J. Quant. Spectrosc. Radiat. Transfer Vol. 36, No. 3, pp. 233–237, 1986
0022-4073/86 $3.00 + 0.00

SHIFT MEASUREMENTS OF H_α AND H_β LINES IN ARC PLASMAS

J. HALENKA* and J. MUSIELOK
Institute of Physics, Pedagogical University Opole, ul. Oleska 48, 45-052 Opole, Poland

(*Received* 4 *June* 1985)

Abstract—Red shifts are reported for the H_α and H_β lines at electron densities of 10^{16}–10^{17} cm^{-3}. The peak shift of the H_α line agrees with the ELC shift. For the H_β line, the dip shift exceeds the ELC shift systematically. The H_β dip shift is proportional to N_e/T.

INTRODUCTION

Increasing accuracy in recent measurements of hydrogen Stark profiles[1-9] has revealed substantial imperfections in currently applied theoretical data.[10-12] The discrepancies concern the asymmetries and shifts of H lines. These relatively small effects have been the subject of numerous theoretical studies[13-17] during the last decade. The central regions of Stark-broadened H-lines are sensitive to the reduced mass of the emitter–perturber pair. Such ion-dynamic effects are, however, not expected to affect shifts and asymmetries.[18,19]

The shifts and asymmetries of H lines are of interest in connection with relativistic red shifts[20,21] of stellar (white dwarf) H-lines, in fusion research and in other laboratory experiments.

As was recently pointed out by Griem,[17] the observed shifts arise from distant electron–atom collisions (red shift) and from ion–atom quadrupole interactions (blue shift). For line-shift studies, a convention regarding the shift definition is required. The currently used definition was introduced by Wiese[2] and is defined by the experimental line center (ELC). According to Griem, this convention is closely equivalent to using theoretical ion-quadrupole shifts calculated by him.[17] The ELC shift results from both electron collisions and ion quadrupole effects, i.e. the ELC shift is a measure of a pure shift modified by asymmetry effects.

In general, the effects caused by inhomogeneities in ion-produced electric fields are relatively more important for the part of the line profile outside the half width. These quadrupole effects affect also the central part of H lines. For the H_α line, because of a non-active, first-order Stark-effect, the quadrupole effects are very important for the position of the central line components and, therefore, for the measured peak shift. For the H_β line, these effects lead, for example to the intensity difference between the blue and the red line shoulders. However, as will be shown, the contribution from these effects to the H_β dip shift is small.

Our study is mainly devoted to the central part of the H_β line. In particular, we have measured the H_β dip shift, which should be governed predominantly by interactions of the emitting atoms with electrons. For comparison, we have also measured the H_α peak shift, where the contribution from quadrupole effects is expected to be essential. The measurements were performed for arc plasmas at electron densities of 10^{16}–10^{17} cm^{-3}. A Plücker tube filled with hydrogen was applied as a wavelength standard.

EXPERIMENTAL STUDIES

The plasma was produced in a wall-stabilized arc operated in Ar with small amounts of H in the central part of the arc at atmospheric pressure. The radiation in the end-on direction was focused on the entrance slit of a grating spectrograph PGS2. The applied optical system allowed us to record the radiation emitted from a homogeneous plasma layer around the arc axis. To obtain the spectral resolution required for reliable shift measurements, the radiation was recorded on

*This work was performed under the partial sponsorship of the Polish Academy of Sciences.

spectral plates using the second-order spectrum. The reciprocal linear dispersion on the plate amounts to 3.5 Å mm^{-1}. After exposing the plate to arc radiation, the emission of the Plücker tube was recorded at the same optical conditions and without changing the position of the plate holder. The H line from the Plücker tube appears on the arc spectrum as a very narrow line, which clearly indicates the unshifted position. The disturbance of the arc spectrum by the Plücker lines was determined by recording arc spectra without exposing the plate to the reference radiation. The tests showed that the disturbances are weak and may be taken into account during shift measurements. Next, the spectra were traced with a microphotometer and the data were converted to the intensity scale. Several experiments have been performed applying different currents in the range 25–140 amp. In this manner, the electron density and the temperature of the plasma were varied. Because the measured H-line profiles (especially the H_β line) are slightly affected by the Ar spectrum, and since our procedure to obtain line profiles involves conversion of the data from blackening of the plate to the intensity scale and may introduce errors in the line shapes, we have not measured the ELC shifts as defined by Wiese[2] but rather shifts of the central maxima and central minima for the H_α and H_β line profiles, respectively. At two electron densities, however, we have also measured the ELC shifts of the H_α and H_β lines for comparison with the shifts of the maximum (minimum) of the line profile and for comparison with other experimental and theoretical results.

The electron density was obtained from the peak separation, as well as from the FWHM of the H_β line. According to Wiese,[21] the ratio of $\Delta\lambda$ for peak separation divided by $\Delta\lambda_{1/2}$ is very sensitive to plasma inhomogeneities. Our measurements show that this ratio remains almost constant over the entire electron density range and falls in the range 0.35–0.36, while only slightly decreasing with increasing electron density. A similar tendency was found by Helbig and Nick.[9] The temperature of the plasma was derived for LTE, using the appropriate N_e value from line-broadening measurements and applying the total line intensity of an H or Ar line. The optical depths of hydrogen lines were checked by comparing the measured absolute intensities of the line peaks with the blackbody radiation at the arc temperature for the corresponding wavelengths. These tests show that it was necessary in only one experiment (H_α at a high N_e value) to make a small correction in the line profile for self-absorption. Since the plasma is homogeneous in the direction of observation, this correction is easily made. The conditions for thin lines in all other experiments were achieved by using appropriate amounts of H in the Ar–H mixture.

RESULTS AND DISCUSSION

The H_α line was investigated at two plasma conditions: at an electron density $N_e = 2.9 \times 10^{16}\,cm^{-3}$, $T = 10{,}800$ K and $N_e = 9.0 \times 10^{16}\,cm^{-3}$, $T = 12{,}600$ K. We do not find any substantial differences between the shifts of the intensity maxima of the line profiles and the ELC shifts. In Fig. 1, our results are compared with those reported by Wiese *et al.*[2] The shifts measured at higher N_e agree well with those obtained by Wiese *et al.*[2] The shifts at low electron density confirm the extrapolation based on results of Wiese *et al.*[2] As was mentioned in the Introduction, we expect

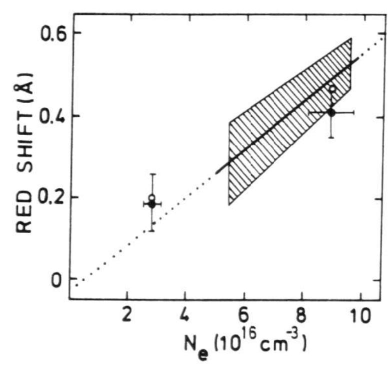

Fig. 1. The H_α red shift is shown vs the electron density. The shaded area represents the ELC shift measurements of Wiese *et al.*[2] The solid line shows the best fit to these results. The solid circles represent our data for the peak shifts, while the open circles show the ELC shifts.

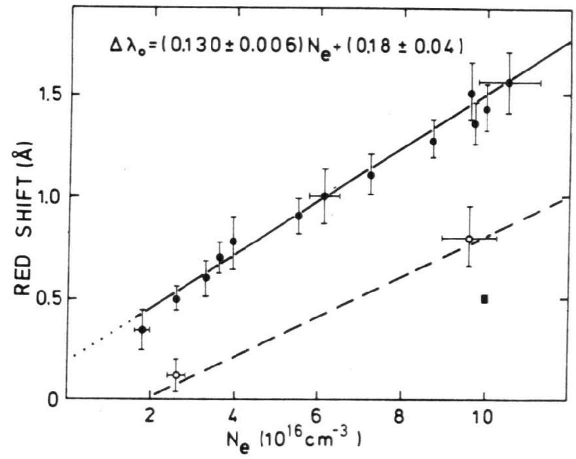

Fig. 2. The H_β red shift is shown vs electron density. The solid circles show the H_β dip shifts and the open circles show the ELC shifts. The dashed line represents the best fit of the ELC measurements of Wiese *et al.*[2] The square shows a dip shift measured by Okasaka *et al.*[4].

that the quadrupole effects may considerably influence the measured peak shift of H_α. According to equation (41) taken from Ref. [14], we have calculated the shifts of the central line components of H_α caused by inhomogeneity of the ion-produced electric field. For our experimental conditions (N_e, T), we obtain blue shifts which are as large as the red shifts produced by interaction with electrons according to Griem.[17] Since the experimental values fit Griem's data well, we suppose that interaction with electrons leads to peak shifts which exceed those predicted by Griem nearly by a factor of two. Because of the crucial influence of quadrupole effects on the H_α peak shift and uncertainties in the theory, shift estimates produced by electrons and based on H_α peak-shift measurements are not advisable.

For the H_β line, we found notable discrepancies between the dip and ELC shifts, with the dip shift systematically exceeding the ELC shift. This line was investigated at several electron densities. Our measurements cover the electron density range from 2.0×10^{16} to $1.1 \times 10^{17}\,\text{cm}^{-3}$. Figure 2 shows the measured dip (solid circles and solid line) and ELC (open circles) shifts as functions of electron density. The dotted line represents the best fit to the ELC shift obtained by Wiese *et al.*[2] Within error limits, our measured ELC shifts agree with the results obtained by Wiese *et al.*[2] It may be seen that the dip shift increases nearly linearly with increasing electron density. Extrapolating these results to $N_e = 0$, a residual shift of $\Delta\lambda_0 \simeq 0.2$ Å is found. We have found only one paper[4] on H_β dip shifts, at two electron densities. These shifts were measured at higher temperature ($T \simeq 30{,}000$ K) for $N_e = 1 \times 10^{17}$ and $2.5 \times 10^{17}\,\text{cm}^{-3}$. One of those results is also shown in Fig. 2. This shift differs considerably from our value at the same N_e but at about half the temperature ($T = 13{,}000$ K).

Different plasma conditions were achieved by changing the arc current. In general, larger N_e correspond to higher plasma temperatures. Since our shift measurements were performed at different N_e and T, we normalized the shifts to an electron density of $10^{16}\,\text{cm}^{-3}$ and studied the temperature dependence of the H_β dip shifts. Figure 3 shows the logarithms of the normalized shifts as functions of the logarithms of the plasma temperature. The dashed line shows the shift produced by collisions with electrons according to calculations of Griem[17] without allowance for quadrupole effects. The solid line represents the best fit to our results and indicates that the shift is proportional to $1/T$. The temperature dependence of the shift obtained from our results is in relatively good agreement with both results taken from Ref. [4]. Including these two results, the exponent in the best fit to $\Delta\lambda_0/N_e = aT^b$ equals 1.4 (dot-dash line in Fig. 3). The temperature range in our experiments was too narrow to obtain reliable data on shift variation with temperature. However, our results, as well as those of Okasaka *et al.*[4] indicate that the H_β dip shifts are proportional to $1/T$ rather than to $T^{1/3}$, as predicted by Griem for shifts caused by collisions with electrons.

In Fig. 4, we present the H_β dip shifts as a function of N_e/T. The solid line represents the best

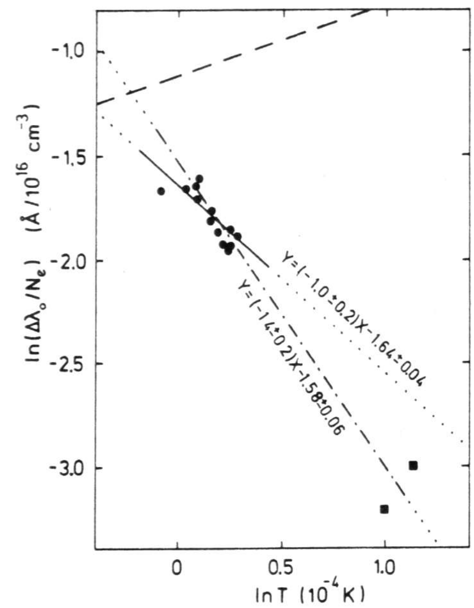

Fig. 3. The logarithms of the normalized H_β dip shifts are shown as a function of the logarithms of the plasma temperature. The circles represent our measurements, while the squares show the results of Okasaka *et al.*[4] The solid line represents the best fit to our results and the dot-dash line is the best fit if the data of Okasaka are taken into account. The dashed line shows the shift caused by electron collisions after Griem.[17]

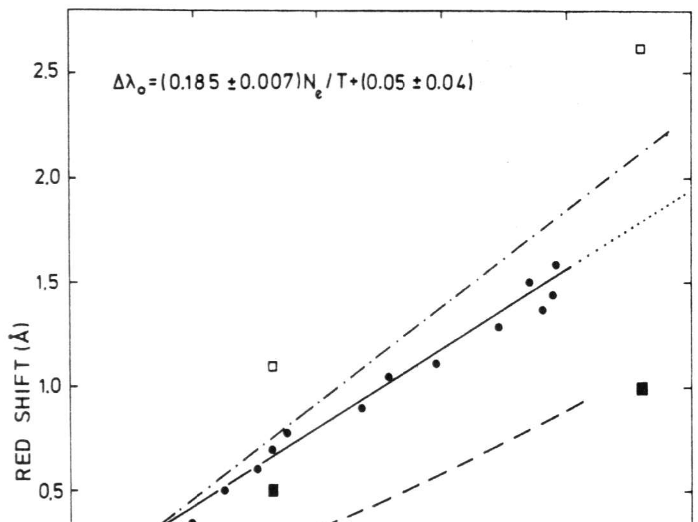

Fig. 4. The H_β dip shift is shown vs the quantity N_e/T. The circles represent our data and the solid squares the data of Okasaka *et al.*[4] The solid line shows the best fit to our results and the dot-dash line represents the shifts of Grabowski and Halenka.[15] The dashed line shows the shift computed after Griem[17] for our values of N_e and T, while the open squares represent these shifts computed for the corresponding plasma parameters of Okasaka *et al.*[4]

fit to our results. Extrapolation of these experimental results to $N_e/T = 0$ yields practically no shift at low electron densities. The solid squares are the results of Okasaka *et al.*[4] The open squares represent the shifts caused by electron collisions, which are computed after Griem for the N_e and T of Ref. [4]. The dashed line shows these same shifts computed for our experimental plasma parameters. The dot-dash line in Fig. 4 shows the shifts predicted by Grabowski and Halenka[15] for the Debye-shielding model. The shift calculated in this manner yields an upper limit of the shielding action by free electrons on the emitting H atom. For the range of plasma parameters used in Fig. 4, the dependence is linear.

As was already mentioned, the H_β dip shift is mainly produced by interaction of the emitter with electrons. However, the influence of quadrupole effects can not be completely ignored, since these effects lead to the enhanced blue line shoulder and may therefore lead to an apparent red shift of the dip. For the plasma-parameter range of our experiments, we have computed the contribution of the red shift from the quadrupole effects according to Demura and Sholin,[14] including also corrections for the quadratic Stark-effect. In the whole plasma parameter range, this red shift does not exceed 10% of the measured value.

CONCLUSIONS

Our measurements show that, in the electron density range of 10^{16}–$10^{17}\,cm^{-3}$, the shift of the intensity maximum of the H_α line and the ELC shift are almost the same. In the same N_e range, the measured H_β dip shift systematically exceeds the ELC shift and is (on average) about two times larger than the shift resulting from electron collisions after Griem. The shift caused by electron collisions should increase with increasing temperature ($\Delta\lambda \sim T^{1/3}$), while the measurements indicate a shift nearly proportional to T^{-1}, as is predicted by the model based on the shielding action of electrons.

Acknowledgement—The authors thank B. Grabowski for helpful discussions.

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