STRONTIUM OPTICAL LATTICE CLOCK WITH HIGH ACCURACY AND STABILITY

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Abstract

Techniques of modern quantum optics allows for the preparation of atoms in well controlled quantum states ideal for precision measurements and tests of fundamental laws of physics. We report on our recent progress with a highly stable and accurate optical atomic clock based on ultracold fermionic ^{87}Sr atoms confined in a one dimensional optical lattice. Currently, we have carried out a detailed evaluation of our clock at the 10^{-16} level and can report stability at 2 x 10^{-15} level at one second. At typical operating parameters for the clock we observe evidence of a density dependent clock shift. Operating the clock at a particular excitation ratio of ground state and excited clock state we observe a shift consistent with zero.

Introduction

The interest in alkaline-Earth and alkaline-Earth-like atoms has increased significantly over the past years. One of the main reasons is the use of these elements for new improved frequency standards and optical clocks. For this purpose the ultra narrow intercombination $^1S_0 \rightarrow {}^3P_0$, and $^3P_1$ lines are promising candidates. Their linewidths range from a few KHz to below mHz depending on the specific element and isotope. In the case of fermionic ^{87}Sr the weakly allowed $^1S_0 \rightarrow {}^3P_0$ clock transition is particularly interesting, leading to a mHz linewidth. Confining cold atoms in an optical lattice, that provides a zero differential a.c. Stark shift between two clock states, we achieve a resonance quality factor exceeding 2 x 10^{14} on the $^1S_0 \rightarrow {}^3P_0$ ^{87}Sr clock transition at 698 nm. High resolution spectroscopy is thus insensitive to Doppler and recoil effects. Our sample of spin-polarized atoms is used for both high-performance clock operations, accurate atomic structure measurements and quantum optics experiments. Recently, the combined efforts of several independent groups working on neutral atomic clocks opens the way for accurate tests of fundamental physical laws targeting time drift of the fine structure constant and coupling of fundamental constants to gravity [1].

^{87}Sr optical lattice clock

We prepare the atomic sample for the ^{87}Sr clock (nuclear spin I = 9/2), using narrow-line Doppler cooling techniques to reach μK temperatures.

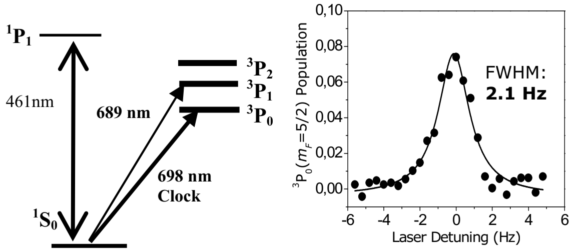

Figure 1: (Left) Energy level diagram for ^{87}Sr and the clock transition. (Right) Scan of the 698 nm clock transition.

Approximately 4000 ^{87}Sr atoms at 2.5 μK are confined in a 1-D optical standing wave operated at the magic wavelength of 813 nm, where the differential a.c. Stark shift is zero. The resulting longitudinal (transverse) trap frequency is 42 kHz (125 Hz) and yields a Lamb Dicke parameter of about 0.3 along the longitudinal direction. The lattice trap depth corresponds to about 45 lattice photon recoil energy. The atom density is approximately $\rho_0 = 1\mathrm{x}10^{11}$ cm^{-3}. Further experimental details can be found elsewhere [2, 3]. Although both clock states have J=0, the nuclear spin I=9/2 permits ten spin states, all of which are populated in the ground clock state after laser cooling. We optically pump the lattice-trapped ground state population to the $m_F = \pm 9/2$ states by exciting the $^1S_0$ F=9/2 - $^3P_1$ F'=7/2 transition. Employing optical pumping, the atoms are (doubly) spin polarized and occupy only the two stretched states $m_F = \pm 9/2$ (m_F = magnetic quantum number). Fig. 2B shows spectra of the π clock transitions ($m_F = 0$) with and without the optical pumping.

Using the spin-polarized sample in a weak bias magnetic field, we interrogate the isolated $m_F = \pm 9/2$ clock transitions for 80 ms, allowing Fourier-limited spectral linewidths of 11 Hz. For these conditions, quantum projection noise would theoretically limit the Sr clock stability to $7\mathrm{x}10^{-16} /\sqrt{\tau}$. Ultimately, we have observed linewidths below 2.1 Hz [2], see figure 1. Recently, we have performed a detailed evaluation of our clock at the 10^{-16} level [5]. To improve the accuracy and precision of the clock, a 3.5 km fiber link is used for direct comparison of the JILA Sr system with the NIST Ca optical clock [6]. To support the needed accuracy and precision, the fiber link has been stabilized such that the transfer instability is below 10^{-17} at 1 s [7].

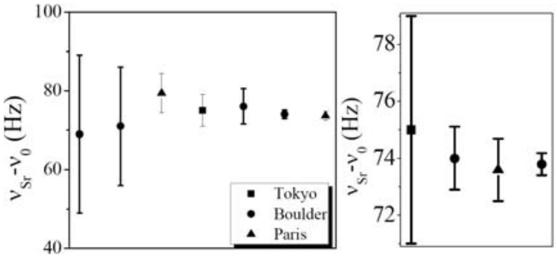

Figure 2: Summery of the latest absolute clock frequency ν_0 measurements (right plot) carried out in Tokyo [8], Boulder [9] and Paris [10].

The evaluation includes probe and lattice laser a.c. Stark shift, line pulling, servo error, density shifts, Zeeman, Black Body Radiation (BBR) stark shift etc. We find the overall fractional systematic uncertainty is 1.5×10^{-16}, the smallest uncertainty reported for any neutral atom standard to date and represents a six-fold improvement over our previous result [5]. The current limit of the clock is given by our inadequate knowledge of Stark shifts of the atomic energy levels induced by the room temperature blackbody radiation. Surprisingly, we do observe a systematic density dependent shift of the clock frequency. The density shift depends on the fraction of atoms in ground state and may originate from slightly inhomogeneous excitation of the atoms in the lattice. With this improved uncertainty evaluation we have made improved measurements on the absolute frequency of the ^{87}Sr clock transition, reaching below the 9×10^{-16} level by comparing to the NIST Cs standard. This is the most accurate absolute frequency measurement performed on a neutral atom clock system and equivalent to the most accurate measurement achieved with trapped ions.

In addition, we will also give an update on our recent quantum optics experiments in the Sr optical lattice, such as the use of electromagnetic-induced transparency for the access of the doubly forbidden transition $^1S_0 \rightarrow {}^3P_0$ in ^{88}Sr.

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