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Stark Broadening of Singly Ionized Nitrogen Lines

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Profiles of nine lines of singly ionized nitrogen have been measured in a dense ($N_e = 1.9 \times 10^{17}$ cm^{-3}) high-temperature (22 800 °K) plasma produced behind the reflected shock wave in a *T* tube. Measurements were carried out that verified the fact that the plasma was homogeneous in both the radial and the axial directions and that the plasma was optically thin at the various wavelengths where the profiles were measured. The half-widths of the measured profiles show large discrepancies with earlier reported measurements of Day and Griem and, in most cases, show significant disagreement with the theoretical predictions.

I. INTRODUCTION

The generalized impact theory for broadening of isolated ion lines in a plasma by Griem *et al.*[1] has recently been modified by Griem,[2,3] and by Cooper and Oertel.[4] As a result, there has generally been improved agreement between theory and experiment.[5-12] In the case of N II, however, the modified theory resulted in worse agreement between theory and experiment than was obtained by the use of the original theory. In this particular case, the modified theory predicts half-widths that are typically larger by a factor of 2 than the experimental half-widths.[13] The cause of this discrepancy was not immediately obvious, and the need for further experimental work was indicated. This paper is concerned with an experimental investigation of Stark broadening in singly ionized nitrogen to determine the cause of this discrepancy.

II. EXPERIMENTAL APPARATUS

An electromagnetic *T* tube was used as the light source for this experiment, and a schematic of the system is shown in Fig. 1. The general description and characteristics of *T* tubes are discussed in the literature[14] and will not be repeated here. The shock tube was constructed of 19-mm-o.d. × 16-mm-i.d. pyrex tubing. The observation ports are 2 mm diam and are so situated that observations may be made along the diameter of the tube and along a chord near the wall. These ports are located 12.5 cm from the electrodes. The capacitor stores 600 J of energy at 40 kV and the circuit has a ringing frequency of 300 kHz. The optical system (Fig. 2) consists of a 0.3-m monochromator which is used to scan the line profile shot by shot.[15] This instrument has a (measured) resolution of 0.28 Å with 10-μ slits and is

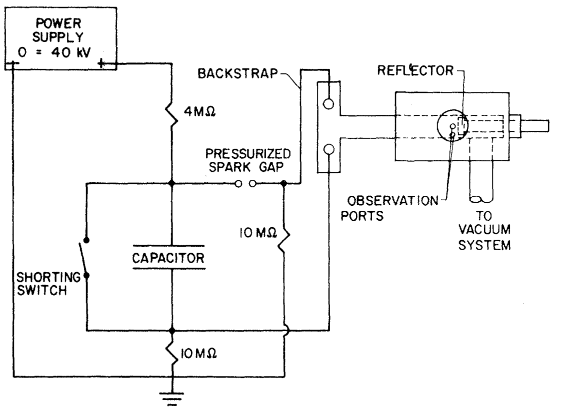

FIG. 1. Schematic diagram of the T-tube experiment.

equipped with an end-on photomultiplier tube. In order to monitor the reproducibility of the plasma from shot to shot, a 0.5-m spectrograph equipped with two side-on photomultiplier tubes was used. One of the tubes measured the total intensity of the 5045 Å N II line and the other measured the intensity of a 15 Å-wide continuum band centered at 5620 Å. The outputs of the photomultiplier tubes were recorded on dual-beam oscilloscopes. In the course of the experiment only those runs were considered satisfactory in which there was not more than a 10% variation in these two monitor signals. Care was taken to ensure that both instruments viewed the plasma volume from the same solid angle. All of the measurements in this experiment were made 2 mm in front of the reflector and behind the reflected shockwave.

III. OPERATING CONDITIONS

The operating conditions for the experiment were determined by experimentally investigating the properties of plasmas produced by various mixtures of helium and nitrogen. It was required that (i) the plasma be reproducible in both temperature and electron density from shot to shot; (ii) the central intensity of the nitrogen and helium lines be greater than the continuum radiation by at least a factor of 3; (iii) the electron density be sufficiently high to ensure adequate broadening of the nitrogen line with respect to both Doppler and instrumental broadening; and (iv) the plasma be homogeneous.

A gas mixture consisting of 85% He and 15% N_2 at an initial filling pressure of 1.2 Torr and a capacitor voltage of 30 kV were finally chosen, as they resulted in all of the above requirements being met. At higher concentrations of N_2, the plasma became inhomogeneous, as discussed subsequently, and at lower concentrations the electron density became too low to broaden adequately most of the N II lines.

The electron density was determined independently by scanning the 3889 Å He I line. The experimental points were corrected for the underlying continuum, and a dispersion profile was fitted to the points by varying the half-width and central intensity until a best fit was obtained. The half-width of this line was determined to be 6.0 ± 0.5 Å which indicates an electron density of 1.9×10^{17} cm^{-3} ($\pm 10\%$).[2] The homogeneity of the plasma in the radial direction was investigated by measuring the profile of the 3889 Å He I line near the wall. Measurements of this line were also made in the axial direction by masking the 2-mm-diam port so that a layer of plasma, 100 μ thick, was observed by the monochromator. This slit was then moved in the axial direction across the port and the 3889 Å He I line profile was measured at several different positions. In every case (radial as well as axial), the half-widths agreed well within experimental error, indicating that the plasma was homogeneous in the radial direction and for at least 2 mm in the axial direction. This same procedure was also used with several N II lines to investigate the uniformity of the plasma in this same volume. Each of the N II lines had a constant half-width within experimental error throughout the volume of plasma investigated. This consistency in the individual half-widths assured that the nitrogen was uniformly distributed throughout the portion of the plasma that was used in the investigation.

The plasma temperature was obtained from the absolute intensity of the N II 4630 Å line under the assumption of local thermodynamic equilibrium. This assumption is justifiable since the electron density and the relaxation time were sufficient to ensure that the plasma was collision dominated.[16] Calibration of the measuring monochromator was accomplished by the use of a carbon arc placed behind the shock tube (see Fig. 2). An image of the crater in the positive electrode was formed at the center of the shock tube by a lens system to coin-

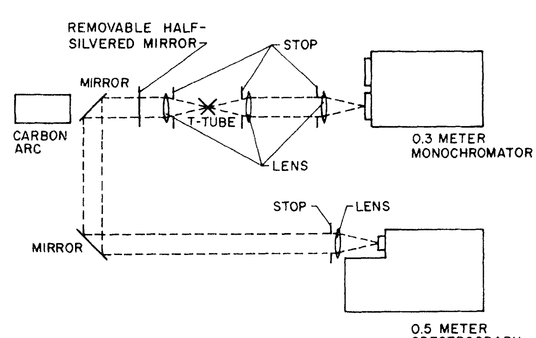

FIG. 2. Optical arrangement.

cide with the point of observation of the plasma. The results of Null and Lozier[17] were used to determine the absolute intensity of the crater. A temperature of 22 800 °K ± 10% was obtained from this measurement.

To ensure that the lines measured were optically thin, the following investigation was carried out. After a line had been scanned and the center of the line located, a half-silvered mirror was placed behind the shock tube (see Fig. 2). One-half of the emitted radiation was then reflected back through the lens located between the mirror and the shock tube and was focused at the center of the shock tube. The scanning monochromator was then set at the line and the central intensity of the line was recorded with and without the mirror. In each case, it was noted that the photomultiplier signal increased by 45 ± 5% for those shots with the mirror in place. This result provided sufficient evidence that the plasma was optically thin for those wavelengths at which measurements were made.

Several of the N II profiles obtained had such sufficiently small half-width that it was necessary to correct for instrumental broadening. The measured instrument profile was very nearly Gaussian, so that it was possible to fit Voigt profiles to the experimental points.[18] The unfolding was then trivial and the (dispersion) profile of the N II line was easily obtained. A typical experimental profile is shown in Fig. 3.

IV. EFFECTS OF INHOMOGENEITIES

The effects on the line half-widths of an inhomogeneity in the plasma in this experiment were investigated. This was done in order to determine the magnitude of the effect that this condition could introduce into the measured half-widths. A mixture of 50% He and 50% N_2 at a pressure of 2 Torr,

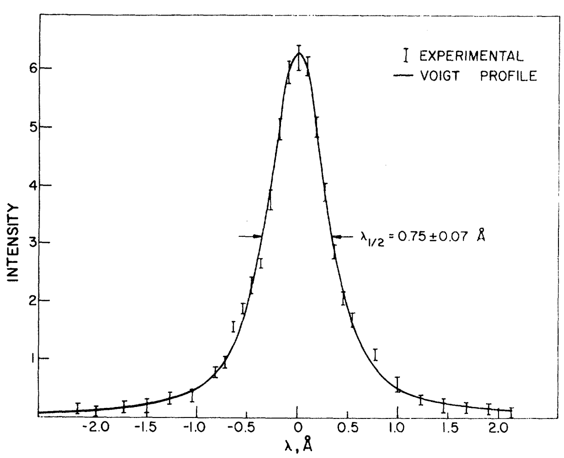

FIG. 3. Experimental profile of 3995 Å N II.

and a capacitor voltage of 30 kV were used for these measurements.

The half-width of the 3889 Å He I line was used to determine the electron density at the center of the shock tube and at the wall. These measurements indicate an electron density of 3.3×10^{17} cm^{-3} at the center of the tube but only 1.6×10^{17} cm^{-3} at the wall. The monitor signals, which were obtained from the center of the shock tube in both cases, indicated that the plasma was fairly reproducible. Scatter in the experimental points, however, resulted in an uncertainty in the above densities of about ±20%. Measurements of several N II line profiles were made at the center of the tube and also at the wall under these conditions. The half-widths of these profiles were in agreement, within experimental error. These results indicate that more helium radiation originates in the higher-density core than in the lower-density layer near the wall, and vice versa for the N II radiation. Comparison of these results with those obtained from the homogeneous plasma verifies this, as the N II line profiles are indicative of the lower density.

V. EXPERIMENTAL RESULTS

Half-widths of nine N II line profiles were obtained in this experiment. The results are summarized in Table I. Theoretical half-widths from the modified theories as given by Griem[2,3] and by Cooper and Oertel,[4] are also listed for comparison. The experimental half-widths obtained in this experiment have been corrected for the contribution from ion broadening (less than 1% except for multiplet 59) and have been extrapolated to an electron density of 10^{17} cm^{-3}.

Five of these lines have been previously measured and reported by Day and Griem.[13] The results of the present experiment are in disagreement with these previous results in that the half-widths reported here are typically larger by factors of approximately 2 to 3. The present results, however, agree with those obtained by Berg *et al.*,[19] within ± 15% with only one exception (4447 Å).

VI. DISCUSSION OF ERRORS

The determination of the electron density from the half-width of the 3889 Å He I line has been shown to be accurate to within 5%.[20] Scatter in the experimental points allowed the half-width of this line to be determined with an uncertainty of about 8% so that the electron density should be accurate to within ±10% (rms value). In the case of the N II lines, the half-width could be determined to within about 8% for those lines for which unfolding was not necessary. For the narrower lines where it was necessary to correct for instrumental broad-

TABLE I. Summary of results.

Multiplet	Transition	λ(Å)	$\lambda_{1/2}$ Griem[a] (Å)	$\lambda_{1/2}$ Griem[b,c] (Å)	$\lambda_{1/2}$ Cooper-Oertel[d] (Å)	$\lambda_{1/2}$ Day and Griem[e] (Å)	$\lambda_{1/2}$ this experiment[f] (Å)
5	$3s\,^3P_2{}^0\text{-}3p\,^3P_2$	4630	0.28	0.25	0.24		0.35
	$3s\,^3P_2{}^0\text{-}3p\,^3P_2$	4643	0.28	0.25	0.24		0.35
	$3s\,^3P_1{}^0\text{-}3p\,^3P_1$	4613	0.28	0.25	0.24	0.14	0.35
12	$3s\,^1P_1{}^0\text{-}3p\,^1D_2$	3995	0.17	0.20	0.17		0.30
15	$3p\,^1P_1\text{-}3d\,^1D_2$	4447		0.26			0.28
18	$3p\,^1P_1\text{-}4s\,^1P_1{}^0$	3007	0.32	0.24	0.32	0.26	0.60
29	$3p\,^3P_2\text{-}3d\,^3P_2{}^0$	5496	0.50	0.43	0.72	0.20	0.58
30	$3p\,^3P_2\text{-}4s\,^3P_2{}^0$	3838	0.40	0.42	0.42	0.58	1.0
59	$3d\,^1F_3{}^0\text{-}4f\,^1G_4$	4530	2.8	1.9[g]	2.0	1.6	2.2

[a]See Ref. 2.
[b]See Ref. 3.
[c]Semiempirical predictions.
[d]See Ref. 4.
[e]See Ref. 13.
[f]±15% (rms).
[g]Value from Griem, Ref. 16. For this multiplet $kT/\Delta E = 0.72$, Coulomb effects are negligible, and the upper-state broadening is described by the data in this reference.

ening, the half-widths of the N II lines could be determined to within about ±10%. Therefore the total error (rms) in the N II half-widths is about 15%.

The Stark profiles have only a slight temperature dependence so that any uncertainty in the temperature would not affect the limits within which the half-width could be determined.

VII. CONCLUSIONS

The half-widths of the N II lines measured in this experiment have been compared to theoretically predicted half-widths obtained from a modified impact theory. The half-widths of lines of multiplets 12, 18, and 30 are larger than the theoretical values by a factor of about 2. Multiplets 29, and especially 59 and 15, are in reasonable agreement with the theoretical values, and lines from multiplet 5 are larger by about 40%.

The discrepancies between theory and experiment observed here indicate the need for further theoretical and experimental work. In some cases (multiplets numbers 18, 30), the modified impact theory does not appear to be in any better agreement with experiment than the previous theory.[16] The results for the three multiplets where theory and experiment agree reasonably well are quite insufficient to allow any conclusion to be drawn concerning the two theories.

Investigation of the effects on measured half-widths by an inhomogeneity in the plasma indicates that it is not always justifiable to assume that the plasma is homogeneous. This assumption can lead to errors in the measured half-widths which may be as large as a factor of 2 or more. Therefore care must be taken in this type of experiment to ensure that the plasma is indeed homogeneous.

The half-width values obtained in this experiment were compared to the experimental values reported by Day and Griem.[13] The results of this experiment were used to calculate half-widths of all lines common to the two experiments at the values of electron densities reported by Day and Griem.[13] The ratio of this calculated half-width to the experimental value reported by Day and Griem[13] was a constant, within experimental error. This result indicates that the electron-density measurements reported for their experiment were in error and that the error was possibly due to inhomogeneities in their plasma.

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[1]H. R. Griem, M. Baranger, A. C. Kolb, and G. K. Oertel, Phys. Rev. 125, 177 (1962).
[2]H. R. Griem, Phys. Rev. Letters 17, 509 (1966).
[3]H. R. Griem, Phys. Rev. 165, 258 (1968).
[4]J. Cooper and G. K. Oertel, Phys. Rev. Letters 18, 985 (1967).
[5]C. H. Popenoe and J. B. Shumaker, J. Res. Natl. Bur. Std. (U.S.) 69A, 495 (1965).
[6]N. W. Jalufka, G. K. Oertel, and G. S. Ofelt, Phys. Rev. Letters 16, 1073 (1966).
[7]K. Murakawa, Phys. Rev. 146, 135 (1966).
[8]M. Yamamoto, Phys. Rev. 146, 137 (1966).
[9]W. R. Powell, dissertation, Johns Hopkins University, 1966 (unpublished).
[10]J. M. Bridges and W. L. Wiese, Phys. Rev. 159, 31 (1967).
[11]D. E. Roberts, Phys. Letters 22, 417 (1966).
[12]J. R. Roberts and K. L. Eckerle, Phys. Rev. 159,

104 (1967).
[13]R. A. Day and H. R. Griem, Phys. Rev. 140, A1129 (1965).
[14]A. C. Kolb and H. R. Griem, in Atomic and Molecular Processes, edited by D. R. Bates (Academic Press Inc., New York, 1962), Chap. 5.
[15]H. F. Berg, A. W. Ali, R. Lincke, and H. R. Griem, Phys. Rev. 125, 199 (1962).
[16]H. R. Griem, Plasma Spectroscopy (McGraw-Hill Book Co., New York,1964).
[17]M. R. Null and W. W. Lozier, J. Opt. Soc. Am. 52, 1156 (1962).
[18]J. T. Davis and J. M. Vaughan, Astrophys. J. 137, 1302 (1963).
[19]H. F. Berg, W. Ervens, and B. Furch, Z. Physik 206, 309 (1967).
[20]J. R. Greig, C. P. Lim, G. A. Moo-Young, and G. Palumbo, Bull. Am. Phys. Soc. 13, 265 (1967).

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Propagation of a Cavity-Dumped CO_2 Laser Pulse through SF_6

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Coherent interactions between short CO_2 laser pulses and a resonant absorbing SF_6 gas medium have been examined carefully, using a laser cavity-dumped rectangular pulse with a width of 20 nsec and input intensities from 10 to 10^4 W/cm^2. Parameters studied included the width, shape, and delay time of the transmitted pulse after propagation through several absorption lengths of SF_6 cell. In addition to these measurements, we have observed two new phenomena, namely, optical free induction decay and edge echo, which are induced by this short rectangular CO_2 laser input pulse. Results indicate that although level degeneracy in SF_6 may be involved, the simple two-level model can account qualitatively for most observed phenomena, with the exception that the observed shape of a 2π pulse deviates significantly from the symmetric hyperbolic-secant function predicted by the simple two-level theory. In the π pulse region, we have demonstrated that the free-induction-decay tail can be valuable for studies of atomic and molecular collision processes.

I. INTRODUCTION

Coherent interaction of a short laser pulse with a resonant medium is currently a subject of considerable interest. It was shown first by McCall and Hahn[1] that a ruby laser pulse of high intensity can propagate through an inhomogeneous absorbing medium (also ruby) without attenuation but with a delay in time. This phenomenon is known as self-induced transparency and has recently been studied in detail.[2] A similar effect has also been observed[3] in SF_6 gas using 10.6-μ pulses from a CO_2 laser. In this paper, we report the observation in SF_6 of an optical free induction decay and an edge echo on an initial short 20-nsec rectangular 10.6-μ $P(20)$ CO_2 laser pulse using the cavity-dumping technique.[4] Similar phenomena with pulses from the $P(18)$ and $P(22)$ CO_2 transitions were also observed. For a simple model consisting of two nondegenerate quantum states with an inhomogeneously broadened line, theory[2] shows that the stable condition of self-transparency results after the initial pulse traversing through a few absorption lengths into the resonant medium and the pulse evolves into a symmetric hyperbolic-secant pulse in time and space with a pulse area corresponding to a "2π pulse." More recently, numerical computations have also been made[5] with the emphasis on the evolution of a pulse as it develops into a 2π pulse. However, there exist differences in interpretation[2,5-7] of previous experiments[3,7] which were performed using a rotating mirror Q-switched CO_2 laser pulse.[8] By using a short and flat-topped CO_2 laser pulse, we have been able to examine in detail the dynamic evolution of this input pulse through an optically thin as well as thick SF_6 absorbing medium. This was accomplished by studies of the pulse shape, pulse