Entanglement, interferometric sensitivity, and macroscopic superposition states by scanning through quantum phase transitions in spinor Bose-Einstein condensates

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Spinor Bose Einstein condensates (BECs) exhibit different ground state phases, when a tunable magnetic field or microwave dressing is applied as a control parameter. Some of them are experimentally well accessible. Others, in contrast, feature strong multipartite entanglement. Thus, driving the system from the former to the latter is a promising approach to the preparation of exciting, highly entangled many-body states. That this can be put into practice, though the gap between the ground state and the first excited state closes at the critical points, has been recently demonstrated in [1,2].

Encouraged by these results, which have been obtained within the F=1 manifold of ^{87}Rb, we have elaborated on the opportunities offered by the quasi-adiabatic crossing of quantum phase transitions (QPTs) in a ferromagnetic spin-1 BEC. For separable states the sensitivity of atom interferometers is fundamentally limited by the standard quantum limit (SQL), which scales as $N^{-1/2}$ with the particle number N. Employing multipartite entanglement allows to shift this bound towards the Heisenberg limit $\sim N^{-1}$. Entanglement that facilitates to surpass the SQL is unambiguously witnessed by the quantum Fisher information (QFI, F_Q). An evaluation of the QFI across all three ground state phases of a ferromagnetic spin-1 BEC unveils an intriguing regime, the state in the center of the broken axisymmetry phase (CBA state), which provides Heisenberg scaling of the QFI and is separated from the initial experimental state by only one QPT. We identify the optimal way of phase imprinting and the optimal measurement prescription to maximize the interferometric sensitivity as experimentally well accessible operations.

Investigating why the CBA state is so particularly sensitive leads up to an unexpected connection to macroscopic superposition (MS) states. A spin-1 system accommodates three magnetic modes, labeled by m_F in {1, 0, -1}. By a change of basis achievable by collective radio-frequency and microwave manipulations, $m_F = 1$ and $m_F = -1$ can be transformed into their (anti)symmetric combinations tagged by g (h). As illustrated in fig. 1, projecting the CBA state onto the particle number in one of these modes, say N_h, mostly yields highly entangled two-mode states resembling NOON states. The large contribution of suitable N_h to the CBA state allows for a probabilistic preparation of MS states being heralded by N_h.

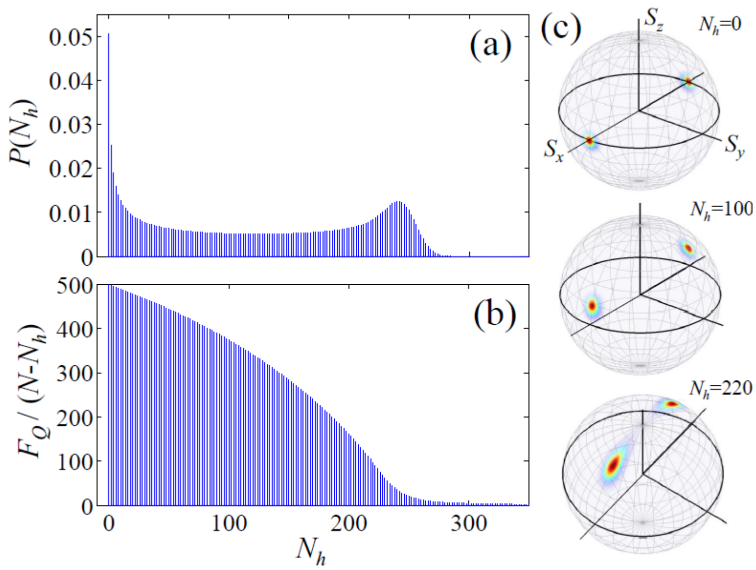

Figure 1. Macroscopic superposition states accommodated by the CBA state of a spin-1 BEC. N_h is the particle number in the antisymmetric mode. (a) With high probability P a measurement of N_h results in a state with (b) large quantum Fisher information F_Q. (c) The Husimi distribution of the projected two-mode states resembles NOON states. Here N=500.

A crucial question regarding the preparation of MSs is its stability. For N=100 particles, we include particle losses during a quasi-adiabatic driving at finite speed as well as a finite precision of the N_h measurement into our analysis. We show that both a large FI and the MS features are well preserved under realistic conditions. Sub-SQL interferometry with the CBA state has by now been demonstrated in [2]. This further emphasizes that the preparation of MS states in spin-1 BECs is brought into reach of current technology by the high stability of the enclosing CBA state.

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[2] Yi-Quan Zou, Ling-Na Wu, Qi Liu, Xin-Yu Luo, Shuai-Feng Guo, Jia-Hao Cao, Meng Khoon Tey, and Li You, *Beating the classical precision limit with spin-1 Dicke states of more than 10,000 atoms,* PNAS **115** (25), 6381-6385 (2018)

[3] P. Feldmann, M. Gessner, M. Gabbrielli, C. Klempt, L. Santos, L. Pezzè, and A. Smerzi, *Interferometric sensitivity and entanglement by scanning through quantum phase transitions in spinor Bose-Einstein condensates,* Phys. Rev. A **97**, 032339 (2018)

[4] L. Pezzè, M. Gessner, P. Feldmann, C. Klempt, L. Santos, and A. Smerzi, *Heralded Generation of Macroscopic Superposition States in a Spinor Bose-Einstein Condensate,* arXiv: 1712.03864 (2017)