The Yb Optical Lattice Clock

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Abstract

We report progress on an optical clock based on neutral Yb atoms confined to a 1-D optical lattice. In particular, we describe the first high precision measurements on the Yb clock transition at 578 nm through use of an even isotope, ^{174}Yb. An evaluation of the two most important systematic effects for the clock has led to the reduction of the total fractional uncertainty for the ytterbium lattice clock to one part in 10^{15}. Comparisons with the other frequency standards at NIST show that the Yb clock has a fractional frequency instability of less than $3 \times 10^{-15}\tau^{-1/2}$.

1. Introduction

Optical atomic clocks based on narrow transitions in neutral atoms show great potential for timing with sub-ps uncertainty. In particular, systems that use atoms confined to an optical lattice are showing the greatest promise due to the long interaction times and reduced systematic effects afforded by the lattice [1]. While a majority of lattice-based optical clock studies have used Sr atoms [1,2,3], Yb lattice clocks provide an interesting alternative due to the variety of abundant Yb isotopes with different nuclear spins (I = 0, 1/2, or 5/2) and the suitability of Yb spin zero isotopes for clock studies [4]. With the feasibility of Yb clocks established in earlier studies [4,5,6], we present here results from the first systematic evaluation of an Yb-based optical lattice clock, one that uses an even isotope, ^{174}Yb. Clocks based on even isotopes have some advantages due to their simpler structure (e.g., the absence of first order sensitivity to magnetic fields, decreased sensitivity to lattice polarization), but in exchange they have two key systematic effects that require careful evaluation (see Section 3).

2. Yb Lattice Clock Apparatus

The apparatus has been described elsewhere in detail [6], so here we summarize the key features of the apparatus. To prepare the Yb atoms for high resolution spectroscopy in the lattice, we first perform two stages of laser cooling. The first stage uses a strong cycling transition at 399 nm and loads atoms from a thermal beam into a magneto-optic trap, which yields an atom number of 10^6 and an atom temperature of 4 mK. The second stage uses a narrower (natural linewidth ~ 180 kHz) transition to cool the trapped atoms to 40 μK. Approximately 10^4 of these atoms are trapped in a high intensity, tightly focused (waist = 30 μm) laser beam that overlaps the magneto-optic trap volume. This beam is retroreflected to form a 1-D (horizontal) lattice. The wavelength of the lattice light (~ 759 nm) is chosen to yield equal Stark shifts for the ground and excited states of the $J = 0 \rightarrow J' = 0$ clock transition at 578 nm, thereby enabling high clock performance. In order to transfer appreciable population to the excited state of the highly forbidden transition, we use a small magnetic bias field (~ 0.5 mT) to mix some of the J' = 0 with more allowed J' = 1 states.

We excite the transition with light derived from a pre-stabilized 578 nm source that is based on sum frequency of two solid state laser sources (a fiber laser at 1030 nm and a Nd:YAG laser at 1319 nm). With 150 mW from each of the infrared lasers we can generate ~ 10 mW of light at 578 nm with a single-passed, periodically-poled non-linear waveguide. The frequency of the light is stabilized by locking it to a narrow fringe (10 kHz) of a environmentally-isolated Fabry-Perot cavity. With this source we have resolved spectroscopic features as narrow as 5 Hz wide (at an optical frequency of 518 THz) with lattice-confined atoms (see Figure 1).

3. Evaluation of the clock shifts

A key aspect of clock development is to determine the various factors that can shift the center frequency of features such as that shown in Figure 1. One of the real strengths of lattice clocks based on $J = 0 \rightarrow J' = 0$ transitions in alkaline earth atoms such as Yb is that shifts are inherently small, most with an absolute value of 1 Hz or less on the optical frequency. Careful evaluations of the dependencies of these shifts on the relevant parameters can then reduce their net uncertainty contributions to near negligible levels. We have investigated the important shifts for the ^{174}Yb lattice clock and summarized these effects in Table 1. For lattice clocks that use even isotopes, the most significant concerns are the second-order Zeeman shift due to the magnetic bias field (and stray magnetic fields) and the AC Stark shift induced by the probe light (the clock transition is much weaker for the even isotopes so require higher probe intensities). In Figure 2 we show a measurement of the second-order Zeeman shift as a function of magnetic bias field – from these measurements we estimate the effect of the field on the clock transition with an uncertainty of 0.1 Hz. To measure these shifts we locked the probe laser to the resonance and compared its frequency (via a fs-laser frequency comb [7]) with that of a second stable optical standard, one based on freely expanding calcium atoms [8]. The time to make these measurements is greatly reduced due to the high stability of the optical sources ($\Delta\nu_{rms}$ < 2 Hz for 1 s averaging time). In a similar way we have evaluated other key effects listed in Table 1 and at this point in time the total uncertainty in our realization of the clock frequency is approximately 0.8 Hz, or fractionally 1.5×10^{-15}.

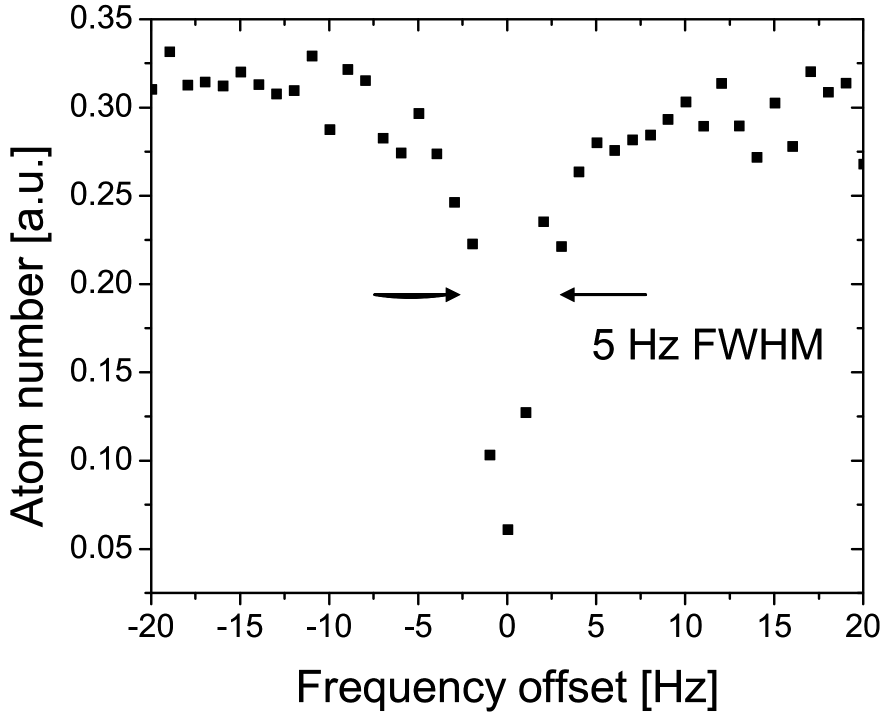

Figure 1. Sample experimental lineshape of ^{174}Yb clock transition. The lineshape has a full width at half maximum (FWHM) of 5 Hz which yields a quality factor of ~10^{14}.

In addition to the two systematic effects that require extra attention when using an even isotope, there are several others in Table 1 that are common to both even and odd isotopes and are worthy of discussion here. Because we use a 1-D lattice with 10-20 atoms per pancake-like potential well rather than an underfilled 3-D lattice, the atoms can interact with their neighbors and cause density-dependent shifts of the clock transition frequency. These effects may be reduced for spin-polarized fermions (as found in the odd isotopes), but non-uniform excitation can still lead to collisional shifts. In either case, clocks based on 1-D lattices need to measure these – for Yb, we have yet to see a shift inconsistent with zero for atom densities of 3×10^{11} cm^{-3}, however further measurement will be required to reduce this uncertainty. Another non-negligible shift results from the effects of background blackbody radiation on the clock transition. For Yb, this shift at room temperature is about 1.3 Hz, with an uncertainty of 130 mHz. This uncertainty is dominated by the uncertainty in the theoretical calculation for the blackbody coefficient [9] but also results from uncertainty in the temperature of the vacuum apparatus that contains the atoms (18 mHz/C). Ultimately, we will want to find a good way to measure the blackbody coefficient and may want to construct a special container whose temperature can be well controlled [9].

4. Conclusion

We have presented an overview of the key issues involved in making an accurate optical clock based on lattice confined Yb atoms. We emphasize that the value for the total uncertainty is not limited by any physical effects, but instead by the measurements themselves. In the near future, improvements in the measurement precision will reduce the clock uncertainties considerably. These measurements are particularly encouraging in that we have not identified any effects that should prevent the clock from achieving a fractional uncertainty of $\sim 10^{-16}$. Moving well below this level will require a more careful treatment of the blackbody shift.

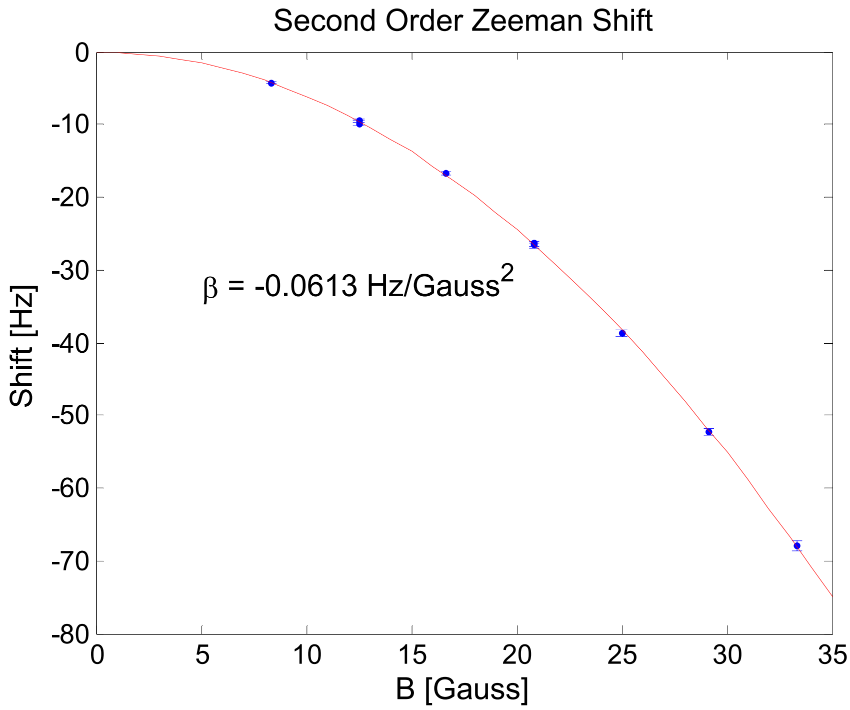

Figure 2. Measurement of the second order Zeeman shift for Yb. Extrapolating the clock shifts to zero magnetic field determines the second order Zeeman shift with an uncertainty of 0.1 Hz or 2×10^{-16} fractionally.

Table 1. Sample uncertainty budget. Shifts depend on actual operating conditions.

Effect	Shift(10^{-15})	Uncertainty (10^{-15})
2^{nd} order Zeeman	-18.5	0.2
Probe light	5.9	0.3
Lattice Polarizability	0	0.6
Hyperpolarizability	0.35	0.07
Density	-0.2	1.1
Servo	0	0.02
Blackbody shift	-2.5	0.3
Total	-15.05	1.4

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6. References

1. Masao Takamoto and Feng-Lei Hong and Ryoichi Higashi and Hidetoshi Katori, "An optical lattice clock," *Nature*, Vol. 435 May 2005 pp. 321-324.

2. A. D. Ludlow et al., "Sr lattice clock at $1x10^{-16}$ fractional uncertainty by remote optical evaluation with a Ca clock," to be published in *Science.*

3. Rodolphe Le Targat and Xavier Baillard and Mathilde Fouche and Anders Brusch and Olivier Tcherbakoff and Giovanni D. Rovera and Pierre Lemonde, "Accurate Optical Lattice Clock with ^{87}Sr Atoms," *Physical Review Letters*, 97:130801, 2006.

4. Sergey G. Porsev, Andrei Derevianko, and E. N. Fortson, "Possibility of an optical clock using the $6^1S_0 \rightarrow 6^3P_0$ transition in ^{171,173}Yb atoms held in an optical lattice," *Physical Review A*, 69:021403(R), 2004.

5. A. V. Taichenachev, V. I. Yudin, C. W. Oates, C. W. Hoyt, Z. W. Barber, and L. Hollberg, "Magnetic field-induced spectroscopy of forbidden optical transitions with application to lattice-based optical atomic clocks," *Physical Review Letters*, 96:083001, 2006.

6. Z. W. Barber, C. W. Hoyt, C. W. Oates, L. Hollberg, A. V. Taichenachev, and V. I. Yudin, "Direct excitation of the forbidden clock transition in neutral ^{174}Yb atoms confined to an optical lattice," *Physical Review Letters*, 96:083002, 2006.

7. T. M. Fortier, A. Bartels, and S. A. Diddams, "Octave-spanning Ti:sapphire laser with a repetition rate > 1 GHz for optical frequency measurements and comparisons," *Optics Letters*, vol. 31, pp. 1011-1013, April 2006.

8. C. W. Oates, F. Bondu, R. W. Fox, and L. Hollberg, "A diode-laser optical frequency standard based on laser-cooled Ca atoms: Sub-kilohertz spectroscopy by optical shelving detection," *The European Physical Journal D*, 7(3):449–460, 1999.

9. Sergey G. Porsev and Andrei Derevianko, "Multipolar theory of blackbody radiation shift of atomic energy levels and its implications for optical lattice clocks," *Physical Review A*, 74:020502(R), 2006.