Frequency Shift Properties of $^1S_0$-$^1P_1$ Transition of a Calcium Beam Optical Clock

Yu Chen
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
yuchen3123@163.com

Yabei Su
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
yabeisu@163.com

Lei Han
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
hanlei1307@163.com

Jun Ge
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
13466728668@163.com

Xiaobo Xue
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
xbxue203@163.com

Shengkang Zhang
Science and Technology on Metrology and Calibration Laboratory
Beijing Institute of Radio Metrology and Measurement
Beijing, China
zhangsk@126.com

***Abstract*—The narrow linewidth of $^1S_0$-$^3P_1$ 657 nm clock transition makes it a promising quantum frequency reference. In this experiment, the fast $^1S_0$-$^1P_1$ 423 nm transition is used to detect the narrow $^1S_0$-$^3P_1$ 657 nm clock transition. Therefore, the frequency stability of the 423 nm laser determines the performance of the optical frequency standard. Here we investigate the frequency shift properties of the neutral calcium atoms' $^1S_0$-$^1P_1$ transition at 423 nm. We measure the frequency shift caused by temperature, laser power, and laser beam pointing.**

Keywords—frequency shift properties, calcium beam optical clock, long-term frequency stability

I. Introduction

Atomic beam frequency standards, such as cesium beam clocks [1], have been widely used in scientific research, industrial manufacture, and daily life. Optical frequency standards based on atomic beam have the potential to operate as time-keeping clocks in the optical band. And researches on calcium [2,3], strontium [4], and ytterbium [5] atomic beams have attained more and more attentions. While most groups focus on the performance of the clocks, researches on the atomic beam itself are rarely reported. Here we investigate the frequency shift properties of the neutral calcium atoms' $^1S_0$-$^1P_1$ transition at 423 nm. Preliminary experimental results are useful for the optimization of calcium beam physical apparatus and the improvement of the calcium beam frequency standard [6].

The atomic energy levels of calcium are shown in Fig. 1. The transition from the ground state $4s4s^1S_0$ to the excited state $4s4p^1P_1$ at 423 nm is a cycling transition, with a wide transition linewidth and a short energy level lifetime of about 4.6 ns. It can be used for atomic cooling and detecting spectroscopy signals. The transition from the ground state $4s4s^1S_0$ to the excited state $4s4p^3P_1$ at 657 nm is the clock transition energy level [7], with a narrow linewidth of about 414 Hz and a longer energy level lifetime of about 0.4 ms. Due to the low signal-to-noise ratio of directly detecting 657 nm clock transition, we consider using electron-shelving detection, which uses the fast $^1S_0$-$^1P_1$ 423 nm transition to detect the narrow $^1S_0$-$^3P_1$ 657 nm clock transition [8]. Therefore, the frequency stability of the 423 nm laser determines the performance of the optical frequency standard.

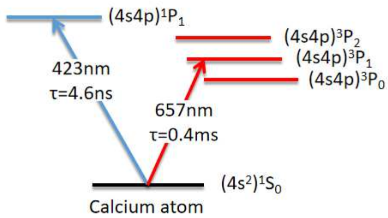

Fig. 1. Atomic energy levels of calcium.

II. Experimental Setup

In this experiment, a fully vacuum-sealed calcium atomic beam tube is used. The signal-to-noise ratio of atomic transition is mainly affected by quantum projection noise, requiring sufficient intensity of atomic beam interacting with laser. The melting point of calcium is 840 ℃. We keep the temperature of the vacuum at 600 ℃, and the atoms are rapidly and directionally sprayed out of the furnace in the form of steam. To further reduce the divergence angle of the calcium atomic beam, a collimated slit is set up in front of the laser interaction zone.

Two atomic beam vacuums are used in this experiment. To minimize the impact of physical systems on the experiment, the designs of vacuums are completely identical. And it is necessary to maintain vacuum in long term. At the same time, the atomic beam sprayed out of the oven has a divergence angle, and the furnace used in the experiment adopts a capillary stacking scheme, greatly improving the efficiency of atomic beam collimation. In the experiment, the ion pump has a pumping speed of 20 L, which can maintain a vacuum degree of 2E-6 Pa.

The frequency shift is measured by beating the two 423 nm lasers, which are locked to the atomic resonance individually. In the optical path, the 423 nm laser is required to be incident perpendicular to the atomic beam, corresponding to the transverse zero velocity atom. The photomultiplier tube (PMT) is used to detect the fluorescence signal generated by the interaction between 423 nm laser and atoms. The 423 nm atomic absorption spectroscopy is obtained and an error signal is generated based on a lock-in amplifier. The 423 nm laser is locked on the atomic transition line.

Here we investigate the frequency shift properties of the neutral calcium atoms' $^1S_0$-$^1P_1$ transition at 423 nm. After locking the frequency of the two 423 nm lasers to the atomic transition frequency, we measure the dependence of the calcium clock frequency on three experimental parameters: temperature, laser power and laser beam pointing. The experimental setup is shown in Fig. 2. And the stability is shown in Fig. 3.

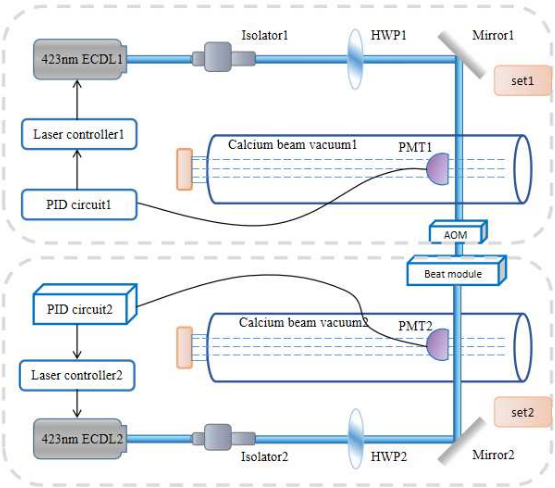

Fig. 2. Schematic of the experimental setup.

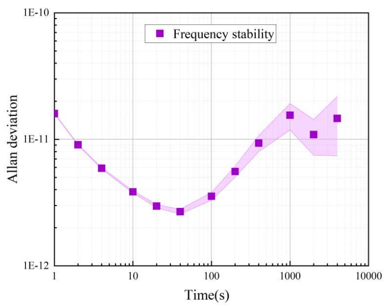

Fig. 3. The stability of 423 nm laser.

The optimal Allan deviation shown in Fig. 3 is 1.6×10^{-11}@1 s at oven temperature of 615 °C. And the mid and long-term stability of the system is mainly affected by temperature.

III. Results

A. Frequency shift of 423 nm transition in calcium as a function of oven temperature

The frequency shift is measured by beating the two 423 nm lasers, which are locked to atomic resonance individually. An acousto-optic modulator (AOM) is used to generate a frequency shift of 144 MHz for set1. We set the temperature of one oven at 600 °C, and change the other one from 595 °C to 630 °C. The frequency shift of 423 nm transition in calcium as a function of oven temperature is shown in Fig. 4. The fitting coefficient between the frequency shift and temperature is 28.6 kHz/K. According to the relationship between atomic beam flux and oven temperature, to improve the signal-to-noise ratio of spectroscopy signals, choosing a relatively higher oven temperature is beneficial for the laser to interact with more atoms simultaneously.

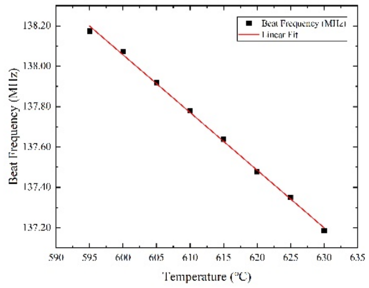

Fig. 4. Frequency shift of 423 nm transition in calcium as a function of oven temperature.

Doppler frequency shift is the main factor affecting frequency shift due to temperature. As temperature increases, the speed of the atomic beam increases, and more doppler shifts from laser-atom interactions. Therefore, the critical temperature control of the oven and ambient temperature is necessary in the experiment.

B. Frequency shift of 423 nm transition in calcium as a function of laser power

We set the temperature of the oven at 600 °C. Laser power is varied by adjusting the half wave plate, which is placed before a polarization beam splitter. One of the 423 nm laser power varies from 25-50 mW, while the other laser power is 17 mW. The frequency shift of the 423 nm transition as a function of laser power is shown in Fig. 5. The fitting coefficient between frequency shift and laser power is 17.5 kHz/mW.

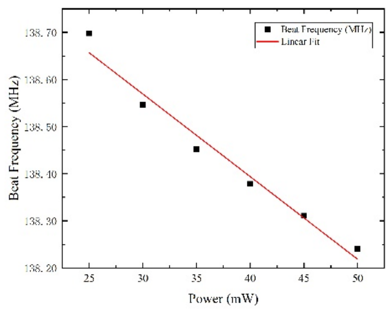

Fig. 5. Frequency shift of 423 nm transition in calcium as a function of laser power.

C. Frequency shift of 423 nm transition in calcium as a function of laser beam pointing

We set the temperature of two ovens at 600 °C. We measure the dependence of clock frequency on laser beam pointing by adjusting the actuator on the last mirror. We measure the frequency dependence on the two orthogonal adjustments of the mirror mount.

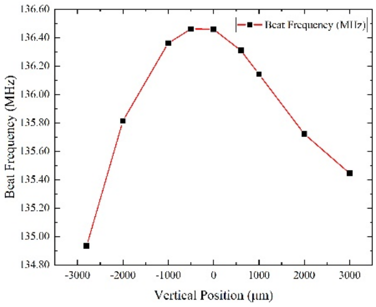

Fig. 6. Frequency shift of 423 nm transition in calcium as a function of vertical position.

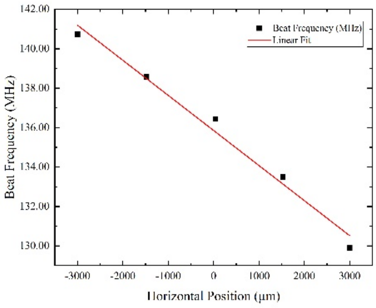

Fig. 7. Frequency shift of 423 nm transition in calcium as a function of horizontal position.

The effects of vertical position and horizontal position on frequency shift is shown in Fig. 6 and Fig. 7, respectively. We find that the most demanding need for pointing stability is the horizontal angle (along the direction of atomic motion), and the frequency shift are relatively small when working at the inflection point of frequency shift in the vertical direction. The frequency shift of 423 nm transition in calcium as a function of laser beam pointing is shown in Fig. 7. The fitting coefficient between frequency shift and laser beam pointing is 1.78 kHz/μm.

IV. CONCLUSIONS

In the calcium atomic beam frequency standard, there are three locking loops, including the locking of the 423 nm detection laser to the atomic resonance, the locking of the 657 nm clock laser to Fabry-Perot cavity, and the locking of 657 nm clock laser to the atomic resonance via feedback to the frequency of an AOM. The locking of the 423 nm laser is crucial in the system, so we measure the frequency shift of 423 nm transition as function of temperature, laser power and laser beam pointing. To achieve the stability of the calcium beam frequency standard, it is necessary to control the frequency shift caused by temperature, laser power and laser beam pointing. Further, we will study the frequency shift properties of the neutral calcium atoms' $^1S_0$-$^3P_1$ transition at 657 nm, which helps to optimize the optical frequency standard.

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