Transport of Bose-Einstein Condensates with Optical Tweezers

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We have transported gaseous Bose-Einstein condensates over distances up to 44 cm. This was accomplished by trapping the condensate in the focus of an infrared laser and translating the location of the laser focus with controlled acceleration. Condensates of order 10^6 atoms were moved into an auxiliary chamber and loaded into a magnetic trap formed by a Z-shaped wire. This transport technique avoids the optical and mechanical access constraints of conventional condensate experiments and creates many new scientific opportunities.

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Since the achievement of Bose-Einstein condensation (BEC) in dilute gases of alkali atoms in 1995, intensive experimental and theoretical efforts have yielded a great deal of progress in understanding many aspects of BEC [1,2]. Bose-Einstein condensates are well-controlled ensembles of atoms useful for studying novel aspects of quantum optics, many-body physics, and superfluidity. Condensates are now used in scientific studies of increasing complexity requiring multiple optical and magnetic fields as well as proximity to surfaces.

Conventional condensate production techniques severely limit optical and mechanical access to experiments due to the many laser beams and magnetic coils needed to create BECs. This conflict between cooling infrastructure and accessibility to manipulate and study condensates has been a major restriction to previous experiments. So far, most experiments are carried out within a few millimeters of where the condensate was created. What is highly desirable is a condensate "beam line" that delivers condensates to a variety of experimental platforms. Transport of charged particles and energetic neutral particles between vacuum chambers is standard, whereas it is a challenge to avoid excessive heating for ultracold atoms. Thus far, transport of large clouds of atoms has only been accomplished with laser-cooled atoms at microkelvin temperatures [3,4]. Condensates are typically a few orders of magnitude colder and hence much more sensitive to heating during the transfer.

In this Letter, we demonstrate an application of optical tweezers that can transfer Bose condensates over distances of at least 44 cm (limited by the vacuum chamber) with a precision of a few micrometers. This separates the region of condensate production from that used for scientific studies. The "science chamber" has excellent optical and mechanical access, and the vacuum requirements in this region may well be less stringent than those necessary for production of BEC. This technique is ideally suited to deliver condensates close to surfaces, e.g., to microscopic waveguides and into electromagnetic cavities. We have used this technique to transfer condensates into a macroscopic wiretrap [5–10] located 36 cm away from the point where the condensates were produced.

An alternative but less flexible method to create condensates close to surfaces is to evaporatively cool directly in a wiretrap, as was accomplished very recently [11,12]. Recently, small condensates were also produced directly in an optical trap [13], eliminating the complexities of magnetic trapping. Although evaporation in these small traps can be very fast due to the tight confinement, the small trap volume fundamentally limits the number of condensed atoms. In contrast, the optical tweezers method combines delivery of condensates into microtraps with the well-established techniques of creating large condensates.

The experiment was carried out in a new sodium condensation apparatus that is an evolution of the original MIT design, which has been described previously [14]. The main challenge was to integrate two additional viewports for the optical tweezers into the stainless steel ultrahigh vacuum (UHV) chamber. The optical tweezers beam had to be perpendicular to gravity, due to the relatively weak axial confinement. As a result, the atomic beam and the Zeeman slower could not be arranged horizontally as in our previous BEC apparatus. The slower was placed at an angle of 33° from vertical. The magnetic trap coils were mounted outside the vacuum in recessed ports. A schematic is shown in Fig. 1. The science chamber was isolated from the trapping chamber by a gate valve that allows the science chamber to be modified or even replaced without compromising the UHV trapping chamber.

The trapping and science chambers were each pumped by separate ion and titanium sublimation pumps, reaching pressures $\simeq 10^{-11}$ torr. The oven chamber was differentially pumped relative to the trapping chamber and can support a factor of 10^5 pressure difference. The Zeeman slower combined decreasing and increasing magnetic field slowing (a so-called "spin-flip slower") and delivered $> 10^{11}$ slowed atoms/s, and $\simeq 10^{10}$ atoms were loaded into a dark spontaneous force optical trap (dark-SPOT) type magneto-optical trap (MOT) after 3 s [1].

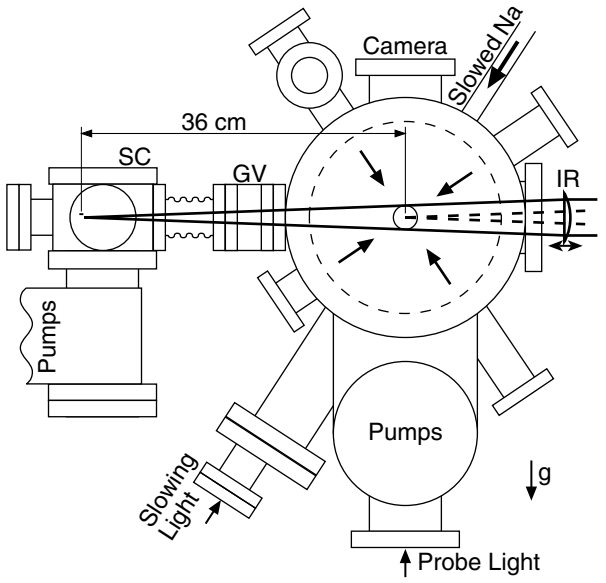

FIG. 1. Schematic of the apparatus, side view. The science chamber (labeled SC) is isolated by a gate valve (GV) from the trapping chamber. The large circle represents a 10 in. Conflat nipple and the dashed circle is the chamber wall. The magnetic trap coils are mounted in 6 in. recessed ports (not shown), bolted onto the 10 in. nipple. The central arrows represent four of the six orthogonal MOT beams. The other two MOT beams pass through the small windows indicated by the small central circle. The end of the Zeeman slower, shown at the top right, is 33° from vertical. The optical tweezers transfer beam is horizontal, with its focus shifting from the MOT position a distance of 36 cm to the Z-shaped wiretrap in the science chamber. Drawn to scale.

Atoms were transferred into an Ioffe-Pritchard–type magnetic trap wound in a cloverleaf configuration with a radial gradient of 140 G/cm, axial curvature of 100 G/cm^2, and axial bias field of 100 G. The atoms were then compressed radially in 3.5 s by reducing the axial bias field. Forced rf evaporative cooling took a total of 30 s during which the gradient field was ramped from 140 to 280 G/cm in 4.5 s for additional compression, held constant at 280 G/cm for 21 s, then finally ramped down in 4.5 s to 140 G/cm to minimize three-body loss. Typical condensates contain $(10-20) \times 10^6$ atoms, and we expect to increase these numbers with further optimization.

The condensate in the magnetic trap had to be decompressed considerably in order to reduce density dependent losses during the transfer and to improve spatial overlap with the optical tweezers (optical dipole trap), because its long axis was along the radial direction of the magnetic trap. The magnetic trap was first decompressed by increasing the axial bias field, which decreased the radial trapping frequency from 200 to 85 Hz. The condensate was further decompressed by lowering the current by a factor of 10 in both the gradient and curvature coils simultaneously.

The optical dipole trap was produced by focusing an infrared laser (1064 nm) onto the center of the magnetic trap [15]. The output of the laser was spatially filtered by a single-mode fiber and its intensity was adjusted with an acousto-optic modulator placed before the fiber. After the fiber, the beam was expanded and collimated, and then focused by a 500 mm achromatic lens placed on a translational stage. This focus was imaged onto the condensate by a relay telescope, yielding a $1/e^2$ beam waist radius at the condensate of $w_0 = 24$ μm.

The condensate was transferred by ramping the infrared laser light linearly up to 180 mW in 600 ms and then suddenly switching off the decompressed magnetic trap. The infrared beam was aligned transversely to within ~ 20 μm of the condensate. The optical trap depth is proportional to P/w_0^2, where P is the power, and was 11 μK for 180 mW [16]. The transfer efficiency into the optical trap was close to 100%. The laser light was then ramped down to 90 mW during the first second of the transfer into the science chamber, in order to minimize three-body loss. The measured optical trap frequencies at 90 mW were 4 Hz axially and 440 Hz radially.

The transport of the condensate to the science chamber was accomplished by translating the 500 mm lens. This was achieved using a linear translation stage (MICOS/Phytron No. MT-150-400-DC220) with 400 mm maximum travel, 0.5 μm encoder resolution, and 120 mm/s maximum velocity. The stage was driven by a dc brushless servo motor, chosen to minimize vibration. A feedback loop in the motor controller servoed the stage position to a trajectory specified in terms of jerk (derivative of acceleration), acceleration, velocity, and distance. Efficient transfer requires smooth, adiabatic motion. We used a trapezoidal acceleration profile that increased with constant jerk, had a flat top upon reaching maximum acceleration, and decreased at constant jerk, followed by a period of zero acceleration upon reaching maximum velocity. For deceleration, the opposite procedure was followed. Initially, we found that mechanical vibrations in the translation stage motion caused loss of atoms due to severe heating. This problem was eliminated by adding two stages of vibration isolation using rubber dampers and lead weights, which reduced the vibrations by a factor of 100.

Once accomplished, the transfer was quite robust and worked for a range of motion parameters, up to 200 mm/s^2 acceleration, 80 mm/s velocity, ~ 1000 mm/s^3 jerk, and with transfer times as short as 4 s. The best transfer was achieved with the following maximum values: jerk = 20 mm/s^3, acceleration = 37 mm/s^2, and velocity = 70 mm/s, yielding a total transfer time of 7.5 s. Routinely we were able to transfer condensates with more than 6×10^5 atoms into the science chamber. A complete systematic study of motion parameters was not practical due to large shot-to-shot fluctuations in the number of atoms transferred. We attribute this to alignment uncertainty of the optical tweezers due to variations in the compression of the rubber vibration dampers when the stage was moved back and forth. We plan to eliminate this problem by installing a smoother translation stage.

The lifetimes of the atoms in the optical dipole trap in both the trapping and science chambers are shown in Fig. 2. In the trapping chamber, the initial loss was due to three-body decay and then the lifetime of 20 ± 2 s was limited mainly by background gas collisions. In the science chamber, the measured lifetime of 16 ± 4 s was limited by background gas collisions. The noise in the lifetime data in the science chamber was due to shot-to-shot fluctuations in the transfer. In general, the pressure and thus the background-limited lifetimes in the science and trapping chambers need not be equal, since the time required to perform experiments may be shorter than the time needed for evaporative cooling. The number of transferred atoms was about 4 times lower than the number remaining in the optical trap after simply holding atoms in the trapping chamber for 7.5 s, which implies that the loss during the translation of the condensate was comparable to the loss from the initial three-body decay. By using a large volume dipole trap with an elliptical focus in which three-body recombination is greatly diminished [17], it should be possible to deliver multimillion atom condensates. First attempts to translate such an elliptical focus failed, probably due to aberrations in the focusing optics.

To demonstrate the utility of the optical tweezers transport, we delivered condensates into a magnetic trap formed by a current I_w in a Z-shaped macroscopic wire [18,19] (diameter = 1.27 mm) and a bias field B_0 coplanar with the Z-shaped wire and orthogonal to its central segment, as shown in Fig. 3. The length of the central wire was $L = 5$ mm, and the supporting end segments were longer than 25 mm. The trap position is located at $z_0 = (\mu_0/2\pi)I_w/B_0$ below the central wire, where the external bias field is equal and opposite in direction to the magnetic field produced by the wire. The two end segments provide the axial curvature $B'' \propto B_0/L^2$ and produce a bias field at the trap bottom $B_{\rm bot} \propto (I_w z_0)/(4z_0^2 + L^2)$ [19]. The radial gradient B' is $(2\pi/\mu_0)B_0^2/I_w$, and the radial trap frequency is proportional to $B'^2/B_{\rm bot}$.

The optical trap was aligned to overlap the original condensate in the trapping chamber magnetic trap and to be about 1 mm below the wire in the science chamber. The current in the wiretrap and the current producing the bias field B_0 were linearly ramped up in 1 s. The optical trap was then slowly ramped down to zero, transferring the condensate into the magnetic wiretrap. Nearly 100% efficient transfer was achieved for $B_0 = 2.9$ G and $I_w = 2.0$ A [20]. The trap frequencies were measured to be 36.0 ± 0.8 Hz radially and 10.8 ± 0.1 Hz axially. The lifetime of the condensate in the wiretrap was measured to be 5 ± 1 s. This lifetime could probably be improved by adding a radio frequency shield to limit the trap depth [14]. By reducing the current in the wire, condensates were also moved to within a few microns from the wire surface.

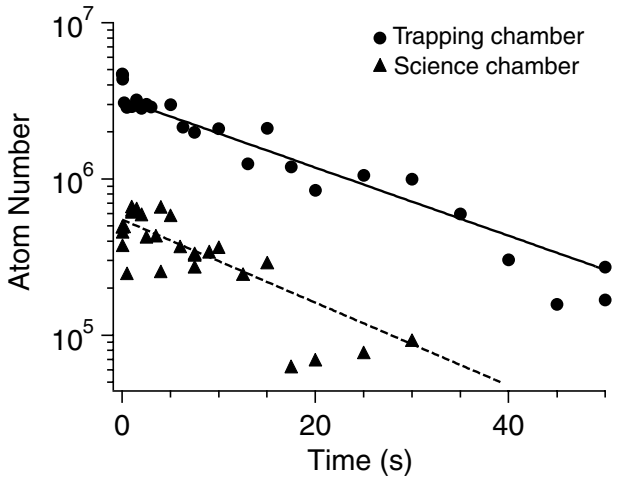

FIG. 2. Lifetime of optically confined Bose-Einstein condensates in the trapping and science chambers. The number of condensed atoms is plotted vs trapping time. Circles and triangles represent data in the trapping and science chambers, respectively. Both traps had the same characteristics with 90 mW power and trap frequencies of 4 Hz axially and 440 Hz radially. The fluctuations in the science chamber data are mainly due to alignment irreproducibilities in the translation stage (see text). The lines are exponential fits to the data. The lifetimes in the main and the science chambers were 20 ± 2 and 16 ± 4 s, respectively.

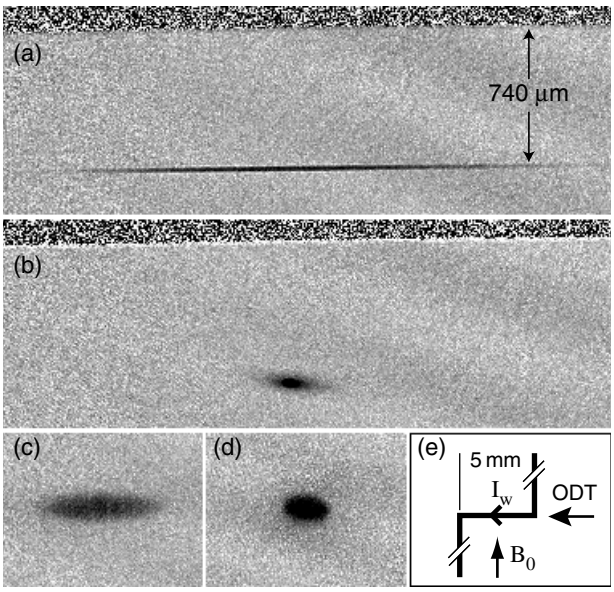

FIG. 3. Absorption images of condensates in the science chamber, side view. All images have the same scale. Condensates of $\simeq 6 \times 10^5$ atoms are shown in (a) optical trap and (b) wiretrap. The center segment of the Z-shaped wire is visible as a dark speckled horizontal strip and is 740 μm above the trapped atoms. The condensate was released from (c) an optical trap after 10 msec time of flight and (d) wiretrap after 23 ms time of flight. (e) Schematic of the wiretrap, top view. $I_w = 2$ A is the current through the wire, and $B_0 = 2.9$ G is the bias field. Atoms are trapped below the 5-mm-long central segment of the wire, which is aligned with the optical trap axis. The supporting end segments, which provide field curvature, are truncated in the figure. The wiretrap was located 36 cm from where the condensates were produced.

In conclusion, we have used an optical dipole trap as a tool for moving and manipulating condensates over a range of 44 cm, and used this tool to load atoms into a magnetic trap 36 cm away from the center of the trapping chamber. The ability to move and position condensates allows them to be produced under optimal conditions, then moved to another region to perform experiments requiring maximal optical and mechanical access. This flexibility will be important for the next generation of BEC experiments, many of which may require close proximity between condensates and other materials.

One key application that is hotly pursued by several groups is to load condensates into microfabricated magnetic waveguides built using lithographic wires on substrates, similar to integrated circuit chips [11,12,18, 21–25]. Such waveguides, analogous to fiber optics for light, may lead to improved manipulation of condensates, enabling sensitive atom interferometers. Other applications include studies of condensate-surface interactions [26,27] and experiments which require extreme magnetic shielding such as some proposed studies of spinor condensates [28,29]. Another possible application is producing a continuous atom laser. Previously demonstrated atom lasers work by depleting a single condensate [30–33]. A continuous atom laser could be produced by repeatedly transferring condensates into a reservoir from which atoms are continually outcoupled. The dipole trap could be used to transfer atoms into an optical or magnetic trap reservoir that is spatially separated from the condensate production region to avoid losses due to scattered light. Finally, one could move condensates into high finesse optical or microwave cavities.

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