Quantum Nondemolition Detection for Strontium Optical Lattice Clock

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***Summary*—The short-term frequency instability of the best optical atomic clock lies in the mid 10^{-17}. However, the Dick effect is still an obstacle for a single operational clock closely followed by the quantum projection noise. To improve the frequency stability of the strontium optical lattice clock, we present a quantum non-demolition detection scheme based on the cavity mediated interaction between the atoms and a probe light that has a large-frequency detuning to the atomic resonance, aiming to bring the detection scheme proposed in [1] to the quantum regime. We obtained a rather small photon scattering rate, measured to be less than 0.1 photon/µs/atom, which allows us to not only preserve the atoms in the lattice but also the atomic wave function as long as the total probe time is on the order of a few microseconds. The detection noise for the number of atoms is 48/√photons atoms, implying that the frequency stability can surpass the standard quantum limit when the number of trapped atoms is larger than 2.3×10^4 with spin squeezing protocols.**

Keywords*— *optical lattice clock; quantum nondemolition; Dick effect; spin squeezing; standard quantum limit

I. INTRODUCTION

As the most stable and accurate frequency references, optical atomic clocks have played an important role in fundamental research [2,3] and practical applications [4-6]. Further improvement in the performance is feasible and promising, indicating that the optical atomic clocks possess great potential in breaking through the boundaries of the contemporary frame of physics. Nevertheless, the frequency stability of the best optical atomic clocks based on cold atomic ensembles trapped in optical lattice still is still limited by the technical noise source (i.e. Dick effect). This effect is not determined by the quantum ensembles but by the performance of the optical local oscillator, and the dead time of the clock operation cycle [7].

To mitigate this problem, diverse routes have been put forward and are being carried out, including improving the performance of the clock laser [8-10] and synchronous clock comparison protocol with two cold ensembles [8,11]. With the continuous efforts engaged in overcoming the Dick effect, we expect that the clock frequency stability will not be limited by the Dick effect finally. However, the quantum projection noise will still be the ultimate limitation. The well-known standard quantum limit can be surpassed by preparing a spin squeezing state of the atomic ensemble, which can be realized with quantum non-demolition (QND) measurements. In [1], we proposed a detection scheme with a SNR high enough to allow for QND measurements, but the photon scattering rate was such that this regime could only be reached with detection times on the order of a few nanoseconds, too short to be practically implemented given the cavity dynamics. In this paper, we propose an essential improvement upon the results of [1], implementing a new detection scheme based on a probe light with a large frequency detuning from the atomic resonance. The small photon scattering rate with this scheme allows us to not only access the classical non-destruction regime, but also the quantum non-demolition regime. By allowing us to preserve and reuse the atoms from cycle to cycle, the dead time of the clock operation cycle and thus the Dick effect can be further reduced. Besides, by using the quantum non-demolition properties [12], the measurements of the number of probes atoms N can surpass the standard quantum limit by spin squeezing protocols, hence further improving the frequency stability [13,14].

II. METHODS AND EXPERIMENTS

As opposed to the typical and traditional detection strategy of the number of atoms on the clock ground state by

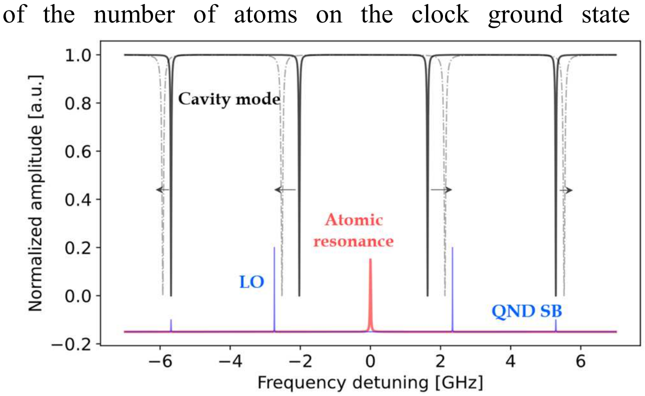

Fig 1. Specific modes of cavity (black curve), atoms (red curve), and QND probe light (blue curve). The shifted cavity modes are displayed by the black-dash line. The horizontal axis indicates the frequency detuning from the atomic resonance.

fluorescence, which totally destroys the atomic coherence [1-4], we use here a 461 nm probe light with a large frequency detuning to the atomic resonance to measure the number of atoms at the clock ground state [1, 12]. Specifically, the 461 nm laser which is generated from the frequency doubling of the 922 nm laser is phase modulated with two cascaded electro-optic modulators (EOMs, one has a modulation frequency of Ω = 2.51 GHz and the other has a modulation frequency of Ω' = 1.48 GHz), and only the modulation sidebands with order (±1, ±2) which have a frequency detuning of ±5.5 GHz to the atomic resonance are coupled into the high finesse bi-chromatic cavity together with the trapping with 813 nm. The carrier of the probe laser is extinct and off-resonant with the cavity. Furthermore, it has an additional 250 MHz frequency detuning from the atomic resonance in order to further reduce the residual scattering it causes. The specific modes between the cavity, atoms, and probe laser are shown in Fig. 1.

The reflected probe light from the cavity is detected by a photodiode and then demodulated at two different frequencies to yield the error signals. The demodulation at the frequency of (2Ω'- Ω), corresponding to the beatnote between the injected sidebands and the reflected (±2, 0) sidebands, yields an error signal proportional to the detuning between the cavity and the probe light. It is fed back to the current of the 922 nm laser and the driver of the AOM simultaneously to ensure the lock of the probe sidebands on the cavity resonance and the elimination of the first-order technical noise. The other error signal demodulated at the frequency of 2Ω', corresponding to the beatnote between injected sidebands and the reflected (±1, 0) sidebands, is fed back to the modulation frequency Ω of the EOM to track the frequency shift of the cavity mode induced by the presence of the atoms. Because the parity of the modulation

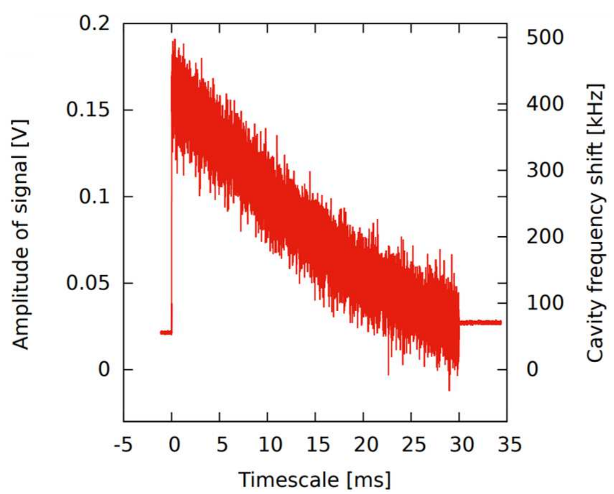

Fig 2. Decayed atomic signal whose amplitude is corresponding to the number of trapped atoms in the lattice. The duration of the detection sequence is 30 ms.

sidebands, the signal is immune to the residual detuning between the probe light and the cavity. The QND probe laser will be used not only to realize the weak measurement of the atomic coherence but also to squeeze the measurement noise of the number of atoms. Determined by the cavity geometry and atomic characteristics, the cooperativity of this scheme is 0.175, which is sufficient to generate the spin squeezing for a typical optical lattice clock.

When the empty cavity starts to be filled with atoms, the cavity mode with positive and negative detuning will experience an opposite frequency displacement, which can be measured by tuning the modulation frequency applied to the EOMs. Readout by the heterodyne measurements, the cavity frequency displacement which corresponds to the number of atoms at the clock ground state can be determined with a high signal-to-noise ratio. The two coupled blue sidebands also form a double with opposite phase at the center of the cavity, such that the atoms are homogeneously coupled with the blue light along the longitudinal direction.

III. Results and Discussions

By adjusting the modulation depth applied to the two cascaded EOMs, the injected power of the two weakly coupled sidebands is reduced to the level of 10 nW, and then we can achieve a rather small photon scattering rate. With a QND detection sequence time T of 30 ms, the decay of the amplitude of the atomic signal (corresponding to the decay of the number of atoms in the lattice) is clearly resolved, as shown in Fig. 2. According to a typical heating function for trapped atoms in the lattice [1], we obtain a fitted photon scattering rate n_γ of 0.06 photon/μs/atom, which is small enough to preserve the atomic coherence when the duration of one probe sequence T is on the order of a few microseconds. Besides, the detection noise δN for the measurement of N, which is acquired from the atomic signal (shown in Fig. 2) after subtracting the heating function fitting

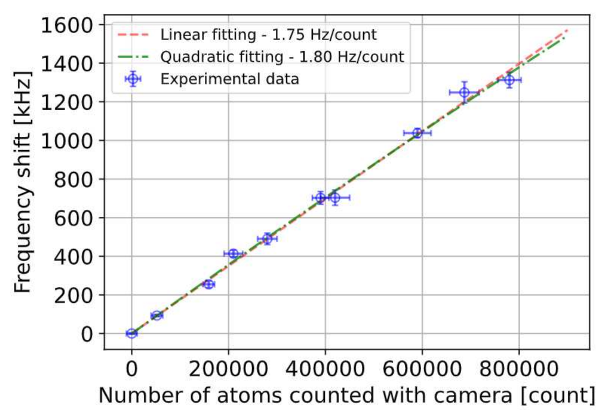

Fig 3. Measured cavity frequency displacement (hollow-blue circles) at different number of atoms which is counted with the intensity of the fluorescence collected by the camera. The red-dash line is the linear fitting curve and green-dot-dash line is the quadratic fitting curve.

data, is determined to be ~ $48/\sqrt{n_\gamma T}$ atoms, where $n_\gamma T$ is the total number of scattered photons for one atom during the probing time T. We found that the detection noise has already approached the photon shot noise determined by the QND probe light. When the total scattering photons $n_\gamma T$ is 0.1 photons, which is necessary for preserving the fragile atomic coherence, the detection noise δN is about 150 atoms, implying that we can in principle observe the quantum projection noise and the spin squeezing state with spin squeezing protocol in case $N > 2.3\times10^4$.

To verify the linearity between the detected signal and the number of atoms, we measured the cavity mode displacement at the different number of atoms which is counted with the intensity of the fluorescence collected by an EMCCD camera, as shown in Fig. 3. We found that there is no obvious difference between the coefficient of the linear fitting and the first-order coefficient of the quadratic fitting. Therefore, the number of atoms at the clock ground state in the cavity can be directly related to the cavity mode displacement which will also be further used as the observable for monitoring the quantum correlations between atoms through multi QND measurements.

IV. Conclusions

We proposed and implemented a quantum non-demolition detection scheme based on a large-frequency detuning probe light, aiming at a direct generation of spin squeezing state on optical clock transition. Benefiting from the large frequency detuning, we obtained a rather small photon scattering rate of 0.06 photons/μs/atom, which can prevent the atoms from escaping from the lattice of an operational clock. Simultaneously, we can also preserve the atomic coherence as long as the total probe time of one probe sequence is on the order of microseconds. Next step, we are going to use the QND protocol to prepare the spin squeezing state on the optical clock transition directly and investigate the metrological improvement with the prepared spin squeezing state [14].

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