

An optical lattice clock based on bosonic Sr

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Abstract—We present experimental results for an optical lattice clock operating on the $^1S_0 \leftrightarrow ^3P_0$ transition in ^{88}Sr , which is excited with the technique of magnetic field-induced spectroscopy. To reduce the complexity of the setup we have developed a set of new experimental techniques that greatly simplifies the clock spectroscopy in Sr atoms. First, we developed a method for finding the clock transition that removes the need for extensive frequency metrology hardware and optical frequency combs. This technique exploits a near coincidence in the atomic wavelengths of the $^1S_0 \leftrightarrow ^3P_0$ clock and $^1S_0 \leftrightarrow ^3P_1$ second stage cooling transitions in Sr, which are only 5 THz far apart. This coincidence enables the use of an optical (transfer) cavity to reference the frequency of the clock transition relative to that of the much stronger cooling transition. Second, all laser sources in the experimental setup are based on semiconductor technology, which greatly reduces the complexity of the apparatus. With this setup, about 10^4 ^{88}Sr atoms are trapped in a 1D lattice formed by 200 mW of radiation tuned near the magic wavelength at 813 nm. Preliminary uncertainty budget for our optical lattice clock is also presented, with particular attention to density dependent collisions, which led to an unexpectedly high signal contrast for long interaction times.

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I. INTRODUCTION

Optical atomic clocks have recently reached levels of performance that are an order of magnitude or more beyond those of their microwave counterparts, which have historically set the standards for precision time/frequency metrology. With this improved level of precision, scientists are performing new and more stringent tests of fundamental physical principles such as relativity and searches for temporal drifts in the fundamental constants [1], [2]. Additionally, we anticipate that many new applications will arise, including improved timing for space travel and accelerator centers, as well as perhaps a new type of relativity-based geodesy [3]. These applications will require more compact, robust, and versatile versions of optical atomic clocks. Thus far, state-of-the-art optical clocks, whether based on neutral or charged atoms, tend to be fairly complicated pieces of scientific apparatus. They usually require multiple (often sophisticated and power hungry) laser systems, operate in well controlled environmental conditions, and rely on links to well developed frequency standards. For these reasons, most optical clocks are being developed in or near metrology institutes.

Here we present a considerably simplified version of one of the most promising optical clock systems, the Sr lattice clock. Due to the favorable laser wavelengths required for its operation, the Sr lattice clock is a good choice for streamlining,

and in fact is the most mature of lattice clocks, with many under development around the world [4]–[6], [8], [9]. In a recent demonstration, a Sr lattice clock achieved an absolute fractional frequency uncertainty (for ^{87}Sr) of 1.5×10^{-16} and a fractional instability of 10^{-16} for an averaging time of 200 s [6]. In our version of a ^{88}Sr lattice clock, we demonstrate two important simplifications [7]. First, we use only lasers that are based on semiconductor laser technology. These lasers considerably simplify the apparatus and greatly reduce the power/size requirements. Second, we take advantage of a coincidence in the Sr atomic energy level system to greatly simplify the needle-in-a-haystack challenge of locating the ultranarrow spectroscopic feature used for stabilizing the clock laser. This transfer cavity-based technique removes the need for support from a standards institute or a GPS-referenced femtosecond-laser frequency comb to calibrate the clock laser, and can correct unexpected length changes in the clock reference cavity (e.g., in a transportable device with a poorly controlled environment). This simplified search method is further aided by a new search algorithm based on chirping the laser frequency over a one-second probe period, which has led to spectroscopic features with a contrast greater than 99 %. These developments represent important steps towards a transportable device, which could enable long-distance frequency comparisons at well below the 10^{-15} level, and could also lead to simpler laboratory-based devices.

II. DIODE LASER-BASED SR LATTICE CLOCK APPARATUS

As pointed out in the introduction, the level scheme of neutral Sr offers some interesting advantages relative to other atoms/ions when realizing a compact optical atomic clock. All of the relevant transition wavelengths for cooling and trapping lie in the visible or near infrared and can be easily reached with semiconductor devices (see Fig.1). Further reduction of the complexity of the setup comes from the use of a magnetic-field-induced spectroscopy scheme to observe the doubly-forbidden $^1S_0 \leftrightarrow ^3P_0$ clock transition on bosonic isotopes [10]–[12]. In this technique a static magnetic field is used to mix the $3P_0$ metastable state with the $3P_1$ state, enabling direct optical excitation of the clock transition with tunable transition rates. Details on our experimental setup and the laser sources used for cooling and trapping ^{88}Sr have been previously reported in [13], [14]. In brief, ^{88}Sr atoms are collected from a slowed Sr beam and cooled in a two-stage magneto-optical trap (MOT). The MOT uses the strong dipole allowed $^1S_0 \leftrightarrow ^1P_1$ transition at 461 nm to cool and collect atoms, and then uses the intercombination $^1S_0 \leftrightarrow ^3P_1$ transition at 689 nm to cool

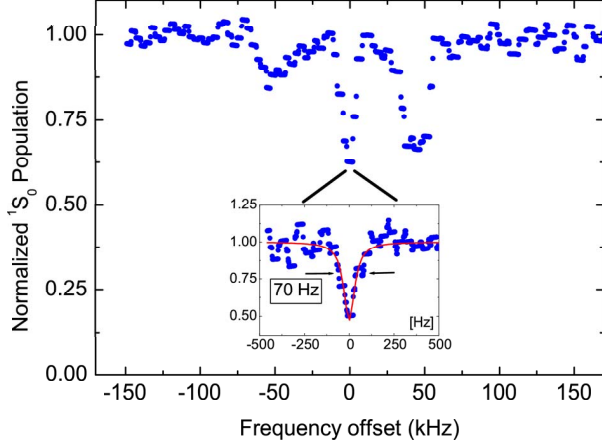


Fig. 2. High resolution spectrum of the $^1S_0 \leftrightarrow ^3P_0$ transition taken by scanning the probe laser frequency (without chirping). The spectrum is obtained with a static magnetic field $B_0 = 13$ mT and probe intensity $I=38$ W/cm² with an interaction period $\tau = 100$ ms. The separation between the carrier and the two sidebands ($\Delta = 50$ kHz) indicates a lattice depth of $55 E_r$. In the inset is shown a scan of the carrier with $B_0 = 1.3$ mT, $I = 6$ W/cm² and the same interaction period. The observed 70 Hz linewidth is limited by the induced Rabi frequency in this condition (see text). For both spectra the lattice wavelength has been tuned near the magic wavelength at 813.428 nm

calibrations (e.g., due to shocks on reference cavities) could be necessary, and where the access to frequency combs and frequency references could be limited. By using the cavity transfer method, even when shocks change the mode numbers considerably, a few trials with different modes of the transfer cavity could be sufficient to reset the offset between the transfer cavity and the probe laser reference cavity without the need of external references.

III. SPECTROSCOPY OF THE CLOCK TRANSITION

We excite the $^1S_0 \leftrightarrow ^3P_0$ clock transition in ^{88}Sr with the technique of magnetic field-induced spectroscopy [10]. We initially find the transition by chirping the probe laser frequency over 200 kHz during each 1 s probe pulse in order to increase the searching rate. With a maximum magnetic field of 16 mT and a probe light intensity of 40 W/cm², the effective Rabi frequency is estimated to be 13 kHz. This frequency is sufficiently high to ensure observable population transfer on resonance within the chirp range. Under these conditions we can find the transition quickly by taking 200 kHz frequency steps around the resonance and measuring the ground state population. We prove this search method to be effective even in the case of a poor knowledge of the probe frequency, calibrated only using a commercial wavemeter.

In Fig. 2 the data were taken without frequency chirping and with a reduced interaction time of 100 ms. The two spectra have been taken with static magnetic fields (B_0) of 13 mT and 1.3 mT (for the spectrum in the inset) respectively, and the probe intensities (I) were 38 W/cm² and 6 W/cm² (for the inset), giving induced Rabi frequencies (Ω) of 10 kHz and

130 Hz (inset). Higher-resolution spectra are shown in Fig. 2). From the frequency spacing and the amplitude ratio between the red and blue sidebands signals, we determined a lattice depth of $U_0 = 55 E_r$ and an estimated temperature of $2.6 \mu\text{K}$.

IV. INELASTIC COLLISIONS BETWEEN ATOMS IN GROUND 1S_0 AND EXCITED 3P_0 STATE

We examined the decay of the ground state population for overdriven Rabi excitation (see Fig. 3) and compared it to the lifetime of the trap in the absence of resonant excitation on clock transition. From the decay plots, it is clear that when resonant clock light is present, the atoms are lost at a higher rate compared to the normal decay rate that results from background gas collisions that limit the trap lifetime to about $\tau = 1/\Gamma = 3$ s. The faster decay in the presence of excitation light can be well described by the solution to a system of coupled rate equations $\dot{n}_S = -\Gamma n_S - \Omega(n_S - n_P) - w n_S n_P$, $\dot{n}_P = -\Gamma n_P - \beta n_P^2 + \Omega(n_S - n_P) - w n_S n_P$ [22]. These equations describe the evolution of density of atoms n_S in the 1S_0 ground state and n_P for the excited 3P_0 state, respectively. In these two equations we introduce additional density-dependent loss terms β and w associated with density-dependent losses due to collisions between atom pairs in the excited state and collisions between ground- and excited-state atoms, respectively. The atomic density in the ground state is estimated from the measurement of the trap frequencies and atom temperature with an uncertainty of 50 %. Assuming a value of $\beta = 4 \cdot 10^{-18} \text{ m}^3/\text{s}$ [23] from the fit of the experimental data with the solution of the decay equations, we estimate the value for interstate collision coefficient to be $w = 3(2) \cdot 10^{-17} \text{ m}^3/\text{s}$ at measurement temperature of

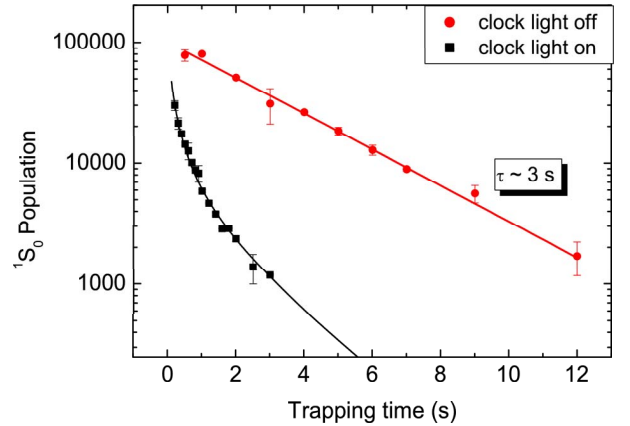


Fig. 3. Comparison of ground-state population decays. Data in circles represent the lifetime of the 813 nm lattice trap and fit well to a single exponential (solid line), vacuum limited to 2.9 s. The second, faster, decay is measured in the presence of the clock light tuned to the carrier resonance at 698 nm. These data agree well with a model based on a system of coupled rate equations (see text) indicated by the solid (lower) line. The non-exponential fast decay indicates an additional density-dependent loss mechanism due to collisions of atoms in the 3P_0 upper state with atoms in the ground state.

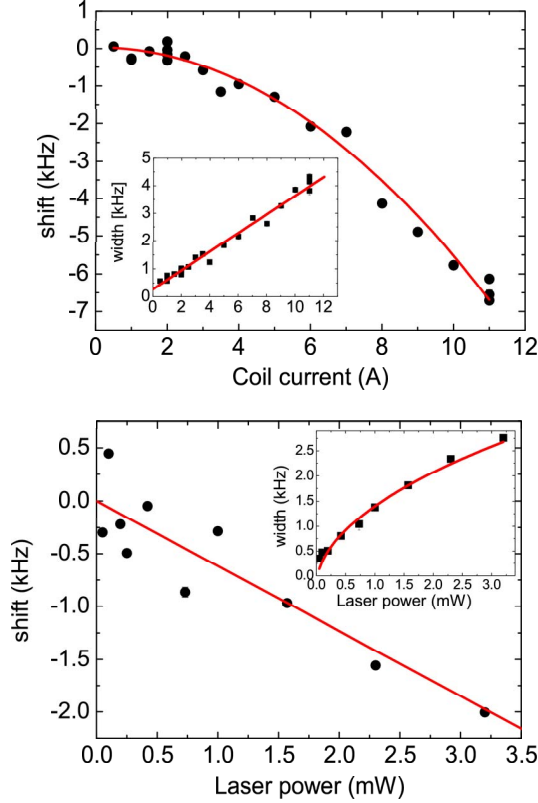


Fig. 4. Measurement of second order Zeeman shift (upper graph) and probe light shift (lower graph) for the 698 nm clock transition in a ^{88}Sr optical lattice clock. In the inset are reported the experimental FWHM of the observed transition. The experimental model agrees well with the theoretical expectation both for the shift and the width of the transition.

$T = 1.5 \mu\text{K}$.

In one sense, this effect has the obvious benefit of making the transition easy to find, even in the presence of reasonably large shot-to-shot atom number fluctuations. Thus overdriving the transition is now a standard part of our search algorithm. However, this effect could also present a strong limitation for operating a ^{88}Sr 1D lattice clock at high densities, and underfilled 2D traps or 3D traps could be the only way to overcome this effect in view of making an accurate optical lattice clock based on bosonic ^{88}Sr .

V. SYSTEMATICS EVALUATION

A preliminary study of the systematics in our clock has been carried out by using an interleaved scheme and using the ULE cavity for the stabilization of the clock laser as a frequency reference. The value for the shift and the width of the clock transition are reported in fig.4 for different values of coil current (used to produce the static magnetic field) and probe power.

Values of expected systematic shifts on the $^1S_0 \leftrightarrow ^3P_0$ clock transition are reported in table I. Values are calculated

TABLE I
EVALUATION OF SYSTEMATIC SHIFT OF $1S_0$ - $3P_0$ CLOCK TRANSITION FOR ^{88}Sr IN TYPICAL CONDITIONS (SEE TEXT FOR DETAILS).

Effect	Shift (Hz)	Uncertainty (Hz)
1^{st} order lattice	-	1.5
2^{nd} order Zeeman	-20.4	10.1
probe AC Stark	-93	250
Blackbody radiation	2.2	0.1
Total uncertainty		252 Hz

for typical experimental condition for spectroscopy with an applied static magnetic field of $B=1.3(0.3)$ mT, probe power $P=150(50)$ μW , and chamber temperature of $T=293(3)$ K.

At present the estimated uncertainty is limited to about 250 Hz by the uncertainty in the determination of probe light shift determined by the fit of data in fig.4. More accurate measurement of this effect would reduce further the overall uncertainty.

VI. SUMMARY

As lattice clocks (and optical clocks in general) continue to improve, it is also important that we continue to look for ways to simplify the clocks, so they can reach a wider range of applications. We have now demonstrated several key facets of an ultimately transportable lattice clock system. We have constructed an apparatus that uses only lasers based on semiconductor technology, which greatly reduces the size and power requirements over previous versions. We have also shown how the comparatively small ^3P fine structure splitting in Sr allows us to quickly find the clock transition without relying on extensive metrology apparatus. In this course of this development, we found a way to achieve extremely high levels of ground-state population depletion (more than 99 %), which further expedites the search procedure. An initial investigation into the source of the unexpectedly high contrast revealed evidence of density dependent collisions, an effect we plan to explore in more detail in future studies.

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REFERENCES

- [1] T. Rosenband, D.B. Hume, P.O. Schmidt, C.W. Chou, A. Brusch, L. Lorini, W.H. Oskay, R.E. Drullinger, T.M. Fortier, J.E. Stalnaker, S.A. Diddams, W.C. Swann, N.R. Newbury, W.M. Itano, D.J. Wineland, and J.C. Bergquist, *Science* **319**, 1808 (2008)
- [2] S. Blatt, A. D. Ludlow, G. K. Campbell, J. W. Thomsen, T. Zelevinsky, M. M. Boyd, and J. Ye, X. Baillard, M. Fouch, R. Le Targat, A. Brusch, and P. Lemonde, M. Takamoto, F.-L. Hong, and H. Katori, V. Flambaum, *Phys. Rev. Lett.* **100**, 140801 (2008)
- [3] D. Kleppner, *Phys. Today* **59**, 10 (2006)
- [4] G. Ferrari, P. Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli, and G. M. Tino, *Phys. Rev. Lett.* **91**, 243002 (2003)

- [5] M. Takamoto, F.-L. Hong, R. Higashi, and H. Katori, *Nature (London)* **435**, 321 (2005).
- [6] A. D. Ludlow, T. Zelevinsky, G. K. Campbell, S. Blatt, M. M. Boyd, M. H. G. de Miranda, M. J. Martin, J. W. Thomsen, S. M. Foreman, Jun Ye, T. M. Fortier, J. E. Stalnaker, S. A. Diddams, Y. Le Coq, Z. W. Barber, N. Poli, N. D. Lemke, K. M. Beck, C. W. Oates, *Science* **319**, 1805 (2008)
- [7] N. Poli, M. G. Tarallo, M. Schioppo, C. W. Oates and G. M. Tino, in press on *Appl. Phys. B* (2009)
- [8] X. Baillard, M. Fouché, R. Le Targat, P. G. Westergaard, A. Lecallier, F. Chapelet, M. Abgrall, G. D. Rovera, P. Laurent, P. Rosenbusch, S. Bize, G. Santarelli, A. Clairon, P. Lemonde, G. Grosche, B. Lipphardt, and H. Schnatz, *Eur. Phys. Jour. D* **48**, 11 (2008).
- [9] T. Legero, J.S.R. Winfred, F. Riehle, U. Sterr, *IEEE proceedings of EFTF-FCS*, 119 (2007) DOI: 10.1109/FREQ.2007.4319045
- [10] A.V. Taichenachev, V.I. Yudin, C.W. Oates, C.W. Hoyt, Z.W. Barber, and L. Hollberg, *Phys. Rev. Lett.* **96**, 083001 (2006).
- [11] X. Baillard, M. Fouch, R. L. Targat, P. G. Westergaard, A. Lecallier, Y. L. Coq, G. D. Rovera, S. Bize, and P. Lemonde, *Opt. Lett.* **32**, 1812 (2007).
- [12] N. Poli, Z. W. Barber, N. D. Lemke, C. W. Oates, L. S. Ma, J. E. Stalnaker, T. M. Fortier, S. A. Diddams, L. Hollberg, J. C. Bergquist, A. Brusch, S. Jefferts, T. Heavner, and T. Parker, *Phys. Rev. A* **77**, 050501 (2008)
- [13] N. Poli, R. E. Drullinger, G. Ferrari, M. Prevedelli, F. Sorrentino, M. G. Tarallo, and G. M. Tino, *Proc. SPIE* **6673**, 66730F (2007) DOI:10.1117/12.739057
- [14] N. Poli, R. E. Drullinger, M. G. Tarallo, and G. M. Tino, *IEEE proceedings of EFTF-FCS*, 655, (2007) DOI:10.1109/FREQ.2007.4319155
- [15] A. D. Ludlow, X. Huang, M. Notcutt, T. Zanon-Willette, S. M. Foreman, M. M. Boyd, S. Blatt, J. Ye, *Opt. Lett.* **32**, 641 (2007)
- [16] M. G. Tarallo, Ph.D. Thesis, Università di Pisa (2009), unpublished. Available at <http://coldatoms.lens.unifi.it/optical-atomic-clock/documents.html>
- [17] M. M. Boyd, A. D. Ludlow, S. Blatt, S. M. Foreman, T. Ido, T. Zelevinsky, and J. Ye, *Phys. Rev. Lett.* **98**, 083002 (2007).
- [18] T. Ido, T. H. Loftus, M. M. Boyd, A. D. Ludlow, K. W. Holman, and J. Ye *Phys. Rev Lett* **94**, 153001 (2005)
- [19] G.M. Tino, M. Barsanti, M. Angelis, L. Gianfrani and M. Inguscio, *Appl. Phys. B* **55**, 397 (1994)
- [20] H. P. Layer, R. D. Deslattes, and W. G. Schweitzer, Jr., *Appl. Opt.* **15**, 734 (1976)
- [21] P. Bohlouli-Zanjani, K. Afrousheh, and J. D. D. Martin, *Rev. Sci. Instrum.* **77**, 093105 (2006)
- [22] Similar set of equations have also been used in J. S. R. Vellore Winfred et al., Poster at 7th Symposium of Frequency standards and Metrology, Asilomar CA (2008)
- [23] A. Traverso et al., arXiv:0809.0936 (2008)