Measurements of Stark Profiles of C II and Ca II Lines*

JAMES R. ROBERTS AND K. L. ECKERLE
National Bureau of Standards, Washington, D. C.
(Received 30 January 1967)

An electromagnetic T tube was the source of a plasma used to measure line profiles of singly ionized atoms. The profiles of C II lines emitted by a plasma composed of He and CO_2 in the ratio 95:5 were scanned with a monochromator. The profile scans were accomplished by repeated firings of the T tube while advancing the monochromator in wavelength steps. Also measured was the profile of the 3934 Å Ca II resonance line emitted by a plasma composed of He, H_2, and CO_2 in the ratio 20:10:70 with Ca as an impurity. The profile of the 3889 Å He I line was also measured and its halfwidth was used to determine the plasma electron density in the case of the C II lines. Likewise H_α was used to determine the electron density in the case of the Ca II line. The experimental C II and Ca II Stark-profile half-widths were compared with the theoretically calculated values.

I. INTRODUCTION

THE Stark-broadening theory for isolated lines[1] of neutral atoms has been experimentally checked for a number of cases.[2] In general 20% agreement has been found between theory and experiment. The experimental tests of the Stark-broadening theory for singly ionized atoms[3–8] other than helium have yielded results differing by as much as a factor of 10 from the theoretically predicted values.[1] Recent improvements[9] on the Stark-broadening theory show closer agreement between these experiments and the theory.

The purpose of this experiment was to provide more data to compare with theory. The general approach to this experiment was to generate the spectra of C II, Ca II, He I, and H using an electromagnetic T tube. Spectral-line profile scans were obtained by repeated firings of the T tube. C II was chosen because of its simple spectral structure and Ca II was chosen because of a recent experiment[6] at a lower electron density (6×10^{16} cm^{-3}). The Stark widths of the 3889 Å He I and H_α were compared with theory[1] and were used to determine the plasma electron density. The spectra of C II and Ca II as well as the strong lines of H, He I, He II, Si II, Si III, and O II were generated in the T tube using mixtures of helium, hydrogen, and CO_2.

II. DESCRIPTION OF APPARATUS AND EXPERIMENTAL METHOD

The source used to generate the emission spectra of C II, Ca II, He I and H was an electromagnetic shock tube (T tube). This source has been described in detail previously[10] and its use for scanning line profiles has also been described.[11,3] This experiment employed a T tube with a quartz side arm 19 mm i.d. in which the reflected plasma was observed. The plasma was generated by the discharge of a 0.5-μF capacitor charged to 35 kV. Two sets of initial conditions were used. The first set of conditions was used to generate the Ca II and H spectra. The initial pressure in the T tube was 5 Torr of a helium, hydrogen, and CO_2 mixture in the ratio 20:10:70. Calcium occurred as a natural impurity. The reflected plasma was observed 3 mm from an aluminum reflector placed 8 cm from the electrodes. In the second case the spectra of C II and He I were generated. The initial pressure was 1 Torr of a helium and CO_2 mixture in the ratio 95:5. The reflected plasma was observed 5 mm from the aluminum reflector placed 10 cm from the electrodes. These two sets of initial conditions were found empirically to optimize signal-to-noise ratios and spectral-line–to–underlying-continuum ratios, and to prevent self-absorption of strong spectral lines.

The radiation emitted by the plasma was measured by two photoelectric monochromators. Both instruments were on the same optical axis and viewed the same portion of the plasma (Fig. 1). Using a telescope, the optical system was aligned to within 0.1 mm. The radiation was split by a half-aluminized mirror, M_4. The 0.5 m Ebert monochromator was used to observe a specific portion of the emitted spectrum and the signal derived from it was used as a monitor for shot-to-shot scanning. The monitor for the C II experiment was the integrated intensity from a C II line. In the case of Ca II, H_α was used as a monitor. The time history of the signals was displayed on a dual-beam oscilloscope and photographed. The line intensity to be measured was evaluated at a time corresponding to a value of the monitor signal which was chosen to be the same for each shot. This condition insured the maximum reproducibility of the line profile because the temperature has been found to be a slowly varying function

* This research is a part of project DEFENDER, sponsored by the Advanced Research Projects Agency, Department of Defense, through the U.S. Office of Naval Research.

[1] H. R. Griem, *Plasma Spectroscopy* (McGraw-Hill Book Company, Inc., New York, 1964).
[2] W. L. Wiese, in *Plasma Diagnostic Techniques*, edited by R. H. Huddlestone and S. L. Leonard (Academic Press Inc., New York, 1965), Chap. 6, p. 279.
[3] R. A. Day and H. R. Griem, Phys. Rev. **140**, A1129 (1965).
[4] C. H. Popenoe and J. B. Shumaker, Jr., J. Res. Natl. Bur. Std. (U.S.) **69A** (1965).
[5] K. Murakawa, Phys. Rev. **146**, 135 (1966).
[6] M. Yamamoto, Phys. Rev. **146**, 137 (1966).
[7] J. M. Bridges, Dissertation, University of Maryland, 1966 (unpublished); J. M. Bridges and W. L. Wiese, Phys. Rev. **159**, 31 (1967).
[8] N. W. Jalufka, G. K. Oertel, and G. S. Ofelt, Phys. Rev. Letters **16**, 1073 (1966).
[9] H. R. Griem, Phys. Rev. Letters **17**, 509 (1966).
[10] H. F. Berg, K. L. Eckerle, R. W. Burris, and W. L. Wiese, Astrophys. J. **139**, 751 (1964).
[11] H. F. Berg, A. W. Ali, R. Lincke, and H. R. Griem, Phys. Rev. **125**, 199 (1962).

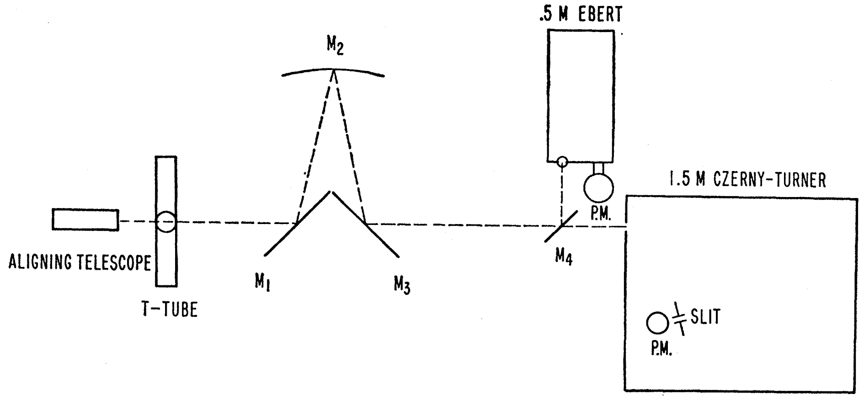

FIG. 1. Schematic diagram of apparatus M_1, M_2, M_3, and M_4 are front surface mirrors (M_4 is half-aluminized on quartz). *P.M.*'s are 1P21–1P28 type photomultipliers.

of time and approximately reproducible from shot to shot.[12] All of the signals were analyzed after the peak of the reflected plasma. The 1.5-m Czerny–Turner spectrometer, used with a fixed exit slit, observed that portion of the emitted spectrum around the spectral line to be scanned. The scanning was accomplished by repeated firings of the T tube while advancing this instrument in wavelength steps. Because only small spectral regions were scanned (<10 Å), calibration of the system with an intensity standard was not necessary.

To insure that only the Stark width of the spectral lines under investigation was measured, the instrumental width was made small enough so it could be neglected in most cases. In order to verify this a preliminary scan of the spectral line profile was taken and its half-width compared to the instrumental half-width which was measured using a very narrow line source. The line source used was an electrodeless Fe-halide lamp[13] excited by microwaves with lines typically less than 0.01 Å in half-width. A Gaussian function was found to be a good representation of the instrumental slit profile. This representation was used for any necessary instrumental unfolding. Because the Stark profile of ion lines can be represented by a dispersion function $1/(1+x^2/\beta^2)$ [14,15] any folding or unfolding of profiles can be accomplished using the Voigt function.[16] With one exception, all the spectral lines had a Stark-broadened half-width large enough so the instrumental width could be neglected. The experimental width corresponded to $<\frac{1}{5}$ of the total profile; therefore, the slit function made up less than 5% of the total profile.[2]

III. RESULTS

For the first set of initial conditions i.e. the Ca II and H spectra, only two lines were scanned. These were the 3934 Å Ca II resonance line and H_α. In this case H_α was used as a reference to measure the plasma electron density. Its profile was compared with theory[1] which predicted a corresponding electron density. For the case of C II and He the following lines were scanned: 2992, 3361, and 3920 Å C II, and 3889 Å He I. The He I line profile was compared with theory[1] to determine the plasma electron density.

The models used to calculate the profiles so they could be compared with theory are as follows:

He I, 3889 Å: For this line the theory has been experimentally checked.[17] Therefore its Stark profile should give a reliable measure of the electron density. Even though tabulated values are given for this profile,[18] they were graphically compared to a dispersion function of the same half-width and discrepancies much less than the experimental scatter were noted. For this reason a dispersion profile model was used for this line. The entrance slit width corresponded to 0.40 Å for this line.

C II, 2992 Å: In this case the entrance slit corresponded to 1.1 Å. Like the He I line a dispersion profile model was used.

The model formula used for the two above profiles was:

$$I(\Delta\lambda)=\frac{I_p}{1+(\Delta\lambda/\Delta\lambda_{1/2})^2}+I_c, \qquad (1)$$

where I_p is the peak intensity of the dispersion profile, $\Delta\lambda$ is $\lambda-\lambda_0$ where λ_0 is the line center wavelength, $\Delta\lambda_{1/2}$ is the dispersion profile half–half-width,[19] and I_c is the intensity of the underlying continuum.

For the 3361 and 3920 Å C II multiplets with slit widths of 0.40 and 0.14 Å, respectively, the model formula for the experimental profile took the form of the sum of two displaced dispersion profiles with one

[12] J. R. Roberts and K. L. Eckerle, Phys. Rev. **153,** 87 (1967).
[13] C. H. Corless, W. R. Bozman, and F. O. Westfall, J. Opt. Soc. Am. **43,** 398 (1953).
[14] H. R. Griem, Astrophys. J. **132,** 883 (1960).
[15] H. R. Griem and K. Y. Shen, Phys. Rev. **122,** 1490 (1961).
[16] J. Tudor Davies and J. M. Vaughan, Astrophys. J. **137,** 1302 (1963).
[17] H. F. Berg, A. W. Ali, R. Linke, and H. R. Griem, Phys. Rev. **125,** 199 (1962).
[18] H. R. Griem, Phys. Rev. **128,** 515 (1962).
[19] The half–half-width is defined as one-half the width at half the maximum intensity of the profile.

TABLE I. C II and Ca II experimental Stark widths.

Run number	λ(Å)	Transition array and multiplet	$\frac{1}{2}\Delta\lambda_{1/2}$(Å) (exptl.)	Exptl. scatter in $\frac{1}{2}\Delta\lambda_{1/2}$(Å)	N_e(×10[17]cm[-3])	$\Delta\lambda_{1/2}$(th)/$\Delta\lambda_{1/2}$(exptl.) Old[a]	New[b]
1	3889 He I	$2s\,^3S$–$3p\,^3P°$ (2)	2.04	±0.20	1.4	1.00[c]	···
1	2992 C II	$3d\,^2D$–$5f\,^2F°$ (8)	3.79	±0.30	1.4	0.39	0.52
1	3361 C II	$3d\,^2D$–$5p\,^2P°$ (7)	0.88	±0.04	1.4	1.13	1.92
1	3889 He I	$2s\,^3S$–$3p\,^3P°$ (2)	2.02	±0.20	1.4	1.00[c]	···
1	3920 C II	$3p\,^2P°$–$4s\,^2S$ (4)	0.72	±0.05	1.4	0.70	0.59
2	3889 He I	$2s\,^3S$–$3p\,^3P°$ (2)	2.23	±0.26	1.5	1.00[c]	···
2	2992 C II	$3d\,^2D$–$5f\,^2F°$ (8)	3.67	±0.20	1.5	0.44	0.58
2	3361 C II	$3d\,^2D$–$5p\,^2P°$ (7)	1.26	±0.05	1.5	0.90	1.46
2	3920 C II	$3p\,^2P°$–$4s\,^2S$ (4)	0.76	±0.06	1.5	0.68	0.60
3	3934 Ca II	$4s\,^2S$–$4p\,^2P°$ (1)	0.12	±0.02	2.35	0.92	1.13
3	6563 H_α	$2p\,^2P°$–$3d\,^2D$ (1)	8.0	±0.4	2.35	1.00[c]	···

[a] Reference 1. [b] Reference 9. [c] Defined as unity and used as reference to determine electron density.

profile multiplied by the branching ratio[20] plus a continuum.

H_α, 6563 Å: This line is not accurately represented as a dispersion function. However, its profile has been numerically tabulated,[1] and this tabulation was used to determine the Stark width of the profile to give a reliable measure of the electron density for the case of the Ca II profile scan. The slit width for H_α was 1.4 Å.

Ca II, 3934 Å: Because this line was narrow for the condition exhibited in the T tube, the 1:5 slit-width–to–total-line-width ratio could not be maintained. The experimental slit width for this line was 0.25 Å and represented about one-half the total line width. It was necessary to use the convoluted profile in this case (a Voigt profile).[16] The convolution of an experimental slit function in the form of a Gaussian function with a Stark profile represented by a dispersion function is as follows:

$$I(\Delta\lambda)=\frac{I_p}{\pi}\frac{\Delta\lambda_G}{\Delta\lambda_{1/2}}\int_{-\infty}^{\infty}\frac{\exp(-\lambda^2)}{1+[\Delta\lambda/\Delta\lambda_G+\Delta\lambda_G/\Delta\lambda_{1/2}]^2}d\lambda+I_c, \tag{2}$$

where $\Delta\lambda$, I_p, and I_c are as before, $\Delta\lambda_{1/2}$ is the dispersion profile half–half-width, and $\Delta\lambda_G$ is one-half the $1/e$ width of the Gaussian function.

The scatter in the scanned line data is attributable to variations in the plasma homogeneity, electron density, and temperature, even though a constant monitor signal was used. However, this scatter was smaller than the inherent uncertainties in the line broadening theory.

The profile data points were made to fit their respective models by using a least-squares fit with the aid of a computer. The parameters $\Delta\lambda_{1/2}$, I_c, and I_p were varied to accomplish this. Samples of these fits are given in Figs. 2 and 3. Figure 2 is a scan of the 3889 Å He line and Fig. 3 is that of the 3920 Å C II multiplet. The error flag represents the standard deviation of the data points as given by the fit. The results of these line profile scans with a comparison between the Stark-broadening theory[1] and its new modifications[9] are presented in Table I. The half–half-width of the experimental pro-

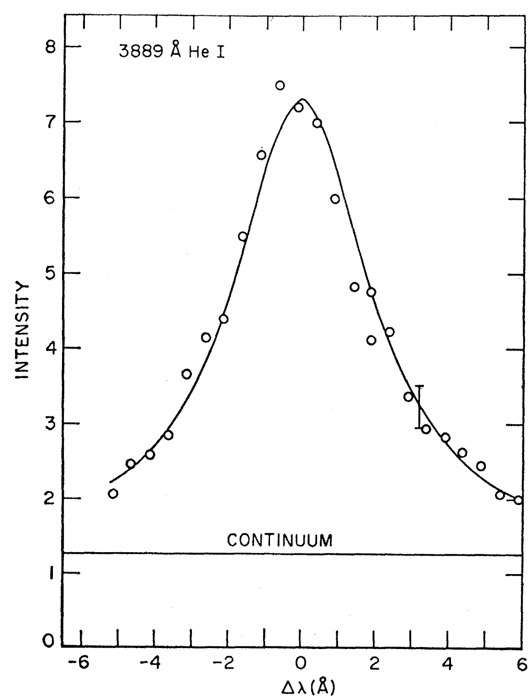

FIG. 2. A plot of the 3889 A He I data points and the least-squares fit of the model (solid lines).

[20] W. L. Wiese, M. W. Smith, and B. M. Glennon, Natl. Std. Ref. Data Ser., Natl. Bur. Std. (U.S.) 4 (1966),

files as well as their experimental scatter are given in Å units. The three C II line profiles were scanned twice each. The He I reference line profile was scanned twice in run No. 1 to assure that the electron density had not changed. The differences between runs 1 and 2 are that the T tube was changed and the two runs were analyzed at different monitor signal heights. The consistency of the half-width ratios of Table I between the same lines is an indication of the experimental precision. The experimental scatter given in Table I is the standard deviation of the half-half-width in Å as given by the least-squares fit. The first column under the half-width ratio is that given by using Ref. 1 and the second column by using Ref. 9.

IV. DISCUSSION OF RESULTS

Most Stark profiles have only a slight dependence on temperature. For this reason an accurate temperature determination was not necessary. The temperature for the initial ratio had been determined in a previous experiment[12] using the same apparatus. For these initial conditions the temperature was approximately 30,000°K. The temperature was estimated at 25,000°K for the 20:10:70 He:H:CO_2 initial conditions from the same previous experiment.[12] This temperature is not critical, however, since a ±10 000°K uncertainty at 30 000°K would produce an uncertainty in the Ca II half-width[1] less than the experimental scatter.

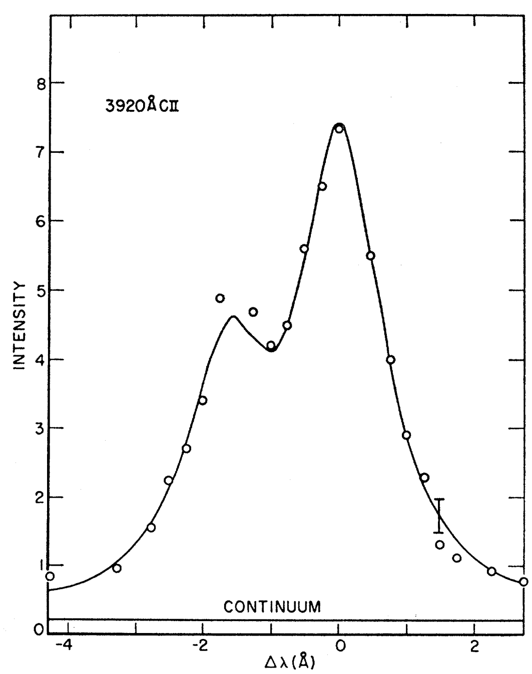

FIG. 3. A plot of the 3920 Å C II multiplet data points and the least-squares fit of the model (solid lines).

The optical depth of the strongest line centers was experimentally checked. The experimental arrangement for this was to replace the telescope of Fig. 1 by a spherical mirror. The position of the mirror was made at twice its focal length from the T tube center so that twice the amount of intensity would reach the spectrograph slit. However, reflection and absorption losses in the mirror and absorption from the light transmitted through the T tube wall reduced this factor somewhat. The optical depth was checked using the 1.5 m instrument which observed the center and wings of the strongest lines in question while the 0.5 m instrument observed the monitored integrated line intensity. The T tube was fired with and without the optical-depth mirror. This was done for five firings each at the line center, the line wing, and the continuum wavelengths. Using a constant monitor signal, the signals were then averaged. Ratios of signals with and without the mirror were compared for the three wavelength settings. The result of this experiment showed the plasma to be optically thin for the lines that were investigated because all ratios were the same within the experimental scatter.

The combined experimental uncertainties from the experimental scatter of the electron density references and the scanned lines are approximately ±10%. Additional uncertainties due to theoretical unknowns in the Stark width calculations[1] of the 3889 Å He I and 6563 Å H_α lines can only be estimated. Comparison between experimentally measured[21] and calculated H_α Stark widths, using the Stark width of H_β as an experimental electron density standard, showed the experimental H_α widths to be within 15% of the theoretically calculated values. The 3889 Å He I had been experimentally checked[17] and 10% agreement between experiment and theory was found. Experimental unknowns such as distortion of observed lines by impurity lines can only be estimated and are put at <5%. This brings the total uncertainty to <±20%.

V. CONCLUSION

It is evident from the comparison between experiment and theory for the C II lines that individual discrepancies are still present. Averages of the last two columns of Table I (excluding the values defined to be 1) gives 0.74 for the old theory and 0.97 for the new theory. On the average, the modified theory[9] is therefore in better agreement with our measurements than the previous theory.[1] However, in individual cases, deviations are even larger than before indicating that further theoretical and experimental efforts are needed if these discrepancies are to be reduced.[22]

[21] J. M. Bridges and W. L. Wiese, in *Proceedings of the Seventh International Conference on Ionization Phenomena in Gases*, (Gradevinska Knjiga Publishing House, Gelgrade, 1965), Vol. III, p. 165.
[22] J. Cooper, Phys. Rev. Letters **17**, 509 (1966).