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
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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]
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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 wave-
guide 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 wave-
guide 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
($\sim \hbar / 2Ma^2$) 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
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 \(\sim 1\) 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 \(s\sin(2\pi x/\lambda)\). At a distance \(z\) above the surface, the magnitude of the field is \(B_{\text{max}}\exp(-2\pi z/\lambda)\) [16]. Such surfaces have been developed recently for 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 \(^{85}\text{Rb}\) 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 \(^{85}\text{Rb}\) 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 \(\lambda = 1\) \(\mu\)m and \(B_{\text{max}} = 2\) 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 \((\lambda/2\pi)\ln(B_{\text{max}}/B_0)\), 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 \(1.6 \mu\)eV or \(19\) mK or 386 MHz. This is very deep compared with optical dipole force traps and compared with the \(1\)–\(10\) \(\mu\)K 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 \(B_{\text{max}}\). 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 \(\mu\)K). Considering the potential to be a planar waveguide for atomic de Broglie waves, this is also the spacing of low-order modes.

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 \(i = (F = 2, m_F = -2)\). 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 \(\nu = 0\) 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

![Figure 1](image-url)
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 $\omega_0$ couples states $i$ and $j$ resonantly at 723 G, and state $j$ is allowed to decay outside the $i,j$ system at rate $\gamma$. 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]

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

(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 $|\psi_j|^2$ of the incoming wave packet as it approaches the surface, interacts with the laser light ($V/\hbar$ 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 $n$th 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 $u_j(v=n)$ 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
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 $f\rightarrow j$ 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 $-C_3/\ell^3$ ($C_3$ is expected to be of order $1$ kHz $\mu$m$^3$) 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 $B_{\text{max}}$ 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 $\hat{n}$ of the magnetic field varies with position $x$ according to $\hat{n} = \cos(2\pi x/\Lambda)\hat{z} + \sin(2\pi x/\Lambda)\hat{x}$, 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 $\lambda = 1$ $\mu$m). 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.

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[27] An unpublished 3D calculation by F. Abeelen and B. Verhaar shows that, in 3D, this cross section has no particular suppression.