Optical Lattice Clock with Neutral Mercury

S. Mejri, L. Yi, J. J. McFerran and S. Bize

LNE-SYRTE, Observatoire de Paris, CNRS UMR 8630, UMPC, 61 Avenue de l'Observatoire, 75014 Paris, France.

Optical lattice clocks offer the possibility to combine accuracy in the 10^{-18} range together with exquisite short stability, 10^{-16} for a measurement time of 1 second or even better [7]. Clocks with such level of accuracy and stability largely outperform the existing primary frequency standard based on the laser-cooled atomic fountain geometry and on an atomic transition in the microwave domain. Optical clocks allow fundamental physics tests with unprecedented accuracy [11] and open the way to new applications such as Earth gravitation potential mapping [12]. The ultimate limitation to the performance of optical lattice clock is still under investigation. Nonetheless, one limiting systematic shifts is clearly identified already: the blackbody radiation shift, the shift of the clock frequency due to the interaction of atoms with the ambient thermal electromagnetic background. At the temperature of 300 K and in fractional terms, this frequency shift is of the order of -5.5×10^{-15} for strontium (Sr) and -2.6×10^{-15} for ytterbium (Yb). Consequently, this effect must be controlled to much better than the percent level for an accuracy of 10^{-17}, a highly challenging task. One motivation for considering mercury (Hg) is its low susceptibility to blackbody radiation [8]. At 300 K, the corresponding fractional frequency shift is only -1.6×10^{-16}, ~16 times smaller than for Yb and ~34 times smaller than for Sr. Hg is also interesting for its high sensitivity to a putative variation of the fine structure constant. Hg has 7 natural isotopes, 6 of them with abundance above 6%, 2 fermions and 5 bosons, which are all candidates for an optical lattice clock. Using Hg for an optical lattice clock remains however a significant technical challenge given that most of the laser wavelengths necessary to manipulate atoms and to probe the clock transition are in the deep ultraviolet range of the electromagnetic spectrum.

In the last few years, we have completed several of the necessary steps toward the realization of an optical lattice clock using Hg. We have developed a vacuum system, accounting for the specificity of Hg. Notably, Hg has a comparatively high vapour pressure, which enables the use of a 2 dimensional magneto-optic trap (2DMOT) has a source of cold atom. The Hg pressure in this 2DMOT is regulated using an under-vacuum 2 stages thermo-electric cooler to cool down to approximately -40°C a small quantity (~1 gram) of Hg. The rest of the vacuum system is kept at the uniform temperature near 300 K, a situation favourable to control the blackbody temperature seen by the atoms. Magneto-optic trapping (MOT) of Hg is performed using the $^1S_0$-$^3P_1$ intercombination transition. The 254 nm laser light necessary to excite this transition is synthesized by frequency quadrupling the output of an Yb-doped thin disk laser operated in a single frequency configuration. Saturated absorption spectroscopy of $^1S_0$-$^3P_1$ is performed in a 1 mm thick room temperature Hg vapour cell in order to stabilize the laser frequency, a simple stabilization scheme allowed again by the high vapour pressure of Hg. This source has been capable to generate up to 800mW of laser light at 254 nm. At this power, quickly occurring damage of optical components is observed. Consequently, most experiments so far have been performed with ~100 mW of 254 nm light [1]. Our magneto-optic trap can capture up to 10^7 atoms (^{202}Hg isotope) and has a lifetime up to ~2.3 s, limited by background gas collisions. We have studied and optimized laser cooling for several fermionic and bosonic isotopes, and shown that sub-Doppler cooling is at work for fermionic isotopes [2]. The lowest achieved temperature so far is ~29 μK for ^{201}Hg. Further details are reported in [2].

We have also developed an ultra stable clock laser system for Hg. The clock transition is the $^1S_0$-$^3P_0$ intercombination transition at 265.6 nm, with a natural linewidth of ~100 mHz [16]. We first implement an ultra stable laser source at 1062.5 nm using a Yb-doped fibre laser stabilized to ultra stable Fabry-Perot cavity, designed for having a low thermal noise limit, a low susceptibility to vibration and highly stable thermal environment, as described in [3]. Measurements against a second similar system have shown combined fractional frequency instability below 5.6×10^{-16} [6]. This ultra stable laser system is linked to a femtosecond optical frequency comb enabling measurements against LNE-SYRTE ultra stable reference [4] which in turn is connected to atomic fountain primary clocks [13]. The 1062.5 nm light is amplified by injection locking a semiconductor laser and frequency quadrupled to reach 265.6 nm and probe the clock transition. Up to 7 mW have been generated at this wavelength. Using this laser source, we have performed the first laser spectroscopy of the clock transitions for the two fermionic isotopes ^{199}Hg and ^{201}Hg on cold atoms released from the magneto-optic trap. We have measured the absolute frequency of these transitions, improving by more than 4 orders of magnitude over previous measurements, a first important step toward the realization of an optical lattice clock with a new atomic species. These measurements are described in detail in [5].

978-1-4244-6051-9/11/$26.00

The next important step is to trap atoms in a tightly confining lattice trap near the so-called magic wavelength, the wavelength of the lattice trap at which the AC Stark shifts (or light shifts) of the two clock states are identical, so that the clock transition itself is unperturbed (to leading order) [7]. We have developed a frequency doubled titanium: sapphire laser system delivering up to 280 mW near the predicted magic wavelength of 360 nm [8]. We have implemented a resonant build-up Fabry-Perot cavity whose mode is overlapped with the magneto-optic trap inside our vacuum chamber. This system is in principle capable of creating an intracavity circulating power in excess of 15 W near 360 nm. In practice, we have observed fast damaged of optical components limiting so far our maximum practical circulating power to 3 W, corresponding to the trapping depth of ~3.6 μK, given the geometry of our lattice laser beam. Under these conditions, we have observed trapping of several isotopes (^{200}Hg, ^{199}Hg) with lifetime in the range of 100 ms [9]. We have then performed spectroscopy of the clock transition for the ^{199}Hg isotope confined into the lattice trap. From a series of measurements of these spectra for several lattice wavelengths and several lattice depths, we have made the first experimental determination of the magic wavelength for Hg [10].

With these important achievements, the feasibility of an Hg optical lattice clock is well established. The next challenges will be to reach deeper lattice traps by overcoming the technical problem of the fast damaging optical components and to implement laser cooling in the lattice trap. This will give access to ultra narrow line spectroscopy (Hz level at 265.6 nm) and to clock operation with high frequency stability (10^{-15} range for measurement time of 1 second). At this point, gradually improving studies of systematic shifts will determine the accuracy limit for the Hg system, down to the 10^{-18} level. Comparisons with other optical [14] and microwave clocks [13][15] will lead to fundamental physics tests and other applications.

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