THE YB OPTICAL LATTICE CLOCK

N. D. LEMKE, A. D. LUDLOW, Z. W. BARBER*, N. POLI†, C. W. HOYT‡, L. S. MA§ , C. W. OATES*, L. HOLLBERG, J. C. BERGQUIST, A. BRUSCH, T. M. FORTIER, S. A. DIDDAMS, T. HEAVNER, S. JEFFERTS, AND T. PARKER

National Institute of Standard and Technology,
Boulder, CO 80305 USA
** E-mail: oates@boulder.nist.gov*

We describe the development and latest results of an optical lattice clock based on neutral Yb atoms, including investigations based on both even and odd isotopes. We report a fractional frequency uncertainty below 10^{-15} for ^{171}Yb.

Keywords: Optical clocks; Optical frequency standards; Optical lattices

1. Introduction

At the previous Symposium on Frequency Standards and Metrology, H. Katori proposed using $^1S_0 \rightarrow {}^3P_0$ transitions in alkaline earth like atoms to make high performance optical clocks based on large numbers of neutral atoms tightly confined in an optical lattice.[1] This proposal was based on the use of Sr atoms, as were the initial experiments.[2–4] In 2004 Porsev et al. proposed the use of the analagous transition in Yb at 578 nm.[5] While there are considerable similarities between the Sr and Yb atomic systems, there are also some important differences. Most significantly, Yb has an abundant isotope (^{171}Yb) that has nuclear spin = 1/2. This leads to far simpler structure than that of the only abundant odd Sr isotope, ^{87}Sr, which has a spin = 9/2. Due to its 1/2 spin, ^{171}Yb has zero tensor polarizability, which could make it more straightforward to use in three-dimensional lattices, for which the sites cannot have uniform polarization.

*Present address: Spectrum Lab Montana State University P.O. Box 173510 Bozeman, MT 59717-3510 USA
†Present address: LENS and Dipartimento di Fisica, Universita di Firenze, INFN - sezione di Firenze - 50019 Sesto Fiorentino, Italy
‡Present address: Bethel University, St. Paul, MN 55112 USA
§Present address: East China Normal University, Shanghai, China

Here we report on our development of Yb lattice clocks. In the course of this work we implemented a technique, magnetic field-induced spectroscopy (MIS), that enables excitation of the $^1S_0 \rightarrow {}^3P_0$ transition, which is completely forbidden in even isotopes.[6,7] This technique involves use of an external magnetic field to provide the required level mixing that occurs naturally in odd isotopes. In this way we can access the conceptually simpler bosonic isotopes, which may be especially attractive for clocks based on atoms confined in three dimensions. There are, however, trade-offs when working with bosons. First, for lattice clocks that have more than one atom per lattice site (e.g., as is usually the case for 1-D lattices), collision shifts are expected to be larger than for clocks based on spin-polarized fermions. Secondly, there are two additional (and potentially significant) frequency shifts to worry about: a second-order Zeeman shift associated with the magnetic bias field, and a light shift that results from the increased probe light intensity required to excite the effectively weaker transition.

We summarize results based on the most abundant Yb isotope, ^{174}Yb (nuclear spin = 0) as well as more recent results on ^{171}Yb. In addition to uncertainty budgets for the two systems, we include absolute frequency measurements made via an octave-spanning femtosecond-laser frequency comb against other microwave and optical standards.

2. Apparatus

The ^{174}Yb apparatus (see Figure 1) has been described in detail elsewhere;[7–9] here we summarize the relevant details and modifications used for the study of ^{171}Yb. In order to load atoms into the lattice it is necessary to first cool the atoms. We achieve this with two stages of laser cooling: the first uses the strong $^1S_0 \rightarrow {}^1P_1$ transition at 399 nm to load atoms into a magneto-optic trap (MOT) from a thermal beam, while the second uses the intercombination line at 556 nm to cool the atoms from 5 mK to about 50 μK, thus requiring optical lattices 5 to 10 times deeper than those used for the colder Sr atoms. After the two stages of laser cooling there are approximately 4 x 10^5 atoms in the trapping region, of which about 10^4 are transferred into the pancake-like potential wells (10 to 20 atoms per well) of the 1-D optical lattice. The horizontally oriented lattice is formed by retroreflecting a tightly focused laser beam (waist = 30 μm, power = 1 W) through the MOT region. We tune the wavelength of the lattice light to its "magic" value for the Yb clock transition, near 759 nm, where the ground and excited clock states experience equal lattice light shifts.

When we perform the spectroscopy with ^{174}Yb, we first turn off all

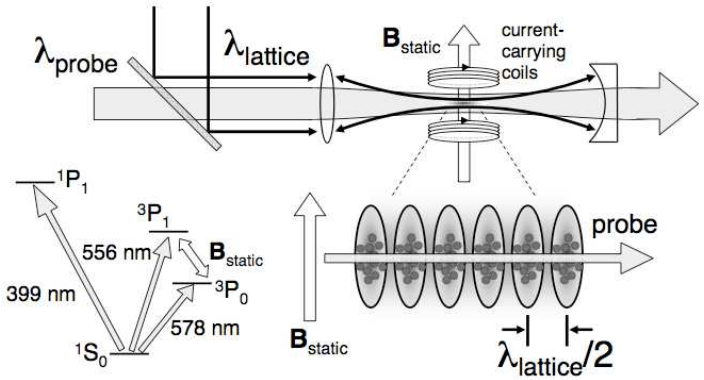

Fig. 1. Schematic of the Yb lattice clock apparatus. After two stages of laser cooling, the atoms are confined in a 1-D optical lattice whose wavelength is tuned near its magic value of 759.4 nm. Prestabilized light at 578.42 nm is used to probe the clock transition. For ^{174}Yb a magnetic bias field is used in conjunction with the probe light to excite the transition.

lasers (except for the lattice) and the magnetic field gradient. We then turn on the probe laser light at 578 nm (that propagates collinearly with the lattice light) and a magnetic bias field of about 1 mT (10 G). The 578 nm light is produced through sum-frequency generation in a periodically poled waveguide of a Nd:YAG source at 1.319 μm and a fiber laser at 1.03 μm. The frequency is pre-stabilized with a vertically mounted, high finesse cavity. With this system we have resolved linewidths as narrow as 4 Hz (see Figure 2) and achieved a single-shot signal-to-noise ratio of more than 15 through use of a repump laser at 1.39 μm that is used to divide out shot-to-shot trap number fluctuations.

With ^{171}Yb we do not need to use a bias field to enable excitation of the transition, since mixing due to the non-zero nuclear magnetic moment yields a natural linewidth of 10 mHz for the clock transition.[5] However, we add a 10 ms period of optical pumping before the spectroscopy in order to spin polarize the sample (typical sample polarization $>$ 98 %). This is accomplished with light at 556 nm tuned to the appropriate resonance (the clock resonances are split by a 0.5 mT magnetic field). We alternate measurement cycles between the m $= \pm 1/2$ states in the presence of a weak bias field (0.1 mT) to split the two resonances by 500 Hz. Locking to the average of this value enables us to suppress stray magnetic field effects and vector light shifts.[10]

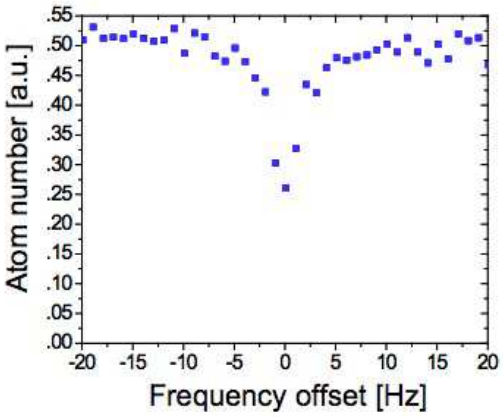

Fig. 2. Spectrum of magnetic field-induced ${}^1S_0 \leftrightarrow {}^3P_0$ resonance with the lattice laser tuned close to the Stark-free wavelength. Each point represents a ∼540 ms experimental cycle. A Gaussian fit to the line yields a Fourier transform-limited FWHM of approximately 4 Hz. The vertical scale is not normalized to full atom depletion.

In order to evaluate the performance of the Yb clock we usually measure against a Ca optical clock at 657 nm that resides in our laboratory.[11] We span the 62 THz gap between the lasers with a femtosecond-laser frequency comb.[12] We also lock the frequency of the optical lattice to the comb to make sure it remains fixed at the magic wavelength. The Ca clock lacks the small absolute uncertainty of the lattice clock, but has good short-term stability and provides a robust flywheel against which we can evaluate the various Yb clock shifts. By alternating conditions for a given parameter we can evaluate its effects at the sub-10^{-15} level in a few minutes (Figure 3 shows the Allan deviation of the beat note between the lasers connected by the frequency comb).

3. Systematic uncertainties for ^{171}Yb and ^{174}Yb

3.1. *Key frequency shifts for the Yb lattice clock*

With the system described in the previous section we have evaluated the systematic effects for both ^{171}Yb and ^{174}Yb. In addition to the common effects such as blackbody radiation shifts and lattice wavelength shifts, each has shifts that are peculiar to the isotope, which we consider first.

Use of the even isotope greatly reduces atom orientation-related effects such as the vector light shift or the first-order Zeeman effect.[1,5] However we

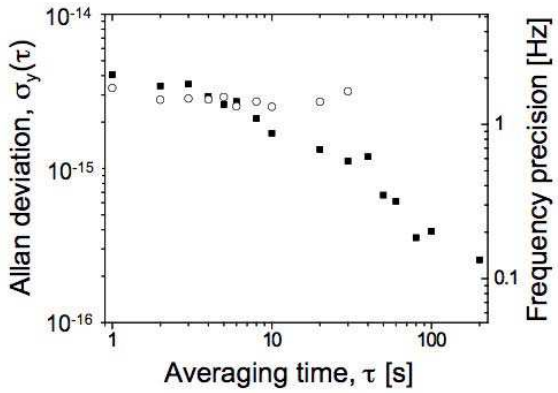

Fig. 3. Frequency instability of the Yb vs. Ca beat note.

need to evaluate carefully the second-order Zeeman effect associated with magnetic bias field and the probe light-induced Stark shift. For magnetic field-induced spectroscopy these shifts are inextricably connected with the strength of excitation; they are typically about the same size as the spectroscopic resolution, so they can be reduced only by working at higher resolution.[6] Ultimately, however, the resolution is limited by the prestabilization of the laser, so clearly clocks based on the MIS method will benefit considerably from better reference cavities.

In order to reduce the uncertainty associated with these two effects, we have evaluated the frequency shifts for a range of values for the magnetic field and probe intensity. We have the ability to turn these "knobs" to values considerably larger than our typical operating values, so we can achieve small uncertainties for these effects. As an example, in Figure 4 we show a plot for the quadratic Zeeman effect vs. magnetic bias field value. From this we can extrapolate to the zero-field value, but we still have to consider how well we can hold these values and how stray magnetic fields will contribute to the uncertainty.

For ^{171}Yb, the protocol that alternates (and averages) between spin polarized m = $\pm 1/2$ states suppresses atom orientation-related shifts.[10] However, since the vector light shift may be important for multidimensional lattices, we made a preliminary measurement of this effect. We varied the polarization of our 1-D lattice from linear to circular and found a frequency shift (equal and opposite for our two states) of 28 Hz. This value is smaller than the estimate by Porsev et al.,[5] but still large enough to merit consid-

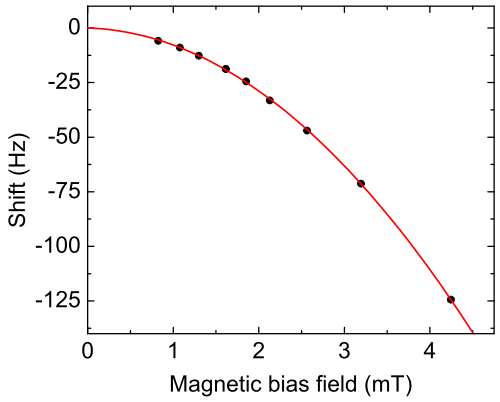

Fig. 4. Shift of the clock frequency vs. magnetic bias field for ^{174}Yb (circles). From the fit (solid line) we determine the Zeeman coefficient (β = -6.12(10) Hz/mT^2), which agrees well with theoretical estimates[5,9]

eration in the design of three-dimensional lattices.

3.2. *Uncertainty budgets for ^{171}Yb and ^{174}Yb*

Table 1 shows the total uncertainty budgets for the frequency standards based on the two isotopes. The total uncertainty for ^{174}Yb is about four times that of ^{171}Yb. This is a result of more precise evaluations of some of the common effects but also reflects the larger values for the magnetic field and probe light uncertainties for the even isotope. Effects due to the lattice (magic wavelength uncertainty, hyperpolarizability) should have similar values for the two isotopes. The hyperpolarizability was originally of considerable concern for Yb-based lattice clocks because of a possible coincidence between the magic wavelength and two-photon transitions from the excited state to higher-lying states. Indeed the magic wavelength turned out to be close to one of these resonances, but an evaluation of these effects has shown them to be small.[8] Interestingly, the collision effects have turned out to be larger for the fermionic isotope, although this is probably a result of the residual atomic temperature that prevents the fermions from being excited in an indistinguishable way. Most of the effects listed have uncertainties that can be reduced well below the 10^{-16} level by simply performing more precise measurements of the type already described. A possible exception is

Table 1. Corrections and uncertainties for ^{174}Yb and ^{171}Yb (fractional frequency shift relative to 578 nm in units of 10^{-16})

	^{174}Yb		^{171}Yb	
Systematic	Corr.	Unc.	Corr.	Unc.
Latt. Pol.	0.0	5.7	0.0	2.9
Hyperpolarizability	3.5	0.7	3.5	0.7
2nd Order Zeeman	-346	3.8	-0.2	0.0
Probe Light Shift	116	3.8	0.2	0.0
Density dependent	-1.9	9.6	-19	1.0
Blackbody shift	-2.5	0.2	-2.5	0.2
AOM Chirp	0.0	0.2	0.0	0.2
Residual Servo Error	4.8	0.2	0.0	0.0
Total Uncertainty (x10^{-16})		15		3.2

the shift due to ambient blackbody radiation (BBR). The uncertainty listed for this effect is due primarily to the uncertainty in the theoretically calculated blackbody coefficient[13] used to extrapolate the transition frequency to that at zero kelvin. Because of the difficulty associated with calculations for a complicated rare earth atom like Yb, it is likely that experimentally derived values will be needed to reduce this uncertainty further. Alternatively, a definition of the transition frequency at room temperature would largely remove the contribution of the coefficient uncertainly and leave mainly the uncertainty of the ambient temperature itself, or about 3 x 10^{-17} K^{-1}).

3.3. *Frequency measurements for ^{171}Yb and ^{174}Yb*

We measured the absolute frequency of the clock transition for both isotopes through use of a mode-locked femtosecond-laser frequency comb that connects the Yb lattice standard to other microwave and optical standards at NIST. In Figure 5 we show independent measurements of the ^{174}Yb clock frequency[9] against a Cs-fountain calibrated maser at NIST[14] and the Hg^+ optical clock.[15] Because these measurements were taken independently on different days over several months, they form a closed loop (in conjunction with Hg^+-Cs frequency measurements) between the three standards and show good agreement at the 1 Hz level. Due to the much higher stability of the optical vs. optical measurements, the time required for a single measurement was minutes rather than the 24-hour period needed to average down the maser noise.

We have more recently measured the ^{171}Yb clock frequency against the NIST time scale and derived a preliminary absolute frequency of 519 295

836 590 863.2(0.8) Hz. The fractional frequency uncertainty of 1.5 x 10^{-15} resulted primarily from uncertainties in the comparison itself.

4. Conclusions and future prospects

Thus far, research with the Yb optical lattice clock has demonstrated its viability as a high performance optical frequency standard. The issue of hyperpolarizability has been resolved, and for the most part the frequency shifts are well understood. Measurements indicate that performance at a level below 10^{-16} seems accessible even with the present 1-D system. To go further, the Yb lattice clock now faces the same issues that exist for other lattice clocks. First of all, if we want to evaluate systematic effects efficiently at the 10^{-17} level and beyond, we need to improve the stability of existing lattice clocks, which is currently limited by the cavities used to prestabilize the probe laser frequency. New cavity designs will be required for the neutral atom clocks to fulfill their potential. As an additional benefit, working at higher resolution will considerably reduce the shifts for the bosonic lattice clock. Second, future lattice clocks will most likely confine atoms in two or three dimensions (underfilled, to remove collision effects) and will use considerably shallower lattices (to minimize lattice shifts).[16]

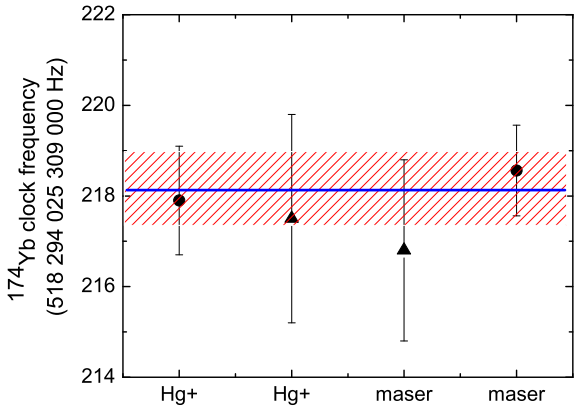

Fig. 5. Independent measurements of the ^{174}Yb clock frequency vs. the Hg^+ optical clock and a maser calibrated by the NIST Cs fountain. The resultant value was 518 294 025 309 217.8(0.9) Hz.

However, we then will need to develop improved laser cooling techniques for Yb (e.g., sideband cooling in the lattice). Finally we will need to address key issues such as the BBR shift, fluctuating gravitational potentials, and the challenges of high-precision clock comparisons over long distances. Comparisons of the ratios of the Yb and Sr optical lattice clocks paired in different locations seem particularly feasible and provide one way to bypass the time-transfer limitations, while still providing stringent tests of clock performance.

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