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Stark broadening of the hydrogen Paschen γ transition at electron densities of the order of 10^{15} cm^{-3}

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Abstract. Stark broadening measurements and calculations of the Paschen γ spectral line of hydrogen ($\lambda = 1.094$ μm) are reported. Investigations have been performed at plasma electron densities between 1.4×10^{15} cm^{-3} and 3.7×10^{15} cm^{-3}. As the light source a wall-stabilized arc operated in a helium-hydrogen gas mixture at atmospheric pressure has been applied. The radiation of the plasma emitted from nearly homogeneous plasma layers in end-on direction, was measured with the use of a grating spectrometer equipped with a charge coupled device (CCD) detector. The radiance calibration was carried out against light outputs originating from a tungsten strip radiation standard. The measured *FWHM* are compared with results of our calculations based on computer simulation techniques (full computer simulation method — FCSM). Our broadening data are also compared with results of other theoretical approaches (MM-method, quasi-static approximation) and with experimental data obtained at electron densities about one order of magnitude larger than ours.

PACS. 52.70.Kz Optical (ultraviolet, visible, infrared) measurements – 32.70.Jz Line shapes, widths, and shifts

1 Introduction

Stark broadening of hydrogen spectral lines is of great interest *e.g.* from the point of view of interpretation of astrophysical spectra as well as because of its wide application in diagnostics of laboratory plasmas. Spectral transitions of Balmer and Lyman series have been the subject of numerous experimental and theoretical investigations, while reports for higher spectral series are rather scarcely available in the literature. However, in the last decade a growing interest in studying Paschen transitions, appearing in the near infrared part of the spectrum is observed. In this wavelength range a quite large number of prominent transitions of atomic carbon, nitrogen and oxygen appear. Because of rather large abundances of these elements in stars their spectral lines are very important for the analysis of radiation transport in stellar atmospheres. The knowledge of the broadening of interfering Paschen lines of hydrogen is therefore of first-rate significance.

Only in the last 7 years numerous papers have been published devoted to the Stark-broadening for the near-infrared transitions of hydrogen [1–6]. Among them the papers by Lemke [5] and by Stehle and Hutcheon [6] comprise comprehensive broadening tables, which are suitable and convenient for comparison with experimental data. The broadening data of Lemke are based on the Vidal, Cooper and Smith (VCS) approach [7]. Lemke [5] extended simply this approximation to higher spectral series and higher transitions within them. The calculations of Stehle and Hutcheon [6] are based on the model microfield method (MMM). This technique has been applied for determination of the electronic as well as the ionic contribution to the line width. Protons have been considered as heavy perturbing particles. In Figure 1 the full widths at half maximum (*FWHM*) of the Paschen γ transition, resulting from these two theoretical approaches are compared for temperatures typical for arc discharges, within the electron density range from 3×10^{14} to 10^{17} cm^{-3}. As can be seen the approach of Stehle and Hutcheon [6] yields half-widths, which systematically prevail the data of Lemke.

Measurements for infrared spectral transitions in hydrogen have been reported to date by Döhrn *et al.* [1], (for the P_γ and P_β transitions), and by Wujec *et al.* [8] (for the P_β spectral line). For the third member of the Paschen series the only available experimental data are those of Döhrn, reported in his Ph.D. thesis [9]. The *FWHM* determined by Döhrn at two electron densities (1.45×10^{16} and 2.36×10^{16} cm^{-3}), agree satisfactorily with Lemke's results — the discrepancies do not exceed typical uncertainties of this kind of measurements. These two experimental data are included in Figure 1. The width predicted by Stehle and Hutcheon for the lower electron density condition of Döhrn's experiment (1.45×10^{16} cm^{-3}), exceeds the measured width by more than 30%. Such discrepancy seems to be significantly larger than the uncertainty limits of both, the experiment and the calculations.

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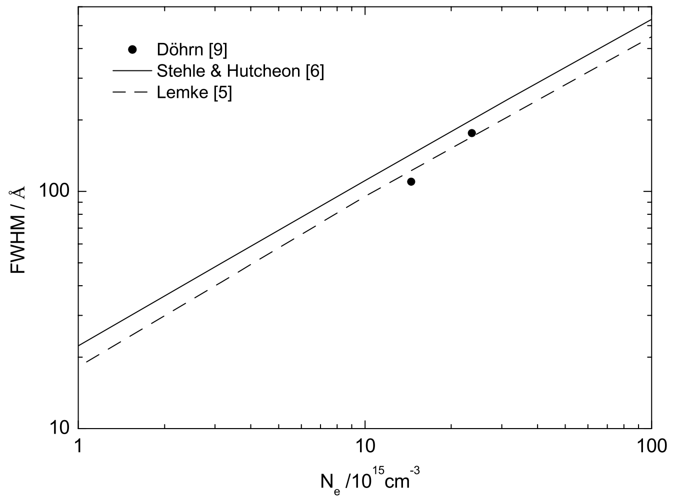

Fig. 1. The full widths at half maximum of the Paschen γ transition of hydrogen broadened by the Stark effect as a function of electron density of the plasma. Two experimental data of Döhrn [9] (solid circles) are compared with results of two calculations: the Model Microfield Method of Stehle and Hutcheon [6] and the quasi-static approximation of Lemke [5]. The theoretical data correspond to the plasma temperature of 14 000 K, obtained by Döhrn in his experiment.

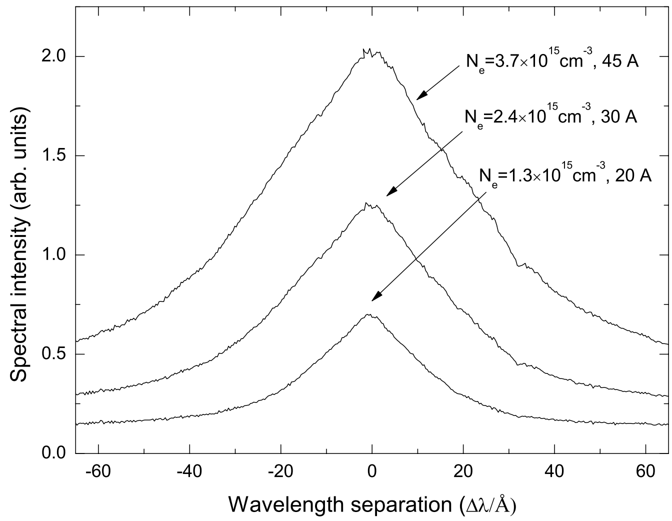

Fig. 2. Measured Paschen γ line shapes at three arc currents (20, 30 and 45 A), corresponding to different electron densities of the plasma. The presented line shapes are after performing radiance calibration of the measured light outputs from the arc. A tungsten strip standard source was applied for calibration purpose.

The aim of this paper is therefore to provide reliable broadening data for the Paschen γ transition and compare them with results of calculations. Since the discrepancies between the two above — mentioned calculations become larger for lower electron densities, we focused our attention to broadening studies at electron densities of the plasma of the order of 10^{15} cm^{-3}, *i.e.* considerably lower than those of Döhrn's experiments. Plasma conditions: $N_e \sim 10^{15}$ cm^{-3}, $T \sim 10^4$ K, are very suitable for testing Stark broadening of the P_γ transition — the Stark effect is the dominating broadening mechanism, significantly prevailing the Doppler effect. Moreover, at such plasma conditions the emission spectrum in the waveband of interest, exhibit an advantageous line to continuum intensity ratio, facilitating the determination of the background continuum radiation, and thus enabling reliable P_γ Stark broadening measurements. The advantages of application of helium arc plasmas (with small amounts of the element under study) as excitation sources of the admixture spectra are outlined *e.g.* in [10].

2 Radiation detection, plasma diagnostics, measurements and calculations of line widths

For the purpose of this study we have applied a wall-stabilized arc operated in a helium-hydrogen gas mixture at atmospheric pressure. Details about the construction and operation conditions of the arc can be found in [8,11,12]. By using helium-hydrogen gas mixtures (90% of He and 10% of H_2 by volume) and applying arc currents from 20 to 45 amperes it was possible to obtain electron densities of the plasma somewhat exceeding 10^{15} cm^{-3} at temperatures between 8 000 and 12 000 K. The experimental setup including the optical imaging system and the spectroscopic instrumentation is described *e.g.* in [8]. The radiation of the plasma in the end-on direction was studied. The applied optical system allows radiation originating from nearly homogeneous plasma layers to be selected. The procedure of self-absorption check described in [8] has been applied to make sure that the measured radiation originates from plasma layers with negligible absorption. At conditions of our experiments (gas composition, arc currents) the hydrogen energy level with $n = 6$ is efficiently populated, yielding spectral line intensities within the P_γ profile significantly exceeding the intensities of the continuum background radiation. Figure 2 shows three selected P_γ spectral line intensity distributions, measured at three different arc currents. In all three cases shown in Figure 2, the radiation originated from plasma layers around the arc axis. The radiance calibration of the measured spectra was performed against light outputs of a tungsten standard lamp. The signals from the arc as well as from the standard source were measured by applying a liquid nitrogen cooled InGaAs photodiode linear array detector. With this device it was possible to measure simultaneously a wavelength interval of 180 Å, *i.e.*, the whole P_γ line profile during a single exposition of the detector.

In order to determine the electron densities (N_e) of the plasma at different arc currents and corresponding to the various plasma layers, the hydrogen H_β line profile has been recorded applying an optical multichannel analyzer (OMA4). From the directly measured full widths at half maximum (*FWHM*), the contribution originating from the Doppler broadening (*FWHM* about 0.36 Å) and the instrumental width (*FWHM* about 0.56 Å) has been subtracted applying an appropriate deconvolution procedure.

From the determined pure Stark widths the electron densities were deduced using the theoretical broadening data of Gigosos and Cardeñoso [13]. For the purpose of plasma temperature determination very small amounts of nitrogen have been introduced into the arc discharge. From measured intensity ratios of two NI spectral lines 9 028.92 and 9 045.88 Å, applying the Boltzmann plot method, temperatures between 8 000 and 12 000 K were obtained for various plasma layers and different arc currents. The corresponding transition probabilities have been taken from [14].

Our Paschen γ line profile calculations are based on the so-called full computer simulation method (FCSM). The formalism and the applied techniques are described in the paper by Halenka and Olchawa [15] and in the Ph.D. thesis of Olchawa [16]. Some additional comments concerning the FCSM may be found also in [8]. Therefore only a short description of our theoretical approach for the P_γ line profile determination is given below. Calculations have been performed within the no-quenching approximation applying the so-called μ^*-model introduced by Kesting [17]. The emitter-plasma interactions were taken with accuracy up to the dipole term, *i.e.*, we applied the Hamiltonian in the following form:

$$H = H_0 - \mathbf{d} \cdot \mathbf{F}(t), \quad (1)$$

where H_0 is the Hamiltonian of the isolated atom (neglecting terms describing the fine structure interaction), $\mathbf{d}$ is the electric dipole moment of the atom, and $\mathbf{F}(t)$ represents the resulting electric microfield produced by ions and electrons. The matrix elements for the operator of the time development were calculated with accuracy up to linear terms with respect to the electric microfield. At the above assumptions we obtained symmetrical and unshifted P_γ line profiles formed by both: the Stark effect (including ion dynamics) and the Doppler effect. The uncertainty of our simulated results were controlled similarly as described in reference [15] and illustrated there in Figure 2. We estimate the uncertainties of our calculated full widths at half maximum of the P_γ transition to be about ±5%.

3 Results and discussion

As an example, in Figure 3 the determined line profiles are presented, which correspond to the three measured spectral line intensity distributions shown in Figure 2. The electron densities quoted in the figure correspond to the respective plasma layers from which the radiation originates. The profiles are area normalized and the corresponding background continua have been subtracted. For the determination of the continuum course and the far line wings the procedure described in detail in [8] has been applied. The far line wings, determined by extrapolation according to the above-mentioned procedure are not shown in Figure 3, *i.e.*, only the measured waveband detected during individual expositions is presented. The line profiles obtained in this way have been then corrected by taking into account the Doppler ($FWHM$ = 0.81 Å) and the instrumental broadening ($FWHM$ = 0.70 Å). From these corrected profiles the pure Stark $FWHM$ have been determined.

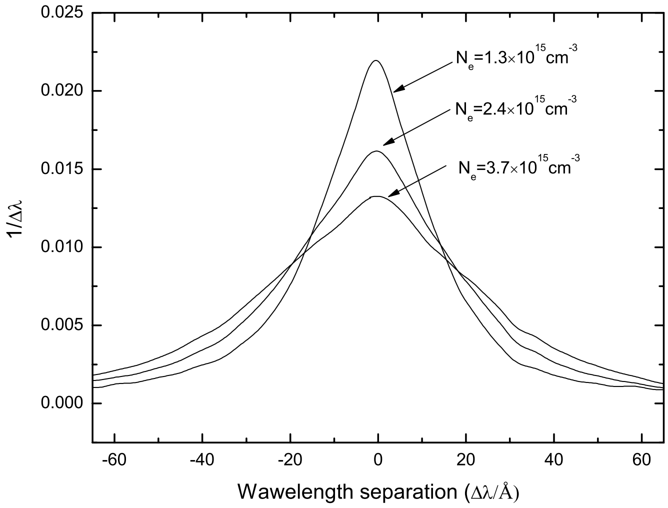

Fig. 3. Area normalized P_γ line profiles corresponding to three electron density conditions of the arc. The continuum background radiation for each measured profile has been determined according to the procedure outlined in [8] and subtracted from measured spectral intensity distributions shown in Figure 2.

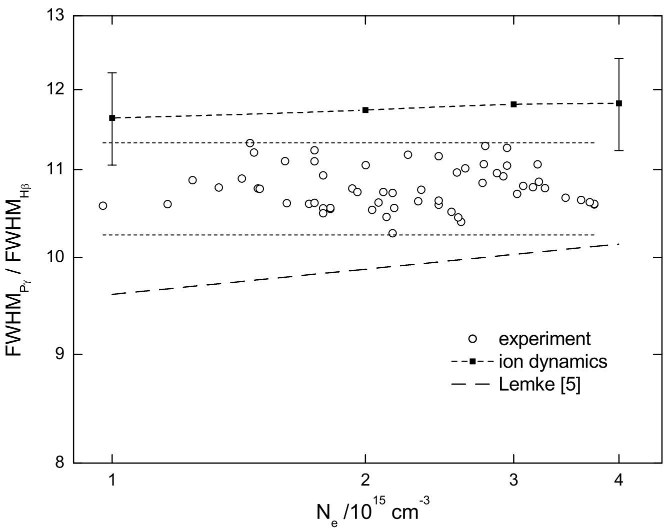

Fig. 4. Ratios of measured Stark widths ($FWHM$) of both studied hydrogen lines: Paschen γ and Balmer β, obtained at different electron densities of the plasma. The experimental data (open circles) are compared with results of our ion-dynamic calculations (solid squares and short dashed line) and the quasi-static approximation (dashed line). The dotted lines represent the statistical uncertainty limits of our experiment *i.e.* excluding possible systematic errors.

In Figure 4 we plot the ratios of the $FWHM$ (Stark widths) of both studied hydrogen lines the Paschen γ and Balmer β line against the electron density of the plasma. As can be seen in the whole N_e range studied in this work

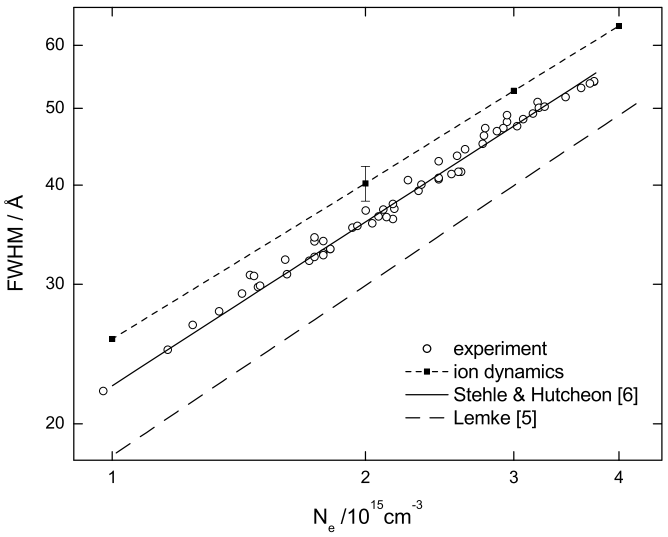

Fig. 5. Comparison of experimentally determined Stark widths (open circles) of the Paschen γ transition with results of theoretical approaches: the MMM calculations of Stehle and Hutcheon [6] (solid line), the quasi-static data of Lemke [5] (dashed line) and our ion-dynamic calculations (squares and short dashed line) as a function of electron density of the plasma.

the ratios are in the range from 10.25 to 11.25 and the mean value is about 10.75. The scatter of the measuring points does not exceed typical uncertainty limits (±5%) of such measurements. In this figure the corresponding ratios resulting from our ion dynamics calculations and the quasi-static approximation are shown for comparison. The last results were obtained taking the P_γ data from Lemke [5] and the data of Vidal, Cooper and Smith [7] for the H_β transition. The error bars shown for our ion-dynamic results reflect the data scatter of individual calculations.

In Figure 5 our final results are presented — the experimentally determined Stark widths (*FWHM*) are plotted *versus* the electron density of the plasma. The measured data are compared with our ion-dynamic calculations, with results of the Model Microfield Method and with the quasi-static results. As expected, the quasi-static approximation yields *FWHM*, which are systematically smaller (about 20%) than the measured widths. On the other hand our ion-dynamic calculations provide P_γ widths, which are systematically larger (about 12%) than the measured data. The results of the MM-method agree well with our experimental data. This, rather good agreement however, has to be regarded as being somewhat accidental. As mentioned in the previous section, our experimental line shape data are based on the analysis of radiation, which originates from nearly homogeneous plasma layers. Similarly as in our previous paper, devoted to the study of the Paschen β transition [8], the contribution to the radiation originating from the near electrode regions of the arc (lower electron densities than those of the bulk plasma) results in an enhancement of the P_γ peak intensity and thus in a reduction of the measured half widths. We estimate this possible systematic uncertainty of the *FWHM* determination to be about 8 to 12 percent, for the higher and lower electron density conditions, respectively. An estimation of the uncertainty of our calculations is more difficult. Nevertheless from the scatter of the calculated data one may infer that the theoretical *FWHM* are charged with an uncertainty of about ±5%. The discrepancies between our measured and calculated P_γ Stark widths, however, do not exceed 12% and, similarly as in the case of the P_β study [8], the discrepancies are smaller for the higher electron density conditions. Thus one may conclude that the experiment-theory agreement can be regarded as being satisfactory.

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