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# Probing many-body interactions in an optical lattice clock

A.M. Rey[a,*], A.V. Gorshkov[b], C.V. Kraus[c,d], M.J. Martin[a,e], M. Bishof[a], M.D. Swallows[a], X. Zhang[a], C. Benko[a], J. Ye[a], N.D. Lemke[f], A.D. Ludlow[f]

[a] JILA, NIST and University of Colorado, Department of Physics, Boulder, CO 80309, USA

[b] Joint Quantum Institute, NIST and University of Maryland, Department of Physics, College Park, MD 20742, USA

[c] Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria

[d] Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria

[e] Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, CA 91125, USA

[f] National Institute of Standards and Technology, Boulder, CO 80305, USA

## HIGHLIGHTS

- Derived a theoretical framework that describes many-body effects in a lattice clock.
- Validated the analysis with recent experimental measurements.
- Demonstrated the importance of beyond mean field corrections in the dynamics.

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## ABSTRACT

We present a unifying theoretical framework that describes recently observed many-body effects during the interrogation of an optical lattice clock operated with thousands of fermionic alkaline earth atoms. The framework is based on a many-body master equation that accounts for the interplay between elastic and inelastic $p$-wave and $s$-wave interactions, finite temperature effects and excitation inhomogeneity during the quantum dynamics of the interrogated atoms. Solutions of the master equation in different parameter regimes are presented and compared. It is shown that a general solution can be obtained by using the so called Truncated

* Corresponding author.
*E-mail address:* arey@jilau1.colorado.edu (A.M. Rey).


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Wigner Approximation which is applied in our case in the context of an open quantum system. We use the developed framework to model the density shift and decay of the fringes observed during Ramsey spectroscopy in the JILA $^{87}$Sr and NIST $^{171}$Yb optical lattice clocks. The developed framework opens a suitable path for dealing with a variety of strongly-correlated and driven open-quantum spin systems.



## 1. Introduction

One of the ultimate goals of modern physics is to understand and fully control quantum mechanical systems and to exploit them both, at the level of basic research and for numerous technological applications including navigation, communications, network management, etc. To accomplish these objectives, we aim at developing the most advanced and novel measurement techniques capable of probing quantum matter at the fundamental level.

Some years ago, the second — the international unit of time — was defined by the Earth's rotation. However, with the discovery of quantum mechanics and the quantized nature of the atomic energy levels, it became clear that atomic clocks could be more accurate and more precise than any mechanical or celestial reference previously known to man. Thus, in 1967 the second was redefined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine energy levels of a cesium atom. Since then, the accuracy of atomic clocks has improved dramatically, by a factor of 10 or so every decade. The characterization of the unit of time plays a central role within the International System of Units (SI) because of its unprecedented high accuracy and because it is also used in the definitions of other units such as meter, volt and ampere.

Thanks to the development of laser trapping and cooling techniques [1,2], the best cesium standards have reached an accuracy of one part in $10^{16}$. However, cesium clocks are limited by the fact that they are based on atomic transitions in the microwave domain. Because the quality factor of the clock is proportional to the frequency, optical clocks with frequencies that can be $10^6$ times higher than microwaves, offer an impressive potential gain over their microwave counterparts. Optical frequencies on the other hand are very difficult to measure, as the oscillations are orders of magnitude faster than what electronics can measure. The implementation of frequency comb technology [3] has provided a coherent link between the optical and microwave regions of the electromagnetic spectrum, greatly simplifying optical frequency measurements of high accuracy. After the development of frequency combs, the interest in optical clocks has grown rapidly. Now, optical clocks based on single trapped ions and neutral atoms are the new generation of frequency standards with a sensitivity and accuracy as high as one part in $10^{18}$ [4–6].

Optical clocks operated with fermionic neutral alkaline earth atoms (AEA), such as $^{87}$Sr or $^{171}$Yb, have matured considerably. Those employ an optical lattice to tightly confine the atoms so that Doppler and photon-recoil related effects on the transition frequency are eliminated. State-of-the-art neutral-atom-optical clocks have surpassed the accuracy of the Cs standard [7] and just recently, thanks to advances in modern precision laser spectroscopy, are reaching and even surpassing the accuracy of single ion standards [6]. The most stable of these clocks now operate near the quantum noise limit [8,9]. The stability arises from the intrinsic atomic physics of two-valence-electron atoms that possess extremely long lived singlet and triplet states (clock states), with intercombination lines nine orders of magnitude narrower than a typical dipole-allowed electronic transition.

The potential advantage of neutral-atom clocks over single trapped ion clocks is that, in the former, a large number of atoms is simultaneously interrogated. This could lead to a large signal-to-noise improvement; however, high atom numbers combined with tight confinement also lead to high atomic densities and the potential for non-zero collisional frequency shifts via contact atom–atom interactions. With atom–light coherence times reaching several seconds, even very weak interactions (*e.g.*, fractional energy level shifts of order $\geq 1 \times 10^{-16}$) can dominate the dynamics of these systems.