Hyperuniformity in Type-II Superconductors with Point and Planar Defects

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We use vortex matter in type-II superconductors as a playground to study how different types of disorder affect the long wavelength density fluctuations of the system. We find that irrespective of the vortex-vortex interaction, in the case of samples with weak and dense point defects the system presents the hidden order of hyperuniformity characterized by an algebraic suppression of density fluctuations when increasing the system size. We also reveal that, on the contrary, for samples with planar defects hyperuniformity is suppressed since density fluctuations have a tendency to unboundedness on increasing the system size. Although some of these results were known from previous works, this paper makes the fundamental discovery that the ability of planar disorder to suppress hyperuniformity grows on increasing the softness of the structure for more diluted systems.

I. INTRODUCTION

Vortex matter in type-II superconducting samples is a system of interacting elastic objects that can be used as a laboratory playground to study the growth of hyperuniform materials nucleated in host media with disorder. The quest for hyperuniform material systems is currently attracting great interest in the condensed matter and materials science communities due to their unique physical properties. Hyperuniform materials are endowed with a novel phenomenon that goes against the conventional wisdom on the effect of structural disorder in systems of interacting objects. For instance, disordered hyperuniform two-dimensional silica structures present a closing of bandgaps for electrical transport resulting in an enhanced conductivity. Also, disordered hyperuniform materials possess complete photonic bandgaps blocking all directions and polarizations for short wavelengths, in contrast to previous assumptions that periodic or quasiperiodic order was a prerequisite for a material to present this optical property.

Hyperuniformity is a topological property of a state of matter that is characterized by strongly-reduced long-wavelength density fluctuations entailing a decaying structure factor \( S(q) \) for small wave-vectors \( q \). The density of constituents in hyperuniform systems is homogeneous at large scales, as in a perfect lattice, but it can present fluctuations at short length scales as in a disordered structure. Hyperuniformity is a structural property defined in an asymptotic limit and ascertaining this property in real systems is thus difficult. For this reason most works show that the systems are effectively hyperuniform.

The structure factor can be directly measured using different X-ray and neutron diffraction techniques depending on the typical lattice spacing of the systems. An alternative way of obtaining this magnitude is to compute it from the real-space positions of the individual constituents considering that \( S(q) = |\hat{\rho}(q_x, q_y)|^2 \), with \( \hat{\rho} \) the Fourier transform of the local density modulation \( \rho \).

In this work we use this approach to study the occurrence of hyperuniformity in vortex matter nucleated in superconducting samples with point and planar crystal defects. The nature of disorder unavoidably present in the host medium affects whether the nucleated structure is hyperuniform or non-hyperuniform. In the case of samples with weak and dense point disorder, some of us revealed that the vortex structure nucleated in the cuprate superconductor Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ is effectively hyperuniform at the sample surface. Later studies report that disordered hyperuniform vortex structures are nucleated in pnictide and Fe-based superconductors with point disorder. Nevertheless, we recently found that the presence of planar correlated defects suppresses hyperuniformity in the vortex structure in an anisotropic fashion. Thus, attention to the nature of disorder in the host medium has to be payed in the search for novel hyperuniform materials composed of interacting objects.

Another relevant parameter that enters into play when trying to nucleate hyperuniform structures is the magnitude of the interaction between constituents that when enhanced will tend to decrease the density fluctuations irrespective of the nature of disorder in the medium. In our case, the vortex density is controlled by the applied field since the lattice spacing \( a_0 \propto (B)^{-1/2} \) and, in addition, the interaction between vortices becomes larger on increasing field. In this work we study how a softening of the vortex structure affects the density fluctuations at long wavelengths or short wavevectors for point and correlated disorder in the samples.

II. EXPERIMENTAL

We image the structure with single vortex resolution at the surface of the samples by means of the magnetic decoration experiments performed at 4.2 K after following a field-cooling process. As demonstrated previously, during this cooling process the vortex structure gets frozen at length-scales of the lattice spacing at a
temperature \( T_{\text{freez}} \sim T_{\text{irr}} \), the irreversibility temperature at which pinning sets in on cooling.\textsuperscript{13} At this crossover temperature the bulk pinning dominates over the vortex-vortex repulsion and the thermal fluctuations.\textsuperscript{19,20} Deco-
oration of individual vortices is performed at 4.2 K by evaporation of Fe clusters in a controlled-pressure helium atmosphere. These magnetized clusters are attracted towards the magnetic halo of the vortex core due to the magnetic force exerted by the local field gradient inherent to vortices. Once the experiment is performed the sample is warmed up to room temperature and the Fe clusters that remain attached to the surface due to van der Waals forces are observed by means of scanning electron microscopy. Vortices are decorated with the Fe clumps and imaged as white dots in the images.

The superconducting samples we study are nearly optimally-doped single crystals of Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_{8+\delta}\) \((T_c \sim 90 \text{ K})\) grown by means of the flux method.\textsuperscript{18} Some of the crystals present few planar crystallographic defects consisting in stacking faults in the crystals separating zones with slightly different orientations of their \(c\)-axis.\textsuperscript{19,20} We also study samples with point disorder only, namely with no planar defects as revealed by means of magnetic-decoration imaging of the vortex structure.

### III. RESULTS

Figure\textsuperscript{[1]} shows snapshots of vortex structures nucleated in samples with point (top panels) and planar (bottom panels) defects for two different vortex densities. Data in the left panels correspond to the vortex structure nucleated at 27 G and on the right panels to the softer vortex structure nucleated at 4 G. In the case of samples with point defects, the more diluted 4 G vortex structure presents a larger amount of density fluctuations at short lengthscales than the one nucleated at 27 G. In samples with planar defects, they are effective to induce vortex rows aligned along the defects irrespective of the vortex density, see highlighted regions in the Figs.\textsuperscript{[1]} (b) and (d).

In the region of these rows, the vortex structure present strong density fluctuations for both magnetic fields. In order to quantify how a softening of the structure affects the density fluctuations at long wavelengths, we calculated the structure factor and then computed its angular-average at every \(q\), \(\langle S(q) \rangle\). The result of this analysis is shown in Fig.\textsuperscript{2} for both vortex densities, plotted as a function of \(q/q_0\) with \(q_0 = 2\pi/(a_0 \cos \pi/6)\) the Bragg wavevector of the hexagonal vortex structure. Data in full symbols correspond to the case of point disorder whereas open symbols come from structures nucleated in samples with planar defects. In the first case, \(\langle S(q) \rangle\) decays algebraically when \(q \rightarrow 0\) with the exponents \(\alpha = 1.1\) for 4 G and 1.2 for 27 G. In both cases these exponents are yielded by fits of the data in the 0.1-0.4 \(q/q_0\) range with an error of 0.3 for 4 G and 0.2 for 27 G. Thus, as already reported on Ref.\textsuperscript{11}, density fluctuations in samples with point disorder decay at long wavelengths in a hyperuniform fashion irrespective of the vortex lattice softness.

In contrast, in the case of samples with planar defects the angularly-averaged structure factor saturates and even has a tendency to unboundedness when \(q \rightarrow 0\). This indicates that vortex density fluctuations do not tend to zero at long wavelengths but they rather enhance with distance. Thus, in samples with correlated disorder the vortex structure does not present the hyperuniform hidden order and is instead anti-hyperuniform. This phenomenology takes place even for the harder vortex structure of 27 G with a larger vortex-vortex interaction, a case where the relative effect of the pinning induced by planar defects is smaller. Nevertheless, \(\langle S(q) \rangle\) grows faster as \(q \rightarrow 0\) when the softness of the structure increases. This indicates that for softer vortex structures the ability of planar defects to suppress hyperuniformity is enhanced. Whether this is related to a different relevance of the finite-size effect that may lead to a recovery of hyperuniformity in samples with planar defects that are sufficiently thick as reported in Ref.\textsuperscript{7}, deserves fur-
FIG. 2: Angularly-averaged structure factor of the vortex structures nucleated in Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ with point (full symbols) and planar (open symbols) disorder for densities of (a) 4 and (b) 27 G. The wavenumber is normalized by the Bragg wavenumber $q_0 = 2\pi/(a_0 \cos \pi/6)$. Full red lines are fits to the data in samples with point disorder considering $\langle S(q) \rangle \sim (q/q_0)^\alpha$ when $q/q_0 \to 0$ yielding the $\alpha$ exponents indicated in each case. Data for the 27 G structures are obtained considering the position of 6189 (2100) vortices in a sample pristine (with planar defects), whereas data for the 4 G structures come from 500 (2170) vortices for a sample pristine (with planar defects).

Here we report that planar correlated disorder is effective to enhance long wavelength density fluctuations as to suppress the hyperuniform hidden order otherwise present in the vortex structure nucleated in samples with point disorder. This effect takes place irrespective of the magnitude of vortex-vortex interaction but it is enhanced in the case of softer structures of interacting elastic objects such as vortices in type-II superconductors.

IV. CONCLUSIONS

1 G. Rumi, J. Aragón Sánchez, J., F. Elías, R. Cortés Maldonado, J. Puig, N. R. Cejas Bolecek, G. Nieva, M. Konczykowski, Y. Fasano, and A. B. Kolton, Phys. Rev. Res. 1, 033057 (2019).

2 J. B. Llorens, I. Guillamón, I. García-Serrano, R. Córdoba, J. Sesé, J. M. De Teresa, M. R. Ibarra, S. Vieira, M. Ortuño, and H. Suderow, Phys. Rev. Res. 2, 033133 (2020).

3 W. Man, M. Florescu, E. P. Williamson, Y. He, S. R.
Hashemizad, B. Y. C. Leung, D. R. Liner, S. Torquato, P. M. Chaikin, and P. J. Steinhardt, Proceed. Nat. Acad. Sci. USA 110, 15886 (2013).
4 D. Chen, and S. Torquato, Acta Materialia 142, 152 (2018).
5 S. Torquato, Phys. Rep. 745, 1 (2018).
6 Y. Zheng, L. Liu, H. Nan, Z.-X. Shen, G. Zhang, D. Chen, L. He, W. Xu, M. Chen, Y. Jiao, H. Zhuang, Sci. Adv. 6, eaba0826 (2020).
7 M. Florescu, S. Torquato, and P. J. Steinhardt, Proceed. Nat. Acad. Sci. USA 106, 20658 (2009).
8 L. S. Froufe-Pérez, M. Engel, P. F. Damasceno, N. Muller, J. Haberko, S. C. Glotzer, and F. Scheffold, Phys. Rev. Lett. 117, 053902 (2016).
9 S. Torquato, and F. H. Stillinger, Phys. Rev. E 68, 041113 (2003).
10 M. A. Klatt, J. Lovric, D. Chen, S. C. Kapfer, F. M. Schaller, P. W. A. Schönhöfer, B. S. Gardiner, A.-S. Smith, G. E. Schröder-Turk, and S. Torquato, Nature Comm. 10, 811 (2019).
11 J. Aragón Sánchez, R. Cortés Maldonado, L. Amigó, G. Nieva, A. B. Kolton, and Y. Fasano, submitted to Phys. Rev. Lett. (2022)
12 J. Puig, F. Elías, J. Aragón Sánchez, R. Cortés Maldonado, G. Rumi, G. Nieva, P. Pedrazzini, A. B. Kolton, and Y. Fasano, Commun. Mater. 3, 32 (2022).
13 Y. Fasano, and M. Menghini, Supercond. Sci. Tech. 21, 023001 (2008).
14 Y. Fasano, M. De Seta, M. Menghini, H. Pastoriza, and F. de la Cruz, Solid State Comm. 128, 51 (2003).
15 N. R. Cejas Bolecek, A. B. Kolton, M. Konczykowski, H. Pastoriza, D. Domínguez, and Y. Fasano, Phys. Rev. B 93, 054505 (2016).
16 F. Pardo, A. Mackenzie, F. de la Cruz, and J. Guimpel, Phys. Rev. B 55, 14610 (1997).
17 Y. Fasano, J. A. Herbsommer, F. de la Cruz, F. Pardo, P. L. Gammel, E. Bucher, and D. J. Bishop, Phys. Rev. B 60, 15047 (1999).
18 V. F. Correa, E. E. Kaul, and G. Nieva, Phys. Rev. B 63, 172505 (2001).
19 M. R. Koblishka, et al., Phys. C 249, 339 (1995).
20 J. A. Herbsommer, V. F. Correa, G. Nieva, H. Pastoriza, and J. Luzuriaga, Solid State Comm. 120, 59 (2001).