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Temperature dependence of the helium induced broadening and shift of the Rb D_1 and D_2 lines

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ABSTRACT

The rates for collisional broadening and shifting of the Rb D_1 ($5^2S_{1/2}$ – $5^2P_{1/2}$) and D_2 ($5^2S_{1/2}$ – $5^2P_{3/2}$) transition induced by ^{4}He have been measured at elevated temperatures of 373–723 K. The shift coefficients exhibit an increase of 20% from 4.36 MHz/Torr to 5.35 MHz/Torr for the D_1 line and an 80% increase from 0.42 MHz/Torr to 0.99 MHz/Torr for the D_2 line over the observed temperature range. Broadening coefficients exhibit a 6% increase from 17.8 MHz/Torr to 18.9 MHz/Torr and 10% from 18.5 MHz/Torr to 20.5 MHz/Torr for the D_1 and D_2 lines, respectively. The experimental values agree well with prior reported values within the temperature overlap regions of $T < 394$ K. Comparison to prior predictions from the Anderson–Talman theory using spin orbit multi reference (SOCI) ab initio potentials are superior to quantum treatments involving Allard and Baranger coupling.

1. Introduction

The diode pumped alkali laser (DPAL) was first proposed in 2001 as an alternative to high-power, diode-pumped, solid-state lasers [1,2]. A high power, >1 kW, system with 48% optical-to-optical efficiency has recently been reported [3], and development for laser weapons applications [4,5] is in progress. The radiation from un-phased diode bars is absorbed by an alkali metal vapor (potassium, rubidium, or cesium) on the D_2 line, $^2S_{1/2} \rightarrow {}^2P_{3/2}$, collisional relaxation populates the lower fine structure split $^2P_{1/2}$ state, and lasing is achieved on the $^2P_{1/2} \rightarrow {}^2S_{1/2}$ transition. The alkali metal vapor is pressure broadened by a rare gas, usually helium, to efficiently absorb the emission from spectrally narrowed diode bars or stacks. The concept of using a gas phase medium for the phasing of large diode arrays combines the best features of electrically driven lasers with the inherent thermal management advantages of a gas lasers. Indeed, the primary factor for DPAL laser weapon development is the promise of improved beam quality over diode pumped solid-state lasers.

In the DPAL system, the cycle rate for pump, collisional fine structure mixing and lasing can be very high, < 0.1 ns, particularly for pump intensities exceeding 10 kW/cm^2 [6]. The initial linear response of output power to input power is degraded at high pump intensity when the system becomes bottlenecked on the fine structure transition [7]. The transition to this bleached limit depends critically on the D_2 absorption line shape relative to the spectral width of the diode pump [8]. Thus, the most important kinetic parameters are the rates for fine structure mixing and line broadening. Spatial variations in diode pump intensity and flow of the gas through the resonator will lead to turbulence and gain medium index variations, reducing beam quality. Rapid fluctuations in the gain medium can not be corrected by adaptive optics and will ultimately limit device beam quality.

The temperature dependence of the mixing and broadening rates is critical to modeling the DPAL performance. Unfortunately, the rates for line broadening and shifting are only available for the Rb–He DPAL system over a limited temperature range, $T = 310$–450 K [9,10]. The rates with the greatest confidence have an even more limited temperature range, $T = 314$–394 K [11–14]. Furthermore, theoretical predictions vary widely, with disagreements on even the sign of the shift rate [9,15]. In the present work we report the temperature dependence of the Rb D_2 and D_1 line broadening and shifting rates for ^{4}He for $T = 373$–723 K. To achieve this broad temperature range, control of the alkali vapor density independent of the gas temperature is required.

The line shape parameters are a sensitive probe of the interaction potentials [16]. By placing the current results in context of prior theoretical predictions, we explore the sensitivity of line shapes to the potential surfaces. The larger objective is to empirically inform potential surfaces to predict both the temperature dependence of the line broadening and fine structure mixing rates, unifying the Rb–He DPAL kinetics.

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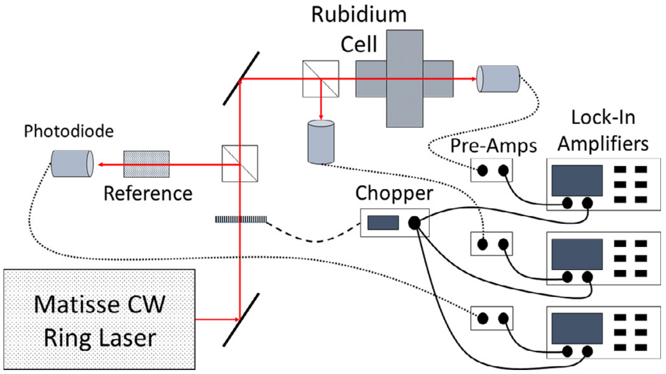

Fig. 1. Laser absorption apparatus.

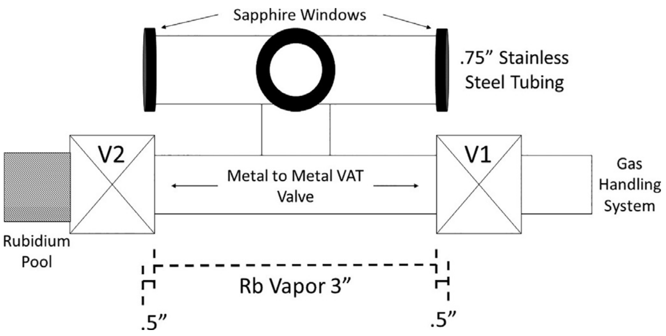

Fig. 2. Alkali containment cell.

2. Experimental setup

The experimental setup for the laser absorption spectroscopy experiment is shown schematically in Fig. 1. A Coherent Verdi 18 pumped continuous wave (CW) Spectra Physics Matisse Ti-Sapphire ring cavity laser, with bandwidth 10 MHz, was tuned over approximately 32.5 GHz centered on the $5^2S_{1/2} \rightarrow 5^2P_{1/2}$ (D_1, $\lambda_1 = 795$ nm) transition and 23 GHz when centered on the $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ (D_2, $\lambda_2 = 780$ nm) transition. The beam was amplitude modulated at 360 Hz then directed through the alkali cell with a small portion of the beam split off into a vacuum sealed Triad Technologies Pyrex 25 mm × 50 mm cell filled with ^{87}Rb to be used as an absolute wavelength reference. Polarization of the laser beam was oriented horizontally with a typical initial output power of 600–800 mW. Various filters and optics reduced the power delivered to the test cell to approximately 94 nW with a beam diameter of 2 mm yielding a beam intensity of approximately 750 nW/cm^2. The calculated saturation intensity for the D_2 line, I_{sat}, is ≈10 mW/cm^2 at vacuum and 5 mW/cm^2 at 150 Torr of He. Three Hamamatsu S2281-04 silicon photodiodes with Hamamatsu C9329 pre-amplifiers connected to Stanford Research Systems SR850 DSP lock-in amplifiers with 11 ms integration time were used to collect the incident, transmitted, and reference absorption signals. Laser wavelength information was collected using a fiber coupled High-Finesse WSU-2 wavemeter. Day to day variations in the absolute frequency reported by the wavemeter relative to the Rb reference cell were 10–20 MHz, with variations during the day of 1–2 MHz.

The alkali containment cell was designed to allow for low alkali number densities, $n = 10^{11} - 10^{12}$ atoms/cm^3, while operating at cell temperatures ranging from 373 K to 723 K [17]. Helium (^{4}He), 99.999% purity, was added to the system through a SAES MC1-902F gas getter providing 99.9999% purity. Pressure was monitored using a MKS model 609A manometer with a 670 signal conditioner for pressures up to 500 Torr. An Agilent model FRG-700 manometer with a XGS-600 signal conditioner was used to measure vacuum pressures to an ultimate pressure of 3.9 µTorr and the leak rate of $<$ 0.5 mTorr/min.

A VAT series 541 metal-to-metal angle valve allows for the alkali melt pool at modest temperature to establish the rubidium vapor pressure and be isolated from the absorption cell. Two wedged sapphire windows are used in the upper cross along the beam path with a non-wedged flat sapphire window and a flat cap on the cross connections parallel to the beam path. The port with the non-wedged window is used to monitor alkali buildup inside the cell.

Heating of the cell is accomplished through the use of three sections of BriskHeat thermal tape. One section of type BIH1010 heater tape is wrapped around the alkali pool with temperature monitoring accomplished using Type J thermocouple and a Watlow Model 96 proportional integral derivative (PID) temperature controller. The rest of the cell is heated using two lengths of BWH1010 high temperature thermal tape, capable of temperatures up to 1000 K. Type K thermocouples were placed at the junction of the T connection and the 5 way cross as well at the top of the 5 way cross. The two high temperature sections are connected to Watlow EZ-Zone PID temperature controllers. The maximum temperature of the apparatus was limited by the braze around the windows, which fails around 823 K.

Cell preparation begins by baking the cell at 723 K and evacuating the cell to 4 µTorr. Once the bake-out is completed the cell is returned to the starting temperature of 373 K, and the cell is isolated from the vacuum system by closing valve 1. Valve 2, leading to the alkali pool, is opened allowing alkali vapor to diffuse throughout the cell. During the diffusion process, the CW laser scans continuously across the transition to monitor the alkali vapor density.

Immediately following the closing of the alkali pool, valve 1 is opened and helium is slowly added ≈ 1 Torr/s and allowed to equilibrate for 15 min. Once the gas has come to a thermal equilibrium the pressure is recorded using the MKS Baratron Manometer. Spectral scans across the transition of interest are taken at each cell temperature. Each new temperature takes approximately 10 min to reach the next set point and is then given 15 min to thermally equalize at the new temperature. Upon completion of the run, the temperature is slowly lowered back down to 373 K to avoid thermal gradients. The cell is evacuated and baked before a new helium pressure is studied.

3. Results

3.1. Observed and simulated absorption spectra

Absorbtion spectra, for the Rb D_2 line at several temperatures are shown in Fig. 3. The absorbance is defined using Beer's Law,

$$A = -ln\left(\frac{I_t}{I_o}\right) = \sigma n l \tag{1}$$

where σ is the absorption cross-section, n is the number density, and l is the path length through the cell. The incident intensity, I_0, and transmitted intensity, I_t, with no rubidium vapor are nearly balanced yielding a baseline of A = 0.2. A slight modulation of ΔA = 0.01 arises during a scan and is accounted for using a 3rd order polynomial. Fig. 3 shows an increase in the absorbance at elevated temperatures probably due to a small amount of alkali metal condensed or absorbed somewhere in the cell. Rubidium density sometimes decreases at elevated temperature, likely from wall outgassing of reactive species. The change in rubidium density is acceptable if the cell does not become opaque, A $>$ 3.

To model the absorption spectra and extract line shape parameters, the hyperfine transition lines, 4 for D_1 and 6 for D_2