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Dear Editors,

We are pleased to submit our manuscript 'Continuously observing a dynamically decoupled spin-1 quantum gas' to *Physical Review Letters*. In it we observe in real-time the continuous dynamical decoupling of a spin-1 quantum gas, probing its spectrum, coherences, and coupling strengths. Dynamical decoupling a system from its environment is not only applicable to quantum information but has broad application to quantum metrology and quantum state estimation. Yet few systems permit dynamical decoupling to be observed in real-time; even weak measurements of superconducting qubits and nitrogen-vacancy (NV) centers require on the order of 10^4 repeated preparation and detection cycles.

This work weds clock-state metrology with continuous measurement, ingredients for new experiments that emulate quantum magnetism in solid-state systems, and advancing a platform for measuring oscillating magnetic fields in noisy environments. More broadly still, the decoupled microscale quantum gas offers magnetic sensitivity in a tunable band, persistent over many milliseconds: this is the length scale, frequency, and duration relevant to sensing biomagnetic phenomena such as neural spike trains.

We advance spectrogram analysis as a time-frequency reduction of the measurement record to extract rich information about the quantum state and Hamiltonian simultaneously. The utility of spectrograms are widely understood, from visualizing gravitational wave signals to analyzing human speech. We 'listen' to the precessing spins of the decoupled quantum gas, and use spectrogram analysis to parse the recorded tones as a signature of dynamical decoupling.

Our manuscript forms a co-submission with D. Trypogeorgos, A. Valdes-Curiel, N. Lundblad, and I. B. Spielman of the Joint Quantum Institute, who present a complementary characterization of the high-order decoupling manifest in this system as insensitivity of the states to magnetic field variations. A distinguishing focus of our work is the continuous weak measurement of the states, which could give rise to new forms of quantum sensing exploting synchronous detection and feedback. Additionally, we demonstrate the ability to probe dressed-state coupling strengths without driving transitions, a form of Hamiltonian parameter estimation. Our work is further distinguished by the analytic results on high-order decoupling, applicable to analogous high-order decoupling in NV centers.

Sincerely,

R. P. Anderson, for the authors