Atom optics with Bose-Einstein condensates: quantum reflection and interferometry

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Abstract. We present recent results on atom optics with Bose-Einstein condensates obtained at MIT. These results demonstrate the flexibility of micro-fabricated atom traps (atom-chips) and the interaction of Bose-Einstein condensates with surfaces through normal incidence quantum reflection.

1. Introduction

At ultra-cold temperatures, the normally compact wavefunctions of individual atoms expand to the micron scale, overlap, and coalesce to form a Bose-Einstein condensate (BEC). Using condensates, it is possible to explore quantum phenomena like superfluidity, matter-wave interference, and quantum reflection. Producing these cold atomic populations requires isolation from the environment, separating the atoms from the deleterious effects of room temperature energy scales and small, disordered potentials. However, manipulation of atomic wavefunctions requires use of micron-size potentials and that those atoms are brought close to a surface, typically at room temperature. Resolving these incongruous conditions is a great challenge for the emerging field of atom optics.

In our sodium BEC experiment at MIT, we take advantage of a flexible apparatus to explore many aspects of condensate physics, focusing on the manipulation of condensates and novel trapping geometries. The apparatus is intended to allow easy manipulation of BEC: after production by forced evaporative cooling, BEC is transported with optical tweezers from the production chamber into the auxiliary "science chamber" [1]. Typically, we are able to transport condensates of $2 \times 10^6 \ ^{23}$Na atoms in the $| F = 1, m_f = -1 \rangle$ state. Once in the science chamber, condensates are loaded into magnetic and optical microtraps for study.

The science chamber affords us unique flexibility in experimental design and access to BEC, as no laser cooling light needs to access the chamber and no high current magnetic traps are needed for evaporation. This design also allows for the rapid cycling of experiments without compromising the vacuum required for condensate production; a new experiment is installed and becomes operational in less than a week. In the following, we demonstrate some of the recent diverse atom optics experiments. The sections are meant to be synthetic accounts of the results; further details of the experiments may be found in the cited references and on our website (http://cua.mit.edu/ketterle_group/experimental_setup/BEC_III.htm).

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Figure 1. Experimental schematic for atom interferometry. (a) An acousto-optical modulator driven with two frequencies created two first order diffracted beams of a red-detuned laser. These beams were focused to create two optical dipole traps with variable separation. A Bose-Einstein condensate was loaded into a single well configuration (b) that was continuously deformed into a double well configuration (c) for the experiment.

Figure 2. Time of flight matter wave interference. (a) Absorption image of condensates released from the optical double-well potential and allowed to expand for 30 ms. The field of view is 600 µm × 350 µm. (b) Radial density profiles were obtained by integrating the absorption signal between the dashed lines, and typical interference patterns had > 60% contrast. The spatial phase of the matter wave interference pattern was extracted from the fit shown.

2. Atom interferometry with Bose-Einstein condensates in a double-well potential
The applicability, accuracy, and sensitivity of atom interferometers may be improved by exploiting the laser-like coherence properties of gaseous Bose-Einstein condensates in combination with the fine manipulation capabilities of atomic microtraps and waveguides. Current proposals for microtrap and waveguide interferometers utilize double-well potentials for beam splitters and recombiners. To implement a prototype of such schemes, we created a trapped-atom interferometer using gaseous Bose-Einstein condensates coherently split by deforming an optical single-well potential into a double-well potential [2].

Sodium condensates were split by deforming an initially single-well potential into two wells separated by 13 µm. To avoid deleterious mean field effects common to traditional in-trap recombination schemes, the relative phase between the two condensates was determined from the spatial phase of the matter wave interference pattern formed upon releasing the atoms from the separated potential wells. The coherence time of the separated condensates was measured to be 5 ms, and was set by mechanical excitations created during the splitting. The separation between the split potential wells was large enough for the condensates to be fully disconnected, allowing the phase of each condensate to evolve independently and either condensate to be addressed individually.

3. Measurement of the relative phase of two Bose-Einstein condensates using light scattering
Time-of-flight recombination schemes, like most proposals for measuring the relative phase of two condensates, require reproducible, excitationless splitting of a BEC. This requirement exists because each measurement of the relative phase is destructive; therefore the initial phase relationship between the two condensates must be constant if the measurement is to have any meaning. We have demonstrated an experimental technique based on stimulated light scattering to continuously sample the relative phase of two spatially separated Bose-Einstein condensates of atoms [3]. This is the first time that the phase of a condensate could be determined in a non-destructive way. The phase measurement process created a relative phase between two condensates with no initial phase relation, read out the phase, and monitored the phase evolution.
Atoms in the optical double well (described above) were exposed to two counter-propagating laser beams, parallel to the separation direction and satisfying the Bragg condition. Atoms that scattered the photons were outcoupled uni-directionally, as the recoil energy was larger than the trap depth. Two streams of atoms, one out of each condensate, were therefore created and overlapped while propagating, carrying the information on the original condensates. While overlapping, the atom stream was either enhanced or suppressed based on the relative phase of the condensates. Oscillations in the relative phase of the two condensates were thereby mapped into oscillations in the outcoupled atom stream and the evolution of the relative phase could be monitored, even for condensates with no initial phase relationship.

More generally, we demonstrated a scheme to measure non-destructively the beat frequency of two previously independent condensates thus establishing phase coherence. The technique could permit the coupling condensates displaced by tens of microns on atom chips or in other microtraps, to explore Josephson oscillations, phase diffusion, and self trapping. We demonstrated already its potential for a novel type of atom interferometer using Bose-Einstein condensates trapped in separate locations, without the need for a coherent beam splitter or recombiner.

4. Quantum reflection of ultracold atoms from a solid surface

Quantum reflection is a process by which a particle reflects from a potential without reaching a classical turning point. Commonly, quantum reflection is studied in the context of the atom surface interaction; the atom surface potential, well described by the Casimir-Polder potential, is attractive at large separations. Observing quantum reflection requires low incident velocity and weak attraction to the surface; conditions previously realized only using liquid helium surfaces or solid surfaces at grazing incidence [4]. We have demonstrated quantum reflection of ultracold sodium atoms from a solid silicon surface at normal incidence [5].
Using Bose-Einstein condensates in a weak gravito-magnetic trap to reduce the atomic motion, atoms were incident on the surface at velocities as low as 1 mm/s, corresponding to collision energies of $k_B \times 1.5$ nK. Atoms were initially confined ~100µm away from a silicon surface. The magnetic trap was shifted horizontally so that the trap center coincided with the surface, accelerating the atoms. Reflectivity of up to 20% is in qualitative agreement with theoretical predictions for incident velocity above 2 mm/s. At lower velocity, the reflection probability remained constant, possibly due to excitations or mean field effects [6].

5. Dynamical Instability of a Doubly Quantized Vortex in a Bose-Einstein condensate
The study of topological excitations and their stability is an active frontier in the field of quantum degenerate gases. Most studies focused on vortices with one quantum of circulation. In earlier work, we created doubly quantized vortices in a Bose-Einstein condensate with a topological phase imprinting technique, consisting in reversing the direction of the bias field in a Ioffe-Pritchard trap [7]. After imprinting vortices, the atoms were not anymore confined in the axial direction, therefore we could not observe the predicted decay. In a new microchip we could instead reverse independently the bias field and the currents causing axial confinement, so that we have studied the time evolution of a doubly quantized vortex state [8]. We could directly confirm its dynamical instability by observing that a doubly-quantized vortex core splits into two singly-quantized vortex cores [9]. The characteristic time scale of the splitting process was determined as a function of atom density and was longer at higher atomic density.
6. Cooling of Bose-Einstein condensates below 500 Picokelvin

The lowest temperatures for trapped atoms are usually achieved in low-density samples. At high densities, interaction effects adversely affect the cooling process and the temperature diagnostics. We have achieved a new record-low temperature of less than 500 picokelvin in a very weak trap using a combination of gravitational and magnetic forces [10]. The partially condensed atomic vapors were adiabatically decompressed by weakening the gravito-magnetic trap to a mean frequency of 1 Hertz, and then evaporatively reduced in size to 2500 atoms. This lowered the peak condensate density to $5 \times 10^{10}$ atoms per cubic centimeter and cooled the entire cloud in all three dimensions to a kinetic temperature of $450 \pm 80$ picokelvin.

These samples are characterized by a thermal velocity of 1 mm/s, a speed of sound of 100 µm/s, and a healing length limited by the 20 µm harmonic oscillator length of the trapping potential. Low temperature and low-density ensembles are important for spectroscopy, metrology, and atom optics. In addition, they are predicted to experience quantum reflection from material surfaces.

7. Distillation of Bose-Einstein condensates in a double-well potential

The characteristic feature of Bose-Einstein condensation is the accumulation of a macroscopic number of particles in the lowest quantum state. Condensate fragmentation, the macroscopic occupation of two or more quantum states, is usually prevented by interactions [11]. However, multiple condensates may exist in metastable situations. Let’s assume that an equilibrium condensate has formed in one quantum state, but now we modify the system allowing for one even lower state. How does the
original condensate realize that it is in the wrong state and eventually migrate to the true ground state of the system? What determines the time scale for this equilibration process? This is the situation, which we have experimentally explored by preparing a Bose-Einstein condensate in an optical dipole trap and distilling it into a second empty dipole trap adjacent to the first one [12]. The distillation was driven by thermal atoms spilling over the potential barrier separating the two wells and then forming a new condensate. This process serves as a model system for metastability in condensates, provides a test for quantum kinetic theories of condensate formation, and also represents a novel technique for creating or replenishing condensates in new locations.

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