Geometrical Confinement Effects in Layered Mesoscopic Vortex Matter

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Abstract We study the geometrical confinement effect in Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ mesoscopic vortex matter with edge-to-surface ratio of 7–12%. Samples have in-plane square and circular edges, 30 μm widths, and ~2 μm thickness. Direct vortex imaging reveals the compact planes of the structure align with the sample edge by introducing topological defects. The defect density is larger for circular than for square edges. Molecular dynamics simulations suggest that this density is not an out-of-equilibrium property but rather determined by the geometrical confinement.

Keywords Vortex matter · Mesoscopic physics · Layered superconductors

1 Introduction

Understanding the confinement effects introduced by sample geometry is crucial for characterizing the static and dynamic properties of mesoscopic vortex matter. This
subject was actively investigated for low-temperature superconductors with dimensions comparable or smaller than coherence length or penetration depth, $\lambda$ [1–6]. Mesoscopic vortex matter in these materials has structural properties strongly influenced by the geometry of the specimens [3], in contrast with results in macroscopic samples for several compounds [7–10]. Confinement effects are in competition with inter–vortex interaction that increases with field and temperature. Materials with an important electronic anisotropy such as layered high-$T_c$’s have a quite large value of $\lambda$ and then inter–vortex interactions become more relevant.

Due to the technical difficulties in fabricating micron-sized samples of layered high-$T_c$’s complex oxides, there are only few works in the literature investigating the effect of confinement in vortex matter nucleated for these materials [11]. In this work, we study this issue in the paradigmatic $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$+δ compound that presents a rich vortex phase diagram governed by thermal fluctuations and extremely anisotropic magnetic properties. In this compound, the phase diagram of macroscopic as well as mesoscopic [21] vortex matter is dominated by a first-order transition [12,13] between a solid phase at low temperatures and a liquid [14] or decoupled gas [15,16] of pancake vortices at high temperatures. The vortex solid phase of macroscopic samples presents quasi long-range positional order [17].

Here, we report on the structural properties of the mesoscopic vortex solid nucleated in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ at low fields and with single-vortex resolution. We study both, experimentally and with simulations, the effect of confinement and inter–vortex interactions for samples with square and circular edges.

2 Methods

We engineered micron-sized superconducting samples from bulk $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ crystals ($T_c = 89$ K). We fabricated circular and square samples with typical dimensions of 30 $\mu$m by means of optical lithography and subsequent physical ion-milling of the negative of the samples [18]. Freestanding 2-$\mu$m-thick disks and cuboids are obtained after cleaving the towers resulting from milling.

We directly imaged the solid vortex phase with single-vortex resolution by means of magnetic decoration experiments performed at 4.2 K after field cooling [19]. In these experiments, the evaporated magnetic nanoparticles land on the sample surface at the places where the gradient of local inductance is maximum, therefore, decorating the vortex positions. The imaged structure corresponds to the vortex solid frozen at the temperature at which pinning sets in, $T_{\text{freez}} \sim T_{\text{irr}}$ [7], of the order of 87–83 K for the low fields studied here [20]. Decreasing the sample size down to microns does not significantly affect the value of $T_{\text{irr}}$ [21].

We also performed molecular dynamics simulations of interacting rigid three-dimensional vortices in order to compare with the experimentally observed vortex matter [22]. We studied the case of 30 $\mu$m diameter disks and focused on the density of topological defects when varying the simulation cooling rate.
3 Results and Discussion

Figure 1 shows snapshots of the mesoscopic vortex structure nucleated in the disk and cuboid \( \text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8+\delta \) samples after field cooling down to 4.2 K at applied fields of 20 and 40 Oe. The local induction calculated as the number of vortices times the flux quantum yields \( B \sim 0.75 \) H, a reduction due to demagnetizing effects (aspect ratio of the disks and cuboids of \( \sim 15 \)). The direction of the compact planes of the vortex structure in micron-sized specimens is affected by the confinement effect introduced by the edges of the samples, particularly in the case of the outer shells of vortices. This finding is in contrast to observations in macroscopic samples where the compact planes are not in register with the edges [7]. The alignment is more evident in the Delaunay triangulations of Fig. 2, a well-known geometrical algorithm that determines the first neighbors for every vortex in the structure [17]. First-neighbors vortices are bounded with lines, and non-sixfold coordinated ones are highlighted in gray. In the case of the cuboid samples, irrespective of the vortex number (447 or 1092), one of the compact planes of the structure is parallel to the sample edge. For the disks, only a few outer shells of vortices mimic the sample edges, and the shell number depends inversely on...
Fig. 2 Delaunay triangulations of the mesoscopic vortex matter shown in Fig. 1. Disclinations are highlighted in gray; sixfold (non-sixfold)-coordinated vortices are indicated in blue (red). The scale-bar corresponds to 10\(\mu\)m (Color figure online)

the vortex density. Towards the center of the sample, a rather ordered vortex crystallite is formed without influence of the edges on the direction of the compact planes. The transition between the orientation of the outer and inner shells is done via the plastic deformations entailed by topological defects.

For the vortex structure studied here, these topological defects are generally disclinations, namely vortices with five or seven first neighbors, and pairs of them or screw-dislocations associated to an extra plane of vortices. For example, isolated dislocations are observed in the middle of the vortex structure nucleated in the cuboid at an applied field of 40 Oe. The density of non-sixfold coordinated vortices, \(\rho_{\text{def}}\), strongly depends on the local induction. In the case of macroscopic \(\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}\) vortex matter, \(\rho_{\text{def}}\) decreases exponentially on increasing field and saturates around 2 % for \(B > 20\) Gauss, see Fig. 3a. This is due to the enhancement of inter–vortex interaction with increasing \(B\). This magnitude follows the same field-evolution for mesoscopic vortex matter but is at least 50 % larger than for bulk samples. In addition, \(\rho_{\text{def}}\) is always larger in disks than in cuboids for roughly the same vortex density. This can be explained by considering that aligning a compact plane of vortices with the edges of a cuboid does not imply to change the orientational order of the structure, whereas in order to do so in a disk, the vortex planes have to bend.
Fig. 3  Density of topological defects (non-sixfold coordinated vortices) in mesoscopic and macroscopic Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ vortex matter. a Experimental data as a function of applied field for the mesoscopic vortex structures nucleated in macroscopic vortex matter, the 30 $\mu$m disk and cuboid, and results of simulations for large cooling times. b Results from molecular dynamics simulations as a function of the simulations cooling time (in thousands of steps of simulations) for the 30 $\mu$m disk and $B = 15$ Gauss (Color figure online)

In the case of macroscopic samples, the structure observed by means of field-cooling decorations at 4.2 K, and therefore its $\rho_{\text{def}}$, is quite close to the equilibrium [17]. The possibility of the increase on the $\rho_{\text{def}}$ on decreasing the system size being an out-of-equilibrium phenomena cannot be discarded. In order to study this, we performed molecular dynamics simulations of the mesoscopic vortex matter nucleated in a 30 $\mu$m disk with a vortex density corresponding to 15 Gauss. In particular, we performed tests on the dependence of $\rho_{\text{def}}$ with the cooling rate, inversely proportional to the time allowed to the system to relax. First, we performed simulations in a macroscopic sample in order to find the pinning magnitude that has to be considered to reproduce the observed $\rho_{\text{def}}$. Then we used this pinning magnitude to perform simulations in micron-sized samples. The results of $\rho_{\text{def}}$ as a function of the cooling rate, see Fig. 3b, indicate that the observed experimental values correspond to the case of large cooling times.

Therefore, we can ascertain that the amount of topological defects observed experimentally in micron-sized samples is not an out-of-equilibrium feature and that the observed structure is quite close to the equilibrium. This finding allows the estimation of the excess energy induced by confinement effects in micron-sized samples. In the case of bulk samples, the mean value of the inter–vortex interaction energy distribution is slightly shifted upward with respect to the value for a perfect Abrikosov lattice with the same vortex density [10]. Since after a field-cooling process, vortices are close to equilibrium, this shifting can only be accounted by the effect of bulk pinning [10]. This energy can be expressed, by unit length, as $\langle \varepsilon_{\text{int}} \rangle^b - \varepsilon_{\text{Abr}} = \varepsilon_p^b$, where $b$ stands for the bulk sample and $\langle \varepsilon_{\text{int}} \rangle$ is the mean value of the inter–vortex interaction energy distribution, $\varepsilon_{\text{Abr}}$ the value of the inter–vortex interaction energy in a perfect Abrikosov lattice (a delta-function), and $\varepsilon_p$ the pinning energy. In the case of mesoscopic vortex matter, an extra term enters into the energy-balance, namely the confinement energy $\varepsilon_{\text{conf}}$ and therefore $\langle \varepsilon_{\text{int}} \rangle^\text{meso} - \varepsilon_{\text{Abr}} = \varepsilon_p^\text{meso} + \varepsilon_{\text{conf}}$, where meso refers to the case.
of mesoscopic vortex matter and the energies are denoted similarly as in the previous case. Assuming that the pinning magnitude is the same irrespective of the sample size, then the excess energy due to confinement is $\varepsilon_{\text{conf}} = \langle \varepsilon_{\text{meso}} \rangle - \langle \varepsilon_{\text{int}}^b \rangle$.

The inter–vortex interaction energy per unit length depends on the inter-vortex distances $r_{ij}$, and for a vortex $i$ has a value $\varepsilon_{\text{int}}^i = \sum_j 2\varepsilon_0 K_0(r_{ij}/\lambda)$, with the sum over neighbor vortices $j$, $\varepsilon_0 \propto \lambda^{-2}$ the vortex line tension, and $K_0$ the zeroth-order modified Bessel function. In real cases, this magnitude is spatially inhomogeneous due to the elastic and plastic deformations of the structure, and therefore there is a distribution of $\varepsilon_{\text{int}}^i$ with an almost Gaussian shape [10]. Only in the case of an ideal Abrikosov lattice, this magnitude is space invariant, and its distribution is a delta function. We have performed inter-vortex energy-distribution calculations in vortex structures observed by magnetic decoration in the macroscopic samples from which the disks and cuboids were engineered. We also performed the same calculations in the mesoscopic vortex matter nucleated in the disks and cuboids at both applied fields. Irrespective of the field, the mean values of $\langle \varepsilon_{\text{int}}^\text{meso} \rangle$ are always larger than in the case of macroscopic vortex matter, what can be reasonably ascribed to the extra deformations introduced by the larger amount of topological defects nucleated in the micron-sized samples. In accordance with this reasoning, the $\langle \varepsilon_{\text{int}} \rangle^\text{meso}$ value is always larger for the structure nucleated in the disks than in the cuboids by a 6–9% on increasing field. The relative excess confinement energy that measures the impact of surface-to-volume effects, $\delta_e = \varepsilon_{\text{conf}} / \langle \varepsilon_{\text{int}}^\text{meso} \rangle$, is in the case of disks equal to 0.08 (0.01), larger(similar) than in the case of cuboids, 0.06 (0.01) for $B = 15(30)$ Gauss within an error of 0.01.

4 Conclusions

The edges of the samples do produce a geometrical confinement effect in mesoscopic vortex matter made evident by the orientation of the outer shells of vortices with compact planes parallel to the edges what produces a concomitant increase of the density of topological defects. By means of molecular dynamics simulations, we show that the density of defects found experimentally is not an out-of-equilibrium feature but rather the effect introduced by geometrical confinement. By means of differences in the mean value of the inter–vortex interaction of the mesoscopic and macroscopic vortex structures, we are able to quantify the confinement energy per unit length. We find that this energy is just $0.11 - 0.13 \varepsilon_0$, slightly larger for the case of disks than for the cuboid geometries.

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