Absolute Frequency Measurements of the $^1S_0$-$^3P_0$ Optical Clock Transition at 578 nm in Neutral Yb

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With atoms cooled to < 84 μK in a magneto-optic trap, we perform the first fs-laser-based absolute measurements (uncertainty < 5 kHz) of the Yb $^1S_0$-$^3P_0$ clock transition at 578 nm for two different isotopes.

Since Katori first proposed using the highly forbidden $^1S_0$-$^3P_0$ transitions in two-electron atoms for ultrahigh performance lattice-based optical atomic clocks[1], several groups have taken up the challenge to develop such clocks. This work has focused on two atoms, Sr and Yb, due in part to the relatively high abundance of their odd isotopes, the use of which is necessary for appreciable direct excitation probability. The Sr clock transition has been measured (with an uncertainty of 20 kHz) using atoms in a magneto-optic trap (MOT)[2], and has been excited with atoms confined in a one dimensional lattice[3]. Here we report direct excitation of the Yb clock transition (at 578 nm) with atoms in a second-stage MOT, and the first fs-laser comb-based absolute measurements of the clock frequency for two different isotopes. These measurements lead to a nearly millionfold improvement in our knowledge of the transition frequencies, an important step toward Doppler-free spectroscopy of Yb atoms in a lattice.

By working with atoms tightly confined in sub-micron-sized potential wells of an optical lattice, residual Doppler shifts and recoil effects are suppressed, thereby removing the dominant contributor to the uncertainty budget of state-of-the-art neutral atom optical standards.[1,4] Additionally, atoms trapped in a lattice can enable long interaction times, which can take advantage of the extremely narrow clock transitions. With an appropriate choice of lattice wavelength (estimated to be 752 nm for Yb [5]), the Stark shifts are equal for the ground and excited states, leaving the clock transition frequency unperturbed. Due to its heavier mass and lower angular momentum, Yb offers an interesting alternative to the Sr based system.[7,8] ^{87}Sr has a nuclear spin of 9/2, while ^{171}Yb and ^{173}Yb have spins of 1/2 and 5/2, respectively. The lower angular momentum leads to slightly higher trap temperatures and magnetic field sensitivities (~ 100 Hz/G for the transitions described here), but could reduce effects due to optical pumping and higher order lattice polarizabilities.[1]

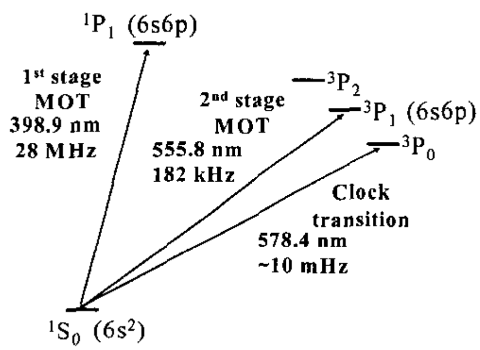

Figure 1. Relevant Yb energy levels.

As an important step towards construction of a lattice-based Yb atomic clock, we have used a second-stage MOT to perform high contrast clock spectroscopy. First, ~10^6 atoms are loaded into a MOT from an atomic beam for 100 ms using the strong $^1S_0$-$^1P_1$ transition at 399 nm (see Figure 1 for Yb energy levels). The trapping light is generated from two slave diode lasers that are injection-locked by a master extended cavity diode laser, which is locked to the desired isotope using a Yb hollow cathode lamp.[5] The resultant temperature of the trapped atoms is ~ 3 mK. We then turn off the blue MOT, reduce the magnetic field gradient from 45 G/cm to 15 G/cm, and transfer 60% of the atoms into a MOT based on the 556 nm intercombination line. The green light is generated by frequency doubling of a fiber laser. After 20 ms of cooling, the atoms have a temperature of ~ 70 μK.

We excite the clock transition with a dye laser at 578 nm, whose frequency is locked tightly to a stable reference Fabry-Perot cavity (resulting linewidth is <10 kHz). Following the method demonstrated by Courtillot et al.[2], we excite the atoms with a series of pulses from a vertical probe beam. With the green MOT beams off, we can generate a π-pulse in 300 μs with 20 mW of probe light collimated in a 2 mm beam diameter. Such a pulse excites a velocity slice with a Doppler width corresponding to ~3 kHz, about 2% of the total Doppler width. Between probe pulses, we turn on green MOT light (for 1 ms), which retraps the unexcited atoms, filling in the velocity holes. Meanwhile, the (untrapped) excited atoms accelerate due to gravity and gain enough velocity to be out of resonance with the next probe pulse. In this way, atoms accumulate in the long-lived excited state, leading to trap depletions as high as 80% for a sequence of 50 pulses. We normalize the signal with resonant pulses at 556 nm before and after the pulse sequence to measure the fraction of atoms excited (the spectra are shown in Figure 2). The lineshapes are fit well by Gaussians and yield different temperatures for the two isotopes (84 μK for ^{171}Yb vs. 48 μK for ^{173}Yb), resulting from their difference in angular momenta.[7]

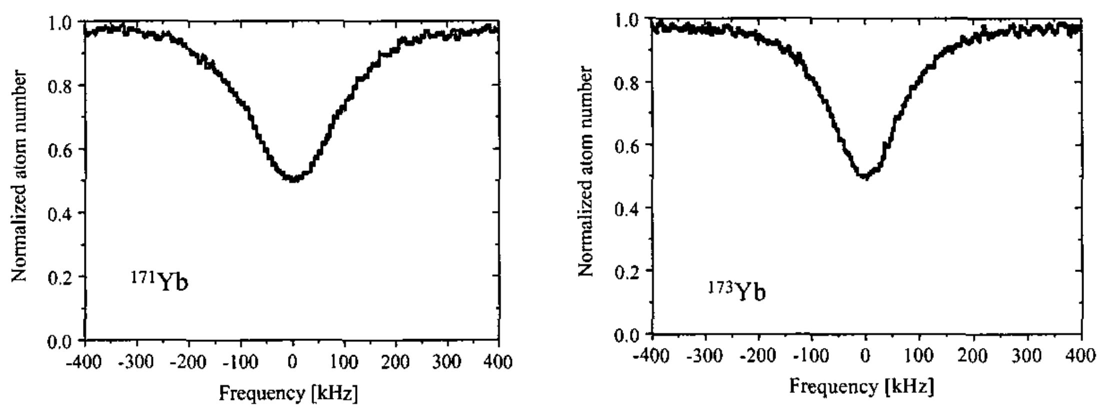

Figure 2. Fractional trap depletion induced by 578 nm light as a function of clock laser detuning from line center. Each curve is the average of four 1 minute scans.

We determine an absolute frequency calibration by fixing the laser frequency at one value and sending cw light to a mode-locked fs-laser frequency comb. The calibration of the self-referenced broadband comb [8] is ultimately traceable to the NIST Cs fountain. The uncertainty in our measurements (4.4 kHz) was dominated by Doppler uncertainties associated with vertical motion of the atoms. The measured frequency of the $(6s^2)^1S_0 \leftrightarrow (6s6p)^3P_0$ transition in ^{171}Yb (F=1/2) is 518,295,836,593.2(4.4) kHz, while the measured frequency of the $(6s^2)^1S_0 \leftrightarrow (6s6p)^3P_0$ transition in ^{173}Yb (F=5/2) is 518,294,576,850.0(4.4) kHz. Previously the frequency of these transitions was known from tables to only a few gigahertz.

Future work will focus on construction of the lattice itself. Progress toward measurements of the shift-canceling wavelength (to check for possible resonance with two-photon transitions [5]) as well as loading of the lattice will be reported at the conference.

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