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Shock-Tube Measurements of van der Waals Broadened Silicon Lines

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The widths of van der Waals broadened Si I spectral lines were measured by using a conventional shock tube and a scanning Fabry–Perot interferometer. The experiments have been performed by using argon as the perturbing gas in the reflected region of the shock wave at a temperature of about 5500°K and over a pressure range of 2–10 atm. The temperature was determined by a line reversal technique; the pressure was measured using a quartz transducer. The scanning Fabry–Perot was driven by a piezoelectric crystal operating at its resonant frequency (10.5 kc/sec); the line profiles were detected photoelectrically and displayed on an oscilloscope for photographing and analyzing. A set of calculated curves was used to obtain the contribution of the pressure broadening to the widths of the spectral lines. The experimental widths thus determined are within a factor of two of the results obtained from theory.

I. INTRODUCTION

The shock tube is an excellent spectroscopic light source for studies of atomic and molecular properties of interest to astrophysicists. In the temperature region of 5000–8000°K and carrier gas densities of the order of 10^{18} cm^{-3} to 5×10^{19} cm^{-3}, observation times of the order of several hundred microseconds are available for the studies of line profiles. This paper describes an experiment devised to measure damping constants (half-widths) of spectral lines.

In the shock tube under the above-stated conditions electron densities will range from about 5×10^{14} to 5×10^{16} cm^{-3}. Whether a spectral line is broadened by electron impacts or by collisions with neutral perturbers depends on the detailed structure of the atom, but typically when the ionization of a gas is less than 1%, the spectral lines emitted from energy levels lying lower in the atom, that is, where the level spacing is large, will more likely be broadened by neutral perturbers, especially if one of the levels is an *s* state. Spectral lines emitted from higher-lying levels are more apt to be broadened by electron impacts.

As a prelude to the study of Stark (electron) broadening processes in a shock tube, the present experiment was performed to assess the reliability of the van der Waals theory as given by Griem.[1] Since the theory as quoted in *Plasma Spectroscopy* is an adiabatic theory, this experiment, which is performed at relatively high temperatures, provides a rough measure of the importance of inelastic processes in van der Waals broadening.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental equipment was a diaphragm type shock tube used with hydrogen as the driver gas. The test gas argon with a 0.1% admixture of $SiHCl_3$. Typical diaphragm breaking pressures were in the range of 60–600 lbs and the corresponding pressures of the test gas were in the range of 15–120 Torr. These conditions gave a reasonably constant temperature (between 5500 and 7000°K) and densities of neutral particles between 2×10^{18} and $\sim 4 \times 10^{19}$ cm^{-3}. The temperature range of about 25% was not significant for the measurement of van der Waals broadening since the predicted temperature dependence is slow, proportional to $T^{3/10}$.

The various measurements were made in the flow region behind the reflected shock wave; about 100 μsec were allowed for the shock wave to equilibrate judged from the time behavior of the intensity of a spectral line. Then, the temperature of the gas was measured spectroscopically by means of a line reversal technique. If the shocked gas is assumed to be in local thermal equilibrium,[2] the temperature can be determined by measuring the emissivity of the gas and the intensity emitted in a given spectral range.

The total pressure of the gas was measured with a quartz transducer. Then, by using the measured temperature and pressure and the known percentage composition of the gas, all of the properties of the gas can be calculated, i.e., densities of atoms, molecules, and electrons.

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[1] H. R. Griem, *Plasma Spectroscopy* (McGraw-Hill Book Company, New York, 1964).

[2] W. R. S. Garton, W. H. Parkinson, and E. M. Reeves, Proc. Phys. Soc. (London) **88**, 771 (1966).

During the temperature measurement, the spectral line is scanned using an oscillating Fabry–Perot.[3] Figure 1 shows a block diagram of the apparatus. The interferometer plates are epoxied to a barium titanate crystal 6 in. long which has a resonant frequency of about 10 kc/sec corresponding to a half-period of oscillation of approximately 50 μsec. The interference pattern is focused on the entrance slit of a monochromator which acts as a narrow band filter and the dispersed light is monitored by a photomultiplier whose output is displayed on an oscilloscope screen. Since the interferometer displacement is sinusoidal with time, part of the voltage applied to the barium titanate tube is picked off and phase shifted, and then used to drive the horizontal sweep of the oscilloscope. Slight modifications to the oscilloscope electronics enabled it to be used in a single sweep mode.

Adjustments in the phase could be made to insure that the sweep of the oscilloscope was linear with wavelength to better than 4%. Then the display recorded photographically could be used directly for the profile reduction. Since only three profiles are scanned in 50 μsec, this technique gave many photons per resolution time, a prime requisite in this experiment which studies optically thin lines emitted from a 6000°K plasma. Even then, for narrow lines, intensity was often a problem so that signal to noise ratios were of the order of five at profile maximum.

A typical set of data acquired during a single shot is shown in Fig. 2. The waveforms of the intensity of the optically thick line Si I λ3905 is exhibited along with the pressure pulse and the Fabry–Perot scan. From such a scan the half-width of the profile could be measured in units of the free spectral range, the distance between fringes. The calibration of this type of sweep is made simply by measuring the separation of the plates with a telemicroscope. A detailed description of the data reduction process can be found in Ref. 4.

III. RESULTS

Figure 3 shows the studies of two spectral lines measured in this manner. λ5949 is a $4s^1P^\circ - 5p^1D$ transition and λ5708 is a $4s^3P^\circ - 5p^3P$ transition. Since they come from rather high-lying levels, both of these lines have a considerable Stark broadening contribution, and this fact is reflected in the rather

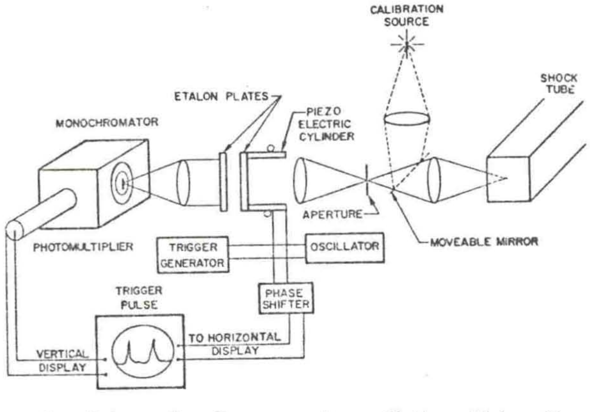

FIG. 1. Schematic diagram of oscillating Fabry–Perot interferometer.

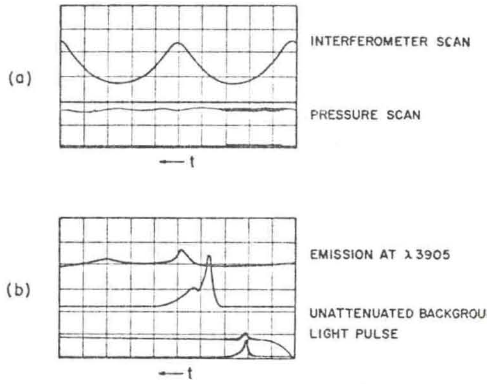

FIG. 2. (a) Upper trace: interferometer scan of spectral lines; total time of trace 50 μsec. Intensity 0.2 V/cm. Lower trace: pressure transducer output (1 V/cm, 20 μsec/cm). (b) Upper trace Si λ3905 emission with attenuated flash lamp signal. Unattenuated flash is also shown 0.1 V/cm, 5 μsec/cm. Lower trace: same display at slower sweep speed (0.2 V/cm, 50 μsec/cm).

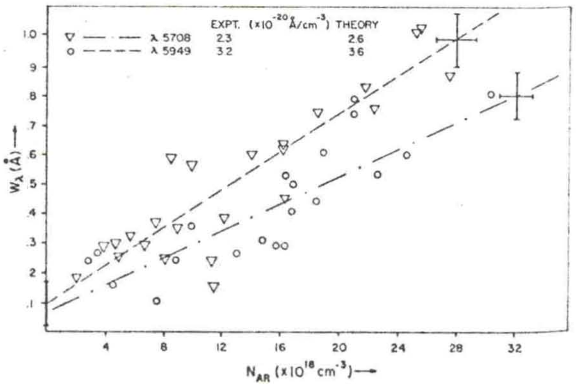

FIG. 3. Widths of silicon lines plotted as a function of total density of perturbing argon atoms. The theoretical and experimental widths are in units of 10^{-20} Å/cm^{-3} λ5708: 2.6, 2.3 ± 0.4 λ5949: 3.6, 3.2 ± 0.5.

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[3] J. Cooper and J. R. Grieg, J. Sci. Instr. **40**, 443 (1963).

[4] R. A. Day, Shock Tube Spectroscopy Laboratory, Harvard College Observatory, Report No. 18 (1967).

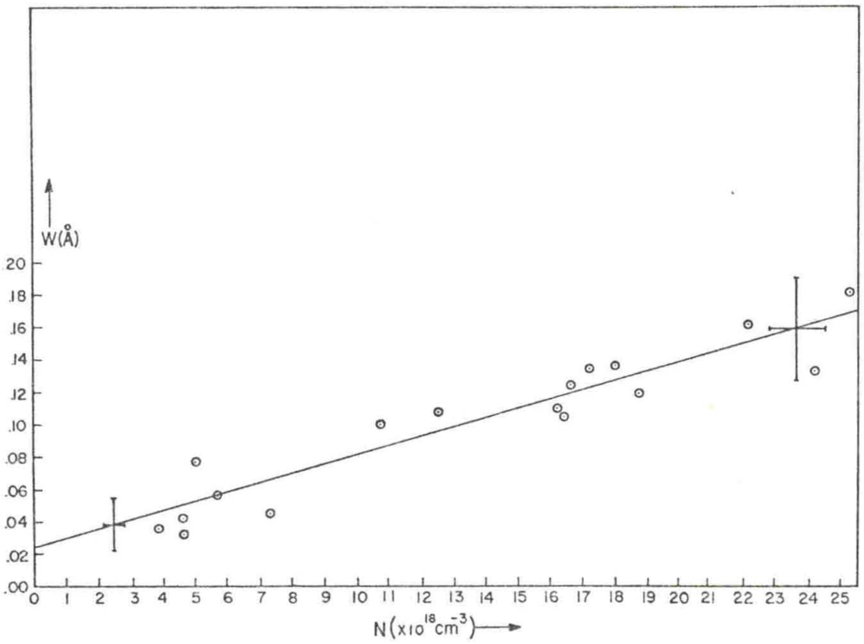

FIG. 4. Width of Si I λ4103 line plotted against number density of perturbing argon atoms. Theory predicts a slope 7×10^{-21} Å/cm^{-3} and experiment gives $5.7 \pm 0.6 \times 10^{-21}$ Å/cm^{-3}.

large scatter in the data points. The indicated lines are "least-square" fits to the data. The temperature dependence of the widths is very slight since it is proportional to $T^{3/10}$; therefore, slight corrections to the widths of the order of 3% were possible and the various data points could all be normalized to 5800°K. The results in this figure, though, were typical, i.e., the measured widths were less than the theoretical widths as calculated from the formulas of Griem.[1] These widths were calculated by simply adding the widths of the upper and lower states.

Figure 4 gives the data obtained for the Si I λ4103 line. This spectral line was negligibly affected by Stark broadening; the improvement in the scatter of the data over Fig. 3 reflects this fact. Again, the experimental widths are smaller by about 30% than the theoretical widths and the width of the spectral line is finite at zero density.

An idea of the accuracy of the technique can be obtained by noting the finite width of the spectral line at zero density. Although isotopic splitting could cause such zero density widths[5] still Kusch[6] in a recent report on arc measurements of the van der Waals broadening of silicon lines by argon did not observe such effects. His work was performed on uv lines using a spectrograph for dispersion; although he has not performed studies of any of the presently reported spectral lines, in principle, one would expect that they would have the same behavior. In spite of this present deficiency, the interferometer-shock-tube combination holds great promise in line broadening studies, and this work is being extended to the measurement of Stark broadening constants.

ACKNOWLEDGMENTS

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[6] H. Feldhausen and H. J. Kusch, Z. Astrophys. **67**, 122 (1967).