Paired atom laser beams created via four-wave mixing

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Sources of matter waves gained a dramatic improvement with the achievement of Bose-Einstein condensation (BEC) in dilute gases and the development of the atom laser [1]. Like optical lasers before them, atom lasers can produce Heisenberg-limited beam profiles and promise high spectral density through their dramatically lower linewidth. Another exciting possibility resulting from having such a coherent source of atoms is the generation of non-classical matter waves through entangled beams. Such entangled beams are useful for tests of quantum mechanics, and are required to perform Heisenberg-limited interferometry. Here, we show that the asymmetric scattering rates between internal states of metastable helium (He*) cause well-defined peaks in the output of an atom laser. These peaks are due to a four-wave mixing (FWM) process, and are experimentally demonstrated.

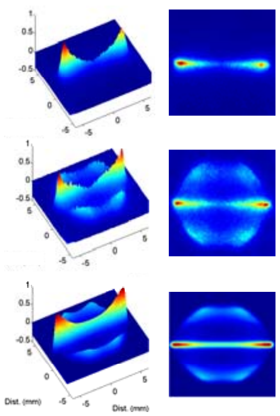

Fig. 1: First two rows show experimental atom laser spatial profiles observed on our MCP 4cm below the trap, in a 3-D rendering (left) and the 2-D image (right). Both sets of data were taken for an outcoupling detuning of 2 kHz, however the Rabi frequency is increased by an order of magnitude between the two sets. The upper row shows the usual He* atom laser, while the middle row demonstrates the appearance of the resonant scattering peaks.

Using existing sources of entangled pairs of atoms for interferometric experiments will be complicated by the high densities of the sources, where the nonlinearities that generated the correlations ultimately degrade the long term coherence of the sample. In our scheme the nonlinear interactions are used to drive FWM in the magnetically trapped condensate, but the resulting untrapped beams that propagate in free space are dilute, potentially avoiding the decoherence problem. Using atoms in the untrapped state also makes the beams insensitive to magnetic field inhomogeneities. We show that pairs of beams can be produced simply by the process of radio frequency (RF) outcoupling from a He* BEC, without the need for Feshbach resonances, optical traps or scattering pulses. Unlike the previous methods, which required pairs of atoms travelling at high kinetic energies as a source, this process involves scattering between atoms initally in the same zero momentum state to create states with non-zero momentum. The energy-momentum resonance comes from the mean field conditions that are obtained during outcoupling from the condensate. Semiclassical and field theoretic simulations of the experiment show that the beams are generated by the same FWM process that generated entangled atom pairs in the earlier experiments.

In summary our experiments show that appropriate outcoupling from a He* BEC can produce well-defined additional peaks in the output beam. Field theoretic and semiclassical models show that these peaks are formed from scattering of pairs of atoms in BEC, and are therefore entangled upon formation. The potential advantages of these correlated beams are that they are spatially well separated from the background of the atom laser and that the quasi-continuous dilute beam will likely remain coherent over larger timescales than trapped fields.

References

[1] M.-O. Mewes, *et al.*, Phys. Rev. Lett. **78**, 582 (1997).