Discrepancies between the Stark-broadening theories of hydrogen and measurements of Lyman-α Stark profiles in a dense equilibrium plasma*

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First observations are presented to the optically thin and reabsorption free-hydrogen resonance line Lyman-α, emitted from a dense equilibrium plasma ($n_e \approx 10^{23}$ m^{-3}, $T_e \approx 10^4$ K). In the core of the line (wavelength range up to three half-widths) the Stark profiles are determined nearly exclusively by the central Stark component, which is broadened significantly more strongly than predicted by the theories. The experimental Ly-α Stark widths are larger by a factor of about 2.5 than theoretical ones.

It is commonly accepted that, in general, the modern Stark-broadening theories of hydrogen satisfactorily describe the Stark-broadening mechanisms in dense equilibrium plasmas. [See, e.g., the available Stark-broadening tables according to the modified impact theory[1] or the unified theory.[2]] In particular, discrepancies in the very center of the Balmer lines[3-5] and in the center of Ly-β[6] have been recently reported. Because of overlapping effects of numerous Stark components, however, these lines are not quite suitable for a reliable verification of the underlying assumptions of the Stark-broadening theories. For this purpose, a Ly-α Stark-profile measurement is necessary which has not been realized up to now. The upper level of Ly-α is composed of only three Stark levels, while the ground level remains unsplit. This leads to the significant aspect that the core of the Stark-broadened Ly-α profile is nearly exclusively determined by the strong central (unshifted) Stark component, while the red or blue wings are determined by the red-shifted or blue-shifted component, respectively. A Ly-α experiment therefore allows the study of the broadening mechanisms of the central component almost in complete isolation.

Several experimental difficulties have to be overcome to realize a reliable Ly-α experiment: (i) The line has to be generated under optically thin conditions. (ii) No reabsorption should occur in the cooler boundary layers of the plasma. (iii) High number densities of the electrons of more than 10^{23} m^{-3} are necessary so that Stark broadening rather than Doppler broadening dominates the profiles. (iv) The influences of Van der Waals broadening has to be investigated.

These requirements have not been satisfied in the early experiments[7,8] nor in the more recent ones.[6,9] In this work Ly-α has been excited in a wall-stabilized argon arc source. The arc source and the spectroscopic apparatus have been connected to each other by an improved differential pumping system (as compared to the system used in Ref. 10, for example), and the aforementioned requirements could be met for a comparatively wide range of arc parameters (channel diameter 4 mm, current between 40 and 220 A, pressure between 0.5 and 4 bar, typical hydrogen concentration in argon 5 ppm). The arc parameters led to the following plasma parameters: number densities of the electrons between $n_e = 1 \times 10^{23}$ m^{-3} and 4×10^{23} m^{-3}, temperature between $T = 12\,000$ and 16 000 K, number densities of the argon atoms between $n_a = 3 \times 10^{22}$ m^{-3} and 2×10^{24} m^{-3}. The number density of the electrons has been determined by measuring the argon continuum at $\lambda = 481.6$ nm using a ξ factor of 2 ± 0.1 as measured in Ref. 11. The local-thermodynamic-equilibrium (LTE) model is valid in sufficient approximation for an argon arc plasma of the given electron densities.[11] T and n_a have therefore been calculated due to the equilibrium relations for measured values of n_e or have been taken as given in Ref. 12.

The Ly-α profiles have been measured at electron densities of (1, 2, 3, and 4) $\times 10^{23}$ m^{-3} in a wavelength range $\Delta\lambda = \pm 0.5$ nm with respect to the line center. The response of the vacuum-ultraviolet (vuv) optical system has been optimized such that the measured relative change of the response over $\Delta\lambda = \pm 0.5$ nm was smaller than 1%. The spectrometer bandwidth was smaller than 0.004 nm and the wavelength scale was reproducible within 0.001 nm.

The measured Ly-α profiles are determined by Stark broadening and a comparatively small amount of Doppler broadening. In the line core significant deviations between measured profiles and those calculated according to the modified impact theory (Griem[1]) and the unified theory (Vidal *et al.*[2]) have been found. Corresponding half-widths are compared in Table I. The calculated Stark widths according to Griem[1] and Vidal *et al.*[2] agree within ±5% or better. Convolution of Stark profiles with Doppler profiles leads to the calculated half-widths

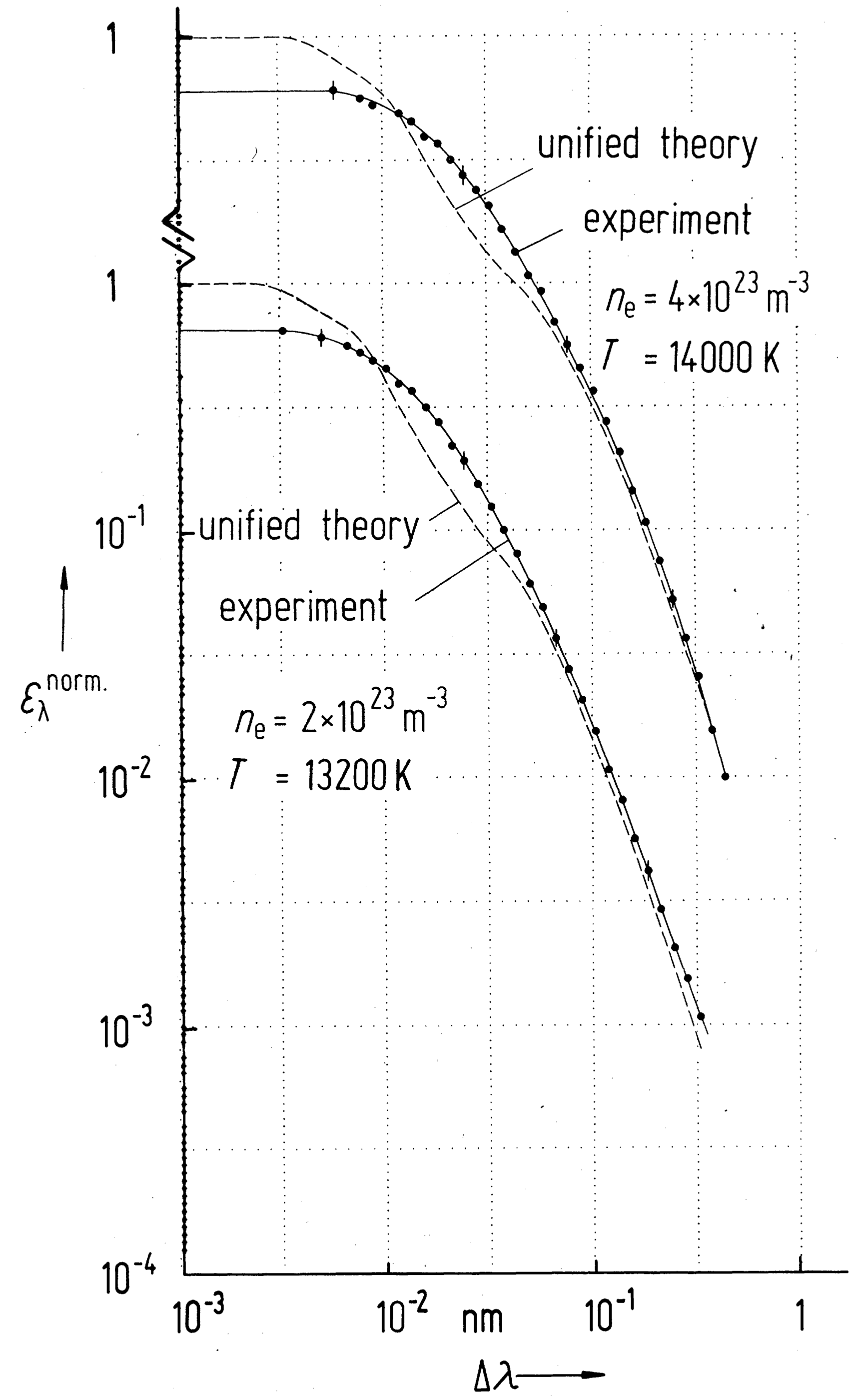

FIG. 1. Comparison of measured and calculated (unified theory, Vidal *et al.*[2]) Ly-α profiles for two number densities of the electrons. The plot shows the normalized coefficient of the spectral emission ϵ_λ^{norm} over $\Delta\lambda$ in log-log coordinates. Measured and calculated profiles are normalized with respect to the same total line-emission coefficient and for the calculated profiles ϵ_λ^{norm} is set equal to 1 for $\Delta\lambda = 0$. For $\epsilon_\lambda^{norm} > 3\times10^{-3}$, the relative uncertainty of the measured profiles $\Delta\epsilon_\lambda^{norm}/\epsilon_\lambda^{norm}$ is smaller than $\pm 7\%$. Within this uncertainty the measured profiles are symmetric with respect to their maximum.

given in Table I, column 5. One realizes that the measured half-widths which include Doppler broadening are larger by a factor of 1.6 for $n_e = 1\times10^{23}\,m^{-3}$. This factor increases to 1.9 for $n_e = 4\times10^{23}\,m^{-3}$. A rough deconvolution of the measured profiles due to the Doppler broadening leads to the result that the experimental Stark widths are larger than the theoretical ones by a factor of about 2.5.

A more-detailed comparison between measured and calculated Ly-α profiles is given in Fig. 1 in log-log coordinates for two electron densities. Note the obvious deviations between calculated and measured Ly-α profiles in the line core (wavelength range up to three half-widths) which can be seen quite impressively in Fig. 2 on a linear

TABLE I. Calculated and measured half-width in nm for Ly-α (uncertainties: $\Delta n_e/n_e < \pm 0.10$, $\Delta T/T < \pm 0.03$; Ly-α Doppler half-width: 0.01 nm for $T = 13\,500$ K).

		Calculated			Measured
		Widths due to Stark broadening		Widths due to Stark and Doppler broadening	
n_e (10^{23} m^{-3})	T (K)	Griem [a]	Vidal *et al.* [b]	Vidal *et al.* [b]	This expt. (±0.002)
1	12 700	0.0055	0.0050	0.014	0.023
2	13 200	0.0095	0.0089	0.016	0.030
3	13 200	0.013	0.013	0.019	0.036
4	14 000	0.016	0.016	0.022	0.042

[a] Reference 1. [b] Reference 2.

scale. Because the profiles in the aforementioned core range are determined by the central Stark component, it may be concluded that the central component is broadened significantly more strongly than predicted by the theories.[1,2] Explanations for these discrepancies have been attempted,[13,14] but at present the discrepancies are not well understood within the common models of plasma interaction underlying the broadening theories. It may be of particular interest to mention that for this experiment the number of charged particles in the Debye sphere is 6.3 for $n_e = 1 \times 10^{23}$ m^{-3} and 2.4 for $n_e = 4 \times 10^{23}$ m^{-3}.

In the wing range, where the red- or blue-shifted Stark component, respectively, begin to determine the Ly-α profile, deviations between measured and calculated profiles are rather small. For this range, measured normalized values $\epsilon_\lambda^{\rm norm}$ (see definition in Fig. 1) are only about 15% larger than the calculated ones, which is in agreement with a recent line-wing measurement.[6] The satisfactory agreement between experiment and theory for the wings is not in contradiction to the discussed deviation in the line core. The unexpectedly strong broadening effect observed for the central component probably has to be taken into account for the red and blue component. This leads, however, to no remarkable influence on the wing shape.

One might ask whether the deviations between experiment and theory could be caused by influence of Van der Waals broadening or could be due to errors in determining the optical depth. Resonance broadening is negligible because of the low number density of the hydrogen atoms ($< 10^{19}$ m^{-3}). Figure 2 shows that the measured Ly-α profiles are not influenced by Van der Waals broadening due to argon atoms. The Ly-α profiles corresponding to one electron density and three different number densities of the argon atoms are in excellent agreement, even when varying the number density of the argon atoms by a factor of about 27. This is not only valid for the limited wavelength range presented in Fig. 2 but for all $\epsilon_\lambda^{\rm norm} > 3 \times 10^{-3}$.

The Ly-α profiles have been measured under controlled optical depth which has been checked as follows. The Ly-α line, excited at the smallest possible hydrogen concentration (≈ 0.6 ppm) has led to the spectral radiance $L_0(\lambda_0)$ in the line center ($\lambda = \lambda_0$). Then the hydrogen concentration has been

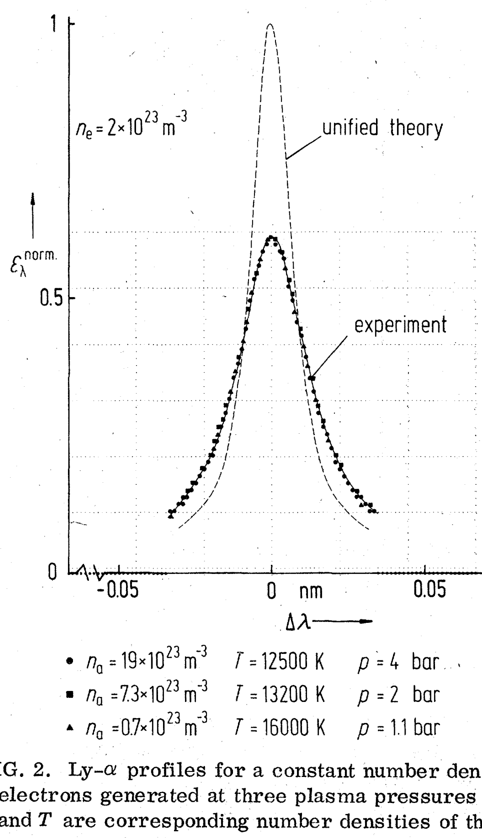

FIG. 2. Ly-α profiles for a constant number density of the electrons generated at three plasma pressures p (n_a and T are corresponding number densities of the argon atoms and temperatures). Concerning Doppler broadening the temperature variation does not affect the profiles because Doppler half-widths vary by less than ±0.001 nm.

increased successively in steps indexed by $j=0,1,2,\ldots,5$ such that the corresponding $L_j(\lambda_0)$ has been increased by a factor of 2 per step. It has been possible to extend j to a maximal value of 5 before the spectral radiance reaches the source-function limit $L^s(\lambda_0)$. The quantities $L_j(\lambda_0)$ can be presented in the form

$$L_j(\lambda_0)=2^jL_0(\lambda_0)<L^s(\lambda_0),\quad j=0,1,\ldots,5\,.$$

For each step index the profile $L_j(\Delta\lambda)$ has been measured. It has been found that the normalized line profiles for step indices $j=0,1,2$ agree within $\pm 5\%$, whereas line profiles for step indices $j=3,4,5$ show an increasing broadening due to optical depth. By using the measured spectral radiance of the source function limit at the Ly-α wavelength, from the measured profiles with $j=3,4,5$ optical thin profiles have been calculated (radiative transfer equation) which then agreed with the profiles for $j=0,1,2$ within the aforementioned $\pm 5\%$. Thus errors in determining the optical depth cannot be responsible for the discrepancies between the measured and theoretical profiles. The results of this experiment, moreover, are independent from possible non-LTE populations of the hydrogen levels.

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