# Experimental Study of Balmer-α Stark Broadening

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The Stark-broadened line profiles of $H_\alpha$ and $D_\alpha$ have been measured in a wall stabilized argon arc at an electron density of $n_e = 1.4 \times 10^{16}$ cm$^{-3}$. Consistent with earlier experiments the obtained line profiles exhibit severe discrepancies to theoretical profiles based on the approximation of static ions and the line profiles were found to depend on the mass of the radiating atom. The measured half width of $D_\alpha$ is about 15% smaller than the $H_\alpha$-value. Recent calculations based on the "Model Microfield Method" greatly improve agreement with experiment.

## Introduction

In recent experimental studies on the Stark-broadening of hydrogen lines [1–6] severe discrepancies were observed between current broadening theories based on the approximation of static ions [7–9] and experiment, in particular for the central minimum of $H_\beta$ and for lines with strong unshifted components, i.e. $L_\alpha$ and $H_\alpha$. The half width of $L_\alpha$ was observed [2] to be about 2.5 times larger than predicted by theory and for $H_\alpha$, experimental half widths exceeding the calculated ones by up to a factor 3 were reported [4]. Furthermore, in case of $H_\alpha$ the unified theory of Vidal, Copper, and Smith (VCS) [7] predicts a much narrower line shape than calculations based on a generalized impact approximation by Kepple and Griem (KG) [8]; both theories, however, were observed to be in disagreement with experiment [1, 4]. The difference between the theoretical $H_\alpha$ profiles is mainly due to a different treatment of the "interference term".

Among various suggestions made in the recent literature [5, 10–13] (see discussion in Ref. [14, 20]) to account for the disagreements between theory and experiment, the neglect of ion dynamics in current broadening theories appears to be the most convincing argument, since ion dynamic effects were observed experimentally in hydrogen line profiles by Kelleher and Wiese [14] and Wiese et al. [15]. While some earlier theoretical investigations on the subject of ion dynamic corrections to hydrogen line profiles [12, 16, 17] yield only minor effects, recent calculations including ion dynamic effects by Voslamber [18] for $L_\alpha$ increase the line width by about a factor 1.9. Seidel [19, 20] applied the "Model Microfield Method" (MMM), introduced by Brissaud and Frisch [21, 22], to hydrogen Stark broadening. These calculations also predict drastic ion dynamic effects and, as far as the central minimum of $H_\beta$ and the half width of $L_\alpha$ and $H_\alpha$ are concerned, greatly improve agreement with experiment. Also, the calculated dependence of the hydrogen line centers on the relative radiator-(ion)perturber velocity (reduced mass) is in, at least, qualitative agreement with experimental observations. For zero radiator-perturber velocity, i.e. the static case, the MMM calculations agree well with the VCS theory.

For the MMM calculations detailed line profile calculations are available and it is the intention of this paper to provide a further comparison between experiment and the various theories. For this purpose the Balmer-α line at an electron density of $n_e = 1.4 \times 10^{16}$ cm$^{-3}$ proved to be optimal for several reasons. First, at low electron densities drastic discrepancies between experimental $H_\alpha$-half widths and VCS as well as KG theory have been observed [4] and, thus, measurements at lower electron densities should be a sensitive check for the MMM calculations [20]. Second, below $n_e \approx 10^{16}$ cm$^{-3}$ Doppler broadening starts to affect significantly the experimental profiles and, in order to obtain pure Stark profiles, an electron density above this value is required. Third, to study the influence of the radiator-(ion)perturber velocity on the Balmer-α profile, the mass of the radiating atom was changed by using the isotopes hydrogen and deuterium [14, 15]. Since these measurements require the elimination of any hydrogen impurity emission while recording the $D_\alpha$ profile and vice versa, a low plasma temperature and, thus, a low electron density is advantageous.

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## Experiment

The light source was a wall stabilized arc running in ultrapure argon containing a small amount ($\sim 1\%$) of hydrogen and deuterium, respectively. The arc column with a diameter of 6 mm was observed down the central axis, the arc current was 20 Å. The usual precautions were taken to secure emission from homogeneous and optically thin plasma layer: only the central part of the arc contained the hydrogen and deuterium admixture, respectively, while the electrode regions were kept filled with the pure carrier gas; spatial averaging over regions of different plasma conditions could sufficiently be avoided by an appropriate aperture of the optical system; by adjusting the hydrogen (deuterium) admixture the optical depth in the line peaks was kept below 0.05.

The spectroscopic device consisted of a photoelectric 2.5 m Ebert monochromator with a resolution of 0.15 Å in first order for the slit settings used. The line profiles were recorded with a strip-chart recorder.

In order to investigate the dependence of the Balmer-$\alpha$ profile on the two different radiator-(ion)perturber systems H-$Ar^+$ and D-$Ar^+$ (the relative radiator-ion velocity is almost the velocity of the radiating atom alone), special care was taken to avoid any hydrogen impurity while the gas mixture in the arc column contained deuterium and also to maintain identical plasma conditions while recording the $H_\alpha$ and $D_\alpha$ profiles. Due to the isotopic shift of 1.8 Å between $H_\alpha$ and $D_\alpha$, any $H_\alpha$-contribution to the very symmetric $D_\alpha$-profile produces an asymmetry of this line (and vice versa) and, thus, the symmetry of the recorded Balmer-$\alpha$ profile was a direct check for the absence of any disturbing isotopic impurity. To maintain identical plasma conditions, especially identical electron density, equal amounts of the small hydrogen and deuterium admixtures — ensured by matching intensities for $H_\alpha$ and $D_\alpha$ — were introduced several times alternately (after an appropriate "clean up time") to the arc center during one run of the arc. While recording the $H_\alpha$ and $D_\alpha$ profiles a fixed electron density was confirmed by the constant half width of $H_\beta$ and $D_\beta$. Experimental [23] as well as theoretical [20] investigations show that the Balmer-$\beta$ half width is not affected by ion dynamic effects. Several independent runs of the arc were made.

The electron density was determined from the half width of Balmer-$\beta$ using a (slightly extrapolated) relationship between electron density and full half width obtained experimentally by Wiese et al. [1]. For a half width of 12.0 Å an electron density of $n_e = 1.4 \times 10^{16}\ \mathrm{cm}^{-3}$ was obtained. The reproducibility of the electron density for the $H_\alpha$-$D_\alpha$ measurements is estimated to be better than 3%, the absolute error should not exceed 10% [1].

The plasma temperature of $T = 9600$ K was determined from argon line intensity measurements assuming LTE [24]. For the present investigations the plasma temperature is not a critical parameter and the experimental profiles are compared to theoretical profiles tabulated for $T = 10^4$ K.

## Results

Figure 1 shows the central parts of the measured $H_\alpha$ and $D_\alpha$ profiles in comparison to the calculations of VCS and KG which are based on the static ion approximation and, thus, predict identical Stark profiles for $H_\alpha$ and $D_\alpha$. Due to the inclusion of the different Doppler widths (full half width: 0.46 Å for $H_\alpha$, 0.34 Å for $D_\alpha$) the theoretical profiles for $H_\alpha$ and $D_\alpha$ exhibit small differences in the very line centers. All profiles are area normalized to unity, in the experimental profiles wing contributions were taken into account by assuming a $\Delta\lambda^{-5/2}$ intensity dependence of the far unmeasured line wings. As can be seen, strong deviations occur between experimental and calculated profiles as well as between both theoretical profiles. Since the narrower theoretical profiles are considerably more affected by the different Doppler broadening than the experimental profiles, it is very obvious from Fig. 1 — e.g. by comparing the $H_\alpha$-$D_\alpha$ difference of the KG profiles with the experimental difference — that the different Doppler broadening alone cannot explain the difference between the experimental $H_\alpha$ and $D_\alpha$ profiles. Taking also into account possible errors due to not quite exactly reproduced electron density while recording the $H_\alpha$ and $D_\alpha$ profiles, only about 5% of the measured 15%-difference between the experimental $H_\alpha$ and $D_\alpha$ profiles can be explained in terms of different Doppler widths and of not exactly reproduced electron density, the major portion ($\approx 10\%$), however, must be attributed to ion dynamic effects. Besides Stark- and Doppler-broadening

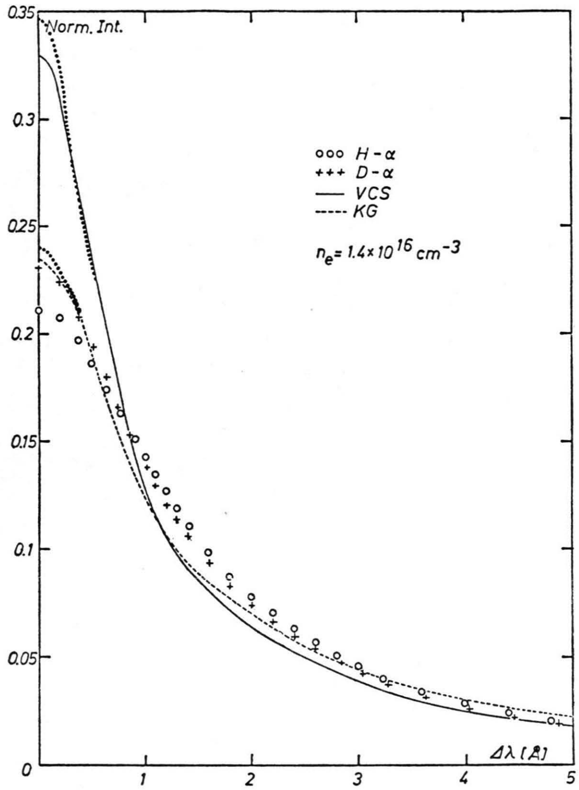


Fig. 1. Measured and calculated Stark profiles for $H_\alpha$ and $D_\alpha$. Total line intensities are all normalized to unity. The experimental profiles were obtained for the H-$Ar^+$ and D-$Ar^+$ systems. Doppler broadening is included in all profiles. The static ion calculations of Vidal, Cooper, and Smith (VCS) as well as Kepple and Griem (KG) predict identical *Stark*-profiles for $D_\alpha$ and $H_\alpha$. Due to the different Doppler broadening the line centers of the theoretical $D_\alpha$ profiles (dotted curves) are slightly different from the calculated $H_\alpha$-profiles.

other broadening mechanisms like neutral atom- and instrumental-broadening are completely negligible. The relative behaviour of the $H_\alpha$-$D_\alpha$ profiles in this experiment is in good agreement with the results of an earlier experiment by Wiese et al. [15] performed at a higher electron density ($6.4 \times 10^{16}$ cm$^{-3}$). However, while in the latter experiment the $H_\alpha$ and $D_\alpha$ line peaks were observed to lie between the VCS and KG line peaks, in the present experiment the observed line peaks lie below both calculations. This fact can readily be understood from recently reported experimental results [4], where a much weaker decrease of the $H_\alpha$ half width with decreasing electron density than predicted by both theories was observed. Therefore, the peaks of the area normalized theoretical profiles increase more strongly with decreasing electron density than the experimental ones.

In Fig. 2 the experimental profiles are compared to those obtained by the MMM calculations [20, 25]. The new calculations greatly improve agreement with experiment, the overall agreement between experiment and theory is within 20% now and may be even better if the combined error bars are taken into account. It is especially worth to note that the relative behaviour of the $H_\alpha$-$D_\alpha$ pairs is very similar in both theory and experiment.

A remarkable feature of the MMM calculations for Balmer-α (as well as Lyman-α) is the fact that the relative difference of the half widths for two different radiator-(ion)perturber systems, e.g. H-$Ar^+$ and D-$Ar^+$, is approximately constant over several orders of magnitude in electron density, though the difference between static and MMM half widths increases strongly with decreasing electron density (see Ref. [20], Fig. 4 and Figure 5). If the present experiment is combined with earlier ones [15, 26] experimental data of $H_\alpha$ and $D_\alpha$ half widths at a fixed electron density are available for more than two orders of magnitude in electron density. These data are shown together with the results of

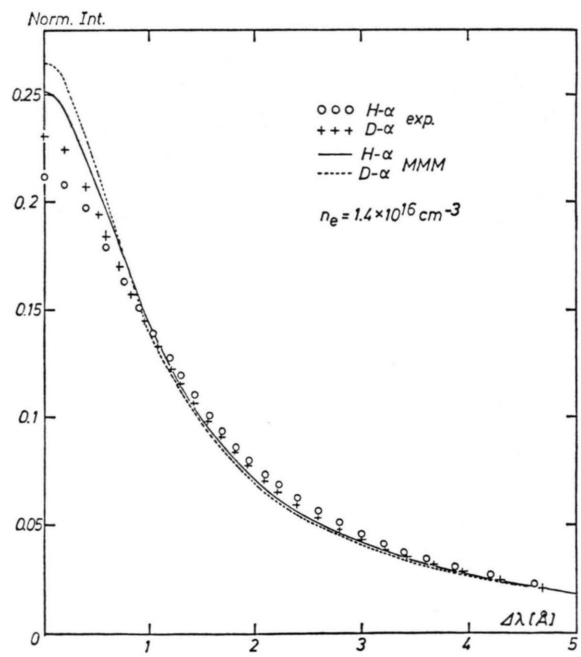


Fig. 2. Same experimental profiles as in Fig. 1, but compared to theoretical profiles based on the "Model Microfield Method" (MMM) which include ion dynamics. Doppler broadening is included in all profiles.

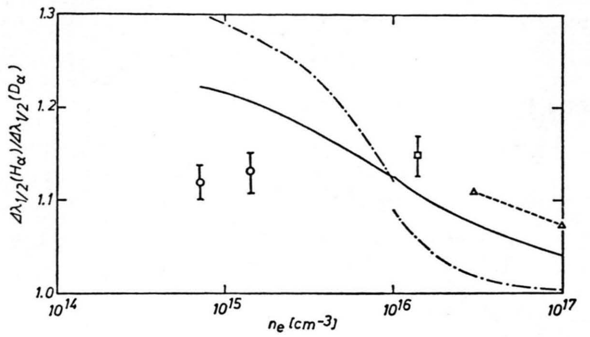


Fig. 3. Measured and calculated ratios of the $H_\alpha$ and $D_\alpha$ half widths $\Delta\lambda_{1/2}(H_\alpha)/\Delta\lambda_{1/2}(D_\alpha)$ plotted vs. electron density. Theoretical as well as experimental values above $n_e = 10^{16}$ cm$^{-3}$ correspond to the D, H-Ar$^+$ systems while the values below this electron density correspond to the D, H-He$^+$ systems. The meaning of the symbols is: □ this experiment; △-----△ experimental data of Wiese et al. [15]; ○ experimental data of Ehrich and Kelleher [26]; ——— MMM calculations including ion dynamics [20, 25], —·—· MMM calculations for static ions [19, 25]. Doppler broadening is included.

the MMM calculations in Fig. 3, where the half width ratios $\Delta\lambda_{1/2}(H_\alpha)/\Delta\lambda_{1/2}(D_\alpha)$ are plotted vs. electron density. Above $n_e = 10^{16}$ cm$^{-3}$ theoretical as well as experimental values are shown for the H-Ar$^+$ and D-Ar$^+$ system while below this electron density the theoretical curves were calculated [25] for the conditions of the experiment of Ehrich and Kelleher [4, 26] (H-He$^+$, D-He$^+$ systems), from where the experimental data (including some umpublished results) are taken. Figure 3 shows MMM calculations including ion dynamics [20] as well as MMM calculations [19] for "static ions", where the difference in the half widths is only caused by the different Doppler broadening. Due to the much narrower line shapes the "static ion" curve is much stronger affected by Doppler broadening than the experimental values, especially at low electron densities. Figure 3 again demonstrates clearly that the observed differences between $H_\alpha$ and $D_\alpha$ in the present experiment (as well as in Ref. [15]) cannot be explained in terms of different Doppler broadening. Though some systematic deviations between experiment and MMM calculations (including ion dynamics) still remain, the experimental results essentially confirm the theoretically predicted tendency mentioned above. The deviations between experiment and theory near $n_e = 10^{15}$ cm$^{-3}$ may be partially due to fine structure splitting [4] which is not included in the calculations. Inspection of Figs. 3 and 2 as well as Figs. 8 and 9 in Ref. [20] may lead to the conclusion that the MMM calculations still behave a little too "static"; in general, however, inclusion of ion dynamics in hydrogen line broadening calculations by applying the "Model Microfield Method" greatly improves agreement with experiment.

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