Stable Neutral Atom Trap with a Thin Superconducting Disc

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A stable magnetic quadrupole trap for neutral atoms on a superconducting Nb thin-film disc is demonstrated. The quadrupole field is composed of the magnetic field that is generated by vortices on the disc introduced by cooling the disc across the transition temperature with a finite field and an oppositely directed uniform field applied after cooling. The trap is stable when all trapping processes are performed above the dendritic instability temperature T_a. When the field intensity is changed below this temperature, the quadrupole field collapses and the trap disappears. The initial vortex density decreases even when the external field is changed at a temperature $T > T_a$. However, the vortex density is stabilized at an equilibrium density, whereas at $T < T_a$, it almost completely disappears. A stable trap can be formed, even when the initial vortices are introduced through a dendritic avalanche.

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The vortices in a type-II superconductor exhibit fascinating characteristics that have attracted the interest of many physicists and engineers. They are indispensable to the production of high field superconducting magnets. On the other hand, the dissipative motion of the vortices is the source of noise in those magnets. They exhibit many interesting characteristics in physics including vortex lattices, phase transitions between various vortex states, and dendritic flux instability. In this Letter, we report the first demonstration of the use of vortices to configure a stable magnetic trap for cold neutral atoms. We also show that the trapping characteristics can be used as a tool for analyzing the physics of vortices.

Neutral atoms with an electronic angular momentum can be trapped near the local minimum of a magnetic field. To form the minimum, we need two spatially diverging fields of opposite polarities. The most commonly used configuration is a set of two circular currents with opposite current directions, which produces a quadrupole field between the two currents [1]. Our strategy for forming a field minimum is to use pinned vortices generated by cooling a superconducting thin disc with a uniform magnetic field perpendicular to the disc surface and by removing the field below the superconducting transition temperature T_c. The second field is generated by applying a uniform field in the opposite direction below T_c. Because the Meissner effect repels the field from the disc, the latter field diverges near the disc surface.

To make a practical neutral-atom trap, the field distribution must be stable and have a predictable shape. The characteristics of type-II superconducting film most relevant to the present study is its dendritic flux instability [2]. This instability has been studied intensively for Nb [3,4], MgB_2, and certain high temperature superconductors [5], in particular, by using the high-resolution magneto-optical imaging technique. When the external field is changed at a temperature below but close to T_c, the flux penetrates or is repelled smoothly, and this can be described qualitatively with the critical-state theory [6]. If the external field is varied at a temperature lower than a certain value $T_a < T_c$, the flux penetration becomes catastrophic. By increasing the external field intensity, many dendritic structures with a high vortex density penetrate deep inside the film from the edge. A similar dendritic avalanche but with the opposite sign occurs when the field is reduced. The same behavior is observed when an external field with the opposite sign is applied to a premagnetized superconducting film. It is generally believed that the instability is of thermomagnetic origin [7]. The dissipative motion of a vortex releases heat. When the vortex velocity is sufficiently slow, the heat is dissipated without inducing substantial temperature change. However, if the velocity exceeds a critical value, the released heat raises the temperature locally. This further increases the velocity of the flux quantum leading to a catastrophic intrusion (or expulsion) of magnetic flux. The maximum temperature T_a that causes instability is approximately 7 K for Nb film and 10 K for natural MgB_2 film.

The superconducting film we used to trap Rb atoms was a 400-nm-thick disc-shaped Nb film with a diameter of 2 mm, which we deposited on a sapphire substrate. The substrate was glued to a 4-cm-high sapphire mount, and the other end of the sapphire mount was attached to the bottom of a liquid helium cold finger. This configuration was chosen to avoid magnetic disturbance arising from the long-lived eddy current generated by the cooled copper structure of the cryogenic apparatus. The temperature was controlled by pumping liquid helium or heating the cold finger. The minimum temperature of the Nb disc was 4.7 K.

The procedure for holding atoms below the disc was as follows [8]. First, a magnetic field B_i that was perpendicular to the disc surface and directed downwards was applied at around 15 K. Its typical intensity was 1–1.5 mT. Then, the disc was cooled to below T_c, and B_i was reduced to zero with a time constant of 30–3 s. We found that the reduction rate did not affect the subsequent results. The disc temperature was changed to a value of $T_0 = 7.4$ K at which we intended to observe the trapping. The laser-cooled rubidium atoms were brought to approximately 3 mm below the disc using a movable quadrupole magnetic trap [9]. The magnetic field of the quadrupole trap was quickly turned off, and simultaneously the perpendicular field B_m, which was in the opposite direction to B_i, was turned on. Figure 1 shows a typical absorption image of the atomic cloud. In this figure, $B_i = 1.5$ mT and $B_m = 1.25$ mT. The illuminating laser was circularly polarized. The atomic cloud was formed below the center of the disc, and its pattern was close to that of a standard quadrupole trap. The temperature of the atomic cloud was estimated from the cloud size and was approximately 120 μK. The lifetime of the cloud was approximately 10 s, showing that the trap was highly stable.

Since the above experiment was performed in a stable temperature range, the observation of stable trapping is not surprising. When the disc is cooled through T_c and B_i is removed, the flux near the edge of the disc is expelled from the superconductor to keep the supercurrent below the critical value. When B_m is applied, flux in the opposite direction (antiflux) enters from the disc edge for the same reason. Although it is not possible to calculate the exact flux distribution on the disc from the cloud shape, the figure shows that the flux density is a smooth function of position. The amount of flux that remained at the time of the trap observation can be approximately estimated from the trap height z_t, the distance from the Nb film to the center of the trapped atomic cloud. If we assume that the flux generated by B_i on the disc is constant over the disc, z_t is obtained as a solution of

$$2\left(1 + \frac{B_i'}{B_m}\right)\left(-\frac{\zeta}{1+\zeta^2} + \tan^{-1}\frac{1}{\zeta}\right) = \pi, \quad (1)$$

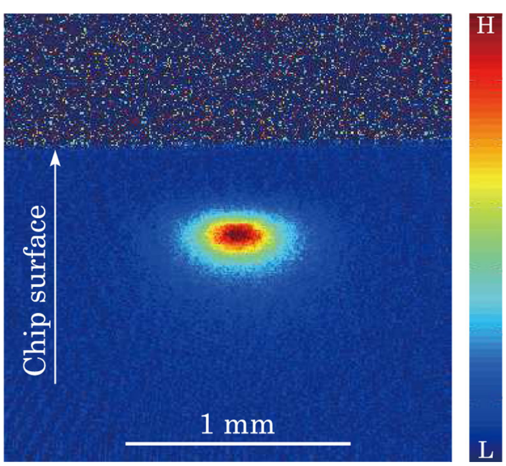

FIG. 1 (color online). An absorption image of the trapped atomic cloud. The bottom of the granular part is the surface of Nb film. $B_i = 1.5$ mT, $B_m = 1.25$ mT, and $T_0 = 7.4$ K.

where $\zeta = z_t/R_0$, and R_0 is the radius of the disc. $\pi R_0^2 B_i'$ is the flux remaining at the time of the trapping observation. Figure 2 shows the trap height as a function of B_i/B_m. The black squares are experimentally obtained values, and the open circles show the theoretical values when $B_i' = B_i$ in Eq. (1). This shows that a large fraction of up to 80% of the initial flux remained trapped at a low B_i and that B_i' saturates when B_i is larger than 2 mT.

To investigate the influence of flux instability at $T < T_a$, we modified the experimental sequence. After the initial field B_i was removed at 7.4 K, the temperature was changed to the second point T_m at which the opposite field B_m was ramped up linearly in 3 s and then ramped down to zero at the same rate. The temperature was restored to 7.4 K, Rb atoms were transported in, and a positive B_o field of 1.25 mT was applied to determine whether a quadrupole magnetic trap was formed. We obtained the absorption image of the trapped atoms 2 s after loading the atoms.

We measured the trap height with a fixed T_m by repeating the application of B_m from the lower to the higher value. We performed measurements at four T_m values of 7.4, 7.0, 6.8, and 6.4 K, and Fig. 3 shows the results. When T_m was above the instability threshold (7.4 and 7.0 K), the trap height gradually decreased with B_m. Therefore, when B_m was applied, antiflux started to penetrate the disc and consumed the initial flux through vortex-antivortex annihilation. However, the change stopped at a finite flux value. The formation of the trapped atomic cloud shows that the flux and antiflux regions remained separated and that their boundary is more or less uniform. When T_m was lower (6.8 and 6.4 K) the atomic cloud disappeared completely above a certain B_m value showing that the initial flux was elim-

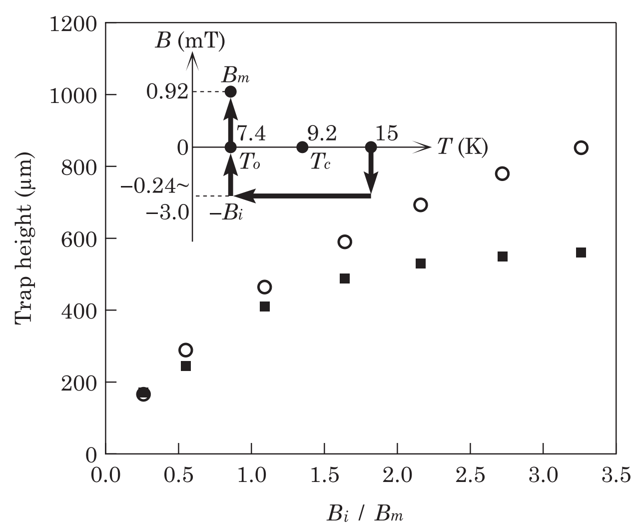

FIG. 2. The trap height as a function of B_i/B_m. $B_m = 0.92$ mT was fixed. The temperature was $T_0 = 7.4$ K. ■: measured trap height. ○: theoretical height when the flux magnitude before cooling was preserved until the time of the trap observation. The inset shows the sequence of the operation in the B-T plane.

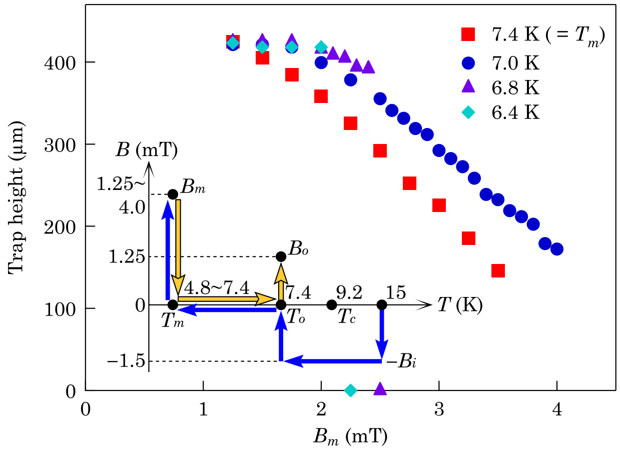

FIG. 3 (color online). Trap height versus applied field B_m at various temperatures T_m. The trap height decreases with B_m. If $T_m > T_a$, the height remains at a finite value. If $T_m < T_a$, the trap suddenly vanishes when B_m exceeds a certain value. Zero height means that trapping was not observed 2 s after the introduction of the atomic cloud. $B_i = 1.5$ mT for all points. The inset shows the sequence of operation.

inated in much less than 2 s. Figure 4 shows the boundary between the stable trapping and no-trapping regions. We believe that the figure shows the boundary of the dendritic instability. Its temperature coincides with the published threshold of dendritic instability. The transition temperature decreases with decreasing B_m because a smaller vortex density means less heating. Although vortex-antivortex annihilation occurs even in the stable temperature region ($T_a < T_m < T_c$), the decay rate is extremely slow. We kept

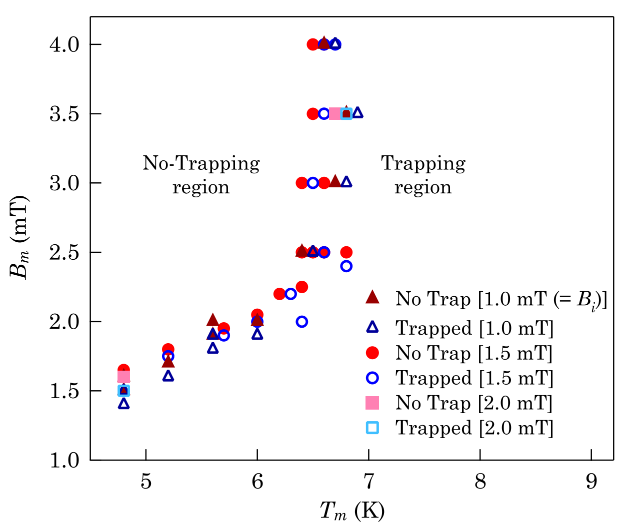

FIG. 4 (color online). The boundary between the trapping and no-trapping regions. The boundary was not a definite line and could be defined up to ± 0.2 K. Open symbols show the case when trapping was observed, and filled symbols indicate that there was no trapping. The figure includes points with different initial field B_i. We found practically no variation.

B_m at 2 mT up to 700 s at $T_m = 7.0$ K. The trap height decreased only 2% meaning that the lifetime of the quadrupole field was nearly 10 h. We saw no atoms in the unstable region at 2 s after loading. Once the dendritic avalanche started most vortices were probably annihilated quickly by pair annihilation with antivortices. If the initial vortices remained, the magnetic field minima must stay above the disc surface, and we would have seen an atomic cloud. The avalanche does not start if the external field is not changed in the instability region $T < T_a$. After the removal of B_i at 7.4 K, we cooled the disc further to approximately 5 K. Then we reheated it to 7.4 K without applying B_m. The atomic cloud was observed at the same height as without the additional cooling process.

Flux instability can occur if the initial field B_i is turned off below the critical temperature. To investigate this, we changed the temperature at which we turned off B_i and measured the trap height by keeping both $B_i = 1.5$ mT and the positive field for the trap observation $B_o = 1.25$ mT constant. Figure 5 shows the result. After B_i was turned off, the temperature was changed to 7.4 K, the atomic cloud was moved in, and a positive field B_o of 1.25 mT was applied to observe the trapped atoms. The trap height was measured 2 s after the transfer of the atomic cloud as in Figs. 2 and 3. The figure clearly shows the onset of flux instability at around 6.2 K. The sudden drop in the trap height shows the reduction in the initial flux. A clearer understanding is obtained by looking at the atomic cloud shape. At 2 s after the introduction of the atom [Fig. 5(b)], its shape is close to that of a standard quadrupole trap. At 10 ms, the atomic cloud shape is elongated along the disc surface [Fig. 5(c)]. Although the cloud is floating above the disc surface near its center, it is almost touching the surface on the left side. Since dendrites grow from the rim of the disc, the magnetic field distribution near the rim is generated from a complicated distribution of vortex and antivortex forming minima of the field close to the disc surface. The vortex distribution is more or less uniform in the central part. Atoms with a larger momentum are lost quickly through the point at which they touch the surface. As a result, the atomic density is small even though the trap height is nearly 1/3 of the height of the atomic cloud generated at $T > T_a$. When the temperature is reduced further, the trap height gradually increases. This shows that the uniform flux region in the disc center increases as the temperature decreases, which is in agreement with the results of previously reported magneto-optical experiments on dendritic instability [3,10].

To form an atom trap, the flux around the center of the disc must be surrounded by antiflux. The flux that was introduced through the dendritic instability can be used as a field source for trapping. The open circles in Fig. 5 show the trap height when the disc was cooled without a magnetic field. A negative field of 1.5 mT was applied at T_m below T_c. Then, the temperature was changed to 7.4 K.

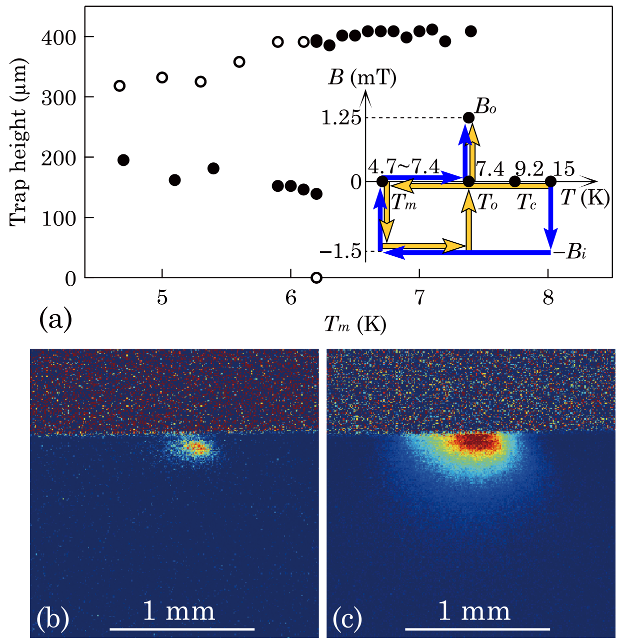

FIG. 5 (color online). (a) Trap height versus ramp-down or -up temperature of the initial field B_i. The filled circles show the trap height when the disc was cooled with the applied field $B_i = 1.5$ mT. The open circles show the height when the disc was cooled without a field. Zero height means that trapping was not observed 2 s after the loading of the atomic cloud. The inset shows the sequence of operation. Dark gray (blue) arrows show the sequence when the disc is cooled across T_c with a finite field, $B_i \neq 0$, (filled circles in the graph). Light gray (orange) arrows show the sequence when T_c is crossed without field, $B_i = 0$ (open circles). Bottom figures are atomic clouds obtained with $B_i = 1.5$ mT and $T_m = 6.0$ K. (b) is at 2 s and (c) at 10 ms after the loading of atomic cloud. (b) is 5 times intensified in density scale.

Finally, we removed the negative field and introduced an atomic cloud to allow us to observe trapping. We observed stable trapping when $T_m < T_a$. When the negative field was removed in the temperature region, $T_a < T_m < T_c$, we did not observe trapping. It is interesting to note that the trap height curve is connected continuously to the curve obtained by premagnetization. The instability boundary T_a in Fig. 5 is approximately 0.5 K lower than T_a in Figs. 3 and 4. In Fig. 5, the instability was triggered by the heating caused by the motion of the vortices. In Fig. 3, vortex-antivortex annihilation released a larger amount of heat. Therefore, the unstable region was larger in the experiment shown in Fig. 3.

In conclusion, we have shown that the flux that remains after the removal of the magnetic field B_i can be used as a stable field source as long as we perform the experiments above the instability temperature T_a. This provides us with a new possibility for atom optics, which cannot be realized if a superconductor functions as a perfect diamagnetic material. Superconducting current wires were used recently to trap atoms [9,11,12]. The main object was to reduce the loss of micro atom traps, and this was only partly successful [13,14]. Our result indicates that dendritic flux instability influences trap loss and that operation in a stable temperature region can improve the performance of supercurrent wire traps.

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