Vortices and Persistent Currents: Rotating a Bose-Einstein Condensate Using Photons with Orbital Angular Momentum

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Abstract
We describe the coherent transfer of the orbital angular momentum of a photon to an atom in quantized units of $\hbar$, using a 2-photon stimulated Raman process with Laguerre-Gaussian beams to generate an atomic vortex state in a Bose-Einstein condensate (BEC) of sodium atoms. We show that the process is coherent by creating superpositions of different vortex states, where the relative phase between the states is determined by the relative phases of the optical fields. We use this technique to generate circular flow of a BEC confined in a toroidal shaped trap. We measure that the flow of atoms persists for up to 10 seconds, which we interpret as the first evidence of persistent currents in a superfluid Bose gas.

1. Generating macroscopic rotational states of atoms

The topological properties of macroscopic quantum states are of fundamental interest in quantum mechanics and many body physics. An example is vortices with quantized angular momentum in superfluid liquid helium. The realization of Bose-Einstein condensates (BECs) of dilute atomic gases, have provided us with another physical system that can be used for the study of topologically interesting macroscopic quantum states. With atomic BECs, however, we have the possibility of coherently generating and manipulating such states, thereby allowing investigation of phenomenon difficult if not impossible to access with liquid helium.

We have recently developed a technique \cite{1} to coherently generate vortex states in a BEC. Our technique involves the coherent transfer of the orbital angular momentum (OAM) of light to a BEC using a Doppler sensitive, stimulated Raman process (a rotational analog of atomic Bragg diffraction \cite{2}). This process, where the OAM of a photon (see below) is transferred to an atom in the BEC, can generate a singly- and multiply-charged vortex in the BEC.

1.1 Orbital angular momentum of light

Light can carry two types of angular momentum along its direction of propagation: Internal or "spin" angular momentum, associated with its polarization, and external or orbital angular momentum (OAM) \cite{3}, associated with its spatial mode. An
example is the set of Laguerre-Gaussian modes (LG\textsubscript{l}\textsubscript{p}), which defines a possible basis set for paraxial laser beams \[4\]. They are characterized by two indices \( l \) and \( p \), where \( l \) is the winding number (the number of times the phase completes \(2\pi\) on a closed loop around the central singularity), and \( p \) is the number of radial nodes with \( \rho > 0 \). In our experiment we use a LG\textsubscript{1}\textsubscript{0} mode (sometimes referred to as a doughnut mode), where the electric field amplitude in polar coordinates at the beam waist varies as:

\[
\text{LG}_{10}(\rho, \phi) = \frac{2}{\sqrt{\pi}} \frac{1}{w_0^2} \rho \exp \left(-\frac{\rho^2}{w_0^2}\right) \exp(i\phi),
\]

(1)

\( w_0 \) is the characteristic beam size. From the above expression it can be shown that a light field in the LG\textsubscript{1}\textsubscript{0} mode carries \( \hbar \) of OAM along its direction of propagation \[3\], in contrast to the common Gaussian laser mode (LG\textsubscript{0}\textsubscript{0}), which carries no OAM. This property has led to numerous proposals for using Laguerre-Gaussian modes to generate vortices in BECs \[5\].

1.2 Rotating atoms with light - Our experiment

The interaction of light with matter inevitably involves the exchange of momentum. The transfer of optical spin angular momentum to atoms has been studied for over a century, and the mechanical effect of spin angular momentum on macroscopic matter was first demonstrated 70 years ago in an experiment where circularly polarized light rotated a birefringent plate \[6\]. More recently, the mechanical effects of optical OAM on microscopic particles \[7, 8, 9, 10\] and atoms \[11, 12\] have been investigated. Although one can safely assume that, in the case of the atoms, mechanical OAM was likely transferred to the atomic clouds, the effect of this transfer was not directly observed. (Such an observation would have been difficult, since the atomic clouds were incoherent, thermal samples.) The use of a BEC, however, allows direct observation of the mechanical effect of the quantized transfer of the OAM of a photon to an atom.

In order to directly demonstrate the mechanical effect of the OAM of light on atoms, we expose our sodium BEC to the combination of a LG\textsubscript{1}\textsubscript{0} and Gaussian (G) beams to drive a stimulated Raman transition, without changing the internal state of the atoms. Figure 1(a)-(c) shows how this stimulated Raman scheme can give rise to OAM transfer from the laser to the atoms. An atom of mass \( M \), initially at rest, absorbs a LG\textsubscript{1}\textsubscript{0} photon and stimulatedly emits a G photon, acquiring \( 2\hbar k \) of linear momentum \((k = 2\pi/\lambda \) with \( \lambda \) the photon wavelength). As with resonant Bragg diffraction with two G beams \[2\], the frequency difference between the two beams, \( \delta \nu \), is \( 4E_r/h = 4\nu_r \), where \( E_r = (\hbar k)^2/2M \) is the recoil energy (see Fig. 1(c)). In addition to the linear momentum (LM) the atoms pick up the OAM difference between the two photons. (The additional energy due to the rotation is small and, for the pulse durations used in this experiment, does not affect the resonance condition.)

We first prepare a BEC of about \( 10^6 \) sodium atoms in the \(|3S_1/2, F = 1, m_F = -1\rangle \) state in a triaxial time-orbiting potential (TOP) trap \[2\] with trapping frequencies of \( \nu_x, \nu_y \) and \( \nu_z \) (gravity along \( z \)) of 20, 28 and 40 Hz, respectively, yielding a typical Thomas-Fermi radius of around 30 \( \mu \)m. A linearly polarized G beam with frequency close to the D\textsubscript{2} line \((\lambda = 589.0 \text{ nm}) \) is split into two and passes through separate acousto-optic modulators (AOMs) in order to control their frequency difference \( \delta \nu \). One of the beams then passes through and diffracts off a blazed transmission hologram \[13\] generating a LG\textsubscript{1}\textsubscript{0} mode. The two beams illuminate the BEC with the LG\textsubscript{1}\textsubscript{0} beam along \( x \) and the G beam along \(-x\) (see Fig. 1(a)). Both beams have the same linear polarization, so that no net spin angular momentum is transferred in the process. The detuning of the laser beams from the D\textsubscript{2} line is \( \Delta = 1.5 \text{ GHz} \) (1500 linewidths), enough to prevent any significant spontaneous photon scattering for typical pulse durations. The Raman beams are applied to the atoms as a square
Fig. 1 Schematic of the experiment. (a) Counter-propagating LG$_{10}^0$ and Gaussian laser beams, with the same linear polarization and a variable frequency difference of $\delta\nu$, are applied to a BEC. (b) The atoms that have undergone the Raman transition (right cloud) separate from the initial BEC (left cloud). A spatially localized pump beam enables independent imaging of each cloud by absorption of a probe beam propagating along the direction of linear momentum transfer. (c) Diagram illustrating energy and momentum conservation of the 2-photon Raman process. (d) Absorption image of a cloud that has undergone the Raman transition, taken along the axis of the LG$_{10}^0$ beam. The vortex core is seen as a hole in the cloud. (e) Interference between a condensate with uniform phase profile and a vortex with $\hbar$ of angular momentum.

pulse using the AOMs. Immediately after the light pulse we turn off the TOP trap and, after 6 ms time of flight (TOF), image the atoms by absorption of a probe beam resonant with the $|3S_{1/2}, F = 2\rangle$ to $|3P_{3/2}, F = 3\rangle$ transition. During imaging the atoms are optically pumped from the $|3S_{1/2}, F = 1\rangle$ state into the $|3S_{1/2}, F = 2\rangle$ state by a spatially localized "repump beam" (see Fig. 1(b)) resonant with the $|3S_{1/2}, F = 1\rangle$ to $|3P_{3/2}, F = 2\rangle$ transition, so that atoms only in one LM state (in this case either 0 or $2\hbar k$) are imaged. Figure 1(d) shows an image of a cloud that has undergone the Raman process ($\delta\nu \approx 4\nu_r \approx 100$kHz), where the vortex core is observed as a hole in the middle of the cloud. (A hole in the atomic density distribution without rotation would fill in during the TOF expansion.)

Figure 2 shows the transfer efficiency as a function of pulse duration. The maximum number of atoms coupled into the $2\hbar k$ LM state with $\hbar$ of OAM is approximately 53%. This is limited primarily by the spatial overlap of the initial, Thomas-Fermi, distribution with the vortex state. That is, atoms in the center of the initial BEC cloud are not coupled into the central region (hole) of the vortex state. The transfer efficiency initially peaks and then exhibits a slight damped oscillatory behavior to a steady state value due to the spatially variation of the laser intensity associated with the LG$_{10}^0$ mode. This spatial variation, which is primarily a linear increase in intensity as a function of radial distance from the center of the
Fig. 2  Plot of the transfer efficiency, of atoms in the initial BEC into the rotational (vortex) state with angular momentum \( h \), as a function of the pulse duration of the Raman beams.

hole (the LG\(_{10}^0\) laser mode is focused to a size approximately three times bigger than the size of the condensate), results in a radial variation of the Rabi frequency of the two-photon Raman process, so that atoms at different radial positions Rabi oscillate between the two states at different rates.

1.3 Measuring the angular momentum of the atoms

Although our two photon Raman process produces an atomic spatial distribution with a hole in the center, it is possible that this is not a vortex state, but simply results from the intensity profile of the LG\(_{10}^0\) beam used. Several techniques have been employed to check that vortex states in a BEC are rotating with quantized angular momentum, or equivalently that it has an integer multiple of \( 2\pi \) phase winding.

The technique used to map the phase profile in the first experiment to realize a vortex in a BEC \[14\] basically involved using interferometry. To implement this interferometric measurement, we use two optical pulses. The first pulse, consisting of the LG\(_{10}^0\) beam and the counter-propagating G beam (LG\(_{10}^0/G\) pulse) with \( \delta \nu \approx 4\nu_r \), transfers about 30% of the atoms to a state with LM \(-2\) and OAM \( h \). The second pulse, consisting of two G beams (G/G pulse) also with \( \delta \nu \approx 4\nu_r \), transfers atoms between the 0 and \( 2h \) \[2\] without any OAM transfer. There is essentially no delay between the pulses so that atoms with different momenta remain well overlapped spatially during the two pulse sequence. Fig. 1(e) is an image of one of the interfering clouds after the two pulses, and corresponds to the superposition of two clouds, with OAM of 0 and \( h \). The interference pattern of the \( h \) (vortex) state with a \( 2\pi \) phase winding and a BEC with uniform phase results in a displacement of the core of the vortex, because the uniform phase of the BEC will result in destructive interference somewhere along the \( 2\pi \) azimuthally varying phase of the vortex state.

Since stimulated two-photon Raman processes are coherent we expect the relative phase between the rotating and non-rotating clouds to be set by the relative phases of the laser beams used for their generation. We have verified this in another similar interference experiment \[1\]. Hence by controlling the relative phases between the different light beams used in the Raman processes, atoms can be put into any desired coherent superposition of different rotational states.

Another technique for checking to see if the donut-shaped atomic state is rotating, is to directly map the velocity distribution using velocity selective Bragg
Diffraction. This technique was first applied to measure the velocity profile of a sodium condensate [15], and more recently was used to map the velocity field of a lattice of vortices [16]. In this detection scheme, long duration Bragg pulses are used. For long pulses the Doppler shift, due to the linear momentum transfer of the two-photon process, is resolved. Hence, a map of the Doppler shift can be made by varying the two-photon Raman detuning. Figure 3 shows the Doppler shift associated with the $\hbar$ state and corresponds to our condensate rotating with a period of approximately a second.

1.4 Higher charge vortex states

It should also be possible to coherently generate higher charge vortex states by either using a higher order Laguerre-Gaussian mode or by transferring additional OAM of photons to the atoms. The latter case can be performed using either a higher-order (multi-photon) Bragg process [2] or by successive application of the two photon process. Figure 4 shows the generation of a vortex state with $2\hbar$ by successively applying the two photon Raman process (and changing the Raman detuning to keep the process resonant) [1]. Note that the core of the vortex is larger due to the higher charge.

2. Persistent flow of atoms in a ring-shaped trap

It is generally accepted by the physics community that superconductivity and superfluidity are manifestations of the same phenomenon in a charged and neutral system, respectively. Furthermore, this phenomenon is intimately connected to Bose-Einstein condensation. Although there is no one definition of superconductivity and superfluidity, such phenomenon is most evident in a multiply-connected topology, such as a ring or torus. One of the most striking manifestation of macroscopic quantum behavior in such a topology is the phenomenon of persistent current. In a superconductor, persistent flow is the flow of electrons without resistance. A current in a loop of superconducting wire will flow forever. The phenomenon of persistent current can also be observed in a superfluid, such as liquid helium below the lambda point, as frictionless flow. Hence the flow of superfluid liquid helium in a hollow toroid would never decay away.

A Bose-Einstein condensate of a weakly interacting atomic gas also exhibits superfluid behavior [17]. Although there have been a number of experiments studying superfluidity in atomic BECs, a persistent current of Bose-Einstein condensed
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Fig. 4 (a) Two consecutive Raman processes transfer atoms into a doubly charged \(2\hbar\) vortex state with linear momentum \(4\hbar k\). (b) Absorption image of the doubly charged vortex cloud. The core is seen to be larger than for the single charged state of Fig. 2(d).

Atoms had not been demonstrated. To do this requires the confinement of BEC in a ring or toroidal shaped trap. Despite a number of proposals for such a trap, previous experiments have only demonstrated the creation of a spatially localized BEC in a local minimum of the trapping potential somewhere along the ring \[13, 19\], or the loading of a condensate into a large diameter ring-shaped trap \[21, 20\] in such a way that when the atoms subsequently spread out to fill the ring (they are no longer in the many-body ground state). In order to create stable, persistent flow, the BEC in a toroidal (multiply-connected) trap should have a uniform density and be characterized by a single order parameter (uniform phase in the ground state). Only recently has a condensate in such a trap been realized.

2.1 BEC in a toroidal-shaped trap

To create a multiply-connected geometry, such as a toroid, we used a blue-detuned laser beam to plug the central region in a magnetic trap. Such a plug beam was originally used to exclude atoms from the zero-field region of a quadrupole magnetic trap in an experiment demonstrating the first realization of a sodium BEC \[13\]. The combined trapping potential of our harmonic (magnetic) trap and a Gaussian laser beam dipole trap can be written as

\[
V(x, y, z) = \frac{1}{2} m (\omega_x x^2 + \omega_y y^2 + \omega_z z^2) + V_0 \exp(-2(y^2 + z^2)/w_0^2),
\]

where \(\omega_x, \omega_y, \omega_z\) are the trapping frequencies in the magnetic trap, \(V_0\) is the maximum dipole potential from the laser beam, and \(w_0\) is the waist of the laser beam. The plug beam pushes atoms away from the trap center, and the atomic-density distribution has a hole in the center if the chemical potential is smaller than the maximum dipole potential, i.e. \(\mu < V_0\). Thus the trap geometry can be conveniently changed from simply-connected (harmonic) to multiply-connected (toroidal) by increasing the laser power. Similarly, the radius of the toroidal trap can be controlled by changing the size of the plug beam.

To load the toroidal trap, we start with a BEC of sodium atoms in the \(|3S_{1/2}, F = 1, m_F = -1\rangle\) state confined in our triaxial TOP trap \[2\]. The trap is then relaxed adiabatically so that the final trapping frequencies are \(\omega_x/2\pi = 36\) Hz, \(\omega_y/2\pi = 51\) Hz, and \(\omega_z/2\pi = 71\) Hz. Simultaneously, the power of the plug
Fig. 5  (a) Trapping potential of a toroidal trap formed by the combination of the magnetic TOP trap and a blue-detuned laser beam.  (b) In-situ image of a BEC in the toroidal trap.  (c) TOF image of a BEC without rotation.  (d) TOF image of a BEC with rotation.

beam is increased from zero to its final value. To reduce heating from this transfer, a final RF evaporation is done in the combined trap. This results in a BEC of about $N = 5 \times 10^5$ atoms in the toroidal trap. The plug beam has a wavelength of 532 nm, waist of 8 µm, and typical power of 100 µW. The beam quality and its directional stability are optimized by sending it through a single-mode optical fiber.

As seen from the above trapping frequencies, our TOP trap is not rotationally symmetric. Hence, although the plug beam is rotationally symmetric along the $x$-axis, the combined trap is not axially symmetric and the depth of the potential varies around the torus. A continuous BEC, however, can still be made in such a trap as long as the variation is less than the chemical potential of the BEC. Fig. 5(a) shows the trapping potential of the combined trap in the $y$-$z$ plane, where the variation in the potential around the minimum can be seen.

### 2.2 Generation of flow

The circulation of atoms is initiated by transferring the orbital angular momentum (OAM) of the photons from a $LG_{10}^0$ beam to the atoms, as described earlier. However, for the present experiment, we want the linear momentum (LM) of the rotating atoms to be zero so that they remain in the bottom of the toroidal trap. We achieve this by using an initial Bragg $\pi$-pulse (with G/G beams) to transfer all atoms to an LM state of $2\hbar k$, and then using the $LG_{10}^0/G$ pulse to transfer atoms to a rotational state with zero LM. The second pulse is not a perfect $\pi$ pulse, and only about 50% of the atoms are brought back to the zero LM state. Thus the remaining atoms, which are in the $2\hbar k$ LM state, need to be removed from the trap. This is done by waiting for one-quarter of the trap oscillation time, such that these atoms have separated maximally from the stationary cloud, at which point we can optically pump these atoms into the untrapped $F = 2$ hyperfine state using a localized laser beam. The whole process takes only a few ms. The transfer, however, results in additional excitation of the cloud. It takes a few hundred ms for this excitation to damp, during which time we keep the rf evaporation on.
In Figs. 5(b-d), we show the absorption images of a BEC initially trapped in the toroidal trap. Fig. 5(b) is an in situ image of a non-rotating BEC. As expected, the density distribution has a hole at the center due to the presence of the plug beam. Fig. 5(c) shows the image of a similar BEC after it is released from the trap, and has undergone ballistic time-of-flight (TOF) expansion for 18 ms. As can be seen, the initial hole disappears during the TOF due to the mean-field expansion. Finally, in Fig. 5(d), we show the image of a rotating BEC, after 18 ms TOF, in which Bragg diffraction by a LG\textsubscript{10}/G pulse has been used to transfer one unit of angular momentum (\(\hbar\)). The hole in the center of the cloud indicates that the BEC was rotating. Thus the rotation of the atoms can be detected easily by looking at the absorption image after TOF expansion.

### 2.3 Observation of persistent flow

In order to study the stability of the flow, we measured the decay of the circulation as a function of waiting time in the trap. In Fig. 6(a), we plot the survival probability of the rotation as a function of the trapping time, for multiple realizations of the experiment. The circulation in the toroidal trap persists without decay for up to 10 s. By contrast, the circulation in our asymmetric TOP trap without the plug beam (the simply connected geometry) decays in less than 1 s. There are two experimental factors that cause the flow to decay after 10 s in the toroidal trap. The first is the overall decay in the number of trapped atoms, with a lifetime of about 15 s. The second and more important limitation is the drift of the magnetic trap center during the long trapping time. The trap center moves by about half the size of the BEC during 10 s. We were able to compensate a large part of this movement by using a shim coil, but the residual movement still caused decay of the flow.

The metastable nature of persistent flow in a multiply-connected geometry arises from the free-energy barrier against decay \cite{24, 25}. An intuitive way to understand this is that, for the flow to decay, the system needs to go through a state with zero density, which costs energy when the interaction energy is much larger than the energy associated with rotation. This condition also corresponds to the speed of the flow being much smaller than the critical velocity of the system. For the weakly interacting uniform Bose gas, the critical velocity is on the order of the speed of sound, given by \(v_s = \sqrt{\mu/m}\), where \(\mu\) is the chemical potential and \(m\) is the mass of the atom. For a quantized circulation around a ring of radius \(r_0\) carrying one quantum of angular momentum, the speed of the flow is \(v_f = h/mr_0\). We chose our typical experimental conditions (number of atoms and trapping frequencies) such that \(\mu/\hbar = 0.5\) kHz, and the power and size of the plug beam such that \(r_0 \approx 10 \mu m\). Under these conditions, \(v_s = 2.9\) mm/s and \(v_f = 0.29\) mm/s, so that the metastability condition is easily satisfied.

### 2.4 Stability of the persistent flow

We also studied the importance of the multiply-connected condition for creating a persistent flow. For this, we measured the survival probability of the rotation after a trapping time of 2 s, for different values of the plug beam power. The power can be expressed in terms of the maximum dipole potential \(V_0\) (using the measured beam power and waist). As shown in Fig. 6(b), the survival probability increases above \(V_0/\mu = 1\), which corresponds to the condition of the trap being multiply- vs. singly-connected. Eventually, when the height of the pinning potential is sufficiently large, the vortex is stable.

Another interesting question regarding the metastability of superfluid flow is the dependence of the decay rate on the relative BEC and thermal (non-condensed) fractions. To study this, we first varied the temperature of the cloud by varying the final rf evaporation frequency. We then measured the survival probability of the
Fig. 6  (a) Survival probability of rotation as a function of the trapping time in a trap without the plug beam (circles) and with the plug beam (squares). (b) Survival probability as a function of the maximum height of the optical potential from the plug beam after a 2 s trapping time. (c) Survival probability as a function of the BEC fraction after 2 s trapping time.

circulation after 2 s of trapping time at these different temperatures. Each TOF absorption image (see Fig. 1(d)) was processed to fit only the large thermal part of the distribution, and then the BEC and thermal fractions were estimated from the total number of atoms in the image. However, because of additional heating in the combined trap, we have observed that the BEC fraction decreases during the trapping time. Hence, the estimated BEC fraction is the final fraction, while the initial fraction is probably higher. As seen in Fig. 6(c), the flow survives with near-unit probability with a BEC fraction as small as 15%. It is interesting to observe the survival of rotation with such a small BEC fraction, since the existence of even a small thermal fraction causes dissipation of a vortex in a simply-connected trap [26].
2.5 Stable higher circulation

Higher circulation should be stable in the toroidal trap, even under conditions for which it is unstable in a simply-connected trap. To demonstrate this, we used a larger waist ($w_0 = 15 \mu m$) plug beam, giving a smaller ratio between the flow velocity of the circulating cloud and the sound velocity, so that the stability criterion can be satisfied for the higher flow. In order to keep the trap sufficiently flat azimuthally with the larger plug, we made the TOP trap closer to cylindrically symmetric [14]. To generate higher circulation, we used an initial LG/G pulse to transfer the atoms into a state with OAM of $\hbar$ and LM of $2\hbar k$. We then used another LG/G pulse, but with a LG beam having opposite OAM, to transfer some fraction of atoms back to the zero LM state with an additional OAM of $\hbar$. Thus, a net angular momentum of $2\hbar$ was transferred.

Fig. 7 shows the TOF images of a circulating cloud after it has absorbed two units of angular momentum. The flow is stabilized in the toroidal trap for 0.5 s, then the plug beam is ramped down in 30 ms and the cloud is allowed to evolve in the TOP (harmonic) trap for some time before being released and imaged after 20 ms of TOF. In Fig. 7(a), we show the image of such a cloud after after only 4 ms in the TOP trap. There is a clear single hole in the center, which is larger due to the higher angular momentum [1, 27]. To confirm that this circulating state corresponds to a pinned, doubly-charged vortex, we allowed the cloud to evolve in the TOP trap for a longer time after the plug beam was removed. The TOF images in Figs. 7(b) and (c) show the splitting of the doubly-charged vortex into two singly-charged vortices after evolving in the TOP trap for 214 and 404 ms, respectively.

In addition to the coherent transfer of the OAM of photons to the condensate atoms, higher flow can be realized by mechanically stirring the BEC. We have observed that if the condensate is loaded into the toroidal trap slightly off axis, the sloshing motion of the BEC around the plug beam gives rise to circulation. (Additional excitations are removed by rf evaporation.) In this manner, we have observed the generation of high circulation states. Figure 8(a) is an image of a rotational state of a condensate with $5\hbar$ of circulation, taken shortly after release from the toroidal trap. The break up of such flow into five individual vortices can be seen in Fig. 8(b) and (c) if the plug beam is removed first before the atomic cloud is released from the trap. Due to the interaction of the vortices with each other, they can arrange in a pentagonal (Fig. 8(b)) and cross (Fig. 8(c)) pattern [29].

2.6 Future prospects

The observation of superfluid flow in a ring geometry raises interesting new possibilities. For example, the addition of a tunnel barrier would enable the observation of quantum tunneling of the flow of Bose-condensed atoms, analogous to the operation of a SQUID in superconductors [28]. It may be possible to create a macroscopic superposition (Schrödinger cat) of two different rotational states. Furthermore, there...
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Fig. 8  TOF images, after 22 ms, of a condensate with an initial circulation of $5\hbar$ excited by the initial sloshing motion of the BEC in the toroidal trap. (a) TOF image of the circulating state taken shortly after release from the toroidal trap. (b) and (c) Breakup of high circulation state into individual vortices after initially removing the plug beam, allow the rotating condensate to evolve in just the magnetic trap and then releasing the atomic cloud for TOF imaging.

is an open question regarding the relation between superfluidity and Bose condensation in lower dimensions. Recent experiments with a 2-D Bose gas [30] demonstrate the need for better signatures of superfluidity, such as the persistence of flow in a multiply-connected trap. With small changes to our set up, it should also be possible to create a strongly-interacting 1-D gas in a tightly-confined ring, and study its superfluid properties.

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References