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Trapping of ultra-cold atoms with the magnetic field of vortices in a thin-film superconducting micro-structure

T Müller\textsuperscript{1,2}, B Zhang\textsuperscript{1}, R Fermani\textsuperscript{1,2}, K S Chan\textsuperscript{1}, Z W Wang\textsuperscript{1}, C B Zhang\textsuperscript{1}, M J Lim\textsuperscript{1,3} and R Dumke\textsuperscript{1,4}

\textsuperscript{1} Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371, Singapore
\textsuperscript{2} Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore
\textsuperscript{3} Department of Physics and Astronomy, Rowan University, 201 Mullica Hill Road, Glassboro, NJ, USA
E-mail: rdumke@ntu.edu.sg

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\textbf{Abstract.} We store and control ultra-cold atoms in a new type of trap using the magnetic fields of vortices in a high-temperature superconducting micro-structure. We generate the attractive trapping potential for the atoms by combining the magnetic field of a superconductor in the remanent state with external homogeneous magnetic fields. We show the control of crucial atom trap characteristics such as an efficient intrinsic loading mechanism, spatial positioning of the trapped atoms and the vortex density in the superconductor. The measured trap characteristics are in good agreement with our numerical simulations.
1. Introduction

Atom-optical systems combined with well-established superconductor technology allow a new generation of fundamental experiments and applications, potentially enabling a coherent interface between neutral atoms and solid-state quantum devices. Important applications include the quantum state transfer and manipulation between atomic and solid-state systems, which are of great interest for quantum information. For this purpose, the combination of atomic or molecular quantum systems with quantum states in superconducting solid-state devices has been proposed in various forms [1]–[8]. Recently, superconducting current-carrying chips have been used to implement micro-traps for neutral atoms [9]–[11] and advantages over conventional chips have been shown [12]–[14]. A prominent approach for quantum state manipulation in superconductors utilizes the magnetic flux quantum [15]–[18]. The flux quantum is of particular interest as an interface between atomic quantum systems and solid-state quantum devices because atoms with a magnetic dipole moment can be manipulated to high precision using magnetic fields. The pairing of atoms with quantized magnetic flux is a promising way for achieving a controlled interaction with possible applications in quantum technology and fundamental studies.

In this paper, we report the magnetic trapping of $^{87}$Rb atoms that relies on the controlled coupling with vortices in a type-II superconductor. This shows that vortices are a useful tool for atomic manipulation and stable trapping. Near-field noise is strongly reduced due to the proximity of the superconductor, and technical noise is minimized as no transport current is applied. We can imprint and control the superconductor magnetization by tuning the externally applied magnetic field in a straightforward manner. The magnetization can be reset by cycling the temperature through $T_c$. We do not observe any heating or trap loss due to vortex fluctuations [19, 20]. However, this could be investigated by operating the superconductor in different temperature ranges or by applying a transport current. Additionally, the dynamics of the vortex penetration at different film temperatures or applied magnetic fields and the influence of dendritic avalanches could be studied via the position and lifetime of the trapped atomic cloud.

2. Basic operational principle of the vortex-based micro-trap

The basic principles of the vortex-based trap are schematically shown in figure 1. The trap is created by a type-II superconducting thin-film strip on a chip substrate. No magnetic field is applied as the superconductor crosses the transition temperature $T_c$. Below $T_c$ the film is ideally...
in the Meissner state, repelling any subsequently applied magnetic field smaller than the first critical field $B_{c1}$ (figure 1(a)). To introduce vortices a magnetic field $B_{z,t0} > B_{c1}$ perpendicular to the chip surface is applied at time $t_0$ and field lines start penetrating the film (figure 1(b)). The magnetic field is raised to a value $B_{z,t0}$ well above $B_{c1}$ but below the second critical field $B_{c2}$. Afterwards the magnetic field $B_{z,t0}$ is turned off. Due to the properties of the thin film, a large fraction of the vortices remains trapped. The vortices remaining in the film are not isotropically distributed and the superconductor is referred to as being in the remanent state [21, 22]. Figure 1(c) represents a simplified picture of the magnetic field due to a vortex trapped in the center of the strip. After preparing the trapped flux, the inhomogeneous field created by the vortices is combined with a magnetic bias field $B_{x,t1}$ at time $t_1$ parallel to the surface of the thin film. This generates a field minimum below the strip (figure 1(d)), which is used to trap ultra-cold atoms.

3. Simulation of the vortex-based micro-trap

We simulate the magnetic potentials of the vortex-based trap by means of mesoscopic models for magnetic flux penetration in type-II superconductors [21]–[23]. In our simulations, we assume that for an increasing external field $B_z$ above $B_{c1}$, the vortices penetrate the superconductor from the edges and move toward the center of the strip. The spatial extent of the flux incursion $b$ from the edges depends on the applied field $B_z$, the critical current density $j_c$, and the width $a$ and thickness $d$ of the strip according to the formula

$$b = \frac{a}{2} \left(1 - \frac{1}{\cosh(\pi B_z/\mu_0 j_c d)}\right).$$

Figure 1. Schematic illustration of the magnetic field distribution during the preparation of the remanent-state superconductor (a)–(c) and the vortex-based micro-trap (d). Illustrated are the field lines (black lines) and equipotentials (colored lines and grayscale) of the magnetic field. An absorption image of $6 \times 10^5$ atoms recorded 1 ms after release from the vortex-based micro-trap is shown in (e).
The superconducting strip is oriented along $y$, it is centered at $z = 0$ and its width stretches from $-200 \mu m$ to $+200 \mu m$ along $x$. (a) Absorption image (false color) showing the atomic density distribution in trap $M_2$. I: Local atomic density maximum induced by vortices. II: Broad density of atoms trapped in quadrupole-type field. (b) Simulated magnetic field of trap $M_2$ in the region near the strip. I: Local field minimum induced by vortices. 2: Large quadrupole-type trapping field. (c) Simulated magnetic field of the trapped vortices combined with the bias field $B_{x,t1}$. The field minimum below the edge of the strip corresponds to the radial trapping potential of trap $M_3$.

The central region of the strip of width $\tilde{b} = a - 2b$ remains flux-free [21, 22]. After the external field $B_z$ has been removed, our model considers the length scale $b$ as the fundamental parameter that characterizes the spatial distribution of the trapped magnetic flux. As the strip thickness $d$ is much smaller than its width $a$ and the typical trap-to-surface distance realized in our experiments, we neglect any effects of the magnetic field $B_{x,t1}$ on the superconducting strip. However, the influence of all perpendicular fields has been included in our simulations of the magnetization of the strip following the description of [21, 22], as well as possible backaction of the superconductor to the fields, e.g. due to field repulsion. Simulations of magnetic fields derived from the described model are shown in figures 2(b)–(c).

4. Experimental procedure

To realize the vortex-based magnetic trap, we prepare a cloud of cold $^{87}$Rb atoms in an ultra-high vacuum chamber using standard laser cooling and trapping techniques. Then the cloud is magnetically transported to the superconducting chip, which is mounted facing downward and cooled using liquid nitrogen. We cool the chip to about 83 K without any additional thermal shielding. This temperature allows us to operate the superconductor far from the regime of dendritic avalanches [24], which occurs typically in YBa$_2$Cu$_3$O$_{7-x}$ (YBCO) for temperatures below $0.4 T_c$ [25] and would lead to unstable trapping.

The superconducting chip is a structured, $d = 800 \text{nm}$ thin film of YBCO on a yttria-stabilized zirconia single-crystal substrate. The thin film has a critical temperature $T_c = 89 \text{K}$
and at liquid nitrogen temperature $j_c = 2.7\, \text{MA cm}^{-2}$. We use a 400 $\mu$m wide strip to generate the main trapping potential. Using standard lithographic techniques, the strip is structured in a Z-shape [26], shown in figure 3, which is commonly used in current-carrying micro-traps. The central strip has a length of 5 mm and is crossed at its center by an additional wire of 200 $\mu$m width intended for trap compression [27]. We use a bare YBCO film as additional metal layers can become the dominant source of magnetic near-field noise [12, 14].

To load the atoms into the micro-trap and simultaneously prepare the superconductor in the remanent state, we employ the following experimental sequence. A standard six-beam magneto-optical trap (MOT) is formed with typically $3 \times 10^7$ atoms at a position 35 mm below the chip center. After a compression MOT, molasses cooling and optical pumping to the $|F = 2, m_F = 2\rangle$ state, we transfer the atoms to a magnetic trap (trap$_{M1}$), which is created by the same coils as used for the MOT. In this quadrupole trap, the vertical magnetic field gradient $(\partial B_{z,t0}/\partial z)$ can be varied between 20 and 35 G cm$^{-1}$. Therefore, the magnetic field generating trap$_{M1}$ can efficiently be used to prepare the superconductor in the remanent state. At the location of the chip, the resulting field component $B_{z,t0}$ perpendicular to the chip surface is 69–121 G. This is well above the first critical field of our chip of about 25 G (at 83 K). After storing the atoms in trap$_{M1}$ for 160 ms, they are adiabatically transferred to a second quadrupole-type magnetic trap (trap$_{M2}$), generated by a coil pair centered close to the chip surface. To transfer the atoms, we slowly ramp down the current for trap$_{M1}$ and simultaneously ramp up the current for trap$_{M2}$ in 460 ms. The magnetic field component $B_z$ at the chip position is reduced well below $B_{c1}$ during the transfer. The vortices created by the magnetic field of trap$_{M1}$ remain in the thin film. We typically transfer $1.5 \times 10^7$ atoms with a temperature of 120 $\mu$K to trap$_{M2}$.

The magnetic quadrupole-type field generated by the coils for trap$_{M2}$ is as expected significantly altered by the trapped vortices. In figure 2(a), we show the trapped atomic density distribution probed by in situ absorption imaging along the strip axis $y$. The field minimum positioned 800 $\mu$m below and 600 $\mu$m to the side of the strip is due to the quadrupole field. Due to the combination of the vortex field and the fringing quadrupole field, a second local minimum is formed below the edge of the strip. This is clearly seen in the high atomic density. This second minimum allows efficient transfer of the atoms to the vortex-based micro-trap (trap$_{M3}$).
Figure 4. Number of trapped atoms in the micro-trap \( M_3 \) for varying bias field \( B_{x,t_1} \). A magnetic field \( B_{z,t_0} \) of 112 G has been used to prepare the vortices in the superconducting film for this measurement.

The observed atomic density distribution and the simulations of the total magnetic field shown in figure 2(b) are in good qualitative agreement.

The atoms are loaded into the vortex-based micro-trap \( M_3 \) by turning off the quadrupole field and applying a homogeneous bias field \( B_{x,t_1} \). Strong radial confinement is realized along \( x \) and \( z \) by the combination of the vortices and the field \( B_{z,t_1} \) (figure 2(c)). The weaker axial confinement along \( y \) is provided by magnetic potentials resulting from vortices at the corners of the central strip, reminiscent of the Z-shape trap geometry [26]. In figure 2(c), we show the simulated contour lines of the total magnetic field in the \( x-z \) plane, which creates the radial trapping potential below the edge of the strip.

5. Characterization of the vortex-based micro-trap

From trap \( M_2 \), we transfer up to \( 1 \times 10^6 \) atoms to trap \( M_3 \), which have a phase-space density of \( 5 \times 10^{-8} \). Typically, we apply additional homogeneous bias fields \( B_{z,t_1} \) and \( B_{y,t_1} \) at time \( t_1 \) along the other two dimensions to improve the performance of the micro-trap. The field \( B_{z,t_1} \) along the vertical direction shifts the atomic cloud position sideways along the width of the strip. This places the trap at different vortex densities as the flux is inhomogeneously distributed across the strip width [21, 22]. To decrease Majorana spin-flip losses, the additional bias field \( B_{y,t_1} \) along the central strip is used to increase the absolute value of the magnetic field at the trap center. Typical bias fields for our trap are \( B_{x,t_1} = 40 \) G, \( B_{z,t_1} = 7.7 \) G and \( B_{y,t_1} = 3.3 \) G. With these parameters the trap lifetime is a few seconds, equal to the lifetimes of trap \( M_1 \) and trap \( M_2 \), which are limited by the background gas pressure in our single-chamber vacuum setup.

To characterize the micro-trap, we measure the atom number and trap-to-surface distance for various fields \( B_{x,t_1} \) as shown in figures 4 and 5. The atom number is inferred from absorption imaging after 1 ms time of flight. With increasing \( B_{x,t_1} \), the position of the trap center is shifted.
Figure 5. Distance from the micro-trap trap\textsubscript{M3} to the chip surface for different bias fields $B_{x,t1}$. The graph shows two series of distance measurements, each using a different magnetic field $B_{z,t0}$ to create the trapped vortices. In the inset, we show the measured trap distance for a fixed $B_{x,t1}$ when $B_{z,t0}$ is varied.

closer to the chip surface and therefore the radial magnetic field gradient at the trap center increases. The minimum field required to trap atoms as shown in figure 4 is 4.6 G. This corresponds to the magnetic field gradient at the trap center being just sufficient to overcome gravity. With increasing bias fields the depth of trap\textsubscript{M3} also increases. Therefore, we observe a sharp increase in the number of trapped atoms for bias fields from 4.6 G to about 10 G as a consequence of the atomic temperature in trap\textsubscript{M2}. With further increasing the $B_{x,t1}$ the atom number starts to saturate, as the increase in trap depth and field gradient is countered by the simultaneous reduction of the trap volume of the micro-trap. For $B_{x,t1} > 41$ G, the size of the trapped cloud exceeds the distance to the chip surface and we observe loss of atoms.

The trap-to-surface distance of trap\textsubscript{M3} is determined by in situ imaging of the trapped atoms using a detection laser beam reflected from the chip surface [28]. In figure 5, we show the measured trap distance as a function of $B_{x,t1}$. The distance is decreased with increasing $B_{x,t1}$. However, for higher fields $B_{x,t1}$ this effect diminishes as the trap distance becomes smaller than the spatial extent of the flux front $b$ on the strip.

We investigate the control of the amount of trapped vortices using the distance measurement displayed in figure 5. As the trap distance is determined by the cancellation of the average vortex magnetic field along $x$ by the bias field $B_{x,t1}$ this measurement is a sensitive probe of the amount of trapped magnetic flux. We perform several series of distance measurements. For each series we use a different field $B_{z,t0}$ to prepare the trapped vortices. Throughout all measurements the thin film is kept in the superconducting state and we increase $B_{z,t0}$ from series to series. We did not observe any reduction of the amount of trapped flux during the measurements. The obtained results agree qualitatively well with the trap-to-surface distance obtained from our numerical simulations, which have been empirically adjusted by a free-scaling parameter of the flux front $b$.

An estimate of the vortex density in the superconductor is $3–5 \text{ \(\mu\text{m}^{-2}\)}$ for the range of $B_{z,t0}$ used in our experiments. As a consequence, the average distance between individual vortices is
still much smaller than the trap distance. Therefore, we do not resolve individual vortices and the atoms sample the field produced by the vortex density. However, by using atomic samples with sub-µK temperatures, the magnetic potential in the near field of surface micro-traps can be resolved with high precision [29]. For such measurements, the vortex density could be varied with the externally applied magnetic field or by changing the chip temperature, e.g. by cooling with liquid helium.

6. Conclusions

A variety of fascinating experiments combining ultra-cold atoms and vortices in superconductors is within reach. Sufficiently cold atoms could be trapped by the combination of a single vortex and externally applied magnetic fields. This could be extended to time-varying potentials [30, 31], to create novel types of magnetic traps or ring guides very close to a surface, e.g. below 1 µm. Periodic or quasi-periodic magnetic potentials created by vortex lattices could be investigated or used to manipulate the atoms. Moreover, ultra-cold atoms can be used for a spectroscopic measurement of the magnetic flux quantum.

In conclusion, we have realized the trapping of ultra-cold atoms with the magnetic fields of vortices in a remanent-state superconductor. We have shown the experimental control of important atom trap characteristics such as efficient loading, atom trap positioning and the vortex density in the superconductor, which agrees well with numerical simulations. The realized trap can be understood as a controlled interaction between atomic and solid-state quantum systems, paving the way for future discoveries in quantum technology and fundamental physics.

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Note added. After preparation and first submission of this manuscript, we became aware of an overlapping, simultaneous work demonstrating a similar trap based on vortices in a thin superconducting disc of niobium [32]. Different from our work, this trap employs a perpendicular bias field, which in combination with the radial symmetry of the magnetic field created with the superconducting disc results in a quadrupole trap. In comparison, the trap presented in our work resembles the Z-wire trapping geometry typical of magnetic micro-traps [26], where the generation of quantum-degenerate gases is possible in future experiments.

References

