A JUGGLING RB FOUNTAIN CLOCK AND A DIRECT MEASUREMENT OF POPULATION DIFFERENCES

Chad Fertig, J. Irfon Rees, and Kurt Gibble, Yale University, New Haven, CT*

ABSTRACT

We demonstrate a new atomic state detection scheme that directly measures the population difference of the two clock states using FM absorption spectroscopy. We also demonstrate a juggling Rb fountain clock that we will use to study collisions of juggled balls of atoms. Juggling can significantly improve the clocks short-term stability without requiring greater signal-to-noise or a larger cold collision frequency shift.

1. INTRODUCTION

Measurements of the cold collision frequency shift in ^{87}Rb fountain clocks have shown the shift to be fractionally at least 30 times smaller than that for Cs. [1,2] The small collision shift allows ^{87}Rb clocks to operate at higher densities and with consequently smaller projection noise. The detections schemes currently used in fountain clocks detect the atomic population in F=4 and then either the population in F=3 or the total number of atoms, to normalize the signal. [1-4] The temporal separation of these two detection pulses aliases the detection laser frequency noise into the detected signal. We are currently exploring detection schemes that simultaneously probe both atomic populations to avoid this difficult source of noise.

We have also begun to juggle atoms in our Rb fountain to study the collisions between juggled balls of atoms. We demonstrate a juggling technique in our single MOT fountain and show a relative stability of the "two" juggled clocks. Juggling will significantly increase the short-term stability of future fountain clocks.

2. DIRECT DETECTION OF POPULATION DIFFERENCES

The naturally large cold collision frequency shift cross-sections for atoms in a fountain clock suggests using as few atoms as possible. To retain sufficient short-term stability to reach the clock's potential accuracy, the detection of the transition probability in the clock should be at least nearly shot-noise limited. Accuracies exceeding 10^{-16} will likely require a short-term stability approaching 10^{-14} per launch. A stability of 10^{-14} per launch requires a detection signal-to-noise ratio S/N of nearly 5,000:1 for ^{87}Rb.

Current fountain clock state detection schemes detect the number of atoms in one state and then either the number in the other state or the total number of atoms. In this way, the transition probability can be normalized to the total number of atoms launched, which is typically stable to not better than 1%. When the 2 detections occur at different times, instabilities in the detection system, such as the frequency noise of the lasers used to excite the atoms, may limit the S/N. To date, the best achieved is S/N = 2300:1. [5]

We have demonstrated a new state detection scheme that directly detects a population difference. We use FM absorption spectroscopy using 2 lasers tuned near the $5S_{1/2}$ $F=2 \rightarrow 5P_{3/2}$ $F'=3'$ and the $1 \rightarrow 0'$ transitions as shown in Figure 1. Because the lasers tuned near $2 \rightarrow 3'$ & $1 \rightarrow 0'$ are on opposite sides of the lines, the partial absorption of each sideband by the atoms creates AM that is phase shifted by 180 degrees as shown in Figure 2. Thus, when the AM's produced by the populations in each clock state have equal magnitudes, the laser light impinging upon the detection photodiode has no AM and the output of the demodulation mixer is zero. Because the detection of both populations is simultaneous, phase locking the lasers probing the different transitions can eliminate the sensitivity to laser frequency noise. McGuirk *et al.* have demonstrated another realization of this idea by stopping the atoms projected into the upper hyperfine state, allowing the atoms projected into the lower state to fall for a short time (spatially separating the atoms), repumping the lower state atoms, and then using differential absorption of the 2 laser beams derived from the same laser (to avoid a sensitivity to laser frequency noise). [6]

The most difficult aspect of our scheme is efficiently detecting the F=1 population. While the $1 \rightarrow 0'$ transition is a closed system, the atoms can quickly optically pump into a non-absorbing m_F state. By applying a magnetic field perpendicular to the linear polarization of the laser, the

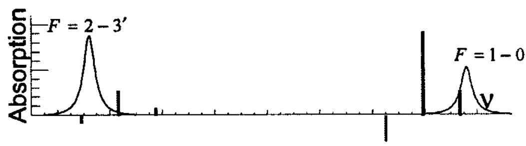

Figure 1. Schematic of ^{87}Rb clock state absorption and the FM laser spectrum. The frequency of the FM is near 50 MHz.

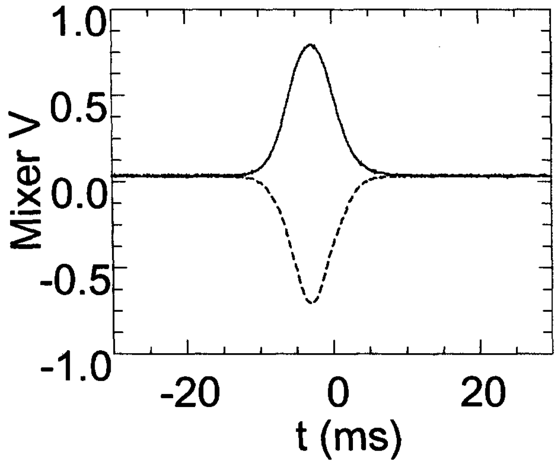

Figure 2. Demodulated time-of-flight FM absorption signal from population in the F=1 state (solid) and F=2 state (dashed). With equal populations, the demodulating mixer output is 0.

atomic absorption is much higher (Figure 3). In Figure 1, we adjust the laser probing 2→3′ to be much less intense than the laser probing 1→0′. Our work to date has almost entirely focused on reducing the ratio of the background detection noise, when there are no atoms, relative to the size of the 1→0′ signal with atoms present.

The most troublesome background noise is residual AM from the EOM phase modulator. We choose the modulation frequency to be not close to piezo-acoustic resonances in the EOM, which can cause a very large and spurious AM. Spatial inhomogeneities in EOM also lead to AM noise. We control the inhomogeneity by launching the laser beam through a single-mode optical fiber after it passes through the EOM. We then servo the AM by detecting the residual AM after the fiber and feeding back with a DC voltage applied across the EOM.[7] Currently this leads to a noise level of 0.26 mV. There is however a quadrature noise that can be much larger. Using balanced detection or different modulation schemes may solve this problem.

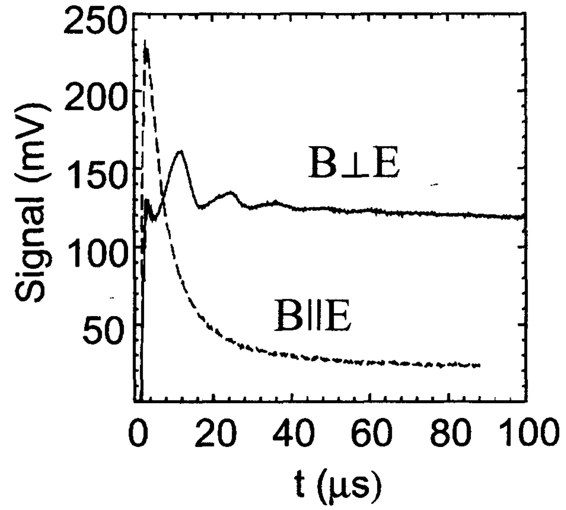

Figure 3. Absorption for the 1→0′ transition as a function of time for B perpendicular to the laser polarization (solid) and parallel (dashed).

3. A JUGGLING RB CLOCK

One can achieve higher stabilities and eliminate the dead time (reducing the requirements for the local reference oscillator) by *juggling* atoms in the fountain[8] as shown in Figure 4. With a S/N = 4600 on a single launch, the frequency uncertainty would be $\delta\nu/\nu = \Delta\nu/(\pi\,\nu\,S/N) = 1\times10^{-14}$. If the cycle time is 1 s, then the fractional instability of the clock after 1s of averaging is $\sigma_y(\tau{=}1s) = 1\times10^{-14}\,\tau^{-1/2}$. By launching balls of atoms at a rate of 25 s^{-1}, the dead time is eliminated and gives a short-term instability of $\sigma_y(\tau) = 2\times10^{-15}\,\tau^{-1/2}$. This improvement is achieved without the technical difficulty of higher S/N or higher atomic densities. There are 2 important problems: 1) shutters, as shown in Figure 4, must be used to block the trapping and cooling light from the interrogation region of the clock; 2) collisions between juggled balls of atoms will shift the frequency of the clock.

We have demonstrated a first version of a juggling Rb fountain to study the frequency shift due to collisions between 2 balls of atoms. The schematic of our single magneto-optic trap (MOT) Rb fountain[1] is shown in Figure 5. Here we rapidly launch 2 balls of atoms at the same velocity from a single trapped ball of atoms. After trapping and launching one ball from the MOT, approximately half of the atoms are depumped into the F=1 ground state. The

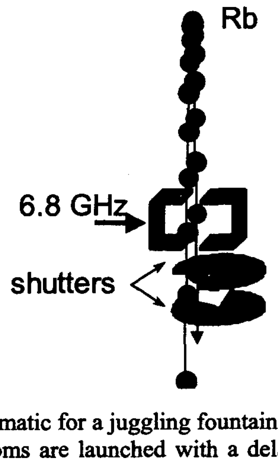

Figure 4. Schematic for a juggling fountain clock. Balls of laser-cooled atoms are launched with a delay smaller than the flight time above the microwave cavity.

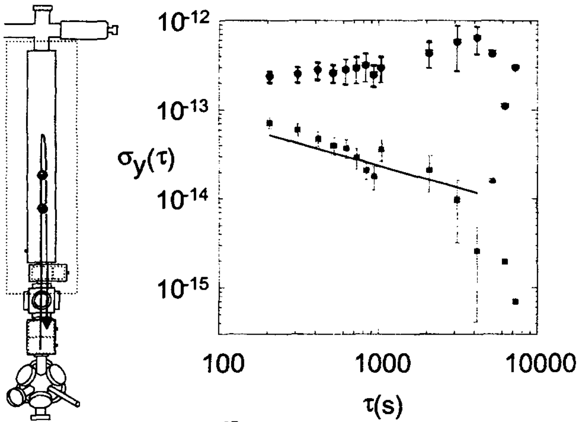

Figure 5. Juggling ^{87}Rb clock. The triangles are the Allan variance for the ^{87}Rb clock versus a quartz oscillator showing the expected deviations of the oscillator. Considering each juggled ball as an individual clock, the squares show the relative stability of these two "clocks" without the oscillator instability.

trapping light is turned back on, recapturing the atoms remaining in F=2. A carefully masked repumping beam keeps these atoms trapped in F=2 until they are launched, 10 to 30 ms later. This second ball is also depumped after launch and then the F=1 m_F=0 atoms in each ball are transferred to the F=2 m_F=0 state with microwaves. The atoms remaining in F=1 are then cleared with a laser beam tuned to the 1→0′ transition.

In Figure 5 we also show the Allan variance for this juggling clock versus the microwaves supplied to the clock which are generated from a quartz oscillator. The triangles show the stability of a "clock" based on each of the two juggled balls of atoms as compared to the quartz oscillator, in agreement with the previously measured stability of the oscillator. We also compare the relative stability of the "clock" based on the first juggled ball against the "clock" based on the second juggled ball, which removes the long-term drift of the quartz oscillator.

In Figure 6 we show a calculation of the s-wave juggling frequency shift for ^{87}Rb.[9] The first Ramsauer-Townsend[10] frequency shift null occurs at 0.12 mK, corresponding to a time delay of 22 ms. Unfortunately, the peak of the s-wave juggling shift is very nearly at a time delay of 44 ms. Therefore, for a juggling rate of 1/(22 ms), the energy for collisions between every other ball would be near the peak of the juggling shift. To cancel the juggling shift, one can launch with a more sophisticated pattern. A pattern that cancels the s-wave shift launches balls with alternate delays of 22 and 55 ms. The energy spectrum for this pattern is also shown in Figure 6. Each ball collides with 1 ball with a 22 ms delay for which there is no shift. Each ball also collides with 1 ball at 55 ms delay, for which the shift is positive, and with 2 balls at 77 ms, where the shift is negative and half as large as the shift at 55 ms, so that there is no net frequency shift. There is no p-wave shift for identical atoms due to Bose symmetry. Higher partial waves will generally have random signs and all of the shifts decrease at higher energies. It is likely that a pattern similar to this will give a high juggling rate and cancel the total juggling collision shift.

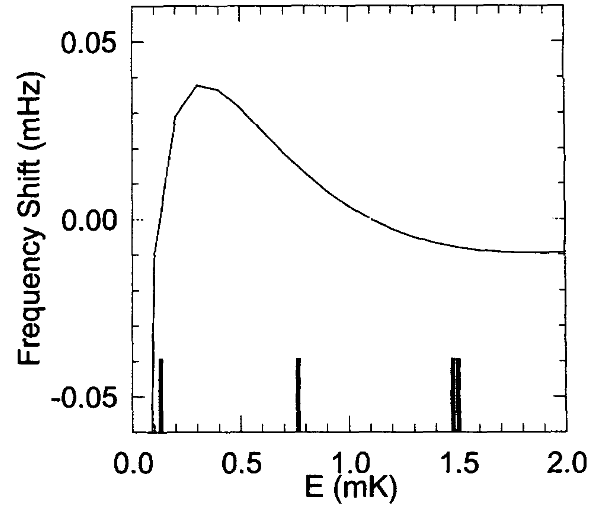

Figure 6. Juggling frequency shift for s-waves. The juggling shift is zero for time delays of 22ms (0.12mK) and 66 ms (1.1mK). The energy spectrum shown corresponds to juggling pattern for alternate launch delays of 22 and 55 ms.

4. CONCLUSIONS

We have demonstrated a new detection technique that directly and simultaneously measures population differences. By detecting simultaneously, the detection can be much less sensitive to the frequency noise of the detection lasers. We have also demonstrated a first version of a juggling fountain clock to study the frequency shifts due to juggling collisions. With a suitable juggling pattern and shutters to block the laser light from the interrogation region, fountain clocks can achieve much higher short-term stability without requiring a higher detection S/N or a larger cold collision frequency shift.

5. ACKNOWLEDGEMENTS

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*Present address: The Pennsylvania State University, University Park, PA.

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