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Propagation of Cold Atoms along a Miniature Magnetic Guide

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A cloud of laser-cooled ^{85}Rb atoms is coupled through a magnetic funnel into a miniature waveguide formed by four current-carrying wires embedded in a silica fiber. The atom cloud has a $\sim 100\ \mu$m radius within the fiber and propagates over cm distances. We study the coupling, propagation, and transverse distribution of atoms in the fiber, and find good agreement with theory. This prototype demonstrates the feasibility of miniature guides as a tool in the new field of integrated atom optics, leading to single-mode propagation of de Broglie waves and the possible preparation of 1D atom clouds.

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There is widespread interest in guiding cold atoms [1,2]. For atom lithography, the goal is to dispense precise quantities of atoms onto specific regions of a surface [3]. In atom optics, the guide can be a "hosepipe," delivering large quantities of atoms to an inaccessible region, or it can be a "single-mode fiber" permitting coherent propagation of de Broglie waves for applications such as interferometry [4] or integrated atom optics [5–7]. In statistical physics, a quantum guide for atoms permits the study of degenerate quantum gases in 1D. Here one might realize a Tonks gas of bosons whose elementary excitations obey Fermi statistics or observe Luttinger liquid behavior with correlation functions that decay algebraically [8].

In several previous experiments [9], cold atoms have been guided inside hollow optical fibers where optical dipole forces confined them on axis. With this approach it is a challenging problem to avoid heating the atoms through intensity fluctuations and spontaneous emission. Confinement by static magnetic fields provides an alternative. On the macroscopic scale, magnetic guiding has been demonstrated using arrangements of permanent magnets [10] and along the side of a current-carrying wire [11]. Here we report on a miniature magnetic quadrupole guide in which we observe an atom cloud of 100 μm radius propagating for several centimeters [12]. We study the motion of atoms in this guide and we discuss the prospects for achieving single-mode de Broglie wave propagation.

Our guide is illustrated in Fig. 1. The supporting structure is a 25 mm-long silica tube fabricated by the Optoelectronics Research Centre at Southampton. Five parallel holes, each of radius $R = 261(5)\ \mu$m, run through the length of the tube parallel to the vertical z axis. Four of them intersect the (x, y) plane on the corners of a square at $(\pm a, \pm a)$, with $a = 522(10)\ \mu$m. These contain copper wires which carry a current I to produce the guiding magnetic field. The fifth hole is on the tube axis where the atoms are guided. To a good approximation the magnetic field vector is a purely quadrupole one: $\mathbf{B} = (B'x, -B'y)$ with $B' = \mu_0 I/\pi a^2 = 1.46(6)I$ T/m. An atom at radius ρ interacting with this field has Zeeman energy $-B'\mu_\zeta \rho$, where μ_ζ is the projection of its magnetic moment onto the local magnetic field direction. For the modest field strengths of interest here, the gyromagnetic ratio is independent of field strength, so, provided the spin does not flip, μ_ζ is a constant of the motion and the potential is linear in ρ. For $\mu_\zeta < 0$ the atom then experiences a constant force directed toward the axis. Nonadiabatic behavior is suppressed at the center by adding a $\sim$300 mG magnetic field along the z direction to maintain an adequate splitting of the magnetic sublevels [13]. This causes the potential to become harmonic at distances less than a few μm from the axis. At the top of the guide the wires spread out (Fig. 1) to form a magnetic funnel of apex angle $\sim 90°$, centered on the axis. A "pinch coil" wound

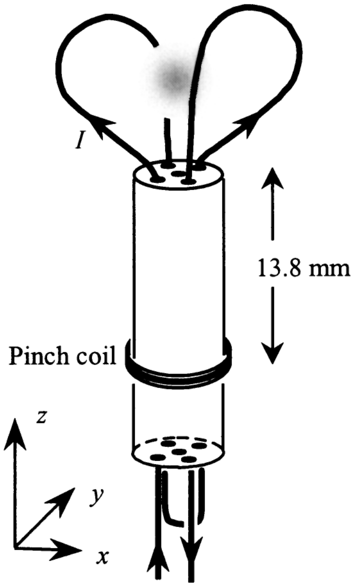

FIG. 1. Schematic view of the quadrupole guide. A cloud of cold atoms falls into the central hole where it is guided down to the pinch coil, reflected, and guided back up to the top. The diameter of the guide is greatly exaggerated.

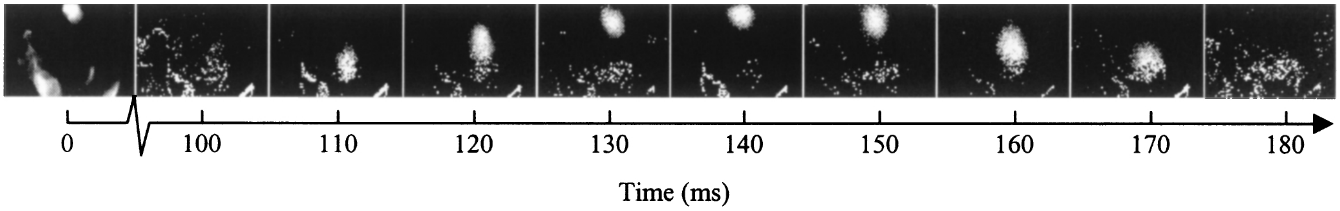

FIG. 2. Atoms released from the MOT at $t = 0$ propagate down the guide and back up again, rising to their original height after 139 ms. Some of the laser light scattered from the input funnel is visible in the background.

on the outside of the guide, 13.8 mm below the top, allows us to add a field in the z direction to close off the guide.

The guide is mounted in a vacuum chamber (10^{-9} Torr) with its entrance 10 mm below a magneto-optical trap (MOT) of standard design [2]. The MOT collects $\sim 5 \times 10^6$ ^{85}Rb atoms from the background vapor (filling lifetime $\sim$5 s). These are then cooled in optical molasses to form a $T = 25\ \mu$K cloud with rms radius $\sigma = 0.72$ mm, which we optically pump into the $(F = 3, m_F = 3)$ ground-state sublevel relative to a uniform magnetic field $B_x \hat{\mathbf{x}}$. As the atoms fall in the dark, B_x is reduced to zero and the guide current is adiabatically turned on. With a field of 40 G at the center of the pinch coil, atoms traveling down the guide should be reflected to reemerge from the entrance aperture. These are detected by a 2 ms pulse of laser light (10 mW/cm^2, -10 MHz molasses), which produces enough fluorescence for a CCD camera to record the distribution of the atoms without appreciably moving them under radiation pressure. We made CCD pictures with the pinch coil on and off. Figure 2 shows the cloud at the moment of release and the subsequent on-off differences as a function of the propagation time. The cloud clearly reemerges from the fiber and rises to its original height, 139 ms after being released, demonstrating that the atoms are indeed being guided in the fiber. Since the total drop height is $h = 2.38$ cm, this round-trip time indicates that the vertical component of the motion is close to free fall. The velocity of atoms along the guide is therefore approximately 45 cm/s near the top and 65 cm/s near the bottom.

When the cloud released from the MOT expands freely, only 0.7% of the atoms enter the guide aperture. By contrast, we find that the funnel gives an optimum efficiency for coupling atoms into the guide of 11% when the guide current I is set at 4.68 A, the value used in all the experiments reported here. The existence of an optimum can be understood as follows. The gravitational energy released by a ^{85}Rb atom falling 10 mm from the MOT to the guide entrance is equal to the magnetic interaction with a field of 15 G. If the field at the edge of the guide exceeds this, the magnetic aperture of the funnel becomes narrower than the physical diameter of the guide, making a constriction which reduces the coupling efficiency. At the same time, the field cannot be much smaller if the atoms are to be confined within the guide because an appreciable fraction of this energy goes into the transverse motion through deflections in the magnetic funnel. The angular momentum of the atoms around the guide axis $L \approx \sqrt{2mkT}\,\sigma$ imposes the additional constraint that the guiding force must be large enough to overcome the centrifugal force $L^2/(m\rho^3)$. Our optimum current makes a field of 17.9 G at the wall of the guide and exerts a force of $B'\mu_\zeta \approx 6 \times 10^{-23}$ N on the atoms, compared with a typical centrifugal force at the wall of $\approx 2 \times 10^{-23}$ N. The coupling is thus a compromise between constriction of the entrance aperture to the guide and rejection of higher angular momenta. A Monte Carlo simulation of the experiment gives 21% coupling efficiency when the MOT is perfectly placed on the symmetry axis, dropping to 10% for an offset of 1 mm between the center of the MOT and the axis of the guide. Such a misalignment is possible in our apparatus.

In Fig. 3 we plot the number of atoms returning from the guide versus the field in the pinch coil. The vertical line marks the field $mgh/\mu_B = 35.8$ G at which the magnetic interaction energy is equal to the entire gravitational energy released by falling. Most of the atoms are reflected at lower fields than this because some of their energy is in transverse motion. Empirically we find that the measured step fits well to the integral of a Gaussian distribution, shown in Fig. 3 by the solid curve. Our Monte Carlo simulation gives the very similar step shown by the dashed line. The slight discrepancy in the absolute position of the step is due to our systematic uncertainty in the conversion from current in the pinch coil to field. The same theoretical model gives a mean energy in the transverse motion

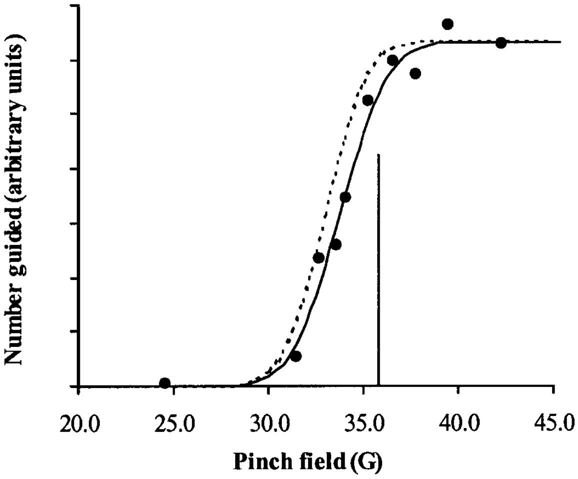

FIG. 3. Reflected atom signal versus magnetic field in the pinch coil. Points: experimental data. Solid line: simple empirical fit described in text. Dashed line: numerical model. Vertical line: mgh/μ_B.

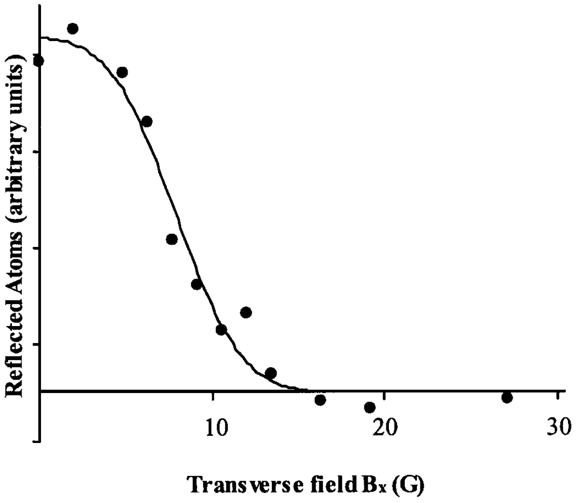

FIG. 4. When a transverse magnetic field is applied, the number of guided atoms decreases because of loss to the wall. Dots: experiment. Line: simple theory described in text.

(divided by μ_B) of 9.6 G, with a standard deviation over the ensemble of 3.3 G. In order to make a direct measurement of this, we adiabatically add a transverse magnetic field B_x to the guide while the atoms are propagating in it. This translates the magnetic potential to the side, lowering the energy required for atoms to escape onto the wall by $\mu_\zeta B_x$. Figure 4 shows how the number of atoms returning from the guide decreases. Fitting these points to the integral of a Gaussian distribution, shown by the solid line, we find a mean transverse energy of 9.9 G with a standard deviation of 3.0 G, in excellent agreement with the numerical model. Expressed as a temperature, this is 670 μK, which is much larger than the initial 25 μK temperature of the atom cloud because the atoms are adiabatically compressed by gravity in the funnel. Noting that the mean potential energy is 2/3 of this total (virial theorem for a linear potential) we deduce from the known field gradient that the radius of the atom cloud in the guide is 98 μm.

In order to increase the distance over which the atoms propagate in the guide, we added a second pinch coil at the top, which is switched on once the atoms have entered to form a very long Ioffe trap. After holding them for any desired length of time, the upper coil is turned off and the atoms emerge to be recaptured in the MOT. The decay time determined in this way is typically 300 ms, depending on the state of the vacuum, and does not appear to be any shorter than the collisional loss lifetime measured for atoms in free flight in the chamber. This shows as predicted [14] that there is no appreciable thermal coupling to the room-temperature glass wall, even at distances of order 100 μm. For a storage time of 300 ms the atoms propagate a distance of ~10 cm along the guide.

The quantum mechanical eigenmodes of this guide [13] are characterized by an energy $(\hbar\mu_B B'/\sqrt{m})^{2/3}$, which scales with current and wire spacing as $I^{2/3}/a^{4/3}$. For our experimental parameters, this energy divided by Boltzmann's constant is ~1 μK, indicating that many transverse modes of the de Broglie waves are occupied in our present experiment. However, we have already demonstrated that similar currents can be passed through structures that are 20 times smaller, in which the mode spacings are ~50 μK. In order to achieve good coupling to such a waveguide, it will be important to introduce some dissipation into the funnel or, alternatively, to use an atom source of smaller phase-space volume, such as a Bose-Einstein condensate.

In conclusion, we have demonstrated that cold atoms can be efficiently coupled into a miniature magnetic quadrupole waveguide where they propagate within a 100 μm radius over tens of cm without appreciable loss other than background gas collisions. This is a prototype which shows the feasibility of miniature guides as a tool in the new field of integrated atom optics, leading to single-mode propagation of de Broglie waves and the possible preparation of 1D atom clouds.

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