Topical: Coherent matter waves in extended free fall

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Quantum sensors based on coherent matter-waves have numerous applications in fundamental physics measurements, gravimetry and gradiometry, as well as inertial sensing. The wave nature of ultra-cold atomic ensembles gets exploited to perform light-pulse atom interferometry, measuring small accelerations with high precision. Extending the free fall duration allows for boosting the performance of the sensor. However, repulsive inter-particle interactions affect the expansion of the atomic ensemble. Different techniques for lowering the ensembles expansion velocity have been developed and tested in various laboratory and free fall environments. They provide the basis for the development of future atomic sources, sensors and tests of fundamental physics with unprecedented sensitivities.

1 Introduction

Ultra-cold atomic ensembles provide an excellent input state for quantum sensors. The wave nature of massive particles gets exploited to enable interferometric measurements, using the atomic ensemble as a probe. The sensitivity of such sensors increases with the square of the duration of the ensembles free evolution for measuring accelerations [3]. Time scales on the order of tens of seconds [4–6] are e.g. anticipated for more stringent quantum tests of the equivalence principle [7–10] and gravitational wave detection [11–15]. Atom interferometry also enables the determination of fundamental quantities, like e. g. the gravitational constant [16, 17] and the fine-structure constant [18, 19]. In addition, ultra-cold atomic ensembles can be used for a variety of measurements, ranging from probing quantum theory [20–22] to the analysis of light field wave-front distortions to estimate their potential bias on atom interferometric measurements [23].

Repulsive inter-particle interactions lead to an accelerated expansion of the atomic ensemble, reducing the signal-to-noise ratio during detection. This limits the duration of the free evolution of the ensemble and hence, the sensitivity of the quantum sensor. Aside from that, the expansion rate of the ensemble leads to contrast lost via dephasing, affects the efficiency of large-momentum beam splitters, proposed for high-precision atom interferometric measurements, and induces biases in the sensor [8, 11, 24–26]. Different techniques are used to reduce the internal kinetic energy of an ultra-cold atomic ensemble. Temperatures of 500 pK and 350 pK were achieved by evaporative [27] and spin gradient cooling [28] respectively. Matter-wave lenses based on electrostatic [29], optical [30] or magnetic forces [31–33] led to internal kinetic energies of as low as 50 pK in two dimensions [34]. Combining a magnetic lens and a collective-mode excitation to a matter-wave lens-system permitted to reduce the internal kinetic energy in all three dimension and reach the so far lowest energy of 38 pK [1].

To unfold their full potential for high-precision measurements, these ultra-cold, slowly expanding quantum gases require either large apparatuses where they can fall freely inside a long vacuum chamber, like atomic fountains [34, 35], or a microgravity environment as can be found in drop towers [36–38], parabolic flights [39, 40], sounding rockets [41, 42], and space [43, 44]. Technologies and methods that open up previously unattainable parameter areas are developed, validated and tested in such environments. This opens up a previously unattainable parameter space for new and more stringent tests and will advance quantum technology and quantum sensing.

2 Matter-wave collimation

Using a matter-wave lens system, the so far lowest expansion rate of an atomic ensemble along the principal axes of

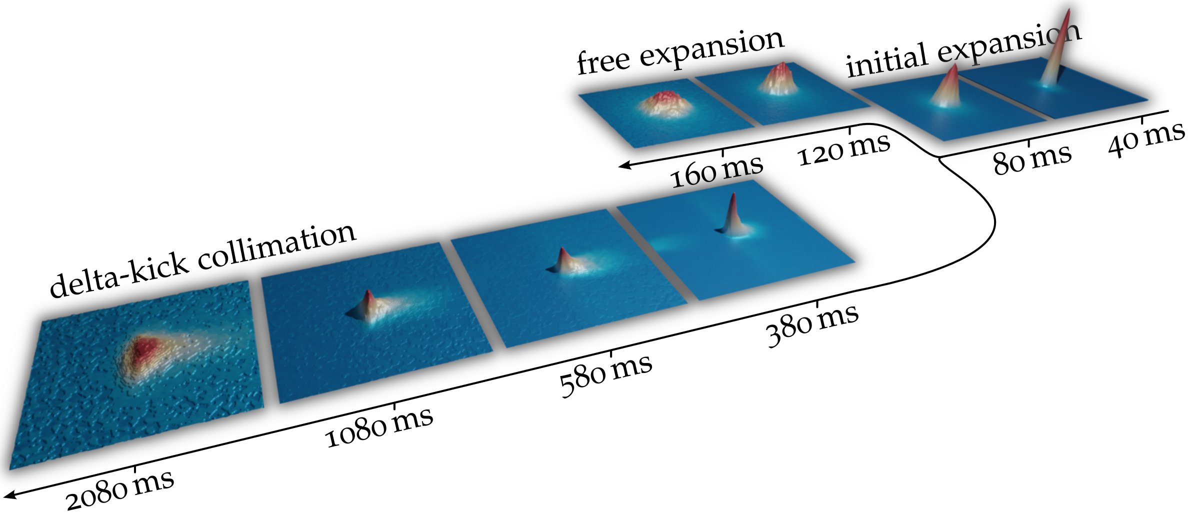

Figure 1
Absorption images of an expanding atomic ensemble without and with matter-wave lensing. After an initial expansion of 80 ms, a magnetic lens is employed, significantly reducing its expansion. The non-lensed, free-expanding ensemble after 160 ms is of a comparable size and particle density as the delta-kick collimated one after 2080 ms (based on exp. data evaluated in [1]. Credit: Christian Deppner, license: CC-BY 4.0 [2]).

$\sigma_v = \{77, 47, 53\}$ µm/s, corresponding to a total internal kinetic energy of 38 pK, was achieved [1]. A Bose-Einstein condensate (BEC) consisting of 100 000 ^{87}Rb atoms was created using the high-flux BEC source detailed in [38]. Inside the final magnetic trap with a cylindrical shape, a collective-mode oscillation of the BEC was excited, leading to an anti-phase oscillation along the longitudinal and radial direction. By releasing the BEC at a turning point of this shape oscillation along the longitudinal direction, it mainly expands in the radial directions. During an initial free expansion of 80 ms, the BECs repulsive interaction energy converts into a total internal kinetic energy of 2 nK. A cylindrical magnetic lens potential, used for delta-kick collimation [32], reduces the BECs expansion along the radial direction to a total three-dimensional internal kinetic energy of 38 pK. The BEC collimated in this way was then detected after up to 2080 ms, as shown in Fig. 1.

The minimal achievable internal kinetic energy is limited by the residual repulsive interaction inside the BEC after the magnetic lens and amounts here to 26 pK for an ensemble comprising 100 000 atoms. An even better collimation could be achieved if a longer initial free expansion is used, since this would reduce the residual repulsive interaction energy. In fact, for ensembles containing one million or more atoms, as proposed for high-precision atom interferometers [10, 12], a longer initial expansion is crucial since the BECs residual repulsive interaction is much larger.

3 Long free fall times

The atomic ensemble detailed in [1] provides an excellent input state for long-duration free-fall experiments. Simulations suggest that the freely expanding BEC would be observable for up to 2.25 s, until it becomes too dilute to be detectable via absorption imaging [45]. Using the matter-wave lens system consisting of collective-mode excitations and a magnetic lens, this time could be extended up to 17 s. However, the magnetic lens used in these experiments has an anharmonic shape, leading to a deformation of the BECs density distribution, as can be seen in Fig 1. This deformation worsens with the BECs size at the time of the lens. BECs with significantly more than 100 000 atoms require a longer initial expansion for the residual repulsive interaction to decrease. Engineering a more harmonic lens potential would reduce the deformation and hence enable the production of slower expanding BECs with larger particle numbers.

Possible facilities for performing such measurements are drop towers, like the Gravi-Tower at ZARM in Bremen [46] and the Einstein-Elevator at HITec in Hannover [37, 47], or space based platforms [48], like the Cold Atom Lab (CAL) [43] and the proposed Bose-Einstein condensate and cold atom laboratory (BECCAL) [44] aboard the international space station (ISS).

4 Atom interferometry with extended free-fall times

With atom interferometry, small accelerations can be measured to a high precision [49]. A typical geometry is the three-pulse Mach-Zehnder interferometer [3] in which the phase shift scales quadratically with the pulse separation time, motivating space-borne platforms to enable extended free fall times. Such measurements are envisioned by space missions like the space-time explorer and quantum equivalence principle space test (STE-QUEST), aiming for unprecedented tests of the universality of free fall using a differential atom interferometer [7–10, 50]. Offering absolute and drift-free measurements, atom interferometry provides a new tool for earth observation [51, 52]. Being sensitive to low frequencies, it is moreover proposed for gravitational wave detection [12–14, 53].

Typically, free-falling atom interferometry on ground is performed on time scales of a few tens to hundreds of milliseconds [49, 54, 55]. In a large fountain, an atom interferometer with a total duration of 2.3 s was demonstrated [56], while proposals for future quantum sensors in space envision tens or even hundreds of seconds of free-fall time [7–10, 12, 13, 50–52]. Matter-wave lens systems using delta-kick collimation, are the key to enable the observability of an atomic ensemble after such long free-fall times [1].

5 Fundamental physics

Ultra-slow expanding atomic ensembles are also used for tests of fundamental physics. Fundamental decoherence processes may lead to a collapse of the wave function after long free-fall times [21]. This was investigated for observed heating rates in atomic ensembles and contrast of atom interferometers in earth-bound laboratories, establishing lower bounds on these models for decoherence [21, 57]. Extended free-fall times provided on space-borne platforms open a new parameter range to explore. Delta-kick collimated BECs are also of interest in investigating proposed nonlinear extensions to the Schrödinger equation, e.g. a logarithmic nonlinearity [22].

6 Conclusion

Ultra-slow expanding BECs with a large number of particles provide a well-defined input state for precision measurements in light-pulse atom interferometry. Possible applications range from gravity measurements, inertial sensing, the determination of fundamental constants to fundamental physics. At the same time, they offer the possibility to study decoherence effects and may as a macroscopic quantum system be of interest for testing fundamental quantum theory.

Exploiting the full potential of ultra-slow expanding BECs will require an extended free-fall environment as provided in drop towers, parabola flights or sounding rockets, a space station and dedicated satellites.

7 License

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