The Yb and Ca Standards: Approaches to High Stability, High Accuracy, and Transportable Optical Atomic Clocks

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Over the past 5-10 years the field of optical atomic clocks has grown rapidly, not only with several new candidates for clock transitions emerging, but with the development of new types of systems as well. These new systems include quantum logic clocks based on pairs of trapped ions [1], as well as clocks based on large numbers of neutral atoms tightly confined in optical lattices [2]. In this talk I will present two different types of neutral atom optical clocks. The first is based on a highly forbidden transition at 578 nm [3] and uses an even isotope of Yb (in contrast to odd isotopes used in other mature lattice-based clocks) [2,4,5]. The second uses a more traditional approach, in which millions of Ca atoms are first trapped in a magneto-optic trap and then released to expand ballistically under the influence of gravity during the spectroscopic period [6]. As I will emphasize in this talk, the differences in potential performance and complexity of these two systems illustrate some of the key trade-offs that currently exist in neutral atom clock design.

Lattice-based clocks have tremendous potential for high accuracy due to the Doppler suppression that results from tight confinement of atoms in the sub-micron potential wells of the optical lattice. Additionally, narrow, high signal-to-noise spectroscopic features can be resolved due to the large number of confined atoms (10^4–10^6) and long confinement times (~ 1 s). In principle, these signals could support a fractional frequency instability as low as 10^{-16} @ 1 s, if one could build a sufficiently stable local oscillator. Yb is an interesting choice for lattice work since it has many abundant isotopes, with three different values of nuclear spin to choose from (I=1/2 for ^{171}Yb, I=5/2 for ^{173}Yb, and I=0 for its many even isotopes). Working with spin zero atoms has some potential advantages due to their experimental simplicity (e.g., no optical pumping effects, reduced magnetic sensitivity), although a modest external magnetic bias field is needed to induce a non-zero probability for excitation of the $^1S_0$- $^3P_0$ clock transition. We are presently working with ^{174}Yb atoms confined in an optical lattice tuned to 759.35 nm, the wavelength that minimizes lattice-induced shifts for the clock transition. As this wavelength lies 0.4 nm below a two-photon transition from the upper clock state to a higher lying J=0 state, it will be important to investigate the possible shifts that could result. Interestingly, it may be possible to suppress these shifts with optimal choice of lattice polarization [7].

Ytterbium atoms are prepared for loading into the lattice through two stages of magneto-optic traps, the first at 399 nm, with the second at 556 nm. We typically load about 10^4 atoms into a 1-D standing wave (well depth ~ 50 μK) with a residual atom temperature of about 15 μK [3]. With the 578 probe light co-propagating with the lattice light, we have resolved spectroscopic features with linewidths below 5 Hz (FWHM). Recently we have constructed a new probe laser system based on sum frequency generation of fiber laser light at 1.03 μm with a solid state source at 1.319 μm. With roughly 50-100 mW from each of the infrared sources, we generate more than 10 mW of yellow light in a single-passed periodically-poled waveguide. This light is then stabilized on a fringe of high-finesse ULE cavity mounted in a vertical geometry [8]. Latest spectroscopic results will be presented.

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The second clock is based on $^1S_0$-$^3P_1$ intercombination line at 657 nm (natural linewidth ~ 375 Hz) in neutral ^{40}Ca [6,8]. Atoms are first loaded from an atom beam into a magneto-optic trap that uses the $^1S_0$-$^1P_1$ cooling transition at 423 nm. More than 50 mW of cooling light can be produced through frequency doubling of a semiconductor laser system at 846 nm. After a 2.5 ms loading period, the atoms are interrogated for 0.5 ms with a four pulse Borde-Ramsey excitation sequence. The probe laser system uses an external cavity diode laser that is prestabilized on a fringe of a environmentally-isolated high finesse resonator. Due to the large number of atoms in the sample (5 x 10^6) and the short measurement cycle, low instability (~ 3.5 x 10^{-15} @ 1 s) can still be achieved with relatively modest spectroscopic linewidths (Δν ~ 1 kHz) . In Figure 1 we show an Allan Deviation for the effective beatnote between the Ca and Yb optical clocks. A broadband mode-locked fs-laser frequency comb was used to bridge the 70 THz gap between the clock frequencies [9]. Due to the relatively simplicity of the laser systems involved, this version of calcium clock is fairly robust (it has stay locked continuously for periods of 12 hours or more) and could be made reasonably compact. Doppler-related effects lead to higher clock uncertainties (>10^{-14}) than those of their lattice-based counterparts, but for many applications, stability and robustness may be more important than absolute frequency performance.

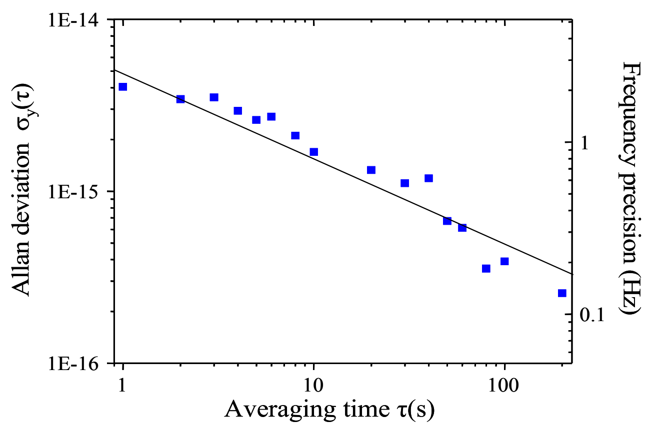

Figure 1. Allan deviation (squares) of the effective beatnote between the Yb and Ca standards. Shown for reference is line corresponding to an Allan deviation of 5 x $10^{-15}\tau^{-1/2}$. We estimate that the standards contribute similarly to the Allan Deviation.

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1) P. O. Schmidt, T. Rosenband, C. Langer, W. M. Itano, J. C. Bergquist, and D. J. Wineland, Science **309**, 749 (2005).

2) M. Takamoto, F.-L. Hong, R. Higashi, and H. Katori, Nature (London) **435**, 321 (2005).

3) Z. W. Barber, C. W. Hoyt, C. W. Oates, L. Hollberg,A. V. Taichenachev, and V. I. Yudin, Phys. Rev. Lett. **96**, 083002 (2006).

4) A.D. Ludlow, M.M. Boyd, T. Zelevinsky, S.M. Foreman, S. Blatt, M. Notcutt, T. Ido, and J. Ye, Phys. Rev. Lett. **96**, 033003 (2006).

5) R. Le Targat, X. Baillard, M. Fouche, A. Brusch, O. Tcherbakoff, G. Rovera, and P. Lemonde, Phys. Rev. Lett. **96**, 103003 (2006).

6) U. Sterr, C. Degenhardt, H. Stoehr, Ch. Lisdat, H. Schnatz, J. Helmcke, F. Riehle, G. Wilpers, Ch. Oates, and L. Hollberg, Comptes Rendues Physique **5**, 845 (2004).

7) A. V. Taichenachev, V. I. Yudin, V. D. Ovsiannikov, and V. G. Pal'chikov, Phys. Rev. Lett. **97**, 173601 (2006).

8) C. W. Oates, E. A. Curtis, and L. Hollberg, Opt. Lett. **25**, 1603 (2000).

9) T. Fortier, A. Bartels, and S.A. Diddams, Opt. Lett. **31**, 1011 (2006).