Lecture 2

Vortex phases in superconductors with & without disorder

- Melting
- Amorphization - peak effect

2. Motion of vortices - Moving Phases
   - Types of motion
   - Transitions among moving phases

History Effects in “Equilibrium”

Imaging in “Meso-scale”
The generic problem:
Elastic media & quenched disorder \( (T = 0) \)

\[
\begin{array}{cccccc}
\bigcirc & \text{\(a_0\)} & \bigcirc & \bigcirc & \bigcirc & \bigcirc & \bigcirc \\
\end{array}
\]
\(:\text{ lattice}\)

\[
\begin{array}{cccccc}
\bigcirc & \bigcirc & \bigcirc & \bigcirc & \bigcirc & \bigcirc \\
\end{array}
\]
\(:\text{ pins}\)

\[
\delta
\]

Competition between elasticity and pinning:
\[
E_{\text{el}} \sim (R)^{d-2}; E_{\text{pin}} \sim (R)^{d/2}
\]

Minimize energy →
loss of long range order: correlation length \(\delta\)

[Larkin]

\[
R_c \sim (K_{\text{el}}/V_{\text{pin}})^2/(4-d)
\]

Threshold phenomena in dynamics:
\[
F_p \sim (R_c)^{-2}
\]

(Soft things get stuck more)
Varying interaction or disorder changes the nature of threshold and dynamics

Interaction dominant: Weak pinning: \(R_c \gg a_0, \delta\)
Disorder dominant: Strong pinning: \(R_c \sim \delta\)

Question: how does the dynamics vary between the two extremes?
In "Equilibrium"

Metastability and "glassiness"
History dependence

Relationship with other glasses

New "Phases" due to disorder?
Nature of phase transition.

Role of thermal fluctuations

Away from Equilibrium in dynamics

Depinning as a critical phenomenon (Fisher)

velocity force relation: \( v \sim (F-F_c)\beta \)
velocity correlation length: \( L_v \sim (F-F_c)^{-\nu} \)

Breakdown of purely elastic response
Role of plasticity

"Moving phases"
Phase diagram of a type-II superconductor

Each flux line carries a flux quantum:
\[ \phi_0 = \left( \frac{\hbar}{2e} \right) = 2 \times 10^{-7} \text{ gauss.cm}^2 \]

Repulsion between flux lines
\[ \rightarrow \text{ flux line lattice (FLL)} \]

Increasing \( H \) increases density of flux lines:

Lattice spacing:
\[ a_0^2 = \frac{2}{\sqrt{3}} \left( \frac{\phi_0}{B} \right) \]

* Interaction in FLL is tunable by \( H \) *
FIG. 2. Phenomenological phase diagram for the anisotropic high-temperature superconductors [parameters for YBCO, NEC Research Institute]
elastic lattice
thermal liquid
pinning glass

weak disorder Bragg glass (Bragg peaks)
strong disorder Vortex glass (no Bragg peaks?)
Vortex slush
Vortex molasses

correlated disorder Bose glass

"GL Scenario"
Structural glass/ "Supercooled" Liquids:

No quenched randomness
Falls out of equilibrium below

Viscosity diverges: \[(T - T_k)\]

But no conventional transition at \(T_g \) (\(\eta \sim 10^{13}\) poise)

\[T_g \gg T_k\]

Cooling-rate dependent properties

Spin Glass

True transition at \(T_f\): cusp in susceptibility

Nonlinear susceptibility diverges

Strong History effects below \(T_f\)

Anomalous time dependence...

Do glassy vortex matter resemble these??
"Seeing Vortices": Different methods

\[ 10^3 \]

\[ 10^7 \]

\( \text{NbSe}_2 : H \sim 50 \text{G} \)

magnetic decoration: few defects

Marchersky et al.

\( \text{NbSe}_2 : H \sim 1 \text{T} \)

STM: no defects

Hess et al.

Fig. 7.43. Lorentz micrograph of a fluxon lattice in a superconducting Nb film. Each spot with black and white contrast pair corresponds to a fluxon.

\( \text{Nb-film: Lorentz microscopy} \)

Tonomura et al.
S.R. Park, B.A. McClain, X.S. Ling (Brown Univ.)
S.M. Choi, D.C. Dender, J.W. Lynn (NIST)
(May 30, 2000, unpublished)
setting or compressing the lattice costs energy; lattice has finite elasticity

\[ C_{11} \text{ (compression)} \]
\[ C_{44} \text{ (tilt)} \]
\[ C_{66} \text{ (shear)} \]

- \[ C_{66} \sim \frac{Bc_2^2}{4\pi}(1 - 1/2k^2)b(1 - b)^2(1 - 0.29b)/8k^2, \]
- \[ C_{11}(k) \sim \frac{B^2}{4\pi}(1 - 1/2k^2)(1 + k^2\lambda^2)^{-1}(1 + k^2\xi^2)^{-1}, \]
- \[ C_{44}(k) \sim \frac{B^2}{4\pi}[(1 + k^2\lambda^2)^{-1} + 1/k_BZ^2\lambda^2]^{-1}, \]

where \( \lambda' = 1/k_h = \lambda/(1-b)^{1/2}, \xi' = 2\xi/(1-b)^{1/2}. \)

FLL is an extremely soft solid: \( H = 1T, C_{11} = 8 \times 10^6 \text{ dynes/cm}^2 \)

\[ \text{e.g., NbSe}_2 \]

\[ C_{66} \sim 5 \times 10^4 \]
\[ a_0 \sim 450 \AA \]
matter phase diagram in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$
T-dependence

peaks across melt (Cubitt, Forgan et al.)

Dependent of the presence of a lattice, and bearing in mind the shear modulus $G_0$, in zero in the liquid state, we may

FIG. 2. Temperature dependence of the integrated intensity of one of the spots in the diffraction pattern, multiplied by $g_0$, to give a quantity proportional to the form factor. Data is shown for 30 m (squares) and 80 m (circles). The solid lines are a guide to the eye.
Magnetization step at the first-order transition

Temperature scan

Solid

Liquid

H_a = 240 Oe

Field scan

B - H_a [G]

B [G]

213.4

213.3

213.2

213.1

213.0

T [K]

58.35

58.40

58.45

58.50

58.55

54

56

58

60

62

H_a [Oe]

T = 80 K

Clapeyron Eqn

\[
\frac{dH_m}{dt} = -\frac{\Delta S}{\Delta M}
\]
Magnetization loop with second magnetization peak

\[ T = 25K \]
• Lindemann scenario of melting/amorphization:

RMS lattice fluctuations: $\langle u^2 \rangle^{1/2}$ too large for stable lattice

$\langle u^2 \rangle^{1/2}/a_o \sim c_L$ (0.1-0.3 typically)

• Melting: fluctuations are thermal: lattice to liquid

• Amorphization: fluctuations are due to quenched disorder
  lattice to glass?
H-dependence of neutron scattering intensity across solid-glass
High $T_c$ phenomenology of solid, glass and fluid:

- BSCCO and YBCO
- Melting transition and second peak or peak effect

Low $T_c$ phenomenology:

- NbSe$_2$, Nb
- Peak effect and "amorphization transition": history effects

Dynamical phases and transitions:

- Elastic flow, plastic flow and fluid flow
- Edge contamination and annealing scenario
Vortex pinning: individual and collective

Strong pinning

Depinning:

\[ F_p = J_c B \]

\[ J_c \] - critical current

\[ F_p = \left( \frac{1}{2} n_p f_p^2 / V_c \right)^{1/2} \]

\[ V_c \sim \sigma_6^2 \sigma_{44} \]

Larkin and Ovchinnikov, 1979.
Anisotropic superconducting parameters for 2H-NbSe$_2$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$H \parallel c$</th>
<th>$H \perp c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa$</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>$\xi$</td>
<td>77</td>
<td>23</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>690</td>
<td>2300</td>
</tr>
<tr>
<td>$J_c$ (1 T, 4.2 K)</td>
<td>1-30 amp/cm$^2$</td>
<td>10-200 amp/cm$^2$ $H_{c2}$</td>
</tr>
</tbody>
</table>

2H-NbSe$_2$ in comparison to other superconductors

<table>
<thead>
<tr>
<th>Quantity</th>
<th>HTSC</th>
<th>LTSC</th>
<th>2H-NbSe$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_i = \frac{k_B T_c}{(H_{c2} \xi^3)} \xi^2$</td>
<td>$10^{-2}$</td>
<td>$10^{-8}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$Q_u = \frac{e^2}{h} \frac{\rho_n}{\xi}$</td>
<td>$10^{-1}$</td>
<td>$10^{-3}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>$j_c/j_0 = (\xi/R_c)^2$</td>
<td>$10^{-2}$</td>
<td>$10^{-1}$</td>
<td>$10^{-6}$</td>
</tr>
</tbody>
</table>

among the cleanest single-crystal systems; i.e., longest Larkin lengths;

Ideally suited to test ideas relevant to clean systems such as melting;
But disorder is important even here.
Temperature dependence of the in-phase ac magnetic susceptibility of a 2H-NbSe$_2$ single crystal, under a superposed dc field of 380 Oe. Note the onset of the peak effect at $T_d = 7.0K$.

Temperature dependence of the line shape asymmetry parameter $\alpha'$, for a field of 400 Oe. Note the sharp change in $\alpha'$ at $T_d = 7.0K$.

Amorphization of VL between the onset and the maximum, between $T_d$ and $T_p$. 

Rao et al. Physica C (98)
first order melting

\[ \frac{dH_m}{dT} = -\frac{\Delta S}{\Delta M} \]
Clapeyron equation