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A ring trap for ultracold atoms in an RF-dressed state

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Abstract. We combine an RF-dressed magnetic trap with an optical potential to produce a toroidal trapping potential for ultracold ^{87}Rb atoms. We load atoms into this ring trap from a conventional magnetic trap and compare the measured oscillation frequencies with theoretical predictions. This method of making a toroidal trap gives a high degree of flexibility such as a tuneable radius and variable transverse oscillation frequency. The ring trap is ideal for the creation of a multiply connected Bose–Einstein condensate (BEC) and the study of persistent flow and we propose a scheme for introducing a flow of the atoms around the ring.

Contents

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1. Introduction

The application of radio frequency (RF) radiation to atoms in a static magnetic trap with the aim of modifying its potential landscape was first proposed by Zobay and Garraway [1] in 2001. The RF radiation mixes the magnetic sub-states and in the combined oscillating and static magnetic fields the eigenstates of the atoms are so-called dressed states; the variation of the eigenenergies of those dressed states with position gives rise to the adiabatic trapping potential. The resultant potentials offer many advantages over purely magnetostatic traps; in particular, novel and flexible trapping potentials may be formed, with the ability to morph smoothly between different trapping geometries. Examples of possible trapping potentials include a double-well potential with a variable well spacing and a ring trap with a precisely controllable radius.

The principle of trapping atoms in RF-modified magnetic potentials was confirmed in an experiment by Colombe *et al* [2]; they showed that atoms can be trapped for many seconds in a superposition of the Zeeman states, and that such superpositions which are the eigenstates of the combined static and RF magnetic fields, are not destroyed by collisions. They also demonstrated the importance of developing a suitable loading scheme to adiabatically transfer atoms into the trap from the starting conditions which are usually atoms in a conventional magnetic trap. More recently, the RF-modification of a very strong magnetic trap (created by trapping atoms very close to the current-carrying wires on an atom chip) was used to coherently split a Bose–Einstein condensate (BEC) with very little heating during the change from a single- to a double-well potential [3]. This recent work has highlighted the importance of considering the spatial variation in the strength of the atomic interaction with the RF; this arises due to the variation in the relative orientation of the static and RF-fields and warrants a vector treatment rather than a scalar one.

We present experimental results for a ring trap with a radius tuneable over the range 0–85 μm. Our quantitative measurements of the oscillation frequency of trapped rubidium atoms can be explained by the theory of Zobay and Garraway. We have also operated our apparatus in a similar regime to that in [3] where a significant change is made to the magneto-static potential by applying an RF field whose magnitude is comparable to the static field and hence cannot realistically be considered as a perturbation. One aspect of this is that the usual rotating-wave approximation is not valid, but in addition for our particular geometry the trap becomes identical to a time-orbiting potential (TOP) [4] trap when the RF field is strong and has a frequency well below the Larmor precession frequency (which is comparable with the resonance frequency for transition between the Zeeman states). While traps that operate beyond the rotating-wave approximation have been studied [5], to our knowledge, the crossover between the regimes of an RF-modified magneto-static potential and a time-averaged magnetic potential has not yet been studied. In our experiment, the toroidal trapping potential arises from RF-modification of a cylindrically symmetric quadrupole with its axis vertical so that atoms can flow around the ring [6]. An alternative method was proposed in [7] which creates a toroidal geometry by applying appropriately polarized RF radiation to modify an Ioffe trap. This scheme was realized in [8], but because the ring-shaped potential lay in the vertical plane, gravity caused the atoms to gather at the bottom of the circular tube.

Ring traps in the form of toroidal waveguides for ultracold atoms have previously been experimentally made in a variety of ways [9]–[12] and are of great interest for high-precision rotation sensors where a large ring radius >1 mm is advantageous. For the study of persistent currents, however, where we require a multiply connected BEC, a smaller ring radius such as that available in our trap, is more desirable. Persistent flow has a direct analogue to a persistent current in a superconducting system; is important in terms of probing the superfluid and coherence properties of a system; and its study is a long-standing goal of the BEC research community [13]. Another advantage of our ring trap over a circular waveguide is the easily tuneable radius. The magnetic and optical fields required for our trap are straightforward to realize and are less sensitive to misalignment than, for example, the plugging of a quadrupole trap with a focused laser beam since our RF trap will raise the potential at the centre of the quadrupole trap without any alignment.

In addition to the experiments reported in [2, 3, 8, 14], there has recently been a considerable amount of experimental activity in which RF-dressed potentials have been used. White *et al* [15] looked at the spin composition of dressed states and were able to determine the Rabi frequencies involving transitions between magnetically trapped and magnetically untrapped states to within 2% and experiments by Jo *et al* [16] demonstrated number squeezing in an RF-induced double-well potential on an atom chip. The scheme for making a time-averaged adiabatic potential (TAAP) starting with an RF-modified magnetic potential described in [17] would allow us to create a purely magnetic toroidal potential with our apparatus, however, this would reduce the strength of confinement of the atoms and it is not clear how one could load such a trap without the use of our current toroidal potential as an intermediate stage—to be practical one requires a method of adiabatically reaching the trapped states from a more conventional trap. Loading may also be a drawback for several schemes that explore the novel trap geometries that can be realized with the new degree of freedom that adiabatically coupled sub-states afford [18]–[20]. Applying a second RF-field to implement evaporative cooling of clouds of atoms in the RF-modified potential has been proposed and used [8, 21]; this could be used as a final stage in the preparation of quantum degenerate gases.

2. Theory

The quadrupole field, produced by a pair of coils in an anti-Helmholtz configuration, is $\mathbf{B} = \frac{1}{2}B_Q'(x\hat{\mathbf{e}}_\mathbf{x} + y\hat{\mathbf{e}}_\mathbf{y} - 2z\hat{\mathbf{e}}_\mathbf{z})$ where B_Q' is the axial magnetic field gradient. The trapping potential from this field affords one of the simplest magnetic trapping potentials, however, cold atoms have a short lifetime in such a trap because of Majorana transitions at the centre where the atoms experience zero magnetic field [4]. For atoms that are confined to move in a plane of fixed $z = z_0 \neq 0$ (in this experiment the confinement is achieved with an optical dipole trap), the radial trapping potential experienced by the atoms is of the Ioffe form

$$U \propto B_0^{\mathrm{DC}} \sqrt{1 + \frac{x^2 + y^2}{4z_0^2}}, \tag{1}$$

where $B_0^{\mathrm{DC}} = -B_Q' z_0$ is equivalent to the bias field in a standard Ioffe trap. This configuration does not suffer the losses in the region close to where $B = 0$ and we shall refer to such a trap as a *biased quadrupole trap*, see figure 1. We consider next the effect on the above trapping geometry of applying a rapidly oscillating, perturbing magnetic field in the radial plane.

For a two-level atomic system, the dressed state Hamiltonian is [22]

$$\mathcal{H}_2 = \frac{1}{2}\begin{pmatrix} \delta & \Omega \\ \Omega^* & -\delta \end{pmatrix}, \tag{2}$$

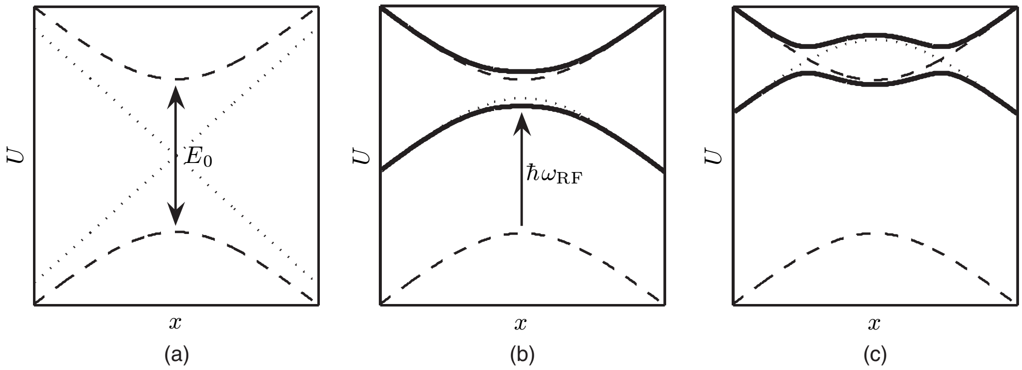


Figure 1. The dressed atom picture for the orientation-dependent and detuning-dependent regimes. (a) Applying a bias field to a quadrupole potential (dotted lines) produces a biased quadrupole potential (dashed lines), which leads to an energy gap of $E_0 = g_F \mu_B B_0^{DC}$ between the adjacent levels at the centre of the trap. (b) In the dressed-atom picture we consider the lower level of the biased quadrupole (dashed line) plus one unit of radiation from the oscillating field (dotted line). The RF radiation mixes the two levels and causes them to move apart (solid line). Here, $\hbar\omega_{RF} < E_0$, whereas in (c) the case for $\hbar\omega_{RF} > E_0$ is shown. The repulsion of the levels leads to avoided crossings where the two (dashed line) levels meet, creating a 'W-' or 'M-shaped' potential. This figure only considers two levels to illustrate the principle clearly, but the situation for a three or more level atom reduces to the same picture.

which has eigenenergies $\pm\frac{1}{2}\hbar\sqrt{\delta^2 + |\Omega|^2}$, where δ is the detuning from resonance, $\delta = \omega_{RF} - \omega_0$ and the frequency difference between the two levels is

$$\omega_0 = \frac{E_2}{\hbar} - \frac{E_1}{\hbar} = \frac{E_0}{\hbar}. \tag{3}$$

The magnitude of the two-level Rabi frequency is $|\Omega| = (\frac{1}{2} g_F \mu_B) B_\perp$, where $B_\perp$ is the component of the RF-field perpendicular to the static magnetic field.

In a three-level system, such as the $F = 1$ manifold of ^{87}Rb, the Rabi frequencies between the adjacent levels are equal: $\Omega_{12} = \Omega_{23} = \sqrt{2}\Omega$ and so the resulting Hamiltonian is

$$\mathcal{H}_3 = \begin{pmatrix} \delta & \frac{1}{\sqrt{2}}\Omega & 0 \\ \frac{1}{\sqrt{2}}\Omega^* & 0 & \frac{1}{\sqrt{2}}\Omega \\ 0 & \frac{1}{\sqrt{2}}\Omega^* & -\delta \end{pmatrix}, \tag{4}$$

where

$$\delta = \omega_{RF} - \omega_0 = \omega_{RF} - \frac{g_F \mu_B}{\hbar} B_{DC}. \tag{5}$$

and B_{DC} gives the local magnitude of the static bias field ($U = \mu B_{DC}$), see equation (1). This Hamiltonian has eigenenergies 0, $\pm\hbar\sqrt{\delta^2 + |\Omega|^2}$. Continuing this treatment for e.g. a five-level system, such as the $F = 2$ manifold, gives eigenenergies $m_F{}'\hbar\sqrt{\delta^2 + |\Omega|^2}$ where $m_F{}'$ is in this case an integer $-2 \leqslant m_F{}' \leqslant 2$.

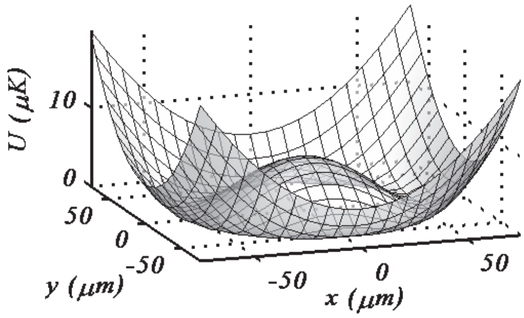


Figure 2. The predicted potential for our experimental parameters: $B_0^{\mathrm{DC}} = 1.3\,\mathrm{G}$, $B_0^{\mathrm{RF}} = 0.25\,\mathrm{G}$, $B_{\mathrm{Q}}{}' = 388\,\mathrm{G\,cm^{-1}}$, $\omega_{\mathrm{RF}} = 2\pi \times 1.15\,\mathrm{MHz}$, $\lambda = 1$ and a phase $\alpha = -\pi/2$.

A general expression for an applied RF field lying in the xy-plane is of the form

$$\mathbf{B}_{\mathrm{RF}} = B_0^{\mathrm{RF}} \begin{pmatrix} \cos(\omega t) \\ \lambda \cos(\omega t - \alpha) \\ 0 \end{pmatrix}. \tag{6}$$

The component of the RF field perpendicular to the static magnetic field, $B_\perp$, is found by performing a rotation from a co-ordinate system aligned along the quadrupole field to the lab co-ordinate system and is given by

$$\left(\frac{B_\perp}{B_0^{\mathrm{RF}}}\right)^2 = \frac{\lambda^2 x^2 + y^2}{x^2 + y^2} + \frac{4z^2}{x^2 + y^2 + 4z^2}\left(\frac{x^2 + \lambda^2 y^2}{x^2 + y^2}\right) - \frac{2\lambda xy\cos\alpha}{x^2 + y^2 + 4z^2} + \frac{4\lambda z\sin\alpha}{\sqrt{x^2 + y^2 + 4z^2}}. \tag{7}$$

For a bias field of magnitude B_0^{DC} that moves the centre of the quadrupole field upwards, the plane in which the atoms are held is $z_0 = -B_0^{\mathrm{DC}}/B_{\mathrm{Q}}{}'$. If we apply circularly polarized RF radiation, i.e. $\lambda = 1$ and $\alpha = \pm\pi/2$, then

$$\left(\frac{B_\perp}{B_0^{\mathrm{RF}}}\right)^2 = 1 + \frac{4z^2}{x^2 + y^2 + 4z^2} \pm \frac{4z}{\sqrt{x^2 + y^2 + 4z^2}}, \tag{8}$$

which, evaluated at the origin, gives $(B_\perp/B_0^{\mathrm{RF}})^2 = 2 \mp 2$ (remembering that z is negative). This is consistent with the fact that the matrix element for driving transitions from $|m_{\mathrm{F}}\rangle$ to $|m_{\mathrm{F}} + 1\rangle$ with σ_- radiation is 0. The correct polarization of the RF field for resonance is therefore $\alpha = -\pi/2$. The potential is plotted for our parameters in figure 2.

There are two distinct regimes of operation for RF-dressed traps. The first regime, which we shall label the *orientation-dependent regime*, occurs when $\hbar\omega_{\mathrm{RF}} < \mu B_0^{\mathrm{DC}}$ so that, while the RF never comes into resonance, it is closest to resonance at the centre of the trap, see figures 1(b) and 3(b). In this regime it is the spatial variation in the relative orientation of the RF and static magnetic fields that creates a spatially varying shift of the eigenenergies that can, if the RF power is sufficiently large, create a bump in the centre of the trap. This bump will be elliptical if the RF field is elliptically polarized and typically a large RF power ($\sim B_0^{\mathrm{DC}}$) is required to achieve a toroidal trap in this regime.

The second regime is what we shall term the *detuning-dependent regime*. This is defined by $\hbar\omega_{\mathrm{RF}} > \mu B_0^{\mathrm{DC}}$, see figure 1(c). In this regime the purpose of the RF field is to evoke an

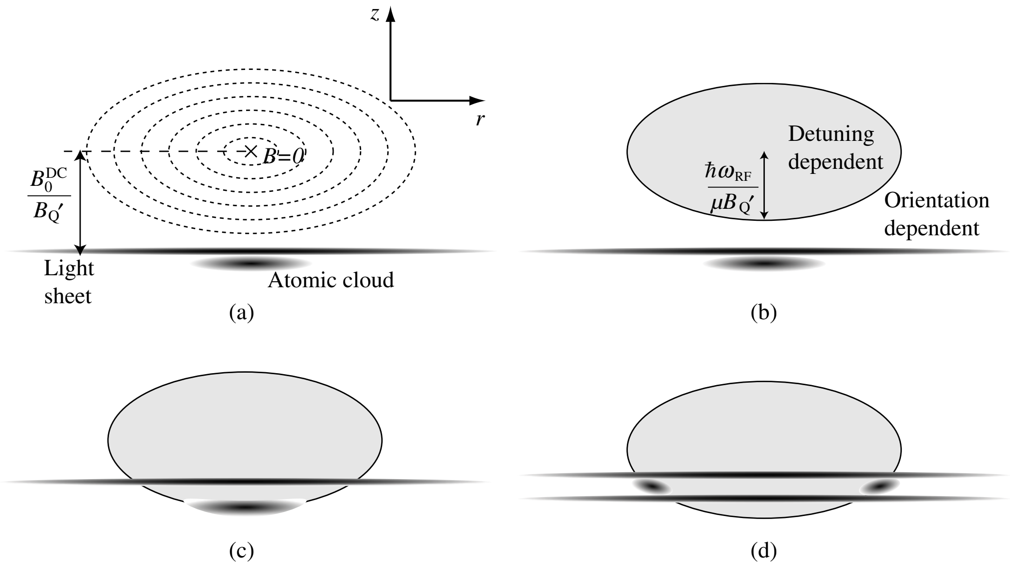


Figure 3. The procedure for loading atoms into the ring trap. In all parts of this figure, the system has axial symmetry. (a) The atoms are loaded into a biased quadrupole trap where the zero field of the quadrupole trap is raised above the plane of the atoms by a bias field of magnitude B_0^{DC} and the atoms are held at a fixed offset from the field zero by a sheet of light which creates a repulsive dipole potential. (b) The RF field is ramped on with a frequency ω_{RF}. The RF is resonant with the static bias field when $\hbar\omega_{RF} = -\boldsymbol{\mu} \cdot \mathbf{B}_{DC}$. The locus of this resonance is a ellipsoidal shell. When the atoms are outside this shell, the RF is below resonance (orientation-dependent regime). (c) The bias field, B_0^{DC}, is ramped down and the RF becomes resonant when $\mu B_0^{DC} = \hbar\omega_{RF}$. Reducing the bias field further gives the detuning-dependent regime. The atoms would spread out over the ellipsoidal surface were it not for gravity causing the atoms to sag to the bottom. (d) If, however, the atoms are constrained to a plane, $z = z_0$, between two sheets of light, the intersection between the ellipsoidal shell (defined by the resonance condition) and the plane is a ring.

avoided crossing between the dressed states. To this end, the RF power has little influence on the trap geometry which is instead predominantly defined by the static biased quadrupole field and the detuning of the RF frequency from the resonance. As the locus of the resonance is described by an ellipsoid surface, the intersection of this surface with the $z = z_0$ plane is a circle. Alternatively, the intersection of the 'V-shaped' potentials, illustrated in figure 1(c) may be seen, when considered in three dimensions (3D), as the intersection of two cones which again describe a circular geometry. An elliptical RF field will create a periodic modulation of the potential around the ring that can split the atomic cloud into two arcs with little effect on the radius of the ring[3]. While this is the easiest regime in which to obtain a toroidal trap, if we were to switch the RF radiation on directly into this regime the atoms would be loaded into the potential with an 'M-shaped' cross-section (figure 1(c)) instead of the desired 'W-shaped' potential. Instead, one

[3] The effect of the RF radiation is to push the atoms outwards as discussed later in this paper, but the radius changes only by ∼1%.

must either ramp the frequency (as was done in [3]) or the bias field so that the atoms start in the orientation-dependent regime and move adiabatically into the detuning-dependent regime.

In our cylindrically symmetric trap the situation in the orientation-dependent regime can become like that in a TOP trap, i.e. when the atomic frequency detuning is far below the resonance the field should be treated by the time-averaged approach of the TOP trap. The orientation-dependent regime also requires a large RF power to create a central bump in the potential; however, should the total field $|B_{\mathrm{Tot}}|^2 = |B_0^{\mathrm{RF}}|^2 + |B_0^{\mathrm{DC}}|^2$ become too large, it will again be seen as an orbiting bias field rather than the perturbing RF field of the dressed atom picture.

3. Implementation and results

We produce a pure condensate of $\sim 10^5$ atoms in the $|F = 1, m_F = -1\rangle$ state of ^{87}Rb using a TOP trap [4]. The trap consists of a quadrupole field with an axial gradient of $B_Q{}' = 388\,\mathrm{G\,cm^{-1}}$ and a bias field rotating in the radial plane at a frequency of 7 kHz. The effect of gravity on the TOP trap is to change the trapping frequencies marginally (<1%) and to cause the atoms to sag lower in the trap, this sag is 8.1 μm for a TOP field of $B_T = 4\,\mathrm{G}$.

We load the BEC into an optical dipole trap created from two blue-detuned light sheets aligned with the atoms, see [23] for technical details. The atoms sit in between these sheets which provide a vertical confinement of $\omega_z \approx 1.6\,\mathrm{kHz}$. We then apply a static bias field $B_0^{\mathrm{DC}} = 2\,\mathrm{G}$ in the axial direction using the dipole trap to hold the atoms at a distance $z_0 = B_0^{\mathrm{DC}}/B_Q{}'$ below the quadrupole centre. The TOP field is now ramped down to zero to leave the atoms sitting in an Ioffe style magnetic trap whose potential is given in equation (1). Since the dipole trap is aligned with the equilibrium position of the atoms in the TOP trap, this corresponds to 8.1 μm below the quadrupole field zero as discussed above; this is equivalent to a bias field of 0.3 G. The effective bias field felt by the atoms is therefore 0.3 G greater than that applied, i.e. 2.3 G.

Next we apply circularly polarized RF radiation at a frequency of 1.15 MHz and an amplitude of 0.25 G through the same coils we used for our TOP field. This radiation is off resonance for the initial loading conditions ($\omega_{\mathrm{res}} = 2\pi \times 1.6\,\mathrm{MHz}$ for 2.3 G) but as the vertical bias field is then reduced to its final value, see figures 1 and 3, the RF approaches resonance and, if the bias field is reduced far enough, will pass through resonance at the centre of the trap creating a toroidal trapping potential where the atoms sit in the locus of zero detuning. Having loaded the condensate into the RF trap, and biased down to a final value of B_0^{DC}, the atoms were kicked in order to excite a dipole oscillation. This was done by flicking off the coils nulling the Earth's magnetic field, waiting for 10 ms and then putting them back on again. By observing the final position of the atoms after 15 ms time of flight for different hold times, the oscillation frequency of the trap was measured. This was repeated for various values of the final bias field B_0^{DC} and the resulting trapping frequencies are shown in figure 4. For large bias fields the RF is far from resonance and so the trapping frequency approaches that of the unperturbed biased quadrupole trap. As the bias field is lowered, the RF gets closer to resonance at the centre of the trap and its effect is to reduce the trapping frequency; this is the orientation-dependent regime. When the bias field is reduced such that $g_F \mu_B B_0^{\mathrm{DC}} = \hbar\omega_{\mathrm{RF}}$, the RF reaches resonance; this occurs at $B_0^{\mathrm{DC}} = 1.64\,\mathrm{G}$. For bias fields lower than this, the detuning-dependent regime is

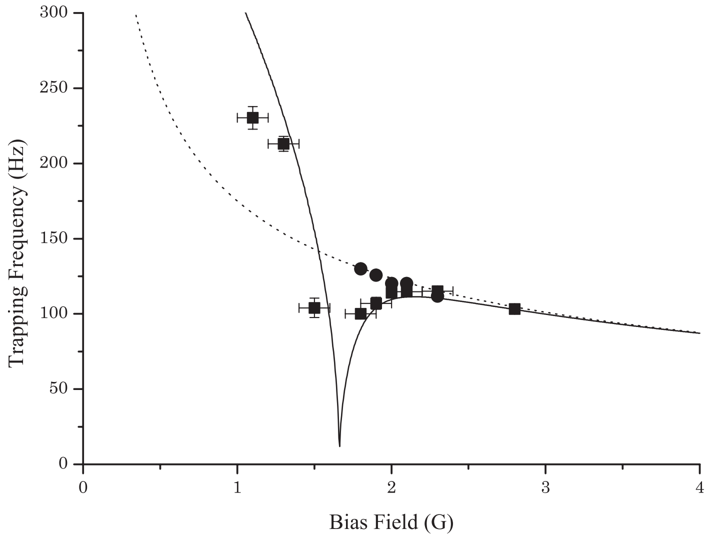
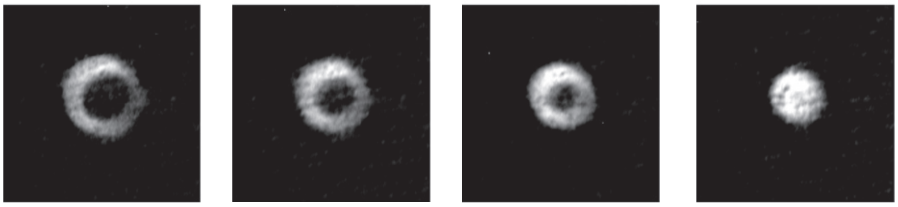


Figure 4. The radial oscillation frequencies of rubidium atoms in the RF trap versus the static bias field, B_0^{DC}. The squares show the results for a phase of $-\pi/2$ between the x- and y-components of the RF field while the circles show the results for a phase of $\pi/2$. Also shown are the predicted frequencies, solid and dotted lines. Bias fields lower than 1.65 G and a negative phase give a toroidal trapping geometry. As noted in the text, it was possible to measure an approximate value for the radial trapping frequency in the toroidal regime by tilting the trap so that the atoms were localized at one place in the ring and were then kicked radially.



(a) $B_0^{DC} = 1.0$ G (b) $B_0^{DC} = 1.1$ G (c) $B_0^{DC} = 1.2$ G (d) $B_0^{DC} = 1.3$ G

Figure 5. In-trap images of thermal atoms (700 nK) in the toroidal trap. Changing the bias field B_0^{DC} changes the radius of the trap.

reached, the atoms sit in a toroidal geometry where the RF is resonant, see figure 5. The data in figure 4 were taken when there was a slight tilt in the trap so that the atoms did not spread completely around the ring but rather were localized at one place in the trap. This enabled us to obtain an approximate value of the radial trapping frequency even in the toroidal geometry by ensuring that the kick they were given was in the radial direction. The pictures in figure 5 were taken after the tilt had been adjusted to be as small as possible.

4. Conclusions and outlook

We loaded atoms into a toroidal trap and aligned it such that the ring lies in the horizontal plane. Compared with plugged quadrupole traps, our potential should be smoother and more flexible. This enables us to pursue the observation of persistent flow.

For the condensate to flow around the ring we require that the plane of the toroidal trap is horizontal. It is straightforward to estimate the variation in the gravitational potential around a tilted ring; e.g. for a radius of 20 μm and a tilt of 1°, the height difference between the two sides is 1.7 μm, corresponding to 72 nK for ^{87}Rb. This potential variation must be less than the chemical potential for the condensate to spread around the ring. The chemical potential (in the 3D limit) for a ring trap is given in [6] as

$$\mu_{\rm c} = \hbar\bar{\omega}\sqrt{\frac{2Na}{\pi r_0}}, \tag{9}$$

where $\bar{\omega}$ is the geometric mean of the trapping frequencies, $\bar{\omega} = \sqrt{\omega_r\omega_z}$, the scattering length (in units of the Bohr radius) is $a = 110a_0$, r_0 is the radius and N is the number of atoms in the ring trap. Taking values of the trapping frequencies as 1.6 kHz axially and 100 Hz radially for a trap of radius 20 μm with 100 000 atoms gives a temperature for the chemical potential ($\mu_{\rm c}/k_{\rm B}$) of 83 nK[4]. This calculation shows that for a tilt of 1° we can obtain a condensate that is continuous around the ring. This is approximately the smallest tilt (or uncertainty in that parameter) that we can obtain by mechanical adjustment of the optical elements. However, finer adjustments can be made by tilting the plane of polarization of the RF radiation. This introduces a z-component into equation (6). The analysis of this in the more general case is more complicated and will be described in a future publication.

A method of making the trapped gas flow around the ring by deforming the circular trap into a rotating ellipse is described in [6] which could equally be applied to our trap by adding auxiliary magnetic coils. However, an alternative method exists for which no extra coils are necessary. Although the shape of the potential in our experiment predominantly arises from the spatial dependence of the frequency detuning, the relative orientation of the RF and static fields does influence the potential, as shown in equation (7) and we utilize this in the following way.

For a toroidal trap in which the atoms are sitting at a position where the resonance condition is fulfilled ($\delta = 0$), the radius is given by

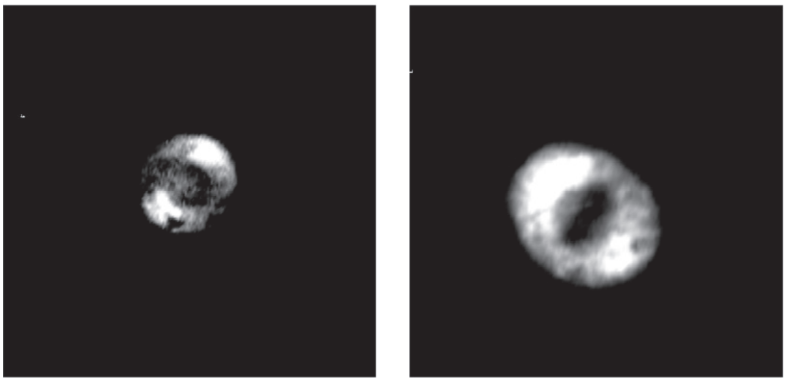
$$r^2 = 4z^2\left(\left(\frac{\hbar\omega_{\rm RF}}{g_{\rm F}\mu_{\rm B}B_0^{\rm DC}}\right)^2 - 1\right) \tag{10}$$

in the plane $z = z_0$ and linearly polarized RF, $\lambda = 0$, the potential varies as

$$U = \frac{g_{\rm F}\mu_{\rm B}B_0^{\rm RF}}{2}\sqrt{\left(\frac{g_{\rm F}\mu_{\rm B}B_0^{\rm DC}}{\hbar\omega_{\rm RF}} - 1\right)\cos^2\phi + 1}, \tag{11}$$

[4] N.b. The requirement for being in a 2D regime is that $\hbar\omega_z \gg \mu_{\rm c}$. A chemical potential of 83 nK is equivalent to a frequency of 1.7 kHz which is greater than the axial trapping frequency of 1.6 kHz. This system is close to the 2D regime and would be reached if the chemical potential is reduced (e.g. by reducing the number of atoms) or the axial trapping frequency increased. In this regime the chemical potential is given by [6]

$$\mu_{\rm 2D} = \hbar\bar{\omega}\left(\frac{\omega_r}{\omega_z}\right)^{1/6}\left(\frac{3Na}{4\sqrt{\pi}r_0}\right)^{2/3}.$$



(a) $\alpha = 0$ (b) $\alpha = \pi$

Figure 6. A relative phase of $\alpha = 0$ between the two RF components creates a modulation of the potential around the ring trap. A relative phase of $\alpha = \pi$ rotates this modulation through 90°.

hence a variation of potential around the loop[5]. Preliminary data for such a modulation are shown in figure 6. Changing the relative phase (α in equation (7)) of the two RF components between 0 and π creates a linearly polarized RF field at an angle of ±45°. This splits the ring trap in an adjustable way.

This modulation of the bottom of the potential well can be moved around the ring by rotating the polarization of the RF field. This will excite a persistent flow in a precisely controllable way as described in [24] and similar estimates to those given in that paper can be made for our experimental conditions, e.g. for $r = 25\,\mu$m, one quantum of circulation (corresponding to an angular momentum of $\hbar$ per rubidium atom) occurs at an angular frequency of $\omega \approx 2\pi \times 0.2$ Hz. On general grounds, the upper limit to the circulation of a persistent current would be expected to be when the atoms move at the speed of sound in the cold gas. The atoms will move faster than the speed of sound in the cold gas when the rotation rate exceeds $\omega_{\rm rot} \approx 2\pi \times 6$ Hz for the above conditions (and with $\sim 10^5$ atoms). The energy of such supersonic flow would be dissipated by the formation of vortices and the excitation of collective modes in the case of superfluid liquid helium in a container with rough walls. However, our RF-dressed magnetic potential should be very smooth, without any bumps at which vortices can nucleate, and so faster rotation should be possible. It will be interesting to see how persistent flow decays in this regime.

Since this work was completed, we have succeeded in loading a BEC into the ring trap without significant heating. Recently, persistent currents have been observed in a toroidal trap [25].

Acknowledgments

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[5] Since the effect of the RF power is to move the atoms to a marginally wider radius ($\sim 0.5\,\mu$m for our parameters) the expression for the radius in equation (10) is approximate. The actual variation of the potential around the slightly deformed ring is $\sim 1\,\mu$K, about twice that predicted in equation (11).

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