Direct determination of the collective pinning radius in high temperature superconductors

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We study finite-size effects at the onset of the irreversible magnetic behaviour of micron-sized Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ single crystals by using silicon micro-oscillators. We find an irreversibility line appearing well below the thermodynamic Bragg-glass melting line at a magnetic field which increases both with increasing the sample radius and with decreasing the temperature. We show that this size-dependent irreversibility line can be identified with the crossover between the Larkin and the random manifold regimes of the vortex lattice transverse roughness. Our method allows to determine the three-dimensional weak collective pinning Larkin radius in a direct way.

Superconducting vortex lattices can display the universal glassy properties that emerge from the frustrating competition between elasticity and disorder. They provide an exceptional test ground for the universal predictions of statistical elastic-field theories, whose methods can be indistinctly applied to periodic systems, such as charge density waves [1, 2] and Wigner crystals [3], or to interfaces, such as magnetic [4, 5, 6] and ferroelectric [7] domain walls, liquid menisci [8] and fractures [9].

Larkin and Ovchinnikov [10] demonstrated the unavoidable impact of arbitrarily weak disorder on the otherwise perfect vortex lattice and determined the basic length-scales of the problem: it is the finiteness of these, so-called Larkin lengths, what fundamentally explains the mere existence of pinning and measures its effective strength on the extended system [11]. In the modern elastic theory, designed to correctly describe the large-scale static and dynamical universal behaviour of the elastic manifold, the Larkin lengths are the fundamental input for making quantitative predictions for a given experimental system. Determining the Larkin lengths for a high-T$_c$ superconductor remains a difficult challenge however. Indirect empirical estimates based on transport properties such as the critical current or the creep barriers are an alternative, but they spoil precise comparisons between experiments and theory. Recently, an experimental finite-size analysis was applied to determine the characteristic dynamical length, predicted by the (bulk) elastic theory, controlling the domain wall creep motion in ferromagnetic nanowires [9]. Here we report a finite-size study of the onset of irreversibility in a micron-sized superconductor that allows to determine the Larkin radius in a direct way.

The elastic theory characterizes the translational order by the roughness function $W(r) = \langle |u(r) - u(0)|^2 \rangle$, with $u(r)$ the vortex displacement field with respect to the perfect lattice. For the Bragg-glass (BG) phase [12], expected for weak pinning at low enough temperatures, a logarithmic growth of $W$ is predicted at large distances. At short distances however, we have a Larkin regime where displacements grow as $W \sim r^{4-d}$, with $d = 3$ the internal dimension of the elastic manifold. A crossover to the Random Manifold (RM) regime at a distance $r_c$ occurs when displacements are comparable to the pinning force range $r_p$, such that $W(r_c) \sim r_p^2$. For a superconductor with vortices directed along the direction $\hat{z}$ of an external magnetic field, this crossover defines the longitudinal ($L_c \equiv |r_c - \hat{z}|$) and transverse ($R_c \equiv |r_c - L_c\hat{z}|$) Larkin lengths. Besides describing a geometrical crossover the Larkin lengths also determine the size of the minimum bundle of vortices that can be individually pinned by the quenched disorder [10].

We fabricated Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ samples with a procedure similar to that of Wang et al. [13].

FIG. 1: Scanning electron microscope images of two samples mounted in the Silicon micro-oscillators. Left (right) sample of radius 6.75 (25) $\mu$m.
Disks of radii $R_a = 6.75, 13.5, 25 \mu m$ and $d = 1 \mu m$ of thickness were made up by lithography and ion etching (see Methods) and then glued to high-Q silicon torsional micro-oscillators [14, 15]. Scanning electron microscope images of two samples are shown in Fig. 1. When an external magnetic field is applied perpendicular to the superconducting planes and the torsional axis, the change in the resonant frequency $\Delta \nu_r$ of the oscillator is proportional to the magnetization of the sample [16].

In Fig. 2 we plot the results obtained for $R_a = 13.5 \mu m$ under two different protocols. In the FC protocol we cool the sample below its critical temperature at an applied field of 176 Oe while registering $\Delta \nu_r$ (upper curve). In the ZFC protocol we cool the sample at zero field up to the lowest temperature, apply the same field as before, and then measure $\Delta \nu_r$ while warming up the sample (lower curve). The onset of irreversibility can be defined at the merging of both curves. Similar data can be obtained from fields loops at constant temperature as shown in the inset of Fig. 2. Two features can be readily observed: the clear size dependence of the irreversibility line, and the wide spanning in temperature of the reversible state compared to that of bulk samples [17]. Phenomenologically, reversibility is reached when thermal fluctuations overcome the stronger pinning mechanism present in the sample. It has been argued that in this material geometrical [18, 19] or surface barriers [20] were the responsible of the irreversibility. Several aspects of the data point against these as the cause of the irreversibility. Geometrical and surface barriers decreases as the aspect ratio (thickness/diameter) increases [21]. Our data shows the opposite behaviour, irreversibility is enhanced as the sample aspect ratio grows as can be directly seen in the inset of Fig. 2. Moreover, our data does not comply with the predictions given for the temperature dependence of the geometrical barrier and its scaling with the first penetration field [21]. It does not comply neither with the expected shape of the magnetization loops [22] for a surface barrier. We show, in the following, that these puzzling finite-size effects can be explained, however by a different and more fundamental mechanism.

We shall analyse the onset of irreversibility as the finite-size crossover at the vortex lattice Larkin length. For an applied field parallel to the $c$-axis, and neglecting the compression modulus contribution, we can use the Larkin-Ovchinikov perturbative result [10],

$$W(r) \approx r_p^2 e^{A \left[ \frac{a_0}{l_c} \right]^3 \left[ \frac{R^2}{\lambda^2} + \frac{a_0^2 L^2}{\lambda^4} \right]^{1/2}},$$

where the so-called single-vortex collective pinning length $l_c$ absorbs the effective pinning strength [11], $a_0 = \frac{2a_0}{\sqrt{3}B}$ is the lattice constant, $\lambda$ the penetration length and $\epsilon$ the anisotropy parameter [11]. At zero temperature $r_p \equiv \xi$ for point impurities, with $\xi$ the vortex core radius. At high temperatures however, fast futile thermal vortex motion induces a growth in $r_p$, thus effectively smoothing the microscopic disordered potential . Eq. (1) which is valid for $L_c \geq L > \lambda^2/a_0$ and $R_c \geq R > \lambda/\epsilon$ (we neglect the dispersivity in the tilt modulus [10, 11]), yields,

$$R_c \approx \frac{\lambda}{\epsilon^4} \left[ \frac{L}{a_0} \right]^3, \quad L_c \approx \frac{\lambda}{a_0} R_c,$$

for the transverse and longitudinal Larkin lengths, respectively. Pinning, metastability and thus ir-
reversibility (and the failure of the perturbation data for samples of different radii. Inset: non-scaled the identification of the Larkin radius with the sample radius at the onset of irreversibility. In Fig. 3 we show that the predicted scaling results can be well described by the expression,

\[ B_i(R_s, T) \sim R_s^{2/3} \exp(-2T/T_0), \]

with a characteristic temperature \( T_0 \approx 25 \) K. Interestingly, Wang et al. [13] have reported size-effects at the second magnetization peak in BSSCO controlled by the same exponential temperature dependence, with a characteristic temperature of 22.5 K, very close to our value. In our calculations, the temperature dependence of \( B_i \) is exclusively attributed to the parameter \( l_c \), as \( l_c(T) \sim \exp(T/T_0) \). In order to grasp the physical meaning of this result we can assume that \( l_c \) represents (as it indeed does in Eq. 1 at zero temperature), the Larkin length of an isolated vortex at finite \( T \). An exponential sensitivity \( \exp[CT^\alpha] \) is consistent with the marginality of the pinning of an elastic string in a three-dimensional disordered medium, and it has been predicted, with \( C \) a constant and \( \alpha \) an exponent which depends on the precise nature of the disorder correlator function [11, 24]. In particular, the value \( \alpha = 1 \) has been predicted [24] for high-\( T_c \) superconductors for vortex displacements \( u \) satisfying \( \xi < u < \lambda \), suitable for our case. More interestingly, the value of \( T_0 \) we get is very close to the one observed in creep [25] (~20 K), ac-transverse permeability [20, 27, 28] (~22 K) and critical current measurements [27] (~20 K) in samples of the same material but with radii one and two orders of magnitude bigger than ours, using the expected Relations of these different quantities with \( l_c \). Being \( T_0 \) ~ \( U_{pc} \), with \( U_{pc} \) the single pancake pinning energy [25], the anomalies observed near \( T_0 \) are commonly attributed to the crossover between a strong 0D pinning regime (when \( l_c \) becomes smaller than the layer spacing and thus pancakes pin individually), to a weak 3D pinning regime (see Kierfield [29] for a recent discussion). The temperature dependence of \( l_c \), and the fact that for \( T > T_0 \) we can use 3D weak collective pinning (Eq. 2) support our identification of the Larkin radius.

Our empirical estimate \( R_s(B, T) \approx R_s [B/B_i(R_s, T)]^{3/2} \sim B^{3/2} \exp(T/2T_0) \), for the weak non-dispersive pinning regime, implies that, in the phase-space region we analyse, very big BSSCO samples are necessary to achieve the vortex matter thermodynamic limit for \( T_0 < T \leq T_m \), with \( T_m \) the BG melting temperature. This is relevant for the predicted crossover in the vortex lattice roughness, from the RM to the asymptotic BG regime [12] at the character-
istic scale \( R_a = R_c(a_0/r_p)^{1/\zeta} \), with \( \zeta \sim 0.2 \) the random-manifold roughness exponent \([30, 31]\). If we can roughly identify the renormalized pinning range with the thermally induced displacement, \( r_p^2 \sim \langle u^2 \rangle_{th} \) \([11]\), the Lindemann criterion with constant \( c_L \sim 0.2 \) lead us to an upper bound for the pinning range, \( r_p^2 \leq c_L^2 a_0^2 \). We thus get \( R_a \gtrsim R_c c_L^{-1/\zeta} \sim 10^3 R_c \). If we evaluate this expression at \( T \) and \( B \sim B_i(T, R_a) \), where we have shown that \( R_a = R_s \) for our three samples, we find that \( R_a \) is of the order of one cm. Our naive estimate thus indicates that the asymptotic logarithmic growth, characteristic of the BG phase, can be only achieved in huge samples in the region of the phase-space we analyse. This striking result seems to be however consistent with magnetic decoration experiments \([31]\) displaying the random-manifold roughness up to distances \( R \approx 80a_0 \), for which \( W(R) \approx 0.05a_0^2 \) in the range \( B \approx 70-120 \) G. Note that the naive extrapolation of the latter to \( R_a \), such that \( W(R_a) = a_0^2 \) gives \( R_a \sim O(mm) \), in fair quantitative agreement with our previous estimate. These results indicate the remarkable possibility of detecting, in normal samples, the crossover from the RM to the BG regime at temperatures \( T_0 \) below the irreversibility line as a finite-size crossover when \( R_a(B, T) \approx R_c \). This would provide an independent experimental tool, different from neutron diffraction \([32]\), magnetic decorations \([30]\), or creep measurements \([24]\), to test the predicted geometrical features of the BG phase \([12]\) in these materials.

In conclusion, we have experimentally determined, in a direct way, the most fundamental pinning length of a disordered elastic system by analysing finite-size crossover effects in micron-sized High-\( T_c \) superconductors. This kind of study, complemented with micron-scale transport measurements can lead to a better understanding of the rich multi-scale physics of pinned vortex lattices, and of the universal properties they share with other pinned elastic manifolds.

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