

High-density alkali vapours: a new platform for ensemble quantum optics

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Optically-probed atomic ensembles have long been central to studies of spin squeezing, exotic entangled states, quantum memories, and sensing beyond the standard quantum limit. Proven implementations include cold atoms, ultra-cold atoms, low-density alkali vapours, and impurity-doped solids. Here we describe our work with high-density alkali vapours, inspired by the extreme performance of these systems in the field of optical magnetometry. Due to an exotic mechanism known as SERF, which suppresses collisional decoherence at high densities, these systems uniquely combine high optical depth with long coherence times.

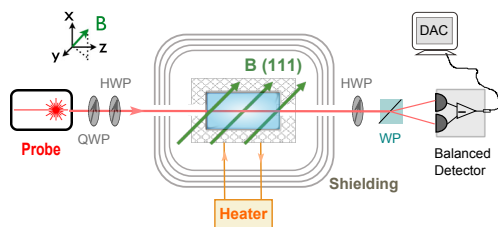


Figure 1: Experimental setup. A linearly polarized probe beam goes through high density hot ^{87}Rb atomic cloud, while the spin precesses around a static magnetic field along the $(1, 1, 1)$ direction. Due to Faraday rotation, the atomic J_z projection is imprinted on the polarization of probe beam, and detected by a polarimeter – a Wollaston prism (WP) plus balanced detector. QWP: Quarter waveplate. HWP: Half waveplate. DAC: Data acquisition.

Toward this goal, we have recently implemented quantum-limited spin readout and efficient Bayesian signal recovery methods [1], developed a quantum metrology framework for variable-density sensors [2], determined the quantum limits of spin-noise-based measurements [3], and shown enhancement of spin noise spectroscopy with squeezed light [4]. The setup is shown schematically in Fig. 1. In difference to prior ensemble experiments, coherence is boosted by immobilizing the alkali atoms with buffer gases, and as noted, by working at high alkali density to boost the spin-exchange collision rate.

While the classical statistical physics of high-density atomic vapours has been well studied, it is not yet known if they can support quantum correlations such as squeezing. The prospects are very encouraging, however. We have developed continuous-time stochastic differential equation methods to describe the evolution of the quantum state, and find excellent quantitative agreement with measured statistics, as shown in Fig. 2. This theory predicts a high degree of spin squeezing by QND measurement, especially at higher densities, including in SERF regime, as shown in Fig. 3. In this talk, we will describe the physics and especially the quantum statistical features of high-density atomic ensem-

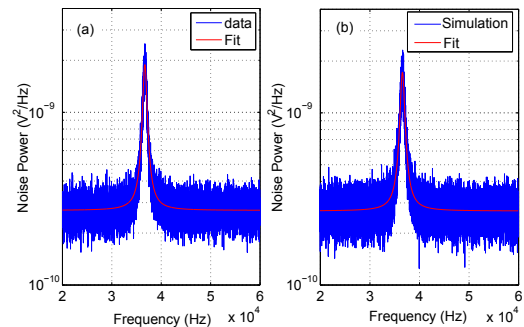


Figure 2: Spin noise spectroscopy in experiment (left) and theory (right).

bles, and experimental progress toward their realization as quantum technology components.

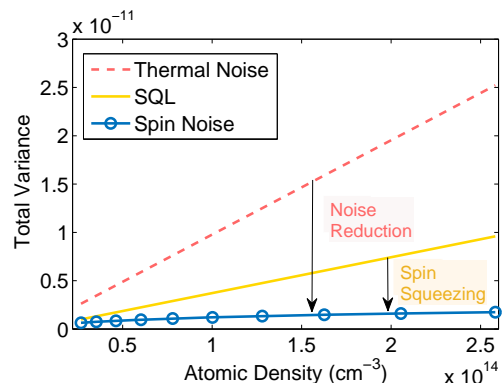


Figure 3: Predicted singlet-type spin squeezing for SERF-regime ensembles probed with off-resonance laser light. The red dashed line shows the total spin variation of a thermal spin state. The yellow line indicates the minimum variation of non-entangled spin state, i.e., standard quantum limit (SQL). The blue dots show computed conditional spin variation following QND measurement.

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- [3] Lucivero, Dimic, Kong, Jiménez-Martínez, and Mitchell, “Sensitivity, quantum limits, and quantum enhancement of noise spectroscopies” *Phys. Rev. A* **95**, 041803(R) (2017).
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