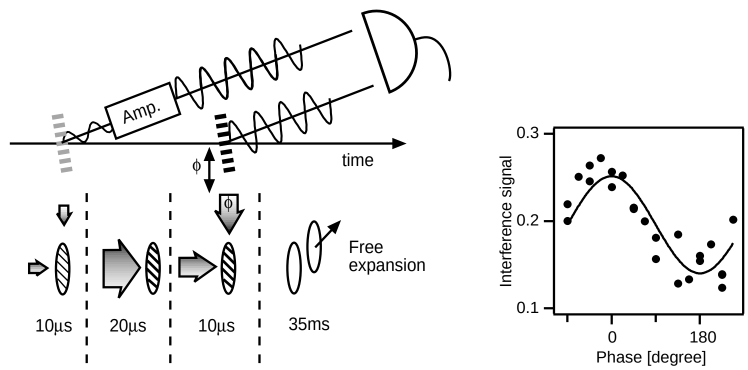
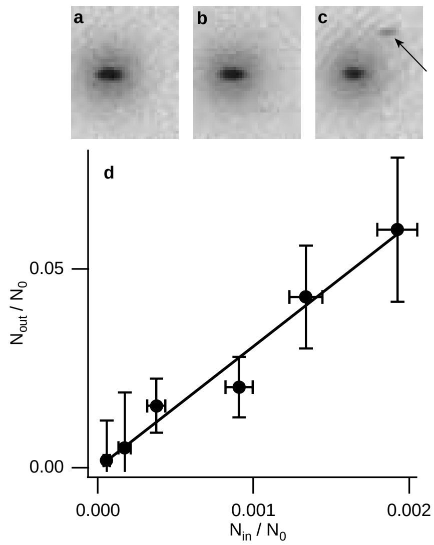
Phase-coherent amplification of matter waves

Atom amplification differs from light amplification in one important aspect. Since the total number of atoms is conserved (in contrast to photons), the active medium of a matter wave amplifier has to include a reservoir of atoms. One also needs a coupling mechanism which transfers atoms from the reservoir to an input mode while conserving energy and momentum. We have used the matter wave superradiance which we observed in a BEC [1] to realize a matter wave amplifier [2] (see figure).



Experimental scheme for observing phase coherent matter wave amplification. A small-amplitude matter wave was split off the condensate by applying a pulse of two off-resonant laser beams (Bragg pulse). This input matter wave was amplified by passing it through the condensate pumped by a laser beam. The coherence of the amplified wave was verified by observing its interference with a reference matter wave, which was produced by applying a second (reference) Bragg pulse to the condensate. The interference signal was observed after 35 ms of ballistic expansion. The fringes on the right side show the interference between the amplified input and the reference matter wave.

The gain process can be explained in a semiclassical picture. The input matter wave of wave vector $\mathbf{K_j}$ interferes with the condensate at rest and forms a moving matter wave grating which diffracts the pump light with wave vector $\mathbf{k_0}$ into the momentum and energy conserving direction $\mathbf{k_i} = (\mathbf{k_0} - \mathbf{K_j})$. The momentum imparted by the photon scattering is absorbed by the matter wave grating by coherently transferring an atom from the condensate into the recoil mode, which is the input mode. The rate of scattering, which is given by the square of the grating amplitude, is proportional to the number of atoms in the input mode N_j, implying an exponential growth of N_j (as long as one can neglect the depletion of the condensate at rest).



Input-output characteristic of the matter-wave amplifier. (**a-c**) Typical time-of-flight absorption images demonstrating matter wave amplification. The output of the seeded amplifier (**c**) is clearly visible, whereas no recoiling atoms are discernible in the case without amplification (**a**) or amplification without the input (**b**). The size of the images is 2.8 mm x 2.3 mm. (**d**) Output of the amplifier as a function of the number of atoms at the input. A straight line fit shows a number gain of 30.

Input matter waves with a well defined momentum were generated by using Bragg scattering to transfer a small part of the condensate into a recoil mode. The input matter wave was amplified by applying an intense radial pump pulse for 20 μs. The number of atoms in the recoil mode was then determined by suddenly switching off the trap and observing the ballistically expanding atoms after 35 ms of time-of-flight using resonant absorption imaging. After the expansion, the condensate and the recoiling atoms were fully separated (see figure). Phase-coherence of the matter-wave amplifier was demonstrated with an interferometric technique (see figure).

Our experiment can be regarded as a demonstration of an active atom interferometer. It realizes a two-pulse atom interferometer with phase-coherent amplification in one of the arms. Such active interferometers may be advantageous for precise measurements of phase shifts in highly absorptive media, e.g. for measurements of the index of (matter wave) refraction when a condensate passes through a gas of atoms or molecules [3]. Since the most accurate optical gyroscopes are active interferometers [4], atom amplification might also play a role in future matter-wave gyroscopes [5]. In an independent effort a group at the University of Tokyo [6] has achieved similar results on the amplification of matter waves.

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