High Spectral Resolution and Accuracy Studies for a Sr Optical Lattice Clock

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***Abstract*—We report recent progress on an optical lattice clock based on the $^1S_0$-$^3P_0$ transition of ^{87}Sr. Improvement of the spectral resolution allows measurement of the magnetically-induced frequency shift with an uncertainty below 10^{-15}. The high line quality factor is expected to yield complete evaluation of systematic effects at that same level in the near future.**

I. Introduction

Optical clocks based on neutral atoms tightly confined in an optical lattice have recently begun to show impressive promise as potential frequency standards [1-4]. These optical lattice clocks provide relatively high signal-to-noise from the large numbers of atoms, while at the same time allowing Doppler-free interrogation of the clock transitions for long probing times. Atomic Strontium provides an exciting candidate for such a clock, since the level structure provides a means for cooling the sample to μK temperatures as well as multiple narrow clock transitions. Several techniques are under investigation for the Sr clock transitions, including free-space spectroscopy of the $^1S_0$-$^3P_1$ transition in ^{88}Sr [5], lattice-based spectroscopy of the $^1S_0$-$^3P_0$ transition in ^{87}Sr [1-4], and state-mixing schemes such as electromagnetically-induced-transparency [6,7] or use of a DC magnetic field [3] for spectroscopy of the strictly forbidden $^1S_0$-$^3P_0$ transition in ^{88}Sr. Currently, detailed evaluations of systematic effects for the sub-Hz natural linewidth transition in ^{87}Sr are being performed in several independent systems [1,2,8]. To this end we present our recent progress toward evaluation of systematic effects below the 10^{-15} level, which has greatly benefited from a much narrower spectral linewidth corresponding to a line quality factor exceeding 2×10^{14}.

II. Experimental System Components

A. Cooling and Trapping Neutral Strontium

The development of optical atomic clocks requires the ability to reach ultracold temperatures with large atom numbers (N). By achieving sufficiently low temperatures, atoms can be tightly confined in the Lamb-Dicke regime in a lattice potential, virtually eliminating adverse Doppler effects on the clock's performance. In addition, the stability of the clock can be improved by $\sqrt{N}$ as larger numbers of atoms are employed. In the case of neutral Sr, we use two cooling transitions (the 32-MHz-wide $^1S_0$-$^1P_1$ transition at 461 nm followed by the 7.4-kHz-wide $^1S_0$-$^3P_1$ transition at 689 nm) in order to cool the atoms to μK temperatures before loading them into the optical lattice. Complete details of the laser cooling apparatus are given in [9,10].

B. Confinement in the Optical Lattice

In order to take advantage of the narrow sub-Hz clock transition offered by ^{87}Sr, the atoms must be held without perturbation to the clock transition for times on the order of 1 s. Free-space spectroscopy of Sr [5] yields troublesome Doppler effects which limit the achievable accuracy. An attractive solution is the tight confinement offered by an optical lattice, which allows long interaction times while essentially eliminating any Doppler or recoil effects. When the optical lattice is operated at the 'magic' wavelength, AC stark shifts induced by the lattice field become equal for the $^1S_0$ and $^3P_0$ energy levels. In this manner, the clock transition frequency is unperturbed by the presence of the lattice field. Our one-dimensional lattice is constructed from a ~300 mW wtanding wave of optical power at the magic wavelength of ~813.4 nm, and is oriented nearly parallel to the direction of gravity. After transfer from the second laser-cooling stage to the lattice, > 10^4 atoms at ~1.5 μK temperatures are confined with a Lamb-Dicke parameter of ~0.3, allowing Doppler- and recoil-free spectroscopy of the clock transition along the axis of the lattice beam.

C. Probe Laser

For the purposes of operating a clock with the best possible stability, it is necessary for the probe laser to have both a narrow intrinsic linewidth as well as small frequency drift and low instability. We probe the extremely narrow natural linewidth of the clock transition in fermionic Sr with a cavity-stabilized diode laser operating at 698 nm. The high-finesse cavity is mounted in a vertical orientation in order to reduce sensitivity to vibrations in the vertical direction [11]. To characterize our clock laser, we compare it to a second stable laser operating at 1064 nm by use of the femtosecond comb described in the next section. Although the probe laser system used for our 2005 systematic measurements had net optical phase noise leading to measured spectra of linewidth > 200 Hz during the measurements, improvements to both the design and construction of the cavity now provide laser linewidths (at 698 nm) below 0.5 Hz for a 3-s integration time and ~ 10 Hz for a 60-s integration time. We believe the measured linewidth is most likely limited by the 1064-nm laser.

D. *Clockwork*

For absolute frequency measurements of the clock transition, we frequency count the probe laser relative to a microwave signal derived from a Hydrogen maser that is calibrated by the NIST primary Cs fountain clock. A diode laser operating near 1320 nm is amplitude-modulated at 950 MHz and transmitted over a 3.5-km fiber optic link from NIST to our lab [12]. A directly-octave-spanning frequency comb similar to that reported in [13] is locked to the probe laser at 698 nm, and is also self-referenced. The ~ 950-MHz harmonic of the comb's repetition rate is frequency counted against the Cs-fountain-calibrated microwave reference in order to perform the absolute frequency measurements. The instability of the frequency-counting signal is $\sim 2.5 \times 10^{-13}$ for a 1-s integration time. At the same time, the frequency comb can be used to form an optical beat against a narrow 1064-nm laser [11] in order to characterize the phase noise and linewidth of the probe laser, as discussed in the previous section.

III. Evaluation of Systematics in 2005

A. *Spectroscopy*

For absolute frequency measurements and investigation of systematic effects, it is first necessary to obtain a repeatable and narrow spectral line. To this end, measurement of the clock transition carrier frequency and its associated motional sidebands (due to confinement in the lattice) was performed. Figure 1(a) shows the axial sidebands well-separated from the narrow carrier. Figure 1(b) also shows a higher-resolution scan of the carrier transition. Typically, spectra with linewidths on the order of ~ 200 Hz were fit as Lorentzians in order to determine the center frequency for evaluation of systematic effects and absolute frequency measurements.

B. *Systematic Effects*

The primary concern for an optical lattice clock is sensitivity of the clock transition to the optical lattice wavelength and intensity. We varied the lattice intensity near our operating wavelength of 813.437(2) nm and determined that a correction to the transition frequency of -17(8) Hz was necessary for the operating intensity of $I_0 \sim 10$ kW/cm^2. By varying the wavelength we also determined

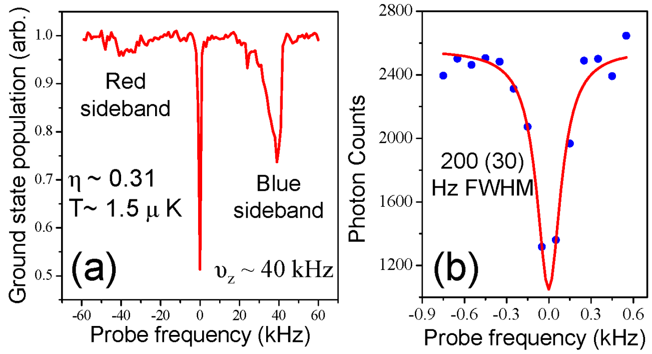

Figure 1. (a) Axial sidebands demonstrating confinement in the Lamb-Dicke regime, and allowing measurement of the sample's temperature. (b) Clock transition, showing the best linewidth used for systematic measurements in 2005 [1].

that for the lattice intensity I_0, the clock transition shifts by ~ 2 mHz for a 1-MHz change in the lattice frequency. From these data the magic wavelength was determined to be 813.418(10) nm, in agreement with [2,4]. For the operation of our lattice clock at the 10^{-18} level of repeatability, our data suggests that the lattice wavelength need only be stabilized within 500 kHz of the magic wavelength.

We also investigated the effect of an applied magnetic field along three orthogonal axes, and determined that no frequency shifts existed to within an uncertainty of 12 Hz. In addition, by varying the density of atoms in the lattice by a factor of 50 we found no statistically significant shift of the transition frequency to within 12 Hz. Finally, the probe intensity was varied, and associated frequency shifts were found to within < 1-Hz uncertainty.

C. *Absolute Frequency*

Taking into account the remaining calculated small frequency shifts (0.7 Hz for the gravitational shift and 2.2 Hz for the blackbody shift), our final reported value for the absolute frequency of the $^1S_0$-$^3P_0$ transition in ^{87}Sr was 429,228,004,229,869 $\pm 19_{sys} \pm 2.8_{stat}$ Hz [1]. From the statistical uncertainty of 6.5×10^{-15}, the excellent stability and repeatability of our apparatus is evident over the full

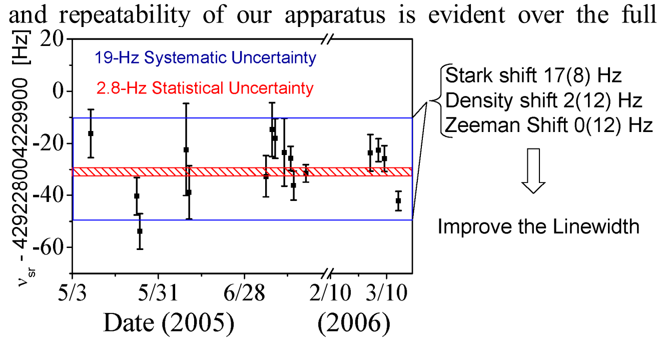

Figure 2. Date record, corrected for systematic effects, of the measured center frequency for the Sr optical lattice clock as reported in [1]. Also included are some preliminary points for additional measurements in 2006. The three most significant sources of systematic uncertainty can be improved by use of a narrower line and with additional averaging.

measurement period of 3 months, as shown in fig. 2. The measurement in [2] used a GPS uplink for the absolute frequency reference, and reported a value that disagrees with ours by ~80 Hz. The 80-Hz error made by [2] has since been resolved; a third independent measurement reported in [8] is now in good agreement with our value. In addition, new preliminary results from the Tokyo group agree [14], although a rigorous and objective check of the measurement still needs to be performed.

The systematic uncertainty of 19 Hz is by no means a limit to the attainable accuracy of our clock; it can easily be significantly reduced by averaging against a more stable reference and taking advantage of a narrower spectral linewidth. The magnetic-induced frequency shift uncertainty has already been improved by a factor of 20 by achieving a much narrower spectral linewidth for the transition, as will be seen in the following section.

IV. Improved Resolution and Accuracy

A. High Spectral Resolution

By improving the design and construction of the probe laser, its linewidth has been dramatically reduced. When compared against the 1064-nm narrow laser via the frequency comb, linewidths of 300 mHz at 1064 nm are revealed, RBW-limited, as shown in fig. 3(a). Most likely the measurement is limited by the performance of the 1064-nm laser. In 60 s of averaging time, the linewidth is < 7 Hz as shown in fig. 3(b), allowing spectroscopic scans of the carrier frequency to enjoy the benefits of a very stable local oscillator.

An interesting measurement allowed by this improved resolution is to directly probe the radial sidebands caused by transverse confinement in the lattice beam, shown in fig. 4(a) at ~ 120 Hz from the carrier. More importantly, the carrier frequency itself now has a repeatable linewidth of < 5 Hz (Q ~ 10^{14}); one example is shown in fig. 4(b). With this improved spectral resolution we are in the progresss of pushing the measurements of systematic effects below the 10^{-15} level of uncertainty, limited by the microwave frequency reference we employ.

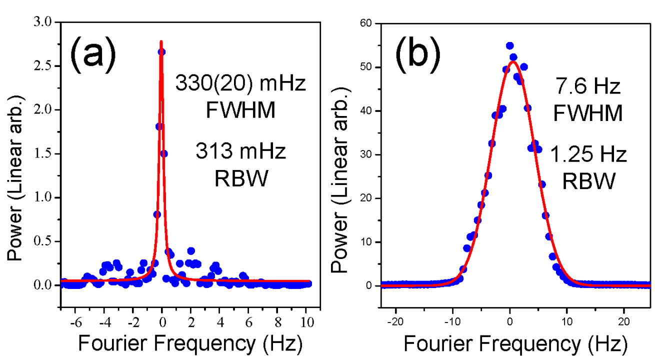

Figure 3. (a) Resolution-bandwidth-limited relative linewidth between the 698-nm probe laser and a narrow 1064-nm reference laser, measured at 1064 nm via a frequency comb, for 3-s averaging time. (b) Identical measurement, taken with a 60-s averaging time

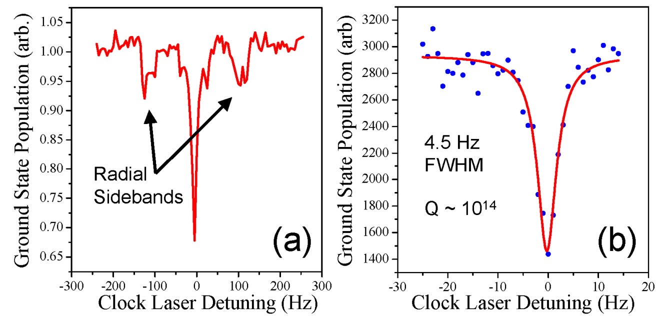

Figure 4. (a) Improvement to the spectroscopic resolution allows the radial sidebands caused by the lattice waist to be measured at ~ 120 Hz offset from the carrier. (b) The clock transition linewidth is now routinely measured to be < 5 Hz.

B. Magnetic Field Systematic

The systematic uncertainty benefiting most directly from the improved line quality factor is the magnetically-induced frequency shift. The differential g-factor of ~ 110 × m_f Hz/G between the ground and excited states of the clock transition can lead to broadening or frequency shifts from stray magnetic fields, depending on the population distribution among the magnetic sublevels. By varying the strength of an applied magnetic field in three orthogonal directions and measuring the spectral linewidth as a function of field strength, the uncertainty of the residual magnetic field has been reduced to < 15 mG for each axis. This is shown in fig. 5(a) for the axis which demonstrated the greatest sensitivity of frequency shift to applied magnetic field, as shown in fig. 5(b). The resulting net uncertainty for magnetically-induced frequency shifts is now 0.5 Hz (1 × 10^{-15}). These measurements were performed using a 50-Hz spectral linewidth; use of the 5-Hz spectra is expected to further decrease the uncertainty of frequency shifts caused by the residual magnetic field.

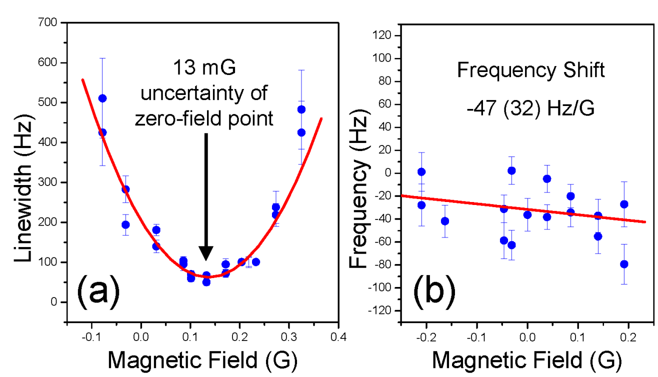

Figure 5. (a) Measurement of the transition linewidth as a function of applied magnetic field along one axis allows calibration of the zero-field point to within an uncertainty of 13 mG. With the improved sub-5-Hz linewidth even more accuracy should be attainable. (b) Simultaneous measurement of the frequency shift with respect to the applied magnetic field then allows the Zeeman shift to be determined with an uncertainty of only ~ 1 × 10^{-15}.

C. *Other Improvements*

Reduction of the other systematic uncertainties (density and lattice intensity) should be straightforward with the improved spectral resolution we now achieve. In fact, in order to take full advantage of the accuracy of our microwave reference, we have begun stabilizing the microwave phase of the fiber link used to transmit the reference from NIST to JILA. Still, the averaging times necessary to achieve 10^{-15} accuracy for all systematic effects are long. Knowing this, we have recently locked the probe laser to the clock transition, with the eventual goal of optically comparing the Sr clock to other nearby optical clocks at NIST such as Hg^+, Al^+, and Yb.

V. Conclusion

We have experimentally measured the dominant sources of systematic uncertainty in an optical lattice clock based on the $^1S_0$-$^3P_0$ transition in ^{87}Sr, including frequency shifts due to lattice wavelength and intensity, magnetic field, density, and probe intensity. The frequency we report is $429{,}228{,}004{,}229{,}869 \pm 19_{sys} \pm 2.8_{stat}$ Hz. The systematic uncertainty was chiefly limited by averaging time or, in the case of the Zeeman shift, spectral linewidth. With an improved probe laser, the spectral linewidth (quality factor) is routinely 4.5 Hz (1×10^{14}). The uncertainty in the Zeeman shift has now been reduced to 1×10^{-15}, and the overall uncertainty from systematic shifts is expected to reach below 10^{-15} in the near future.

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