Ground-based Research to Improve Future Atomic Clocks and Interferometers for Fundamental Physics in Space

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Ground-based research is needed to fully realize the advances of atomic clock accuracy and atom interferometer precision that satellites provide these quantum sensors. With long-term goals of stabilities exceeding 10^{-20}, problems to address for future space missions include uncertainties due to blackbody radiation and non-linear lattice light shifts. Approaches include developing techniques beyond operational magic wavelengths, engineering thermal environments, and using atoms with small sensitivities to blackbody radiation, which is likely to entail proving UVA laser sources for space.

Atomic clocks realize the most accurate measurements and their accuracy on Earth is expected to soon be limited, via General Relatively, by tidal variations of the gravitational potential on the Earth's surface. For future fundamental physics experiments, Mid-Earth and higher orbits have minimal tidal perturbations and can provide the pristine gravitational environment needed for atomic clock and interferometer measurements, allowing fractional frequency accuracies exceeding 1 part in 10^{19}.

Optical lattice clocks can provide the high short-term frequency stability required of most fundamental physics tests and their current accuracies approach 1 part in 10^{18} [1--13]. The largest contributions to their frequency uncertainties are the frequency shifts from black-body radiation (BBR) and non-linear lattice light shifts. These, for example, are expected to be the limitations for the proposed FOCOS mission [14], for a clock based on Ytterbium, and the BBR sensitivity of Strontium is slightly, 2.2 times, higher. Ground-based advances in a number of areas are needed, especially on SWaP (size, weight, and power) for the laser systems and the ultrastable cavity for the local-oscillator. Beyond these, advances in clock accuracies, for both clocks and atom interferometers, are needed to realize the full benefits of these quantum sensors in space and to enable the ultrahigh precision to detect gravity waves and tests Fundamental Physics.

The current most accurate clock is an aluminum ion clock at 9×10^{-19} [15], which is highly insensitive to BBR. The most common and accurate lattice clocks are based on strontium and ytterbium, which has a BBR sensitivity that is 0.45 of strontium's. FOCOS aims for an accuracy of 1×10^{-18} with the largest contributions being from BBR at 5×10^{-19} and lattice light shifts at 7×10^{-19}. For Strontium, smaller lattice light shifts could be expected at the expense of a larger BBR uncertainty. Work is needed to achieve an environment with sub-mK absolute temperature accuracy, including uncertainties from gradients and potentially from cosmic ray exposure in mid-Earth orbits (MEO) or higher orbits, for a physics package that is very unlikely to be rechecked after being launched.

Another technique being explored is using the atoms as temperature sensors [16,17], which would almost certainly increase SWaP. Currently, there are significant uncertainties due to atomic properties. These measurements will likely improve for ground-based clocks, independent of potential space missions, although the possibility of clocks in a space environment would motivate higher accuracies for measurements of BBR sensitivities.

Fig. 1. Cadmium energy levels. The narrow, 67 kHz wide, 326 nm $^1S_0$-$^3P_1$ directly yields low temperature atoms. The 361 nm metastable $^3P_2$-$^3D_3$ MOT significantly increases the loading rate of the cadmium bosonic and fermionic isotopes, and provides cycling state detection [12]. The 468 and 480 nm light optically pumps atoms from $^3P_1$ to $^3P_2$. The Cd magic wavelength is 420 nm [13] and the $^1S_0$-$^3P_0$ clock transition is 332 nm.

Another path to reducing BBR uncertainties is developing clocks based on atoms with small BBR sensitivities. Leading candidates for ground based clocks are mercury [8-11] and cadmium [13], which have BBR sensitivities an order of magnitude smaller than strontium and ytterbium. Mercury is currently more developed but requires UVB laser light, and so far, reasonably high power 254 nm light is required [9]. Cadmium is at an earlier stage – it has been trapped and the magic lattice wavelength has been measured [13]. We have recently demonstrated that cadmium can be efficiently trapped and cooled with only UVA laser light at 326 nm and 361 nm, along with two low power visible repumping laser light (468 nm & 480 nm), as depicted in Fig. 1. The power required for 326 nm and 361 nm light could be as low as 50 mW for a cadmium lattice clock. We have operated these sources for weeks at higher powers with no identified degradation. The RIKEN cadmium clock [13], with its 229 nm UVA light for the $^1S_0$-$^1P_1$ transition, was constructed as a portable clock and the Penn State cadmium trap uses only semiconductor lasers and a single fiber amplifier. Ground-based research is needed to prove the long-term reliability of these sources, for cadmium or mercury, as well as those for ytterbium for FOCOS, including for long-term operation in high orbits.

The narrow intercombination transitions of strontium and cadmium provide low temperatures, which help accurate evaluations of lattice light shifts. Ytterbium, and almost certainly mercury too, can be cooled to low temperatures with additional SWaP. Ongoing research to advance Earth based clocks is expected continue to reduce the uncertainties of lattice light shifts, including techniques beyond operational magic wavelengths [18-21].
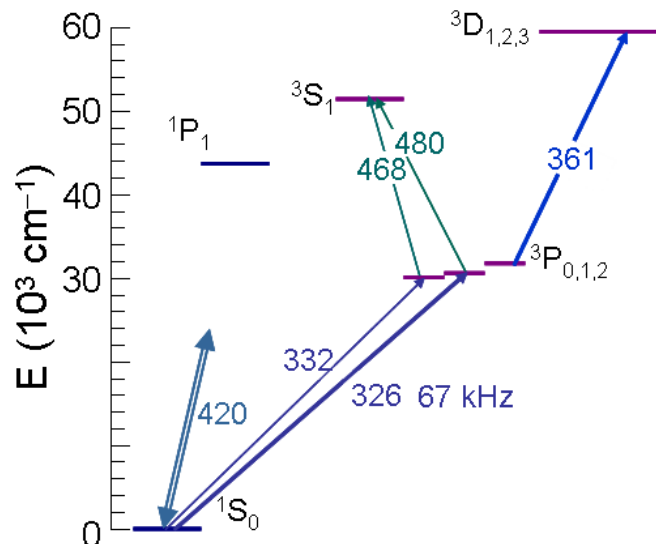
Group-II atoms also offer advantages for atom interferometry, including for future missions to observe gravity waves, search for Dark Matter, and test Fundamental Physics. The $^1S_0$-$^3P_0$ clock transitions are sufficiently narrow and these transitions between two J=0, m=0 states, with no hyperfine structure, have importantly smaller sensitivities to magnetic field variations [22-24], in comparison to transitions between m_F=0 alkali hyperfine clock states. In addition to the smaller differential DC Stark shifts of the cadmium clock states, cadmium has a series of 6 bosonic nuclear-spin 0 isotopes, from ^{106}Cd to ^{116}Cd. The relatively small polarizability of cadmium and its moderate atomic mass leads to the mass change from ^{106}Cd to ^{116}Cd adding just over one bound state to the three potentials for ground and excited clock state Cd-Cd interactions. Thus, in 6 steps the s-wave scattering lengths spanning the range of small and large scattering lengths, allowing a selection of the collision shifts for atom interferometers, and possibly also for bosonic cadmium lattice clocks. The existence of two spin ½ fermion isotopes, ^{111}Cd and ^{113}Cd, similarly allows avoiding large s-wave collision cross sections for the more likely ultimate cadmium lattice clock.

The first seven years after the first lattice clocks demonstration saw dramatic improvements in accuracy [1,2]. Since 2010, the rate may have slowed to be comparable to the historical exponential improvement of atomic clocks, an order of magnitude every seven years. The history of the development of atomic clocks suggests that a follow-on space clock mission after FOCOS will aim for fractional frequency accuracies at least of order 5×10^{-20} and, after several more years of advancement, clocks or clock-like atom interferometers will have sensitivities to detect mid-band gravity waves in space. In addition to significant effort to reduce the SWaP for clock space missions, these advancements will require technical innovations in many areas, including ultrastable clock lasers, quantum entanglement and spin squeezing, cold-atom interactions and background gas collision shifts, and technical improvements on locking errors and clock links. This paper describes the motivation to explore atoms with small sensitivities to blackbody radiation, to improve resistive or atomic temperature measurements, and to study lattice light shifts. For tests of fundamental physics in space, these are needed to reduce the currently dominant uncertainties due to blackbody radiation, as well as stray electric field from cosmic ray charging, and lattice light shifts to fully realize the atomic clock accuracy and atom interferometer precision that space missions enable.

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