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SHIFT OF THE PEAKS OF THE H_β SPECTRAL LINE

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Abstract—Red shifts for the intensity peaks and for the central dip of the H_β line have been measured in a hydrogen–argon arc-plasma and in a hydrogen plasma produced in an electromagnetically-driven shock tube, for electron concentrations N_e between 10^{22} and $6 \times 10^{23}\,\mathrm{m}^{-3}$. The dip shift exceeds the peaks shift systematically. We have calculated the shift parameter $\delta\lambda_{P-D} = (\lambda_B + \lambda_R)/2 - \lambda_D$ taking into account multi-ion–atom quadrupole interactions and the quadratic Stark effect. The calculated $\delta\lambda_{P-D}$ are distinctly smaller than the measured values for the entire range of N_e values.

INTRODUCTION

It is well known that H spectral lines emitted from plasmas are asymmetric and red-shifted. These relatively small effects are similar to large-scale broadening and result from interactions of an emitter with the internal electric field of the plasma. The principal cause of the observed shift is interactions with free electrons. The asymmetry results from inhomogeneities of the ion-produced electric field (ion–atom quadrupole interactions) and from non-negligible second-order alterations arising from the homogeneous term of the ionic field. In Refs. 1–3, it was shown that the description available for these effects remains unsatisfactory. In the quoted references, an analysis of the contributions of both electronic and ionic interactions to the observed shift and asymmetry of spectral lines is presented, including the H_β line, which is the most extensively investigated case. The present study is a continuation of these investigations.

CALCULATIONS

Calculations have been performed on the basis of the formula derived in Ref. 2 for the H-line profile. In these calculations, we have assumed that the shift $\Delta\omega^e$ caused by interactions of an emitter with free electrons is constant within the entire range of the profile. Furthermore, because the ion–atom quadrupole interactions and quadratic Stark effect are second-order corrections, the H-line profile including these corrections and also the $\Delta\omega^e$-shift, may be described by the expansion

$$I(\Delta\omega) \simeq I^d(\Delta\omega + \Delta\omega^e) + \Delta I(\Delta\omega),$$

where I^d is the symmetrical H-line profile, which is calculated for the approximation of ion–atom dipole interaction and is well described by the theory.[4] The $\Delta I(\Delta\omega)$ correction has been calculated in simplified form, i.e., the off-diagonal matrix elements of the impact operator have been neglected. The dip shift with respect to the unperturbed H_β position λ_o is equal to $\delta\lambda_D = \lambda_D - \lambda_o$. We have used $\delta\lambda_P = (\lambda_B + \lambda_R)/2 - \lambda_o$ as a measure of the peak shift of H_β, where λ_B and λ_R are wavelengths of the blue and red peaks, respectively. To estimate the efficiency of the quadrupole effects, a more useful measure is the shift of the peaks with respect to the dip position, $\delta\lambda_{P-D} = (\lambda_B + \lambda_R)/2 - \lambda_D$. If $\Delta\omega^e = \text{constant}$, then the shift $\delta\lambda_{P-D}$ does not depend on $\Delta\omega^e$ and, therefore, does not depend on uncertainties in the description of the electronic shift. The assumption about $\Delta\omega^e$ is an approximation which requires discussion.

In some papers, e.g., in Refs. 5 and 6 for the H atom and in Ref. 7 for highly charged ions, the screening of an emitter is considered as a cause of the shifts of energetic levels (the plasma polarization shift); in Refs. 8–10, the shift results from electron collisions. All calculations under consideration, independent of the sophistication of the theoretical description, are carried out by using the unperturbed wave functions of the H-atom. As a result, the shifts also depend on the quantum number l. However, the ion-produced field mixes levels, and the shift averaged over l should therefore be interpreted as a shift of the center of gravity of the fine structure, around which splitting in the plasma electric field occurs.[8] The resulting asymmetry of the line profile is a second-order alteration as compared with the shift. For hydrogenic ions, the significance of this asymmetry increases with increasing nuclear charge Z. When Z increases, the splitting of the fine structure also increases, and the relative significance of the splitting caused by the ion-produced fields decreases systematically (e.g., Ref. 11). The assumption $\Delta\omega^{\mathrm{c}} = \text{constant}$ for the hydrogen H_β line-profile and for the range of plasma conditions studied appears to be a good approximation.

The shifts $\delta\lambda_{\mathrm{P-D}}$ have been calculated for electron concentrations in the range $10^{22} < N_{\mathrm{e}}$, $\mathrm{m}^{-3} < 6 \times 10^{23}$ and for temperatures corresponding to this range of N_{e}. In the calculations, a small correction resulting from the so-called trivial asymmetry (see, e.g., Ref. 10) is included.

MEASUREMENTS

Measurements have been performed using two different plasma sources: a wall-stabilized arc for $N_{\mathrm{e}} \lesssim 10^{23}\,\mathrm{m}^{-3}$ and an electromagnetically-driven shock tube (T-tube plasma) for $N_{\mathrm{e}} \gtrsim 10^{23}\,\mathrm{m}^{-3}$.

The arc was operated in Ar, with a small amount of H in the central part of the arc. The plasma was homogeneous along the channel axis but had radial gradients in the plasma temperature and densities of the plasma components. The spatial resolution of our optical system allows us to select the radiation from various, nearly homogeneous plasma layers parallel to the arc axis. In this manner, the H_β line profiles from plasmas with different T and N_{e} could be obtained. The optical depth of H_β was checked by comparing the measured absolute intensity of the line peak ($J_{\max}$) with the blackbody radiation intensity (J_{b}) at the arc temperature. The ratio $J_{\max}/J_{\mathrm{b}}$ was always $< 5\%$. The measured H_β line profile was corrected for optical thickness and N_{e} was derived from the peak separation and from the FWHM of the H_β line; T was calculated for LTE, using the intensity of H_β or of ArI spectral lines. The criterion for plasma homogeneity was satisfied, i.e., $0.35 < \Delta\lambda_{\text{peak sep.}}/\Delta\lambda_{1/2} < 0.36$[12] for plasma layers with radius $r < 1.8$ mm from the axis of the arc channel, the diameter of which was equal to 5 mm. In experiments with $N_{\mathrm{e}} \lesssim 3 \times 10^{22}\,\mathrm{m}^{-3}$, the specified criterion for homogeneity was not satisfied. Therefore, we used a considerably smaller arc current ($15 \leqslant i$, $\mathrm{A} \leqslant 25$) and obtained the profiles only by looking along the axis, where this criterion[12] was satisfied.

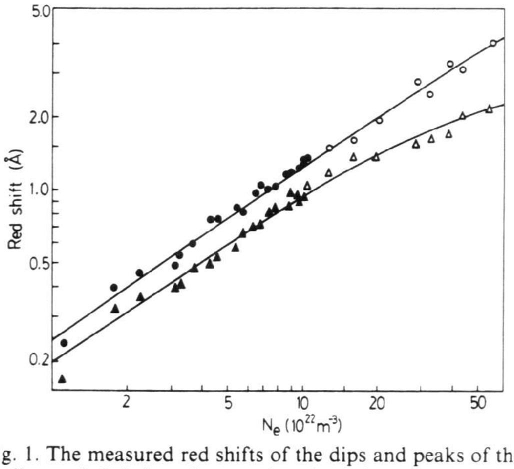

Fig. 1. The measured red shifts of the dips and peaks of the H_β line and their best fits as a function of electron density. Circles show the H_β dip shifts and triangles show the peak shifts; the solid symbols refer to arc data and the open symbols to T-tube results.

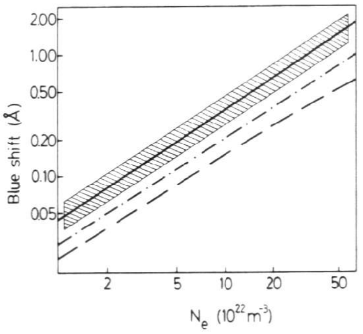

Fig. 2. The peak shift with respect to the wavelength of the dip for H_β as a function of N_{e}. For further explanations, see the text.

This method for N_e determination was also used for the T-tube plasma. The temperature was obtained from H_β-line-to-continuum intensity ratios. The T-tube was operated with pure H. The T-tube and methods for the determination of plasma parameters are described in detail in Ref. 13.

The shifts $\delta\lambda_D$ and $\delta\lambda_P$ have been measured with respect to the H_β line using the H, Br and Cd lines from low-pressure tubes. For our plasma conditions, the quantity $\delta\lambda_D$ is greater than $\delta\lambda_P$, as is shown in Fig. 1.

RESULTS

The values of $\delta\lambda_{P-D}$ determined experimentally (solid line) and calculated (dashed line) are shown in Fig. 2. The solid curve is the difference of the best fits of the measured values of $\delta\lambda_D$ and $\delta\lambda_P$, as presented in Fig. 1. In this manner, we have minimized the uncertainties of the measured shifts $\delta\lambda_{P-D}$. The shaded area represents the maximum uncertainty for measurements of $\delta\lambda_{P-D}$. We have estimated that the peak shift contributes about two-thirds and the dip shift about one-third to the calculated values of $\delta\lambda_{P-D}$. We have also estimated the effects of ion dynamics on the dip shift. To this end, we replaced the calculated profiles I^d by measured profiles that were made symmetrized with respect to λ_D. The $\delta\lambda_{P-D}$ values calculated in this manner are shown in Fig. 2 by the dot–dash curve. These results are about 25% greater than the previously obtained values. We note, however, that despite taking account of this last correction in the calculations, our measured shifts exceed the calculated values.

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