Quantum metrology with non-classical states of Bose-Einstein condensates

T. Zibold, M. Fadel, B. Décamps, Y. Li, P. Colciaghi, and P. Treutlein

Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland.

We report experiments on quantum metrology with non-classical states of Bose-Einstein condensates on an atom chip (for a recent review of the field see [1]). Using chip-based microwave near-field potentials we control collisional interactions in a two-component BEC of ^{87}Rb atoms. This allows us to generate spin-squeezed states with typically 8 dB of spin-squeezing according to the Wineland criterion. These states are useful for quantum metrology, which we demonstrate experimentally by performing atom interferometry with a precision of 7 dB beyond the standard quantum limit.

To further study the non-classical correlations in the spin-squeezed state, we perform high-resolution imaging of the spin state of an expanded condensate [2]. This allows us to directly measure the spin correlations between spatially separated regions of various shapes, confirming the presence of entanglement in this system of indistinguishable atoms. Our data show bipartite correlations strong enough for Einstein-Podolsky-Rosen (EPR) steering: we can predict measurement outcomes for non-commuting observables in one spatial region based on corresponding measurements in another region with an inferred uncertainty product below the Heisenberg bound. This demonstrates the EPR paradox with a massive many-particle system. This method could be exploited for entanglement-enhanced imaging of electromagnetic field distributions.

Furthermore, we detect multi-partite Bell correlations in our squeezed condensate using a quantum-mechanical witness inequality [3,4]. Concluding the presence of Bell correlations is unprecedented for an ensemble containing more than a few particles. Our work shows that the strongest possible non-classical correlations are experimentally accessible in many-body systems, and that they can be revealed by collective measurements. This opens up new perspectives for using many-body systems in a variety of quantum information tasks.

[1] L. Pezzè, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein, *Quantum metrology with nonclassical states of atomic ensembles*, Rev. Mod. Phys. **90**, 035005 (2018).
[2] M. Fadel, T. Zibold, B. Décamps, and P. Treutlein, *Spatial entanglement patterns and Einstein-Podolsky-Rosen steering in Bose-Einstein condensates*, Science **360**, 409 (2018).
[3] R. Schmied, J. D. Bancal, B. Allard, M. Fadel, V. Scarani, P. Treutlein, and N. Sangouard, *Bell correlations in a Bose-Einstein condensate*, Science **352**, 441 (2016).
[4] F. Baccari, J. Tura, M. Fadel, A. Aloy, J.-D. Bancal, N. Sangouard, M. Lewenstein, A. Acín, and R. Augusiak, *Bell correlations depth in many-body systems*, arXiv:1802.09516 (2018).