Plasma shifts of the He II H_α and P_α lines

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Shift measurements for the H_α (1640 Å) and P_α (4686 Å) hydrogenic ion lines of He II have been done over an electron density range 2×10^{22} to 2×10^{23} m^{-3} and for an electron temperature of 4 eV. The plasma was produced in a linear Z discharge. Systematic red shifts linear in density are observed. The experimental data are compared with combined theoretical estimates for electron-impact and ion quadrupole effects. The experimental results are in agreement with our earlier results for P_α.

I. INTRODUCTION

During the past two decades there have been numerous studies of the shifts of hydrogeniclike ion lines of He II. We have measured line shifts[1–3] of the Paschen series in He II in a low-temperature, medium-density plasma. Shifts in other hydrogenic ion species in hotter plasmas are now being investigated, however, this work is motivated by the potential use of such shift as a nonperturbing plasma diagnostic; their measurement and interpretation have been a matter of controversy. The shift of hydrogenic ion lines has often been primarily associated with the so-called plasma-polarization shift (PPS). Berg *et al.*[4] first invoked PPS in an experiment to explain observed blue shifts for the 4686-Å ion line. According to the PPS, an ion emitter will attract an excess negative charge density in its surrounding plasma environment. The excess charge density in turn perturbs the energy levels of the emitting ion, causing level shifts. The level shifts, having an n dependence, are seen as a line shift when emission between two levels occurs.

The investigation of PPS has been clouded by conflicting results in a number of experiments. Shifts to shorter (blue) wavelengths,[5] longer (red) wavelengths,[1–3] or no shifts at all[6] have been reported. Several reviews describing the earlier results have been written.[7,8] More recent experimental results, including our own, have generally reported red shifts for the visible lines of He II although there are differences in the magnitude for the shift. Hashimoto[9] reported further evidence of a red shift for the Pashen lines of He II. However, when compared with our earlier results,[2,3] Hashimoto measured shifts which are almost 4 times smaller for the P_α line, and approximately 3 times larger for the P_β line. Because of this discrepancy we again measured the shift of the 4686-Å P_α line using a new plasma source and an improved multichannel optical detector, and extended the work to the vuv spectral region to study the 1640-Å H_α line of the He II.

II. EXPERIMENT

As shown in Fig. 1, the plasma source consists of a quartz tube as the outer vacuum vessel. Inner tubes with end (viewing) windows protrude through the electrodes and into the plasma. The end windows were made of quartz to view the 4686-Å line and LiF for the 1640-Å observation. For the 1640-Å line a metal shield was placed in front of the LiF window protecting it from damage by the plasma. The shield consists of a 5-mm-thick brass disk pierced by a 6×6 mm array of 25 holes (each about 1 mm in diameter) matching the spectrometer aperture. The plasma discharge was formed in pure helium at filling pressures between 66.7 to 200 pascals (0.5—15 torr). The discharge current was derived from a capacitor bank consisting of 8—15-μF capacitors connected in parallel through series inductors (lumped delay-line configuration). The charging voltage ranged between 5 and 10 kV. The current waveform approximated a square wave with a 140-μsec half-period. The peak current varied between 5 to 10 kA.

Figure 2 shows the general setup of the experiment. We used two spectrometers for this work. A $\frac{3}{4}$-m Spex Industries spectrometer equipped with an OMA (optical multichannel analyzer) was mainly used as an intensity monitor of the 4686-Å line and the nearby He I 4713-Å line to determine the electron density (and electron temperature) on a shot-to-shot basis. The reproducibility of the source was found to be excellent, with the electron density and line-intensity shot-to-shot variations within 5%. A vuv 10.7-m normal-incidence spectrometer with a 1200-lines/mm grating blazed at 3000 Å was used for observing the detailed characteristics of both He II

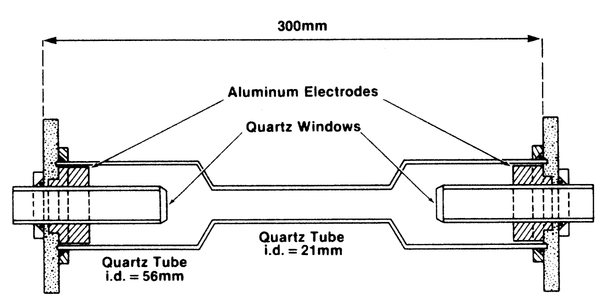

FIG. 1. Schematic of the discharge tube showing the viewing tubes protruding into the discharge vessel. LiF windows were used for the vuv work.

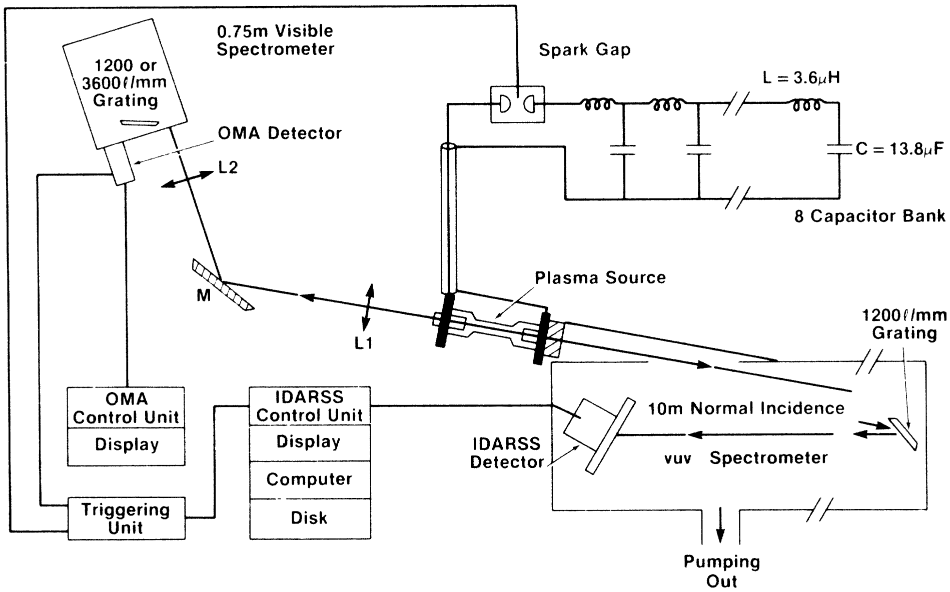

FIG. 2. Experimental layout. A 10.7-m normal-incidence vuv spectrometer with a IDARSS detector measured the line profiles. A $\frac{3}{4}$-m visible spectrometer equipped with an OMA monitored the 4686-Å line.

lines. The plate factor was 0.78 Å/mm at 4686 Å and 0.384 Å/mm at 3280 Å (second order 1640 Å). A Tracor Northern IDARSS detector was placed at the focal plane of the spectrometer. This detector uses a cooled Reticon array attached to an image intensifier unit. The Reticon array consists of 1024 channels each 25 μm wide. The cooling of the array reduced thermal noise and allows detection of weak light levels not otherwise observable. The dispersion was 0.0186 Å/channel at 4686 Å and 0.0095 Å/channel for the 1640-Å line. The image intensifier was gated for 20 μsec during the first half-period of the discharge current. The electron density remains reasonably constant (10% variations) on this time scale. The digitized data from the detector and its controlling electronics were fed into a Digital Equipment Corporation LSI-11/2 minicomputer via a CAMAC (computer-aided measurement and control system) crate. Wavelength calibrations were obtained using a spectrum of very narrow lines emitted from a thorium lamp source. The channel-to-channel intensity calibration was obtained using calibrated tungsten strip and deuterium lamps. The calibration for the 1640-Å line was done with radiation emitted about the 3280-Å spectral region, and it was considered that the response of the scintillator placed in front of the intensifier photocathode was constant down to the 1640-Å wavelength region. The specifications of the scintillator show a flat response below 3500 Å. Figure 3 shows the response of the IDARSS detector using a tungsten lamp source. The observed spiky, sawtoothlike features are due to detector imperfections. Smooth line profiles, especially for the 4686-Å line, were obtained once the calibrations were applied. But for the 1640-Å line the profile was noisier since the intensity calibration was not as effective. This was primarily because of the low light levels being measured.

III. MEASUREMENTS

The electron temperature was obtained from the ratio of intensities of the He II 4686-Å line to the He I 4713-Å line. At temperatures around 4 eV the 4686-Å line is much stronger in intensity compared with the 4713-Å line. However, both lines were observed simultaneously using the OMA detector by placing a neutral-density filter over one-half of the front end of the detector. A collisional-radiative model formulated by Mewe[10] was applied to our plasma. The measured temperatures ranged from 3.8 to 4.5 eV for the various firing conditions. The electron density was measured using a He-Ne laser interferometer. The interferometer is very similar to that described by Jacobson and Call.[11]

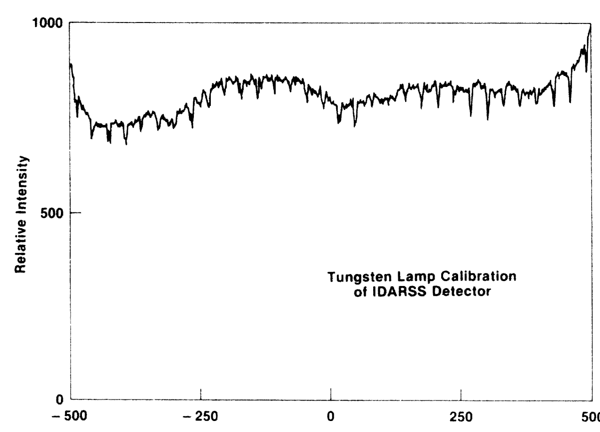

FIG. 3. Intensity response of the IDARSS detector using a tungsten strip lamp. Spiky features seen in the signal are apparently due to the fiber-optic coupling in the front end of the detector.

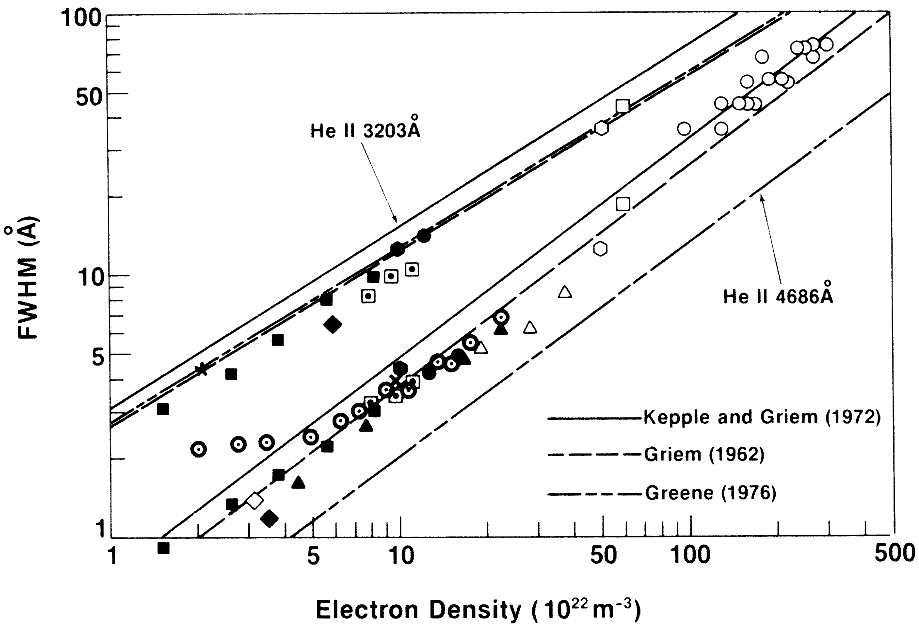

FIG. 4. Comparison of measurements of the full width of the He II 4686- and 3203-Å lines with theory as a function of electron density. Theoretical calculations are from Kepple and Griem (Ref. 14), Griem and Shen (Ref. 13), and Greene (Ref. 23). The experimental data are as follows: ○, Ref. 24; □, Ref. 12; O, Ref. 25; △, Ref. 26; ▲, Ref. 27; ●, Ref. 28; ●, Ref. 29; ⊡, Ref. 30; ×, Ref. 31; ♦, Ref. 32; ◇, Ref. 33; *, Ref. 34; ■, Ref. 2; ⊙, this experiment. This graphic is an extension of that presented in Ref. 12.

The results of our half-width measurements and comparisons with other experiments and theory are shown in Fig. 4. This figure is an extension of a figure given in Bernard *et al.*[12] It shows the various theoretical calculations for both the 3202-Å ($n=5 \rightarrow n=3$) and 4686-Å ($n=4 \rightarrow n=3$) He II ion lines. Also illustrated are experimental results that were obtained during the past two decades by various authors. Our measurements agree well with some other data at high electron densities but deviate at densities below 5×10^{22} m^{-3}. This is probably due to plasma inhomogeneities in the source at low filling pressures. Calculations have shown that fine-structure effects and Doppler broadening are not important at these densities and therefore they are not included.

The line shifts for both lines were measured as a function of the electron density. We also used the 4686-Å line full width as a secondary density diagnostic. The 4686-Å full width was related to the electron density using the following relationship:

$$N_e = 2.04\times10^{22}(\Delta\lambda_{\mathrm{FWHM}})^{1.21}\ \mathrm{m}^{-3}\ . \qquad (1)$$

This equation was based on a fitting of the experimental data given in Fig 4 and in fact, closely agrees with the calculations by Griem and Shen.[13]

For the 4686-Å line (see Fig. 5), the high quality of the IDARSS data allowed us to measure its profile on a single-shot basis. The profiles obtained were extremely smooth with well-defined wings. The two impurity lines seen in the line wings were determined to be Si III and O II lines. The impurities become stronger very late in the discharge (after 60 to 80 μsec following discharge ignition). The line profiles were generally measured at times earlier than this.

Figure 6 shows the 1640-Å line profiles taken for various firing conditions. The detected light levels were much less than for the 4686-Å line. This is primarily due to the low quantum efficiency of the scintillator and the low light throughput of the LiF window. The profiles shown are accumulations of three to five shots. The line also turned out to be somewhat self-absorbed. This is shown in Fig. 6 where the profiles are seen to be flat topped. For a given density the measured full width of the line was approximately a factor of 5 larger than those determined from calculations be Kepple and Griem.[14] An attempt to reduce the self-absorption by firing with different gas

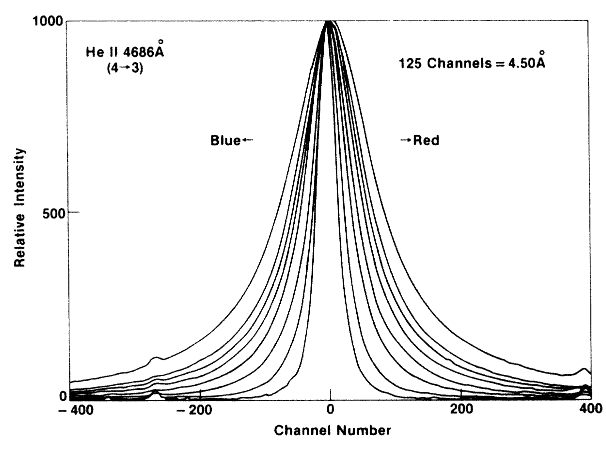

FIG. 5. Superimposed line profiles of He II P_α at various firing conditions. Electron density range is 2×10^{22} to 2×10^{23} m^{-3}. A small shift towards longer wavelengths (positive channel number) with increasing FWHM can be seen in the data.

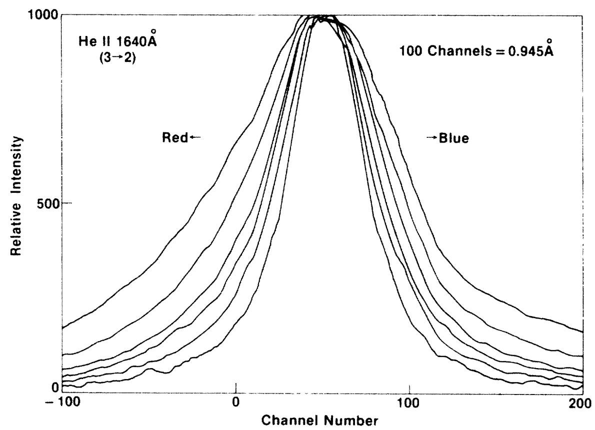

FIG. 6. Superimposed profiles of He II H_α at different firing conditions. Red shifts are seen to negative channel numbers since the detector was inverted as opposed to Fig. 5.

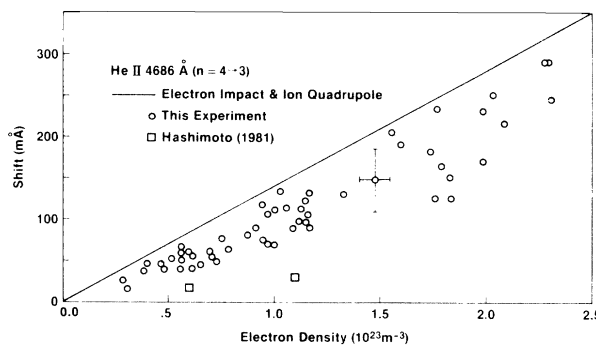

FIG. 7. Experimental red shift of the He II P_α line vs electron density. Computed shifts include electron-impact shifts estimated by Griem (Ref. 15) and ion quadrupole shift. Smaller red shifts were measured by Hashimoto (Ref. 9).

mixtures of helium and neon was only partially successful. The line profiles were observed to become narrower but strong continuum background precluded a good line-shift measurement. It is believed, however, that the self-absorption did not significantly alter the observed line shifts, as is discussed in Sec. IV.

Previously, for our measured shifts, we took the bisector of the profile at the half-width as the line center, i.e.,

$$\Delta\lambda^s = \frac{(\lambda_r - \lambda_0) - (\lambda_b - \lambda_0)}{2}, \tag{2}$$

where λ_r and λ_b are the measured wavelengths at the half-width at half maximum (HWHM) on the red and blue side of the line, respectively. The unperturbed line center λ_0 was computed as the center of gravity of the fine-structure components. In this experiment, with the aid of the LSI-11 computer, we were able to compute the shift at many points over the profile as well as at the HWHM of the line. We determined the shift using Eq. (2) for 1000 points between the $\frac{3}{4}$ and $\frac{1}{4}$ intensity points of the profile and used the average as the line shift.

IV. RESULTS

The profiles of the He II P_α line shown in Fig. 5 were obtained over a density range from 2×10^{22} to 2×10^{23} m^{-3}. The red shift of the line is clearly seen in this figure. Figure 7 shows various experimental points which are compared with theoretical estimates[15] (see discussion in the next section). The experimental error is approximately ±2 detector channels (±40 mÅ) for the shift observations and ±0.2 Å for the line full width. Some of the scattering of the experimental points may have been due to saturation of the IDARSS detector by large light levels. The agreement between experiment and theory is only reasonably good. Discussion of theoretical estimates is given below. The experimental results of Hashimoto[9] are also presented in this figure and very little agreement is seen. This disagreement may be due to differences in the two sources and the method of measuring the line profiles. Hashimoto used a high-density capillary discharge viewed side on, indicating that she was looking through density inhomogenities. She also measured the line profile photographically, integrating over the time history of the density variations. Both of these effects would lead to smaller shifts. However, because of our fast-framing camera measurements we know we have a homogeneous plasma in our pulsed arc at the time of interest. We also used a gated detector which was gated at a time when the density was not changing.

For the 1640-Å line, a slight red shift can be seen in Fig. 6. One cannot assert with certainty that the self-absorption did not somewhat influence the line shift. In a homogeneous plasma, the important factor is the amount of ionquadrupole shift that would be expected for a self-absorbed profile. In Fig. 8, we show the quadrupole shift

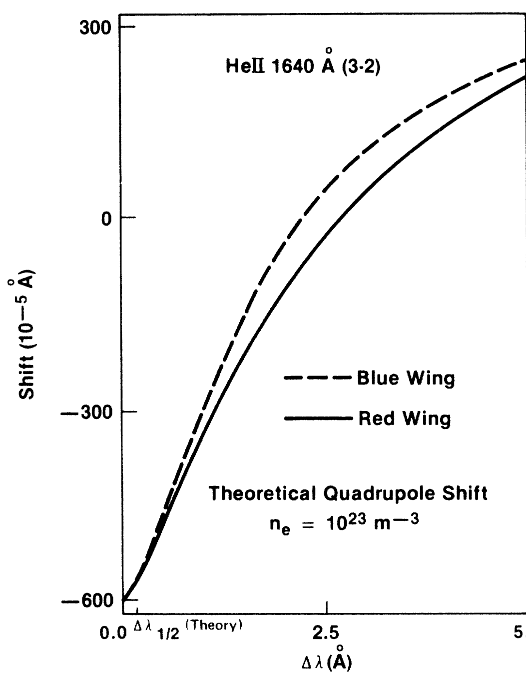

FIG. 8. Calculated ion quadrupole shift of the He II P_α line vs $\Delta\lambda$. Shift is towards blue wavelengths in the line core and becomes red only in the distant line wings. Theoretical half half-width, $\Delta\lambda_{1/2}$, indicated on the abscissa is calculated by Griem (Ref. 35).

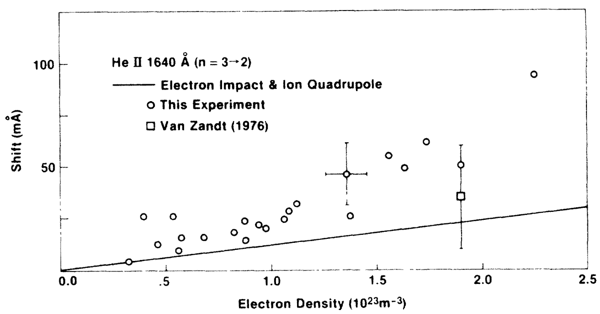

FIG. 9. Experimental red shifts of the He II H_α line vs electron density. Computed shifts (solid line) included are from Griem (Ref. 15) and include his estimate for the ion quadrupole shift. The measurement by Van Zandt *et al.* (Ref. 6) is also included.

at a density of 10^{23} m^{-3} as a function of distance from the line center calculated using Ref. 16. It is seen that in the line core the calculated ion quadrupole shift is to blue wavelengths and that it does not change rapidly with wavelength. Typically, our measured FWHM for this line was >1 Å. At these distances from line center the ion quadrupole shift changes by about 20% compared with that at the line peak. Therefore, the total shift of the line should not be strongly influenced by self-absorption, as long as the absorption is not too strong and as long as the shift is obtained from measurements between the $\frac{3}{4}$ and $\frac{1}{2}$ intensity points and not at the peak. We empirically estimate the absorption coefficient k to be $kl<1$, where l is the plasma length ($\sim$13 cm). Using a fast ($\sim$10 sec) framing camera we were able to observe the plasma as reasonably homogeneous between the viewing windows with small boundary layers (several mm) near the windows. If inhomogeneities did occur, they would tend to reduce the line shift. Figure 9 shows the experimental points together with the experimental results by Van Zandt *et al.*[6] Since we did not have an absolute wavelength calibration for these data, the uncertainty in the line-center position was approximately ± 10 mÅ.

V. THEORETICAL CONSIDERATIONS

In two previous papers,[2,3] we compared our measured shifts of He II Paschen lines with the Debye model for plasma polarization. Use of the model represents a lowest-order estimate of the effect of the mean quasistatic correlations between the charged radiator and perturbers; the charge of the ionic radiator polarizes the surrounding plasma and thereby induces an excess of negative charge in the vicinity of the radiator. Other more elaborate estimates have been performed using numerical self-consistent solutions of the Schrödinger equation.[17,18] These calculations have generally yielded shifts that are about a factor of 3 smaller than the Debye model. The self-consistent-field calculations of Davis and Blaha[18] predict red shifts for neutral hydrogen in addition to hydrogenic ions.

We note, however, that in Refs. 19 and 20 it has recently been shown that in general the observed spectral line shift is not given by the mean value of the radiator-perturber interaction such as that calculated in the Debye model or other static models. In fact, dynamical contributions or "fluctuations" are extremely important in the core of the line. For example, the electron-perturber contribution to the width is entirely dynamic. The problem is not so intractable as it may seem, however, According to the analysis of Refs. 19 and 20, a properly performed scattering calculation, with suitable shielding of the long-range part of the interaction potential, includes all the correlations required for computing the line shape and shift. No additional "plasma-polarization" terms are warranted. The only essential approximations required to make calculations from the general theory feasible are the separation of the effects of electrons and ions, and the binary approximation that strong electron collisions do not overlap in time. Emitter-perturber correlations are included via, e.g., Coulomb waves in a fully quantum-mechanical calculation, or via hyperbolic orbitals in a semiclassical calculation. The impact approximation for electrons is generally valid in the core of the broadened profiles.

Extensive semiclassical calculations as mentioned in the above paragraph have been performed by Griem; for example, he has tabulated widths and shifts of many isolated (non-l-degenerate) lines of neutral and singly ionized species.[21] Similarly computed semiclassical calculations for electron-produced shifts of hydrogenic neutral and singly ionized species have been reported by Griem,[15] together with estimates of ion quadrupole contributions based on the work of Demura and Sholin.[16] Probably the greatest uncertainty in these calculations results from the approximate treatment of the strong electron collisions. Such uncertainties are inherent to any semiclassical calculation, and are particularly likely to be significant for hydrogenic species and at low temperatures. The scattering calculations of Yamamoto and Narumi[22] appear to require an expanded basis set for target states, to include at least the $n+1$ states, where n is the principal quantum number of the upper state (see the discussion by Griem[15]). Currently, the only "dynamical" calculations of the shifts of He II lines are the semiclassical calculations of Griem.[15] Hence, we have used these calculations for comparison with our experimental results in Figs. 7 and 9.

VI. CONCLUSIONS

We have measured the shifts of the He II H_α and P_α ion lines using a new Z-discharge pulsed-arc plasma source and a new optical multichannel detector system. We found red shifts that are small compared with the linewidth. The new P_α results are in agreement with our earlier measurements.[2,3] We compare our results with the calculations by Griem[15] of shifts from electron collisions, plus estimates of ion quadrupole contributions. The results for the Paschen-α line agree to within 25%, but the calculated shifts for the Balmer-α line are a factor of 2–3 smaller than measured. We estimate the experimental uncertainty, due principally to the optical thickness of the Balmer-α line, to be significantly smaller than this discrepancy.

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