Shift and width measurements of the Stark-broadened ionized helium line at 1215 Å†

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Time-resolved measurements were made of the shifts of the ionized helium lines at 1640 Å ($n = 3 \rightarrow 2$) and 1215 Å ($n = 4 \rightarrow 2$), and of the Stark profile of the λ1215-Å line. An electromagnetic shock tube was used as a light source. The plasma conditions **corresponded** to electron temperatures of ~ 3 eV and electron densities of $\sim 2 \times 10^{17}$ cm^{-3}. No significant shifts were found for the λ1640-Å line. The λ1215-Å **line underwent a red shift of** $\lesssim 0.5$ Å, consistent with semiclassical estimates of plasma polarization shifts. The measured Stark width of the λ1215-Å line was 10–45% greater than the calculated width based on the measured width of the λ4686-Å line.

I. INTRODUCTION

The considerable theoretical and experimental efforts in plasma spectroscopy have resulted in good understanding of the pressure broadening and shifts of spectral lines due to the Stark effect of nearby charged perturbers. Particular attention has been paid to the lines of hydrogen and the hydrogenic ions, for which most quasistatic and impact theories predict considerable broadening but no shifts. However, in 1962, Berg *et al.* suggested that the reduction of the Coulomb potential of the nucleus by the polarization of the plasma near a radiating ion might cause a line shift.[1] In 1970, Greig *et al.* reported a blue shift of the He II 304-Å line.[2] Subsequent photographic measurements did not verify the shift of the 304-Å line, but higher series members (256 Å, 243 Å, etc.) exhibited shifts which could have been due to plasma polarization.[3,4] The most recent measurement[5] showed blue shifts for the 256- and 243-Å line, with a greater shift for the 304-Å line, in agreement with the result of Ref. 2.

The polarization shift is expected to be important for high-Z ion lines and may limit wavelength accuracies in, for example, laser-produced plasmas. The theoretical treatments of this effect have been unsatisfactory,[1,2,6-8] and no attempts have been reported to measure shifts of the "Balmer" (or "second-Lyman") series lines of ionized helium, at 1640, 1215, 1084, ... Å. The primary aim of this experiment was to search for such shifts, and investigate their possible dependence on plasma conditions. A secondary purpose was to measure the Stark broadening of the higher series members, to check the theoretical calculations.[8,9]

A T tube was chosen as a source because it produces a fairly homogeneous plasma[5] near local thermal equilibrium (LTE),[10,11] at a density and temperature suitable for the emission of ionized helium lines. The line positions were measured relative to nearby impurity lines. Plasma conditions were determined from photoelectric measurements of the He II 4686-Å line, and plasma reproducibility was checked by monitoring the total intensities of the 4686-Å line and the continuum near 4976 Å.

II. APPARATUS AND EXPERIMENTAL METHODS

The plasma studied in this work was produced in a T tube similar to those developed by Kolb[12,13] and used in several previous experiments at the University of Maryland.[1,2,5,10,14-18] In the present device[14] an aluminum electrode is sealed into either end of the top of a T-shaped tube of high-temperature glass with inside diameter of 16 mm. This tube is filled with the helium test gas at a pressure near 0.5 Torr (70 Pascals). A discharge across the 10-mm gap between the electrodes ionizes the gas and ohmically heats it. The current in the backstrap creates a transverse magnetic field near the current-carrying plasma, which is accelerated down the leg of the tube by its internal pressure and the Lorentz force. A luminous front travels 12 cm down the expansion tube at several cm/μsec and strikes an adjustable reflecting plate, where some of its directed energy is converted to random thermal energy. Longer expansion tubes and higher fill pressures are required for the formation of a separated shock,[19] but our device produces the high temperatures (3–4 eV) and electron densities (2×10^{17} cm^{-3}) needed to excite Stark-broadened ionized helium lines. The decaying plasma lasts approximately 1 μsec.

The electrical circuit consists of a 0.5 μF capacitor with a pressure switch mounted directly on it, a coaxial high-voltage transmission line, and the T tube. The discharge is initiated by releasing the nitrogen from the pressure switch, originally at 30 lb/cm² above atmospheric. The quarter-cycle time is 0.675 μsec, indicating a total circuit inductance of 370 nH. A carbon resistor, which forms part of the transmission line, damps out the oscillations after two cycles.

During the experiment, gas was leaked into the T tube through a liquid-nitrogen cold trap and pumped away through the entrance slit of the vacuum monochromator, thus maintaining a constant pressure within the T tube. Between experimental runs, the tube was kept clean by a separate diffusion pump which could run continuously.

Vacuum-ultraviolet spectroscopy was done with a McPherson 225 1-m monochromator, with a 1200-lines/mm concave grating. Its 50-μm entrance slit is flush with the wall of the T tube, about 0.5 mm from the reflector. Since the plasma conditions change sharply as the reflector is moved, the position was chosen which gave the most reproducible plasma. For photographic work, Kodak SWR film was used. The reciprocal dispersion was measured to be 8.5 Å/mm. For photoelectric measurements, a p-terphenyl coated scintillator disk with an EMI 6522 photomultiplier tube detected the light signals, and the ultraviolet lines were scanned shot to shot. The instrument response function is approximately Gaussian with width 0.41 Å. The instrument function and wavelength calibration were checked using a low-pressure capillary discharge tube.[20] For some work, a 2-mm thick MgF_2 filter was used to remove light from second order, since it transmits 40% of the light at 1215 Å but essentially none below 1100 Å.

For diagnosis of the plasma conditions, three Jarrell-Ash visible-light monochromators were used. One $\frac{1}{2}$-m monochromator, with instrument width 0.4 Å, scanned the He II 4686-Å line shot to shot to determine the electron density (from line width[8]) and temperature (from line:continuum ratio[21]). The reproducibility of the plasma was monitored on each shot by two $\frac{1}{4}$-m instruments, one for the continuum at 4976 Å (sensitive to electron density) and one for the He II 4686-Å line (sensitive to temperature, and used for later data processing).

Photomultiplier (PM) tube response was checked using neutral density filters and pulses from a light emitting diode, and was found linear for signals up to 0.2 V (1.1 mA) with a PM supply voltage of 900 V.

Each PM tube housing was insulated from its monochromator, and signals were taken from both the anode (negative pulse) and last dynode (positive pulse), carried by shielded coaxial cables terminated by 90-Ω resistors, subtracted to suppress noise, amplified, and stored by a waveform recorder.

The waveform recorder was designed and built for this experiment to reduce the error and delay of manual data taking (with the usual Polaroid oscillographs). It consists of five analog-to-digital converters, two digital-to-analog converters, solid-state memory, and control circuitry. In each analog-to-digital converter, the signal is amplified and applied simultaneously to 31 comparators. A voltage divider provides reference voltages for the comparators, so for a given signal some of the comparators will be "on" and the rest "off." Integrated circuits accept the output of all the comparators, count the number "on," and store the corresponding five-bit binary number in a five bit by 64-word random-access memory. When triggered, control circuits advance the memory address counter and give write commands once every 100 nsec (or at selectable, slower rates) for a total of 64 cycles. The device then switches to "playback" mode, supplying the stored numbers for two of the five channels to a digital-to-analog converter. These analog signals are reconstructed versions of original signals, and can be displayed on an oscilloscope. If the waveforms were acceptable, twelve "fixed data" thumbwheel switches were set, and all stored information, the shot number and the thumbwheel settings, were transferred to nine-track digital tape. If the shot was unacceptable (due to switch misfire or abnormal time history of a monitor signal, for example), recording was bypassed.

The tape generated by the waveform recorder was read by a computer and the best-fit values of four parameters (total line intensity I, line position λ_0, background B, and electron density N_e) were found using the following procedure. Assume we have the n measured intensities $y_i(\lambda_i)$ and the corresponding calculated values $T_i = F_0^{-1} T(|\lambda_i - \lambda_0|/F_0)$, where $T(\alpha)$ is the theoretical profile after convolution with the instrument profile $G(\alpha)$:

$$T(\alpha) = \int_{-\infty}^{\infty} S(\alpha - \alpha') G(\alpha')\, d\alpha' , \qquad (1)$$

and the instrument function has been transformed into α-space. ($F_0 = 2.6\, eN_e^{2/3}$ is the Holtsmark field strength and α the usual reduced wavelength difference from line center, $\Delta\lambda/F_0$.[8]) The best-fit values minimize the sum

$$\sigma^2 = \frac{1}{n-4} \sum_{i=1}^{n} [y_i - (IT_i + B)]^2 \qquad (2)$$

(for four fitted parameters), giving the conditions

$$(\partial/\partial I)\sigma^2 = (\partial/\partial B)\sigma^2 = 0 \ . \qquad (3)$$

Therefore, I and B were found by solving the linear system

$$\begin{pmatrix} \sum T_i^2 & \sum T_i \\ \sum T_i & n \end{pmatrix} \begin{pmatrix} I \\ B \end{pmatrix} = \begin{pmatrix} \sum y_i T_i \\ \sum y_i \end{pmatrix}. \quad (4)$$

The computer "guessed" an electron density (or F_0) for the transformation of the instrument function and convolved the theoretical and instrument profiles to give an approximate $T(\alpha)$. Using this $T(\alpha)$, the computer then found σ^2 from (2), subject to (3), for many values of N_e and λ_0. When the best values were found, the new N_e was used to again transform the instrument function. The entire convolution and fit were repeated until successive values of N_e were sufficiently close, e.g., within 2% of each other. An estimate of the variance-covariance matrix of the four parameters was also calculated.[22] (For the runs discussed in this paper, we had $n \approx 100$.)

III. RESULTS AND DISCUSSION

A. Results

Examples of photoelectric measurements of the emission profiles of the ionized helium lines at 4686 and 1215 Å are shown in Figs. 1 and 2. The solid lines are the best-fit (mostly with respect to N_e) theoretical curves of Kepple,[8,9] convolved with the instrument profile (taken to be Gaussian). Dashed lines are the best-fit continuum levels, determined primarily by points far from line center, which are not shown for the uv line. Crosses represent points not used in the best-fit procedure.

The 4686-Å line was found to be unshifted, as in a previous experiment.[23] Its profile was in good agreement with theory, and the plasma electron density and temperature were deduced from its width and line:continuum ratio, respectively.

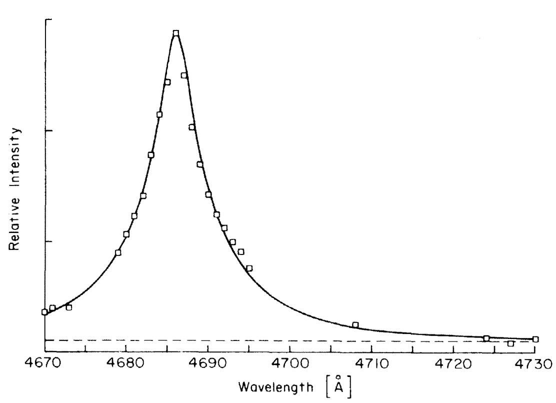

FIG. 1. Measured (signal averages) and best-fit theoretical profiles of He II λ4686-Å line. Dashed line is best-fit value for continuum.

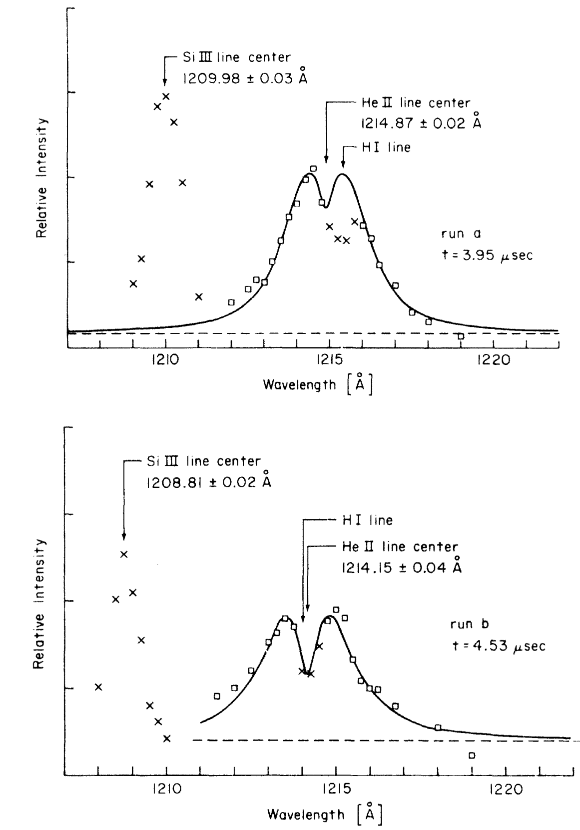

FIG. 2. Measured and best-fit theoretical profiles of He II λ1215-Å line for runs *a* and *b*. Crosses are experimental points excluded from fitting procedure (see text), and the wavelengths are relative. In (b), intensities for λ > 1211 Å were multiplied by a factor ~3.

The position of the He II 1640-Å line was measured relative to the Al II 1670-Å line, and red shifts between 0.01 and 0.06 Å were obtained. Photographic (time-integrated) measurements gave shifts ≲ 0.05 Å, using a number of reference lines. No conclusions could be drawn about the Stark width of this helium line, because the observed profile was dominated by instrument broadening.

The relative positions of the He II 1215-Å and Si III 1210-Å lines were measured photoelectrically. The helium line was found to have relative red shifts Δλ ranging from 0.2 to 0.7 Å, depending on density and temperature histories during the discharges. The electron density N_e corresponding to the 1215-Å line was also determined as part of the best-fit procedure. These data are shown in Fig. 2 and Table I. The shift data were essentially confirmed by photographic measurements which gave a red shift of ~0.25 Å, using the same reference line, or 0.10 ± 0.04 Å using a set of eleven

TABLE I. Plasma conditions and wavelength shifts for the He II λ1215-Å line[a].

t (μsec)		κT (eV)	N_e (10^{17} cm^{-3}) λ4686 Å	λ1215 Å	$\Delta\lambda$ (Å)
run *a*	3.86	3.85 ± 0.35	2.23 ± 0.07	2.91 ± 0.19	0.04 ± 0.09
	3.95	3.55 ± 0.10	1.93 ± 0.05	2.71 ± 0.12	0.11 ± 0.04
	4.04	3.50 ± 0.10	1.78 ± 0.05	2.68 ± 0.11	0.09 ± 0.04
	4.12	3.50 ± 0.10	1.66 ± 0.05	2.55 ± 0.12	0.08 ± 0.04
	4.19	3.50 ± 0.10	1.62 ± 0.06	2.55 ± 0.12	0.09 ± 0.04
	4.25	3.40 ± 0.10	1.46 ± 0.07	2.40 ± 0.11	0.17 ± 0.04
run *b*	4.38	3.00 ± 0.05	2.50 ± 0.32	4.38 ± 0.49	0.49 ± 0.10
	4.46	3.00 ± 0.10	2.90 ± 0.51	3.70 ± 0.23	0.52 ± 0.05
	4.53	3.00 ± 0.05	3.07 ± 0.50	3.52 ± 0.22	0.51 ± 0.04
	4.59	2.90 ± 0.05	2.61 ± 0.39	3.44 ± 0.25	0.49 ± 0.04
	4.65	2.80 ± 0.10	2.20 ± 0.35	3.61 ± 0.23	0.49 ± 0.05

[a] The indicated errors are calculated from the variance-covariance matrix for the best-fit parameters.

Si II and III reference lines in the range 1190–1250 Å. (See Sec. III B 5 for a wavelength correction which is included in Fig. 3 and Table I, and note that large photoelectrically determined shifts correspond to small intensities.)

B. Discussion of possible systematic errors

1. Impurity lines

Photographs of spectra[24] near each of the helium lines showed many Si, O, and Al lines. The Jarrell-Ash ½-m monochromator could easily resolve the Si III and O II lines near He II 4686 Å, and photoelectric scans were made using points between these impurity lines.

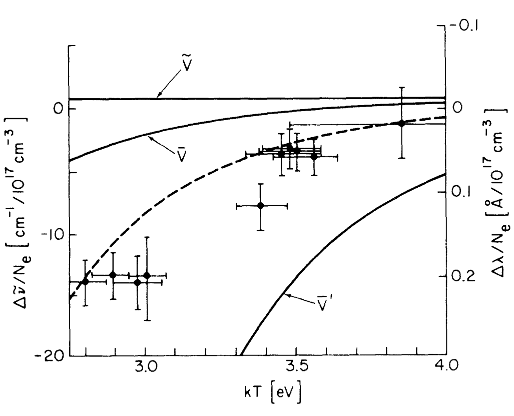

FIG. 3. Estimated and measured shifts of He II λ1215-Å line. The estimates are calculated according to Eq. (6), with interaction energies V_n as discussed in the text. The dashed curve corresponds to $V_n = \bar{V}_n$, with the measured temperature reduced by 20% to account for relaxation effects. Error flags correspond to statistical errors only, and electron densities from the λ4686-Å line profile are used to normalize the shifts to an electron density $N_e = 10^{17}$ cm^{-3}.

Many Si, O, and Al lines were identified near the 1640-Å line in both first and second orders, none of them obscuring the helium line. The nearby Al II 1670-Å line, chosen as the wavelength reference for position measurements of the 1640-Å line, was partially obscured by second-order lines of O II and O III. To eliminate second-order lines during photoelectric scans, a MgF_2 filter was therefore placed between the exit slit and the scintillator.

Photographic spectra near 1215 Å showed many O II, O III, O IV, Si II, and Si III lines, including the second-order O IV 608-Å line on the red wing of the helium line. To eliminate these, the MgF_2 filter was again used for both photographic and photoelectric runs.

The resonance lines of N II at 1084 Å prevented any observation of the next member of the He II series, while the He II 1025-Å line proved too weak for reliable observation.

2. Wavelength standards

All line position measurements were made relative to nearby impurity lines, and the accuracy of the procedure had to be verified. The Stark shifts of these ion lines are expected to be small[8] (just as their widths are small), but a plasma polarization shift certainly cannot be ruled out *a priori*. To check for such shifts, several photographic measurements were made using a Grant comparator microphotometer. Except for the Si III 1210-Å line, all shifts were less than the measurement accuracy of ~0.05 Å. This is consistent with previous measurements,[2] in which no shifts were found for the O III and N III lines near 300 Å. However, with respect to the other ten reference lines near 1215 Å, the Si III 1210-Å line was blue shifted by 0.15 Å, although its position did not change as the plasma cooled. Only the statistical errors in the measured shifts are indicated in Table I and Fig. 3.

The monochromator wavelength scale was checked by measuring photographically the wavelength displacement between settings corresponding to the centers of the helium and reference lines. The errors in both cases were less than the setting error: ±0.02 Å.

3. *Helium-line asymmetry*

The He II 1215-Å line was expected to have a symmetric double-peaked Stark profile (like that of H_β), but photoelectric scans first showed only the peak on the blue side. This was interpreted as due to reabsorption by hydrogen in a cooler boundary layer, since the hydrogen Lyman-α line lies 0.53 Å to the red of the (unshifted) helium line center. To check this explanation, two special scans were made, using mixtures of helium plus 0.5% hydrogen, and helium plus 1.0% deuterium, respectively. The amount of absorption increased with the increasing admixture of hydrogen, and, in the case of the deuterium mixture, the dip shifted to the blue, as expected. The residual concentration of hydrogen was estimated from these runs to be approximately 0.2%. Since natural, Doppler, and Stark broadening[6,8] are all very small for the hydrogen line (<0.1 Å), wavelength points near the dip were excluded from the fitting procedure [see Fig. 2(a)]. (Excluding 2–10 additional points increases the red shift by 0.02–0.08 Å.) Figure 2(b) shows a profile scanned at higher density and lower temperature which is symmetric (double peaked), probably because the shifted helium line center now almost coincides with the Lyman-α line.

4. *Departure from LTE*

Temperature determination from a helium-ion line:continuum ratio requires that local thermal equilibrium (LTE) holds also for the ion ground-state populations, so that the line intensity (proportional to the population in the excited state) and the continuum intensity (due mainly to recombination radiation) both have their equilibrium values. The equilibration time for excited states can be estimated[6] to be only a few nanoseconds, for both neutral and ionized helium. On the other hand, the recombination times[25] (into the ground states) are several μsec for formation of both singly ionized helium and neutral helium. The degrees of both single and double ionization are, therefore, expected to be higher than in LTE, simulating a temperature higher than the true electron temperature during the decay of the plasma.

Since the actual electron density is about an order of magnitude lower than that required[6] for complete LTE, and the continuum intensity is proportional to the product of ion and electron densities while the line intensity depends explicitly only upon ion density, we estimate that the line : continuum ratio may be too high by an order of magnitude compared to the LTE value at our electron temperature. Thus, the ratio indicates a temperature (e.g., 3.5 eV) that is too high by about 0.5 eV. Similarly, if the neutral excited state population density were too low by an order of magnitude, the intensity ratio of an ionized and a neutral line would overestimate the temperature by about 0.5 eV. A measurement of the intensity ratio of the He II 4686-Å and the He I 3889-Å lines was performed, yielding a temperature near 4.1 eV. Since the two effects (excess ionization due to recombination relaxation during the rapid cooling, and overpopulation of excited states of He II due to low collision rates) are additive, the true electron temperature is again estimated to be near or slightly below 3.0 eV.

5. *Summary of errors*

Errors in the determination of electron density from the 4686-Å line were ≲15% due to statistical fluctuations and (10–15)% due to theoretical uncertainties.[8] Errors in temperature measurements were estimated to be 0.1-eV statistical and 0.2-eV theoretical[21] (after applying a −20% correction). These possible diagnostic errors were not judged to endanger the principal conclusions of the work. The tables and figures indicate only statistical errors, except for the dashed curve in Fig. 3.

Errors in the measurements of the shifts were about 0.05 Å due to statistical fluctuations. Systematic errors due to shifts of the reference lines could not be ruled out, but should be allowed for by subtracting ~0.15 Å from the wavelengths measured relative to the Si III 1210-Å line. To account for residual effects from Lyman-α, ~0.05 Å should be added to these wavelengths (run *a* only). After such total wavelength corrections, systematic errors are expected to be negligible. This expection is supported by the observed time dependence of the shift, and the fact that this time dependence is insensitive to the number of excluded points.

C. Discussion of results

Previous shift measurements of ionized helium lines have concentrated on the Lyman-series lines ($n_{\rm lower}=1$). In principle, these measurements can be used to calculate the energy level perturbations, and the shifts of the "Balmer"-series lines can be found in turn. Since the agreement between the various measurements is so poor,[5] little was learned in this way.

The polarization shift is difficult to treat theoratically, and only estimates have been made so far. Conceptually, the radiating ion is expected to attract plasma electrons, which partially screen the nuclear charge seen by the optical electron. A simple classical argument[2] leads to wavelength (or wave-number) shifts of the Lyman-series lines with upper quantum number n of

$$\frac{\Delta\lambda}{\lambda_0} \approx -\frac{\Delta\tilde{\nu}}{\tilde{\nu}} \approx -\frac{8}{3}\pi\frac{N_e a_0^3 n^2(n^2+1)}{z^4}\exp\left(\frac{V}{kT}\right), \qquad (5)$$

where a_0 is the Bohr radius, and V is the interaction energy between the perturbing plasma electron and the radiating ion (nuclear charge ze). Since the wave packet of the perturbing electron will be comparable in size to the ion, one might use the averaged interaction $\overline{V}=(z-1)e^2/\overline{r}$, where $\overline{r}$ is the characteristic distance between the nucleus and the optical electron: $\overline{r}=n^2a_0/z$. Neiger and Griem propose[5] the modified formula $\overline{V}'=(3/2)\overline{V}$, which is the electrostatic energy of a uniform sphere of charge e and radius $\overline{r}$ in the field of an equal but opposite charge at its center. Burgess and Peacock argue[26] that the density of electrons near an ion is low enough that their velocities are not in equilibrium with the surrounding plasma, being directly related to their electrostatic energies. They suggest using the interaction energy at the average perturber-perturber distance, $\tilde{V}=(z-1)\times e^2N_e^{1/3}$. (Note that all these estimates predict blue shifts for all Lyman-series lines approximately proportional to N_e, but decreasing with temperature, and give only negligible shifts for the ground state.)

Denoting by V_n the chosen interaction energy when the optical electron has principal quantum number n, and expressing the unperturbed energy levels in terms of the Rydberg constant R, we find, for the wave-number shifts of the "Balmer"-series lines,

$$\Delta\tilde{\nu} \approx \tfrac{8}{3}\pi(N_e a_0^3/z^2)R\left[(n^4-1)\exp(V_n/kT) - (2^4-1)\exp(V_2/kT)\right]. \qquad (6)$$

[In other words, we multiply Eq. (5) by $\tilde{\nu}$ and subtract $\Delta\tilde{\nu}$ for $n=2$, which actually dominates except when $\tilde{V}$ is used.] This can be converted to a wavelength shift by multiplying with λ_0^2, or an energy shift by multiplying by hc. Shifts predicted by the three choices for V ($\overline{V}=2e^2/n^2a_0$, $\overline{V}'=3e^2/n^2a_0$, and $\tilde{V}=e^2N_e^{1/3}$) are plotted in Fig. 3 for $n=4$. For all lines, Burgess and Peacock's proposal[26] results in very small (blue) shifts, nearly independent of temperature. Using $\overline{V}$ gives somewhat larger (red) shifts, while the stronger interaction $\overline{V}'$ proposed in Ref. 5 gives large red shifts with strong temperature dependence. Using the measured values of the temperature, the data are consistent with an interaction energy between $\overline{V}$ and $\overline{V}'$, while $\tilde{V}$ appears to be ruled out by the data. To illustrate the effect of the systematic error discussed above in the temperature measurement, the shift corresponding to $\overline{V}$ was recalculated using a 20% lower temperature, the results being shown by the dashed curve in Fig. 3. After this correction, the $\overline{V}$ interaction energy gives the best fit to the data. Corresponding shifts calculated for $n=3$ are $\lesssim 0.05$ Å, i.e., consistent with the λ1640 Å line measurements, before the temperature correction, and $\lesssim 0.15$ Å after this correction. Even the latter value may not be inconsistent with the measured values $\lesssim 0.05$ Å, since combined statistical and systematic errors of ~0.1 Å (normalized to $N_e = 10^{17}$ cm^{-3}) cannot be excluded.

The halfwidth of the 1215-Å line was 10–45% greater than that calculated by Kepple.[8,9] This is to be compared to a previous measurement[27] on a theta-pinch plasma. In this case the ratio of the widths of the 4686- and 1215-Å lines agreed with the calculated value. However, the experiment was done at a substantially higher temperature, $T_e \gtrsim 10$ eV, so that the difference may not be significant.

IV. SUMMARY AND CONCLUSIONS

Shifts have been observed for the second member of the "Balmer" series of ionized helium. These red shifts are consistent with a plasma polarization shift, where the interaction energy between the radiating ion and the perturbing plasma electrons corresponds to the Coulomb interaction near the excited state Bohr radius. The experimental upper limit for the shift of the first member of this series barely reaches what would be predicted by the theoretical expression giving the best fit to the data for the second member. The theoretical estimates may therefore exaggerate the dependence of level shifts on principal quantum number. However, the $n=2$ level is clearly shifted more than the $n=4$ level, a result supporting some of the "Lyman"-series measurements.[2,5] at least qualitatively. (Quantitative agreement cannot be expected, because different portions of the line profiles are involved in the shift determinations, especially for the optically thick λ304-Å line and the optically thin λ1215-Å line, so that profile asymmetries and shifts of central peaks or intensity minima cannot be well separated.) For example, the $n=4$ level is shifted with respect to $n=2$ by about (7 ± 3) cm^{-1} at $N_e \approx 2 \times 10^{17}$ cm^{-3}, $\kappa T \approx 3.5$ eV (uncorrected). This relative level shift corresponds to an additional wavelength shift of the λ304-Å line over that of the λ243-Å line by ≲0.01 Å. The new result for the $n = 3$ level shift relative to $n = 2$, $\Delta\tilde{\nu} \lesssim 2$ cm^{-1}, restricts any additional shift of the resonance line over that of the λ256-Å line to ≲0.002 Å for these conditions. Combining all experimental evidence[2-5] with the present results, we conclude that the $n = 2, 3, \ldots, 9$ levels of ionized helium are shifted upward, relative to $n = 1$, by ~30 cm^{-1} in plasmas with parameters similar to ours.

The Stark width of the 1215-Å line of ionized helium has been measured and found to be (10–45)% greater than calculated by Kepple.[9] This excess broadening tends to increase as the temperature and density of the plasma decrease at the end of the discharge and is relative to the Stark width of the 4686-Å line. Since the calculated width of the latter line is very sensitive to the upper-lower state interference term in the broadening by electrons,[28] theoretical errors[29,30] in the evaluation of this term may well account for this difference.

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