Abstract

Vortices in clean d-wave superconductors at low temperatures can behave as quantum particles. Their quantum dynamics is made possible by the smallness of their cores, due to short coherence length in typical cuprates, and by the presence of massless fermionic quasiparticles, which give rise to certain universal effects. We calculate a small finite renormalization of vortex mass by the nodal quasiparticles, and demonstrate the absence of Bardeen-Stephen damping of vortex motion in the limits of zero temperature, no disorder and vanishing core size. Being liberated from strong friction, light vortices can experience significant quantum fluctuations that can explain several phenomena observed in cuprates, including the Nernst effect and density waves. We also show that quantum fluctuations of localized vortices can significantly affect quasiparticle spectra. The local density of states (LDOS) near a quantum fluctuating vortex shows no zero-energy peak, but has satellite features at energies set by the vortex trapping potential. These are proposed to be the origin of the sub-gap LDOS peak observed in recent STM experiments near the vortex cores.

Unconventional physics of high-Tc superconductors

Nerst effect:
- vortex motion in the normal phase
- persists down to $T=0$ in the normal underdoped region
- large Nernst signal: small vortex damping

Vortex core structure:
- checkerboard pattern inside the core region (STM)
- energy dependence of LDOS (see the right column)

Competing orders:
- density wave checkerboard pattern in the normal phase, seen by STM
- unit cell – 4 lattice constants near 1/8 doping

Physical picture:
- vortex fluctuations destroy superconductivity, even at $T=0$
- light frictionless vortices?

Effective vortex action obtained by “integrating out” quasiparticles:

$$S_V = \int \frac{a^2}{2} \left[ F_1(\alpha) \right] d\alpha$$

Quasiparticle contribution to vortex dynamics:

$$F_1(\alpha) = -\eta |\omega| + A_{\omega}^2 \log |\omega| + \frac{mv_\alpha^2}{2} + A_2|\omega|^2$$

Conclusions:
- for a typical $g=10$, vortex mass is about 3.3 electron masses!
- vortex friction vanishes in the limit $T=0$, disorder energy scale (zero energy bulk DOS) enters the friction terms the same way as temperature
- consistent with simple scaling argument, which treats quasiparticles as a quantum critical system (with dynamical exponent $z=1$)
- vortices are light and essentially frictionless at low temperatures in clean d-wave superconductors
- quasiparticle mediated forces between vortices: magnetic field dependence of the vortex mass, pinning of the vortex lattice orientation with respect to the substrate
- extra transversal forces on moving vortices in Zeeman fields
- no “zero-bias” peak due to the smallness of the core
- possible to measure vortex mass and trapping potential

References:

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Mutual influence of vortices and quasiparticles in d-wave superconductors

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Vortex dynamics

Quasiparticles provide a significant and often dominant contribution to vortex dynamics. Conventional BSC superconductors ($s$-wave):
- Large core, numerous core states
- Heavy core + Bardeen-Stephen friction
- Classical dynamics (Kopnin, Volovik...)

Cuprate superconductors ($d$-wave):
- Small core, no core states
- Light core, no Bardeen-Stephen friction
- Quantum dynamics

Interaction between a vortex and quasiparticles:

Bogoliubov-de Gennes Hamiltonian, linearized in the vicinity of four “nodal” points.

$$H = H_V(r_V) + \sum |\gamma \rangle \langle \gamma | H_{BdG}(r, r_V)|\gamma \rangle$$

Vortex core structure:
- checkerboard pattern inside the core region (STM)
- energy dependence of LDOS (see the right column)

Competing orders:
- density wave checkerboard pattern in the normal phase, seen by STM
- unit cell – 4 lattice constants near 1/8 doping

Physical picture:
- universal effect of vortex quantum fluctuations on partially filled lattices

Quasiparticle spectra near a vortex

Hamiltonian of a localized vortex (due to a trap, or nearby vortices in a vortex lattice):

$$H_V = \frac{D}{2m_V} + \frac{1}{2} m_V \omega^2 r_V^2$$

Coupling to quasiparticles: linearized Bogoliubov-de Gennes model (see the center column). Vortex is light ($m_V \rightarrow 0$) and frictionless at $T=0$. Quantum motion of the vortex affects quasiparticle spectra (local density of states (LDOS) observed by STM).

Perturbation theory:

$$H_0 = -\phi^\dagger \phi - \int d^2r \psi^\dagger \hat{V} \psi$$

$$H_I = \int d^2r \left\{ \nabla \cdot (\psi^\dagger \hat{V} \psi) + \text{resonant scattering of quasiparticles from the vortex} \right\}$$

Universal quasiparticle LDOS:

$$\rho(\epsilon, r) = \frac{\omega}{\pi} \int d^2q e^{i\epsilon(\lambda q - z)}$$

The perturbation parameter $g$ is small if the core size is smaller than the amplitude of vortex zero-point fluctuations (presumably true in cuprates). LDOS qualitatively agrees with STM measurements already at one-loop level.

Conclusions:
- no “zero-bias” peak due to the smallness of the core
- possible to measure vortex mass and trapping potential

Unified picture: Vortices of d-wave superconductors are light and experience very little friction; their dynamics is quantum.