Optical Ramsey Spectroscopy with Superradiance Enhanced Readout

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***Summary*—We experimentally realize a cavity superradiance enhanced Ramsey spectroscopic signal. This is a fast and sensitive readout of the excited state population, with the potential for reusing atoms in multiple sequences per MOT cycle, thereby reducing experimental dead time in an atomic clock or quantum sensor.**

Keywords—atomic clock; Ramsey spectroscopy; superradiance; cavity QED

Measuring the frequency of a transition between two energy levels in an atom has been at the heart of experimental atomic physics over the past century. Stabilizing a laser to a very narrow transition in an atom constitutes the inner workings of today's most precise atomic clocks, which can reach fractional frequency instabilities of a few parts in 10^{19} [1,2]. Improvements in clocks and lasers will continue to advance a broad range of science and technology such as tests of general relativity [3,4], variations of fundamental constants [5], and gravitation potential sensing for geodesy [6].

Since fluorescence detection directly on long lived clock states is too slow and inefficient, current population readout techniques rely on electron shelving and destructive fluorescence measurements on fast transitions. This requires the cooling and preparation of an entirely new atomic sample after each interrogation cycle. The associated dead time in between atomic interrogations causes frequency noise aliasing, called the Dick effect [7]. Ways to mitigate this include interleaving of clocks [8,9] and nondestructive cavity enhanced dispersive measurements [10,11]. Here we demonstrate a new type of nondestructive measurement which uses superradiant emission from excited atoms in a cavity as a spectroscopic readout.

Superradiance is a collective radiation phenomenon, which can occur when emitters are placed close to each other compared to the emission wavelength, or are placed inside of a resonator. Dipole-dipole correlations emerge during the spontaneous decay, leading to stronger and faster radiation emission compared to that of independent emitters.

If a large non-inverted atomic sample is placed inside of an optical cavity, there will be no cavity assisted superradiance because the phases of the dipoles will destructively interfere. But if the sample is inverted, superradiant pulses can be emitted into the cavity mode, with area and peak intensity related to the excited state population. A recent theoretical proposal [12] suggests taking advantage of the feature of emission suppression for a non-inverted sample as a free evolution period in a Ramsey scheme. This would allow for a fast and sensitive readout of the excited state population with minimal heating, allowing for multiple interrogations per experimental cycle.

In this work, we experimentally realize this proposed cavity sub- and superradiantly enhanced Ramsey spectroscopy and discuss its feasibility as a technique for laser stabilization.

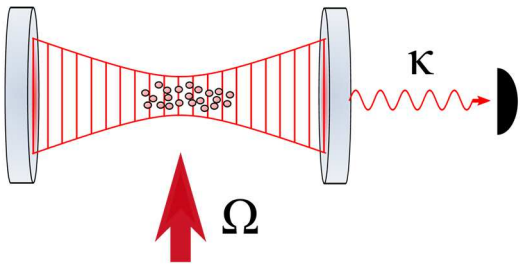

Fig. 1. Experimental schematic. Atoms are cooled and trapped inside of an optical cavity. Excitation pulses are applied perpendicularly to the cavity axis. Superradiant readout is detected behind the cavity mirror.

In our experimental system, we cool and trap ^{88}Sr atoms inside of an optical cavity, as depicted in Fig. 1. We tune a TEM_{00} resonance of the cavity to the 7.5 kHz linewidth dipole forbidden $^3P_1$ to $^1S_0$ transition. We operate in the weak single-atom coupling regime with Purcell factor $C = 4.4 \times 10^{-4} \ll 1$ but large collective coupling regime $NC \gg 1$, where N is the effective atom number in the cavity mode.

Next we turn off all cooling lasers and magnetic fields, and apply our excitation pulses orthogonal to the cavity mode on the $^3P_1$ to $^1S_0$ transition. If the excitation pulse causes positive inversion of the atomic sample, then a superradiant pulse can be detected. We vary atomic inversion, or excitation angle, by varying the time of the Rabi excitation pulses. We observe a threshold for our experimental configuration which requires an inversion of around 0.1 for a superradiant pulse to be detected. For higher inversions, the peak height scales linearly and fits well with the theoretical simulation. By applying two $\pi/2$ pulses separated by a dark time evolution period on the atoms with various detunings, we detect peak emitted intensity and

map out a Ramsey fringe pattern. Compared to a traditional Ramsey lineshape, this method only yields a signal with a positively inverted atomic sample, as depicted in the green box in Fig. 2.

We see good agreement with the predicted lineshape from the theory with fringes of width determined by the free evolution time, envelope of the fringes dictated by the $\pi/2$ pulse time, and flat dead-zones in the detuning intervals where the atomic sample has not been inverted and no superradiant pulse is detected.

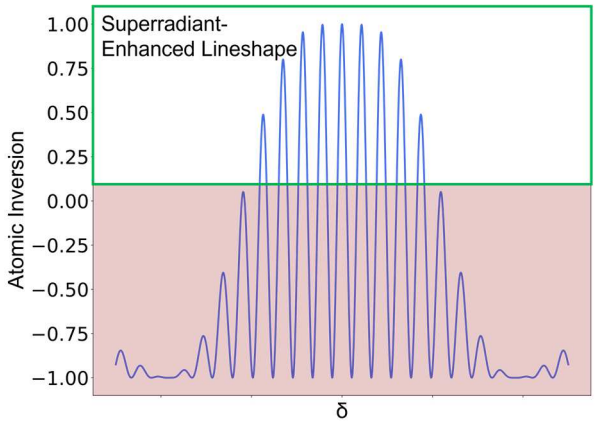

Fig. 2. Normal Ramsey spectroscopic lineshape. Because superradiance is detected only if the atoms are above 0.1 inversion, in this method the superradiant-enhanced lineshape would appear as the region encosed by the green box.

Utilizing the feature of cavity assisted sub-superradiant emission, we are the first to map out an enhanced Ramsey spectroscopic lineshape as proposed in [12]. We further show that the cavity assisted readout is minimally destructive with the possibility of conducting multiple Ramsey sequences on the same atomic ensemble, with short cooling periods in between. This provides an alternative technique which is fast and sensitive to the excited state population, especially relevant for long lived excited states.

REFERENCES

[1] S. Campbell, R. Hutson, G. Marti, A. Goban, N. Oppong, R. McNally, L. Sonderhouse, J. Robinson, W. Zhang, B. Bloom, and J. Ye, "A Fermi-degenerate three-dimensional optical lattice clock," Science 358, 90, 2017.

[2] S. Brewer, J. Chen, A. Hankin, E. Clements, C. Chou, D. Wineland, D. Hume, and D. Leibrandt, "$^{27}Al^{+}$ Quantum-Logic Clock with a Systematic Uncertainty below 10^{-18}," Phys. Rev. Lett. 123, 033201, 2019.

[3] S. Kolkowitz, I. Pikovski, N. Langellier, M. Lukin, R. Walsworth, and J. Ye, "Gravitational wave detection with optical lattice atomic clocks," Phys. Rev. D 94, 124043, 2016.

[4] P. Graham, J. Hogan, M. Kasevich, and S. Rajendran, "New Method for Gravitational Wave Detection with Atomic Sensors," Phys. Rev. Lett. 110, 171102, 2013.

[5] T. Rosenband, D. Hume, P. Schmidt, C. Chou, A. Brusch, L. Lorini, W. Oskay, R. Drullinger, T. Fortier, J. Stalnaker et al., "Frequency ratio of Al^{+} and Hg^{+} single-ion optical clocks; metrology at the 17th decimal place," Science 319, 1808, 2008.

[6] C. Chou, D. Hume, T. Rosenband, and D. Wineland, "Optical clocks and relativity," Science 329, 1630, 2010.

[7] G. Dick, Proceedings of the 34th Annual Precise Time and Time Interval Systems and Applications Meeting, ION, 1987, pp. 133–147.

[8] E. Oelker, R. Hutson, C. Kennedy, L. Sonderhouse, T. Bothwell, A.Goban et al., "Demonstration of 4.8×10^{-17} stability at 1 s for two independent optical clocks.," Nat. Photonics 10.1038/s41566-019-0493-4, 2019.

[9] M. Schioppo, R. Brown, W. McGrew, N. Hinkley, R. Fasano, K. Beloy et al., "Ultrastable optical clock with two cold-atom ensembles," Nat. Photonics 11, 48–52, 2017.

[10] J. Lodewyck, P. G. Westergaard, and P. Lemonde, "Nondestructive measurement of the transition probability in a Sr optical lattice clock," Phys. Rev. A 79, 061401, 2009.

[11] M. A. Norcia, J. K. Thompson, "Strong coupling on a forbidden transition in strontium and nondestructive atom counting," Phys. Rev. A 93, 023804, 2016.

[12] C. Hotter, L. Ostermann, and H. Ritsch, "Cavity sub- and superradiance enhanced ramsey spectroscopy," Phys. Rev. Res. 5, 013056 (2023).