Observation of Long-Lived Vortex Aggregates in Rapidly Rotating Bose-Einstein Condensates

P. Engels, I. Coddington, P. C. Haljan, V. Schweikhard, and E. A. Cornell*

JILA, National Institute of Standards and Technology and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440, USA

(Received 9 January 2003; published 1 May 2003)

We study the formation of large vortex aggregates in a rapidly rotating dilute-gas Bose-Einstein condensate. When we remove atoms from the rotating condensate with a tightly focused, resonant laser, the density can be locally suppressed, while fast circulation of a ring-shaped superflow around the area of suppressed density is maintained. Thus a giant vortex core comprising 7 to 60 phase singularities is formed. The giant core is only metastable, and it will refill with distinguishable single vortices after many rotation cycles. The surprisingly long lifetime of the core can be attributed to the influence of strong Coriolis forces in the condensate. In addition we have been able to follow the precession of off-center giant vortices for more than 20 cycles.

DOI: 10.1103/PhysRevLett.90.170405 PACS numbers: 03.75.Lm, 32.80.Pj, 67.40.Vs, 67.90.+z

The phenomenon of quantized vortex formation is a unifying feature present in many quantum mechanical systems. Vorticity is intimately connected to superfluidity and thus is a premier means for fundamental and comparative studies of different "super" systems. In dilute-gas Bose-Einstein condensates (BEC), vortex experiments have ranged from the study of individual or few vortices [1–4] and vortex rings [5,6] to the first creation of vortex lattices [7] and the study of systems containing large amounts of vorticity [8,9].

Using a refinement of our experimental technique, we have now been able to generate a giant vortex. We will use the term "giant vortex" to denote a region, containing multiple units of vorticity, in which the density is completely suppressed such that the individual vortices are no longer discernible. We note that some authors reserve this term for higher order phase singularities. The possible existence of stable giant vortices under certain conditions like supersonic flow in potentials that have strong quartic terms has been theoretically predicted (Refs. [10–12], see also Ref. [13]), and in Ref. [14] it is shown that a pinning potential can lead to stable multiquantum vortices. In our case, however, the giant vortex formation arises as a dynamic effect. Nevertheless the lifetime of our giant vortices can extend over many seconds, which we attribute to a stabilization of density features in a rapidly rotating condensate due to strong Coriolis forces. Previously, only short-lived regions containing a few phase singularities with suppressed density have been observed experimentally in Ref. [15] in the form of stripes and in Ref. [16] as the result of topological vortex formation. The influence of Coriolis forces can also induce oscillations of the giant vortex core size in the early stages of its evolution.

Our experimental starting conditions are similar to the ones described in our previous papers [9,15]. We start with a cloud of uncondensed ^{87}Rb atoms in the $|F=1, m_F=-1\rangle$ state, held in a time-averaged orbiting potential (TOP) magnetic trap and precooled to a temperature slightly above the critical temperature for Bose-Einstein condensation. By elliptically deforming the magnetic trap in the horizontal xy plane and suddenly changing the angle of the deformation, we impart angular momentum around the vertical z axis to the cloud. We then restore axial symmetry and perform a quasi-one-dimensional evaporation in a trap with frequencies $\{\omega_\rho, \omega_z\} = 2\pi\{8.3, 5.4\}$ Hz. This evaporation preferentially removes atoms close to the axis of rotation (z axis), thus spinning up the cloud. At the end of this step, we routinely achieve fast rotating condensates consisting of 3×10^6 atoms with a rotation rate of 95% of the radial trap frequency, with no detectable thermal cloud. This rotation rate is deduced from the aspect ratio, which changes from the value of 1.53 for a static cloud to 0.48 because of the centrifugal forces created by the rotation. These condensates typically contain 180 or more vortices as seen in Figs. 1(a) or 2(a). After careful optimization of the trap roundness and in the presence of a quasi-1D rf shield we are able to observe the BEC rotation for times exceeding 5 min. While we do lose atoms from the condensate over this time scale, the rotation rate remains at its initial value.

The evaporative spin-up mechanism is limited because eventually all the uncondensed atoms have been removed or condensed during the quasi-one-dimensional evaporation. However, the angular momentum per particle in the condensate can be further enhanced by selectively removing atoms with low angular momenta by a resonant, focused laser beam sent through the condensate on the axis of rotation. Since the rotating BEC typically has a Thomas-Fermi radius of 66 μm, the width of the laser beam of about 16 μm, stated here as the full width at half maximum (FWHM) of the Gaussian intensity profile, is small enough to provide sufficient selectivity. The frequency of the laser is tuned to the $F''=1 \rightarrow F'=0$ transition of the D2 line, and the recoil from

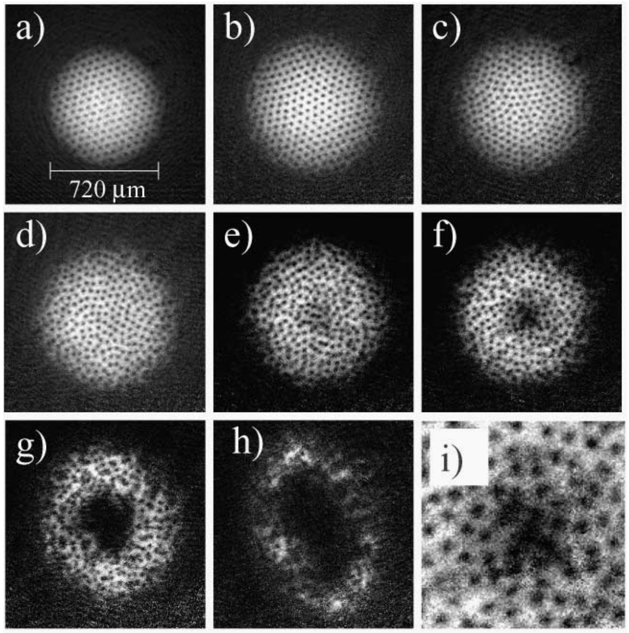

FIG. 1. Different stages of the giant vortex formation process. (a) Starting point: BEC after evaporative spin-up. (b)–(h) Laser shone onto BEC for (b) 14 s, (c) 15 s, (d) 20 s, (e) 22 s, (f) 23 s, (g) 40 s, and (h) 70 s. Pictures are taken after 5.7-fold expansion of the BEC. Laser power is 8 fW. (i) Zoomed-in core region of (f).

spontaneously scattered photons blasts atoms out of the condensate.

Using this new technique we are able to substantially increase the vorticity in the BEC and can now routinely obtain condensates containing more than 250 vortices [Fig. 1(b)]. Since these vortex cores are too small to be imaged when the BEC is held in trap, the images in Figs. 1–3 and 6 are taken after having let the BEC expand. For this, a rapid adiabatic passage technique is employed to change the hyperfine state of the atoms from the original trapped $|F = 1, m_F = -1\rangle$ state to the anti-trapped $|F = 2, m_F = -1\rangle$ state. Subsequently the minimum of the magnetic trapping field is rapidly moved below the position of the atoms so that the atoms are supported against gravity while at the same time they are radially expelled [17]. After a chosen expansion time the magnetic fields are switched off and the atoms are imaged along the original axis of rotation. This technique allows us to expand the condensate to an adjustable diameter that can exceed 1.4 mm [18].

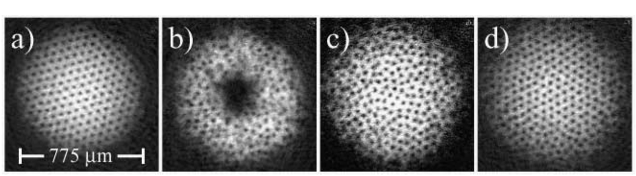

FIG. 2. Lattice reforming after giant vortex formation. (a) BEC after evaporative spin-up. (b) Effect of a 60 fW, 2.5 s laser pulse. (c),(d) Same as (b), but additional 10 s (c) and 20 s (d) in-trap evolution time after the end of the laser pulse. Images taken after a sixfold expansion of the BEC.

If the removal of central atoms is driven strongly enough, a giant vortex appears. The core is surrounded by a ring-shaped superflow. The circulation of this superflow is given by summing up all the “missing” phase singularities in the core and can assume very large values. Using the fact that for large amounts of circulation the rotation of the velocity field can be obtained classically, we determine that in some cases the BEC supports a ring-shaped superflow with a circulation of up to 60 quanta around the core. We can easily control the amount of this circulation by changing the intensity or the duration of the laser beam that removes atoms along the axis of rotation.

In our experiment the formation of the giant vortex comes about in a sequence of very distinct stages as shown in Fig. 1. For this expansion image sequence a rapidly rotating BEC is first formed by our evaporative spin-up technique. Then the atom-removal laser is applied with a fixed power of 8 fW for a variable amount of time, followed by a 10 ms in-trap evolution time and a 45 ms expansion in the antitrapping configuration described above. During the atom removal an rf shield is left on to constantly remove uncondensed atoms that tend to decelerate the condensate rotation. Figure 1(a) shows the result of only the evaporative spin-up. This particular condensate contains 180 vortices and has a Thomas-Fermi radius of 63.5 μm when held in the trap. When the atom-removal laser is applied for 14 s as in Fig. 1(b), the number of vortices is increased to 250 and the Thomas-Fermi radius to 71 μm. The rotation rate, determined from side view aspect-ratio images, has increased from $0.94\omega_\rho$ to $0.97\omega_\rho$. After atom-removal times of 15 to 20 s, the vortex lattice becomes disordered [Figs. 1(c) and 1(d)], and the giant vortex core starts to develop in the center [Figs. 1(e) and 1(f)]. An enlarged view of the core region in this early stage of giant vortex core formation is seen in Fig. 1(i), which nicely demonstrates how the individual vortices in the center consolidate. For the

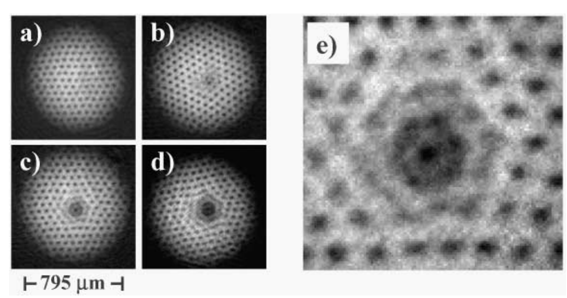

FIG. 3. Core developing after a 5 ms short, 2.5 pW laser pulse. In-trap evolution time after the end of the pulse is (a) 0.5 ms, (b) 10.5 ms, (c) 20.5 ms, and (d) 30.5 ms. Images taken after sixfold expansion of BEC. (e) Zoomed-in core region of (c).

larger removal times shown in Figs. 1(g) and 1(h), a clear elliptical deformation is observed. This deformation is due to residual static asymmetries of the trapping potential that can nearly resonantly drive quadrupolar surface modes when the rotation frequency of the condensate approaches the radial trapping frequency. We have verified this explanation by deliberately changing the roundness of the trapping potential and observing corresponding changes in the ellipticity and in the direction of the ellipse. If the trap roundness is not optimized, the ring-shaped superflow has a tendency to fragment into typically five to eight blobs that continue to rotate around the core.

If the atom-removal laser is applied only for a limited amount of time, the giant vortex will fill in and the vortices refreeze [19] into a well-ordered lattice again after a sufficiently long evolution time. An example is shown in Fig. 2. Here, the starting point is the condensate in Fig. 2(a), containing 190 vortices and rotating at $0.95\omega_\rho$. A pulse from the atom-removal laser creates the core seen in Fig. 2(b). Crudely assuming that, consistent with the observed atom removal of 35%, all atoms originally within a cylindrical volume of 0.4 times the Thomas-Fermi radius have been removed, we can perform an integral over the Thomas-Fermi density profile with a rigid-body-rotation velocity distribution and find that only 10% of the angular momentum has been removed. Since in equilibrium the total number of vortices should be linear in the average angular momentum per atom [20], we would expect that the original 190-vortex cloud should reequilibrate to form a cloud with 266 vortices, in good agreement with the value of 260 vortices observed in the reequilibrated cloud shown in Fig. 2(d).

In our case the formation of the giant vortex is not connected to a repulsive conservative optical potential produced by the central laser beam, but is due only to the removal of atoms from the axis of rotation by spontaneous photon scattering. To prove this, we have varied the laser frequency over the range from -6 MHz to $+6$ MHz around the $F'' = 1 \rightarrow F' = 0$ resonance and in all cases have been able to generate a giant vortex.

In Refs. [10–12] it is shown that quartic terms in the potential can lead to stable giant vortices. In our experiment, quartic terms are small and the giant vortex arises as a dynamical effect. We have calculated the term of the TOP trap potential that depends on the radial position as r^4. At the outer edge of the condensate this quartic term produces a correction to the potential on the order of 10^{-3}, compared to the effective r^2 term, even though the latter is much weakened by the centrifugal force. Moreover, our anharmonic terms have the wrong sign [10–12] to generate stable giant vortices. Empirically, the refilling and refreezing we observe (Fig. 2) indicates that the giant vortex is not an equilibrium configuration but has instead only dynamical stability.

We suggest an intuitive, classical picture describing the formation as a dynamical effect: the removal of atoms from the center of the condensate produces a pressure gradient due to mean field energy that tries to drive atoms from the outer regions into the center, so as to close the hole. Because of Coriolis forces, however, atoms moving radially towards the center are deflected and assume a fast azimuthal motion around the core rather than filling the core, thus creating the giant vortex.

Some exotic features of the early stages of core formation are revealed when we apply only a very short, weak atom-removal pulse and observe the subsequent evolution as in Fig. 3. Here, the atom-removal laser has a power of 2.5 pW and a fixed pulse length of 5 ms. Its FWHM of 16 μm is approximately twice the lattice spacing, 7 μm. By varying the delay time between the laser pulse and the expansion, we see (Fig. 3) that the core formation clearly lags behind the laser pulse. Figure 3(e) shows a zoomed-in view of the core region of Fig. 3(c). It is very interesting to observe that for these short, weak pulses the density depression appears to develop in discrete steps, and the step boundaries follow the hexagonal lattice pattern.

When applying stronger laser pulses, we detect clear, damped oscillations of the core area as shown in Fig. 4. We study these oscillations by analyzing in-trap images taken after a variable evolution time between the end of the atom-removal pulse and the expansion, such as the ones shown in the inset of Fig. 4. The oscillation frequency depends on the initial conditions; for the case of Fig. 4 with initially 2.2×10^6 atoms at a rotation rate of $0.9\omega_\rho$ we obtain a frequency of $3.5\omega_\rho$. Decreasing the initial rotation rate of the condensate leads to faster core-oscillation frequencies and increases the amplitude of

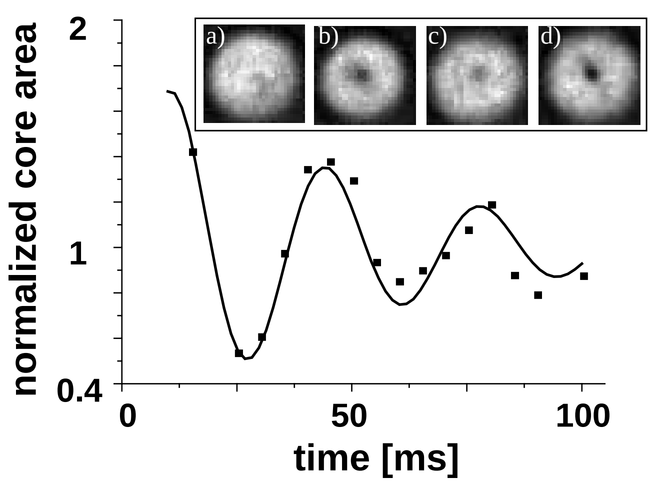

FIG. 4. Oscillation of core area after an 8 pW, 5 ms laser pulse. Starting conditions are 2.5×10^6 atoms with rotation rate $0.9\omega_\rho$. Time given is the in-trap evolution time after the end of the pulse. Core area is normalized to mean of all data points. Inset: Initial condition 3.5×10^6 atoms with rotation rate $0.78\omega_\rho$; in-trap images taken after a 14 pW, 5 ms laser pulse followed by evolution time of (a) 20 ms, (b) 40 ms, (c) 60 ms, and (d) 80 ms.

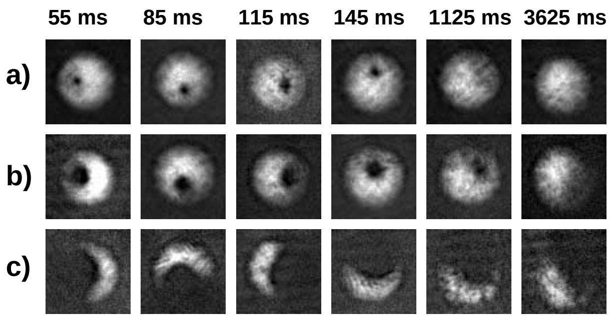

FIG. 5. Giant core precession. Cores created by a 10 ms off-centered laser pulse with a power of (a) 4.2 pW, (b) 33 pW, and (c) 470 pW. Time given in figure is in-trap evolution time after the end of the laser pulse. For reference, a naive expectation for the lifetime of a giant vortex given by the radius of the core divided by the speed of sound in the surrounding cloud would be 13 and 30 ms for (a) and (b), respectively.

this oscillation; for rotation rates below $0.9\omega_\rho$ in-trap images even show a near complete closure of the core, followed by the core opening again (see inset of Fig. 4). Presumably these oscillations arise when a sudden removal of atoms leaves forces from the density gradient and Coriolis forces initially out of equilibrium. The core oscillation is not observed to be related to an overall breathing mode of the condensate.

In addition we can observe the precession [2] of an off-center giant vortex. For this, the atom-removal laser is deliberately offset from the center of cloud rotation. The duration of the removal pulse is kept short (10 ms) in comparison to the initial vortex lattice rotation period $[2\pi/(0.95\,\omega_\rho) = 126\text{ ms}]$ so as to create only a local hole. By using different laser powers, we can vary the size of the core from a small hole as in Fig. 5(a) all the way to the extreme case of a big hole that leaves only a crescent segment of the BEC as shown in Fig. 5(c), and the precession of these holes can be monitored by applying variable evolution times of the trapped BEC after the atom-removal pulse is finished. In all three cases the measured precession frequency is approximately ω_ρ. In the case of Figs. 5(b) and 5(c) we are able to follow the precession for more than 20 cycles. If, instead, the laser is left on for approximately a full lattice rotation cycle, a complete ring can be cut out of the condensate [Fig. 6(a)], which eventually breaks up into many individual blobs [Fig. 6(c)], each of which supports remnants of the original lattice. Both the long-lived core precession as well as the ring structure in Fig. 6 are impressive demonstrations of the stability of density features due to Coriolis forces in rapidly rotating condensates.

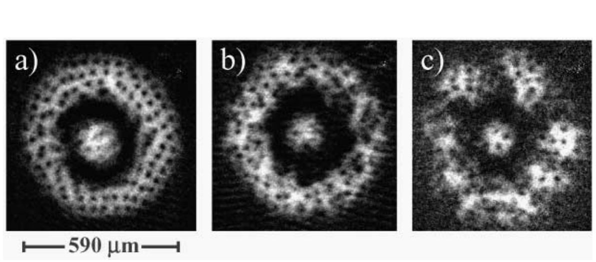

FIG. 6. Ring cut out of a BEC by a 125 ms long, off-centered laser pulse. Expansion image taken (a) directly after the end of the pulse (b) after an additional in-trap evolution time of 200 ms after the end of the pulse and (c) evolution time 2 s.

Finally, we also observe that the sudden extraction of atoms can launch transverse modes in the lattice [21], which will be the subject of a future publication.

The work presented in this paper was funded by the NSF and NIST. P. E. acknowledges support by the Alexander von Humboldt Foundation.

*Quantum Physics Division, National Institute of Standards and Technology.

[1] M. R. Matthews *et al.*, Phys. Rev. Lett. **83**, 2498 (1999).
[2] B. P. Anderson, P. C. Haljan, C. E. Wieman, and E. A. Cornell, Phys. Rev. Lett. **85**, 2857 (2000).
[3] K. W. Madison, F. Chevy, W. Wohlleben, and J. Dalibard, Phys. Rev. Lett. **84**, 806 (2000).
[4] E. Hodby, G. Hechenblaikner, S. A. Hopkins, O. M. Maragó, and C. J. Foot, Phys. Rev. Lett. **88**, 010405 (2001).
[5] B. P. Anderson *et al.*, Phys. Rev. Lett. **86**, 2926 (2001).
[6] Z. Dutton, M. Budde, C. Slowe, and L. V. Hau, Science **293**, 663 (2001).
[7] K. W. Madison, F. Chevy, V. Bretin, and J. Dalibard, Phys. Rev. Lett. **86**, 4443 (2001).
[8] J. R. Abo-Shaeer, C. Raman, J. M. Vogels, and W. Ketterle, Science **292**, 476 (2001).
[9] P. C. Haljan, I. Coddington, P. Engels, and E. A. Cornell, Phys. Rev. Lett. **87**, 210403 (2001).
[10] E. Lundh, Phys. Rev. A **65**, 043604 (2002).
[11] K. Kasamatsu, M. Tsubota, and M. Ueda, Phys. Rev. A **66**, 053606 (2002).
[12] U. R. Fischer and G. Baym, cond-mat/0111443; G. M. Kovoulakis and G. Baym, cond-mat/0212596.
[13] A. L. Fetter, Phys. Rev. A **64**, 063608 (2001).
[14] T. P. Simula, S. M. M. Virtanen, and M. M. Salomaa, Phys. Rev. A **65**, 033614 (2002).
[15] P. Engels, I. Coddington, P. C. Haljan, and E. A. Cornell, Phys. Rev. Lett. **89**, 100403 (2002).
[16] A. E. Leanhardt, A. Görlitz, A. P. Chikkatur, D. Kielpinski, Y. Shin, D. E. Pritchard, and W. Ketterle, Phys. Rev. Lett. **89**, 190403 (2002).
[17] H. J. Lewandowski, D. M. Harber, D. L. Whitaker, and E. A. Cornell (to be published).
[18] We hope eventually to use the strength of Fourier peaks of a vortex lattice as a measure of condensation (J. Sinova, C. B. Hanna, and A. H. MacDonald, cond-mat/0209374). Enhanced expansion is needed, or the outer rings of peaks in the Fourier plane will be lost because of insufficient imaging resolution.
[19] J. R. Abo-Shaeer, C. Raman, and W. Ketterle, Phys. Rev. Lett. **88**, 070409 (2002).
[20] D. L. Feder and C. W. Clark, Phys. Rev. Lett. **87**, 190401 (2001).
[21] J. R. Anglin and M. Crescimanno, cond-mat/0210063.