

## OPTICAL ATOMIC CLOCKS BASED ON LASER-COOLED CA AND YB ATOMS

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Intercombination transitions in alkaline earth-like systems can provide nearly ideal references for state-of-the-art optical atomic clocks due to their narrow linewidths, insensitivity to external perturbations, and convenient wavelengths. We are presently developing two clocks based on such transitions in our neutral atom optical clock laboratory. One clock uses laser-cooled calcium atoms [1] that freely expand during the clock spectroscopy, while the other uses ytterbium atoms that are held in an optical lattice [2,3].

The calcium clock is based on the  $^1S_0 \leftrightarrow ^3P_1$  transition at 657 nm, which has a natural linewidth of 375 Hz. Using the strong  $^1S_0 \leftrightarrow ^1P_1$  transition at 423 nm, we load  $10^7$  atoms from a Zeeman-slowed thermal beam into a magneto-optic trap (MOT) with a resulting atom temperature of 2 mK. If further cooling is desired, a second stage of laser cooling based on quenching the clock transition can reduce the atom temperature to 10  $\mu$ K [1]. With microkelvin atoms we have performed absolute frequency measurements of the clock transition with an uncertainty of 3.4 Hz (or fractionally,  $\Delta\nu/\nu_0 = 7.5 \times 10^{-15}$ ) [4]. Presently we are investigating the performance capabilities of a calcium clock that uses just the first stage of cooling and thus can have a very short measurement cycle time (atom preparation time + clock spectroscopy time = 3 ms) [5]. The apparatus for such a system could be fairly compact yet still achieve high stability ( $< 4 \times 10^{-15}$  @ 1 s), making it suitable for many transportable clock applications.

The second optical clock is based on the highly forbidden  $^1S_0 \leftrightarrow ^3P_0$  transition at 578 nm in  $^{174}\text{Yb}$  [3]. We load  $10^4$  atoms into a 1-D optical lattice through the use of two stages of laser cooling. During the first stage, atoms are loaded from an atomic beam into a MOT and cooled to  $< 5$  mK with light tuned just red of the strong  $^1S_0 \leftrightarrow ^1P_1$  transition at 399 nm. In the second stage, we reduce the temperature of the atoms to 40  $\mu$ K by transferring the atoms to a MOT based on the  $^1S_0 \leftrightarrow ^3P_1$  intercombination line at 556 nm. During these cooling stages, the lattice light remains on and captures a small fraction of the atoms. The lattice is formed by tightly focusing ( $w_0 = 30 \mu\text{m}$ ) and retroreflecting about 1 W of light at 759.35 nm, the value at which the Stark shifts for the ground and excited state are approximately equal. We excite the clock transition with a pulse of highly pre-stabilized light at 578.42 nm. In order to achieve measurable excitation for the even isotope we also use a weak magnetic field during the spectroscopy to mix a very small fraction of the more strongly allowed  $^3P_1$  state into  $^3P_0$ . The use of an even rather than an odd isotope (as is used in other lattice clock experiments) simplifies the cooling and the spectroscopy; however the use of bosons rather than spin-polarized fermions does permit the possibility of collision shifts, especially in 1-D lattices. However, no collision shifts are evident at the present level of precision. With this apparatus, spectroscopic line Q's higher than  $10^{14}$  ( $\Delta\nu = 4$  Hz FWHM) have been achieved due to the long interaction time and suppressed Doppler shifts provided by confinement in the lattice.

The authors thank Jim Bergquist for his assistance with the stabilized 578 nm light.

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