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Progress on the optical lattice clock

Les progrès accomplis dans le domaine des horloges optiques en réseau

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ABSTRACT

Optical lattice clocks have made significant leaps forward in recent years, demonstrating the ability to measure time/frequency at unprecedented levels. Here we highlight this progress, with a particular focus on research efforts at NIST and JILA. We discuss advances in frequency instability and the characterization of key systematic effects, with a brief outlook to the future.

RÉSUMÉ

Les horloges optiques en réseau ont fait des progrès significatifs ces dernières années, en démontrant la possibilité de mesurer le temps et les fréquences à un niveau jamais atteint auparavant. Dans cet article, nous illustrons ces progrès en nous focalisant sur les efforts de recherches au NIST et au JILA. Nous discutons les avancées au niveau de l'instabilité de fréquence et de la caractérisation des effets systématiques clés, et nous donnons un bref aperçu des perspectives futures.

1. Introduction

Atomic clocks based on optical transitions have long held the potential to measure time and frequency beyond the levels of state-of-the-art primary standards using a radio frequency transition in laser-cooled cesium atoms. Researchers have explored multiple architectures for realizing this type of advanced optical timekeeper. One type of system, the optical lattice clock, is based on large ensembles of ultracold neutral atoms confined in an optical lattice, and exhibits exceedingly high optical transition quality factors [1]. The lattice clock has now been developed for roughly a decade. The large atom number enables measurement with reduced noise from quantum projection of the atomic state. The tight atomic confinement in a specially designed laser potential enables atomic excitation free from Doppler and motional effects, which are pronounced for untrapped atoms. The far-detuned laser potential is operated at the magic wavelength, where light shifts on the electronic states being probed are canceled [2]. After the first proposal of an optical lattice clock [3], early demonstration

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experiments advanced rapidly. Today, scientists around the world have or are constructing dozens of these next-generation timekeepers based on laser-cooled strontium, ytterbium, mercury, and magnesium. Systems based on strontium and ytterbium have been accepted internationally as a secondary representation of the SI second. These clocks now push to uncharted domains of performance in the key figures of merit for optical frequency standards: frequency uncertainty and instability. In so doing, they enable new and more precise atomic clock measurements relevant for tests of fundamental physics and exploration of quantum physics and technology.

State-of-the-art primary frequency standards traditionally use laser-cooled cesium in an atomic fountain. Over the last decade, these systems have improved, reaching a fractional frequency uncertainty and instability at the 10^{-16} level. During the comprehensive evaluation of a strontium lattice clock at JILA in 2008 [4] and of an ytterbium lattice clock at NIST in 2009 [5], frequency uncertainty and instability also reached fractional levels of 10^{-16}. In order to move further, it became clear that several aspects of the optical lattice clock needed additional study and advancement. The measurement capability of these frequency standards, given by the stability, fell far short of the standard quantum limit. They were limited by an important technical noise, known as the Dick effect. Thus a major research effort has been launched at improving the stability of clock lasers—the optical local oscillators. Significant perturbative shifts of the electronic 'clock' states being probed resulted from the blackbody Stark effect and ultracold atomic interactions. Research efforts at JILA and NIST since that time have largely focused on these areas, and here we highlight that work. Improved clock performance and the study of these effects have helped evaluate a range of other physical effects that become important as we push the total clock uncertainty into the 10^{-18} regime [6,7]. Significant progress worldwide has made these timekeepers among the most promising next-generation atomic clocks.

2. Optical lattice clock stability

Like any other atomic clock today, the optical lattice clock exploits narrowband transitions between long-lived electronic states. These long-lived, highly-coherent states can be driven for long durations and can thus discriminate photon frequency very precisely: only a field tuned near-exactly in resonance with the transition frequency can transfer population. With electronic transitions at optical frequencies and with natural line widths at the mHz level, atoms in an optical lattice clock can be superb frequency discriminators. However this discrimination requires one to measure population transfer between quantum states, a process limited by the randomness of quantum measurement. The quantum projection noise of a two-level system sets the fundamental precision of an atomic clock measurement, and thus the fractional stability of any frequency standard using atoms. Fortunately, the optical lattice clock employs ensembles of thousands to millions of atoms, where the quantum projection noise can be averaged down by the square root of this large atom number. By so doing, optical lattice clocks based on strontium and ytterbium might achieve fractional frequency instability of $\leq 10^{-17}$ in a mere second of measurement. However, in practice, until recent years we typically observed instability of 10^{-15} at the timescale of one second [4,5].

A number of effects can compromise performance and prevent reaching the quantum limit. However, one effect is particularly troublesome and relevant to optical atomic clocks: the Dick noise [8]. Excitation of the clock transition is not continuous. Instead it is limited to a finite time, usually given by frequency instability of the laser field driving the excitation (typically ≤ 1 s). Furthermore, consecutive excitations of the clock transition are interrupted by operations such as cooling and trapping of atoms into the optical lattice, as well as atomic state preparation and readout. This periodic interrogation of the clock transition introduces unwanted sensitivity to frequency noise of the laser driving field: noise at harmonics of the measurement cycle frequency is aliased by the periodic atom–laser interaction. This aliased noise compromises the atomic response and thus the stability of the optical clock, and is known as the Dick effect. Even though laser frequency noise is typically reduced by pre-stabilization to high-finesse, ultra-stable optical cavities, the resulting noise levels were sufficient to limit normal lattice clock operation at the 10^{-15} level at one second of measurement.

The most obvious solution to the Dick effect is to reduce the laser frequency noise spectrum, consequently reducing the aliased noise. Such an approach requires enhanced pre-stabilization of the interrogation laser, which is limited by the length stability of the optical cavity to which the laser frequency is stabilized. This limit is typically given by Brownian thermo-mechanical fluctuations of the optical cavity mirrors [9]. In order to minimize the influence of these fluctuations on the fractional length stability of the optical cavity, the cavity length should be large and the mirror substrate material should have low mechanical loss (e.g., fused silica). Enhanced cavity-stabilized lasers were constructed for the NIST Yb lattice clock [10] and the JILA Sr optical lattice clock [11,12]. The reduced frequency noise spectrum enabled the Dick effect to be lowered by roughly one order of magnitude. As an added benefit, these lower-noise laser systems exhibit longer coherence times, allowing the spectroscopic interrogation time of the lattice-trapped atoms to be extended, resolving optical features at or below the Hz level [13,10]. Recent comparisons between two Yb lattice clocks [14] and between two Sr lattice clocks [6] highlight the benefits of the reduced noise. Frequency instability of 3.4×10^{-16} was realized at one second, averaging down as white frequency noise to >10,000 seconds, approaching an instability of 1×10^{-18} (see Fig. 1). A more recent experiment using 1 s clock interrogation time was able to demonstrate instability of 2.2×10^{-16} at one second [7].

Under such conditions, these clocks are still influenced by the Dick effect, with lingering room for improvement. This is especially true when long atomic interrogation times yield further reductions in the limit set by quantum projection