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Hydrogen fine-structure effects at low electron densities

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Measurements of the plasma-broadened H_α line shape in a wall-stabilized arc show considerable differences between experimental and theoretical line profiles at electron densities below 10^{16} cm^{-3}. The half-width of the experimental profile is up to three times larger than predicted theoretically. At low electron densities ($\lesssim 10^{15}$ cm^{-3}), part of such discrepancies can be attributed to the neglect of fine-structure splitting in current Stark-broadening calculations, especially for H_α, L_α, and hydrogenic-ion lines.

In the past years many theoretical and experimental investigations have been carried out concerning the shape of plasma-broadened hydrogen lines. While theoretical profiles are available in a wide range of electron densities,[1,2] most of the experimental work was done in the electron-density range between approximately 10^{16} and 2×10^{17} cm^{-3}.[3-15] Only a few experimental data exist at low electron densities.[16-21] To our knowledge there exist no experimental results for H_α at electron densities below 10^{16} cm^{-3}. In this paper we report some results concerning H_α obtained in the electron-density range between approximately 4×10^{14} and 1.5×10^{16} cm^{-3}. These results indicate an increasing disagreement between experiment and Stark-broadening calculations at lower electron densities. While ion-motion effects apparently account for an appreciable part of this discrepancy, atomic fine structure (FS) appears to play an increasingly significant role at low densities. The possible influence of FS in the line broadening of hydrogen has been mentioned earlier,[22] but has not been incorporated in any calculations or otherwise taken into account. It will be discussed here in some detail.

Our spectroscopic setup consisted of a 2-m Czerny-Turner monochromator. The resolution with optimal slit settings was 0.03 Å, as determined by a ^{198}Hg microwave discharge. The light source, a wall-stabilized arc with a channel diameter of 3.2 mm, was run in ultrapure helium with a small admixture of 0.1% hydrogen in the arc center. The plasma column was observed end-on down the central axis. In order to cover a wide range of electron density the arc was operated both at atmosphere and 70 torr. The arc column was enclosed in a vessel which acted as a pressure reservoir. A vacuum regulator was used to induce the gas flow required to maintain the desired pressure. To avoid systematic errors in the recorded line profiles, we paid particular attention to the following experimental factors.

(i) *Homogeneity and stability of the observed plasma region containing the hydrogen admixture.* Homogeneity of the plasma region emitting the hydrogen lines was obtained by ±0.065 mm spatial resolution (a solid angle of $f/140$ was used), and by introducing hydrogen only in the central part of the arc column, while a "plasma window" of pure helium was maintained in the electrode regions. The stability of the arc (and the photoelectric registration equipment) enabled a long time integration and led to an excellent signal-to-noise ratio.

(ii) *Optical depth.* Emission from the optically thin plasma layer was checked directly by focusing the light passing through the back end of the arc back onto the arc axis by means of a spherical mirror. By adjusting the hydrogen concentration in the arc center, the optical depth in the peak of H_α was always kept below 0.02.

(iii) *Electron density.* The electron density was determined from the half width of H_β using Stark-broadening tables published by Vidal, Cooper, and Smith.[2] Doppler broadening was taken into account. The error should be less than 10% for the higher electron densities and is possibly somewhat higher for lower values.

(iv) *Gas temperature.* The kinetic temperature of the ions and neutral atoms was determined from the Doppler width of the 6402-Å line of Ne I. For this purpose trace amounts of neon were added to the arc center. At our experimental conditions Doppler broadening for this line dominates all other broadening effects, and a Voigt profile analysis was applied to determine the pure Doppler width. We obtained gas temperatures between 4000 ($N_e = 10^{15}$ cm^{-3}) and 15 000 K ($N_e = 1.5\times10^{16}$ cm^{-3}) with an estimated error of about ±10%.

(v) *Electron temperature.* The electron temperature is not a critical factor in this experiment, since the hydrogen profiles depend rather weakly on this physical quantity. By adding trace amounts of argon to the arc center, the electron temperature was estimated from the intensity ratio of the Ar II 4348- and Ar I 8115-Å lines assuming a local thermodynamic equilibrium population of the argon states. Because of the very strong temperature dependence of this intensity ratio, even large local thermodynamic equilibrium deviations only cause small errors in the electron temperature. We obtained electron temperatures between 17 000 ($N_e = 10^{15}$ cm^{-3}) and 20 000 K ($N_e = 1.5\times10^{16}$ cm^{-3}).

(vi) *Background under the lines and impurity lines*. Before each data run, the spectrum of the pure-helium arc was recorded in the wavelength region around the investigated lines to check for structure in the continuum intensity and impurity lines. After introducing the study gas into the arc center, a fast scan was made to obtain the background intensity on both sides of the lines. Finally, three to five low-speed scans were made to obtain the central part of the line profile.

(vii) *Other broadening mechanisms*. For the conditions of this experiment, broadening mechanisms other than Stark broadening have to be taken into account for H_α profiles. In order to obtain the pure Stark half width, we took advantage of the fact that the measured H_α profile at low electron densities has approximately the same Lorentzian shape as measured at higher densities where Doppler and instrumental broadening are almost negligible. These H_α Stark profiles—with a known shape and with the Stark half width as a parameter—were convolved with the Doppler and instrumental profile. In this way we were able to construct our

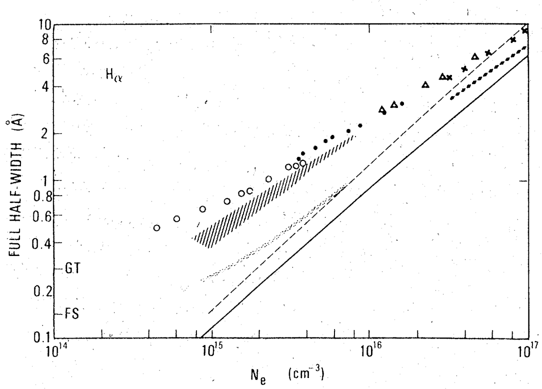

FIG. 1. Full half width of H_α vs electron density. ○: this experiment (helium arc at 70 torr and 1 atm, respectively), ×: Wiese *et al.* (Ref. 3), △: Ehrich and Kusch (Ref. 9). The curves indicate the calculated half widths. Dashed line: Kepple and Griem (Ref. 1), solid line: Vidal, Cooper, and Smith (Ref. 2), diamonds: Roszman (Ref. 25), connected crosses: weighted superposition of FS components, each having a Lorentzian half width given by the KG calculation. The hatched area indicates the estimated H_α half widths without Doppler and instrumental broadening. Fine structure is the wavelength separation between the two strongest FS components, and GT the H_α half width determined by means of a Geissler tube ($N_e \approx 10^{12}$ cm^{-3}).

measured H_α profiles and to obtain an estimation of the pure Stark half-width. Possible correlations between Stark and Doppler broadening have not been taken into account. We have estimated the combined uncertainties in the Doppler correction by the hatched area in Fig. 1, the uncertainty being of the same magnitude as the correction.

Zeeman splitting due to the magnetic field from the arc current is about 0.003 Å, i.e., negligible. Van der Waals broadening by the neutral helium atoms (atomic polarizibility is 2.07×10^{-25} cm^3) has been estimated by a modified version[23] of an approximate classical expression given by Griem[24] to be about 0.008 Å full width at half maximum for the low-pressure arc (70 torr) and about 0.04 Å for the 1-atm arc. This amounted to about 7% of the measured widths, a contribution which has been subtracted out to give the estimated Stark widths indicated in the shaded area in Fig. 1.

Figure 1 shows the results of our measurements for H_α in a log-log scale. We included previous arc measurements[3,9] which overlap the present results and extended them to higher electron densities. The measurements cover the electron density range between 4×10^{14} and 1×10^{17} cm^{-3}. For comparison we included the calculated half widths of Kepple and Griem (KG),[1] Vidal, Cooper, and Smith (VCS),[2] and Roszman.[25] Roszman uses the VCS theory, except that the time ordering of the electron-atom interaction Hamiltonian is correctly accounted for. The hatched area indicates the estimated pure experimental Stark half widths and includes the uncertainty of the above-mentioned procedure. The curves show the calculated Stark half widths of H_α without Doppler and instrumental broadening. As can be seen in Fig. 1, the discrepancy between Stark-broadening calculations and measured widths increases toward lower electron densities, e.g., at $N_e = 10^{15}$ cm^{-3} the calculations yield a full half width of 0.12 (VCS) and 0.15 Å (KG), respectively, while the experimental half width is approximately three times larger. It should be noted that these results are comparable in electron-density dependence and magnitude with observed discrepancies in the central dip of H_β.[14-16]

The wavelength separation of the two strongest fine-structure components (FS) and the Geissler-tube half width of H_α (see Fig. 2) are marked at the left side in Fig. 1. The experimental half width including Doppler broadening apparently approaches the Geissler-tube value asymptotically (the Geissler-tube value actually corresponds to an electron density on the order of 10^{-12} cm^{-3}). The pure experimental Stark width should approach roughly the FS value. The calculated half widths, however, already have the same magnitude as the FS splitting at $N_e = 10^{15}$ cm^{-3} and become much smaller than the FS splitting at lower electron densities.

It can be concluded from recent experiments by Wiese *et al.*[14] that a considerable portion of the observed discrepancies between theory and experiment in our investigations is due to the neglect of ion dynamic effects in the theories. However, from Fig. 1 it clearly appears that FS splitting, too, must be taken into account at low electron densities. Fine-structure splitting, which is due mainly to the electron spin, is not included in any currently published hydrogen-line-broadening calculations.

Figure 2 shows an experimental H_α profile emitted from a Geissler tube (instrumental width: 0.035 Å). The underlying theoretical FS components are indicated below the profile. The two strongest FS components are separated by 0.14 Å. This separation in practice limits the smallest measurable linewidth, and the H_α width obtained with the Geissler tube may be considered as a lower limit to the width of an H_α line emitted from a plasma.

Because the state with the principal quantum number $n=2$ has the largest FS splitting, this effect may also be important for some other Balmer lines at very low electron densities, for L_α and, in particular, for corresponding lines of hydrogen-like ions (e.g., He^+), because FS splitting increases strongly with the charge of the nucleus ($\sim Z^4$), while Stark broadening decreases. Table I shows the magnitude of the FS and Stark broadening at the indicated electron densities.

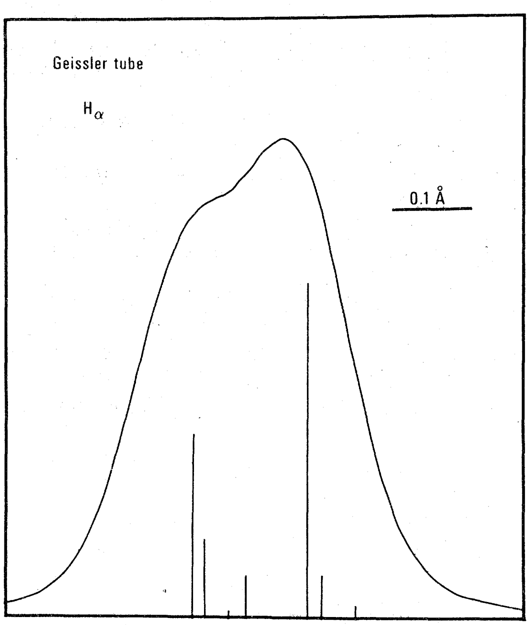

FIG. 2. Photoelectric scan of H_α emitted from a Geissler-tube plasma and underlying FS components of the undisturbed line. The length of the lines gives the intensity in arbitrary units; the position of the FS pattern within the recorded lines is estimated. The two strongest FS components are resolved in the experimental profile.

TABLE I. Indicates the electron densities at which the fine-structure splitting is approximately equal to full Stark width of L_α and H_α.

	Electron density (cm^{-3})	Full Stark width (VCS) (Å)	Fine-structure splitting (Å)
L_α	10^{16}	0.007	0.0055
H_α	10^{15}	0.12	0.14

Calculations for the first four hydrogen levels and Stark component intensities for H_β and L_α, including FS, were carried out by Lüders[26] for static Stark fields. Also, detailed calculations have recently been carried out by Leitner[27] for H_α. These calculations yield a FS-splitting of some of the usual Stark components, including the strong unshifted central components of L_α and H_α, into several subcomponents. This fact limits the smallest width of these components. In particular, the unshifted central components of L_α and H_α are limited to smallest widths of about $\frac{2}{3}$ of the FS structure of the undisturbed line.

Plasma-broadened hydrogen profiles are produced by the superposition of several independent lines (the Stark components). Thus, FS is important when this additional splitting of an individual Stark component is comparable to its broadening, which can be considerably less than the total Stark width of a tabulated line. For lines which have an unshifted central component, like L_α and H_α, the tabulated profiles and widths result from the superposition of the electron-broadened central unshifted components and an "H_β-like" part, which results from a folding of the electron and ion broadening of the Stark-shifted components. Crude estimates for H_α suggest that, in the investigated electron-density range, the unshifted central component dominates strongly in the line core, the shifted components contribute only between approximately 20% (at low electron densities) and 60% of the total linewidth. While the broadening of the shifted Stark components masks their splitting completely, the splitting of the unshifted component ($\approx$0.1 Å) is nearly equal to its computed electron broadening at $N_e = 10^{15}$ cm^{-3}. Because the H_α half width is predominately determined by the broadening of the unshifted component, FS should contribute significantly to the (calculated) total linewidth at low electron densities, but it should become insignificant above, say, 4×10^{15} cm^{-3}.

It should be noted that account of the effect of FS on the central component must be taken *before* superposition with the shifted components. Thus, profiles corrected for FS cannot be generated from currently published profiles by, for example, superposing them at each unshifted FS component. However, such a correction should not be too inaccurate in cases where the unshifted component dominates the core of the line. The cross-hatched line in Fig. 1 represents the result of such a superposition, each FS component having a Lorentz width equal to the KG Stark width (dashed line). Zero-field FS splitting was used in this superposition.

We conclude that, while ion dynamic effects appear to play an important role in the center of H_α, at low electron densities the atomic FS must also be taken into account. This is the case for all transitions, especially those involving the $n=2$ level. The FS will only affect the core of the lines, however, and the profiles tabulated in the literature should still be very useful in determining spectral distributions in the line wings.

In an ensuing publication, we will report detailed results on the effect of ion dynamics as low electron densities, which, together with FS effects, appear to account for most of the discrepancies with present calculations.

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[1]P. Kepple and H. R. Griem, Phys. Rev. 173, 317 (1968); University of Maryland Technical Report No. 831 (unpublished).

[2]C. R. Vidal, J. Cooper, and E. W. Smith, Astrophys. J. Suppl. Ser. 25, 37 (1973).

[3]W. L. Wiese, D. E. Kelleher, and D. R. Paquette, Phys. Rev. A 6, 132 (1972).

[4]E. A. McLean and S. A. Ramsden, Phys. Rev. 140, 1122 (1965).

[5]R. A. Hill and J. B. Gerardo, Phys. Rev. 162, 45 (1967).

[6]R. A. Hill and E. H. Beckner, Appl. Opt. 3, 929 (1964).

[7]R. A. Hill, J. B. Gerardo, and P. Kepple, Phys. Rev. A 3, 855 (1971).

[8]J. C. Morris and R. U. Krey, Phys. Rev. Lett. 21, 1043 (1968).

[9]H. Ehrich and H. J. Kusch, Z. Naturforsch. A 28, 1794 (1973).

[10]J. D. Hey and H. R. Griem, Phys. Rev. A 12, 169 (1975).

[11]J. B. Shumaker, Jr. and C. H. Popenoe, Phys. Rev. Lett. 21, 1046 (1968).

[12]K. Behringer, Z. Phys. 246, 333 (1971).

[13]B. Wende, Z. Naturforsch. A 22, 131 (1967).

[14]W L. Wiese, D. E. Kelleher, and V. Helbig, Phys. Rev. A 11, 1854 (1975).

[15]D. E. Kelleher and W. L. Wiese, Phys. Rev. Lett. 31, 1431 (1973).

[16]D. D. Burgess and R. Mahon, J. Phys. B 5, 1756 (1972).

[17]J. Ramette and H. W. Drawin, Z. Naturforsch. A 31, 401 (1976).

[18]G. Fussman and G. Himmel, Z. Phys. 259, 347 (1973).

[19]D. L. Evans, D. P. Aeschliman, and R. A. Hill, Phys. Rev. A 10, 2430 (1974).

[20]R. D. Bengtson and G. R. Chester, Phys. Rev. A 13, 1762 (1976).

[21]R. D. Bengtson, J. D. Tannich, and P. Kepple, Phys. Rev. A 1, 532 (1970).

[22]H. Schlüter and C. Avila, Astrophys. J. 144, 785 (1966).

[23]D. E. Kelleher, thesis (University of Maryland, 1977) (unpublished).

[24]H. R. Griem, *Plasma Spectroscopy* (McGraw-Hill, New York, 1964).

[25]L. J. Roszman, Phys. Rev. Lett. 34, 785 (1975).

[26]G. Lüders, Ann. Phys. (Paris) 8, 301 (1951).

[27]R. Leitner, Acta. Phys. Austriaca (to be published).