Sculpting microscopic magnetic flux landscapes in a Bi$_2$Sr$_2$CaCu$_2$O$_8$+δ vortex lens

D. Cole, S.J. Bending, Sergey Savel’ev, T. Tamegai, and Franco Nori

1Department of Physics, University of Bath, Claverton Down, Bath, BA2 7AY, UK
2Frontier Research System, The Institute of Physical and Chemical Research (RIKEN), Wako-shi, Saitama 351-0198, Japan
3Department of Physics, Loughborough University, Loughborough LE11 3TU, UK
4Department of Applied Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
5Frontier Research System, The Institute of Physical and Chemical Research (RIKEN), Wako-shi, Saitama, 351-0198, Japan
6Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, MI, 48109-1040, USA

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We demonstrate experimentally that the micromagnetic profile of the out-of-plane component of magnetic induction, $B_z$, in the crossing lattices regime of layered superconductors can be manipulated by varying the in-plane magnetic field, $H_{\parallel}$. Moving Josephson vortices drag/push pancake vortex stacks, and the magnetic profile, $B_{\parallel}(x)$, can be controllably sculpted across the entire single crystal sample. Depending on the $H$-history and temperature we can increase or decrease the flux density at the center and near the edges of the crystal by as much as $\sim 40\%$, realising both “convex” and “concave” magnetic flux lenses. Our experimental results are well described by molecular dynamics simulations.

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In recent years dramatic progress has been made in the control of static flux structures in superconductors by the introduction of artificial vortex pinning sites (e.g. antidots and ferromagnetic dots) 1, 2, 3, 4, 5. The next major challenge is to achieve dynamic vortex control, so that different flux profiles can be realised in the same superconducting sample. Control of vortex motion has recently been proposed 6 and demonstrated in so-called ratchet devices which incorporate a spatially-asymmetric ratchet potential to achieve rectification of ac drives. However, a spatially asymmetric ratchet substrate is not a fundamental requirement for ratchet operation, and recent proposals 7, 8, 9, 10, 11 have described novel methods to control the motion of tiny particles in a binary mixture by the dragging of one component by the other. Here we describe the first such experimental implementation of a flux lens in the binary vortex system present in highly anisotropic layered superconductors under tilted magnetic fields.

Direct visualization 12, 13, 14, 15, 16, 17, 18 has revealed that a tilted (away from the crystalline c-axis) magnetic field penetrates the highly anisotropic Bi$_2$Sr$_2$CaCu$_2$O$_8$+δ (BSCCO) superconductor in two interpenetrating vortex arrays, known as crossing vortex lattices 19, 20. One vortex sublattice consists of stacks of pancake vortices (PVs) aligned along the c-axis, while the other sublattice is formed by Josephson vortices (JVs) confined between CuO$_2$ layers. Superconducting currents generated by JVs deform stacks of PVs, resulting in a mutual attraction between PVs and JVs 20, 21. This has been experimentally confirmed 14, 15, 16, 17, 18 by the observation of PV chains which decorate underlying JV stacks in tilted magnetic fields. JVs are usually very weakly pinned and can easily be driven by changing the in-plane magnetic field $H_{\parallel}$ (≡ $H_{ab}$), dragging PVs along with them 22. This joint JV-PV motion can be used to develop vortex-pumps, vortex-diodes and vortex-lenses which have two clear advantages over other existing ratchet devices. (i) The motion of vortices can be controlled without the need for nanofabricated samples with fixed spatial asymmetry, and (ii) the focusing efficiency can be easily varied by changing either the PV density (via the corresponding magnetic field component $H_z$) and/or temperature. Here we describe how to implement such lenses experimentally.

Experimental results.— Our vortex lensing experiments have been performed on an as-grown BSCCO superconducting single crystal ($T_c = 91$K, dimensions 1mm×0.75mm×50μm). The changes in $B_z$ arising from PV lensing/antilensing were detected using a 25μm wirewidth micro-Hall probe array patterned in a GaAs/AlGaAs 2D electron gas 23. The BSCCO single crystal was positioned directly above our sensor and secured with paraffin wax. The array has thirteen addressable elements, of which twelve were situated at different positions under the crystal and the remaining uncovered one acted as a reference. The sensor was driven by a 45μA 32 Hz ac current and the Hall voltages detected with a lock-in amplifier. The out-of-plane $H_z$ and in-plane $H_{\parallel}$ magnetic field components are varied independently using a solenoid and Helmholtz coil pair (one of which could be precisely positioned vertically on a micrometer driven stage), respectively. We use the in-plane ‘lock-in’ transition 24 to align the in-plane field within ±0.006° of the ab crystallographic planes. The exact alignment position is inferred from plots of $1/H_{\parallel}$ at lock-in as a function of the height of the movable Helmholtz coil, in a small fixed out-of-plane magnetic field. At the start of lensing experiments a fixed PV density was established by field-cooling the BSCCO crystal from above
FIG. 1: (Color online) Changes in the local out-of-plane magnetic induction, $\tilde{B}_z$ (vertically offset for clarity), versus the in-plane magnetic field, $H_\parallel$, measured near the center (a) and near the edge (b) of the sample at 77 K. Arrows indicate the direction of the $H_\parallel$ field sweep. The left hand inset in (b) shows sketches of PV density profiles across the crystal for increasing $H_\parallel$ (bottom to top). The right hand inset in (b) plots the vortex lensing amplitude ($\Delta B_z = B_{z}^{\text{max}}(H_\parallel) - B_{z}^{\text{central}}(H_\parallel)$) at $H_\parallel = 5.3$ Oe for the central sensor as a function of temperature.

$T_c$ in a known value of the out-of-plane field, $H_z$. The in-plane magnetic field $H_\parallel$ was then cycled several times until a steady-state loop was obtained. During each cycle, $H_\parallel$ was slowly (1.7 Oe s$^{-1}$) ramped up to a maximum of 150 Oe and down to a minimum of -150 Oe and back to zero, while the Hall voltage was monitored at a chosen element to measure the magnetic induction, $B_z$. In practice the observed lensing was a function of the measurement position under the crystal. For the sake of brevity we only present data here for two elements, one at the sample center and one 225$\mu$m from one of the edges parallel to $H_\parallel$, which fully illustrate the extremes of behaviour seen. Fig. 1 shows lensing data measured (a) at the central location and (b) near the edge of the sample at 77K for different values of $H_z$. In all cases the data have been symmetrized ($\tilde{B}_z \uparrow$ ($H_\parallel$) = $\frac{1}{2}(\tilde{B}_z \uparrow$ ($H_\parallel$) + $\tilde{B}_z \downarrow$ ($-H_\parallel$))) to account for a small misalignment between the plane of the BSCCO crystal and the Hall probe array. In both cases for $H_z < 2$ Oe, the PV system shows a weak reversible response which inverts when $H_z$ is inverted, attributable to the dragging of PV stacks which are all trapped on JV chains. For $H_z > 2$ Oe, free PVs exist between chains (mixed chains/lattice state) and we start to see stronger, irreversible behaviour related to the compression of free PVs and their cutting through JV stacks at high in-plane fields. At higher $H_z$ the magnetization loop $B_z$($H_\parallel$) for the central element has a “butterfly” shape exhibiting: (i) a fast increase of PV density when $H_\parallel$ increases from zero, followed by weaker (saturation-like) dependence of $\tilde{B}_z^{\text{central}}(H_\parallel)$; (ii) a rapid reduction of $\tilde{B}_z^{\text{central}}(H_\parallel)$ when $H_\parallel$ decreases from its maximum value, followed by a remarkable antilensing (an overshoot in the reduction of PV density) effect $\tilde{B}_z^{\text{central}}(H_\parallel) > 0 < \tilde{B}_z^{\text{central}}(H_\parallel) = 0$. Note that on the $H_\parallel$-increasing branch of the lensing loop, $\tilde{B}_z^{\text{central}}(H_\parallel)$ is always higher than on the decreasing branch on the right-side ($H_\parallel > 0$) of the hysteresis cycle, i.e., $\tilde{B}_z^{\text{central}}(H_\parallel, dH_\parallel/dt > 0) > \tilde{B}_z^{\text{central}}(H_\parallel, dH_\parallel/dt < 0)$. We denote such loops as “clockwise”.

The data from the Hall element near the sample edge (Fig. 1b) provide insights into the spatial distribution of the PV density in our lensing experiments. In stark contrast to Fig. 1a, we now see strong antilensing behaviour for $H_z < 6.5$ Oe. This is easily understood in terms of the PV profiles generated during our experiments. Since PVs are pushed from two opposite edges of the sample towards the center, there must be regions near these edges which experience a decrease in PV density, while accumulation is occurring in the crystal center (see sketched profiles in the left hand inset of Fig. 1b). It is interesting to note that the counter-clockwise loops at low $H_z$ transform to clockwise ones when $H_z$ increases. This is best illustrated in the curve at $H_z = 6.5$ Oe, which shows an extra crossing point for $H_\parallel > 0$ between traces on the sweep-up and sweep-down. At such high values of $H_z$ PVs penetrat-
The right hand insert of Fig. 1b shows a plot of the lensing amplitude at $H_z=5.3$ Oe as a function of temperature. Surprisingly, we find that the lensing amplitude falls rapidly with temperature, being very weak at 84 K and undetectable at 86 K. Since this is well below the critical temperature of the BSCCO crystal ($T_c \sim 91$K), and the crossing lattices interaction strength is only very weakly temperature dependent \cite{20}, we conclude that efficient lensing requires finite bulk pinning to prevent PVs escaping from focus regions laterally parallel to JV stacks. The effectiveness of bulk pinning will drop rapidly at elevated temperatures leading to a rapid reduction in efficiency.

Simulations.— The minimal model to simulate the observed lensing effects describes the overdamped dynamics of JV and PV rows using a set of coupled equations of motion: \[ \gamma J \frac{dJ_i}{dt} = f_{iJ}^H + f_{iJ}^P, \]
\[ \eta_P \frac{dP_i}{dt} = f_{iP}^P + f_{iP}^H + f_{iP}^J, \]
where $J_i$ and $P_i$ are the positions of JVs and PVs with distances between JVs(PVs) in a row $a^* / \gamma (a^*)$ and anisotropy parameter $\gamma$, while $\eta_J$ and $\eta_P$ are the JV and PV viscosities. The viscous forces slowing down the vortex motion are balanced by: (1) the repulsive force $f_{JJ}^H$ between JV rows (including images with respect to the sample surface); (2) the interaction $f_{iJ}^H$ of JV rows with Meissner currents generated by the externally-applied time-dependent magnetic field $H_{||}(t)$; (3) the repulsion $f_{PP}^P$ between PV rows (including images); (4) the interaction $f_{iP}^H$ of PV rows with $H_z$; and (5) the attractive forces $f_{JP}^P$ between rows of JVs and PVs.

The interaction between vortex rows decays exponentially \cite{20}: \[ f_{iJ}^H / \tau / \eta_J = (a^* \beta / a^*) \sum \text{sgn}(x_i^j - x_i^j / \lambda_e) \]
\[ f_{iP}^P / \tau / \eta_P = \sum \text{sgn}(x_i^P - x_i^P / \lambda_{ab}), \]
where the interaction lengths are the in-plane $\lambda_e$ and $\gamma$-axis $\lambda_e$ penetration lengths, while $\beta = \eta_P / (\gamma \eta_J)$ is the relative viscosity. Hereafter, we normalize all distances by the half-width of the sample $D$ and all time scales by $\tau = 16 \pi \lambda_e^2 a^* \tau / \Phi_0 D$. The distances between PV and JV rows are related to the JV and $H_{||}$ magnetic field components by $a^* \approx (\Phi_0 / H_{||})^{1/2}$ and $a^* \approx (\gamma \Phi_0 / H_{||})^{1/2}$. The interaction with the Meissner current decays exponentially on the scales $\lambda_e$ and $\lambda_{ab}$ from the surface ($x=\pm 1$) of the sample, for JVs and PVs, respectively. The corresponding forces can be modelled \cite{20} as \[ f_{iJ}^H / \tau / \eta_J = -(2 \pi \alpha / a^*) \sinh(x_i^j / \lambda_e) / \cosh(D / \lambda_e) \]
and \[ f_{iP}^P / \tau / \eta_P = -(2 \pi \alpha / a^*) \sinh(x_i^P / \lambda_{ab}) / \cosh(D / \lambda_{ab}). \]
The JV-PV attraction can be approximated as \[ f_{iJ}^H / \tau / \eta_J = \gamma \lambda_e^2 \alpha / a^* \sum \text{sgn}(x_i^j - x_i^j / \lambda_e) \exp(-2 \pi |x_i^j - x_i^j| / a^*) \]
and \[ f_{iP}^P / \tau / \eta_P = \gamma \lambda_{ab}^2 \alpha / a^* \sum \text{sgn}(x_i^P - x_i^P / \lambda_{ab}) \exp(-2 \pi |x_i^P - x_i^P| / a^*), \]
where $\alpha \sim 6 \pi / \lambda_e^2 a^*$. The tilt elasticity of PV stacks is related to the tilt elasticity of PV stacks. The qualitative agreement between the very complex and nontrivial experimental data and simulations indicates that the model used captures the essential physics.

Our molecular dynamics simulations follow the experiments. First $H_{||}$ was slowly increased from zero to $H_{||}^{\text{max}}$, and then decreased back to zero over the same period of time. Such cycles were repeated several times to achieve steady-state loops. The average PV density was monitored as a function of $H_{||}$ both at the center and near the edges of the sample.

Comparison theory-experiment.— The simulated...
clockwise $B_z(H_z)$ “butterfly” loops for the PV density at the center of the sample show the same features that were observed in experiments (c.f. Figs. 1a and 2a) and can be easily interpreted: (i) First, $B_z^{\text{central}}$ increases with $H_z$ as JVs move towards the sample center and drag PVs with them. This is consistent with theoretical predictions [12]; (ii) At a certain in-plane field $H_{\parallel}$, the PV density at the center of the sample saturates and even starts to decrease. The PV density at the center is now large enough that PV-PV repulsion becomes very large. PVs start to cut through the JV rows and, near the maximum compression point, some of these PVs escape the narrow potential produced by the JVs and are lost; (iii) On the decreasing branch of the loop, both experiments and simulations exhibit a remarkable anti-lensing effect. This arises because a smaller total number of PVs now spreads out over the whole sample, resulting in a deficit of PVs at the center. Also the ratio of the lensing to antilensing effect, \[ \frac{\max(\tilde{B}_z^{\text{central}}(H_{\parallel})) - \tilde{B}_z^{\text{central}}(0))}{\min(\tilde{B}_z^{\text{central}}(H_{\parallel}) - \tilde{B}_z^{\text{central}}(0))} \] decreases to about one when the out-of-plane field increases, in agreement with experiments (this produces rounder loops for higher $H_z$, see Figs. 1a, 2a).

The simulations also capture all the main features found in the experiments near the sample edge: (i) At very low out-of-plane fields, $H_z$, the area of this remarkable counterclockwise loop increases with $H_z$; (ii) at higher out-of-plane fields the counterclockwise loops narrow, transform into clockwise loops and broaden again.

Fig. 3 illustrates the experimental (main figure) and simulated (inset) dependence of lensing amplitude on out-of-plane magnetic field. In both cases the amplitude shows a pronounced peak as a function of $H_z$. At 77K the experimental lensing efficiency exhibits a maximum of nearly 40% at $H_z \sim 5$ Oe. This field value is in reasonable agreement with the predicted maximum in JV pinning strength (by PVs) at $H_z \sim 0.26 \frac{\Phi_0}{(\gamma s)^2} \sim 6$ G [28].

Conclusions.— We have experimentally realized concave and convex magnetic vortex lenses which focus and defocus the out-of-plane magnetic flux in a Bi$_2$Sr$_2$CaCu$_2$O$_8$+δ sample. Remarkably, this was done by employing the “dragging” of PVs by JVs with no fixed spatial asymmetry in the sample. We show that the PV density near the center/edges of the sample can easily be controlled by changing either the in-plane or the out-of-plane fields, as well as by varying the temperature. The experimental results are well described by a simple model considering the dragging of one vortex species by the other. This novel method of quantum-motion-control (a ratchet with no ratchet potential) opens up new avenues for the manipulation of flux quanta and nanoscale particles.

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Animations illustrating vortex lensing are available at http://dml.riken.go.jp/vortex-dc

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