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OSCILLATOR STRENGTHS OF THE RED AUTOIONIZING LINES OF CALCIUM

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ABSTRACT

A shock tube experiment was designed to measure relative gf-values of the calcium autoionizing lines near λ6360. Results from other experimenters for normal transitions have been used to place the gf-values on an absolute scale, with an estimated error of 20 per cent. The laboratory line strengths are compared with the observed line depths in the solar spectrum.

I. INTRODUCTION

Since autoionizing lines in stellar atmospheres are formed by a process of pure absorption, these lines can serve as a useful test in model atmosphere calculations, (Goldberg 1966). The absolute oscillator strengths of such lines are required and at present they must be obtained by experimental means. The strongest identified autoionized lines in the visible solar spectrum are the 3d4p $^3F^\circ$ - 3d4d ^3G multiplet of neutral calcium (Mitchell and Mohler 1965), and an experiment was therefore designed to measure the f-values of these lines.

Since the lower energy levels of this multiplet lie 4.43 ev above the ground state, a high temperature is required to excite the autoionizing lines. To determine the relative populations of the levels, a plasma in local thermodynamic equilibrium (LTE) and isothermal along the line of sight is desirable. Finally, the absolute number density of calcium atoms in the line of sight must be known.

II. EXPERIMENTAL DETAILS

A shock tube, used with a coaxial flash tube to provide a very bright background continuum, can satisfy the above conditions, although the determination of the number density of calcium depends on measuring other lines whose absolute oscillator strengths are known. Temperatures in the 4000° - 8000° K range are easily obtained in the reflected shock, and the very rapid creation of these temperatures suppresses the formation of sizable boundary layers, i.e., radiative and conductive losses are inadequate to destroy an initially isothermal plasma. The assumption of LTE is strongly supported by the agreement between temperatures measured simultaneously in both a normal line and in a member of this strong calcium red autoionizing multiplet (Garton, Parkinson, and Reeves,1966), in conditions similar to those of the present experiment. The method of measuring temperature has been described by Parkinson and Reeves (1964).

To achieve a uniform distribution of calcium atoms, an aerosol loading device was used (Watson, Morsell and Hooker 1966). Finely-powdered calcium sulfide mixed with argon gas was allowed to flow into the evacuated shock tube just before the shock was initiated. A variety of pressures of the pre-shocked gas produced a range of reflected shock temperatures from 5185° to 7293° K. The flash tube which emitted the background continuum discharged about 175 μseconds after the shock arrived at the end wall of the shock tube. A high-speed shutter developed by Grasdalen, Huber and Newsom (1968) was used so that excessive emission by the shocked gas would not fill in the absorption lines. A three-meter spectrograph of the Eagle type with a reciprocal dispersion of 5.51 Å/mm in the first order in the red was used to record the spectrum. The I-F plates were calibrated by photographing the spectrum of the flash tube through various natural density filters.

III. DATA REDUCTION

The plate transmission as a function of wavelength both for the background continuum and the absorption spectra was measured by a microphotometer with digital output. A computer program was used to derive the optical depth as a function of wavelength and to correct for the effects of emission by the shocked gas.

A second computer program, based on an iteration scheme developed by H. Stone (1962) and the Shell Development Company, was written to perform a least-squares fit of dispersion profiles to the observed lines. The comparison lines used, at wavelengths 6716.7, 6122.2, and 6102.7 Å were saturated near line center in most cases, and therefore the profiles were fitted to the wings alone when necessary. We noted that far from line center, where the quantity $\left(\frac{\nu-\nu_0}{\Gamma/2}\right)^2$ is large, the dispersion relation,

$$\tau_\nu = \frac{\tau_0}{1 + \left(\frac{\nu-\nu_0}{\Gamma/2}\right)^2}$$

can be approximated by

$$\tau_\nu \approx \frac{\tau_0}{\left(\frac{\nu-\nu_0}{\Gamma/2}\right)^2} = \frac{\tau_0\ (\Gamma/2)^2}{\left(\nu-\nu_0\right)^2} \quad .$$

For this case, only the product $\tau_0(\Gamma/2)^2$ can be determined although the integrated absorption coefficient, and hence the f-value, is proportional to $\tau_0(\Gamma/2)$. When a line is saturated over many half-widths, an independent method of deriving half-widths is required.

The profile of the comparison line at λ6717 was known reasonably close to line center on all plates, and thus useable integrated absorption coefficients were available for this line. Computations showed that the f-values of the autoionizing lines relative to this line were independent of temperature. To convert these relative f-values to absolute oscillator strengths, the f-values of the λ6717 line relative to the intercombination line $4s^2\ {}^1S_0$ - $4s4p\ {}^3P_1^\circ$ at λ6572 was taken from Olsen, Routly, and King (1959) and the strength of λ6572 was compared to the resonance line of calcium as determined by Ostrovskii and Penkin (1961a). Ostrovskii and Penkin (1961b) placed these relative values on an absolute scale by measuring the absolute oscillator strength of the resonance line. From the derived absolute oscillator strength of λ6717 and the measured integrated absorption coefficients, the number density of neutral calcium in the lower level of this transition is found. The Saha-Boltzmann equation can then be solved to yield the electron density, with the (accurate) assumption that all the free electrons are produced by calcium ionization.

The lines at 6102 and 6122 Å were generally saturated over many half-widths, and theoretical half-widths were necessary to yield accurate integrated absorption coefficients. The electron densities found by the above method, combined with the Stark broadening parameter for these lines computed by Griem (1964), lead to an evaluation of the Stark broadening. The other significant process, van der Waals broadening, depends on the total number density in the reflected shock, which was found from the measured pressure and temperature and from the shock equations for a real gas. If the parameter of van der Waals broadening is computed from the formula of Griem (1964), temperature-dependent f-values are found. However, if the theoretical ratio of van der Waals parameters for λλ6122 and 6102 relative to λ6717 is multiplied by the experimental parameter of λ6717, the resulting van der Waals widths, added to the Stark widths, gave relative f-values for the autoionizing lines which were independent of temperature.

Since Olsen, Routly, and King (1959), as well as Ostrovskii and Penkin (1961a), have measured the f-values of λλ6122 and 6102 relative to λ6572, we must decide which of these experimental results should be used to place these oscillator strengths on an absolute scale. The agreement between these two sets of measurements is good for lines with 4s4p $^3P^\circ$ lower levels, indicating that measured equivalent widths and hook separations are accurate. Errors in these two experiments which result from uncertainties in temperature, and hence in population, can be estimated by comparing relative f-values of lines with different energies for the lower levels. However, the intercombination line λ6572 was the only line measured by both sets of experimenters which did not originate from the 4s4p $^3P^\circ$ levels. Of the 22 lines common to both experiments, this intercombination line is one of only two where agreement is poor. Temperature errors in one of the experiments may possibly have affected the f-values of the lines at λλ6122 and 6102 relative to λ6572. However, the shock tube measurements of the relative oscillator strengths of λλ6122, 6102, and 6717, involving 4s4p $^3P^\circ$ and 4s3d ^1D lower levels, agree very well with the corresponding values of Olsen, Routly, and King (1959). The discrepancy between the measurements of Olsen et al. and of Ostrovskii and Penkin (1961a) for λ6572 is therefore assumed to result from a temperature error in the latter experiment. Note that Ostrovskii and Penkin derived temperatures by an indirect procedure, and that a 3 per cent error in temperature would account for the discrepancy.

IV. RESULTS AND ESTIMATED ERROR

The derived absolute f-values for the autoionizing lines are based on the relative f-values of Olsen et al. for λλ6717, 6122, and 6102 relative to λ6572 on Ostrovskii and Penkin's (1961a) measurements of the strength of λ6572 relative to the calcium resonance line, and on the absolute f-value for the resonance line of Ostrovskii and Penkin (1961b). The following values were derived:

λ	f	gf
6362	0.66	5.9
6343	0.55	3.9
6318	0.33	1.65

Random experimental errors amounted to about 4 per cent, but systematic errors (e.g., those resulting from temperature uncertainties and from deviation of the comparison line profiles from symmetrical dispersion profiles) are estimated to amount to 10 per cent to 15 per cent.

Errors in converting the relative values to an absolute scale can be estimated by comparing the results of Olsen et al. and Ostrovskii and Penkin for lines with 4s4p $^3P^\circ$ lower levels. For these 21 relative line strengths, the standard deviation of the sample is 9 per cent, which may be used to estimate both the error in the f-value of λ6572 relative to the resonance line, and the errors in the oscillator strengths of λλ6717, 6122, and 6102 relative to λ6572. The absolute f-value of the resonance line is estimated to be accurate to 2.7 per cent (Ostrovskii and Penkin 1961b). The error in establishing an absolute scale is therefore estimated at 15 per cent, and the probable error in the absolute autoionizing f-values is estimated at 20 per cent.

V. CALCIUM AUTOIONIZING LINES IN THE SOLAR SPECTRUM

Measurements of the red calcium autoionizing lines in the solar spectrum are given in Table 1.

TABLE 1

Wavelength (Å)	6362	6343	6318
Equivalent width (mÅ); Mitchell and Mohler (1965)	65	78	79
Maximum depth (%); Mitchell and Mohler (1965)	2.4	3.0	3.3
Maximum depth (%); Goldberg et al. (1965)	4.3±0.1	2.8±0.2	---

The depth of λ6318 was not measured by Goldberg et al. because of severe blending with metallic lines.

The strengths of λ6362 relative to λ6343 disagree strongly in these two studies, but the close agreement between the measured gf-values and the line depths of Goldberg et al. strongly indicates that the latter are more accurate.

Professor Leo Goldberg originally pointed out the need of measuring the autoionizing line f-values, and Dr. William H. Parkinson provided valuable guidance in the laboratory

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