Back ground gas induced collision shift for ^{88}Sr: $^1S_0$-$^3P_1$ transition

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***Abstract*—Precision saturation absorption spectroscopy on a vapor cell was performed for ^{88}Sr $^1S_0$ - $^3P_1$ spin-forbidden transition. Various kinds of rare gas were introduced into the cell as buffer gas (BG) and the collision shift due to the BG was detected at ~kHz level. The results and theory to validate the experiment may help to correctly estimate the influence on state-of-the-art lattice clocks whose clock transition $^1S_0$ - $^3P_0$ is similar to the transition investigated here.**

I. Introduction

Latest progress of optical clocks is so rapid that atomic clock makers have turned out to consider novel systematic shifts that they have so far ignored. Among those potential systematic effects, collision shifts induced by residual gas in vacuum chambers may ultimately limit the accuracy of optical clocks as the evaluation of the effect seems difficult. The loss of trapped atoms on the deliberate injection of buffer gas prevents a background gas pressure large enough to enable the finite measurement in real clock apparatuses.

From the beginning of laser spectroscopy, frequency shifts and broadening caused by the buffer gas (BG) were measured by using a gas cell with BG pressures of 10^2- 10^5 Pa, where the shifts and broadening resulted in the order of ~100MHz. This level of high BG pressure causes some high order effects, making it difficult to evaluate the 1st order collision shift. In this work, based on precision saturation absorption spectroscopy for the ^{88}Sr ($5s^2$) $^1S_0$ - ($5s5p$) $^3P_1$ spin-forbidden transition (λ = 689.4 nm; linewidth: 7.4 kHz [1]), buffer gas induced shifts of a few kHz were detected with low gas pressure of ~10mTorr. Since this transition resembles the lattice clock transition $^1S_0$ - $^3P_0$, our experiment may give us valuable knowledge to estimate the systematic shifts in real state-of-the-art optical clocks.

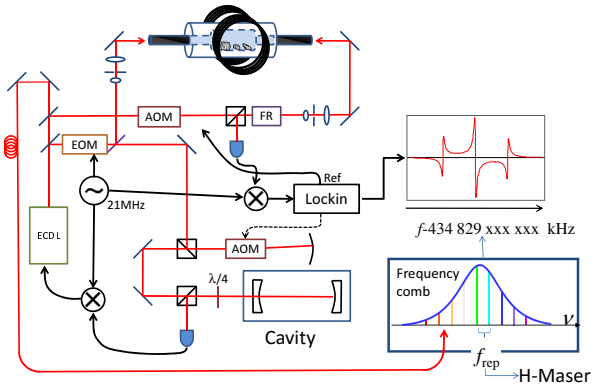

Fig.1. Schematic diagram of precision saturated absorption spectroscopy.

II. Experimental Setup

The experimental setup is schematically shown in Fig. 1. Strontium is contained in a heat pipe with Brewster window plates at both ends. Typical temperature of the pipe is 728 K. Both ends of the active area (20 cm length) are water-cooled so that the strontium is not deposited on the window. The buffer gas is provided from one end and Pirani gauges are installed at both for the confirmation of equilibrated pressures in the tube. The magnetic sublevels are well defined by a bias magnetic field of 3 Gauss produced by a Helmholtz coil pair.

The spectral width of an external cavity loaded diode laser (ECDL) is reduced to be less than 500 Hz by locking laser frequency to a cavity with the Pound-Drever-Hall (PDH) method [1]. The modulation index and frequency ω_M is 0.17 and 21.7 MHz, respectively. This modulation is used for the saturation absorption spectroscopy as well. The pump and probe beam of the saturation spectroscopy is linearly

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polarized to excite the π transition with respect to a quantization axis taken to be parallel to the bias magnetic field. Two Pinholes are placed in both arms to overlap the pump and probe beam. Peak intensity and $1/e^2$ radius of the pump beam (probe beam) is 270 $\mu W/cm^2$ and 4.2 mm (50 μ W/cm^2 and 3.3 mm), respectively. Passing thorough Sr vapor, the polarization of the probe beam is 90 degree rotated and coupled out by a polarization beam splitter. Pump beam is frequency shifted for 80 MHz from the probe beam in order to avoid interference. In addition, the pump beam is chopped with a frequency of 5 kHz to extract the saturation-related signal induced by the pump beam. The signal is first demodulated with ω_M and then lock-in detected. The absolute frequency of the laser is always monitored by a frequency comb referenced to Atomic Time (TA).

III. Instavbility of the Laser Locked to the Vapor Cell

Adjustment of the relative phase in PDH method gives a dispersive curve in demodulated signal. A sample of the curve is shown in Fig. 2(a). The full width half maximum (FWHM) is 107 kHz, which mainly consists of saturation broadening (80 kHz) and transit time broadening (31kHz). Laser frequency was locked to the atomic resonance by using this dispersion as an error signal. The stability of the laser frequency is compared against frequency comb whose repetition rate is locked to a hydrogen maser. The modified Allan deviation is shown in Fig. 2 (b). The instability hits the bottom in 4×10^{-14} at 100s. Various fluctuations of Sr and residual gas pressure and beam intensity hamper further reduction of the instability

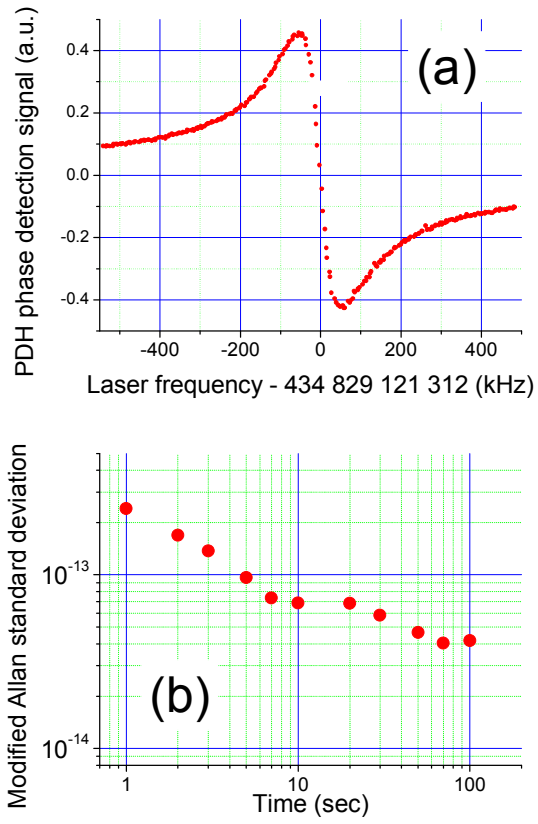

Fig. 2. (a) PDH Phase detection signal. The dispersion shape works as an error signal to lock the laser frequency to the atomic resonance. 434 829 121 312 kHz is the resonant frequency obtained from ballistically expanding cold atoms [3]. (b) Instability of the laser frequency locked to the atomic resonance.

IV. Buffer Gas Induced Broadening and Shift

Buffer gas induced broadening and shift is summarized in Fig. 3 (a) and (b), respectively. We introduced various rare gas such as helium, neon, argon, and xenon as the buffer gas. The discrepancy of -4 kHz from the true atomic resonance is mainly attributed to residual Doppler shift and two body Sr-Sr collision shift. Mutual tilt of pump and probe beam together with anisotropic velocity distribution of atoms cause 1st order Doppler shift. Two pinholes placed in this work still admit mutual beam tilt of 62 µrad, which corresponds to 11kHz of shift in case of completely biased velocity distribution. In terms of the homonuclear collision shift, we measured the shift coefficient, which corresponds to a negative shift of 1 kHz in this situation. Only helium shows a positive and the largest shift. The coefficient of the shift is 5.2 kHz/Pa. This shift corresponds to the fractional shift of $1.2 \times 10^{-11} Pa^{-1}$.

In our case, the broadening and shifting caused by collisions with perturbers can be described in the impact approximation [4], where the phase shift induced by the collision is the time integral of the differential interaction potential of $Sr(^1S_0)$ - $Rg(^1S_0)$ and $Sr(^3P_1)$ - $Rg(^1S_0)$ molecule, where Rg denotes rare gas. The positive shift in case of the He buffer gas indicates that repulsive part of the quasimolecular potential plays a crucial role. Based on the impact approximation with straight line trajectory, theoretical calculation of the shift and broadening coefficient is currently underway and will be described elsewhere.

V. Discussion

Strontium system is currently studied extensively in various national standards labs as it has a clock transition $(5s^2)^1S_0 - (5s5p)\ ^3P_0$ on which large part of lattice clocks are realized. This clock transition shares the ground state with the $^1S_0$-$^3P_1$ transition investigated here, and the excited state $^3P_0$ and $^3P_1$ belong to an identical triplets. In case of $^1S_0$-$^3P_1$, quasi molecular transition is denoted $A^3 0^+$ - $X\ ^1 0^+$ and $B^3 1$ - $X^1 0^+$, respectively [5]. The dispersion coefficients C_6 for Sr-Rg interaction are calculated for excited states $^3\Sigma^+$ and $^3\Pi$ by Zhang and Mitroy. The results are converted to appropriate coefficients for states $A^3 0^+$ and $B^3 1$ by following relations

$$C_6 (A^3 0^+) = C_6 (^3\Pi)$$
$$C_6 (B^3 1\ ) = C_6 (^3\Sigma^+) + C_6 (^3\Pi)$$

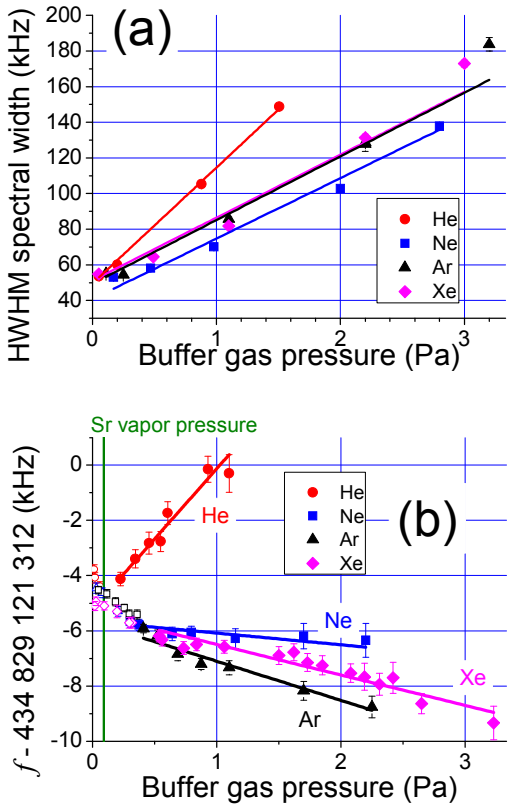

Fig. 3. (a) broadening and (b) shifts induced by buffer gas. Equilibrium of the vacuum is obtained when the buffer gas pressure is sufficiently larger than the Sr vapor pressure.

On the other hand, there is only one adiabatic molecular potential denoted $^3 0^-$ in case of the lattice clock transition $^1S_0$-$^3P_0$. The dispersion coefficient in this case is written as

$$C_6\,(^3 0^-) = C_6\,(^3\Pi),$$

which is the same as $A^3 0^+$ of the case investigated here. Therefore the knowledge obtained here should help to estimate the possible impact of the residual gas induced collision shift in the state-of-the-art optical lattice clock

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