Surface Wave Discharges as Sources of "Super Hot" Hydrogen Atoms

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"Super-hot" (with kinetic energy ~ 4 - 8 eV) and "hot" (kinetic energy ~ 0.3 eV) hydrogen atoms were detected throughout the volume of a surface wave generated H_2 plasma column, at pressure p = 0.01 mbar, from the analysis of the H_β, H_γ, H_δ, and H_ε emission line profiles. Population inversion between the levels 5→4 and 6→4 was also observed. At pressure p = 0.2 mbar, super-hot atoms were not detected while hot atoms are still present. It was also found that the kinetic temperature of excited H (n = 4 -7) atoms, as determined from the fitting of the spectral lines with a single Gaussian profile, increases with the upper level principal quantum number.

The discharge takes place inside a Pyrex tube with internal and external radii of 2.25 cm and 2.5 cm, respectively, using a surfatron-based setup [1,2]. The wave power is progressively dissipated by the plasma electrons along the wave path and the absorbed power per unit length, as well as the electron density, decrease gradually towards the plasma column end. The electron density decreases from about 2×10^{10} cm^{-3} at the beginning of the column to (1–2) × N_{cr} ($N_{cr} \approx 7 \times 10^9$ cm^{-3}) at its end, while calculated effective values of the microwave electric field intensity sustaining the discharge are in the range 1-7 V/cm [3].

The H_δ line profile at axial distance Δz = 35 cm and pressure p = 0.01 mbar is shown in Fig. 1. The H_β , H_γ and H_ε line profiles have typically the same shape. This type of spectrum reveals the existence of two groups of atoms, *viz.*, a "hot" group corresponding to the central peak, with a kinetic temperature of ~ 1,700 K (average kinetic energy ~ 0.2 eV), and a "super-hot" group corresponding to the broadened part, with a kinetic temperature of ~ 52,000 K (average kinetic energy ~ 7 eV).

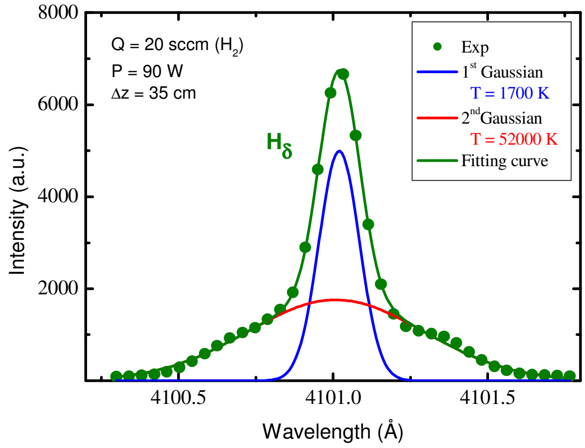

Fig. 1

The evolution of the Hγ line profile along the discharge is shown in Fig. 2. The broader base starts to appear near the middle of the plasma column length and it expands towards the column end, where widely broadened wings are well established. The corresponding kinetic temperatures exhibit significant axial variations (Fig. 3). The kinetic temperature of the super-hot component is ~ 25,000-30,000 K up to 20 cm axial distance and, then, steadily increases to ~ 60,000 K close to the end, at Δz = 40 cm, whereas the temperature corresponding to the sharp Gaussian peak decreases from ~ 1,800 K to ~ 1,400 K close to the end. The latter temperatures are about three times higher than the rotational temperature, which decreases from 600 K to 400 K along the plasma column. Note that the wall temperature, as measured by an infrared sensitive optical thermometer, is ~ 100 K below the rotational temperature as seen in Fig. 3.

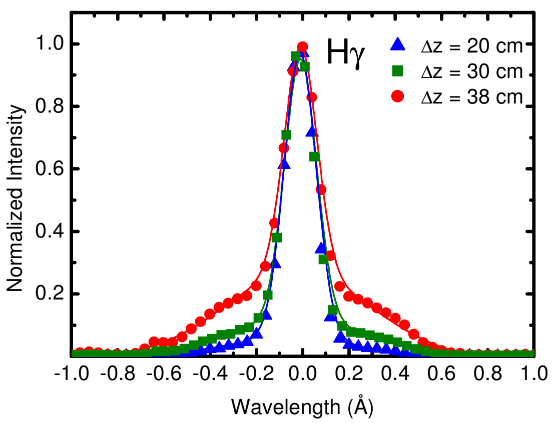

Fig. 2

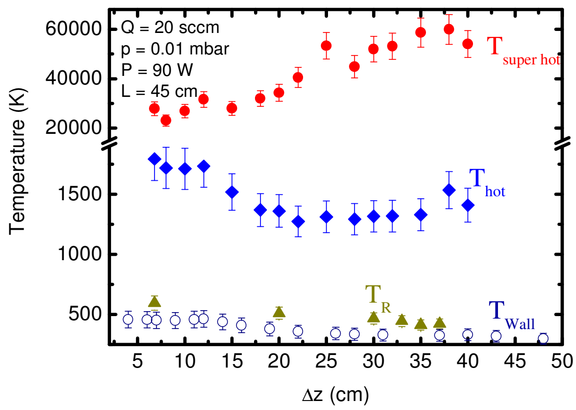

Fig. 3

The relative population distributions of the hot and super-hot components are shown in Fig. 5 for Δz = 35 cm and 0.01 mbar pressure (the plot represents the relative line intensity of each Gaussian component divided by the transition probability and the level degeneracy *vs.* the excitation energy of the level *n*). As seen, the super-hot component exhibits an inversion of population between the pairs of levels 5 - 4 and 6 – 4 away from the launcher, the same effect being not observed for the hot component. No population inversion is observed close to the launcher.

When the pressure increases up to 0.2 mbar the broad base disappears and the profiles become single-Gaussian. This means that super-hot atoms are no longer present, only the hot group remains. It appears that super-hot atoms H (*n* = 4-7) can only originate from charge acceleration followed by neutralization. At the lower pressures, typical ion mean free paths λ_{ion} are larger than the tube radius (the mean free path for an H^+ ion with energy $\varepsilon_{ion} \geq 0.5$ eV at 0.01 mbar pressure is about 3 cm), therefore H^+ ions fall freely on the wall and acquire a kinetic energy equal to the radial potential energy drop, which is of the order of KT_e (note that the electron temperature is in the range 4-6 eV). After wall recombination, the excited atoms are desorbed to the plasma with approximately the same kinetic energy $\varepsilon \approx \varepsilon_{ion}$. As the pressure increases and λ_{ion} (~ 0.15 cm at 0.20 mbar) becomes smaller than *R*, ion transport to the wall becomes dominated by diffusion and the kinetic energy gained in the radial transport is much smaller. This might explain why super-hot atoms disappear with increasing pressure.

The kinetic temperatures of the single-Gaussian Balmer lines (hot component) at 0.20 mbar and fixed axial distance increase with the upper level principal quantum number *n* as shown in Fig. 5.

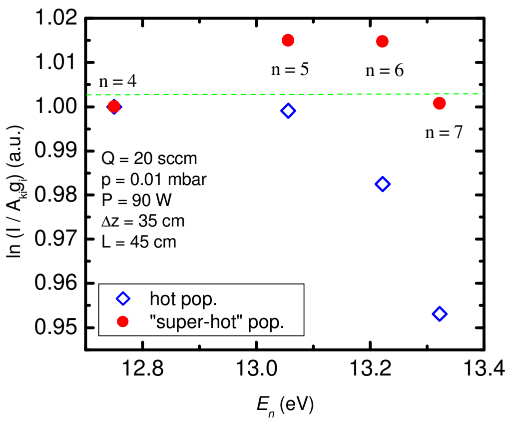

Fig. 4

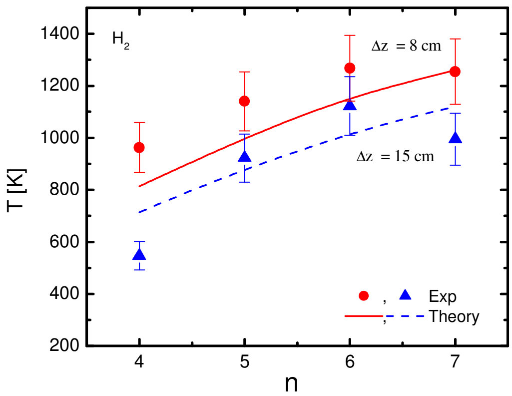

Fig. 5

This behavior can be interpreted considering two distinct excited H atoms creation processes, one being dissociation by electron impact with vibrationally excited molecules leading to the creation of "hot" excited atoms (R1) and the other the generation of "cold" excited hydrogen atoms due to direct electron impact excitation from ground state atoms (R2).

$$H_2(X, v=1\text{-}4) + e \rightarrow H_2^*(\varepsilon = 17\text{-}19 \text{ eV}) + e \rightarrow H_{hot}(n=1) + H_{hot}(n=4\text{-}8) + e \qquad (R1)$$

$$H(1) + e \rightarrow H(n \geq 2) + e \qquad (R2)$$

The corresponding population distributions, N_n^{hot} and N_n^{cold}, have been calculated in the framework of a global, self-consistent model previously developed [2] and it has been shown how the interplay of the relative contributions of (R1) and (R2) can produce an increase in the overall (of both populations) kinetic temperature when the principal quantum number increases. The kinetic temperatures of the levels n = 4-7 as calculated from the above model are shown in Fig. 5 along with the experimental ones. These self-consistent calculations further yield the values of $T_{cold} = T_g$, T_{vib}, T_e, N_e, [H], and [H_2]. [3]

The calculations show qualitative agreement with the results, i.e., they predict an inversion of population between the pairs of levels 5 - 4, 6 - 5, and 6 - 4. For the upper levels ($n \geq 6$), the main population/depopulation mechanisms are electron collisions while for the lower ones radiative processes dominate. The inversion of population occurs because the radiative lifetime decreases when the principal quantum number decreases.

References

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