Simultaneous tracking of spin angle and amplitude beyond classical limits

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Measurement of spin precession is central to extreme sensing in physics,geophysics,chemistry,nanotechnologyand underlies powerful magnetic resonance spectroscopies.Because there is no spin-angle operator, any measurement of spin precession is necessarily indirect, e.g., inferred from spin projectors F_α at different times. Such projectors do not commute, and thus quantum measurement back-action (QMBA) necessarily enters the spin measurement record, introducing errors and limiting sensitivity. Here [1] we show how to reduce this disturbance below $\delta F_\alpha \sim \sqrt{N}$, the classical limit for N spins, by directing the QMBA almost entirely into an unmeasured spin component. This generates a planar squeezed state[2] which, because spins obey non-Heisenberg uncertainty relations [3], allows simultaneous precise knowledge of spin angle and amplitude. We use high-dynamic-range optical quantum non-demolition measurements[4–6] applied to a precessing magnetic spin ensemble, to demonstrate spin tracking with steady-state angular sensitivity **2.9 dB** beyond the standard quantum limit, simultaneous with amplitude sensitivity **7.0 dB** beyond Poisson statistics. This method for the first time surpasses classical limits in non-commuting observables, and enables orders-of-magnitude sensitivity boosts for state-of-the-art sensing[7] and spectroscopy.

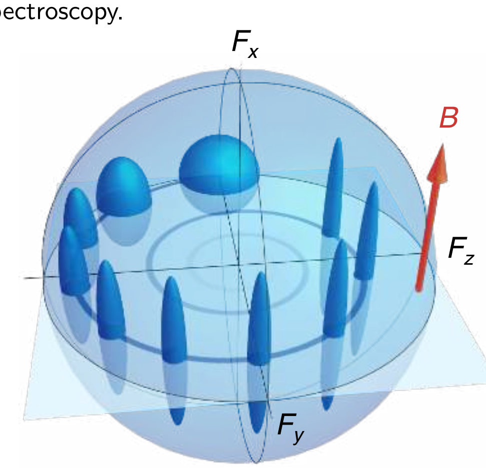

FIG. 1. Simultaneous, precise tracking of spin angle and amplitude. Bloch-sphere representation of the atomic state evolution. Ellipsoids show uncertainty volumes (not to scale) as the state evolves anti-clockwise from an initial, F_y-polarized state with isotropic uncertainty. An x-oriented magnetic field **B** drives a coherent spin precession in the F_y–F_z plane. Quasi-continuous measurement of F_z produces a reduction in F_z and F_y variances, with a corresponding increase in var(F_x).

[1] G. Colangelo, F. Martin Ciurana, L. C. Bianchet, R.J. Sewell, Simultaneous tracking of spin angle and amplitude beyond classical limits, *Nature* **543**, 525 (2017).

[2] Q. Y. He, S.-G. Peng, P. D. Drummond, M. D. Reid, Planar quantum squeezing and atom interferometry, *Phys. Rev. A* **84**, 022107 (2011).

[3] H. P. Robertson, The uncertainty principle, *Phys. Rev.* **34**, 163 (1929).

[4] M. Koschorreck, M. Napolitano, B. Dubost, M. W. Mitchell, Quantum nondemolition measurement of large-spin ensembles by dynamical decoupling, *Phys. Rev. Lett.* **105**, 093602 (2010).

[5] R. J. Sewell, M. Napolitano, N. Behbood, G. Colangelo, M. W. Mitchell, Certified quantum non-demolition measurement of a macroscopic material system, *Nat. Photon.* **7**, 517 (2013).

[6] F. M. Ciurana, G. Colangelo, R. J. Sewell, M. W. Mitchell, Real-time shot-noise-limited differential photodetection for atomic quantum control, *Opt. Lett.* **41**, 2946 (2016).

[7] O. Hosten, N. J. Engelsen, R. Krishnakumar, M. A. Kasevich, Measurement noise 100 times lower than the quantum-projection limit using entangled atoms, *Nature* **529**, 505 (2016).

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