Fast non-Maxwellian atoms in a linear magnetized plasma

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The sheaths between the unperturbed plasma and plasma boundary, such as surfaces or diagnostic probes, play a fundamental role in plasma research [1, 2]. The potential difference $\phi_{\text{sheath}} = \phi_{\text{wall}} - \phi_{\text{plasma}}$ results in acceleration of either positive or negative ions towards the wall, depending on the boundary conditions (e.g., the potential at the wall). After being neutralized at the wall surface, reflected neutral atoms have a kinetic energy in the order of magnitude $E_{\text{kin}} \sim Ze_0\phi_{\text{sheath}}$, with Ze_0 being the ion charge. The kinetic energy of this population of fast non-Maxwellian neutral atoms is higher than the average thermal energy. Observations of such *fast atoms* have been reported in a variety of plasmas, e.g., rf plasmas [3], glow discharge plasmas [4] or atmospheric plasmas [5, 6, 7]. Even though fast atoms can often be present in the plasma, they do not necessarily radiate and so can not be characterized at all. The different atomic, molecular or chemical processes can contribute to the population of excited states of hydrogen atoms. In fusion plasmas, for example, temperatures are high enough to efficiently excite neutral hydrogen by charge exchange or electron collisions [8, 9, 10, 11]. In low temperature plasmas these processes are less efficient, but emission of fast hydrogen increases with the presence of argon [3]. The source of emission of fast atoms is, however, controversially discussed in literature [3, 4].

This work reports on the observations of fast non-Maxwellian hydrogen atoms in hydrogen-argon plasmas as well as first observations of fast atoms in hydrogen mix plasmas with other noble gases, i.e., D/He, D/Ne, D/Kr and D/Xe [12]. The experiments are conducted in the linear magnetized plasma of the device PSI-2 [13, 14]. In the present work the electron densities are in the range of $n_e \sim 10^{17} - 10^{18}\,\text{m}^{-3}$ and the electron temperatures between $T_e \sim 8 - 20\,\text{eV}$. A tungsten target (surface area of $1\,\text{cm}^2$ with target normal facing towards the source) is introduced into the plasma column at $r \approx 2.4\,\text{cm}$ where the hollow plasma profile peaks. An additional negative potential can be applied to the target to further accelerate positive ions and produce reflected fast atoms. The plasma in front of the target is simultaneously observed using two lines of sight, shown schematically in Fig. 1. The imaging ($\approx$ 0.1 Å/ch) and Echelle ($\approx$ 0.01 Å/ch) spectrometer observe the plasma at the

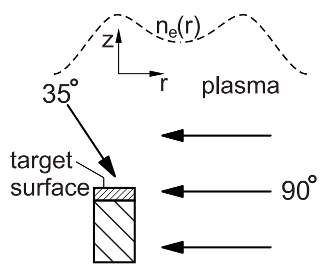

Figure 1: *Spectroscopic observation directions.*

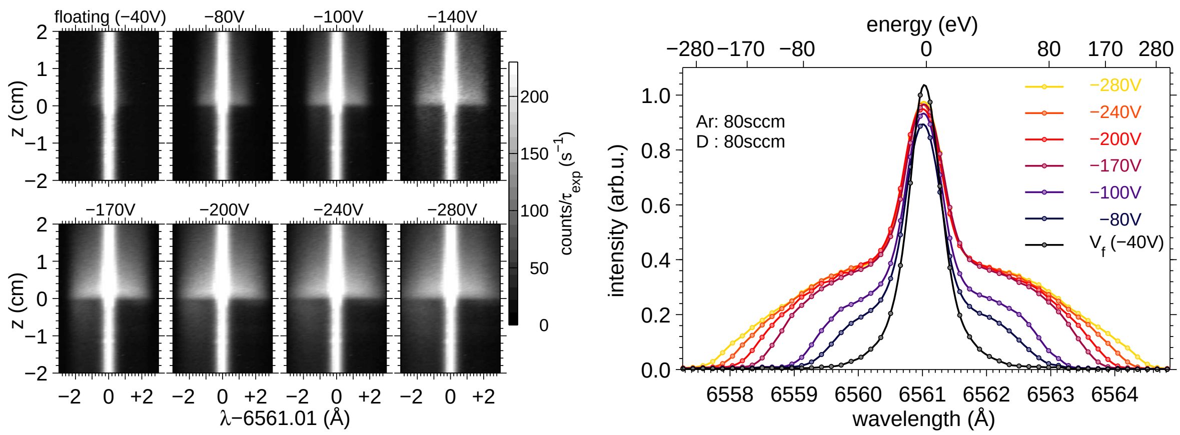

Figure 2: *(left) Measurement of D_α for a scan of the acceleration potential at the target in an Ar/D mix plasma (target surface at $z = 0\,\mathrm{cm}$). (right) Spectra obtained by averaging between $z = 1-6\,\mathrm{mm}$.*

angles of 90° and 35° towards the z axis.

In pure deuterium plasma, the emission of fast hydrogen is spectroscopically not detected above the signal-to-noise level, independent of the applied potential (0 to $-280\,\mathrm{V}$) at any used gas pressures ($p = 0.01-0.3\,\mathrm{Pa}$). However, the emission line profile of D_α drastically changes as soon as argon gas is added. Figure 2 illustrates the emission spectra measured with the imaging spectrometer. The emission of fast atoms, namely the blue- and red-shifted components around the D_α line, appear by increasing the negative potential. If the potential is more negative, the measured emission is more intense and the Doppler shift becomes larger. The blue- and red-shifted components are equal in intensity resulting in a symmetric emission profile of D_α. According to the Doppler shift $v/c = \Delta\lambda/\lambda_0$ the kinetic energy $E = (1/2)m_D v^2$ is calculated, with c being the speed of light in vacuum and m_D the mass of the deuterium atom. The emission of the Doppler-shifted components can be ascribed to the emission from fast neutral atoms, since the kinetic energy of these neutral D atoms is proportional to the applied acceleration potential. Fast atoms are also observed by means of the lines shift for D_β and D_γ.

Figure 3 depicts measurements of the D_α line at 35° observation. The spectrum in Fig. 3(a) shows a large passive component and blue- and red-shifted “wings”. Compared to the intensity of the wings, the cold component is larger than for the 90° observation. The reason is the longer line-of-sight through the plasma from this steep angle of view. However, as plot (b) in Fig. 3 reveals, the main difference is the asymmetry between the blue- and red-shifted wings. The intensity of the red-shifted wing is smaller by a factor of $\sim 0.5-0.6$ than the intensity of the blue-shifted wing. The schematic in Fig. 3 illustrates the interpretation of this effect by means of reflected emission on the target surface [3]. The photon γ emitted from a fast excited atom

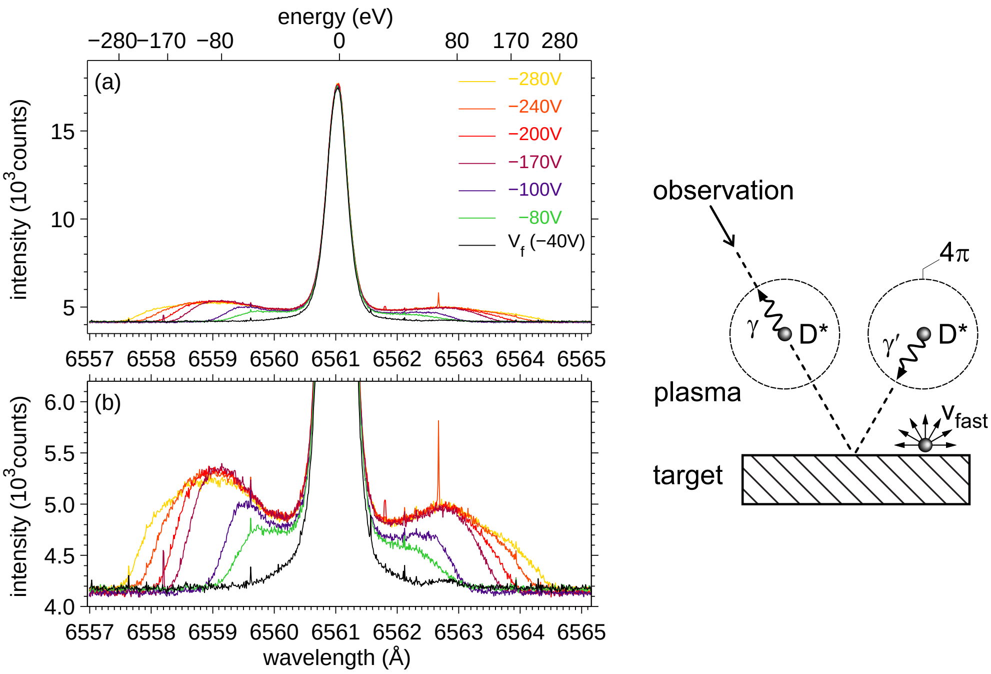

Figure 3: *(left) Scan of acceleration potential: Measurement of D_α from the 35° observation. (right) With 35° observation direct light is seen with a blue Doppler shift, reflected emission is seen with a red Doppler shift.*

D^* moving away from the target towards the plasma is detected with a Doppler shift towards smaller wavelengths, whereas the backwards radiated photon γ', being reflected at the target surface, is detected with a Doppler shift towards larger wavelengths.

The observation of emission of fast atoms in hydrogen mix plasmas with the other noble gases Kr, Xe, Ne and He leads to the following results. First, the emission of fast atoms in all cases is significantly lower than in the case of Ar/D plasmas. While D_α emission of fast atoms could be still distinctly observed in Kr/D plasma, in hydrogen mix plasmas with helium, neon and xenon this emission could hardly be detected above the signal-to-noise level. Second, when the gas flow ratio between argon and deuterium is scanned at constant pressure from pure deuterium to pure argon, the maximum of fast atom emission is observed at the gas flow ratio of approximately Ar/D=1:1. The emission is zero when either argon or deuterium flow is zero. Thus, the source driving excitation of the fast atoms is the binary collision process between argon and deuterium. Two processes could be of importance. The first process (i) is the excitation of hydrogen atoms by collisions with argon ground state atoms: $D_{fast} + Ar \rightarrow D^*_{fast}$+Ar. The second process (ii) is the so-called *excitation transfer* between excited states of argon and hydrogen atoms: $D_{fast} + Ar^* \rightarrow D^*_{fast}$+Ar [16]. The cross sections for process (i) for Balmer-line emission for H impact on Ar, He, Ne, Kr and Xe are given in Refs. [17, 18, 19, 20]. Krypton and argon exhibit the largest cross sections ($\sim 5\times10^{-17}\,\mathrm{cm}^2$), followed by Xe ($\sim 1\times10^{-17}\,\mathrm{cm}^2$), He and Ne ($\sim 3\times10^{-18}\,\mathrm{cm}^2$). The expected excitation of fast atoms, according to these cross sections, does not really match the experimental observations. Even though the emission of fast atoms is the highest observed for Ar/D and Kr/D plasmas, the discrepancy of emission in Kr/D being smaller by a factor of $\approx 0.25\times$ than in Ar/D plasma seems too large. The comparison of the energy levels of hydrogen, argon and krypton shows that the two lowest metastable states of Ar and Kr are considerably closer to D($n=3$) (Ar: $3p^5 4s$, $\Delta E = 0.36\,\mathrm{eV}$ and $\Delta E = 0.53\,\mathrm{eV}$; Kr: $4p^5 5s$, $\Delta E \sim 1.53\,\mathrm{eV}$ and $\Delta E \sim 2.17\,\mathrm{eV}$). It is, therefore, very probable that the quasi-resonant excitation transfer between the metastable states of argon (or krypton) and hydrogen (n=3, ...) is the source for the pronounced emission of fast atoms via the Balmer series ($\mathrm{D}_{\alpha,\beta,\gamma}$).

We are not aware about any theoretical cross sections for the excitation transfer leading to the emission of $D_{\alpha,\beta,\gamma}$ lines. We hope that this work stimulates such calculations. By making visible the emission of fast atoms, one obtains not only new insights in the theory of plasma-wall interaction, but also a completely new diagnostic tool for testing theoretical models and kinetic codes.

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