Stable and Accurate Single-ion Optical Clocks

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Abstract

Single-trapped-ion frequency standards based on a 282 nm transition in $^{199}Hg^+$ and on a 267 nm transition in $^{27}Al^+$ have been developed at NIST over the past several years. Their frequencies are measured relative to each other and to the NIST primary frequency standard, the NIST-F1 cesium fountain, by means of a self-referenced femtosecond laser frequency comb. Both ion standards have demonstrated instabilities and inaccuracies of less than 3×10^{-17}.

1. Introduction

In recent years, several groups throughout the world have initiated research toward the development and systematic evaluation of frequency and time standards based on narrow optical transitions in laser-cooled atomic systems. I will discuss some of the key ingredients to the make-up and operation of single-atom, optical clocks and why they offer higher stability and accuracy than the best clocks of today. I will then present some of the results obtained at NIST through comparative studies of the Hg^+ single-ion optical clock, the Al^+ single-ion optical clock and the Cs fountain, primary frequency standard (NIST-F1) [1-4]. The frequencies of the clocks are compared with each other using an octave-spanning optical frequency comb (OFC), which is tightly phase locked to one of the clock lasers. The most recent frequency comparison between the Hg^+ optical clock and NIST-F1 shows an uncertainty of $\sim 9 \cdot 10^{-16}$ limited by the integration time, and recent measurements of the frequency ratio between the Al^+ and Hg^+ standards show an overall uncertainty of several parts in 10^{-17}. A microwave-to-optical frequency comparison yields a measurement of the optical frequency in terms of the SI (International System of Units) second, which is based on the cesium hyperfine frequency. According to our evaluation of their systematic uncertainties, both the mercury and aluminum standards are more accurate than current primary cesium frequency standards. This places a limitation on the accuracy of measurements of the mercury and aluminum optical resonance frequencies in terms of the SI second. However, measurements of the ratio of the mercury and aluminum frequencies are not subject to this limitation. Measurements of this ratio as a function of time place limits on the variation of the fundamental constants, such as the fine-structure constant α.

Tests of the temporal stability of the fine structure constant α are possible with both the Hg^+/Cs and the Hg^+/Al^+ frequency comparisons. From our Hg^+/Cs measurements, temporal variation of α is estimated to be lower than $1.3 \cdot 10^{-16}$ yr^{-1}, assuming stability of the other fundamental constants involved [3]. This limit is determined from the historical series of frequency comparisons of these two standards spanning more than five years. From the measurements of the frequency ratios of various optical clocks it is possible to directly estimate any present-day temporal variation of α without constraints on other constants. Preliminary data from the measurements of the Hg^+/Al^+ frequency ratio spanning a period of more than a year indicate a 10-fold more stringent limit on the time variation of α [4].

Results from Hg^+/Cs frequency comparisons can also be used to test the postulate of Local Position Invariance (LPI). LPI states that atomic clocks experience the same fractional frequency shift when they move through the same change in gravitational potential. The test presented here uses the natural variation of gravitational potential given by the earth's revolution about the sun to set limits on possible violations of LPI [3].

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