Frequency shifts of the $^{88}$Sr $^1S_0 - ^3P_1$ transition induced by buffer gas collisions

Tetsuya Ido$^{1,2}$, Nobuyasu Shiga$^1$, Ying Li$^1$, Hiroyuki Ito$^1$, and Shigeo Nagano$^1$

1 Space-Time Standards Group, National Institute of Information and Communications Technology (NICT), 4-2-1 Nukui-kitamachi, Koganei, Tokyo, 184-8795 Japan
2 JST, PRESTO & CREST, 5 Sanbancho, Chiyoda-ku, Tokyo, 102-0075 Japan

E-mail: ido@nict.go.jp

Abstract. Buffer gas induced collision shift for $^{88}$Sr$^1S_0 - ^3P_1$ transition is investigated by precision saturation spectroscopy of thermal gas in a heat cell. The cell was filled with rare gas of helium, neon, argon, and xenon as buffer gases. Helium showed the largest fractional shift coefficient of $1.6 \times 10^{-9}$ Torr$^{-1}$. The result could be useful to evaluate the background gas collision shift of Sr lattice clocks.

1. Introduction

Latest progress of optical clocks realized an ionic clock with an accuracy of $\sim 10^{-17}$[1]. This rapid improvement urgently requires the physicists pursuing optical atomic clocks to consider other systematic shifts which have been so far ignored. Among those potential systematics, the collision shifts induced by residual gas in the vacuum chamber may ultimately limit the accuracy of optical clocks as the evaluation of the effects is not straightforward. Deliberate injection of the buffer gas into the chamber often causes the loss of trapped atoms, preventing a background gas pressure large enough to enable the finite measurement.

From the beginning of the laser spectroscopy, measurements of the frequency shifts and broadening induced by the buffer gas were performed by using a gas cell with buffer gas pressures of $1 - 10^3$ Torr, where the shifts and broadening resulted in the order of $\sim 100$ MHz. In this work based on precision saturation absorption spectroscopy for the $^{88}$Sr$(5s^2)^1S_0 - (5s5p)^3P_1$ spin-forbidden transition ($\lambda = 689.4$ nm, linewidth : 7.4 kHz), we detected the buffer gas induced shifts of a few kHz with low gas pressure of $\sim 10$ mTorr. Since this transition is quite similar to the lattice clock transition $^1S_0 - ^3P_0$ [2, 3], our experiment may give us valuable information to estimate the systematic shifts in real state-of-the-art optical clocks using neutral strontium atoms.

2. Experimental setup

Fig. 1 shows the experimental setup of the precision saturation absorption spectroscopy. The transition from the ground state $^1S_0$ to the $m_J = 0$ magnetic sublevel of $^3P_1$ was probed by FM sideband technique [4]. The pump and probe beam of the saturation spectroscopy is linearly polarized to excite the $\pi$ transition with respect to a quantization axis taken to be parallel to a bias magnetic field of 3 Gauss. Only the probe beam is phase modulated by an electro-optic
modulator (EOM). The pump beam free from the phase modulation is chopped by acousto-optic modulator and the signal induced by the saturation effects is lock-in detected from the demodulated signal [5]. Two pinholes of 25µm diameter are placed to guide the paths of pump and probe beam. The overlapping of the two beams are realized by the two pinholes. The 1/e² beam radius of the pump and probe beam is 4.2mm and 3.3mm, respectively. The temperature of the heat pipe is typically 455 °C. A frequency comb referenced to Atomic Time (TA) always monitor the absolute frequency of the probe beam.

3. Results and discussion
The frequency shift induced by various buffer gas [6] is investigated. The coefficient of the frequency shift to the pressure of various buffer gases are summarized in Fig. 2. Only helium shows a positive frequency shift. The largest shift is obtained for helium with a shift coefficient of 680 kHz / Torr. This shift corresponds to the fractional shift of 1.6 × 10⁻⁹ Torr⁻¹. In our case, the broadening and shifting caused by collisions with perturbers can be described in the impact approximation, where the phase shift induced by the collision is the time integral of the differential interaction potential of Sr(1S₀) − Rg(1S₀) and Sr(3P₁) − Rg(1S₀) 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.

The 1S₀ − 3P₁ transition of the strontium resembles the lattice clock transition 1S₀ − 3P₀. The ground state is shared and the excited states belong to the same multiplets. The quasimolecular potentials with the asymptote of Sr(3P₁) − Rg(1S₀) consists of two potentials 3Σ⁺ and 3Π, whereas only 3Π contributes to the quasimolecular potential with Sr(3P₀) − Rg(1S₀) asymptote. The effects of the 3Σ⁺ and 3Π molecular potentials for the 1S₀ − 3P₁ case are in same orders of magnitude. Since the transition strength of the 1S₀ − 3P₀ clock transition is too small to
Figure 2. Frequency shift of the resonance frequency induced by various kinds of buffer gas. $f_0$ is the laser frequency of true atomic resonance which was obtained from balistically expanding ultracold atoms [7]. The points in low buffer gas pressures comparable to the Sr vapor pressure are excluded in the linear fitting because the area under spectroscopy no longer has same background gas pressure as the value provided by vacuum gauges.

perform saturation absorption spectroscopy, the information obtained here works for the coarse evaluation of the background gas collision shifts in real lattice clocks.

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