Accuracy Evaluation of an Optical Lattice Clock with Bosonic Atoms

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

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The recent advent of optical lattice clocks has opened a very promising avenue for the future of atomic frequency standards.\textsuperscript{1–4} Like single ion clocks\textsuperscript{5–8} they allow to efficiently cancel motional effects thanks to the lattice confinement.\textsuperscript{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 $\tau$ the averaging time in seconds) combined with a control of systematic effects in the $10^{-18}$ range.\textsuperscript{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.\textsuperscript{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,\textsuperscript{4} the observation of hyperpolarizability effects,\textsuperscript{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.\textsuperscript{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 Zee-man 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.\textsuperscript{23} So far, only one of these schemes,\textsuperscript{20} which consists in adding a static magnetic field, has been experimentally demonstrated.\textsuperscript{2}\footnote{\textsuperscript{2} The experiment was performed with $^{172}$Yb atoms and led to the observation of sub 10 Hz resonance linewidths and of a frequency stability below $10^{-14} \tau^{-1/2}$. The experiment was performed with $^{172}$Yb atoms and led to the observation of sub 10 Hz resonance linewidths and of a frequency stability below $10^{-14} \tau^{-1/2}$.}

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.\textsuperscript{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.\textsuperscript{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 $\mu$K temperatures using the narrow $^1S_0 \rightarrow ^3P_1$ transition at 689 nm.\textsuperscript{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 $B_0 = 1.68 \text{ mT}$, an interrogation time of $20 \text{ ms}$, and an intensity $I_0$ of the interrogation beam seen by the atoms of about $6 \text{ W/cm}^2$. The transition probability is finally measured by detecting the populations of the $^1S_0$ and $^3P_0$ states after interrogation.

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. 2 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 $^{87}\text{Sr}$. 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 $B_0 = 1.68 \text{ mT}$ is $\Delta B = -65.8(1.3) \text{ Hz}$.

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 $\Delta \nu = -74(11) \text{ Hz}$, 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, $\Omega/2\pi = \eta \sqrt{\Delta L \Delta R}$. Ref. $^{20}$ predicts $\eta = 0.3$ leading to an expected Rabi frequency $\Omega/2\pi = 20.9(1.6) \text{ Hz}$. A direct observation of the Rabi oscillations in the same experimental conditions is plotted on Fig. 3 and gives a frequency of $16(1) \text{ Hz}$.

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 $n_0 = 2.5 \times 10^{11} \text{ at/cm}^3$. A linear fit to these data gives a frequency shift compatible with zero of $-10.4(30) \text{ Hz}$ at density $n_0$, or $1(3) \times 10^{-25} \text{ cm}^3$ in fractional units. In comparison, the density shift observed in atomic fountain clocks is of the order of $10^{-21} \text{ cm}^3$ for $^{87}\text{Sr}$ and $10^{-23} \text{ cm}^3$ for $^{87}\text{Rb}$. $^{28,29}$ 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 $^{87}\text{Sr}$, $^{11}$ and we made measurements for two different depths of the trap. No detectable effect due to the trapping light was measured.

The average value of our data corrected for systematic effects gives a clock frequency of $429 \text{ 228 006 418 008.6 Hz}$ with a statistical uncertainty of $2.6 \text{ Hz}$. The final uncertainty for this measurement is $32 \text{ Hz}$ (see Table 1), or $7 \times 10^{-14}$ in fractional units. This measurement in turn gives the first accurate determination of the isotope shift for the $^{87}\text{Sr}$-$^{88}\text{Sr}$ $^1S_0 \rightarrow ^3P_0$ transition, $\nu_{88} - \nu_{87} = 62 \text{ 188 135.4 Hz}$ with relative uncertainty $5 \times 10^{-7}$.

Our measurements validate the possibility of measuring the $^1S_0 \rightarrow ^3P_0$ transition for $^{88}\text{Sr}$ at a metrological level using a coupling static magnetic field. To reach the goal of an ultimate accuracy below $10^{-17}$,
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 10−17, 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, 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/cm² 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 1S0 → 3P0 clock transition is insensitive to magnetic field at first order, one possibility would be to use the 1S0 → 3P1 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 87Sr from time to time.

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

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