The use of increasingly sophisticated magnetic potentials has been crucial to the evolution of cold atom research. The time-averaged adiabatic potential (TAAP) trap proposed in [1] combines the techniques of time-averaging and radio frequency (RF) dressing to produce versatile potentials with a rich variety of different geometries. Since the RF dressing only couples electronic ground states of the atom the rate of relaxation by spontaneous processes is negligible. The potential is smooth with no small scale corrugations because the trapping region is located far from the field generating coils. As shown in [1], the TAAP can easily sculpt complex trapping geometries such as a double-well or ring trap, which can be adiabatically modified. Here we present an experimental realization of the particular case of a double-well TAAP and an efficient way of loading it from a time-orbiting potential (TOP) trap.

The technique of time-averaging involves the introduction of a time dependence to a static potential at a frequency higher than the atomic Larmor frequency which drives transitions between Zeeman sub-levels in a hyperfine manifold of the atom’s electronic ground state. The applicability of this technique is limited by the presence of spontaneous processes. As a result the eigenstates of the system are the dressed states [19]. The variation of the corresponding eigenenergies with position gives rise to an adiabatic potential (AP) given by

\[ U_{AP}(r) = m_F \hbar \sqrt{\delta^2(r) + \Omega_{AP}^2(r)}, \]

where \( m_F \) is the reduced Planck constant, \( \hbar \) is the Landé g-factor, \( \mu_B \) is the Bohr magneton, \( B_r \) is the magnetic field, \( \omega_r \) is the oscillation frequency of atoms in the trap, and \( \Omega_{AP} \) is the oscillation frequency of the AP.

The repertoire of magnetic potentials was further extended by RF dressing, as proposed by Zobay and Garraway [10]. Their technique brought about the possibility of highly asymmetric 2D magnetic potentials [11, 13]. It has also been applied in atom chip experiments to give flexible double-well potentials [14, 15] as described in detail elsewhere [10, 16, 18]. RF dressing involves a magnetic field oscillating at a frequency \( \omega_{RF} \) comparable to the atomic Larmor frequency which drives transitions between Zeeman sub-levels in a hyperfine manifold of the atom’s electronic ground state. Here the eigenstates of the system are the dressed states [19]. The variation of the corresponding eigenenergies with position gives rise to an adiabatic potential (AP) given by

\[ U_{AP}(r) = m_F \hbar \sqrt{\delta^2(r) + \Omega_{AP}^2(r)}, \]
The oscillating bias field of the TOP trap, dressed to give the ellipsoidal surface as described above. This is maximum at one pole and zero on the other [20].

\[
\delta(r) = \frac{|g_f \mu_B B(r)/\hbar| - \omega_{RF}}{2} \text{ is the angular frequency detuning and } \Omega_R(r) \text{ the Rabi frequency given by}
\]

\[
\Omega_R(r) = \left| \frac{g_f \mu_B}{2\hbar} \frac{B(r)}{|B(r)|} \times B_{RF} \right|.
\]

In this experiment we use a quadrupole field of the form

\[
B_q'(r) = B_q' x \hat{e}_x + y \hat{e}_y - 2z \hat{e}_z,
\]

where \(B_q'\) is the radial gradient. When dressed with an RF field \(B_{RF}\), the upper dressed state has a minimum on an ellipsoidal iso-B surface where \(\delta(r) = 0\). The vectorial nature of the coupling (see Eq. 2) gives a variation of the potential on the ellipsoidal shell itself: for linearly polarized RF with \(B_{RF}(t) = B_{RF} \cos(\omega_{RF} t) \hat{e}_z\) the coupling varies from maximum on the equator to zero at the poles. For circularly polarized RF with \(B_{RF}(t) = B_{RF} \cos(\omega_{RF} t) \hat{e}_x \pm \sin(\omega_{RF} t) \hat{e}_y\), the coupling is maximum at one pole and zero on the other [20].

RF dressed-state adiabatic potentials may themselves be time-averaged to give a new class of potentials referred to as time-averaged adiabatic potentials. We have generated a double-well TAAP by applying RF radiation to a conventional TOP trap. The instantaneous potential of the TOP is a quadrupole field, in a TAAP trap this is dressed to give the ellipsoidal surface as described above. The oscillating bias field of the TOP trap, \(B_T(t) = B_T \cos(\omega_T t) \hat{e}_x + \sin(\omega_T t) \hat{e}_y\), causes the ellipsoidal surface to orbit in the xy-plane about the axis of rotation as illustrated in Fig. 1. When \(\omega_{RF} > |g_f \mu_B B_T/\hbar|\) the ellipsoidal surface intersects the rotation axis at two points; these two points define the minima of the time-averaged potential.

![FIG. 2](image2.png)

**FIG. 2.** The instantaneous potential of the (a) TOP, (b) TAAP loading and (c) TAAP potentials along the x-axis at time \(t_1\) during the rotation cycle and \(t_2\) half a period later.

![FIG. 3](image3.png)

**FIG. 3.** (a) A contour plot of the AP in the \(xz\)-plane for a gradient of \(B_T = 84\ G/cm\) and for linearly polarized RF with \(B_{RF} = 0.5\ G\). The dashed lines indicate the position of the rotation axis of the ellipsoid for different values of \(B_T\). (b) Shows the potential along these lines for the three dressed states. The slope in the potentials corresponds to the gravitational potential energy of a \(^{87}\text{Rb}\) atom. Note the variation of the coupling at the atom’s position.

We load atoms into the double-well TAAP from a TOP using the following procedure. First, we prepare a sample of cold atoms in the TOP trap (see Fig. 2(a)). The RF dressing field is then rapidly switched on while ensuring \(B_T\) satisfies the inequality \(\omega_{RF} < |g_f \mu_B B_T/\hbar| < 2\omega_{RF}\) (Fig. 2(b)). The lower bound ensures the atoms are loaded into the correct dressed state while the upper bound is to prevent higher harmonics of \(\omega_{RF}\) coming into resonance and causing unwanted evaporation. At this stage the modification of the time-averaged potential is minimal (the ellipsoids of Fig. 1 do not yet intersect with the rotation axis). Decreasing the TOP field to \(\omega_{RF} = |g_f \mu_B B_T/\hbar|\) transfers the atoms onto the ellipsoidal shell (Fig. 2(c)). A further decrease in the TOP field gives rise to a double-well potential in the \(z\) direction. Note that the atoms stay on resonance at all times in the TAAP trap. The well separation is given by the
distance between the points of intersection of the ellipsoidal surface with the rotation axis: a decrease in $B_T$ moves the atom clouds further along the ellipsoid thus increasing their separation. The TAAP potential in the $z$ direction is that along the rotation axis of the ellipsoid as depicted in Fig. 3. The effect of the time-averaging is to give confinement along the surface thus preventing the atoms spreading out over the ellipsoid.

Our TOP trap (with $\omega_T = 2\pi \times 7 \text{ kHz}$) apparatus routinely produces BEC’s of $1 \times 10^6$ atoms of $^{87}\text{Rb}$ in the $|F=1, m_F = -1\rangle$ hyperfine state. The RF dressing field is applied through coaxial coil pairs placed symmetrically about the trap center along the $x$, $y$ and $z$ axes; this allows any arbitrary polarization but in these experiments it was either polarized circularly with $\mathbf{B}_{RF}(t)$ in the $xy$-plane or linearly with $\mathbf{B}_{RF}(t) \propto \hat{e}_z$.

In Fig. 4 the vertical position of atoms in the lower well of the TAAP trap is plotted as a function of the magnitude of the rotating bias field $B_T$ for two different quadrupole gradients. Here we apply linearly polarized RF along the $z$ direction with $B_{RF} = 0.5 \text{ G}$ and $\omega_{RF} = 2\pi \times 1.4 \text{ MHz}$. For these parameters the ellipsoidal surface touches the rotation axis when $B_T = 2 \text{ G}$ at which stage the atoms are loaded into the TAAP trap. The polarization effects mentioned above and the gravitational sag of the atoms mean that as $B_T$ is lowered the atoms do not follow the perfect ellipsoidal trajectory that one would expect from the idealized picture above (in Fig. 3 compare the dotted ellipsoid to the actual position of the minima shown in black).

It is evident in Fig. 3 that gravitational sag makes it impossible to load into the upper well for this quadrupole gradient (as denoted by the discontinuity in the black line in Fig. 3, indicating positions where there is no minimum in the upper half of the potential). This difficulty can be overcome by loading at higher gradients ($230 \text{ G/cm}$) and lowering $B_T$ to a final value of $1.7 \text{ G}$. A subsequent decrease in the gradient over $\sim 400 \text{ ms}$ (limited by speed of power supply) to $80 \text{ G/cm}$ fully splits the cloud (see absorption image of Fig. 1). Using higher values for $B_T$ during this loading procedure decreases the barrier height and prevents atoms from staying in the upper well. Lower values for $B_T$ decrease the coupling at the potential minima and result in an insufficient lifetime to observe the separated clouds. The chosen values balance these competing effects.

In addition the reduced lifetime explains why no data was taken in Fig. 4 for $B_T < 0.4 \text{ G}$ as the lifetime proved to be insufficient to make reliable measurements of the position. This effect is due to Landau-Zener (LZ) transitions to untrapped dressed states. The LZ transition probability for transitions between adjacent dressed states in the $F = 1$ manifold is given by [21]

$$P_{LZ}(r) = 1 - \left(1 - \exp\left(-\frac{\pi \hbar^2 \Omega(r)^2}{2 g_F \mu_B B_T v^2}\right)\right)^2,$$  \hspace{1cm} (4)

where $v$ is the velocity of the atom through the avoided crossing. The lifetime $\tau$ of atoms in the TAAP trap varies as $\tau \propto 1/P_{LZ}(r) + \tau_0$ where the offset $\tau_0$ takes into account the finite extent of the cloud. Fig. 5 shows the variation in trap lifetime for a TAAP dressed with linearly polarized RF. For this polarization $\Omega_R(r)$ is a linear function of $B_T$ and the lifetime changes by two orders of magnitude as $B_T$ is ramped down. By choosing circularly polarized RF of the appropriate handedness one can
engineer a situation where the Rabi frequency increases as $B_T$ is lowered. In this case we apply RF fields in two directions each with an amplitude of $B_{RF} = 0.5 \, \text{G}$. The predicted Rabi frequency $\Omega_R \sim 300 \, \text{kHz}$ close to the south pole of the ellipsoidal surface agrees well with spectroscopy measurements of the trap bottom. These effects combine to give a lifetime of up to 10 s in the lower TAAP well. In addition, we have measured trapping frequencies as a function of $B_T$ and observed good agreement with theoretical predictions as shown in Fig. 6. In this trap we have successfully cooled a thermal cloud to quantum degeneracy. Starting with a sample of $1.5 \times 10^6$ atoms at $\sim 0.7 \, \mu \text{K}$ in the TOP trap, we observe an atom loss of approximately a third during the TAAP loading process with no substantial heating. The loss mechanism is attributed to increased Landau-Zener losses when the avoided crossing spirals through the cloud. A subsequent rf-evaporation sweep over 3 s with an additional weaker field ($\sim 0.05 \, \text{G}$) cools the sample below the critical temperature creating a BEC of $5 \times 10^4$ atoms. For these frequency sweeps we have used transitions both within and beyond the rotating-wave approximation (RWA) and observed comparable efficiencies [10]. A BEC can be held in the TAAP trap without any evaporative rf for more than 3 s without any discernible heating.

In conclusion we have presented the first realization of a time-averaged adiabatic potential which promises an accessible route to a large variety of purely magnetic trapping geometries with tunable parameters. The loading scheme presented above has acceptable losses and negligible heating. Furthermore, we show it is possible to evaporatively cool atoms to below quantum degeneracy in such a potential. Since completing the work presented above, we have successfully employed the TAAP trap as an intermediate stage for loading a radio frequency dressed-state potential (lowering $B_T$ to zero) which is of interest for studying of low dimensional physics [10].

This work has been supported by the EPSRC under grant EP/D000440.

---

[1] I. Lesanovsky and W. von Klitzing, Phys. Rev. Lett. 99, 083001 (2007).
[2] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell, Science 269, 198 (1995).
[3] N. R. Thomas, A. C. Wilson, and C. J. Foot, Phys. Rev. A 65, 063406 (2002).
[4] A. S. Arnold, C. S. Garvie, and E. Riis, Phys. Rev. A 73, 041606 (2006).
[5] P. F. Griffin, E. Riis, and A. S. Arnold, Phys. Rev. A 77, 051402 (2008).
[6] S. Gupta, K. W. Murch, K. L. Moore, T. Purdy, and D. M. Stamper-Kurn, Phys. Rev. Lett. 95, 143201 (2005).
[7] P. Rudy, R. Ejnisman, A. Rahman, S. Lee, and N. Bigelow, Opt. Express 8, 159 (2001).
[8] N. Friedman, L. Khaykovich, R. Ozeri, and N. Davidson, Phys. Rev. A 61, 031403 (2000).
[9] K. Henderson, C. Ryu, C. MacCormick, and M. G. Boshier, New J. Phys. 11, 043030 (2009).
[10] O. Zobay and B. M. Garraway, Phys. Rev. Lett. 86, 1195 (2001).
[11] Y. Colombe, E. Kayazchyan, O. Morizot, B. Mercier, V. Lorent, and H. Perrin, Europhys. Lett. 67, 593 (2004).
[12] M. White, H. Gao, M. Pasienski, and B. DeMarco, Phys. Rev. A 74, 023616 (2006).
[13] O. Morizot, C. L. G. Alzar, P. E. Pottie, V. Lorent, and H. Perrin, J. Phys. B 40, 4013 (2007).
[14] T. Schumm, S. Hofferberth, L. M. Andersson, S. Wildermuth, S. Groth, I. Bar-Joseph, J. Schmiedmayer, and P. Krüger, Nat. Phys. 1, 57 (2005).
[15] S. Hofferberth, I. Lesanovsky, B. Fischer, J. Verdu, and J. Schmiedmayer, Nat. Phys. 2, 710 (2006).
[16] S. Hofferberth, B. Fischer, T. Schumm, J. Schmiedmayer, and I. Lesanovsky, Phys. Rev. A 76, 013401 (2007).
[17] I. Lesanovsky, T. Schumm, S. Hofferberth, L. M. Andersson, P. Krüger, and J. Schmiedmayer, Phys. Rev. A 73, 033619 (2006).
[18] I. Lesanovsky, S. Hofferberth, J. Schmiedmayer, and P. Schmelcher, Phys. Rev. A 74, 033619 (2006).
[19] C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grynberg, Atom-Photon Interactions (Wiley, 1992).
[20] In making the rotating wave approximation the time dependence of the Rabi frequency is removed.
[21] N. V. Vitanov and K. A. Suominen, Phys. Rev. A 56, R4377 (1997).