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Magnetic transport of trapped cold atoms over a large distance

Markus Greiner, Immanuel Bloch, Theodor W. Hänsch, and Tilman Esslinger
Sektion Physik, Ludwig-Maximilians-Universität, Schellingstraße 4/III, D-80799 Munich, Germany
and Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany

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We report the transport of magnetically trapped cold atoms over a large distance. Atoms are captured in a magneto-optical trap (MOT) and loaded into a magnetic quadrupole trap. The quadrupole potential is then moved over a distance of 33 cm into an ultra-high-vacuum (UHV) chamber using a chain of quadrupole coils. By running suitable currents through the quadrupole coil pairs the trapping geometry of the potential is maintained during the transport process, thus minimizing heating of the trapped atom cloud. Magnetically trapped ^{87}Rb atoms at an initial temperature of $T=125$ μK were heated by less than 20 μK during the transport process, and up to 10^9 atoms were transferred into the UHV chamber. Due to the spatial separation of the final magnetic trap and the MOT we have been able to capture atoms in the MOT, while storing magnetically trapped atoms in the UHV chamber.

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The controlled transport of ultracold atoms opens intriguing new perspectives for experiments in atomic physics. Atom lasers [1] based on continuously operated Bose-Einstein condensates and quantum computers using neutral atoms are some of the most fascinating possibilities. A crucial step towards the continuous production of a Bose-Einstein condensate [2] is the simultaneous operation of different cooling and trapping stages. By transporting atoms between spatially separated cooling sites, a condensate could be held in a trap while other atoms undergo laser cooling. It is also conceivable to transport various atomic or molecular species to a common trapping site, where sympathetic cooling [3] could then be used to create a variety of degenerate quantum gases not accessible to present cooling techniques. In order to implement proposed schemes for quantum computation with neutral atoms, the atoms have to be brought into an unperturbed environment, where quantum gates might be realized with a high degree of coherence. The underlying quantum interactions could be based on controlled collisions between atoms loaded into optical standing-wave fields [4] or by using the interaction of cold atoms with the field of a high-Q cavity [5].

A widely used method to ballistically transport cold atoms is the moving molasses technique [6], where the atoms are launched from a magneto-optical trap in a variable direction with a precise initial velocity. However, during the ballistic transport the cloud of atoms expands and its density is reduced. Promising attempts have been made to circumvent this severe limitation by guiding atoms in two-dimensional potentials generated by far-off-resonant dipole potentials [7] or by current carrying wires [8]. In this Rapid Communication we report on a general and versatile method to transport any magnetically trapable atomic or molecular species over large distances with a high degree of control. During the transport process the atoms or molecules are magnetically confined in all three dimensions, thus eliminating any ballistic expansion of the trapped gas [9,10].

In the experiment a magnetic quadrupole potential with a trapped cloud of ^{87}Rb atoms is moved over a distance of more than 33 cm around a 90° corner into an UHV chamber [see Fig. 1(a)]. After the transport, the magnetic quadrupole potential is converted into an Ioffe-type potential using the QUIC-trap mechanism [11]. By employing rf-induced evaporation to cool the trapped ^{87}Rb atoms, we have been able to reach Bose-Einstein condensation in this setup. The spatial separation between the magneto-optical trap (MOT) and the final magnetic trap has furthermore allowed us to store atoms in the magnetic trap while loading new atoms into the MOT, which is a crucial step for experiments aiming

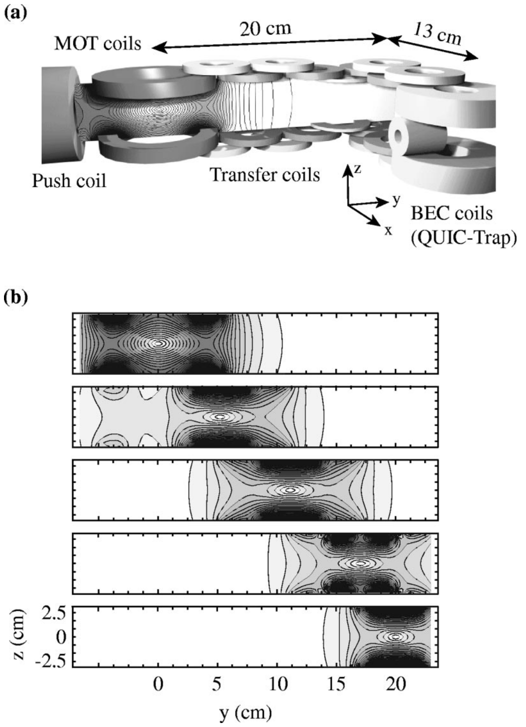

FIG. 1. (a) Experimental setup of the quadrupole coil pairs for the transport process. The magnetic trapping potential is moved over 33 cm around a 90° corner into an UHV vacuum region of a glass cell. (b) Contour plots, showing the absolute value of the magnetic field during different stages of the first half of the transport sequence.

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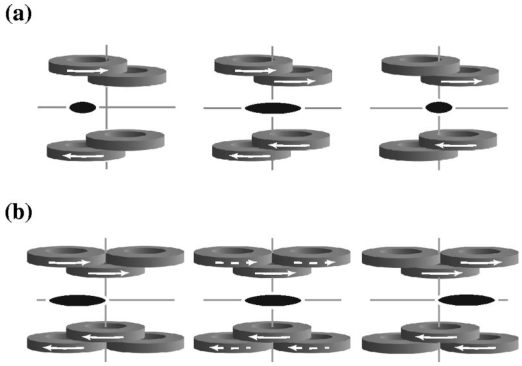

FIG. 2. Schematic setup for the transfer of a magnetic quadrupole trapping potential. The solid and dashed arrows indicate the current direction and strength. (a) By increasing the current in the second quadrupole coil pair and afterwards decreasing the current in the first quadrupole coil pair, the trapping potential may be moved. Here the aspect ratio is changed during the transport process. (b) By running suitable currents through three quadrupole coil pairs it is possible to maintain a constant aspect ratio during the transport process.

towards the continuous production of Bose-Einstein condensates. The absence of a MOT in the UHV region in combination with the 90° corner in the transport track permits unconstrained optical access along all six directions to the atoms in the final trap. This configuration is ideally suited for realizing optical standing-wave potentials in all three dimensions.

A magnetic quadrupole potential may be shifted in position by using two partly overlapping quadrupole coil pairs and running suitable currents through these coils. Consider the setup sketched in Fig. 2(a). Initially current is flowing only through the first quadrupole coil pair that creates a magnetic quadrupole potential in which the atomic ensemble is trapped. As the current in the neighboring quadrupole coil pair is increased to the same value as the current in the first coil pair, the center of the trapping potential is displaced towards the common center of the two overlapping quadrupole coil pairs. Finally the current in the first quadrupole coil pair is reduced to zero while a maximum current is kept running in the second quadrupole coil pair. The center of the trapping potential will then shift towards the center of the second quadrupole coil pair. By adding additional coil pairs it is then possible to displace a trapped atomic cloud over a large distance.

A drawback of the above scheme is that the aspect ratio and the geometry of the trapping potential change significantly during the transfer process. Consider the case when the same current is flowing through the two quadrupole coil pairs. In the overlap region of the coil pairs the generated magnetic fields cancel due to the opposite current directions in the coils. The magnetic field generated in this configuration is therefore similar to that of a single elongated quadrupole coil pair, resulting in a strongly deformed trap geometry. A repetition of such a transfer process would consequently lead to a modulation of the aspect ratio of the trapping potential, which in turn could heat the trapped atomic ensemble.

By using an additional third quadrupole coil pair it is possible to maintain the trapping geometry during the transport process [see Figs. 1(b) and 2(b)]. Consider a situation where current is initially flowing through the first two coil pairs. Then the current is decreased in the first coil pair and simultaneously increased in the last coil pair such that the trap geometry remains constant and the trapped cloud moves to the center of the second quadrupole coil pair. Finally the current in the first coil pair is reduced to zero as the current in the last coil pair is increased to full strength. The atomic cloud has then moved to the center of the last two quadrupole coil pairs while the trap geometry has remained constant during the transfer process.

Our experimental setup consists of two vacuum chambers at different base pressures. The first chamber at a pressure of 6×10^{-10} mbar is used for the collection of atoms in a vapor cell MOT. The second chamber consists of an UHV glass cell at a pressure of 2×10^{-11} mbar. The glass cell is made of 4-mm-thick optical quality windows and its outer dimensions are 26 mm×26 mm×120 mm, with the long dimension mounted horizontally. The two vacuum chambers are connected by standard 15-cm-long vacuum tubing, where the cross section of the tubing has been reduced to 8 mm in diameter over a distance of 7 cm in order to maintain the pressure difference between the two chambers.

The laser light for the operation of the vapor cell MOT is generated by external cavity laser diode systems [12]. The main cooling and trapping light on the $5S_{1/2}(F=2)\rightarrow5P_{3/2}(F'=3)$ transition is amplified to a power of 200 mW with the help of a master-oscillator power-amplifier (MOPA) system. For the MOT 100 mW of this laser power are available. A second external cavity laser diode system provides 6 mW of laser light tuned to the $5S_{1/2}(F=1)\rightarrow5P_{3/2}(F'=2)$ repumping transition. Both laser beams are apertured to a diameter of 40 mm in a six-beam counterpropagating MOT configuration. With this setup we are able to trap 3×10^{9} atoms within 3 s at a detuning of -18 MHz to the red of the cooling transition. Before transferring the atoms into the magnetic trap, a compressed MOT phase [13] is initiated by detuning the cooling laser to -25 MHz while simultaneously increasing the detuning of the repumper over 90 ms. This is followed by 8 ms of polarization gradient cooling of the atoms to a temperature of ≈60 μK with the magnetic quadrupole field switched off. Then a 1-G bias field is applied for 1 ms and the atoms are optically pumped into the low-field-seeking $|F=2,m_F=2\rangle$ state. The magnetic quadrupole field is rapidly (<600 μs) switched on to an axial gradient of 70 G/cm that is increased to 130 G/cm during the first 200 ms after the magnetic transfer sequence has been initiated.

For the transport of the atoms nine overlapping quadrupole coil pairs are used. Each coil consists of 36 windings with a total diameter of $d=60$ mm, a height of $h=5,5$ mm and an average separation of 6 cm between the individual quadrupole coils of a single coil pair. The transfer coil pairs are arranged so that each coil pair overlaps with its next-neighbor coil pair [Fig. 1(a)]. Three programmable HP6671A-J03 power supplies are used to energize three neighboring quadrupole coils simultaneously. A numerical

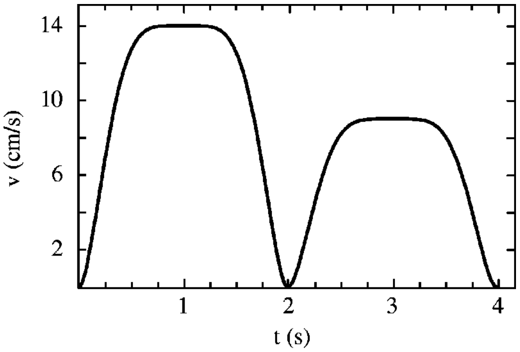

FIG. 3. Transfer curve describing the velocity of the potential minimum during the transport sequence. After half of the transfer sequence has evolved the atoms are brought to rest before they are moved along an orthogonal direction into the glass cell. A larger velocity is chosen during the first half of the sequence, in order to minimize the time the atoms spend in the vapor cell.

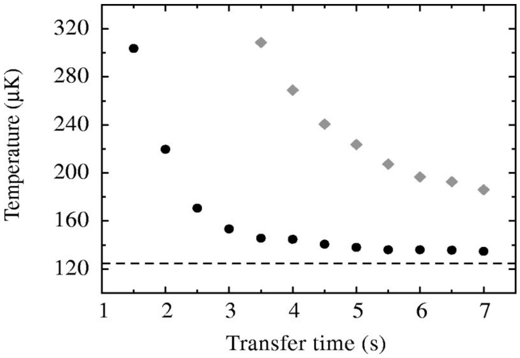

FIG. 4. Measured temperature of the transported cloud of atoms for variable transfer times. The black circles show the results obtained with a three-coil-pair transfer sequence [Fig. 2(b)] while the gray diamonds show the results for a two-coil-pair transfer sequence [Fig. 2(a))] The dashed line denotes the temperature of the atoms in the magnetic trap before the transport sequence.

optimization algorithm was used to calculate the currents in the three coil pairs to achieve a given center position and fixed geometry of the resulting potential. At the end of a three-coil-pair transport sequence [see Fig. 2(b)] the current in the first quadrupole coil pair has dropped to zero and the power supply used to drive this coil pair is switched to the next quadrupole coil pair in order to continue the transport process. Care has to be taken that during the switching process the currents in the coils to be switched have indeed dropped as close to zero as possible, since this would otherwise lead to a sudden displacement of the potential and in turn to a heating of the atoms. We are able to achieve a variable acceleration and velocity of the moving potential, by controlling the currents through the coil pairs. For the initial transfer sequence out of the MOT an additional push coil is used that reduces the changes in the trap geometry due to the different sizes of the transfer coils and the MOT quadrupole coils.

The geometry of our experiment [see Fig. 1(a)] is such that atoms are first moved out of the MOT over a 20-cm-long straight line into the UHV vacuum chamber where the atoms are subsequently brought to rest. The trapping potential is then moved over 13 cm orthogonal to the initial direction into the UHV glass cell.

In order to measure the temperature of the transferred atoms, absorption images of ballistically expanded clouds of atoms were captured with a charge-coupled-device camera after an adjustable time-of-flight period. Using this technique we have measured the temperature of the transferred atoms versus the transfer time for a fixed magnetic quadrupole gradient of 130 G/cm in the axial direction during the transfer process. A transfer curve, describing the velocity of the center of the trapping potential versus time, was used that gradually accelerates and decelerates the atoms, as shown in Fig. 3. This transfer curve was then scaled in time to achieve different total transfer times. In Fig. 4 the temperatures of the transferred cloud of atoms versus transfer time after a 4-s equilibration period in the final magnetic trap are displayed. The initial temperature of the atoms in the magnetic trap was measured to be $125\pm5\ \mu$K.

As can be seen in Fig. 4 transferring the atoms with a variable trap geometry and aspect ratio by using only two coils for the transport process [see Fig. 2(a)] yields much higher temperatures than a transfer process with a constant trap geometry by driving three coils simultaneously [see Fig. 2(b)]. This larger temperature increase can be attributed to the modulated aspect ratio during the transport process and the fact that the current wave forms in the two-coil transfer process are more affected by the limited modulation bandwidth of the power supplies and switching time imperfections. As a compromise between minimum transfer time, which minimizes losses in the magnetic trap due to background collisions in the vapor cell, and minimum heating rate, we typically use total transfer times of 4 s with a maximum velocity of the atoms during the transport of 14 cm/s (see Fig. 3). For these transfer times the heating due to the magnetic transport process is less than $19\pm5\ \mu$K.

A high rubidium background pressure in the vapor cell will decrease the MOT loading time and increase the number of atoms in the MOT but simultaneously decrease the magnetic trap lifetime in this vapor cell region. We have found that for a background pressure of $4-6\times10^{-10}$ mbar 3×10^{9} ^{87}Rb atoms may be captured in the MOT within 3 s. With a 4-s total transfer time we can transfer up to 9×10^{8} of these atoms into the final magnetic trap in the UHV region.

In a further experiment we have been able to store magnetically trapped atoms in the UHV chamber while loading new atoms in the MOT. Here atoms were transported into the UHV glass cell within 4 s, where they were held in a final magnetic trap. Then a shutter between the UHV and MOT chamber was closed to block any resonant stray light from the MOT and opened again, after the renewed MOT loading process was finished. We did not detect any loss or heating of the trapped cloud of atoms in the UHV chamber after the second MOT loading process. This ability to load new atoms while simultaneously storing cold atoms opens the path to many new exciting experiments in atomic physics. It is for example possible to first load a certain atomic species into the magnetic trap and then load a second atomic species that is subsequently combined with the first magnetic trap. One could therefore mix any two species of magnetically trappable atoms without facing the problem of enhanced losses in a mixed species MOT [14].

In conclusion we have demonstrated a method for transporting large number of cold atoms into an UHV environment while simultaneously preserving the density and temperature of the transported atomic ensemble. This method is a versatile tool whenever a MOT is undesirable in the experimental region, such as in cavity QED experiments, experiments with miniaturized magnetic traps, or experiments with cold atoms in the quantum degenerate regime. Furthermore it can be used for the simple creation of mixed species of cold atoms or maybe even for the continuous production of Bose-Einstein condensates.

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