Stark shift in ionized boron*

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Stark shift of B II λ3451 Å due to plasma microfields was measured in a luminous shock tube. Line profiles, photographically recorded in second order, were compared to closeby wavelength fiduciaries from low-pressure rare-gas lamps. Electron densities [$(3\text{–}16)\times 10^{16}$ cm^{-3}] for each exposure were found by fitting H_β profiles to theoretical line shapes. Results, estimated reliable to 25–30%, are compared with theoretical predictions.

INTRODUCTION

Treatment of ionic line shifts in plasmas has been the subject of active refinement for more than a decade.[1] Pending better qualifications astrophysically observed shifts cannot be fully utilized for deducing intrastellar convective motion.[2] Reliable experimental data are rare,[3] owing in part to a scarcity of well-behaved ionic line sources.

Most measurements of ion line shifts have involved light sources whose mean thermal energies $E=kT$ exceed inelastic thresholds $(E_i - E_f = \Delta E_{if})$.[1,6] Theory in such cases must contend with both strong and weak collisions, as well as the possibility of significant resonances near threshold. For nonhydrogenic ions,[4] shift data for $kT/|\Delta E| \ll 1$ have been lacking. In our shock tube, average electron energies are typically a factor of 4 too small to inelastically perturb the levels producing the Br II 3451 Å line.

In 1-eV thermal plasmas (including atmospheres of type O, A, and B stars) B II λ3451.41 Å is the most prominent boron feature from the near uv to the near ir. Comparatively few perturbing states must be considered for semiclassical computations. A lack of inelastic cross sections and elastic scattering amplitudes precludes a fully quantum mechanical treatment.[5] Recently measured B II lifetimes,[7] differing considerably from central-field predictions,[8] appreciably alter the outcome of shift approximations.

EXPERIMENTAL

Spectroscopic plasmas are generated in a 6×9 cm^2 conventional shock tube. Driving 1000 psi (absolute) of ambient temperature hydrogen into 5–35 Torr of test gas produced stationary and quiescent plasmas behind first-reflected shocks. Steady-state durations are 30–150 μsec. Photoelectric monitoring of sensitive temperature indicators, such as the brightness of Ne I λ5852 Å, discloses when occasional random transients occur. A battery of earlier tests[9,10] confirmed freedom from repeatable inhomogeneities. Homogeneity is further checked by comparing H_β red-blue peak separation with H_β half-width.[11]

Judicious selection of test gas composition and pressure maintained good brightness in B II λ3451 Å and H_β throughout the electron density range $(5\text{–}20)\times 10^{16}$ cm^{-3}. Mixtures consisted of a neon carrier plus 1% B_2H_6, or $\frac{1}{2}$% B_2H_6 + $\frac{3}{4}$% SiH_4, or $1\frac{1}{2}$% B_2H_6 + 40% Ar (all molal). With these mixtures, electron density could be changed over a factor of 4 while temperatures in most experiments remained within ±10% of 11 600°K.

Electron density resulted from comparing H_β profiles (recorded in synchrony with the B II 3451 Å profile) with theoretical line shapes.[12] Red and blue wings were averaged prior to the dimensionless fitting. Accuracy of electron density data is typically 20–25%. In the majority of runs, electron densities were also computed from pressure and temperature data.[13] A black-body temperature measured by the line-reversal technique was averaged with an excitation temperature from Ne I 5852 Å line brightness. Pressure was recorded by two quartz transducers. Reliability of these two state variables was 5–7% and 10–14%, respectively, allowing electron densities to be computed by the Saha-Boltzmann relation with accuracies of 25–30%. On the average, $N_e(p, T)$ and N_e via H_β shape agreed satisfactorily.

A stigmatic spectrograph with second order reciprocal dispersion of 3.7 Å/mm recorded

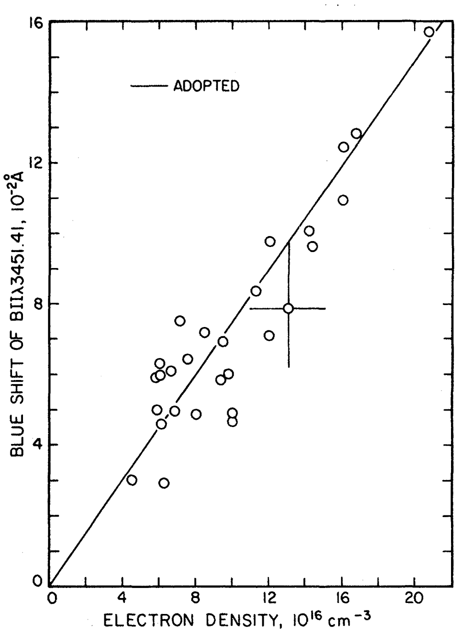

FIG. 1. Blue shift of B II 3451.41 Å plotted against measured electron density.

BII λ3451 Å profiles. A synchronized fast shutter was adjusted for 20–60 μsec[14] exposures. Grain of the fast Kodak No. 2475 emulsions limited resolution to 0.25 Å. Local dispersion was by fitting first-order neon ($\lambda = 6717.04$ Å, $\lambda = 6929.47$ Å), xenon ($\lambda = 6882.16$ Å, $\lambda = 6925.53$ Å), and krypton ($\lambda = 6904.68$ Å) Osram lamp lines to a 3*d* degree polynomial. Lamp lines were superimposed on the shock tube spectrograms without disturbing the photographic plate. Separation between second-order BII λ3451.41 Å and Kr I 6904.68 Å (separation of 1.86 Å) was read directly from the plates by a Grant photoelectric comparator. Interpreting line centers as the wavelengths of maximum intensity, shifts could be read with a precision of 0.01–0.015 Å, depending on signal-to-noise ratios.

Attempts to determine BII λ3451 Å Stark broadening had to be abandoned because resolution was inadequate for quantitative compensation for radiative trapping. Stark width data for B II λ3451 Å is therefore merely an upper-limit determination: full halfwidth <0.3 Å at 10^{17} electrons/cm^3. Shift measurements are unaffected by optical depth uncertainties so long as no boundary layer reabsorption occurs, as is the case for ionic emitters in the shock tube.

RESULTS AND DISCUSSION

Blue shifts of BII λ3451 Å from 27 experiments are plotted against measured electron density in Fig. 1. The mean and standard deviation of the shift parameter d/N_e are -0.075 Å per 10^{17} cm^{-3} and 5%, respectively. Estimated accuracy including estimated systematic error of the shift parameter is 25–30%.

As a control, blue BII λ3451 Å shifts were tested for correlation with simultaneously measured red NeI λ6717 Å shifts. The two shifts were linearly related and the slope, within experimental precision, had a zero intercept. This is the behavior expected if electron impacts are primarily responsible for the shifts.

Comparison data from three impact theories appear in Table I. The first column lists predictions by the semiempirical (SE) method of Griem[18] and the semiclassical models of Jones, Bennet, Griem (JBG)[6] and Sahal-Brechot (SB).[20] In all cases, the shift is due primarily to the mutual interaction of the upper and lower ($2p^2\,{}^1D$-$2s2p\,{}^1P^o$) states for the λ3451 Å transition and all predictions depend strongly on the choice of A value for this dominant upper-lower level interaction. When Weiss's[8] refined calculation, $A = 2.2 \times 10^8$ sec^{-1}, is used, the Stark shifts predicted by JBG essentially coincides with shock tube findings, while the SE and SB results are slightly beyond estimated experimental tolerance. This picture of general agreement is upset by employing the transition probability recently inferred from lifetime data,[7] a value fourfold smaller than Weiss's, and known to conform well to systematic trends in line strengths.[17] Using this experimental A value, all the theories markedly underestimate our shock tube observed line shifts. An earlier comparison[19] of experimental and predicted ion line shifts found that the experimental shifts were systematically more blue shifted (approximately 0.2 Å) than theory called for.

Theory and experiment are drawn together if allowance is made for a polarization shift.[4,15] The

TABLE I. Comparison of measured and predicted Stark shifts of B II 3451.41 Å ($N_e = 10^{17}$ cm^{-3}, $T = 1$ eV).

Source	Stark shift (Å)	Plasma polarization shift (Ref. 18) (Å)	Total shift[a] (Å)
This experiment			−0.075 ±30%
Griem (Ref. 18)	−0.048[b]	−0.019	−0.067
(SE)	0.029[c]	−0.010	−0.039
JBG (Ref. 19)	−0.075[b]	−0.049	−0.124
	−0.041[c]	−0.032	−0.073
Sahal-Brechot (Ref. 20)	−0.042[b]	−0.045	−0.087

[a]Assuming linear additivity of the Stark shift and polarization shift.

[b]Computed using NBS (Ref. 8) value of line strength.

[c]Computed using lifetime data (Ref. 7).

third column in Table I gives (blue) polarization shifts d_p computed in the approximation[9,18]

$$\frac{d_p}{W}\approx\frac{-Z^{3/2}(Z+1)^{3/2}}{5}\frac{E_H}{kT}\left(\frac{n_i-n_f}{\bar{g}_i n_i^4+\bar{g}_f n_f^4}\right),$$

where n_i is principal quantum number and $\bar{g}$ is the Gaunt factor. At 1 eV temperatures and 10^{17} cm^{-3} electron density, d_p equals -0.32 times the impact halfwidth W. Reservations have been expressed over other proposed models of polarization shift.[16,21] Theoretical development is still preliminary. Attention is focusing on a factor $\exp(X_{z-1}/kT)$, where X_{z-1} is the ionization potential of the preceding stage: work with energetic plasmas indicates that the factor fails to extrapolate to multiply ionized species.[16] Experimental conditions in the shock tube and in both the well known[15] and more recent[21] T-tube work on He II resonance line shifts[15,21] are represented by similar arguments in this exponential term (e.g., 8 eV/1 eV versus 24 eV/4 eV). The latter studies in this regime do seem to confirm polarization shift. Assuming linear additivity,[1] and that the lifetime-based A value is the more reliable, a combining of Stark and polarization shifts improves agreement between theory and shock tube line shift measurements.

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