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Twin-atom beam generation in a one-dimensional Bose gas

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ABSTRACT

One of the most fascinating aspects of quantum physics is particle-wave duality, leading to striking analogies in the behavior of light and matter. Wave-like phenomena of matter on a macroscopic scale are especially pronounced in quantum-degenerate atomic gases. In these, strongly populated matter-wave modes give rise to coherence properties resembling those of laser light, enabling interferometry and homodyne measurements with Bose-Einstein condensates. In recent years, numerous experiments and theory proposals have been developed to extend this analogy into the realm of quantum optics, highlighting the complex interplay of wave and particle aspects of a degenerate atom gas. In quantum optics, a powerful theory framework is readily available, and numerous ground-breaking experiments with non-classical light have been performed. The realization of similar experiments using matter waves holds promise for both fundamental tests of quantum mechanics, and future metrology applications. This approach is promoted by the intrinsic atom-atom interactions in a condensate, that allow to efficiently access non-classical quantum states, without the need for non-linear media as in light optics.

In this thesis, a scheme to generate twin-atom beams, confined to a one-dimensional wave-guide geometry on an atom chip, was realized. The twin beams emerge from a degenerate one-dimensional Bose gas, propagate as wave packets with opposite momenta, and show quantum correlations that ideally lead to complete suppression of relative population fluctuations (number squeezing). This process, which operates in a strongly Bose-enhanced regime, is in close analogy to twin-photon beam generation in an optical parametric oscillator, a key tool in both fundamental and applied photonics. In our experiment, using time-of-flight fluorescence imaging, almost perfect number squeezing between the twin beams is observed, for the first time in the regime of high mode population. Furthermore, the dynamics of the stimulated twin-beam emission is analyzed quantitatively, and good agreement with a newly developed theoretical model is found.

In analogy to a pumped gain medium in optics, the starting point of the twin-beam emission process is a population-inverted state in the transverse vibrational degree of freedom of the elongated confinement. The preparation and characterization of this source state, which resembles a Fock state of a single-particle system, is the second main result of this thesis. To reach the pumped state, we apply a purely mechanical technique, where the transverse wave function of the condensate is controlled by displacement of the anharmonic trapping potential. The precise trajectory of the trap motion is obtained from quantum optimal control theory, which has been applied to the excitation of a condensate for the first time. By time-resolved observation of the system response, excellent agreement between experiment and theory, and a near-unit efficiency of the excitation process is obtained. Also, an effective two-level description is developed, that allows to capture the dynamics in an intuitive way.
The availability of quantum-correlated twin-atom beams opens up a plethora of research opportunities towards strongly entangled many-body states, enabling both fundamental experiments, and quantum-enhanced metrology techniques.