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Dynamics of Quadruply Quantized Vortices in ^{87}Rb Bose–Einstein Condensates Confined in Magnetic and Optical Traps

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We studied the dynamics of quadruply quantized vortices in ^{87}Rb Bose–Einstein condensates. Vortices were created in magnetically trapped condensates with hyperfine spin $F = 2$ by employing topological phase imprinting technique, wherein the direction of atomic spin is adiabatically reversed by applying a bias magnetic field. Vortices were observed for a holding time of up to 10 ms. Disappearance of the vortices was attributed to considerable expansion and excitation of the condensates, which were caused by the distortion of the magnetic potential. In order to observe the long-term behavior of the vortices, we transferred the condensates to a crossed-type optical dipole force trap after creating the vortices. In this case, the vortices were observed for a holding time of up to 22 ms. We also observed density profiles, which indicated the presence of split vortices.

KEYWORDS: quantized vortex, Bose–Einstein condensate, topological phase, optical dipole force trap, instability
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1. Introduction

Quantized vortices are characteristic phenomena of quantum fluids such as superfluid helium,[1] superconductors,[2] and gaseous Bose–Einstein condensates[3] and play an important role in the dynamics of such quantum fluids. Vortices in gaseous condensates have been experimentally created by employing various methods such as dynamical phase imprinting,[4] rotation of an anisotropic potential,[5–8] slicing of an atomic cloud with a laser,[9] use of a soliton decay,[10,11] topological phase imprinting,[12,13] and transformation of an orbital angular momentum of a photon to an atom.[14] Especially, the last two methods are very distinct since they yield a multiply charged vortex.[15,16] To date, doubly and quadruply quantized vortex states have been created,[12–14] and their decay dynamics and time evolution have been studied.[17,18]

The topological phase imprinting method has been applied to condensates confined in an Ioffe–Pritchard magnetic trap.[12,13] In order to create a vortex, atomic spins, which are initially almost parallel to the axial direction of the trap, are adiabatically rotated to the opposite direction by applying an additional bias magnetic field. During this process, each spin located at a different position in the trap follows the local magnetic field direction, and the phase winding with a magnitude of spin times 4π is imprinted onto the condensate wave function.[15,16] If the parameters of the Ioffe–Pritchard magnetic trap are maintained constant during applying the additional bias field, the final magnetic potential for weak-field-seeking atoms changes to a deformed shape with a saddle point. As a result, the condensate is no longer trapped in the axial direction and continues to deform, thereby considerably affecting the generated vortex. The observation time of vortices is limited to less than few tens of milliseconds when the direction of axial magnetic field is reversed by the additional bias field alone.[12,13] In order to remove this limitation, a research group from MIT changed the direction of the currents that generate axial confinement of the magnetic trap in addition to the ramping of the bias field strength. They observed the dynamical instability of doubly quantized vortices in condensates for a trapping time of 80 ms.[17] On another front, a research group from Kyoto applied an optical dipole force in addition to employing the magnetic trap to suppress the deformation of condensates in the trap, and they measured the splitting of quadruply quantized vortices for approximately 10 ms.[18]

Another promising method to control the deformation of condensates and perform long-term measurements of vortex dynamics involves transferring the condensates to an optical dipole force trap from the magnetic trap. In an optical trap, in contrast to the case of the magnetic trap, a magnetic field can be used as an experimentally controllable parameter, since the optical dipole force on atoms is insensitive to an external magnetic field. In addition, the optical trap liberates the internal spin degrees of freedom of atoms,[19] thereby enabling the study of spinor condensates.[20,21] The spinor condensates in vortex states play important role for studying theoretically predicted various topological structures such as skyrmions,[22,23] knot structures,[24] and half-quantum vortex.[25]

In this study, we successfully transferred the vortex-imprinted condensates to a crossed-type optical trap from the magnetic trap. Quadruply quantized vortices were created in the magnetically trapped condensates by topological phase imprinting. The lifetime of the vortices in the magnetic trap was up to 10 ms which was approximately two times longer than that in previous study.[13] For the vortex-imprinted condensates transferred into the optical trap, the expansion of atomic cloud was considerably suppressed and vortices were observed even after 22-ms confinement. Additionally, we observed the plural vortices that were expected to be generated from the splitting of a quadruply quantized vortex.

2. Experimental

The experimental setup and technique used for preparing ^{87}Rb Bose–Einstein condensates and a crossed-type far-off-resonant optical dipole force trap are described in detail in

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previous studies.[26,27] More than 10^9 cold atoms were collected by using a double magneto-optical trap system, subsequent to which they were transferred into a clover-leaf configuration Ioffe–Pritchard (IP) magnetic trap.[28] The atoms were then cooled to form the condensate by forced radio-frequency evaporation. Typically, the created condensates comprised approximately 5×10^5 atoms.

The IP magnetic trap consists of a steep radial gradient field and a gradual axial curvature field.[29] Hence, the condensate is cigar-shaped and extended along the axial direction. Since the radial field strength is considerably weak when compared with the axial field strength in the vicinity of the bottom of the trap potential, the field strength around that point is ruled by the curvature field. Hence, the spins of the condensed atoms are nearly parallel to the axial direction. In our experiment, the field strength at the bottom of the potential was 0.5 G.

In order to generate vortices by topological phase imprinting, the spins of the condensed atoms were adiabatically reversed to the opposite direction by applying a bias magnetic field. Since the atomic spins follow the respective local magnetic field directions during field reversal, the rotation of the spins is different at different location in the magnetic trap. A very simple visualized explanation for the changes in the spin directions and the topological phases when the atomic spin equals one is provided in Fig. 2 in ref. 16. As a result of the field (spin) reversal, phase winding with a magnitude of spin times 4π is imprinted onto the condensate. In this study, since we employed ^{87}Rb condensates with $F = 2$, the imprinted phase winding was 8π, which corresponded to a quadruply quantized vortex.

Figure 1(a) shows the timing chart associated with vortex creation in the magnetic trap. We applied an axially directed bias field immediately after evaporative cooling and ramped it from 0 to -1.0 G. Hence, the total field strength at the bottom of the potential eventually became -0.5 G. We varied the ramp time from 3 to 20 ms and found that vortices were observed at 100% reproducibility when the field was reversed for 5 ms. Therefore, we carried out all the measurements in this study with the 5-ms field reversal. We observed the evolution of vortices in the magnetically trapped condensates without turning off the applied bias field.

We employed a crossed-type configuration with far-off-resonant laser beams as the optical dipole force trap. We used two single-mode diode lasers with a wavelength of 850 nm and a power of 150 mW. One of the focused laser beams was horizontally irradiated to the condensates along the long axis, which corresponds to the axial direction, of the elongated condensates. The second focused beam was also horizontally irradiated to the condensates such that this beam rectangularly crossed the first beam at the trap point of the condensates. Various parameters for the trapping lasers and the optical trap are the same as those in refs. 26 and 27. We introduced the optical trap 50 ms before the end of evaporative cooling and exponentially increased the laser power in 50 ms as shown in Fig. 1(b). We started to ramp the bias field just after the optical trap reached the optimum potential depth (approximately 1 μK), and we turned off the magnetic trap and the bias field at the end of the field reversal.

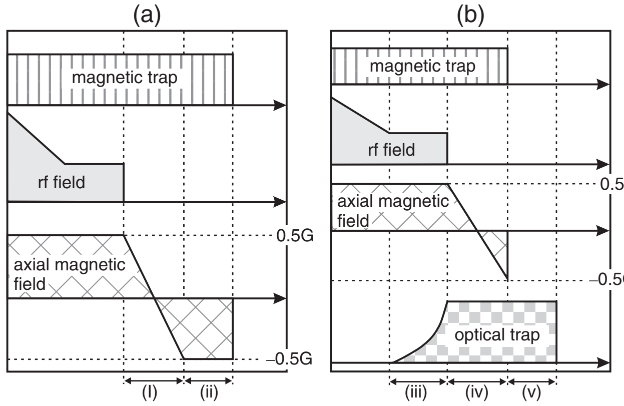

Fig. 1. Timing charts associated with (a) vortex creation in the magnetic trap, and (b) transfer into the optical trap. Operations corresponding to a magnetic trap, radio frequency field for evaporative cooling, axial magnetic field, and optical trap are indicated. (i) and (iv) indicate the reversal times of the axial field, (ii) and (v) show the holding times in the trap, and (iii) denotes the ramp time of optical trap.

Condensates were released from the trap after different holding times, and absorption images were taken to confirm the existence of vortices and observe their dynamics. We took images from two directions — one parallel and the other vertical to the axial direction.

3. Results and Discussion

3.1 *Vortices in magnetically trapped condensates*

We first discuss the dynamics of vortices in magnetically trapped condensates. Absorption images of the vortices are shown in Figs. 2(b)–2(d). Images were taken from the axial direction after free expansion for 19 ms. At the center of the condensate, defects in atomic density, which provide evidence for the existence of vortex, are confirmed. If the defects are produced due to atomic spin flips into untrapped states, which are referred to as Majorana flops[29] and may occur when the field passes over zero point, the defects collapse during a free expansion of the condensates. A typical image of a normal condensate without a vortex is shown in Fig. 2(a) for drawing a comparison. We did not employ a method which provides an image of a thick-slice part of the condensate;[17] hence, the existence of a vortex could be verified if the arrangement of the defect was linear to the imaging direction.

Here, we discuss about the lifetime of vortices in magnetically trapped condensates. In the context of this study, lifetime refers to the time for which a vortex is evidently visible in an image. We checked the existence of vortices by changing the holding time at an interval of 1 ms. Images for the holding times of 6 ms and 10 ms are shown in Figs. 2(c) and 2(d), respectively. We could confirm the existence of vortices up to the 10-ms holding time; however, the probability of observing the vortices at this holding time was approximately 10%. Vortices were not observed for a holding time greater than 11 ms.

The restriction on the lifetime of vortices would be caused by bending or slanting of vortex line toward the imaging beam, or tangling of singly quantized vortices resulted from the decay of quadruply quantized vortex, in combination with the expansion of condensates induced by the field

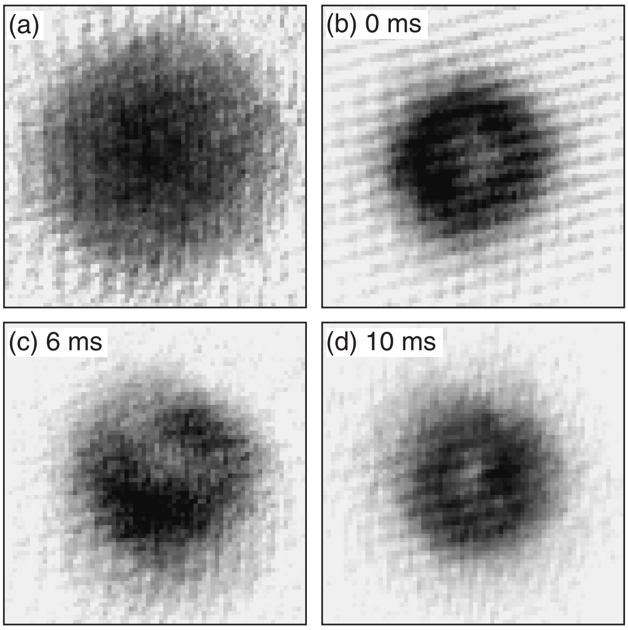

Fig. 2. Absorption images of condensates taken from the axial direction after free expansion for 19 ms. (a) Normal condensate without vortex. The number of atoms is 4×10^5. (b)–(d) Vortex-imprinted condensates held in magnetic trap for 0, 6, and 10 ms. The number of atoms is approximately 1.5×10^5. The field of view in each image is $185 \times 185\,\mu\text{m}^2$.

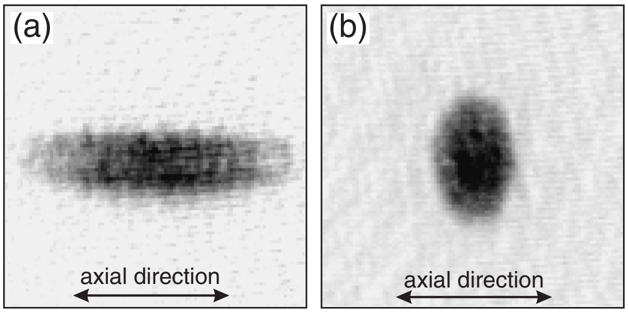

Fig. 3. Absorption images of condensates taken from the radial direction. (a) Image of condensate with field reversal taken after the holding time of 10 ms and the free expansion of 15 ms. The number of atoms is 1.5×10^5. (b) Normal condensate without field reversal taken after the free expansion of 18 ms. The number of atoms is 5×10^5. The field of view in each image is $495 \times 495\,\mu\text{m}^2$.

reversal (we discuss the decay of the vortex later). Figure 3 shows the absorption images of condensates taken from the radial direction, namely which correspond to lateral images of atomic clouds shown in Fig. 2. An image of Fig. 3(a) shows the condensate taken after the 10-ms holding time and the 15-ms free expansion. In comparison with a free-expansion image of the normal (without field reversal) condensate [Fig. 3(b)], we can see an enormous expansion of the condensate along the axial direction due to trap deformation by the field reversal. We also show the evolution of condensates with field reversal for various holding times taken after the free expansion of 19 ms in Fig. 4. All the images were taken from the radial direction. One can see that the length of condensates along the axial direction increases almost proportional to the holding time. We derived the velocity of the expansion to be 17 mm/s. From this value, we calculate the average kinetic energy per

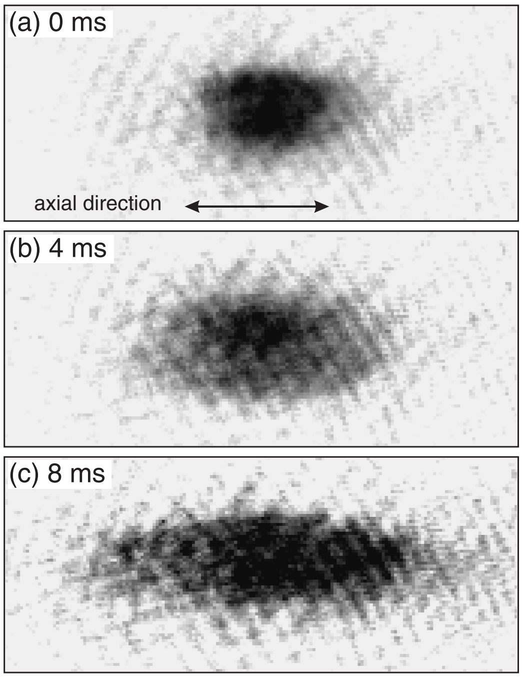

Fig. 4. Images of condensates with field reversal taken after various holding times in the magnetic trap from the radial direction. The free-expansion time is 19 ms. The holding time is shown in each image. The field of view in each image is $840 \times 355\,\mu\text{m}^2$.

atom to be 150 nK. This is 1.7 times larger than the chemical potential of a condensate with 1.5×10^5 atoms. Such large velocity fields considerably disturb the vortex, and then probably induce bending or slanting of vortex line, or tangling of plural singly quantized vortices. And in this study, the vortex could not be observed clearly if the vortex line was parallel to the imaging direction as mentioned. As a result, the disappearance of vortices would occur at short time.

The vortex lifetime was as short as 10 ms; however, this value is more than two times larger than the value in ref. 13, in which quadruply quantized vortices in ^{87}Rb condensates were studied. The ramp time employed in ref. 13 is a few milliseconds shorter than our value. Therefore, the condensates in ref. 13 are expected to move more rapidly in the trap during the field reversal than the condensates studied herein. As a result, the created vortices might be more disturbed and destroyed in a short time.

We often observed density profiles with deformed defects as shown in Fig. 2(c). Similar density profiles were occasionally observed at a holding time greater than 5 ms. These profiles are very similar to the density profiles observed by the Kyoto group,[18] in which four singly quantized vortices formed a board-like structure that resulted in the decay of the quadruply quantized vortex. Unfortunately, the reproducibility of these profiles was not high in our experiments, and hence, we could not observe the dynamics such as precession of split vortices, which were observed by the Kyoto group.

3.2 Vortices in optically trapped condensates

Here, we discuss about the observation of vortices in optically trapped condensates. We employed a crossed-type optical dipole force trap as mentioned above. Although we

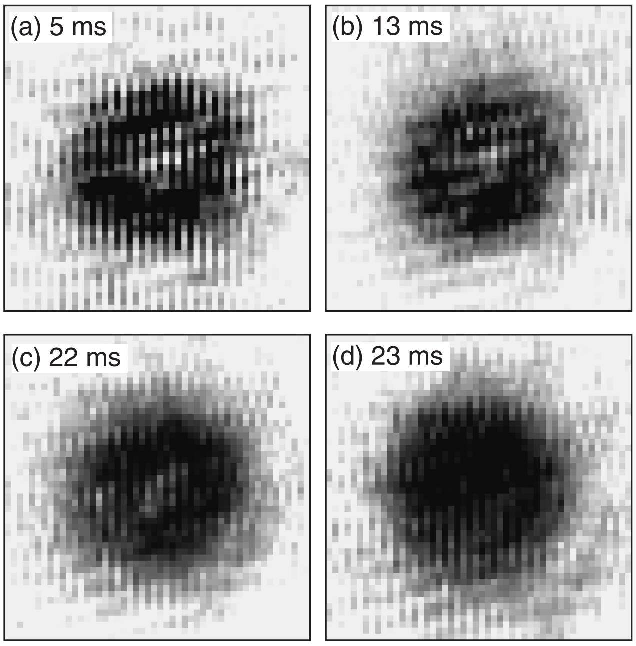

Fig. 5. Absorption images of vortex-imprinted condensates released from an optical trap after the holding time of (a) 5, (b) 13, (c) 22, and (d) 23 ms. Image (a) was taken after the free expansion of 14 ms and all the other images were taken after the free expansion of 12 ms. The fine stripes seen in the images are the interference patterns caused by a probe laser. The field of view in each image is $130 \times 130\,\mu m^2$.

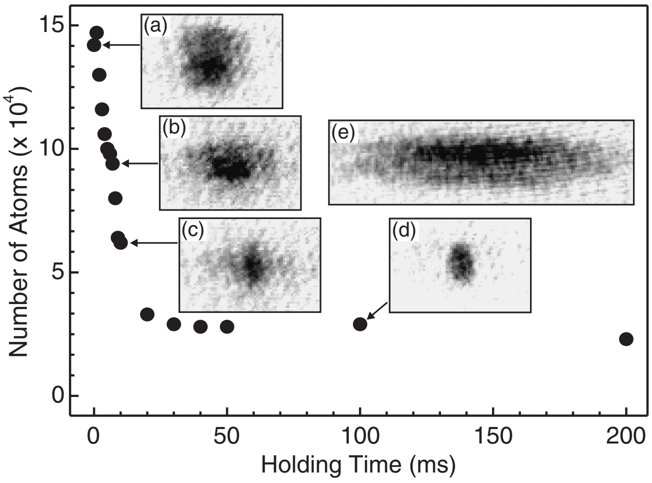

Fig. 6. The number of condensed atoms as a function of the holding time in an optical trap. Absorption images taken from the radial direction for the holding time of (a) 0, (b) 5, (c) 10, and (d) 100 ms. The field of view in each image is $340 \times 220\,\mu m^2$. (e) Image obtained by radial probing of a magnetically trapped (without optical trap) condensate with field reversal for the holding time of 10 ms. The field of view is $750 \times 200\,\mu m^2$. All the images were taken after the free expansion of 15 ms.

could successfully transfer condensates from a magnetic trap to an optical trap at 100% efficiency in previous studies,[26,27] the transfer efficiency in this study was restricted to 60%. We expect that this atomic loss is caused by an expansion and a gravitational sag[13,30] of the condensates during field reversal. We aligned the trapping beams such that the transfer efficiency in the case without field reversal is maximized. Under this condition, the center of the optical trap nearly overlapped with the center of the condensates confined in the magnetic trap. Since both laser beams used for the crossed-type optical trap propagate horizontally, trapping force is reduced for the movement of the condensates in the direction of gravity. Consequently, it is probable that the atoms partly spill over from the optically trapped region due to the expansion and the sag of condensates.

We performed lifetime measurements for vortices in optically trapped condensates. Figure 5 shows the free-expansion images of vortex-imprinted condensates taken for various holding times. The existence of a vortex could be confirmed for the holding time of up to 22 ms. This value is two times larger than the holding time in the case of magnetically trapped condensates. The probability of observing vortices in a series of measurements were more than 90% for the 5-ms holding time, approximately 50% for the 13-ms holding time, and a few percent for the 22-ms holding time. The images in Fig. 5 are slightly unclear in comparison with images in Fig. 2. This could be attributed to the rapid loss of atoms in the optical trap. Figure 6 shows the number of condensed atoms in the optical trap as a function of holding time. Radial absorption images taken after the free expansion of 15 ms are also shown for some holding times. The $1/e$ lifetime for the data up to 20 ms was obtained to be 12.5 (1.0) ms. In our previous study,[26] the lifetime of condensed atoms in an optical trap for normal condensates was measured to be 4.0 (1.6) s. Therefore, the rapid decrease in the number of condensed atoms is probably induced by the momentum given to condensates through field reversal and the transfer of condensates from magnetic trap to optical trap. On the other hand, we observed considerable suppression of deformation of condensates, as shown in Figs. 6(a)–6(d). We expect that this contributes to an increase in the lifetime of vortices. The gradual loss of atoms in the region of the holding above 20 ms could be due to the damping of excitation in condensates.

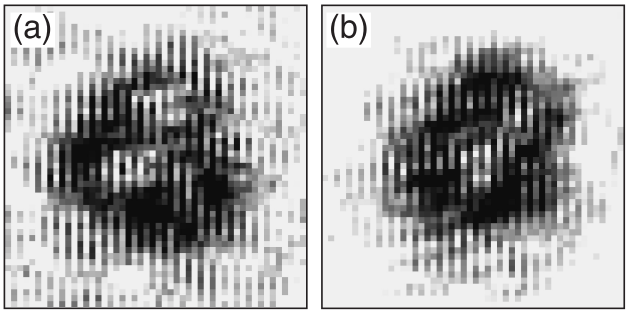

Fig. 7. Examples of images suggesting multiple vortices. The holding and free-expansion times are 10 and 15 ms, respectively, for (a), and 18 and 13 ms, respectively, for (b). The fine stripes seen in the images are interference patterns caused by the probe laser. The field of view in each image is $130 \times 130\,\mu m^2$.

While carrying out lifetime measurements, we occasionally observed density profiles that suggested the existence of multiple vortices in a condensate. Figure 7 shows the typical examples. Although the images are rather unclear, one can see two or three holes in Fig. 7(a), and two in 7(b). These density profiles appeared at a holding time greater than 10 ms. Decay dynamics of quadruply quantized vortices were investigated by the Kyoto group.[18] They reported that four singly quantized vortices, which resulted in the decay of the quadruply quantized vortex, form a board-like structure. However, the appearance of two or three density defect areas were not reported. Although the systematic studies were desired to demonstrate the decay process of the quadruply quantized vortex and the dynamics of the observed plural vortices in detail, it was difficult to carry out the systematic investigations because of the low reproducibility of the plural vortices.

4. Conclusions

We studied the dynamical behavior of quadruply quantized vortices in magnetically and optically trapped ^{87}Rb Bose–Einstein condensates. The vortices were successfully created in magnetically trapped condensates by employing topological phase imprinting method. For suppressing the rapid expansion of magnetically trapped condensates induced by the imprinting with field reversal and achieving long-term measurements of the vortex dynamics, the vortex-imprinted condensates were transferred into the crossed-type optical trap and all-optically confined.

In the case of magnetically trapped condensates, we could observe vortices for a holding time of up to 10 ms. The short lifetime would be attributed to the vortex dynamics, such as the bend and the slant of vortex line or the tangle of plural vortices, and the expansion of condensates caused by the deformation of the trap. We occasionally observed density profiles, which were probably caused by the decay of the quadruply quantized vortex and a board-like structure formed by four singly quantized vortices reported in ref. 18.

In optically trapped condensates, vortices were observed for a holding time of up to 22 ms in spite of the rapid loss of atoms. The longer lifetime could be attributed to the suppression of expansion and excitation of condensates. We occasionally observed condensates with multiple holes. However, a systematic study was not undertaken because of the fairly low reproducibility of the results of observation.

In principle, one can not avoid the deformation of condensates if the topological imprinting method is applied to the magnetically trapped condensates for creating the vortices. By applying this method to optically trapped condensates, the disturbance on condensates can be exceptionally improved. Motivated by this advantage, we plan to realize the experimental system for applying the topological imprinting method to the condensates confined in the optical trap and study profound dynamics of multiple quantized vortex, such as the formation of spiral, chainlike, and mesh-like structures.[31–33)]

Acknowledgments

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1) D. R. Tilley and J. Tilley: *Superfluidity and Superconductivity* (Hilger, Bristol, U.K., 1986); R. J. Donnelly: *Quantized Vortices in Helium II* (Cambridge University Press, Cambridge, U.K., 1991).
2) M. Tinkham: *Introduction to Superconductivity* (MacGrow-Hill, New York, 1996).
3) C. J. Pethick and H. Smith: *Bose–Einstein Condensation in Dilute Gases* (Cambridge University Press, Cambridge, U.K., 2002); L. Pitaevskii and S. Stringari: *Bose–Einstein Condensation* (Oxford University Press, Oxford, U.K., 2003).
4) M. R. Matthews, B. P. Anderson, P. C. Haljan, D. S. Hall, C. E. Wieman, and E. A. Cornell: Phys. Rev. Lett. **83** (1999) 2498.
5) K. W. Madison, F. Chevy, W. Wohlleben, and J. Dalibard: Phys. Rev. Lett. **84** (2000) 806.
6) J. R. Abo-Shaeer, C. Raman, J. M. Vogels, and W. Ketterle: Science **292** (2001) 476.
7) P. C. Haljan, I. Coddington, P. Engels, and E. A. Cornell: Phys. Rev. Lett. **87** (2001) 210403.
8) E. Hodby, G. Hechenblaikner, S. A. Hopkins, O. M. Maragò, and C. J. Foot: Phys. Rev. Lett. **88** (2001) 010405.
9) S. Inouye, S. Gupta, T. Rosenband, A. P. Chikkatur, A. Görlitz, T. L. Gustavson, A. E. Leanhardt, D. E. Pritchard, and W. Ketterle: Phys. Rev. Lett. **87** (2001) 080402.
10) Z. Dutton, M. Budde, C. Slowe, and L. V. Hau: Science **293** (2001) 663.
11) B. P. Anderson, P. C. Haljan, C. A. Regal, D. L. Feder, L. A. Collins, C. W. Clark, and E. A. Cornell: Phys. Rev. Lett. **86** (2001) 2926.
12) A. E. Leanhardt, A. Görlitz, A. P. Chikkatur, D. Kielpinski, Y. Shin, D. E. Pritchard, and W. Ketterle: Phys. Rev. Lett. **89** (2002) 190403.
13) M. Kumakura, T. Hirotani, M. Okano, Y. Takahashi, and T. Yabuzaki: Phys. Rev. A **73** (2006) 063605.
14) M. F. Andersen, C. Ryu, Pierre Cladé, Vasant Natarajan, A. Vaziri, K. Helmerson, and W. D. Phillips: Phys. Rev. Lett. **97** (2006) 170406.
15) M. Nakahara, T. Isoshima, K. Machida, S. Ogawa, and T. Ohmi: Physica B **284–288** (2000) 17.
16) T. Isoshima, M. Nakahara, T. Ohmi, and K. Machida: Phys. Rev. A **61** (2000) 063610.
17) Y. Shin, M. Saba, M. Vengalattore, T. A. Pasquini, C. Sanner, A. E. Leanhardt, M. Prentiss, D. E. Pritchard, and W. Ketterle: Phys. Rev. Lett. **93** (2004) 160406.
18) T. Isoshima, M. Okano, H. Yasuda, K. Kasa, J. A. M. Huhtamäki, M. Kumakura, and Y. Takahashi: Phys. Rev. Lett. **99** (2007) 200403.
19) D. M. Stamper-Kurn, M. R. Andrews, A. P. Chikkatur, S. Inouye, H.-J. Miesner, J. Stenger, and W. Ketterle: Phys. Rev. Lett. **80** (1998) 2027.
20) T. Ohmi and K. Machida: J. Phys. Soc. Jpn. **67** (1998) 1822.
21) T.-L. Ho: Phys. Rev. Lett. **81** (1998) 742.
22) J. Ruostekoski and J. R. Anglin: Phys. Rev. Lett. **86** (2001) 3934.
23) U. A. Khawaja and H. Stoof: Nature (London) **411** (2001) 918.
24) Y. Kawaguchi, M. Nitta, and M. Ueda: Phys. Rev. Lett. **100** (2008) 180403 [Errata; **101** (2008) 029902].
25) S. Hoshi and H. Saito: Phys. Rev. A **78** (2008) 053618.
26) T. Kuwamoto, K. Araki, T. Eno, and T. Hirano: Phys. Rev. A **69** (2004) 063604.
27) S. Tojo, A. Tomiyama, M. Iwata, T. Kuwamoto, and T. Hirano: Appl. Phys. B **93** (2008) 403.
28) M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. M. Kurn, D. S. Durfee, and W. Ketterle: Phys. Rev. Lett. **77** (1996) 416.
29) W. Ketterle, D. S. Durfee, and D. M. Stamper-Kurn: in *Bose–Einstein Condensation in Atomic Gases*, ed. M. Inguscio, S. Stringari, and C. E. Wieman (ISO, Amsterdam, 1999) p. 67.
30) Y. Kawaguchi, M. Nakahara, and T. Ohmi: Phys. Rev. A **70** (2004) 043605.
31) M. Möttönen, T. Mizushima, T. Isoshima, M. M. Salomaa, and K. Machida: Phys. Rev. A **68** (2003) 023611.
32) J. A. M. Huhtamäki, M. Möttönen, T. Isoshima, V. Pietilä, and S. M. M. Virtanen: Phys. Rev. Lett. **97** (2006) 110406.
33) T. Isoshima: J. Phys. Soc. Jpn. **77** (2008) 094001.