Electron Densities from Stark Widths of the HeI 5016 Å and HeI 3889 Å Lines and Helium-Neon Laser Interferometry *

W. T. Chiang, D. P. Murphy, Y. G. Chen, and H. R. Griem

University of Maryland, College Park, Maryland 20742

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Measurements of the neutral helium line widths were made in a high pressure electric shock tube plasma of electron density $\sim 1 \times 10^{17}\,\mathrm{cm}^{-3}$ and temperature ~ 1.5 eV. The measured halfwidths are in $\sim 10\%$ agreement with the calculated widths based on GBKO theory. Electron densities were independently determined using a He-Ne laser interferometer. A factor ~ 1.7 discrepancy between measured and calculated Stark widths (or electron densities) reported by Kusch and recently by Einfeld and Sauerbrey could not be confirmed.

I. Introduction

Stark broadening of isolated neutral helium lines has been studied for many years to test the theory of Griem, Baranger, Kolb and Oertel [1] (GBKO). The GBKO theory has usually been rather successful in predicting widths and shifts of isolated neutral helium lines [2, 3]. However, Kusch [4] concluded from measurements in a wall-stabilized pulsed discharge that measured widths resulted in electron densities too high by a factor ~ 1.7 if the GBKO theory was used, and recently Einfeld and Sauerbrey [5] presented their measurement of the halfwidth of the HeI 5016 Å line from a similar discharge, confirming this discrepancy. Such a factor is surprisingly large in view of the $\sim \pm 20\%$ agreement to GBKO theory observed in several experiments [3] involving different devices.

The halfwidth measurements of the HeI 5016 Å and HeI 3889 Å lines reported here also agree with the GBKO theory. We did the measurements in two steps. First, we measured the line profiles of the HeI 5016 Å and 3889 Å lines, using the measured width of the 3889 Å line as electron density standard because it had been proved [3, 6] to be very reliable. Second, we compared line broadening results for the electron density based on multiple shot runs to results from He-Ne laser interferometer measurements averaged over the shots.

II. Apparatus and Experimental Procedure

A high pressure electromagnetically driven T-type shock tube [7–10], with 87 cm length and 2.5 cm inner diameter, was used. The T-tube was filled with a ~ 30 torr mixture of helium and $0.5-1\%$ (molecular) hydrogen. This filling gas was continuously flowing. A plasma of electron density $\sim 10^{17}\,\mathrm{cm}^{-3}$ and temperature ~ 1.5 eV was produced by discharging a capacitor bank of 108 μF charged to 9.5 kV. Observations, all side-on, were made on the partially ionized plasma produced behind the reflected shock.

The reproducibility was checked by using two quarter-meter monochromators as monitors. One was set at ~ 5270 Å to monitor the (recombination and bremsstrahlung) continuum, the other was set to observe the total intensity of the HeI 5016 Å line. Two half-meter monochromators were used to scan simultaneously, on a shot-to-shot basis, the profiles of the HeI 3889 Å and 5016 Å lines. Dividing the scanner signals by the total intensity of the HeI 5016 Å line, we obtained the line profiles. A high speed digital data acquisition system [11] recorded all data from the four monochromators and the interferometer.

To compare HeI 5016 Å line broadening results with laser interferometry, we replaced the HeI 3889 Å line monitor by a Michelson-type interferometer. This instrument includes a 3 mW He-Ne laser (λ 6328 Å) and a Si photodiode detector with a 10 Å bandwidth filter [6]. The monochromators were aligned along an optical axis passing through the same portion of the plasma but in a direction orthogonal to the laser beam, which passed through the plasma twice with the help of a corner cube reflector.

III. Experimental Results and Discussions

During each run, we recorded on magnetic tape the data from all shots having reasonably consistent monitor signals. After initial computer processing, we discarded shots at each wavelength which yielded

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Reprint requests to Prof. Dr. H. R. Griem, Department of Physics and Astronomy, University of Maryland, *College Park*, Md. 20742 USA.

signals much different ($\gtrsim 20\%$) from the average signal. Even so, only 25% of the data were discarded.

The half-intensity widths of both lines (λ 3889 Å and λ 5016 Å) were found by best fitting the experimental profiles to theoretical profiles [1-3] by graphical procedures. The lines are asymmetric due to broadening by ions (see Figure 1a). This asymmetry, especially of the λ 5016 Å line, caused some difficulty in choosing the correct line center, but did not affect the line width determination.

Although the instrumental widths and the Doppler widths were clearly small compared with the measured line widths, we made corresponding corrections in order to improve the accuracy of our measurements. The instrumental profiles were determined using an Osram helium lamp. Their shapes were found to be close to Gaussian. The Doppler widths [12] were estimated for helium at a temperature of 1.5 eV. The helium line profiles to be corrected were assumed to be Lorentzian, and we used the Voigt profiles, tabulated by Wiese[12], and Davies and Vaughan [13] to calculate the true Stark widths of the helium lines. The corrections were negligible, less than 1% at maximum.

The calculated Stark broadening of the λ 3889 Å line is very insensitive to temperature, as long as Debye shielding is negligible, which was indeed the case. Electron densities were calculated from the true halfwidth of the λ 3889 Å line using GBKO theory [3], including the contribution from ion broadening, according to the approximate formula

$$w_{\text{total}} \cong [1 + 1.75\, a (1 - 0.75\, r)]\, w\,.$$

Here w is the width due to electron impacts, w_{total} is the total width due to both ions and electrons, a is the ion broadening parameter [1, 2], and r is the ratio of the mean distance between ions and the Debye radius. Electron impact contributions to the widths were ~87% for the λ 3889 Å line and ~73% for the λ 5016 Å line.

We can compare the results from the λ 5016 Å line and the λ 3889 Å line in two ways. The first comparison is through the calculated electron densities from both lines. The second is to use the electron densities obtained from λ 3889 Å to predict the halfwidth of the λ 5016 Å line according to GBKO theory.

The first comparison is shown in Table 1. The calculated electron densities based on GBKO theory are in very good agreement, the differences being

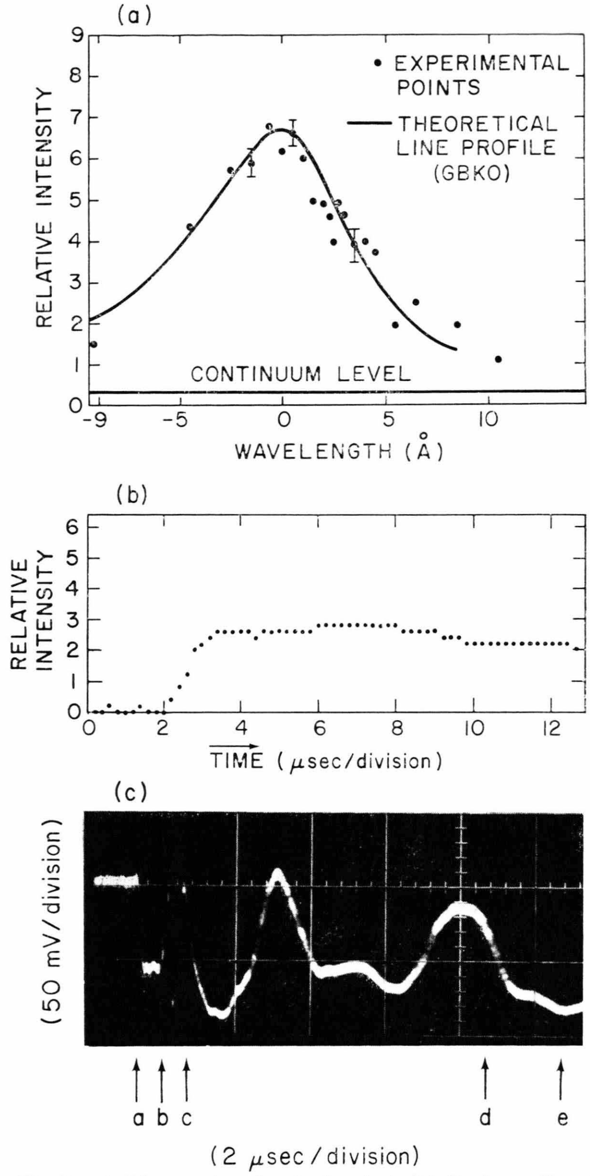

Fig. 1. a) Measured and calculated (solid line) profile of HeI λ 5016 Å line for $n_e = 1.06 \times 10^{17}\,\text{cm}^{-3}$, $T_e = 1.5$ eV. The asymmetry of the line profile is due to ion effects. b) Digitized trace of HeI λ 5016 Å line (total) intensity as function of time (2 μsec/division). c) The interferometer detector output as function of time for the same shot as in b and on the same time scale. The ratio V/V_0 was measured from the digitized form of this trace, and from this ratio the phase shift, Φ, and thus the electron density were calculated as described in the text. Point (a) corresponds to the arrival of the nonluminous shock front (see Ref. [8]), point (b) to the arrival of the luminous front (also see Ref. [8]). Point (c) indicates the arrival of the reflected shock front. Point (d) is at the time when Stark broadening measurements were taken. (The electron density and total line intensity are only slowly varying in the vicinity of this point.) Point (e) corresponds to the maximum phase shift, in this case 8.30 radians, which results in an electron density $n_e = 1.37 \times 10^{17}\,\text{cm}^{-3}$.

Table 1. Comparison between the density measurements from HeI 3889 Å and 5016 Å line widths.

RUN	n_e (λ 3889 Å)		n_e (5016 Å)		$\frac{n_e (5016)}{n_e (3889)}$	$\frac{\lvert n_e (3889) - n_e (5016) \rvert}{n_e (3889)}$
	n_e (cm^{-3})	Error	n_e (cm^{-3})	Error		
020	1.41×10^{17}	$\leqq 6\%$	1.31×10^{17}	$\leqq 5\%$	0.93	7%
021	1.08×10^{17}	$\leqq 7\%$	1.01×10^{17}	$\leqq 7\%$	0.94	7%
022	1.08×10^{17}	$\leqq 8\%$	1.05×10^{17}	$\leqq 7\%$	0.97	3%

Table 2. Comparison between measured and predicted widths of the HeI 5016 Å line by using the electron density obtained from the width of the HeI 3889 Å line.

RUN	Measured width		Predicted width w_{GBKO} (Å)	$\frac{w_{exp}}{w_{GBKO}}$	$\frac{\lvert w_{exp} - w_{GBKO} \rvert}{w_{exp}}$
	w_{exp} (Å)	Error (Å)			
020	6.0	$\leqq 0.3$	6.38	0.94	7%
021	4.6	$\leqq 0.4$	4.83	0.95	6%
022	4.8	$\leqq 0.3$	4.83	0.99	1%

less than 8%. The second comparison is given in Table 2. The ratios of the measured widths to the predicted widths of the λ 5016 Å line are 0.94 to 0.99. Both comparisons indicate very good agreement between the width measurements of the λ 3889 Å and λ 5016 Å lines and GBKO theory, although they do not rule out some common factor with respect to the actual electron density. However, such a common factor is ruled out by the following comparison of λ 5016 Å line profile results with interferometry. We have taken considerable care to allow for the neutral atom contribution to the measured phase shift, because the electron temperature in our plasmas was only ~ 1.5 eV, calculated [2, 10] from measured line-to-continuum ratios. For a thermal equilibrium plasma [2, 10], this temperature corresponds to a degree of ionization for helium of only $\sim 1.6\%$, or neutral atom densities $n_0 = (6.5 - 7) \times 10^{18}\ cm^{-3}$. Adding the contributions from free electrons and neutral atoms, we have the refractive index [2, 15]

$$n = 1 - \frac{1}{2} \frac{\omega_p^2}{\omega^2} - \frac{1}{2} \frac{4 \pi e^2}{m} \sum_i \frac{n_0 f_0}{\omega^2 - \omega_{0i}^2}$$

$$= 1 + \frac{1}{2} \frac{\omega_p^2}{\omega^2} \left(\frac{n_0}{n_e} \sum_i \frac{f_{0i}}{\omega_{0i}^2/\omega^2 - 1} - 1 \right).$$

Here, ω_p is the plasma frequency, ω is the He-Ne laser frequency, the ω_{0i} are neutral helium resonance line frequencies, and the f_{0i} are the corresponding absorption oscillator strengths. The phase shift between waves in the different arms of the interferometer, Φ, was calculated by

$$V = V_0 \sin(\omega_0 t + \Phi),$$

where $2 V_0$ is the peak-to-peak voltage of the oscillation in the detector output. Also, $\omega_0 \sim 1.6 \times 10^4$ rad/sec is the drive frequency of the external reference oscillation, chosen such that Φ varies more than $\omega_0 t$ during the experiment. The ratio of V/V_0 was taken from the digitized output to find Φ. (Figure 1 c is a typical scope trace of the detector output which was then digitized.) The quantity

$$\Phi = (2 \pi/\lambda) \int_0^L dl\, (n - 1)$$

was used to relate the phase shift with $(n-1)$, and finally the electron density n_e was obtained using the above formula.

A comparison of the electron densities from HeI 5016 Å line profiles and the interferometry is given in Table 3, while for Table 4 we used the densities measured interferometrically to predict the λ 5016 Å line widths from GBKO theory. Again, there is very good agreement.

Our experimental results therefore do not show any significant discrepancy between width measurements of the λ 5016 Å and λ 3889 Å lines and GBKO theory. Systematic errors in our present work, e. g., from inhomogeneities along the line of sight should also be small, both in view of the reasonable agreement of hydrogen Lyman-α and β measure-

RUN	Line broadening				Interferometry	
	Measured width		Electron density		Electron density (cm^{-3})	Standard deviation of the mean
	Å	Error (Å)	cm^{-3}	Error		
007	4.8	$\leqq 0.3$	1.06×10^{17}	$\leqq 6\%$	1.05×10^{17}	8%
008	5.1	$\leqq 0.4$	1.12×10^{17}	$\leqq 7\%$	1.26×10^{17}	5%

Table 3. Comparison between Stark broadening of HeI 5016 Å line and He-Ne laser interferometer measurements.

RUN	Measured width		Predicted width w_{GBKO} (Å)	$\frac{w_{exp}}{w_{GBKO}}$	$\frac{\lvert w_{exp} - w_{GBKO} \rvert}{w_{exp}}$
	w_{exp} (Å)	Error (Å)			
007	4.8	$\leqq 0.3$	4.77	1.01	1%
008	5.1	$\leqq 0.4$	5.77	0.88	13%

Table 4. Comparison between the measured width and the predicted width of the HeI 5016 Å line by using the interferometrically measured electron density.

ments [7, 8] using the same device with other measurements [16, 17], and the recent investigations of the H_β line [10] which yielded some limits on plasma conditions near the T-tube wall. Moreover, our conclusions are consistent with those obtained from previous experiments [3] (except, of course, Refs. [4] and [5]) on rather different devices and with a new measurement by Kelleher [18] on a stabilized arc. Probably the measurements by Kusch [4] and Einfeld and Sauerbrey [5] were therefore affected by some systematic error, possibly from opacity effects in the electrode regions of the pulse discharge tubes or errors in the electron density determinations. We note that this most important plasma parameter had been inferred [4] from the Stark width of the hydrogen H_β line, whose emission may well have a different spatial distribution than HeI lines, and that any error from this source may have been transferred [5] via the use of the HeI 5016 Å line [19].

The most likely source of a systematic error in our work is connected with the neutral atom contribution to the refractive index. Quite probably the neutral atom densities are somewhat larger than those obtained assuming thermal equilibrium [2]. Correction for such deviations would result in higher electron densities and therefore larger predicted line widths than those measured in the present experiment, i. e., in an experiment-theory discrepancy opposite to that deduced by the authors of Refs. [4] and [5]. The magnitude of our systematic error can be estimated if we replace the spectroscopically estimated neutral atom density by the values obtained from conservation relations across incoming and reflected shock waves (Rankine-Hugoniot relations). This method [7, 8, 20] gives for our incoming shock velocities of ~ 0.8 cm/μsec neutral atom densities $n_0 \approx 9 \times 10^{18}$ cm^{-3}, corresponding to electron densities $\sim 25\%$ in excess of those in Table 4. This should be an upper bound on this systematic error, because actual compression ratios are smaller than those predicted assuming one-dimensional flow. We finally note that neutral atom contributions to the refractivity from cooler layers near the wall should be negligible. This fact is suggested by a two-wavelength interferometric measurement [21] of the electron density in a T-type shock tube filled with hydrogen, where such contributions were found to be $\sim 10\%$. In our case, corresponding corrections would be much smaller, because we have small percentage ionization throughout, whereas in the hydrogen experiment the plasma was nearly completely ionized in the bulk of the volume.

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