Lecture 3

- Is & field-dependent: MSR
- STM on high-Tc
- Theoretical work on d-wave vertices
- Importance of band structure
- STM of NbSe2 and related theony
- Normal core model
- Single-vertex structure

![Diagram](Image)
requires numerical solution for arbitrary $k = \frac{1}{2}$

Vortex Structure in Ginzburg-Landau

Supercurrent Distribution

vortex

path of integration

$\int_0^\infty \delta \xi \cdot d\xi = n \Phi_0$

$\frac{\hbar}{e}$

$v_s = \frac{k}{\hbar}$

$v_s = \frac{\hbar}{m_e}$

$v_s = \frac{\hbar}{2e}$

$\Phi_0 + m_e \delta v_s \cdot d\xi = n \Phi_0$

$\delta$
must be cut off for $r \gg r_c$, where

$$r_c = \frac{\sqrt{\pi}}{\gamma} \left[ \frac{\gamma}{\gamma + 0.12} \right]^{\frac{1}{2}} \approx \frac{Z \mu}{\alpha} \left( \frac{r}{\alpha} - \frac{1}{r} \right)$$

For $r \gg r_c$, use London model to find $h(r)$

$$h(r) \approx \frac{Z \mu}{\alpha} r \frac{1}{r}$$

where $C$ is $o(1)$

Diagram:

\[\text{Graph of } h(r)\]

\[\text{Graph of } \rho(r)\]

For $r = r_c$, we find $E(r) = 0$.

Taking $v_s = \frac{\beta}{4}$.

Deeper shift of excitation energies (semiclassical)

How large is the case? Estimation 1.


\[
\frac{2\pi x}{\sigma} = \frac{\phi(r)}{K_0(R)} (r/v)
\]

Compare to London model for \( k \gg 1 \)

\[
\phi(r) = \frac{2\pi x}{\sigma} \frac{K_0(R)}{K_0(r/v)}
\]

\( R = \frac{r_1 + r_2}{2} \)

\( R = \text{cylindrical radius} \)

\( x = \text{various internal parameter} \)

\( \sigma \) = sample conductivity

\( \sigma \) = normal core of radius \( R \)

\( \phi(0) \) = London's \( \phi \)

\( \phi_{GL} \) = Celm 1947

How large is the core? Estimation #1

Hand-drawn Picture:

Normal core of radius \( \sigma \)

London's \( \phi \) also in intermediate \( k \) values:

\( \sigma \) = core, \( R \) = London radius

\( \sigma_{GL} \) = Celm 1947

Convergence length \( \sigma \) with

\( 1/k \) \( \propto \) \( \sqrt{\gamma} \) for

Lowest energy excitation

\( \gamma \) = wavepacket bound states

\( I = \frac{E}{Z^2} \)

\( \frac{\gamma}{Z} \)


Vertex Core Structure
Traditional Mixed-State Specific Heat

\[ \frac{\gamma}{\nu T} = \frac{\gamma}{\nu T} \]

Vortex Cores \( \approx \) Cylinders of Normal Metal

The figure shows a graph with axes labeled and data points indicating a specific relationship or measurement. The text context suggests a discussion related to physical phenomena or experimental data, possibly in the context of a scientific paper or review.
STM spectroscopy of vortex cores and the flux lattice

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The present slide was given by H.F. Hess.

Fig. 1. Tunneling spectra given by dI/dV vs. V showing the CDW gap at 35 mV (upper curve at 4 K) and a more detailed view of the BCS gap (lower curve at 50 mK).

B = 250 Gauss
θ = 15°

Fig. 6. (a), (b) and (c): Grey scale image of dI/dV(V, I) showing how it evolves along the three lines sketched in Fig. 5. The horizontal scale is bias voltage ranging from -1.65 to +1.35 mV. The vertical scale corresponds to 1000 Å sampling line with a vortex positioned about 250 Å from the bottom. This line may not intersect the vortex exactly but should cross the center by more than 25 Å resulting in some variation of the center spectra. The magnetic field is about 250 G. The grey scale in the normalized conductance indicates that a black is white and 0 is black. (a), (b) and (c) show the energy of the sub-gap peak vs. radius at three angles. The outer-most or higher-energy peak is not strongly angle sensitive, while the inner peak is sensitive and collapses to zero at 30°. The dashed and solid lines represent eqs. (4) and (5), respectively.
\[ n = \text{angular momentum} \]
\[ e = \frac{\hbar^2}{2m} \frac{\partial^2}{\partial r^2} + V(r) \]

Physical origin of gap-peak.

Induced scattering

More stringent calculations

Combined zero-bias peak

F. Jorgensen and M. Schülter 1994

Peak splits away from center

Zero bias peak at vertex center

5. D. Shore et al 1989

Improved Bogoliubov Equations Calculations (BEC)

\[ \text{Gap anisotropy:} \]
\[ \text{atomic crystal structure} \]
\[ \text{Possible effects} \]

Undiminished at larger separations

Different correlation at different bases

Empirically: not from physics

Six-fold symmetry involvement
Star-Shaped Local Density of States around Vortices in a Type-II Superconductor

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(Received 6 June 1996)

The electronic structure of vortices in a type II superconductor is analyzed within the quasiclassical Eilenberger framework. The possible origin of a sixfold "star" shape of the local density of states, observed by scanning tunneling microscope (STM) experiments on NbSe2, is examined in the light of the three effects: the anisotropic pairing, the vortex lattice, and the anisotropic density of states at the Fermi surface. Outstanding features of only parallel rays of this star are well explained in terms of an anisotropic $\pi$-wave pairing. This reveals not only a rich internal electronic structure associated with a vortex core, but also unique ability of the STM spectroscopy. [S0031-9007(96)01546-3]

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Tunneling spectroscopy and STS observation of vortices on high temperature superconductors

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FIG. 1. Tunneling conductance images observed by Hess et al. at 0.1 T for the bias voltage 0.0 mV (a), 0.24 mV (b), 0.48 mV (c), where 1759 A × 1759 A is shown (d) see Refs. [5-6]. The nearest-neighbor direction of the vortex lattice is in the horizontal direction. The LDOS images calculated for $E = 0$ (d), 0.2 (e), and 0.32 (f), where $6f$ × $6f$ is shown.

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Observation of the Low Temperature Pseudogap in the Vortex Cores of Bi2Sr2CaCu2O8+δ

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Vortices cores in under- and overdoped Bi2Sr2CaCu2O8+δ are studied by local probe tunneling spectroscopy. At the center of the cores, we find a gaplike structure at the Fermi level which scales with the superconducting gap, but no quasiparticle bound states. This low temperature pseudogap is intimately related to the superconducting gap and shows striking similarities with the normal state pseudogap measured above Tc. A possible interpretation is that both pseudogap structures reflect the same "normal" state containing phase incoherent excited pair states. [S0031-9007(98)05816-5]

High-Tc STM

Evidence suggesting pseudogap in vortex cores of BSCCO (Geneva) and evidences of G0 and Gt clearly observed in YBCO vortex cores (Berkeley)
\[ N_{\text{deloc}}(E_F) \sim \frac{v}{2} \]

Density of states at the Fermi level in a "d-wave vortex" by Volovik 1993.
Measurement of the Fundamental Length Scales in the Vortex State of YBa$_2$Cu$_3$O$_{6.68}$


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The internal field distribution in the vortex state of YBa$_2$Cu$_3$O$_{6.68}$ is shown to be a sensitive measure of both the magnetic penetration depth $\lambda_\text{m}$ and the vortex-core radius $\rho_0$. The temperature dependence of $\rho_0$ is found to be weaker than in the conventional superconductor Nb$_3$Sn, and much weaker than theoretical predictions for an isolated vortex. The effective vortex-core radius decreases sharply with increasing $H$, whereas $\lambda_\text{m}(H)$ is found to be much stronger than in Nb$_3$Sn. [S0031-9007(97)04251-8]

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Expansion of the vortex cores in YBa$_2$Cu$_3$O$_{6.68}$ at low magnetic fields


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Mossbauer resonant spectroscopy has been used to measure the effective size $r_0$ of the vortex cores in optimally doped YBa$_2$Cu$_3$O$_{6.68}$ as a function of temperature $T$ and magnetic field $H$ deep in the superconducting state. While $r_0$ at $H=2$ T is close to 26 Å and consistent with that measured by scanning tunneling microscopy at 6 T, we find a striking increase in $r_0$ at lower magnetic fields, where it approaches an extraordinarily large value of about 100 Å. This suggests that the average value of the superconducting coherence length $\xi_0$ in cuprate superconductors may be much larger than previously thought at low magnetic fields in the vortex state. [S0031-9007(98)0702-9]