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Dear Editors,

We are pleased to submit this Letter titled '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 simultaneously. Dynamically decoupling a system from its environment, first pursued in quantum information applications, has branched out to quantum metrology and quantum state estimation. Because our quantum gas is a coherent spin ensemble, weak measurement allows dynamical decoupling to be observed in real-time with a single experimental preparation. With this we show that one pair of spin states is protected to higher order in magnetic field instabilities than conventional dynamical decoupling.

Our manuscript forms a co-submission with D. Trypogeorgos *et al.*, who present a complementary characterization of the high-order decoupling manifest in the same system. A distinguishing focus of our work is the continuous weak measurement, which could give rise to new forms of quantum sensing exploiting 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 new analytic results identifying where the optimum decoupling occurs; this result is applicable to any multi-level system including NV centers.

We advance spectrogram analysis as a time-frequency reduction of the measurement record to extract rich information about the quantum state and Hamiltonian simultaneously. Spectrograms have been applied widely, 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 multiple tones as a signature of dynamical decoupling.

Our measurement exposes an unconventional coupling of all spin states, an ingredient for new experiments emulating quantum magnetism in solid-state systems. The decoupled quantum gas measures oscillating magnetic fields in noisy environments. The microscale sensing volume, tunable kilohertz band-center, and many milliseconds measurement time are the length scale, frequency, and duration relevant to sensing biomagnetic phenomena such as neural spike trains.

Sincerely,

R. P. Anderson, for the authors