Macroscopic spin singlet generated via quantum non-demolition measurement

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We report the production of a macroscopic spin singlet (MSS) in an atomic system [1] using collective quantum nondemolition (QND) measurement as a global entanglement generator [2]. Using an unpolarized ensemble of up to 10^6 cold atomic spins, we observe 3 dB of spin squeezing and detect entanglement with 5σ statistical significance using a generalized spin- squeezing inequality [3], indicating that at least half the atoms in the sample have formed singlets.

Generating and detecting large-scale spin entanglement in many-body quantum systems is of fundamental interest [4] and motivates many experiments with cold atoms [5] and ions [6]. For example, macroscopic singlet states appear as ground states of many fundamental spin models [7, 8] and even in quantum gravity calculations of black hole entropy [9]. Our techniques complement existing experimental methods and can be readily adapted to measurements of quantum lattice gases [10, 11]and spinor condensates [12]. In future work, we aim to combine our measurement with quantum control techniques [13] to produce an unconditionally squeezed MSS, and to use our spatially extended MSS for magnetic field gradiometry [14]. Because of its SU(2) invariance, the MSS is a good candidate for storing quantum information in a decoherence-free subspace or sending information independent of a reference direction.

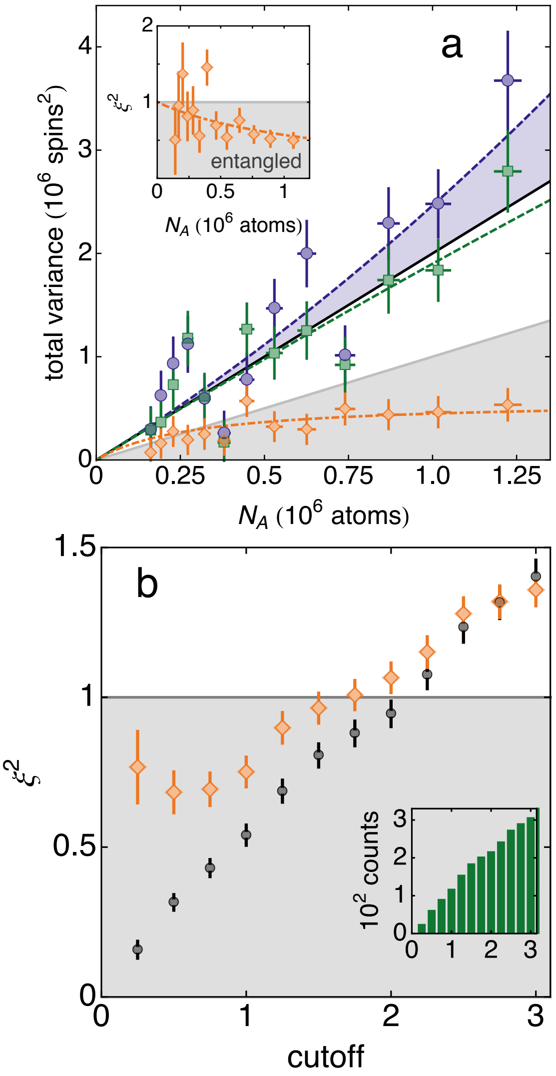

FIG. 1. (a) Noise scaling of total variance of the first (blue circles) and second (green squares) QND measurement of the atomic spin distribution, and conditional variance (orange diamonds). Shaded area represents region indicating spin squeezing and entanglement. Inset: Semi-log plot of detected spin squeezing parameter. Horizontal and vertical error bars represent 1σ statistical errors, and read-out noise has been subtracted from the data. (b) Spin squeezing parameter ξ^2 (orange diamonds) calculated from the second QND measurement as a function of a post-selection cutoff parameter. For reference, the same parameter calculated from the first QND measurement is also plotted (black circles).

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[1] N. Behbood *et al.*, Phys. Rev. Lett. **113**, 093601 (2014).
[2] R. J. Sewell *et al.*, Nat. Photon. **7**, 517 (2013).
[3] G. Tóth and M.W. Mitchell, New J. Phys. **12**, 053007 (2010).
[4] M. Lewenstein, A. Sanpera, and V. Ahufinger, *Ultracold Atoms in Optical Lattices: Simulating quantum many-body systems*, Oxford University Press, Oxford (2012).
[5] D. Greif *et al.*, Science **340**, 1307 (2013).
[6] R. Islam *et al.*, Science **340**, 583 (2013).
[7] P. W. Anderson, ‘Science **235**, 1196 (1987).
[8] L. Balents, Nature **464**, 199 (2010).
[9] E. R. Livine and D. R. Terno, Phys. Rev. A **72**, 022307 (2005).
[10] K. Eckert *et al.*, Nat. Phys. **4**, 50 (2008).
[11] P. Hauke *et al.*, Phys. Rev. A **87**, 021601 (2013).
[12] K. Eckert *et al.*, Phys. Rev. Lett. **98**, 100404 (2007).
[13] N. Behbood *et al.*, Phys. Rev. Lett. **111**, 103601 (2013).
[14] I. Urizar-Lanz *et al.*, Phys. Rev. A **88**, 013626 (2013).