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Shifts of the H_β line in dense hydrogen plasmas

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The H_β line shifts were measured in dense T-shaped-tube plasmas for electron densities from 2.1×10^{17} to 7.8×10^{17} cm^{-3} and temperatures between 19 000 and 35 000 K. Comparisons of these shifts with recent theories [H. R. Griem, Phys. Rev. A **28**, 1596 (1983); **38**, 2943 (1988)] that take the dynamical quadratic Stark effect for $\Delta n=0$ and $n'=n+1$ interactions and ion quadrupole effects into account are presented. Also, comparisons with some experimental results [H. L. Wiese, D. E. Kelleher, and D. R. Paquette, Phys. Rev. A **6**, 1132 (1972)] were made. Our results are in agreement with an extrapolated experimental best fit to the experimental results of Wiese *et al.*, but the measured shifts are larger than the theories predict.

I. INTRODUCTION

The quasistatic approximation of the linear Stark effect for slowly varying ion-produced electric fields results in symmetrical and unshifted profiles of hydrogen lines.[1] However, measured profiles, especially H_β line profiles, are asymmetrical and slightly red shifted.[2-7] These shifts are 2–3 % of the total half-width of the lines. They could be of great importance in astrophysical applications, since they may effect measured gravitational red shifts. There are two physical effects that cause the shifts. One is the so-called dynamical quadratic Stark effect, caused by plasma electrons,[8,9] and the other is quadrupole atom-ion interaction effect caused by inhomogeneities of ion-produced electric fields.[9,10] The shifts caused by the first effects are red while the other ones are blue.

The calculations of the quadratic Stark effect[8,9] take interactions between level groups of principal quantum numbers n and $n+1$ and interactions for $\Delta n=0$ into account. Both red and blue shifts are nearly linear functions of electron density.

In this paper we present some results of H_β line-shift measurements which are compared with recent theory[8,9] and experimental results[4] obtained for lower electron densities than in the present work (less then 1×10^{17} cm^{-3}). The comparison of the experimental and above-mentioned theoretical results[8,9] in the electron-density range $2\times10^{17}-8\times10^{17}$ cm^{-3} is not yet available.

II. EXPERIMENTAL SETUP AND DIAGNOSTICS

The plasmas were produced in a small magnetically driven T-shaped shock tube with an internal diameter of 27 mm. The T tube was energized from a 4-μF capacitor bank charged to 18 kV. The discharge circuit was critically damped. The discharge current lasted about 2.5 μs, after which the measurements of the spectral intensities started. The fillings gas was pure hydrogen at a pressure of 300 Pa. The plasma light was focused into the entrance slit of a 1-m McPherson monochromator equipped with a photomultiplier at the exit slit. The photomultiplier signals were taken by the shot-to-shot technique and recorded by an oscilloscope equipped with a 35-mm camera. The spectral sensitivity of the spectroscopic assembly was calibrated by using a standard lamp. The total instrumental half-width of 0.5 Å at the H_β wavelength was also measured using a low-pressure lamp with slit widths of 50 μm. The instrumental half-width is negligible compared to the Stark widths of the H_β line.

The spectral intensities were measured for the times $\tau=0.5$, 1.0, 1.5, 2.0, 2.5, and 3.0 μs after the reflected shock front passed the observation point. Two runs of the measurements under approximately the same conditions were done. An example of the experimental line profiles is shown in Fig. 1. The root-mean-square devia-

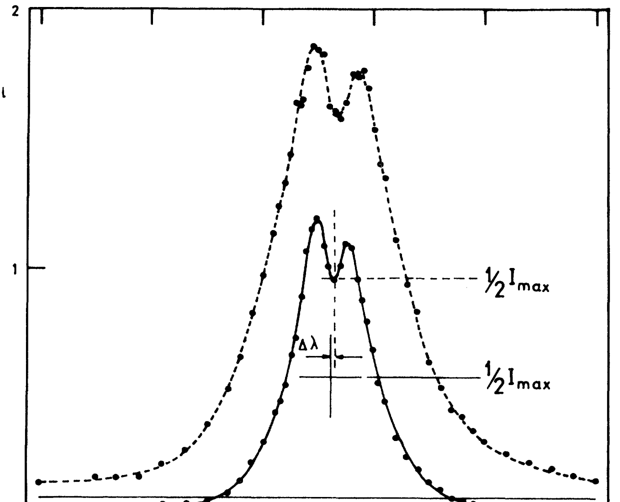

FIG. 1. Two experimental H_β line profiles for $N_e=4.6\times10^{17}$ cm^{-3} at $\tau=1.5$ μs and $N_e=2.1\times10^{17}$ cm^{-3} at $\tau=3.0$ μs and the procedure for shift measurements are shown. The dotted lines is for $\tau=1.5$ μs and the solid line is for $\tau=3.0$ μs. In this case, $\Delta\lambda_i=2.0$ Å.

tion σ_n in the wavelength scale of the experimental points related to the best-fit curve in the region between $0.3I_{\max}$ and $0.8I_{\max}$ was estimated to be in the limits between 0.3 and 0.6 Å for the profiles obtained for $\tau=3.0$ μs and $\tau=0.5$ μs, respectively. The values of $\sigma_n/\Delta\lambda_{1/2}$ are about 0.5%, $\Delta\lambda_{1/2}$ being the total half-width whose values were between 80 Å for $\tau=3.0$ μs and 200 Å for $\tau=0.5$ μs.

The electron densities were determined from the half-width of the H_β line,[11] while temperatures were determined from line-to-continuum intensity ratios.[12] The electron densities were between 2.1×10^{17} and 7.8×10^{17} cm^{-3} and temperatures between 19 000 and 35 000 K. The maximum Doppler half-width, corresponding to the highest temperatures, was 0.7 Å. Taking into account uncertainties in half-width determination caused by the scattering of experimental points around best-fit line profiles, Doppler half-widths, instrumental half-widths, and errors estimated by Wiese, Kelleher, and Paquette,[4] the estimated error in electron-density measurements is $\leq 8\%$. The error in temperature measurements is caused mostly by uncertainties in the continuum emission intensity determination, which is estimated to be about 10%.

III. SHIFT DETERMINATIONS

The line shifts were measured at the half-of-peak-intensity points of the experimental profiles. We assumed that profiles obtained at the late times ($\tau=3$ μs) of plasma decay and lowest electron densities ($N_e=2.28\times10^{17}$ cm^{-3} for one run and 2.1×10^{17} cm^{-3} for the other one) were the least shifted ones. The profiles obtained at earlier times ($\tau_i<3$ μs) and at higher electron densities ($N_e>2.3\times10^{17}$ cm^{-3}) were shifted by $\Delta\lambda_i$ in respect to the profiles obtained at $\tau=3$ μs. An example of these measurements is given in Fig. 1. In order to make our results continuous with the other experimental[4] or theoretical results,[8,9] we added $\Delta\lambda_i$ to the shifts predicted by the experiment[4] ($d_{\mathrm{expt},0}$) or theories[8,9] ($d^{(1)}_{\mathrm{theor},0}$ or $d^{(2)}_{\mathrm{theor},0}$) at our lowest electron densities ($N_e=2.28\times10^{17}$ cm^{-3} or 2.1×10^{17} cm^{-3}). The resulting shifts are then

$$d^{(e)}=\Delta\lambda_i+d_{\mathrm{expt},0}$$

and

$$d^{(1)\text{ or }(2)}=\Delta\lambda_i+d^{(1)\text{ or }(2)}_{\mathrm{theor},0}\ .$$

The same procedure was used before; for example, in Ref. 13. Following this procedure the values presented in Figs. 2 and 3 are obtained. The error of $\Delta\lambda_i$ is between 0.3 Å (at $\tau=3$ μs) and 0.6 Å (at $\tau=0.5$ μs). The previous results[4,8,9] are given only up to an electron density of 10^{17} cm^{-3}, so an extrapolation of these results had to be done in order to compare them with our results. In Fig. 2 the comparisons of our results (○ and △ using $d^{(1)}_{\mathrm{theor},0}$ and ● and ▲ using $d_{\mathrm{expt},0}$) from our two runs with theory[8] (solid line) and experiment[4] (dashed line) are presented. The dashed line is the best fit from Ref. 4. The slope of this line is 9×10^{-18} Å/cm^{-3} with an error of 8%, while the slope that could be obtained from our measured shifts is 9.44×10^{-18} Å/cm^{-3}, with an error of 9%. Both the best-fit-line slopes and the corresponding errors have been obtained using the least-squares method.

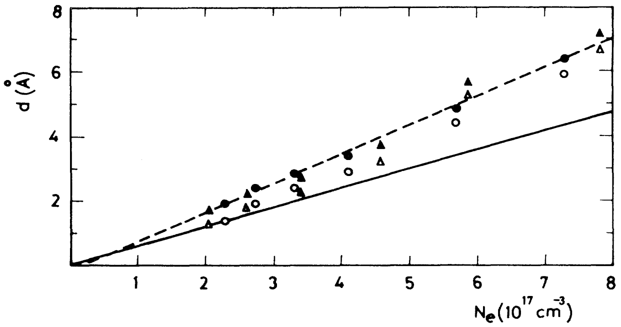

FIG. 2. Values for H_β line shifts measured in this work compared to the experiment (Ref. 4) and theory (Ref. 8). — — —, extrapolated best fit from Ref. 4; ——, theory from Ref. 8; ▲ and ●, our results from two independent measurements using $d_{\mathrm{expt},0}$; △ and ○, our values from two independent measurements using $d^{(1)}_{\mathrm{theor},0}$.

In Fig. 3 a comparison of our results (points ○ and △) with theory[9] (solid line) is presented. The experimental best fit from Ref. 4 is also drawn (dashed line). Although the temperatures in this work differ from temperatures in Ref. 4 and from the temperatures for which theoretical values were calculated, the above comparisons could be done because of the weak dependence of the shift on temperature.[8,9]

Some trivial effects, such as an unadjusted monochromator, plasma inhomogeneities, and overlapping with neighboring lines could have contributed to the line asymmetry and line shifts. We checked the adjustment of the monochromator when recording the H_β line profile emitted from a low-pressure tube. If the monochromator had not been adjusted, the asymmetry of the recorded profile would have been very strong; such asymmetry did not appear.

It has been generally accepted[14,15] that plasmas produced in small electromagnetic T-shaped shock tubes are

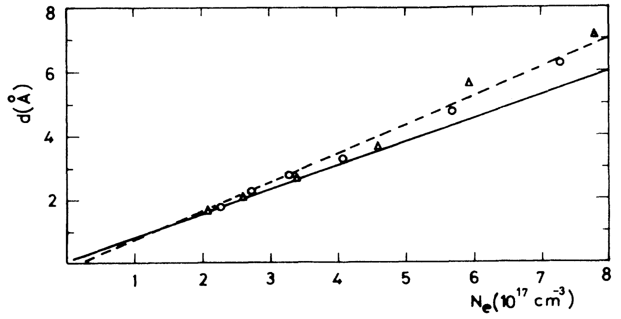

FIG. 3. Points △ and ○ represent our values of H_β line shifts from two independent measurements using $d^{(2)}_{\mathrm{theor},0}$. ——, theory (Ref. 9); — — —, experimental best fit from Ref. 4.

quite homogeneous, both radially and axially, behind the reflected shock front. The only inhomogeneities occur in the boundary layers between the inner plasma and the cold glass-tube walls, but they do not influence the line shape.[16] We also checked the plasma homogeneity by measuring the peak separation relative to the half-width of the H_β line, which should have been 0.35–0.37 if the plasmas had been homogeneous.[17–19] This criterion was satisfied for all measured profiles.

The overlapping with neighboring lines was checked for the highest values of electron densities. In the worst case, the contribution of this effect was less than 1%.

IV. DISCUSSION AND CONCLUSIONS

From Figs. 2 and 3 it can be seen that certain incongruences exist between experimental and theoretical results. Both of them predict an almost linear shift dependence on electron density but with different slopes. Namely, in calculations from Ref. 8 for the dynamical quadratic Stark effect for the interaction $n'=n+1$, as mentioned in the Introduction, the dipole interaction was taken into account. The dipole interaction for $n'\neq n+1$ and the quadrupole interaction for $n'=n+1$ were taken into account only as corrections. The resulting shift is red. In the calculations of ion-produced shifts, the quadrupole and dipole interactions were taken into account. These shifts are blue. Combination of these effects results in a reduction of the red shifts. In calculations from Ref. 9 the $\Delta n=0$ dipole interactions with electrons were also taken into account, resulting in increased red shifts and in better agreement with experiments.

Agreement between our experimental results and results from Ref. 4 is excellent. The slope obtained from our results agrees well within the errors with the slope of the best-fit line from Ref. 4. Thus our results are in agreement with continuations of the values from Ref. 4.

In this work, we extended the range of previous measurements and compared the obtained results for the shifts of the H_β line to recent theories. From Figs. 2 and 3, it can be seen that the trends and slopes of the shift dependence on electron density are in agreement with results from the previous experiment, while the slope that is given by the theory[8] is considerably smaller. The improved theory[9] is in significantly better agreement with experiments, but the slope is slightly smaller than the one obtained from experiments. The experiment-theory difference of about 15% (from Fig. 3), compared to the error of the experimental line slope of 9% (which includes the errors of electron density and shift measurements), shows that theory[9] still gives slightly smaller shifts than experiment. One of the possibilities for improving theory-experiment agreement could be to include higher-order effects (such as the quadrupole $\Delta n=0$ interaction, for example) in the theoretical calculations, which would probably result in increasing red shifts of the H_β line.

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