Spectroscopy of neutral ^{174}Yb in a one-dimensional optical lattice

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We report spectroscopy of the $^1S_0$ - $^3P_0$ clock transition in neutral ^{174}Yb atoms confined to a one-dimensional optical lattice at the ac Stark shift-canceling wavelength of 759.35 nm. Spectroscopic linewidths as narrow as 4 Hz, full width at half-maximum, are shown with good contrast and signal-to-noise ratios. An upper limit on frequency instability is demonstrated to be 3×10^{-15} at one second by measuring with respect to another stable laser through a Ti:sapphire femtosecond laser frequency comb.

Precision spectroscopy has played a central role in the dramatic advances of time and frequency metrology in recent years. In particular, stable local oscillators have been referenced to optical transitions in single ions and ensembles of neutral atoms to achieve remarkable levels of frequency stability and accuracy. A relatively new implementation of this is the neutral-atom optical lattice clock [1, 2] – a system that is expected to combine the accuracy of single-ion standards with exceptionally high stability. Crucial to this scheme is an atom with a narrow-linewidth clock transition that is insensitive to external fields and lattice perturbations. Several groups have recognized ytterbium as an excellent candidate and are pursuing lattice-based clocks that will use its $^1S_0 \leftrightarrow {}^3P_0$ transition [3–6].

In 2005 this narrow (~10 mHz natural linewidth) transition at 578.42 nm was observed in the odd isotopes of Yb [4, 5] and its frequency was measured with an uncertainty of 4.4 kHz [5]. In these experiments, a cold atomic cloud in a magneto-optical trap was probed with narrow-linewidth light. The resulting spectroscopic linewidths were Doppler-broadened to hundreds of kilohertz or a few megahertz as set by atomic temperatures. Narrower lines are needed for high-accuracy and -precision clocks. In addition to extended probe interaction times, the removal of Doppler broadening is a primary benefit of optical clocks based on tight (Lamb-Dicke) confinement to a lattice. Here we demonstrate narrow spectroscopic lineshapes – as narrow as 4 Hz – using ^{174}Yb confined to a one-dimensional (1D) optical lattice.

Until the work presented here, lattice clocks have been based on the use of odd isotopes in alkaline earth-like atoms (^{87}Sr [1, 2, 7], ^{171,173}Yb [3–5]). The hyperfine interaction in these isotopes that have non-zero nuclear spin leads to a narrow natural linewidth on the clock transition (~10 mHz). This linewidth is attractive for optical clocks that promise high accuracy and stability, and the J=0↔J=0 clock transition is insensitive to lattice polarization. However, the hyperfine interaction leads to first-order sensitivity to magnetic fields (~1-10 kHz/mT, or ~0.1-1 Hz/mG), some residual lattice polarization sensitivity, and optical pumping issues [8, 9]. The use of even isotopes in alkaline earth-like atoms (zero nuclear spin) would remove or significantly reduce these issues [10–12]. However, the $^1S_0 \leftrightarrow {}^3P_0$ clock transition is normally completely forbidden in the even isotopes.

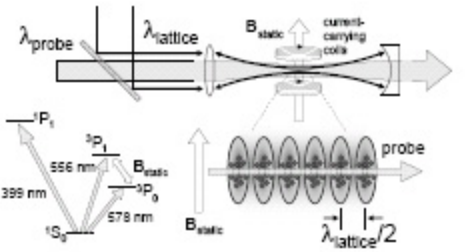

FIG. 1: Magnetic field-induced lattice spectroscopy. Approximately ten thousand ^{174}Yb atoms were cooled, trapped, and loaded into a lattice at the Stark-free wavelength of 759.35 nm. A pair of current-carrying coils generated a static magnetic field to mix a small portion of the $^3P_1$ state into the $^3P_0$ clock state split by a frequency Δ. A single 578.42 nm spectroscopic laser was aligned collinear to the lattice with a dichroic mirror. The tight confinement of the atoms in the probe direction provided for Doppler- and recoil-free excitation of the clock transition. Excitation was measured by ground-state fluorescence of the atoms on the 398.9 nm transition. The simplified energy level diagram is not to scale.

As illustrated in Fig. 1, a static magnetic field can be used to induce a non-zero transition probability on the clock transition in even isotopes [12]. The applied external magnetic field mixes a fraction of the nearby $^3P_1$ state into the upper clock state, $^3P_0$. The mixing fraction is the ratio of magnetic dipole interaction energy ($\hbar\Omega_B \equiv \langle {}^3P_1, m_J = 0 | \vec{\mu} \cdot \mathrm{B} | {}^3P_0 \rangle$) to the $^3P_0$–$^3P_1$ fine structure splitting, Δ. The induced Rabi frequency on the clock transition with a laser tuned to the $^1S_0 \leftrightarrow {}^3P_0$ optical splitting can be written $\Omega_B \Omega_L / \Delta$, where Ω_L is the laser field Rabi frequency

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for the $^1S_0 \leftrightarrow {}^3P_1$ transition. This means that the induced Rabi frequency for the clock transition is proportional to $\sqrt{I}|B|$, where I is the laser intensity and $|B|$ is the magnetic field magnitude. The constant of proportionality in this relationship is similar for the alkaline earth-like atoms Yb, Sr, Ca and Mg (see Ref. [12]), suggesting that this method is widely applicable.

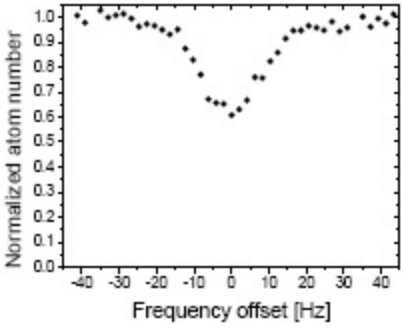

FIG. 2: Spectrum of magnetic field-induced $^1S_0 \leftrightarrow {}^3P_0$ resonance in lattice-confined ^{174}Yb atoms. The lattice laser was tuned close to the Stark-free wavelength of 759.35 nm. Each data point represents a 400 ms cycle of cooling, trapping, probing and detection (see text for details). A Gaussian fit to the line yields a full width at half-maximum of 20.3 Hz.

Figures 2 and 3 show lineshapes obtained using the magnetic field-induced spectroscopic technique with ^{174}Yb atoms confined to a 1D lattice. The experimental details are described comprehensively in Ref. [6]. For the data in Fig. 2, a single 400 ms measurement cycle begins with two sequential stages of magneto-optical traps (MOTs) on the $^1S_0 \leftrightarrow {}^1P_1$ (398.9 nm) and $^1S_0 \leftrightarrow {}^3P_1$ (556 nm) transitions. Approximately 10^4 atoms with a temperature of 40 μK were then loaded into the lattice ($1/e^2$ waist of $\sim$30 μm) that was generated by $\sim$1.1 W of light from an injection-locked Ti:sapphire laser [13]. A 64 ms pulse from a highly stable (sub-hertz linewidth [14]) dye laser at 578.42 nm was applied along the 1D lattice axis as shown in Fig. 1. The static magnetic field had a value of $|B| = 1.29$ mT – obtained by switching the current direction in one of the MOT coils – and the probe intensity was $I \approx 280\,\mathrm{mW/cm^2}$. The remaining ground state population was then measured with a 398.9 nm probe. The total scan time in Fig. 2 was $\sim$20 s. A Gaussian fit to the line yields a full width at half-maximum (FWHM) of 20.3 Hz. The depletion of 40 % was achieved with single pulse excitation.

The resonance lineshape in Fig. 3 was obtained under conditions similar to those for the data in Fig. 2. The vertical axis in Fig. 3 is not normalized to full atom depletion as is the case in Fig. 2. In Fig. 3 the excitation pulse duration was increased to 200 ms and

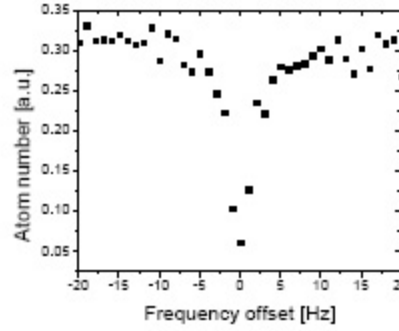

FIG. 3: Spectrum of magnetic field-induced $^1S_0 \leftrightarrow {}^3P_0$ resonance with the lattice laser tuned close to the Stark-free wavelength. Each data point represents a $\sim$540 ms experimental cycle. A Gaussian fit to the line yields a Fourier transform-limited FWHM of approximately 4 Hz. The vertical scale is not normalized to full atom depletion.

the cycle time was correspondingly increased. Additionally, the $1/e^2$ width of the probe beam in the vicinity of the atoms was increased from $\sim$40 μm to $\sim$120 μm with respect to the conditions in Fig. 2, although this change alone was shown to have no noticeable effect on linewidth. The power was adjusted for the increased beam width and pulse duration such that a π-pulse was achieved with the same magnetic field ($\sim$1.3 mT). A Gaussian fit to the line yields a transform-limited FWHM of approximately 4 Hz.

Estimates of potential frequency instability can be made from the lineshapes in Figs. 2 and 3. Using a signal-to-noise ratio of 10 for the former, the data support a one-second frequency instability of $\sim 3 \times 10^{-15}$. The narrowing of linewidth by a factor of five in Fig. 3 implies a potential one-second instability of 6×10^{-16}, or about $\sim$300 mHz at the clock frequency. With straightforward efforts this can be improved even further. The cycle-to-cycle noise that dominates the noise in Figs. 2 and 3 can be significantly decreased by use of a normalization scheme based on optical pumping from the metastable $^3P_0$ clock state. Possible transitions include $^3P_0 \leftrightarrow {}^3S_1$ (6s7s) and $^3P_2 \leftrightarrow {}^3S_1$ (6s7s) by use of lasers at 770 nm and 649 nm, or $^3P_0 \leftrightarrow {}^3D_1$ (6s6p) with a single laser at $\sim$1.39 μm. Together with a very stable local oscillator, a factor of five improvement in signal-to-noise ratio would support one-second instabilies for Yb below 100 mHz. This degree of precision would allow rapid (10 mHz in $\sim$100 s) exploration of systematic uncertainties for frequency measurements, delivering one of the key benefits that neutral-atom standards have promised.

The lattice-confined Yb system has already demonstrated high stability. Figure 4 shows a diagram of the technique used to lock the clock laser to the ^{174}Yb

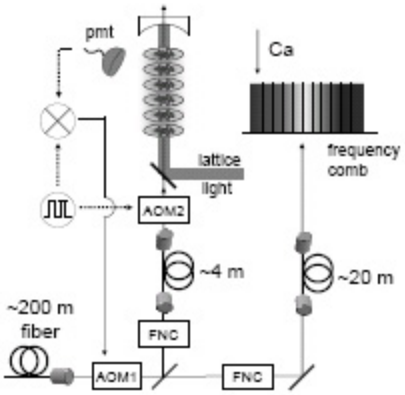

FIG. 4: Diagram of the technique used to lock the local oscillator at 578.42 nm to the clock resonance ($^1S_0 \leftrightarrow {}^3P_0$) of lattice-confined ^{174}Yb atoms. AOM2 is used as a switch that determines probe pulse duration, and is also frequency modulated across the spectroscopic line (see text for details). Also shown is the transfer of locked light to a femtosecond laser-based optical frequency comb. Fiber noise canceler (FNC); acousto-optic modulator (AOM); photomultiplier tube (pmt).

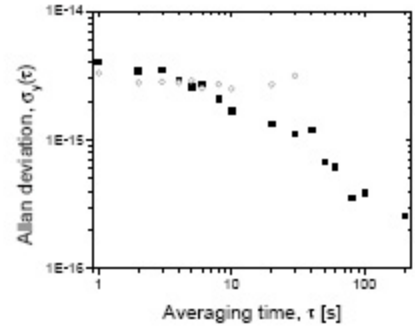

FIG. 5: Frequency instability of the lattice-based Yb optical standard using a lineshape with a 20 Hz width under the same conditions as those for the data in Fig. 2 (i.e., S/N $\sim$ 10, total measurement time $\sim$800 ms). A beat frequency with light at 657 nm is measured with a Ti:sapphire femtosecond-laser based frequency comb. The 657 nm light was locked to the clock transition in Ca (filled squares) and locked only to a stable cavity (open circles). A cycle period of 7 ms and spectroscopic linewidth of 1.15 kHz were used in locking the 657 nm light to the Ca atoms.

$^1S_0 \leftrightarrow {}^3P_0$ resonance. The stable light at 578.42 nm for spectroscopy was transferred from another laboratory through $\sim$200 m of fiber and passed through an acousto-optic modulator (AOM1) that was used for low-frequency corrections to the atomic resonance. Noise induced by transferral through the long fiber is canceled before the fiber in a standard manner by use of phase information from the output facet internal (back) reflection [15, 16]. After exiting the long fiber and passing through AOM1, part of the light was directed through another fiber noise canceler and through a short length of fiber to the experiment. The probe light then passed through another acousto-optic modulator (AOM2) near the experiment that was used as a switch to define the probe pulse duration. AOM2 was frequency modulated with a square wave: modulation depth was equal to half the spectroscopic linewidth, and the modulation period was twice the cycle time (*e.g.*, 2 $\times$ 400 ms for a 20 Hz linewidth). After AOM2 the probe light was combined with the lattice light by means of a dichroic mirror. The spectroscopic signal from a photomultiplier was demodulated by a microprocessor, and a correction signal – proportional to the signal difference between both sides of the lineshape – was sent to AOM1, as shown in Fig. 4.

Also shown in Fig. 4 is the method used to measure relative optical frequency stability. A fraction of the stabilized light at 578.42 nm was sent to a self-referenced optical frequency comb [17, 18]. The comb was locked to the Yb light, enabling the comb to coherently transfer the stability of the Yb laser to a comb component [19] near the frequency of the NIST neutral Ca frequency standard at 657 nm [20, 21]. We recorded the beat frequency between the 657 nm light and its nearest Yb-referenced comb component for a 1 s gate time. Figure 5 shows the results of the Ca-Yb comparison, where frequency instability is expressed as the Allan deviation. The open circles indicate measurements taken when the light at 657 nm was not locked to the Ca atoms, but only to its stable optical cavity. The one-second value of $\sim 3 \times 10^{-15}$ continues for gate times up to 30 *s*, consistent with long-term cavity drift. The filled squares show results obtained with the 657 nm light locked to the Ca atoms by use of a cycle time of 7 ms and spectroscopic linewidth of 1.15 kHz. With decreased cycle time and increased servo gain for the Ca system the one-second instability can be decreased to $\sim 3 \times 10^{-15}$.

The preliminary data in Fig. 5 suggest that the upper limit on the ten-second instability of the Yb frequency reference is $\sim$1-2 $\times 10^{-15}$. As can be seen in the figure, the relative frequency imprecision between Ca and Yb reached the mid-10^{-16} level in less than 100 s of averaging. This means that with a 20 Hz linewidth and a signal-to-noise ratio of 10 – both of which can be significantly improved, as we have seen – systematic uncertainties can be evaluated for the Yb clock at the 100 mHz level in $\sim$100 s.

What are the dominant inaccuracies that need to be evaluated for an Yb optical lattice clock? For any

lattice clock the residual light shift due to the lattice laser must be suppressed. To first order in intensity, the slope of the differential light shift with respect to lattice laser frequency is $\sim 10^{-8}$ Hz/Hz in the vicinity of the ac Stark shift zero-crossing for the upper and lower clock states. A millihertz frequency shift, for example, would be caused by a lattice laser frequency shift of ~100 kHz away from the shift-canceling wavelength (λ_{ac}). Control of the lattice laser frequency to this level should be straightforward, but λ_{ac} would need to be measured to $\sim 10^{-4}$ pm for millihertz-level uncertainty. Our preliminary measurements yield λ_{ac}=759.3547 ± 0.0005 nm. While determining λ_{ac} to three more digits is nontrivial, the stability improvements indicated above should allow identification of λ_{ac} to sufficient precision. The odd isotopes have an additional requirement on the first-order light shift cancelation for millihertz uncertainty: because of the vector nature of the states, the lattice laser polarization must be controlled to 1 mrad or better [8, 9].

Suppression of the first-order light shift is sufficient only if higher-order terms in lattice intensity can be neglected. This is the case for the Sr lattice clock, where higher-order effects have been shown to contribute a fractional frequency uncertainty of 10^{-18} (<1 mHz) [7]. The second-order polarizability, or hyperpolarizability, generally depends strongly on polarization and proximity to two-photon resonances. For Yb, the $^3P_0$ (6s6p)↔$^3P_0$ (6s8p) transition at 2 × 759.7098 nm is the nearest allowed two-photon transition. Since this is only ~200 GHz from λ_{ac}, it will be necessary to look carefully for nonlinear frequency shifts with lattice intensity. So far we have seen no nonlinearities at the hertz level for intensity variations in the ~30-85 kW/cm^2 range for lattice wavelengths ranging from 759.350 to 759.357 nm. If necessary, this resonance can be suppressed by ensuring a single circular lattice polarization at each atom, which can be achieved for multidimensional lattice geometries [22].

A lattice clock based on the odd isotopes (nonzero nuclear spin) must control the magnetic field at the atoms to 0.1-1 nT (1-10 μG) in order to reach millihertz uncertainty [2, 9]. As stated above, for Yb and Sr this is due to the hyperfine mixing between the upper clock state ($^3P_0$) and the nearby $^3P_1$ (6s6p) state (i.e., g_J nonzero for $^3P_0$), which brings first-order field sensitivity [23]. Although at first it may seem problematic to build a frequency standard based on a relatively high bias magnetic field, the even-isotope (zero nuclear spin) scheme described above appears more amenable to minimizing B-field uncertainty. Specifically, the requirements for field control leading to millihertz uncertainty are relaxed by one to two orders of magnitude, and the even isotopes have no magnetic substructure. In the case of Yb, the field at the atoms can be calibrated through spectroscopy on the field-sensitive $^1S_0$ (m=0) ↔ $^3P_1$ (m=±1) transition at 556 nm. The Lande-g factor is known to be 1.49282 for this transition [24]. Resolution of kilohertz shifts on this transition corresponds to 0.1 μT (1 mG) field resolution, which could be done with lattice-based or even cold atomic cloud spectroscopy. For a bias field of ~1 mT (~10 G) as is used in even-isotope spectroscopy, the quadratic Zeeman shift on the clock transition is a few hertz. As shown in Fig. 5, we can readily observe frequency shifts at the 100 mHz level and lower. Together with 0.1 μT (1 mG) knowledge and control of the field – through fine control of low current in a second set of coils collocated with the MOT coils, for example – this should allow us to determine the second-order Zeeman shift coefficient to sufficient precision for millihertz confidence on the field-related clock frequency shift. The use of magnetic field shielding is not necessary in this process, which presumably could be necessary with the ~1-10 kHz/mT (~0.1-1 Hz/mG) sensitivity of an odd-isotope lattice clock.

Frequency shifts due to atom-atom interactions are expected to be negligible for three-dimensional lattice clocks with less-than-unity occupation [8, 25]. The fermionic odd isotopes can generally have the advantage of negligible collision shifts, but the ensemble must be nuclear spin-polarized into a single M_F state. (Isotopes ^{87}Sr, ^{173}Yb, and ^{171}Yb have nuclear spin I=9/2, 5/2, and 1/2, respectively.) The magnitude of the density shift is unknown for bosonic ^{174}Yb and must be experimentally determined. The blackbody shift (BBS) for Yb has been calculated to be -1.25 ± 0.13 Hz at T = 300 K [26]. The fractional frequency error due to the uncertainty in this calculation is $\sim 3 \times 10^{-16}$. High precision experiments – using an off-resonant infrared laser, for example [27]– are ultimately needed to determine the frequency inaccuracy due to the BBS. The high stability shown here should allow us to evaluate systematic error in the Yb lattice clock to high precision. Focusing first on the higher-order lattice light shift and the density shift, we could be able to report a sub-hertz ($<10^{-15}$) absolute frequency measurement in the near future.

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