Hyperuniform vortex patterns at the surface of type-II superconductors

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Vortex matter in a type-II superconductor can form **hyperuniform two-dimensional point pattern** for any constant-z cross section. **Analytical, numerical and experimental evidence.**

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Introduction

Hyperuniformity is characterized by a complete suppression of the density fluctuations in the the large-wavelength limit [1]. From the definition $\lim_{q\to 0} S(q) = 0$, in the case power law behavior $S(\mathbf{q}) \sim q^{\alpha}$, we can define, in the asymptotic limit ($N \gg 1$),

$$\sigma_N^2(R) \sim \begin{cases} R^{d-1}, & \alpha > 1 \quad \text{I} \\ R^{d-1}\ln R, & \alpha = 1 \quad \text{II} \\ R^{d-\alpha}, & 0<\alpha<1 \quad \text{III} \end{cases} \quad \textit{class} \tag{1}$$

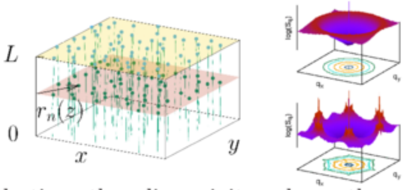
where $\sigma_N^2(R) = \langle N^2(R)\rangle - \langle N(R)\rangle^2$ is the variance and $R \to \infty$.

Hydrodynamics theory

In equilibrium the structure factor of a 3D line system with short range interaction, at small enough wave-vector take the form

$$S^{3d}_{\text{liq,sol}}(\mathbf{q}, q_z) = \frac{n_0 k_B T q^2}{q^2 c_{11}(q, q_z) + q_z^2 c_{44}(q, q_z)} \tag{2}$$

where $c11$ and $c44$ are the compressional and tilt bulk modulii [2,3]. At constan-z we can compute the **two-dimensional structure factor** $S(q) \approx \frac{2\pi}{s}\int_0^{2\pi/s} dq_z S^{3d}(q, q_z)$.



Neglecting the dispersivity along the z-direction, we have

$$S_{\text{liq}}(q) \approx S_{\text{sol}}(q) = \frac{n_0 k_B T}{\sqrt{c_{44}(q,0)c_{11}(q,0)}} q, \tag{3}$$

for the clean system y the **liquid** and **Abrikosov** phase.

References

[1] Torquato, Salvatore. "Hyperuniform states of matter." Physics Reports 745 (2018): 1-95.

[2] Marchetti, M. Cristina, and David R. Nelson. "Hydrodynamics of flux liquids." Physical Review B 42.16 (1990): 9938.

[3] Marchetti, M. Cristina, and David R. Nelson. "Translational correlations in the vortex array at the surface of a type-II superconductor." Physical Review B 47.18 (1993): 12214.

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Analytical predictions

Generalizing Equation 2 for different disorder potentials (weak, point and columnar) we arrive to

- $S_{\text{pin-liq}}(q) = \frac{n_0^3 \Delta}{\sqrt{c_{44}(q,0)c_{11}^3(q,0)}} q + S_{\text{liq}}(q)$
- $S_{\text{pin-sol}}(q) \sim \frac{q^{-2\zeta}}{\sqrt{c_{44}(q,0)c_{11}^{2+2\zeta}(q,0)}}$
- $S_{\text{col-liq}}(q) \approx \frac{n_0 k_B T}{\sqrt{\tilde{c}_{44}(q,0)\tilde{c}_{11}(q,0)}} q + \Delta_1 \frac{n_0^3}{\tilde{c}_{11}^2(q,0)}$

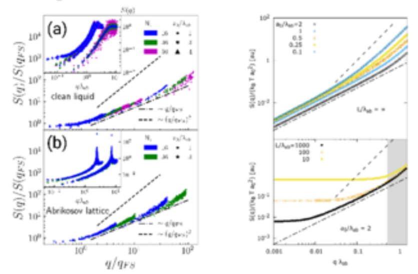
Phases	*hyperuniformity*
Liquid without disorder	**Yes** : Class II $\alpha = 1$
Liquid with weak uncorrelated disorder	**Yes** : Class II $\alpha = 1$
Liquid with correlated disorder by CDs	**No**
Abrikosov crystal	**Yes**: Class II $\alpha = 1$
Bragg Glass	**Marginal**: $\alpha = 0$
Bose Glass	**No**
Mott Glass	**Yes**: Unknown Class.

Finite size effects

we perform numerical simulations of a line system with in-plane interaction $V(r_\perp) = K_0(r/\lambda)$, and armonic in of-plane. There is a crossover from $S(q) \propto q$ to saturation in

$$q_{FS} \sim \sqrt{\frac{c_{44}(q_{FS}, 2\pi/L)}{c_{11}(q_{FS}, 2\pi/L)}} \frac{2\pi}{L} \tag{4}$$

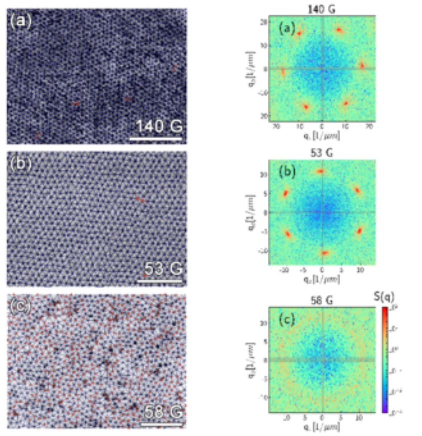
destroying hyperuniformity. Similar results are obtained integrating Equation 2 with anisotropics $c11$ and $c44$.



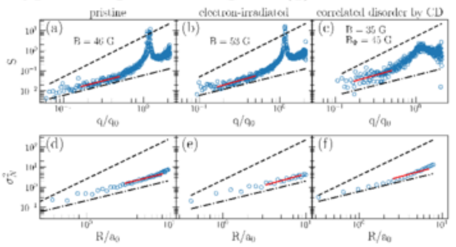
Experimental results

We perform field cooling magnetic decorations experiments in the $Bi_2Sr_2CaCu_2O_{8+\delta}$ system at 4.2K with

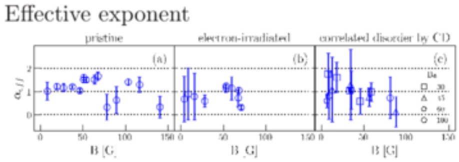
- three different disorder potential
- applied field in the range of $5 < H < 150$ Oe



Typical angular-averaged $S(q)$ and variance



Effective exponent



Conclusion

- Experiments shows that vortex array are nearly hyperuniform at the surface, with $S(q) \sim q^{\alpha_{\text{eff}}}$ and $\alpha_{\text{eff}} \approx 1 \pm 0.3$.
- Results agrees with the equlibrium hydrodynamics predictions.
- **Memory effects** during the field cooling protocol, **dispersivity** of elastics constants and **finite-size effects** are relevant for a systematic study of large scale density fultuations in vortex matter.

More information in

ArXiv 2019.