New frequency ratios with a PHz-scale atomic clock

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Abstract
Atomic clocks are a tour de force when it comes to rigorous tests of measurement. The ultimate validation of one’s careful assessments is to find agreement on a given parameter with a completely independent laboratory. Frequency ratios between clock transitions of different atomic species make for quintessential tests of measurement precision. Tyumenev et al (2016 New J. Phys. 18 113002) report on frequency ratio measurements between a $^{199}$Hg optical lattice clock and three other atomic frequency standards: $^{133}$Cs, $^{87}$Rb and $^{87}$Sr, two of which are unprecedented in accuracy. Most notable is the level of agreement for the $^{199}$Hg/$^{87}$Sr frequency ratio found between two independent laboratories at $1.7 \times 10^{-16}$; further indication that optical lattice clocks are fulfilling their early expectations.

1. Perspective
The rate of improvement in optical frequency standards has remained unabated over a number of decades [1, 2]. Influential in this rate of progress has been the invention of the optical lattice clock [3, 4], permitting a large number (N) of quantum absorbers to be maintained in the Lamb–Dicke regime [5, 6]. Because the frequency instability of clocks reduces as $1/\sqrt{N}$, the time required to investigate various systematic shifts reduces in accordance. While lattice clocks are complicated by design and are prone to a large number of systematic frequency shifts, the improvement in frequency instability helps to hasten the overall evaluation procedure. Numerous systematic shifts have been carefully studied through the comparison of duplicated clocks—those with same atomic species. These investigations give us confidence that lattice clocks with accuracies in the low $10^{-18}$ range can be constructed [7, 8]. However, the ultimate test of atomic clocks is for separate laboratories to find agreement on frequency ratios between non-identical clocks; that is, those based on different atomic species (or different transitions in the same atom/ion). Any one frequency ratio measurement involves a great deal of complexity, since completely separate laser and optical systems need to be set in place for each atomic clock. The authors of [9], not being content with two atomic clocks, have carried out frequency ratio comparisons using four systems: two in the optical domain and two in the microwave domain. Moreover, one of the lattice clocks is based on a transition in mercury, where all the necessary wavelengths lie in the ultraviolet (and mostly in the deep UV). Although pioneers such as J Bergquist and D Wineland were bold enough to carry out spectroscopy requiring deep UV light decades ago [10, 11], today it is still a significant challenge to operate at sub-300 nm, especially when more than 100 mW is desired.

The Hg transition has the advantage that its susceptibility to background thermal radiation is more than an order of magnitude weaker than that of equivalent transitions in neutral strontium or ytterbium. Hence the accuracy to which the temperature of the surrounding apparatus needs to be known is relaxed. However, the flip-side is that the intensity required to produce the same depth optical trap is nearly fifty times greater (a quantity that is also affected by the difference in magic wavelength [12, 13]).

Three frequency ratios have been reported in [9] all involving the $(6s^2)\, ^3P_0 \rightarrow (6s6p)\, ^3P_0$ transition in $^{199}$Hg. The uncertainties associated with each ratio are summarised in figure 1. The key to establishing these ratios was the improvement in the mercury reference (now accepted as a recommended standard frequency by the
Consultative Committee of Time and Frequency). Gains have been made over earlier reports by the LNE-SYRTE team by creating a deeper lattice trap and spin polarizing \cite{14} the atoms through state selection. The $^{199}\text{Hg}$ isotope has a nuclear spin of $1/2$, thus rather than the usual cascade of magnetic substates, here there are only two; simplifying the state selection process. The state selection scheme leaves the atoms in the upper state and discards those that may remain in the ground state. The main spectroscopic pulse then drives the atoms back down from the upper metastable state, leaving only those atoms that make the Rabi-flop to the ground state for detection. The ultra-stable probe light (at 266 nm) is locked to the atomic transition by alternate sampling of the mid-points either side of the resonance centre. To determine the sensitivities to various perturbations this lock remains in place while a parameter relevant to a particular systematic is adjusted in a periodic fashion. By measuring the size of the correction in the servo, aided with integration time, the strength of the systematic effect can be carefully quantified.

The team have gone to great lengths to validate the accuracy of the mercury clock. The systematic effects investigated include: atomic collisions, AC Stark (linear and higher-order), ambient thermal radiation, and magnetic field shifts. The dominant systematic uncertainty for the Hg clock frequency is that of the lattice light shift, with the linear term remaining the most prevalent. From this perspective there are relatively easy gains to be made for further reduction in the overall uncertainty. This rests on the prospect that the lever used for light shift tests can be further lengthened by way of a deeper trap, or through transferring a larger number of cold atoms to the optical trap.

The frequency ratios measured in \cite{9}, along with others \cite{15–19}, relate to our present epoch. There is no guarantee that they will hold for all time \cite{20}, and in fact there are strong arguments that they are unlikely to remain so \cite{21}. Perhaps in the not-to-distant future the extraordinary precision exhibited by contemporary atomic clocks will invalidate an assumption about the constants of nature that, until now, has had an annoying tendency to hold fast.

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