Complex world of topological solitons. Magnetism and dynamics in type II superconductors

Baruch Rosenstein

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Outline

1. Superconductivity, TC and basic experimental facts.
3. A systematic method to obtain the vortex lattice solutions of GL equations.
4. Quantum mechanical analogy and the thermal fluctuations in London approximation.
5. Thermal fluctuations and melting of the vortex lattice (a review).
Discovery of dissipationless flow
Low Tc superconductors

Theoretical predictions of resistivity of metals at low T

Kamerlingh Onnes (1911)
Experimental results on resistivity of Hg at low T

Kamerlingh Onnes (1911)
Summary of \( R(T) \) at low temperatures

**Theoretical predictions**

First basic property of superconductors:

**perfect conductivity**
# Superconductivity Transition Temperatures

<table>
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<tr>
<th>Element</th>
<th>Transition Temperature (K)</th>
<th>Al</th>
<th>Si*</th>
<th>P*</th>
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<td>Pa</td>
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<td>Lu</td>
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</table>
Critical temperature of superconductors

"conventional" superconductors: metals and alloys
2. High Tc superconductors

\( (\text{La}_{1.85}\text{Ba}_{0.15})\text{CuO}_4 \)
\( \text{YBa}_2\text{Cu}_3\text{O}_7 \)
\( \text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8 \)
\( \text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10} \)
\( \text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{10} \)
\( \text{Hg}_{0.8}\text{Tl}_{0.2}\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{8.33} \)

\( \text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8 \)

\text{CuO}_2 \text{ double layer}

\text{Atom Key}
- Cu
- O
- Sr
- Bi
- Ca
Critical temperature of superconductors

High-temperature superconductors (HTS)
$T_c > 140$ K

Graph showing the increase in critical temperature $T_c$ over time.
Magnetic flux is expelled from a Type I superconductor.

However the situation in the Type II superconductors (including all the high $T_c$) is much more complex: a strong enough magnetic field does penetrate in the form of an array of magnetic “vortices”.

Two defining electromagnetic properties of superconductor:

1. Zero resistivity
2. Perfect diamagnetism
Magnetic (Abrikosov) vortices in a type II superconductor

The first defining property, perfect diamagnetism, is lost

Electron tomography
Vortex line repel each other forming highly ordered structures like flux line lattice (as seen by STM and neutron scattering)

Pan et al (02)  Park et al (00)
High Tc superconductors (YBCO is shown) have a fourfold symmetry, which is spontaneously broken in the rhombic phase of the vortex lattice.

Brown et al., PRL92,067002 (04)
Increased role of thermal fluctuations in new type II materials or high magnetic fields leads to qualitatively new effects like melting of the lattice into a liquid.

1. Ginzburg number characterizing the strength of thermal fluctuations is much larger for high Tc:

\[ Gi \equiv \frac{1}{2} \left( \frac{T_c}{H_c^2 \xi^3} \right)^2 \]

- Metals, low Tc: \( Gi \approx 10^{-8} - 10^{-6} \)
- High Tc: \( Gi \approx 10^{-4} \rightarrow 0.1 \)

2. Strong magnetic field effectively reduces dimensionality of fluctuations from D to D-2.
Melting of the vortex lattice

with a magnetization (entropy) jump and a spike on top of the jump in specific heat

Schilling et al

Zeldov et al
Fast dynamics on the mesoscopic scale

Fluxons are light and move. The motion is generally a friction dominated one with energy dissipated in the vortex cores. An external current “induces” the flux flow, causing voltage.

Troyanovsky et al (04)

Field driven flux motion probed by STM on NbSe2
The current “induces” flux flow, causing voltage via “phase slips”.

Phenomenologically the friction force is described (in 2D) by:

\[ f_{dissipation} = \eta \frac{dx}{dt} = \eta v \]
The second defining property, zero resistivity, is lost in magnetic field just above $H_{c1}$.

This however is not end of the story.

Pinning restores loss-free current.
Point-like disorder
Defects are pinning centers of vortices

Disappearance of Bragg peaks as disorder increases

STM of both the pinning centers (top) and the vortices (bottom)

Pan et al PRL 85, 1536 (00)

Gammel et al PRL 80,833 (1998)
Vortex loops, KT pairs and avalanches

Current produces expanding vortex loops even in the Meissner phase leading to non-ohmic “broadening” of I-V curves

\[ J_{\text{ext}} \]

\[ \rho \equiv \frac{V}{I} \propto e^{-\text{const}/(TI)} \]

In 2D thermal fluctuations generate a curious Kosterlitz–Thouless vortex plasma exhibiting many unique features well understood theoretically
Unstable normal domain under homogeneous quench splits into vortex-antivortex (KT) plasma

Polturak, Maniv (2004)

Kirtley, Tsuei and Tafuri (2003)

Scanning SQUID magnetometer
Spontaneous flux in rings

(a) $2.1 \times 10^{-4}$ K/sec
(b) $9.2 \times 10^{-3}$ K/sec
(c) 0.5 K/sec
(d) 21 K/sec

Kirtley, Tsuei and Tafuri (2003)

FIG. 1. Scanning SQUID microscope images of a $12 \times 12$ array of 20 $\mu$m inside diameter, 30 $\mu$m outside diameter thin film rings of $\text{Mo}_3\text{Si}$, cooled in zero field through the super-...
Vortex front propagation is normally shock wave like, but occasionally creates avalanches.

Magneto-optics in YBCO films, 10K, B=30mT, size 2.3x1.5 mm

*Boltz et al (2003)*

Fig. 1. Magnetic flux profiles after a time delay of 67.8 ns and of the final state ($T = 30$ K, $B_s = 15.2$ mT).
Point-like disorder

Defects are pinning centers of vortices

Disappearance of Bragg peaks as disorder increases

STM of both the pinning centers (top) and the vortices (bottom)

Pan et al. PRL 85, 1536 (00)

Gammel et al. PRL 80, 833 (1998)
Disorder profoundly affects dynamics leading to the truly superconducting vortex glass state in which exhibits irreversible and memory dependent phenomena (like hysteresis, aging...).

**Magneto-optics in Nb**

Johansson et al (04)

It became perhaps the most convenient playground to study the glass dynamics
Dependence on magnetic history: the field cooled and the field cooled with return protocols result in different states.

Transport in Nb

Reversible region

Irreversible region

Generic vortex matter phase diagram of a HTSC

LaSCO

Divakar et al,
PRL92,237004 (04)
First-order Melting transition

Amorphous Glass

Bragg Glass

Liquid

\[ \langle u^2 \rangle_D > \alpha_0^2 \]

\[ \langle u^2 \rangle_T < \alpha_0^2 \]

\[ \langle u^2 \rangle_D, \langle u^2 \rangle_T < \alpha_0^2 \]