Transport of cold atoms in a miniature guide

M Key, W Rooijakkers and E A Hinds
Sussex Centre for Optical and Atomic Physics, University of Sussex, BN1 9QH, UK
E-mail: e.a.hinds@sussex.ac.uk

New Journal of Physics 2 (2000) 25.1–25.6 (http://www.njp.org/)
Received 7 June 2000; online 12 October 2000

Abstract. We have developed a waveguide for atoms based on magnetic confinement within a hollow glass fibre. Weak-field-seeking atoms are transported along a central hole and are prevented from hitting the wall by the magnetic field due to four current-carrying wires embedded in the fibre. A 'pinch' coil wound around the fibre plugs the guide at one end with a magnetic field strong enough to reflect the weak-field-seeking atoms. We have demonstrated that all the positive $m_F$ sublevels of the $^{85}\text{Rb} F = 3$ ground state are guided and have made a movie of the atom dynamics.

1. Introduction

Recently there has been great interest in building miniature magnetic structures for guiding atoms. This idea has been realized in several laboratories, using either supported wires [1]–[3], printed circuits [4]–[8] or microscopic patterns of permanent magnetization [9, 10]. Miniaturization has the virtue of providing strong field gradients [11] and hence large splittings of the vibrational modes of the de Broglie waves. This offers the possibility of propagating de Broglie waves in a single transverse mode in one dimension [12] or two dimensions [13]. Although this has not yet been realized in the laboratory there are several compelling motivations to do so. On the one hand there is great practical interest: such waveguides may be used in future versions of the atom laser [14], in ultra-high-sensitivity atom interferometers [15] or integrated with other components to form a microchip for cold-atom optics [16]. On the other hand, there is also interest in the fundamental physics of weakly interacting quantum gases confined to one dimension [17]. At the Sussex Centre for Optical and Atomic Physics we have been working to develop various magnetic trapping and guiding structures for cold atoms [3, 9, 13, 18, 19]. This article describes some first steps in our efforts to develop a miniature magnetic quadrupole guide for cold atoms.
2. Description of experiment

A schematic drawing of our set-up is shown in figure 1. A hollow fibre with four current-carrying wires is mounted vertically in a vacuum chamber. The wires inside the fibre are located on the corners of a square ($\pm a, \pm a$), with $a = 522 \, \mu m$. The atoms are guided within a central hole of radius $261 \, \mu m$, where the magnetic field gradient is well approximated by the quadrupole formula $\frac{dB}{dr} = \mu_0 I / \pi a^2$, $I$ being the current through the wires. Above the top of the fibre, the wires spread out to form a magnetic funnel to help guide atoms into the entrance aperture. The photograph in the lower part of figure 1 shows a piece taken from the same length of fibre that we used to make the guide.

A magneto-optical trap (MOT) initially collects $1 \times 10^7 ^{85}\text{Rb}$ atoms [3] in a cloud centred 11 mm above the top of the fibre. Next, we switch off the magnetic field of the MOT and adjust the detuning of the laser from $-11$ MHz to $-18$ MHz to achieve polarization gradient cooling. After 10 ms the temperature of the cloud is approximately $25 \, \mu K$ and the laser beams are turned
off. Now, we switch on the guide current and apply a 0.5 G field in the z-direction to remove the zero of magnetic field along the centre of the guide, thereby avoiding possible Majorana flips [12]. The falling cloud is guided into the fibre by the magnetic funnel and propagates downwards until it encounters the small pinch coil at the bottom (16 turns on approximately 2 mm radius), where the magnetic field is strong enough to retro-reflect the atoms. Finally, 140 ms after the cloud was first released, we switch the MOT back on for 15 ms and record the resulting fluorescence intensity from the recaptured atoms to determine how many were guided down the fibre and back up. Recaptured atoms are distinguished from those captured from the background vapour by subtracting the fluorescence signal obtained without any current in the pinch coil.

3. Video sequence

In order to demonstrate atom transport we have made a video sequence of atoms being guided by the funnel and subsequently disappearing from view as they propagate inside the fibre. The movie shows the cloud expanding as it begins to fall, then becoming narrower again, particularly at the bottom, as it propagates down the funnel and is pushed toward the axis by the Stern–Gerlach force. After 40 ms the cloud disappears inside the fibre where it continues to propagate downward until it is reflected at the bottom. The atoms then travel back up, reaching their maximum height approximately 140 ms after being released. For clarity, the fibre and the wires (in brown) were artificially added to the picture. The movie comprises a series of 80 fluorescence images taken with a CCD camera. When an image is made, we turn off the guide field and flash on the MOT light for 2 ms to scatter approximately $10^3$ photons/atom. The net recoil of approximately 30 photon momenta/atom alters the subsequent evolution of the cloud and therefore each new frame requires the whole experiment to be run again. Our first image shows the cloud immediately after preparation in the molasses. For subsequent frames the free evolution time was increased in steps of 2.5 ms. We are able to remove the extraneous scattered light from the early pictures by subtracting an image taken without filling the MOT. Once the cloud has reached the pinch coil (70 ms), we adopt our more usual method of subtracting an image taken with the pinch coil off.

4. Distinguishing the magnetic sublevels

Figure 2 shows the number of reflected atoms, measured as a function of the magnetic field at the centre of the pinch coil. At the lowest fields we see that there is no reflection. At approximately 33 G there is a sharp rise in the signal, due to the reflection of the $m_F = 3$ atoms. From previous measurements [3], we know that such steps are well characterized by the integral of a Gaussian distribution, i.e. by the error function. We therefore fit this step to the form $\text{erf}[(B - B_3)/w_3]$, in which the centre is $B_3 = 33$ G and the width is $w_3 = 2.7$ G. Since the centre of the pinch coil is 25 mm below the MOT, we might expect this step to occur at 37 Gauss (i.e. at $mgh/\mu_B$), but in fact it lies a little lower because part of the gravitational energy is converted into transverse motion by reflections in the magnetic funnel [3]. The width of the step is due both to the spread in this transverse heating and to the distribution of initial heights because of the finite (∼1 mm) size of the initial cloud. At higher fields we see second and third steps, due to the onset of reflections for the $m_F = 2$ and $m_F = 1$ atoms. Within the experimental uncertainty these are centred on $\frac{3}{2}B_3$ and $3B_3$, and are similarly wider, as one would expect from the ratios of the magnetic moments in these sublevels. The full curve in figure 2 is a sum of erf functions fitted to the data.
Figure 2. Relative number of atoms recaptured after reflection from the pinch coil, plotted against the field at the centre of the pinch coil. The three steps are due to the three magnetic sublevels $m_F = 3, 2$ and 1 of the $^{85}$Rb ground state $F = 3$. The points show the experimental data and the curve is a phenomenological fit to the data.

5. Step heights and coupling efficiency

The heights of the steps are in the ratio 11:8:5. At first thought one might have expected a ratio of 1:1:1 on the grounds that the magnetic sublevels are equally populated in the optical molasses. However one must take into account the possibility that different $m_F$ states may suffer different losses while propagating in the guide and could be coupled into the guide with different efficiencies.

In order to take the propagation losses into account, we drop atoms into the guide and hold them there by turning on a second pinch coil located at the top of the fibre. They are then held in this Ioffe trap for a variable length of time before being released and detected. A full description of these experiments is in preparation [20]. These measurements show that the decay time in the guide is about 600 ms, due to collisions with the background gas. Consequently, the atom numbers presented in figure 2 are attenuated by only about 10% as a result of the time spent propagating in the guide. Moreover, we have no reason to think that this pressure loss would depend on $m_F$. We therefore conclude that it has no influence on the ratio of step heights in figure 2.

Turning now to the question of coupling efficiency, we set the pinch coil field to 45 G, in the centre of the first plateau of figure 2. The reflected $F = 3, m_F = 3$ atom signal is then measured as function of the current in the guide/funnel with the result shown in figure 3. At a low current the funnel potential provides insufficient confinement to guide the atoms into the hole. At a large current, the hole becomes energetically inaccessible except very close to the axis. However, most of the atoms are excluded from that region by angular momentum conservation and therefore mill around inside the magnetic funnel. Thus we expect to find an optimum coupling when the
Figure 3. Fraction of $m_F = 3$ atoms coupled into the guide against the current in the guide/funnel. The points show the experimental data and the curve is a phenomenological fit to the data. At the peak of this curve, the $F = 3, m_F = 3$ atoms are coupled into the guide with approximately 11% efficiency.

energetically allowed aperture is comparable with the physical opening of the guide. We see in figure 3 that there is an optimum and we know from the measurements reported in [3] that it corresponds to coupling approximately 11% of the $F = 3, m_F = 3$ atoms into the guide. This optimum occurs at 4.7 A, which is the current we used to take the data in figure 2. Let us call this $I_0$.

For the coupling of $m_F = 2$ atoms we make the reasonable assumption that their motion in the magnetic field of a current $I_0$ is the same as $m_F = 3$ atoms near a current of $2I_0/3$. Similarly for $m_F = 1$, the equivalent current is $I_0/3$. Indeed, if $I_0$ were the only source of magnetic field in the experiment, this scaling would be exact since the linear Zeeman interaction would then be proportional to the product $m_F I$. In this approximation, the curve of figure 3 implies that the coupling efficiencies for $m_F = 3, 2$ and 1 are in the ratio 11:7:2. On dividing the step heights of figure 2 by these relative coupling efficiencies, we deduce that the initial populations of the $m_F = 3, 2$ and 1 sublevels are in the ratio 1:1.1:2.5. This apparent preference for lower values of $|m_F|$ is a surprising result, because optical molasses, although locally very inhomogeneous, is intended to be isotropic on average. We therefore checked to see if the pinch coil current or the bias field current had any significant effect on the coupling efficiency, which would invalidate our $m_F$ scaling argument. No substantial effect was found and we are therefore forced to conclude that the sublevels may not have been equally populated, even though our atom cloud was seen to expand spherically in the molasses.

6. Conclusion

We have demonstrated that a cloud of cold atoms can be coupled by a magnetic funnel into the small aperture of a miniature magnetic waveguide and we have investigated how the efficiency of this coupling is affected by the strength of the field. We have shown that atoms can be made to propagate in the guide and that a simple, normal-incidence Stern–Gerlach experiment can...
distinguish atoms in different magnetic sublevels. These measurements seem to suggest that the atoms prepared in our molasses have a preference for smaller values of $|m_F|$. The motion of the atoms is captured most graphically by a movie. In the future we aim to reduce the dimensions of the fibre to reach the regime where the de Broglie waves propagate in a single transverse mode of the structure. For a discussion of the feasibility of this and of the relative merits of various guides we refer the reader to sections I and VII of [12] and to section 3 of [16].

Acknowledgments

We are indebted to D Richardson and P Kazansky of the Southampton Optoelectronics Research Centre for providing the guiding fibre and to B E Sauer and I G Hughes for many valuable discussions. This work was supported by the European Union and by the EPSRC.

References

[1] Fortagh J, Grossman A, Zimmerman C and Haensch T W 1998 Phys. Rev. Lett. 81 5310
[2] Denschlag J, Cassetari D and Schmiedmayer J 1999 Phys. Rev. Lett. 82 2014
[3] Key M, Hughes I G, Rooijakkers W, Sauer B E, Hinds E A, Richardson D J and Kazansky P G 2000 Phys. Rev. Lett. 84 1371
[4] Reichel J, Hansel W and Hansch T W 1999 Phys. Rev. Lett. 83 3398
[5] Müller D, Anderson D Z, Grow R J, Schwindt P D D and Cornell E A 1999 Phys. Rev. Lett. 83 5194
[6] Müller D, Cornell E A, Prevedelli M, Schwindt P D D, Zozulya A and Anderson D Z 2000 arXiv:physics/0003091
[7] Dekker N H, Lee C S, Lorent V, Thywissen J H, Smith S P, Drndic M, Westervelt R M and Prentiss M 2000 Phys. Rev. Lett. 84 1124
[8] Folman R, Kruger P, Cassetteri D, Hessmo B, Maier T and Schmiedmayer J 2000 Phys. Rev. Lett. 84 4749
[9] Rosenbusch P, Hall B V, Hughes I G, Saba C V and Hinds E A 2000 Phys. Rev. A 61 R31 404
[10] Rosenbusch P, Hall B V, Hughes I G, Saba C V and Hinds E A 2000 Appl. Phys. B 61 709
[11] Weinstein J D and Libbrecht K G 1995 Phys. Rev. A 52 4004
[12] Hinds E A and Eberlein C 2000 Phys. Rev. A 61 33 614
[13] Hinds E A, Boshier M G and Hughes I G 1998 Phys. Rev. Lett. 80 645
[14] Andrews M R, Townsend C G, Miesner H-J, Durfee D S, Kurn D M and Ketterle W 1997 Science 275 637
[15] Lenef A, Hammond T D, Smith E T, Chapman M S, Rubenstein R A and Pritchard D E 1997 Phys. Rev. Lett. 78 760
[16] Gustavson T L, Bouyer P and Kasevich M A 1997 Phys. Rev. Lett. 78 2046
[17] Hinds E A and Hughes I G 1999 J. Phys. D: Appl. Phys. 32 R119 (and references therein)
[18] Olshanii M 1998 Phys. Rev. Lett. 81 938
[19] Monien H, Linn M and Elstner N 1998 Phys. Rev. A 58 R3395
[20] Roach T M, Abele H, Boshier M G, Grossmann H L, Zetie K P and Hinds E A 1995 Phys. Rev. Lett. 75 629
[21] Saba C V, Barton P A, Boshier M G, Hughes I G, Rosenbusch P, Sauer B E and Hinds E A 1999 Phys. Rev. Lett. 82 468
[22] Key M, Rooijakkers W, Jones M P A, Vale C and Hinds E A, to be published