Accuracy Evaluation of an Optical Lattice Clock with Bosonic Atoms

Xavier Baillard, Mathilde Fouché*, Rodolphe Le Targat, Philip G. Westergaard, Arnaud Lecallier, Yann Le Coq, Giovanni D. Rovera, Sebastien Bize, and Pierre Lemonde

LNE-SYRTE, Observatoire de Paris, 61, avenue de l'Observatoire, 75014 Paris, France

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We report the first accuracy evaluation of an optical lattice clock based on the ${}^1S_0 \rightarrow {}^3P_0$ transition of an alkaline earth boson, namely ^{88}Sr atoms. This transition has been enabled using a static coupling magnetic field. The clock frequency is determined to be 429 228 066 418 009(32) Hz. The isotopic shift between ^{87}Sr and ^{88}Sr is 62 188 135 Hz with fractional uncertainty 5×10^{-7}. We discuss the conditions necessary to reach a clock accuracy of 10^{-17} or less using this scheme. © 2007 Optical Society of America

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The recent advent of optical lattice clocks has opened a very promising avenue for the future of atomic frequency standards.[1–4] Like single ion clocks[5–8] they allow to efficiently cancel motional effects thanks to the lattice confinement.[9] In addition, they can operate with a large number of atoms and their expected ultimate performance is a relative frequency noise well below $10^{-15}\,\tau^{-1/2}$ (with τ the averaging time in seconds) combined with a control of systematic effects in the 10^{-18} range.[10,11] These new clocks use as a quantum reference the transition between the two lowest ${}^1S_0$ and ${}^3P_0$ states of alkaline-earth(-like) atoms: Sr, Yb, Mg, Ca, Hg, etc. This transition is only slightly allowed by hyperfine quenching in the fermionic isotopes of these elements, and exhibits exquisitely narrow natural widths, in the mHz range.[12–14] Most of the experimental results demonstrated so far were obtained with fermionic ^{87}Sr: these include the observation of optical resonances with Hz linewidth,[4] the observation of hyperpolarizability effects,[11] and accuracy evaluations progressively improved down to 10^{-15}.[3,15–17]

Several proposals have been made to extend the lattice clock scheme to bosonic isotopes. In the absence of hyperfine structure, the true $J = 0 \rightarrow J = 0$ transition is forbidden to all orders for a one photon excitation, but can be enabled by adding supplementary coupling fields.[18–22] The simpler structure of the clock transition in this case has been advocated as potentially reducing sensitivity to some systematic shifts like first order Zeeman effect or polarization dependence of the lattice light shift. A further motivation of such proposals is that they dramatically increase the number of candidate species for lattice clocks experiments and that they offer the possibility to measure isotope shifts with unprecedented accuracy. Furthermore, interesting possibilities arise, like the study of cold collisions in a new regime.[23] So far, only one of these schemes,[20] which consists in adding a static magnetic field, has been experimentally demonstrated.[2] The experiment was performed with ^{174}Yb atoms and led to the observation of sub 10 Hz resonance linewidths and of a frequency stability below $10^{-14}\,\tau^{-1/2}$.[24]

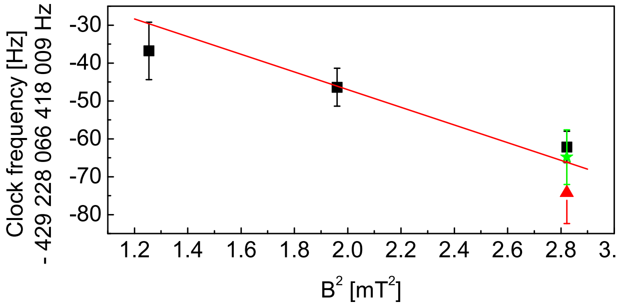

Fig. 1. Dependence of the clock frequency on the static magnetic field. The line is a fit to the experimental data with an adjustable offset, the slope being fixed to the theoretical value of Ref. [20] ■: $I/I_0 = 1$, ▲: $I/I_0 = 0.83$, ★: $I/I_0 = 0.4$.

We report here the first accuracy evaluation of an optical lattice clock with bosons, namely ^{88}Sr. We use the same simple magnetic coupling as in Ref. [20] and report an experimental study of the shifts induced by the coupling field. The apparatus is derived from the ^{87}Sr optical lattice clock described in Ref. [3] Atoms are first loaded into a magneto-optical-trap (MOT) based on the ${}^1S_0 \rightarrow {}^1P_1$ transition at 461 nm, while a 1D optical lattice at the magic wavelength and crossing the center of the MOT is constantly on. Thanks to two lasers tuned to the lowest ${}^1S_0 \rightarrow {}^3P_1$ and ${}^3P_1 \rightarrow {}^3S_1$ transitions, cold atoms are continuously drained into the metastable ${}^3P_0$ and ${}^3P_2$ states. These lasers are then switched off, and the atoms trapped in the optical lattice are pumped back into the ground state, where they are further cooled to μK temperatures using the narrow ${}^1S_0 \rightarrow {}^3P_1$ transition at 689 nm.[25,26] At this point, the coupling magnetic field for the interrogation is turned on, and the clock transition is probed using a 698 nm laser beam from an extended cavity diode laser stabilized to a high finesse cavity. The magnetic field is induced by two coils in Helmoltz configuration and is parallel to the linear polarization of the probe laser beam. The coils are fed by a power supply that switches from 0 to 6 A in a few ms. A delay of 20 ms is added between the end of cooling and the beginning of the interrogation to allow for field stabilization. The typical values used for our measurement were a static field $B_0 = 1.68\,\mathrm{mT}$, an interrogation time of 20 ms, and an intensity I_0 of the interrogation beam seen by the atoms of about $6\,\mathrm{W/cm^2}$. The transition probability is finally measured by detecting the populations of the $^1S_0$ and $^3P_0$ states after interrogation.

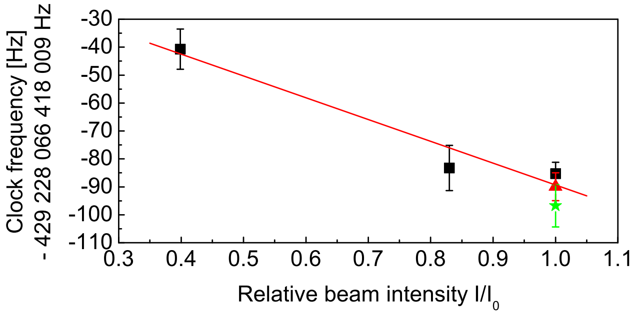

Fig. 2. Light shift due to the interrogation laser for different values of the magnetic field. ■: 1.68 mT, ▲: 1.4 mT, ★: 1.12 mT. $I_0 \simeq 6\,\mathrm{W/cm^2}$ corresponds to the clock laser intensity at standard operating conditions. The line is a linear fit to the data.

We made an evaluation of the frequency shifts that are specific to this clock configuration: the quadratic Zeeman shift and the light shift due to the interrogation laser. Fig. 1 shows the clock frequency as a function of the square of the coupling magnetic field. The latter is calibrated to within 1% by measuring the linear Zeeman shift of ^{87}Sr. Also plotted (line) is the expected dependence on the magnetic field as calculated in Ref. [20] Our result is in agreement with these expectations. The quadratic Zeeman shift for a magnetic field $B_0 = 1.68\,\mathrm{mT}$ is $\Delta_B = -65.8(1.3)\,\mathrm{Hz}$.

The evaluation of the light shift due to the interrogation laser is not as straightforward. Both the matrix elements that determine the light shift and the absolute intensity actually seen by the atoms are difficult to determine accurately. Instead we performed frequency measurements for various probe laser intensities which are referenced relative to I_0. The results are plotted in Fig. 2. For intensity I_0, the measured light shift is $\Delta_L = -74(11)\,\mathrm{Hz}$, where a conservative uncertainty of 15% has been assigned to the relative intensity evaluation.

These two shifts can in principle be related to the Rabi frequency of the transition, $\Omega/2\pi = \eta\sqrt{\Delta_L\Delta_B}$. Ref. [20] predicts $\eta = 0.3$ leading to an expected Rabi frequency $\Omega/2\pi = 20.9(1.6)\,\mathrm{Hz}$. A direct observation of the Rabi oscillations in the same experimental conditions is plotted on Fig. 3 and gives a frequency of 16(1) Hz.

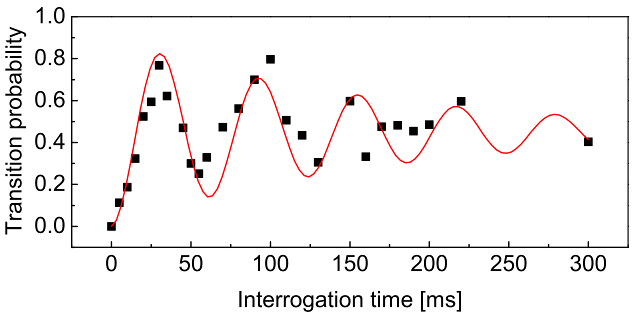

Fig. 3. Experimental observation of the Rabi oscillations for $B = 1.68\,\mathrm{mT}$ at maximum intensity $I_0 \simeq 6\,\mathrm{W/cm^2}$. The line is a fit corresponding to classical Rabi oscillations attenuated by an exponential decay. The frequency of the oscillations is 16(1) Hz, the time constant of the decay is about 100 ms which corresponds to the coherence time of the interrogation laser.

Finally, we corrected all the data for the Zeeman and light shifts to evaluate any possible density shift. Fig. 4 shows the clock frequency as a function of the atomic density around $n_0 = 2.5 \times 10^{11}\,\mathrm{at/cm^3}$. A linear fit to these data gives a frequency shift compatible with zero of $-10.4(30)\,\mathrm{Hz}$ at density n_0, or $1(3) \times 10^{-25}\,\mathrm{cm^3}$ in fractional units. In comparison, the density shift observed in atomic fountain clocks is of the order of $10^{-21}\,\mathrm{cm^3}$ for Cs[27] and $10^{-23}\,\mathrm{cm^3}$ for ^{87}Rb.[28, 29] Another effect which has been considered is the light shift due to the trapping field. The lattice is tuned to the magic wavelength measured for ^{87}Sr,[11] and we made measurements for two different depths of the trap. No detectable effect due to the trapping light was measured.

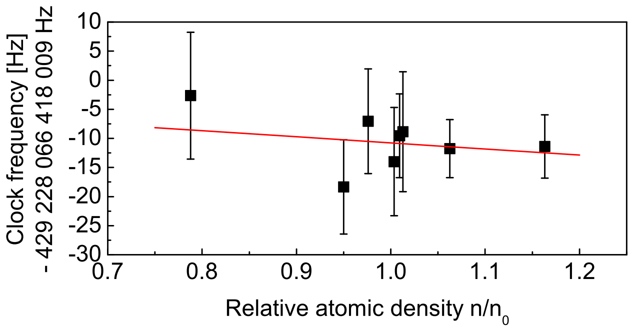

Fig. 4. Clock frequency vs atomic density. All the points have been corrected for the Zeeman and the light shifts. The line is a linear fit to the data. We have $n_0 = 2.5 \times 10^{11}\,\mathrm{at/cm^3}$.

The average value of our data corrected for systematic effects gives a clock frequency of 429 228 066 418 008.6 Hz with a statistical uncertainty of 2.6 Hz. The final uncertainty for this measurement is 32 Hz (see Table 1), or 7×10^{-14} in fractional units. This measurement in turn gives the first accurate determination of the isotope shift for the ^{87}Sr-^{88}Sr $^1S_0 \rightarrow {}^3P_0$ transition, $\nu_{88} - \nu_{87} = 62\,188\,135.4\,\mathrm{Hz}$ with relative uncertainty 5×10^{-7}.

Our measurements validate the possibility of measuring the $^1S_0 \rightarrow {}^3P_0$ transition for ^{88}Sr at a metrological level using a coupling static magnetic field. To reach the goal of an ultimate accuracy below 10^{-17},

Table 1. Uncertainty budget. All numbers are in Hz. The values are given in conditions (I_0, B_0, n_0).

Systematic effects	Correction	Uncertainty
Quadratic Zeeman shift	65.8	1.3
Clock laser light shift	74.1	11.2
Cold collisions shift	10.4	30
Blackbody radiation shift	2.4	$\ll 1$
Statistical uncertainty	-	2.6
Total	152.7	32

significant improvements have to be made. The first point is a refined study of the effect of collisions between cold atoms. Besides that, a control of the relative laser intensity to within 1% and of the magnetic field to within a few μT is certainly doable with our current setup. However, with our 20 Hz Rabi frequency, the accuracy would be still be limited to a few 10^{-15}, even if the collisional shift turns out not to be problematic at that level. A 10^{-17} accuracy would therefore require to work in a narrower linewidth (lower Rabi frequency) regime. Assuming a state-of-the-art laser,[30] we could lower the Rabi frequency down to 0.3 Hz while remaining compatible with the clock laser linewidth. Under those conditions, the goal accuracy would be within reach for a 6 mW/cm^2 probe intensity and 500 μT magnetic field, but would still require a challenging control of the probe intensity to a 10^{-3} level, and of the magnetic field at better than 0.5 μT. Magnetic shielding as well as real time magnetic field measurement would then probably be required. As the ${}^1S_0 \rightarrow {}^3P_0$ clock transition is insensitive to magnetic field at first order, one possibility would be to use the ${}^1S_0 \rightarrow {}^3P_1$ transition regularly for calibration, although great care should be taken as this transition is sensitive to lattice trapping field intensity and polarization effects. Alternatively, we could switch to ^{87}Sr from time to time.

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*Present address, IRSAMC, Université Paul Sabatier, 118, route de Narbonne, Toulouse, France

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