

Enhancing Clocks with Collective Effects: Spin Squeezing and Superradiance

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The field of atomic and optical physics has developed a myriad of tools to gain nearly complete control over the quantum state of individual atoms and ions: both their internal and external states. These tools have been leveraged to build extremely precise and accurate sensors of time, fields, and motion. A new frontier of atomic and optical physics is to learn how to extend these single-atom tools to now realize, control, and exploit interactions *between* atoms in order to create interesting quantum and classical correlations between the atoms. This effort is at the heart of both quantum computers and the simulation of condensed matter systems.

We are interested in understanding how to create correlations and collective states of atomic ensembles that are useful for enhancing precision measurements. The goal is to move away from a purely single-atom paradigm of precision measurement, and move toward a many-body paradigm in which collective effects will provide new tools to advance the precision and accuracy of quantum sensors. In this talk, we will discuss two proof-of-principle experiments, entangled state generation and superradiant lasing, that may one day lead to improved optical lattice clocks and perhaps matter-wave interferometers.

We will present collective measurements that project an ensemble of $N = 4.8 \times 10^5$ ^{87}Rb atoms into an entangled state [1]. We directly observe an entangled, spin-squeezed state with quantum phase resolution improved in variance by a factor of 10.5(1.5), or 10.2(6) dB, compared to the initially unentangled ensemble of atoms. Crucially, the reported number reflects no background subtractions or corrections for experimental imperfections.

We will next discuss the realization of a proof-of-principle Raman laser that operates with <1 photon on average inside the laser cavity [2]. In this deep superradiant regime, almost all of the laser's phase information is collectively stored inside the ensemble of atoms where it is strongly protected from corruption by motion of the laser cavity's mirrors—whether it arises from technical sources of vibration or the thermal vibration noise that limits today's most narrow linewidth lasers. We will briefly discuss our new effort to realize a superradiant laser using the mHz optical clock transition in strontium. Such a laser might one day achieve a mHz linewidth, advance both time keeping and long baseline optical interferometry, and provide a way to move narrow linewidth lasers out of low-vibration laboratory environments for both scientific and practical applications.

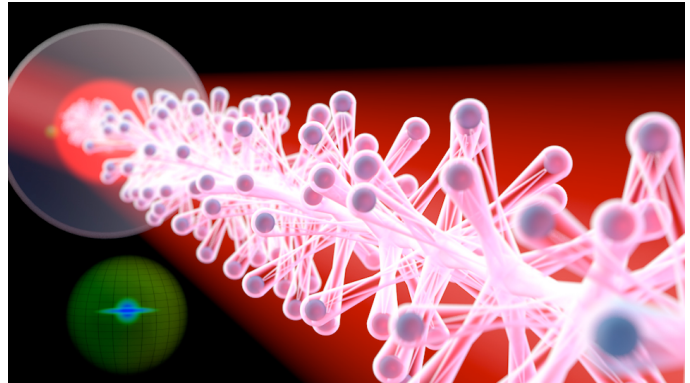


Fig. 1 Rubidium atoms (balls) become quantum entangled (visualized as links) when probed by laser light (red glow) inside an optical cavity. By forging quantum connections between the atoms, the intrinsic quantum noise of the atoms can be squeezed ten times below the standard quantum limit, visualized by the squeezing and antisqueezing of the blue quantum noise distribution on the green Bloch sphere.

- [1] Justin G. Bohnet, Kevin C. Cox, Matthew A. Norcia, Joshua M. Weiner, Zilong Chen, J. K. Thompson, “Reduced spin measurement back-action for a phase sensitivity 10 times beyond the standard quantum limit,” *Nature Photonics* **8**, 731-736 (Sept. 2014)
- [2] J. G. Bohnet, Z. Chen, J. M. Weiner, D. Meiser, M. J. Holland, J.K. Thompson, “A Steady State Superradiant Laser with <1 Intracavity Photon,” *Nature* **484** 78-81, (April 5, 2012).