Near-Unitary Spin Squeezing with Ytterbium

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State of the art atomic sensors operate near the standard quantum limit (SQL) of projection noise, where the precision scales as the square root of the particle number. Overcoming this limit by using atom-atom entanglement such as spin squeezing [1] is a major goal in quantum metrology [2].

Spin squeezing can be realized with the techniques of cavity quantum electrodynamics (cQED) by coupling an atomic ensemble to a high-finesse optical resonator. The resulting collective atom-light interaction allows for both measurement [3] and cavity feedback squeezing [4]. These methods for producing spin squeezing are typically non-unitary and generate more anti-squeezing than the minimum prescribed by the uncertainty principle, due to a residual entanglement between the atomic ensemble and probing photons. We find that non-unitarity significantly lowers the potential metrological gain from squeezing in atomic clocks and other quantum sensors [5].

We couple an ensemble of approximately 1000 $^{171}$Yb atoms to a high-finesse asymmetric micromirror cavity [6] with single-atom cooperativity $\eta = 1.8 \pm 0.1$. A laser pulse induces an effective one-axis twisting Hamiltonian $H = \hbar \chi S_x^z$ for the atoms, producing the desired squeezed spin state (SSS). We detune the probing light from atomic and cavity resonance by several linewidths to limit the undesirable entanglement between atoms and light [7].

We characterize the produced SSSs by state tomography, measuring the $S_z$ variance after a rotation by a variable angle $\alpha$, as shown in Figure 1. For moderate normalized atom-atom interaction strength $Q = N\chi t$, we observe states with a nearly equal level of noise reduction and enhancement, confirming the production of a near-unitary spin squeezed state.

This experimental platform will allow for the creation of quantum states with metrologically useful entanglement on the clock transition of $^{171}$Yb.

![Graph showing state tomography of spin squeezed states of $N = 1.0 \pm 0.1 \times 10^3$ $^{171}$Yb atoms for normalized state shearing strength $Q = \{0.5, 2.1, 3.8, 6.2\}$ shown in blue circles, cyan squares, gold triangles, and red diamonds respectively. Points are experimental measurements, while the curves are fits to a two-parameter model yielding the shearing strength $Q$ and state area $A$. Note that the points displayed at $\alpha = 0.01$ were actually measured at $\alpha = 0$. The dashed horizontal line at $-15\text{dB}$ indicates the precision limit of our state detection. The inset schematically shows the uncertainty ellipses of the produced quantum states for different values of $Q$.](image)


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