# QUANTUM METROLOGY WITH LATTICE-CONFINED ULTRACOLD SR ATOMS

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Quantum state engineering of ultracold matter and precise control of optical fields have together allowed accurate measurement of light-matter interactions for applications in precision tests of fundamental physics. State-of-the-art lasers maintain optical phase coherence over one second. Optical frequency combs distribute this optical phase coherence across the entire visible and infrared parts of the electromagnetic spectrum, leading to the direct visualization and measurement of light ripples. At the same time, ultracold atoms confined in an optical lattice with zero differential ac Stark shift between two clock states allow us to minimize quantum decoherence while strengthening the clock signal. For $^{87}$Sr, we achieve a resonance quality factor >2.4 x $10^{14}$ on the $^1S_0 - {}^3P_0$ doubly forbidden clock transition at 698 nm [1]. The uncertainty of this new clock has reached 1 x $10^{-16}$ and its instability approaches 1 x $10^{-15}$ at 1 s [2]. These developments represent a remarkable convergence of ultracold atoms, laser stabilization, and ultrafast science. Further improvements are still tantalizing, with quantum measurement and precision metrology combining forces to explore the next frontier.

## 1. Introduction

In the last decade, the performance of frequency standards based on optical atomic transitions has grown considerably. The performance advancements of these systems are derived from their superior resonance quality factors. Currently, the most accurate optical clocks are based on single trapped ions [3], due to the exquisite control that is possible over their electronic and motional quantum states, as demonstrated in both clock and quantum information experiments. On the other hand, large ensembles of neutral atoms enjoy high measurement precision from the simultaneous measurement of each atom in the ensemble, providing a powerful averaging of measurement noise. However, a

longstanding challenge for these neutral atom systems is achieving control and measurement at uncertainties similar to that for single, trapped particles. In particular, motional effects have played a prominent role in limiting neutral atom systems, where traditionally ion-based standards have benefited from a strongly confined measurement environment. Recently, properly designed optical traps [4] have made the use of large neutral atom ensembles compatible with the benefits of atomic confinement. This is possible by ensuring that the ac Stark shifts induced on the two clock states by the optical lattice are equal, leading to zero shift of the clock transition [5]. Implementing a carefully designed frequency standard based on atomic strontium in a one dimensional optical lattice, we have demonstrated an optical frequency standard with a systematic uncertainty at the $10^{-16}$ level [2], smaller than that of the best Cs fountain primary standards. The evaluation was made possible by a remote comparison of the Sr optical lattice frequency standard to the NIST cold Ca optical standard over a phase-stabilized optical fiber network [6].

Through rigorous experimental evaluations of the Sr standard at this level, we highlighted two key systematic shifts that must be overcome to further improve this system. The first is frequency shifts induced by the blackbody radiation. We offer approaches to improving the precision of the known blackbody shift and also reducing its uncertainty. Secondly, high precision characterization of the Sr frequency standard has uncovered surprisingly non-negligible frequency shifts induced by collisions between the fermionic Sr atoms trapped in the optical lattice. By experimentally identifying the underlying collisional mechanism responsible for these shifts, we have shown that this effect can be substantially reduced and controlled, facilitating further progress of the Sr optical lattice standard.

## 2. Characterization of the Sr optical frequency standard

Our Sr optical frequency standard is based on ultracold neutral $^{87}$Sr atoms confined in a one dimensional optical lattice where the differential Stark-shift between the clock states is cancelled [4]. Depending on the operational mode, the Sr sample undergoes state preparation by spin-polarization to one or two nuclear spin states prior to spectroscopic probing. The clock transition from each of the two nuclear spin states is excited one at a time. Spectroscopy of both states allows for measurement and cancellation of some nuclear spin-dependent shifts on the clock transition, such as the first order Zeeman shift and the vector ac Stark shift induced by the optical lattice. Further details of the

experimental operation of the Sr optical standard can be found in several references [e.g., 7,2].

To characterize the Sr optical standard located at JILA, we have constructed a remote fiber optic link between JILA and the NIST Boulder Campus [6] with optical carrier phase stabilization. This link permits high precision measurement between the Sr system and other optical standards at NIST. In particular, frequency measurement against a free-space Ca optical standard enabled direct determination of the most critical systematic shifts of the Sr standard at or below $10^{-16}$ fractional uncertainty [2]. The results of these measurements are summarized in Table 1, presenting the final error budget for the Sr standard. The combined uncertainty is $1.5 \times 10^{-16}$, which demonstrates the high potential accuracy of this system, with room for further improvement.

Table 1. Systematic frequency corrections and their associated uncertainties for the $^{87}Sr\ ^1S_0 - {}^3P_0$ clock transition.

| Contributor | Shift ($10^{-16}$) | Uncertainty($10^{-16}$) |
|---|---|---|
| Lattice Stark (scalar/tensor) | -6.5 | 0.5 |
| Fourth order lattice | -0.2 | 0.2 |
| Blackbody Stark | 52.1 | 1.0 |
| Probe ac Stark | 0.2 | 0.1 |
| First-order Zeeman | 0.2 | 0.2 |
| Second-order Zeeman | 0.2 | 0.02 |
| Collision | 8.9 | 0.8 |
| Line pulling | 0 | 0.2 |
| Servo error | 0 | 0.5 |
| Second-order Doppler | 0 | <<0.01 |
| Other | 0 | .1 |
| TOTAL | 54.9 | 1.5 |

The stability of the Sr standard has been measured by making frequency comparisons between the Sr standard at JILA and the Yb standard at NIST [8], both optical lattice clock systems. The results of this measurement are shown in Figure 1, in the form of total deviation. The 1-s instability of $1 \times 10^{-15}$ is given by the free-running stabilities of the interrogation lasers. At longer timescales

just above 1000 s, the combined instability of the two standards reaches below $1 \times 10^{-16}$.

We have also performed a 50-hour-long absolute frequency measurement of the strontium transition referenced to the NIST-F1 Cs fountain standard [7]. This yields a value for the Sr clock transition frequency with a fractional uncertainty of $8.6 \times 10^{-16}$, limited by the NIST H-maser and the Cs fountain standard used in the measurement. This represents our fifth, and the most accurate, measurement of the $^{87}$Sr clock frequency. It is also one of the most accurate absolute frequency measurements of an optical standard to date. Combining these measurements with those of other groups (Paris, Tokyo), a measurement record of the Sr clock transition is established as the most agreed upon optical standard and it has been used to more tightly constrain fundamental constant variations due to gravitational coupling [9].

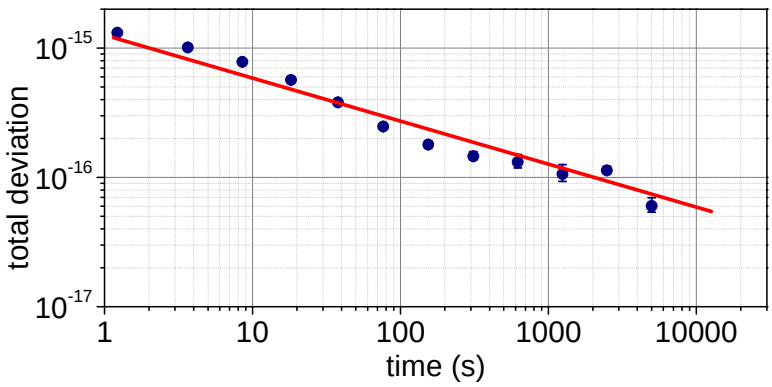


Figure 1. Instability between Sr and Yb optical lattice clocks as measured by the total deviation, in units of fractional frequency.

We have identified two main systematic uncertainties limiting the overall Sr clock accuracy. The first is the uncertainty in the blackbody-radiation-induced frequency shift and the second is the density-dependent shift of the clock transition. We now discuss each of these two mechanisms in more detail, emphasizing the further reduction of their contributions to the overall uncertainty.

## 3. Blackbody-induced shift

The fractional frequency shift caused by the blackbody radiation is proportional to the differential static polarizability of the two clock states, $5s^2\ ^1S_0$ and $5s5p\ ^3P_0$. Because of its dominant coupling to the well-characterized $5s5p\ ^1P_1$ state, the $5s^2\ ^1S_0$ ground state has a static polarizability that has been determined with an uncertainty of ~ 0.1%. Meanwhile, the static polarizability of the $5s5p\ ^3P_0$ state is known only at the 1% level. The $^3P_0$ state therefore dominates the uncertainty in the differential static polarizability. This yields a $7 \times 10^{-17}$ uncertainty in the blackbody shift of the Sr clock transition [10]. By reducing the uncertainty of the $^3P_0$ state polarizability to a similar 0.1% level as for the $^1S_0$ state, the possibility is opened for nearly an order of magnitude reduction in the blackbody shift uncertainty, down to $1 \times 10^{-17}$.

We have identified four low-lying even-parity intermediate states that have a combined contribution to the total static polarizability of the $^3P_0$ state at the level of 90%. When the combined contributions from these four states are determined from experimental data at 0.1% accuracy and the contributions of all other discrete and continuum states are known at the level of 1-2% from calculations, the final 0.1% uncertainty for the polarizability of the $^3P_0$ state will be achieved. The residual contributions from the states outside the four dominant ones have indeed been calculated at the percent level, leaving an urgent need for high precision measurements of contributions from the four dominant states [11]. Their dipole coupling strength to the $^3P_0$ clock state must be determined. Some constraints on their values are already available because of the strong contributions these couplings make to the dynamic polarizability. For example, at the magic wavelength near 813 nm, the dynamic polarizability of $^3P_0$ is identical to the well known value of that of $^1S_0$. Also, measurements of the ac Stark shift at the clock transition frequency have been made [2], helping to determine the dynamic polarizability of $^3P_0$ at 698 nm. When these types of measurements are combined with others, like direct decay rate measurements from the intermediate states to $^3P_0$, the individual contributions can be fully constrained. Reference [11] provides more detailed discussions on this theory and the corresponding experimental planning.

Another important effort to reducing the blackbody shift uncertainty is to bathe the atoms in a more well-defined and controlled blackbody environment than what has been typically accomplished in optical lattice systems. This reduces primarily to a task of maintaining careful temperature homogeneity of the blackbodies surrounding the atomic sample. Cryogenic shields have been used in trapped ion experiments to reduce the blackbody shift and thus its

uncertainty. An alternative approach [2] is to load the atoms into a blackbody cavity prior to clock spectroscopy, similar in spirit to those used in infrared radiation metrology. By limiting optical access to small solid-angle viewports for the lattice and clock lasers, the effective emissivity inside a carefully designed blackbody chamber can reach very nearly unity. Then with a careful, homogenous temperature control over the small blackbody chamber, the radiation bath surrounding the atoms can be measured and controlled to enable direct determination of the blackbody shift as the chamber temperature is varied. This direct measurement will then further constrain the differential static polarizability. While such an approach incurs experimental complexity in loading atoms into and controlling the blackbody chamber, it avoids many complexities associated with cryogenic operations. Note that this approach is particularly feasible for atoms held by laser beams, where no trap electrodes are present that can introduce uncontrolled heat loads into the atom environment [12].

## 4. Collision induced shift

An interesting discovery in our push for ever increasing accuracy of the $^{87}$Sr standard is the collision-induced frequency shift on the clock transition. The result is somewhat unexpected, as these atoms are fermions prepared at ultracold temperatures. As the Pauli exclusion principle dictates that identical fermions avoid interactions at ultracold temperatures, interatomic collisions should be strongly suppressed. However, with confinement in the 1-D optical lattice, atoms in different transverse motional states could experience slightly different Rabi rates of excitation. Therefore, at a particular lattice site, while each atom evolves coherently, the atoms evolve to non-identical superpositions of the clock states, at which point they are able to collide. The Rabi excitation pulse is on the order of 100 ms, while the transverse trap oscillation frequency in our lattice is about 450 Hz, giving ample opportunity for collisions. As shown in Figure 2, we have measured this density-dependent collisional shift and its dependence on the excited state fraction, for different atomic sample temperatures. The shift becomes larger at warmer temperatures as the atoms occupy more (transverse) motional states and the Rabi excitation inhomogeneity becomes more pronounced. By misaligning the clock probe beam relative to the strong confinement axis of the lattice, we can further enhance the excitation inhomogeneity, as the effect increases along the weaker, transverse confinement axes. In this case, we also observe an increase in the observed shift [13]. Collision theories incorporating the excitation-inhomogeneity-induced s-wave

collisions between fermionic atoms have confirmed these experimental observations.

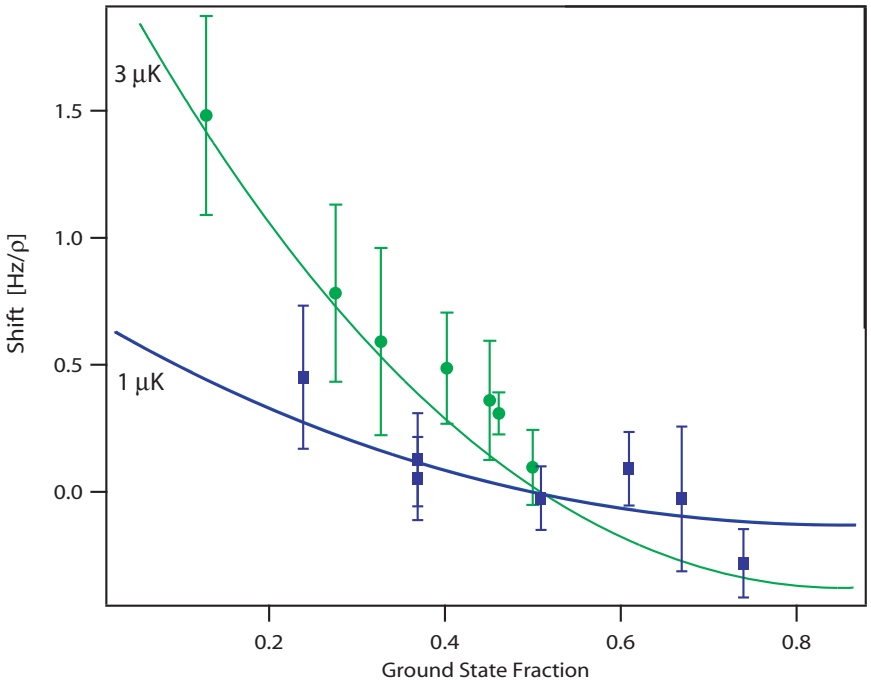


Figure 2. Collisional frequency shift at a given density, as a function of ground state fraction after spectroscopy. The solid circles present the observed shifts for atoms at 3 μK, while the solid squares are for atoms that have been cooled to 1 μK. The solid lines represent theory calculations that are based on excitation-inhomogeneity-induced s-wave collisions between $^{87}$Sr atoms during the clock excitation sequence. Note the zero crossing in the shift near the 50-50 mixture of ground and excited state atoms. ρ is the atomic density of $10^{11}$/cm$^3$.

Significant to the clock operation, we have experimentally observed that if we operate the clock transition at near the 50% excited state fraction (see Figure 2), the collision shift reduces to zero. Since the excitation fraction can be straightforwardly controlled at or better than the few percent level, we can further reduce the collision shift uncertainty beyond the value reported above. Therefore, with a proper design, the 1-D optical lattice clock system continues to offer increased performance. Furthermore, moving to higher dimensional lattices has two possible advantages from the perspective of collisional effects. The first is that by going to higher dimensions, the number of lattice sites

increases, giving fewer atoms per lattice site and thus reducing collisions. Second, with strong confinement along all dimensions, the atoms are excited more uniformly. As the excited atoms remain identical, the collision mechanism we have identified is further suppressed. We anticipate that atomic collisions will not be a problem in these optical lattice clocks. As we advance the clock inaccuracy below 1 x $10^{-17}$, resonant dipole interactions between neighboring atoms and the related frequency shift might become an interesting interaction to study [14].

## 5. Conclusions

In our earlier studies we identified two main systematic uncertainties that limited the accuracy of our $^{87}$Sr optical clock at the 1 x $10^{-16}$ level [2]. Since then we have performed a theoretical study of the blackbody radiation-induced frequency shifts and a detailed experimental measurement of density-dependent collisional frequency shifts. These studies now show that both systematic uncertainties have potential to be reduced by an order of magnitude or more.

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## References

1. M. M. Boyd, T. Zelevinsky, A. D. Ludlow, S. M. Foreman, S. Blatt, T. Ido, and J. Ye, "Optical atomic coherence at the one second time scale," Science **314**, 1430 – 1433 (2006).
2. A. D. Ludlow, T. Zelevinsky, G. K. Campbell, S. Blatt, M. M. Boyd, M. H. de Miranda, M. J. Martin, J. W. Thomsen, S. M. Foreman, J. Ye, T. M. Fortier, J. E. Stalnaker, S. A. Diddams, Y. Le Coq, Z. W. Barber, N. Poli, N. D. Lemke, K. M. Beck, and C. W. Oates, "Evaluation of a Sr lattice clock at 1x$10^{-16}$ via remote optical comparison with a Ca clock," Science **319**,1805-808 (2008).
3. T. Rosenband, D. B. Hume, P. O. Schmidt, C. W. Chou, A. Brusch, L. Lorini, W. H. Oskay, R. E. Drullinger, T. M. Fortier, J. E. Stalnaker, S. A. Diddams, W. C. Swann, N. R. Newbury, W. M. Itano, D. J. Wineland, and

J. C. Bergquist, "Frequency ratio of Al+ and Hg+ single-ion optical clocks; Metrology at the 17th decimal place," Science **319**,1808-1812 (2008).

4. J. Ye, H. J. Kimble, and H. Katori, "Quantum state engineering and precision metrology using state-insensitive light traps," Science **320**, 1734-1738 (2008).
5. H. Katori, M. Takamoto, V. G. Pal'chikov, V. D. Ovsiannikov, "Ultrastable Optical Clock with Neutral Atoms in an Engineered Light Shift Trap," Phys. Rev. Lett. **91**, 173005 (2003).
6. S. M. Foreman, A. D. Ludlow, M. H. G. de Miranda, J. Stalnaker, S. A. Diddams, and J. Ye, "Coherent optical phase transfer over a 32-km fiber with 1-s instability at $10^{-17}$," Phys. Rev. Lett. **99**, 153601 (2007).
7. G. K. Campbell, A. D. Ludlow, S. Blatt, J. W. Thomsen, M. J. Martin, M. H. de Miranda, T. Zelevinsky, M. M. Boyd, J. Ye, S. A. Diddams, T. P. Heavner, T. E. Parker, and S. R. Jefferts, "Absolute frequency measurement of the $^{87}$Sr optical clock transition," Metrologia **45**, 539 – 548 (2008).
8. N. Poli, Z. W. Barber, N. D. Lemke, C. W. Oates, L. S. Ma, J. E. Stalnaker, T. M. Fortier, S. A. Diddams, L. Hollberg, J. C. Bergquist, A. Brusch, S. Jefferts, T. Heavner, and T. Parker, "Frequency evaluation of the doubly forbidden $^1S_0$ - $^3P_0$ transition in bosonic $^{174}$Yb," Phys. Rev. A **77**, 050501(R) (2008).
9. S. Blatt, A. D. Ludlow, G. K. Campbell, J. W. Thomsen, T. Zelevinsky, M. M. Boyd, J. Ye, X. Baillard, M. Fouché, R. Le Targat, A. Brusch, P. Lemonde, M. Takamoto, F.-L. Hong, H. Katori, V. V. Flambaum, "New limits on coupling of fundamental constants to gravity using $^{87}$Sr optical lattice clocks," Phys. Rev. Lett. **100**, 140801 (2008).
10. S. G. Porsev and A. Derevianko, "Multipolar theory of blackbody radiation shift of atomic energy levels and its implications for optical lattice clocks," Phys. Rev. A **74**, 020502 (2006).
11. S. G. Porsev, A. D. Ludlow, M. M. Boyd, and J. Ye, "Determination of Sr properties for a high accuracy optical clock," Phys. Rev. A **78**, 032508 (2008).
12. M. Chwalla, J. Benhelm, K. Kim, G. Kirchmair, T. Monz, M. Riebe, P. Schindler, A. S. Villar, W. Haensel, C. F. Roos, R. Blatt, M. Abgrall, G. Santarelli, G. D. Rovera, and Ph. Laurent, arXiv:0806.1414 (2008).
13. G. K. Campbell, et al., to be published (2008).
14. D. E. Chang, J. Ye, and M. D. Lukin, "Controlling dipole-dipole frequency shifts in a lattice-based optical atomic clock," Phys. Rev. A **69**, 023810 (2004).