Magnetic waveguide for trapping cold atom gases in two dimensions

Article (Published Version)

PHYSICAL REVIEW
LETTERS

VOLUME 80 26 JANUARY 1998 NUMBER 4

Magnetic Waveguide for Trapping Cold Atom Gases in Two Dimensions

E. A. Hinds, M. G. Boshier, and I. G. Hughes
Sussex Centre for Optical and Atomic Physics, University of Sussex, Brighton, BN1 9QH, United Kingdom
(Received 28 August 1997)

We have devised a way to trap atoms above a magnetic surface using the Zeeman effect. The method is generally applicable to any paramagnetic atom with hyperfine structure and results in very strong confinement and, hence, a high vibrational frequency perpendicular to the surface. This allows the atomic de Broglie wave to propagate as in a single-mode 2D waveguide. We show how atoms can be continuously and unidirectionally coupled with high efficiency into the lowest mode of the waveguide. This invention makes possible the study of weakly interacting gases in 2D. [S0031-9007(97)05101-6]

PACS numbers: 03.75.Be, 32.80.Pj, 32.80.Lg, 39.10.+j

Advances in laser cooling have given birth to the fields of atom optics [1] and Bose-Einstein condensation in alkali atom vapors [2]. Before condensation, the atoms are weakly confined in all three dimensions ($kT \gg \hbar\omega$). In contrast, this Letter describes a new technique to constrain the atomic de Broglie wave strongly in one dimension, leaving it able to propagate in the other two. Atoms much colder than the transverse mode spacing of the waveguide have no freedom for dynamics in the transverse direction and constitute a weakly interacting 2D gas. The physics of low dimensional structures has proved in condensed matter to be particularly rich, but, so far, the limit of weakly interacting gas offered by atomic vapor has not been accessible in the laboratory except in 3D.

As in conventional optics, atoms confined to a waveguide can be transported without suffering a loss from beam divergence. Moreover, a horizontal waveguide can prevent atoms from falling quickly out of the apparatus under gravity, while allowing them to be accelerated, if so desired, by tilting the plane of the waveguide. Our waveguide might also be used to produce a continuous laserlike source of matter waves [3] because bosonic atoms coupled into the waveguide by a spontaneous transition favor decay into the most occupied mode. This kind of atom laser is not expected to work with a 3D trap because absorption of the spontaneously emitted radiation hinders the formation of a degenerate gas [4].

The 2D waveguide is also a promising system in which to study the physics of cold gases. One expects the critical exponents of phase transitions to depend on the dimensionality and, in addition, one may hope to find new phenomena which do not occur at all in 3D. At present, all experimental information on such 2D effects comes from dense systems in condensed matter physics where one cannot clearly separate the roles of quantum statistics and particle interactions. By contrast, a degenerate 2D gas of cold neutral atoms would be very weakly interacting and could be used to probe the most basic aspects of the theory [5], as are atomic Bose-Einstein condensates in 3D traps [6]. Moreover, it is possible that the atom-atom interaction cross section can be varied by the addition of external fields in order to study the role of interactions [7].

These possibilities have generated considerable interest in the idea of a waveguide for atoms [8]. Desbiolles and Dalibard [9] have discussed the possibility of forming a 2D gas in a two-color optical dipole force trap [10], and Renn *et al.* [11,12] have used hollow optical fibers to demonstrate multimode cylindrical guides also based on the optical dipole force. The smallest natural length scale a of an optical dipole force waveguide is set by the wavelength of the confining light, so the mode spacing ($\sim h/2Ma^2$) for an atom of mass M is rather small, not more than 10 kHz, corresponding to an energy of 500 nK. Since this energy interval is considerably lower than the

0031-9007/98/80(4)/645(5)$15.00

temperature of most atomic sources, these waveguides are more suited to multimode operation, and even if coupling into a single mode is achieved, interactions between the forward and the transverse motions will subsequently excite a range of transverse modes. The mode spacing can usually be made larger by increasing the intensity of the confining light, but only at the expense of an increase in the spontaneous emission rate which heats and dephases the de Broglie waves. Despite these difficulties, a number of laboratories are attempting to realize a 2D atom waveguide based on the optical dipole force, and considerable progress has been made in this direction [13,14].

We present a waveguide based on static magnetic forces alone [15], which induce no spontaneous emission and produce tight confinement with a correspondingly large mode spacing of ~ 1 MHz. We call this device a Zeeman effect surface trap (ZEST). This Letter shows how a single mode of such a waveguide can be loaded continuously and with good efficiency from a conventional slow atom source.

The magnetic field of the waveguide is provided by a surface whose magnetization varies with position as $\sin(2\pi x/\lambda)$. At a distance z above the surface, the magnitude of the field is $B_{\max}\exp(-2\pi z/\lambda)$ [16]. Such surfaces have been developed recently for reflecting and focusing slow atomic beams through the Zeeman interaction, which is able to retroreflect atoms dropped from heights of many centimeters [17–21]. Here, we show how the Zeeman shift in sublevel $F = 3, m_F = -2$, labeled f in Fig. 1, can be used to trap ^{85}Rb atoms in the direction normal to the mirror. The principle applies to a wide range of atoms, but, in order to present a specific and fully developed analysis, we focus here on the ^{85}Rb atom for which the ground state hyperfine splitting is $\Delta\nu = 3036$ MHz and the nuclear spin is $5/2$.

The main part of Fig. 1 illustrates the energies of sublevels i and f versus distance for a magnetized surface with $\lambda = 1$ μm and $B_{\max} = 2$ kG. The magnetic binding energy for an atom in state f has its minimum at $B_0 = \Delta\nu/3\mu_B = 723$ G. The "bond length," i.e., the equilibrium position $(\lambda/2\pi)\ln(B_{\max}/B_0)$, is 162 nm from the surface for our particular values. The binding energy is given by $(3 - \sqrt{5})h\Delta\nu/6$ and has the value 1.6 μeV or 19 mK or 386 MHz. This is very deep compared with optical dipole force traps and compared with the 1–10 μK thermal energy of laser-cooled atomic clouds, although it is extremely weak in comparison with ordinary physisorption and with molecular binding. The quantized vibration of an atom in this trap has a minimum width of 9 nm, proportional to $\lambda^{1/2}(\Delta\nu M)^{-1/4}$ and independent of $B_{\max}$. The spacing of low-lying vibrational levels in this potential is proportional to $(\Delta\nu/M)^{1/2}\lambda^{-1}$ and, in this example, equals 2 MHz (100 μK). Considering the potential to be a planar waveguide for atomic de Broglie waves, this is also the spacing of low-order modes.

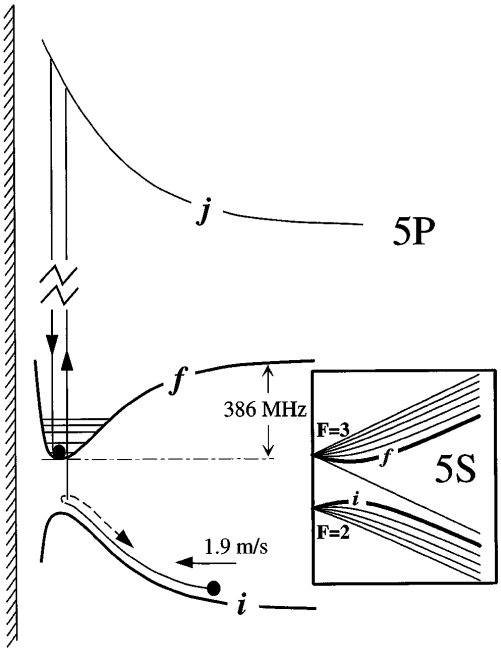

FIG. 1. Inset: the Breit-Rabi diagram for ^{85}Rb, showing the Zeeman shifts of the ground state hyperfine levels drawn to scale. The bold lines show the initial state i of the atoms to be loaded into the waveguide and the final trapped state f. Main diagram (not to scale): Atoms in state i are projected toward the magnetized surface and come to rest at the position of minimum energy for state f, 162 nm from the surface. A laser field couples states i and j, coming into resonance only over a narrow band of positions close to the turning point. The excited atoms decay spontaneously into the trapped state f with a high probability of going into the lowest vibrational mode.

The method of coupling atoms into this waveguide is also illustrated in Fig. 1. A conventional cold source, e.g., optical molasses [22], fires atoms vertically towards the horizontal magnetic surface at approximately 1.9 m/s. On the way, they are optically pumped into the state $i \equiv (F = 2, m_F = -2)$. This velocity is chosen so that the atoms come to rest at the maximum of the potential curve, where the energy of state f is a minimum. Here, the Zeeman shift brings the atoms into resonance with a cw laser beam which excites state j $(5P_{3/2}, m_J = 3/2, m_I = -5/2)$. We have calculated that, in field B_0, this state decays spontaneously back to i with 48% probability and into the bound state f with 52% probability, so, after a small number of excitations, the atoms are all pumped into the waveguide. The region of resonance is only a few nanometers wide because of the strong field gradient $(2\pi B_0/\lambda = 4.5$ G/nm) and this allows us to introduce atoms into the waveguide in a well-defined region determined by our choice of laser frequency. In particular, it is possible to achieve high coupling efficiency into the $v = 0$ ground state of the waveguide because the width of that state is also a few nanometers. The photons scattered during the loading process do not

cause significant heating of atoms that are already trapped in the waveguide because of the 2D geometry [4].

To estimate the loading efficiency, we have solved the Schrödinger equation for a minimum-uncertainty wave packet initially traveling towards the mirror at 1.9 m/s in state i. The width of the packet is chosen to be 100 nm—corresponding approximately to the single-photon recoil momentum. The laser field of frequency ω_0 couples states i and j resonantly at 723 G, and state j is allowed to decay outside the i, j system at rate γ. After making the rotating wave approximation and writing the two-component wave function as $\psi(z,t) = (\psi_i, e^{-i\omega_0 t}\psi_j)$, the center-of-mass motion is described by [23]

$$i\hbar \frac{\partial}{\partial t}\begin{pmatrix}\psi_i \\ \psi_j\end{pmatrix} = \begin{pmatrix} T + U_i & V \\ V & T + U_j - \hbar\omega_0 - \frac{1}{2}i\hbar\gamma \end{pmatrix} \times \begin{pmatrix}\psi_i \\ \psi_j\end{pmatrix}, \quad (1)$$

where T is the kinetic energy operator $-(\hbar^2/2m)(\partial^2/\partial z^2)$, U_i and U_j are the potentials shown in Fig. 1, and V is the transition matrix element.

Figure 2(a) shows the density $|\psi_i|^2$ of the incoming wave packet as it approaches the surface, interacts with the laser light (V/h is 23 MHz), and then recedes greatly attenuated. In Fig. 2(b), we plot the very narrow excited state wave packet $|\psi_j|^2$ as a function of time. Spontaneous decay out of this state fills the nth mode of the waveguide at a rate which we take to be $R_n(t) = \gamma|\langle u_j(t)|u_f(v = n)\rangle|^2$ in the usual Franck-Condon approximation, where u signifies the spatial part of the excited wave function and the trapped states $u_f(v = n)$ are found by numerical integration. The final state populations P_n are obtained by integrating $R_n(t)$. Figure 3 shows how the population of the fundamental waveguide mode P_0 varies with the initial velocity of the wave packet and illustrates the optimum mode-matching at 1.92 m/s, where the incident wave packet comes to rest just at the minimum of the state f potential. In a real experiment, the thermal distribution of initial velocities would typically be 0.05 m/s, corresponding to ten times the single-photon recoil velocity. The coupling does not vary greatly over this range, and we conclude that it is possible to achieve continuous coupling into the fundamental mode with an efficiency exceeding 10%. Alternatively, if the waveguide is to be loaded in a single pulse, a second laser can be used to drive the i-j-f Raman transition, and its frequency can be tuned to favor any desired waveguide mode. The disadvantage of this stimulated loading scheme is that atoms already in the trap would be coupled out.

The principal approximation in our calculation is that we have not taken into account spontaneous decays from state j back into state i. This requires integration of

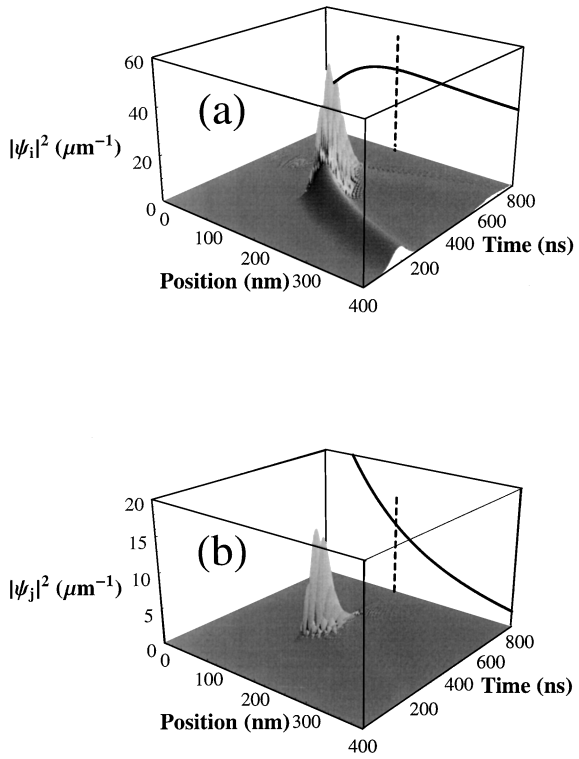

FIG. 2. (a) Calculated probability density for the incoming wave packet in state i. After coming into resonance with the laser field, the reflected packet is reduced greatly because half of the atoms are excited to state j. The potential U_i is shown in the background together with the position of resonant coupling, chosen to be at the center of the waveguide. (b) Calculated evolution of probability density in the excited state j. The packet is narrow in the z direction because the Zeeman shift depends strongly on the distance from the surface, restricting resonant excitation to a narrow range. The appearance of the excited atoms coincides with the arrival of the incident packet at the resonant region and its disappearance is due to decay back to the ground state.

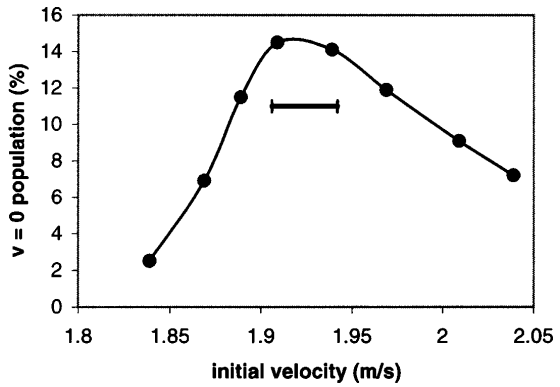

FIG. 3. Efficiency for coupling atoms into the lowest mode of the waveguide versus the initial velocity of the incident atoms with $V/h = 23$ MHz. The 15% peak efficiency occurs when the incident wave packet comes to rest just at the minimum of the state f potential. For comparison, we show the velocity spread of a 20 μK cold Rb atom source.

the density matrix master equation, or, equivalently, a Monte Carlo treatment of the Schrödinger equation, and is currently in progress in our group. Although the fuller treatment will give a more precise result for the coupling efficiency into the waveguide, it will not change our main conclusion: First, nearly all of the atoms are transferred to the waveguide when the optical excitation is optimized; second, a substantial fraction goes into the lowest mode because its width is comparable with that of the resonance region.

A simple way to detect whether atoms are trapped in the waveguide is to illuminate it with light tuned to the f-j transition: The atoms are then pumped into state i and jump off of the surface with a velocity of 1.9 m/s. With a natural width of 6 MHz, the production spectrum of liberated atoms would not quite resolve the 2 MHz mode spacing, but it would provide an excellent diagnostic tool for the state of the atoms in the waveguide.

Once a gas is trapped in the waveguide, one could investigate the van der Waals interaction $-C_3/z^3$ (C_3 is expected to be of order 1 kHz μm^3) by its effect on the inner wall of the trapping potential and, hence, on the spectrum of waveguide modes. This effect, due to the interaction between the atomic dipole and its electrostatic image in the magnetic surface, is negligible for our parameter, but becomes significant when $B_{\max}$ is reduced below 1 kG. So far, the van der Waals interaction between an atom and a surface has been studied in atoms moving transiently above the surface [24–26] or in physisorption where the van der Waals attraction is balanced by short-range exchange forces. Now it becomes possible to study bound states in which the van der Waals force is in equilibrium with a well-characterized magnetic interaction.

Because of the way the surface is magnetized, the direction $\hat{\mathbf{n}}$ of the magnetic field varies with position x according to $\hat{\mathbf{n}} = \cos(2\pi x/\lambda)\hat{\mathbf{z}} + \sin(2\pi x/\lambda)\hat{\mathbf{x}}$, imposing an adiabatic spin rotation on the gas as it propagates through the waveguide in the x direction but not in the y direction. The associated geometric phase causes an unusual anisotropy in the quantum propagation of the gas whose consequences we are currently investigating. The study of 2D gas in the waveguide is not restricted to traveling waves; with a curved magnetic substrate, a depth of 1 mm is sufficient to contain ^{85}Rb up to 14 cm/s, speeds much greater than we would expect. In the confined 2D gas, it would be very interesting to increase the phase space density to the point where the de Broglie wavelength is comparable with the interatomic spacing and quantum statistical effects become important. It is not known at what point relaxation will limit the density of the 2D gas but the strongest loss mechanism is expected to be spin exchange, in which two $F = 3$, $m_F = -2$ atoms collide and emerge in the states $F = 3$, $m_F = -1, -3$. The cross section for this process at 723 G has not been calculated [27]. It will also be possible to contour the waveguide, either physically or by recording a suitable magnetic pattern, so that the 723 G surface has channels, making a kind of "printed circuit" with paths along which the atoms must flow if they are slow enough.

This new technique is broadly applicable to paramagnetic atoms with hyperfine structure. Heavier atoms, which have larger hyperfine interactions, require a stronger waveguide field B_0, but the mode spacing is relatively constant because the relevant factor $\sqrt{\Delta\nu/M}$ is approximately constant throughout the periodic table. Among the alkali metals, the smallest mode spacing is 0.6 MHz for ^{41}K and the largest is 3.4 MHz for ^{133}Cs (taking $\lambda = 1$ μm). Correspondingly, the width of the lowest waveguide mode varies only by a factor of 5, from a maximum of 24 nm for ^{7}Li to a minimum of 5 nm for ^{133}Cs.

In this Letter, we have presented a new kind of waveguide for use in atom optics which is based on magnetic interactions with a surface. The large mode spacing will make it possible to propagate de Broglie waves in a single mode of this waveguide at substantial velocities without scattering into other modes. We have shown how atoms from a standard cold source can be coupled with high efficiency into the lowest mode of the waveguide by taking advantage of the position-dependent Zeeman shift, and we have demonstrated this explicitly by a model wave packet calculation. The 2D gas produced in this way opens up a new area of study for atom optics and for the physics of cold gases.

We are indebted to R. L. Cardiff for assistance with the computer simulation, to B. M. Garraway for discussions about wave packets, and to the U.K. Engineering and Physical Sciences Research Council for funding this work.

[1] Special Issue on Atom Optics, edited by E. Arimondo and H.-A. Bachor [Quantum Semiclass. Opt. **8**, 495 (1996)].
[2] M. H. Anderson *et al.*, Science **269**, 198 (1995); C. C. Bradley, C. A. Sacket, J. J. Tollet, and R. G. Hulet, Phys. Rev. Lett. **75**, 1687 (1995); K. B. Davis *et al.*, Phys. Rev. Lett. **75**, 3969 (1995).
[3] R. J. C. Spreeuw, T. Pfau, U. Janicke, and M. Wilkens, Europhys. Lett. **32**, 469 (1995).
[4] T. Pfau and J. Mlynek, OSA Trends Opt. Photon. **7**, 33 (1997).
[5] V. Bagnato and D. Kleppner, Phys. Rev. A **44**, 7439 (1991).
[6] K. Burnett, Contemp. Phys. **37**, 1 (1996).
[7] P. O. Fedichev, Yu Kagan, G. V. Shlyapnikov, and J. T. M. Walraven, Phys. Rev. Lett. **77**, 2913 (1996).
[8] J. P. Dowling and J. Gea-Banacloche, Adv. At. Mol. Opt. Phys. **37**, 1 (1996).
[9] P. Desbiolles and J. Dalibard, Opt. Commun. **132**, 540 (1996).
[10] Yu. B. Ovchinnikov, S. V. Shul'ga, and V. I. Balykin, J. Phys. B. **24**, 3173 (1991).

[11] M. J. Renn *et al.*, Phys. Rev. Lett. **75**, 3253 (1995).
[12] M. J. Renn *et al.*, Phys. Rev. A **53**, R648 (1996).
[13] H. Gauck, D. Schneble, M. Hartl, and T. Pfau (to be published).
[14] Yu. B. Ovchinnikov, I. Manek, and R. Grimm, Phys. Rev. Lett. **79**, 2225 (1997).
[15] The idea was first suggested in I. G. Hughes, P. A. Barton, M. G. Boshier, and E. A. Hinds, SPIE Proc. **2995**, 182 (1997).
[16] G. I. Opat, S. J. Wark, and A. Cimmino, Appl. Phys. B **54**, 396 (1992).
[17] T. M. Roach *et al.*, Phys. Rev. Lett. **75**, 629 (1995).
[18] A. I. Sidorov *et al.*, Quantum Semiclass. Opt. **8**, 713 (1996).
[19] W. G. Kaenders *et al.*, Phys. Rev. A **54**, 5067 (1996).
[20] I. G. Hughes *et al.*, J. Phys. B **30**, 647 (1997).
[21] I. G. Hughes, P. A. Barton, T. M. Roach, and E. A. Hinds, J. Phys. B. **30**, 2119 (1997).
[22] P. D. Lett *et al.*, J. Opt. Soc. Am. B **6**, 2084 (1989).
[23] B. M. Garraway and K. A. Suominen, Rep. Prog. Phys. **58**, 365 (1995).
[24] V. Sandoghdar, C. I. Sukenik, E. A. Hinds, and S. Haroche, Phys. Rev. Lett. **68**, 3432 (1992).
[25] M. Oria *et al.*, Europhys. Lett. **14**, 527 (1991).
[26] A. Landragin *et al.*, Phys. Rev. Lett. **77**, 1464 (1996).
[27] An unpublished 3D calculation by F. Abeelen and B. Verhaar shows that, in 3D, this cross section has no particular suppression.