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Mach-Zehnder interferometry with interacting Bose-Einstein condensates in a double-well potential

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ABSTRACT

Particle-wave duality has enabled the construction of interferometers for massive particles such as electrons, neutrons, atoms or molecules. Implementing atom interferometry has required the development of analogues to the optical beam-splitters, phase shifters or recombiners to enable the coherent, i.e. phase-preserving manipulation of quantum superpositions. While initially demonstrating the wave nature of particles, atom interferometers have evolved into some of the most advanced devices for precision measurement, both for technological applications and tests of the fundamental laws of nature.

Bose-Einstein condensates (BEC) of ultracold atoms are particular matter waves: they exhibit a collective many-body wave function and macroscopic coherence properties. As such, they have often been considered as an analogue to optical laser fields and it is natural to wonder whether BECs can provide to atom interferometry a similar boost as the laser brought to optical interferometry.

One fundamental difference between atomic BECs and lasers fields is the presence of atomic interactions, yielding an intrinsic non-linearity. On one hand, interactions can lead to effects destroying the phase coherence and limiting the interrogation time of trapped BEC interferometers. On the other hand, they can be used to generate non-classical (e.g. squeezed) states to improve the sensitivity of interferometric measurements beyond the standard quantum limit (SQL).

We present the realization of a full Mach-Zehnder interferometric sequence with trapped, interacting BECs confined on an atom chip. Our interferometer relies on the coherent manipulation of a BEC in a magnetic double-well potential. For this purpose, we developed a novel type of matter-wave recombiner, an element which so far was missing in BEC atom optics.

We have been able to exploit interactions to generate a squeezed atomic state with reduced atom number fluctuations that could potentially yield a sensitivity improvement beyond the SQL. We used this state to study the interaction-induced diffusion of the quantum phase. For the first time we directly evidenced the link between fundamental atom number uncertainty and phase diffusion, and demonstrated extended coherence times by the use of a non-classical state. This constitutes an important step towards the use of BECs for quantum-enhanced matter-wave interferometry and contributes to the understanding of interacting many-body quantum systems. It opens new possibilities for the generation, manipulation and detection of non-classical atomic states, and calls for further studies of the role of interactions as a resource for matter-wave interferometry.