Interferometry and EPR Entanglement in a BEC

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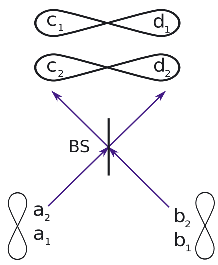
Entanglement is the basis of the EPR paradox, and macroscopic entanglement is a challenging frontier in modern physics [1]. It also has potential applications in sub shot-noise interferometry and ultra-sensitive detection beyond the standard quantum limit. Bose Einstein condensates (BEC) of ultracold atoms are excellent candidates to provide entangled states involving a large number of massive particles, with novel applications. Recent experiments have observed spin-squeezed states in a BEC of ^{87}Rb atoms [2].

We have theoretically shown that entanglement is possible between ground-state BECs with attractive interactions, trapped in two potential wells at nano-Kelvin temperatures, using a modified Hillery-Zubairy non-Hermitian operator product criterion [3]. This is more powerful than the spin-squeezing criterion, as it clearly demonstrates entanglement between the spatially separated two modes. We also show the criterion is a direct indicator of a phase measurement below the standard quantum limit.

In order to extend squeezing measurements to true EPR entanglement at spatially separated sites, a common procedure in optics is using quadrature measurement via phase-sensitive local oscillators. For the two-mode scheme, a BEC local oscillator is not readily obtainable. Experimentally, the two-mode technique requires a phase-sensitive interference of particles from the two wells, which is useful for interferometry, but not for demonstrating true EPR entanglement.



Instead, we propose a dynamical entanglement scheme in which the signature of entanglement comes from spin measurements. We consider four-mode interferometry with two spin orientations in each of two separated potential wells. The BEC is prepared in a phase-coherent state. Then, the inter-well barrier is increased, followed by a microwave Rabi rotation, dynamical evolution in each well, and finally recombination via a modulated inter-well potential barrier and another microwave Rabi rotation. The entanglement witnesses used are spin versions of the Heisenberg-product entanglement criterion. These are closely related to entanglement techniques developed in fiber optics. The schematic diagram of EPR spin entanglement is shown on the right.

In extending such techniques to greater numbers of atoms, for increased precision, it is necessary to consider a multi-mode environment with nonlinear losses. We have shown how to carry out such calculations quantitatively, using a truncated Wigner method. Comparisons with atom interferometry experimental measurements in the SUT atom chip laboratory [4] show excellent agreement between experiment and theory [5]. This provides a highly promising avenue for extending quantum-enhanced measurements into regimes of macroscopic atom numbers. In future, this can be extended to demonstrate the EPR paradox using ultra-cold atomic physics.

References

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