An Optically Plugged Quadrupole Trap for Bose-Einstein Condensates

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We created sodium Bose-Einstein condensates in an optically plugged quadrupole magnetic trap (OPT). A focused, 532nm laser beam repelled atoms from the coil center where Majorana loss is significant. We produced condensates of up to $3 \times 10^7$ atoms, a factor of 60 improvement over previous work, a number comparable to the best all-magnetic traps, and transferred up to $9 \times 10^6$ atoms into a purely optical trap. Due to the tight axial confinement and azimuthal symmetry of the quadrupole coils, the OPT shows promise for creating Bose-Einstein condensates in a ring geometry.

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Developing new experimental methods has been key to the exploration of quantum gases. In recent years, successes at loading atoms directly onto fabricated structures, evaporation in purely optical traps, and transport of atoms from one vacuum chamber to another have created Bose-Einstein condensates (and in some cases degenerate gases of new species) in environments where enhanced optical access and proximity to surfaces allows for the discovery of new phenomena.

Large volume magnetic traps are a workhorse of the field due to their significant capture range compared with optical traps. However, they possess an intrinsic trade-off between tight confinement and optical access, the former requiring a number of opaque coils to be placed in close proximity to the atoms. In this work we created Bose-Einstein condensates (BECs) using an “optically plugged” quadrupole magnetic trap (OPT) that significantly alleviates this trade-off. An earlier version of the OPT was used by Ketterle’s group to demonstrate the first BEC in sodium. The central result of this paper is a 60-fold improvement in atom number, achieving the 3rd largest alkali BEC reported. Moreover, although the OPT does not have a simple harmonic potential energy surface (see below), we have transferred up to 9 million atoms into a purely optical trap created by a single, focused infrared laser beam. This demonstrates that the OPT is an excellent starting point for BEC experiments.

Our OPT should considerably simplify the process of attaining a BEC, as it requires, apart from the “plug” laser, just one pair of electromagnets driven by a single power supply (this also makes the magneto-optical trap, or MOT, ensuring exact overlap between their respective centers). We can achieve the high loading efficiency of a magnetic trap without the complexity and restricted optical access of a multi-coil arrangement typical of Ioffe-Pritchard (IP) traps such as the cloverleaf design. Moreover, the focusing of an additional, intense laser beam adds only a minor complexity to the apparatus, comparable to that required for optical confinement of BECs. Our design uses a stable, solid state “plug” laser at 532 nm requiring little or no adjustment for several weeks of operation. Finally, we show here that it may be possible to scale down the required laser power to less than 1 watt.

A simple configuration of coils which will trap low magnetic field seeking particles is the quadrupole trap, formed by a pair of coils running current in the opposite direction in the so-called “anti-Helmholtz” configuration.

FIG. 1: The Optically Plugged Trap (OPT). a) A pair of coils which will trap low magnetic field seeking particles is the quadrupole trap, which has a hole in the center where atoms are lost by Majorana spin-flips. b) An optically plugged trap (OPT) is realized by focusing an intense, blue-detuned laser beam to the center that repels atoms from the hole, resulting in a Bose-Einstein condensate free to move along a ring. c) Using an elliptically shaped focus, the symmetry of the ring is broken, and two distinct minima form along the minor axis of the ellipse. About each minimum the atoms experience 3-dimensional, harmonic confinement with 3 distinct frequencies. (d-f) Potential energy versus position in the x-y plane corresponding to the trapping geometries of (a-c).
(see Fig. 1a). Unfortunately, by itself this trap is not so useful for evaporative cooling—within a region of \(1 - 2\mu m\) radius near the magnetic field zero at the trap center, the atoms can spontaneously undergo spin flips and are lost from the trap [12]. This Majorana loss can be eliminated if one removes the field zero from the cloud, for example, by a fast, rotating bias field [13, 14], or alternately, using a Ioffe-Pritchard design which has a finite bias field at the trap minimum [12]. Our approach is based on an idea of Ketterle to use the optical dipole force of a blue-detuned laser beam to repel atoms from the region containing the hole [1]. The resulting potential energy surface depends on both laser and magnetic fields, and the minimum is displaced from the coil center so that the atoms experience a non-zero magnetic field.

Our experimental sequence starts with a Zeeman slowed \(^{23}\text{Na}\) atomic beam based on a “spin-flip” design whose flux is about \(10^{11}\) atoms/s. About \(10^5\) atoms are loaded in 3 seconds into a dark MOT in the F=1 hyperfine level [12]. Roughly 1/3 of the atoms (the weak-field seekers) are transferred into the OPT (the magnet and laser beam are turned on simultaneously), whose axis of symmetry is oriented vertically. Each coil has 24 windings of \(1/8"\) square cross-section copper tubing. The average diameter of each coil is 4 inches and their spacing is 2.25 inches. A current of 350 A flows through the tube walls, while cooling water flows through the tube itself, and the total voltage drop including a high current switch is 20 Volts. The predicted field gradient is 320 Gauss/cm at this current. Following the loading of the trap, rf evaporative cooling for 42 seconds resulted in an almost pure Bose-Einstein condensate of \(10 - 30 \times 10^6\) atoms. In order to achieve such high atom numbers, we reduced the trap current by a factor of 14 toward the end of the evaporation stage, thus lowering inelastic losses associated with current by a factor of 14 toward the end of the evaporation.

To achieve such high atom numbers, we reduced the trap to a beam waist of \(40 \mu m\) using a 589 nm filter. To suppress the power of the beam during the absorption measurement, we placed a dichroic mirror, a 589 nm interference filter and up to 2 bandpass edge filters in the beam path, for a total suppression of up to 13 orders of magnitude. The focus of the plug beam was aligned to the center of the atom cloud in the trap by steering the beam output before the final focusing lens using a mirror mount with a micrometer actuator. After coarsely positioning the focus at the center of the circular absorption image, we performed a fine-tuning by searching for an enhancement of evaporative cooling, as detailed below.

**Ring Trap.** To understand the potential energy surface of the combined optical and magnetic fields, we consider an ideal case where the laser beam has a Gaussian profile with perfect azimuthal symmetry. Since the quadrupole potential also possesses this symmetry (see Fig. 1b), this results in a ring-shaped Bose-Einstein condensate. Neglecting the variation of the laser beam along \(z\) due to the long Rayleigh range of a few millimeters, the minimum of the combined laser and magnetic potential is a circle of radius \(r_0\) in the \(x-y\) plane, which is located mid-way between the coils (see Fig. 1e). \(r_0\) satisfies \(\frac{\partial}{\partial r} U_0 e^{-2r^2/W_0^2} \big|_{r=r_0} = \mu B'/2\), with \(U_0\) the peak AC stark shift from the plug beam, \(W\) the beam waist, \(B'\) the axial quadrupole magnetic field gradient, and \(\mu = 1/2\times\) the Bohr magneton is the magnetic moment for atoms in the \(|F = 1, m_F = -1\rangle\) hyperfine state. Typically, \(r_0 > W\). Near \(r = r_0\) and \(z = 0\), the potential \(U\) varies harmonically in the \(r\) and \(z\) directions, with radial curvature \(\partial^2 U / \partial r^2 = \frac{B'}{2r_0} (4r_0^2/W^2 - 1)\). Along the \(z\)-direction \(\partial^2 U / \partial z^2 = 2\mu B'/r_0\).

**Harmonic Trap.** A real laser focus does not have a perfect Gaussian intensity profile. The deviation is most significant in the wings, and for blue-detuned beams this is where the atoms primarily reside. Small imperfections in a round focus would result in one or more minima at random locations. To exert control over the potential, we artificially broke the symmetry by creating an elliptical focus whose aspect ratio was \(a\). We inserted a slit into the beam path before the final focusing lens to create a spatial profile with roughly the inverted aspect ratio \(1/a\). The resulting beam focus was elliptical, with its minor axis orthogonal to the slit direction. The ring symmetry was broken, resulting in two distinct minima on the minor axis \(y\) of the ellipse at \(y = \pm y_0\) (see Fig. 1c,1f). Typically, \(W_y = 42 \mu m\) and \(W_x = a W_y\) with \(a = 2.5\), \(B' = 23\) Gauss/cm in our decompressed trap, and \(U_0/\hbar B = 65\mu K\) for 2.7 Watt of laser power delivered to the atoms.

Near each minimum the potential is harmonic, with 3 distinct frequencies. If one neglects gravity and takes \(a \to \infty\), one has \(\omega_x^2 = \mu B'/(2M y_0)\), \(\omega_y^2 = \omega_z^2 (4y_0^2/W^2 - 1)\), and \(\omega_z^2 = 4\omega_y^2\). For our parameters, gravity and the finite value of \(a\) introduce corrections of 10 % to \(\omega_x, \omega_z\), yielding predicted frequencies of \(\omega_y, x, z = 2\pi \times 215, 60\) and 125 Hz, respectively. In practice, there can also be an asymmetry between the two minima which is discussed
cally trapped ideal gas is trapped at a frequency of 150 kHz we saw a nearly pure condensate. Time-of-flight images from the side (y-direction) show two separated clouds near the two minima of the potential. Each view in (d) is 1.6 mm (y) × 0.8 mm (x,z), while (e) is 0.8 mm × 0.8 mm.

The presence of an elliptical focus dramatically changed the time-of-flight distribution of the trapped gas. For final rf frequencies above 500 kHz we observed a symmetric distribution in the x–y plane when imaged along the z-direction, indicating a thermal cloud (Fig. 2a). Below 500 kHz we observed a bimodal distribution with an anisotropically expanding condensate in the shape of a cigar (Figs. 2b,2c). The long axis of the cigar was parallel to the minor axis of the ellipse. While we expect that this axis should rotate if the ellipse is made to rotate, we could not easily observe this simply by rotating the slits due to a residual ellipticity in the laser beam profile. At a frequency of 150 kHz we saw a nearly pure condensate. Time-of-flight images from the side (x-direction) showed that the condensate expanded anisotropically in 3 dimensions (Fig. 2d).

The measured temperature just above the transition was 1.9 µK. The theoretical prediction for a harmonically trapped ideal gas is 
\[ T_C = \frac{\hbar}{6\pi^2} (N/1.202)^{1/3}, \]
where \( \bar{\omega} = (\omega_x^2 + \omega_y^2 + \omega_z^2)^{1/3} \). For the estimated frequencies above, with \( N = 31 \times 10^6 \) atoms in 1 (2) wells, we get a temperature of 1.7 µK (1.3 µK). The true prediction lies somewhere in between, since there are two minima whose relative population depends on the precise laser alignment and profile, which we can control only with limited precision. A systematic underestimate of the atom numbers may be responsible for the higher temperature measured. The agreement between theory and prediction is reasonable given the uncertainties in the exact shape of the potential due to beam alignment as well as the effects of anharmonicity.

Below the transition, we studied the anisotropic expansion of the condensate. Assuming harmonic confinement, in the Thomas-Fermi limit the chemical potential \( \mu \) is related to the expanded cloud sizes through the relation 
\[ \mu = \frac{M}{2}(W_x^2 + W_y^2 + W_z^2) \]
where \( W_i \) is the Thomas-Fermi radius along the \( i \)-th direction obtained from a parabolic fit to the time-of-flight image. For our geometry, roughly 65%, 25% and 10% of the energy is released in the \( y, z \) and \( x \)-directions, respectively. We estimate \( \mu/k_B = 600 \) nK from the measured cloud sizes. The Thomas-Fermi prediction is 
\[ \mu = \frac{\hbar^2}{2} \left( \frac{\bar{\omega}}{a_s} \right)^{2/3} \]
where \( N \) is the number of condensed atoms, \( a_s = 2.75 \) mm is the scattering length, and \( \bar{\omega} = \sqrt{\hbar/M\bar{\omega}} \) is the harmonic oscillator length. Estimating the atom number to be \( \approx 20 \times 10^6 \) atoms in 1 (2) wells, we compute \( \mu/k_B = 530 \) nK (400 nK). Both release energy and transition temperature are slightly higher than the predictions, as would be expected for an underestimate of the atom number.

![FIG. 2: Transition to BEC in the OPT. Absorption images taken at final rf frequencies of a) 0.55, b) 0.45, c) 0.30 MHz show the formation of a Bose condensate. The field of view in each image is 2.7 × 2.7 mm. Below each image is a horizontal slice through a 2-dimensional bimodal fit to the absorption data. (d) Views along the z and x directions (40 ms and 20 ms time-of-flight, respectively) show the 3-dimensional anisotropic expansion of the condensate. (e) A view in the trap along the z direction shows two separated clouds near the two minima of the potential. Each view in (d) is 1.6 mm (y) × 0.8 mm (x,z), while (e) is 0.8 mm × 0.8 mm.](image)

![FIG. 3: Plugging the hole. Catastrophic loss results if the “plug” is not carefully aligned. In b) it is aligned precisely with the magnetic field zero (indicated by a dashed line), resulting in a large number of atoms near the end of the rf evaporation stage, while in a) and c) it is misaligned along the y-direction by +90µm and −65µm, respectively, resulting in very few atoms. The plug laser power also dramatically affects the number of condensate atoms achieved, as shown in d), although large condensates were obtained even when the plug is not completely capable of repelling atoms loaded from the MOT, whose initial temperature was \( T_i = 190 \) µK. The field of view in each image is 1mm × 1mm.](image)
the magnetic field center by more than 50µm along any direction (Figs. 3a-3c), tremendous losses ensued and very few atoms remained near the end of the evaporation ramp. However, when it was correctly aligned, as in Fig. 3b, we obtained a huge increase in probe absorption, an unmistakable signature that the hole had been successfully plugged and that we could produce a BEC.

While the plug beam is clearly necessary, a natural question is how high the potential barrier must be to prevent Majorana loss. One estimate is that it should exceed the average energy of atoms passing nearby. This implies that $U_0 \geq 3/2 \delta_B T_1$, where $T_1$ is the initial temperature of atoms loaded into the quadrupole trap. The MIT group used a Stark shift of 350µK for atoms at 200µK in the first plug trap. However, the dependence on plug power was not determined in that work. In Fig. 3d we plot the final atom number in the condensate versus plug laser power. At our maximum laser power we achieved condensates of up to $30 \times 10^6$ atoms, close to the state-of-the-art achieved in IP traps. Surprisingly, the peak Stark shift was only 60µK, about $30 \%$ of $k_B T_1$, which we measured to be 190 µK. Thus the estimate above appears rather conservative. Indeed, on occasion we have observed condensates of more than $10^6$ atoms using a total power output from the laser of only 1 Watt, corresponding to $U_0/k_B T_1 \simeq 0.1$. We interpret this to mean that Majorana loss becomes critical only when the cloud size becomes small. Our observations suggest that by focusing more tightly to a beam waist of 20µm or less, one may only need a 0.5-1 watt plug laser.

Finally, we address a drawback of the hybrid magnetic and optical trap—the exact potential energy surface depends on the precise laser beam alignment and its profile in the wings, parameters which are difficult to control. We demonstrate that the OPT can be used as a “cooling stage” to achieve quantum degeneracy, followed by transfer of atoms (in a procedure similar to [14]) into a single mode optical fiber before being focused onto the magnetic field center by more than 50 µm along any direction. A unique feature of our condensate is the non-uniform magnetization due to the inhomogeneous quadrupole field, which may allow for the creation of novel spin textures.

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