $T_s = 1100$ K, only a small increase of the temperature of the cold component appeared from $kT_c = 0.25$ eV up to 0.32 eV. The measurement shows here also no variation in the composition of the three components. Above the threshold temperature of $T_s = 1100$ K, the composition of the release mechanisms obviously changes. kT_c decreases strongly down to 0.18 eV at $T_s = 1400$ K. In addition, the total amount of this component increases from 43% up to nearly 63%, whereas the amount of the lukewarm component decreases from 50% down to 33%. At the same time kT_l increases at high T_s up to 4.3 eV. More atoms are released from the surface, and these are colder on average. The increase of the total amount of atomic Balmer-intensity is also depicted in Fig. 5. The radially resolved D_γ spectrum shows an increase of the intensity above a temperature of $T_s = 1100$ K. The maximum of additionally produced atoms is located near to the surface (< 10 mm). With increasing T_s, even

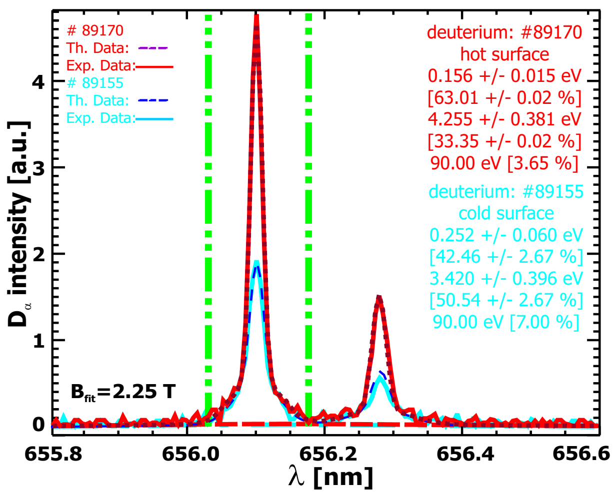

Figure 4: *D_α for high and low T_s*

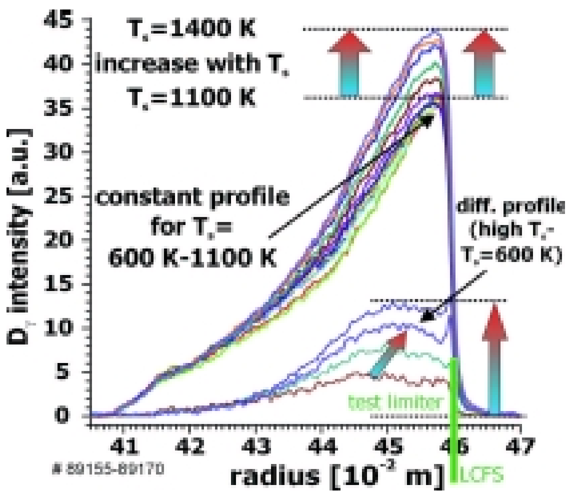

Figure 5: *Variation of D_γ with T_s*

a further shift to the surface appeared. This demonstrates a decrease of the penetration depth of the atoms.

Conclusion

Different conclusions about the properties of atoms and molecules can be drawn from the electrically pre-heated test limiter experiment. As a main result, the particle fluxes can be determined; by simultaneously measuring atomic and molecular D, the total D flux (Γ^{tot}) from a graphite PFC can be derived from the photon flux (Fig. 2). By means of the conversion factors D/XB for the molecules and S/XB for the pure atomic case, the change in the ratio of the atomic to molecular species concentration in the edge layer can be accounted for. The total deuterium flux from the surface is characterised by $\Gamma_D^0 = \Gamma^{tot} = \Gamma_D + 2 \times \Gamma_{D_2}$ (Fig. 6). At high temperatures, when all molecules are absent, the intersection of the extrapolated curve with the ordinate corresponds the total atomic deuterium flux for the given plasma parameter set. The ratio $S/XB = 15$, usually applied for these plasma conditions, is only valid for the pure atomic case [11]. When molecules are present, the ratio of $\Gamma_{D_2}/\Gamma^{tot}$ determines the necessary correction to this value. The definition of an effective $(S/XB)_{eff}$ with an efficiency factor η is required as follows

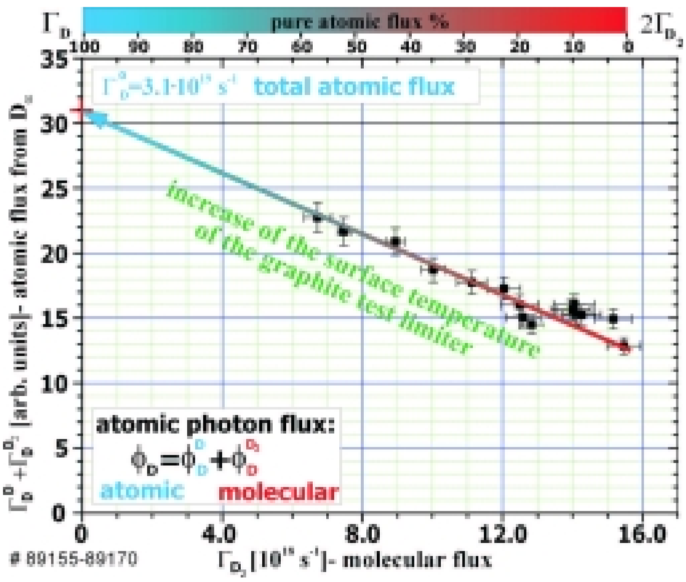

Figure 6: *Change of the composition of the total deuterium flux with increase of T_s*

$$\left(\frac{S}{XB}\right)_{eff} = \frac{S}{XB} + \eta \frac{2 \times \Gamma_{D_2}}{\Gamma^{tot}} \text{ with } \eta \approx 15.$$

η is in the present case about 15, which means that one D_α-photon per molecule is emitted. For the non-heated case of the test limiter ($T_s = 620$ K), the correct value for $(S/XB)_{eff}$ is about 30. As Fig. 6 depicts as well, for the normal case of a TEXTOR edge plasma, the molecules usually dominate in contrast to the atoms, but at high surface temperatures molecules are practically negligible. The deuterium flux from the surface is then determined by thermal release mechanisms.

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