Melting of 2-D vortex lattice through intermediate hexatic liquid phase in a-MoGe thin film

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Melting of a solid: Routes

- **Scenario I**: RMS Vibration > ‘a fraction’ of lattice constant: Solid melts into liquid via 1st order phase transition: Lindemann Criterion

- **Scenario II**: BKT+HNY theory: Two continuous phase transitions mediated by “Topological Defects” from Solid to Hexatic fluid to Isotropic liquid

Crystalline Solid

Hexatic fluid: **Dislocation**
(i) Zero shear modulus
(ii) Orientational order persists

Isotropic Liquid phase: **Disclination**
Quantification of solid, liquid and other phases

• For a perfect lattice, $\cos(\vec{K} \cdot \vec{r}) = 1$,
  \(\vec{K}\): Reciprocal lattice vector and \(\vec{r}\): Lattice vector;
  Positional Order Parameter: $G_K = \langle \cos(\vec{K} \cdot \vec{r}) \rangle$

• For a perfect lattice, $\cos(6\theta) = 1$;
  Orientational Order Parameter: $G_6 = \langle \cos 6(\theta(r) - \theta(0)) \rangle$
Quantification of solid, liquid and other phases

<table>
<thead>
<tr>
<th>$r \to \infty$</th>
<th>$G_K(r)$</th>
<th>$G_6(r)$</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>Perfect Lattice</td>
</tr>
<tr>
<td>Const.</td>
<td>Const.</td>
<td></td>
<td>Real Lattice</td>
</tr>
<tr>
<td>$e^{-r/\xi_K}$</td>
<td>$e^{-r/\xi_6}$</td>
<td></td>
<td>Liquid</td>
</tr>
<tr>
<td>$1/r^a$</td>
<td>Const.</td>
<td></td>
<td>Bragg Glass</td>
</tr>
<tr>
<td>$e^{-r/\xi_K}$</td>
<td>$1/r^b$</td>
<td></td>
<td>Hexatic</td>
</tr>
</tbody>
</table>
Search for true Hexatic liquid phase: a-MoGe

- Problem in other systems: Orientational coupling between atomic lattice and vortex lattice (eg. NbSe₂).
- Solution: Amorphous superconductor, hence no effect from lattice
- Pinning is very weak
- BCS type superconductor

Tunneling conductance,

\[ G(V) = \int_{-\infty}^{\infty} N_S(E) \left[ -\frac{\partial f(E - eV)}{\partial E} \right] dE \]

where,

\[ N_S = \frac{|E| + i\Gamma}{\sqrt{(|E| + i\Gamma)^2 - \Delta^2}} \]
Our STM and how we do vortex imaging

Homebuilt He$_3$ STM of TIFR
- $T_{\text{min}}$ = 350 mK
- $H_{\text{max}}$ = 90 kOe

450 mK, 0.9 T, 1umx1um, NbSe$_2$
Real space evolution of vortex lattice as a function of magnetic field at 2 K
Thermally generated dislocations

$t = 0$

$t = 1.5$ hours

$t = 3$ hours
Thermally generated dislocations

$t = 0$

$t = 1.5$ hours

$t = 3$ hours
Thermally generated dislocations

$t = 0$

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$t = 3$ hours
Bulk measurements and Critical current at 2 K

Data taken by Surajit Dutta, Aditya N. Roy Choudhury and Somak Basistha in TIFR
Bulk measurements and Critical current at 2 K

When, Lorentz force on vortex > Pinning force: Vortices are in Flux Flow regime.
Here, \( V = R_{ff} (I - I_c) \),
where, \( R_{ff} \) is Flux Flow Resistance.

Data taken by Surajit Dutta, Aditya N. Roy Choudhury and Somak Basistha in TIFR
Melting observed using bulk measurements
Thermally Activated Flux Flow (TAFF)

TAFF Resistance: $R_{TAFF}$ is slope of linear region of V-I curves, for $I < 100 \mu A \ll I_c$

For $I \ll I_c$, due to Thermally Activated Flux Flow, $R_{TAFF} = V/I = R_{ff} \exp(-U/kT)$

Differentiating solid from hexatic liquid

\[ \frac{V}{I} = R_f f \exp(-\frac{U}{kT}) \]

Solid: \( U(I) = U_0(I_c/I)^\alpha \)

Below \( H=1.9 \text{ kOe} \),
\( V-I \) curves are well fitted,
taking \( \alpha=1 \)

Liquid: \( U \) is independent of \( I \)

Above \( H=1.9 \text{ kOe} \),
\( V-I \) curves deviate from
the exponential form;
rather becomes linear.

At 2 K, \( H=1.9 \text{ kOe} \) is the transition point
from Vortex solid to Hexatic fluid.

Data taken by Surajit Dutta, Aditya N. Roy Choudhury and Somak Basistha in TIFR
Real space imaging of thermally activated vortex creeps
Hexatic to vortex liquid transition

• Six-fold Orientational Order Parameter:
\[ \Psi_6 = \frac{1}{N} \langle \sum_{k,l} e^{6i(\phi_k - \phi_l)} \rangle \]
(For perfect hexagonal lattice, \( \Psi_6 = 1 \))

• Hexatic liquid to Isotropic liquid transition point is identified.

• \( H_{c2} \) is determined.
Constructing the full phase diagram

Diagram showing a phase diagram with axes labeled as $H$ (kOe) on the y-axis and $T$ (K) on the x-axis. The phase diagram includes regions labeled as Vortex liquid, Normal state, Hexatic fluid, and Vortex Solid. The $H_c^2$ line is indicated with a green triangle marker.
Conclusion

• We have observed a true BKTHNY melting in vortex lattice via realization of a true Hexatic fluid phase.
• The Phase diagram of the 2-D vortex lattice is constructed.

Outlook

• Can the Phase diagram be generalized to any 2-D system?
• To what extent this can be applied to layered 3-D, effective 2-D systems?

Current works being done

• We have observed the core of the vortices in a-MoGe films to be gapped, unlike a clean BCS superconductor.
• We have also observed that the Vortex solid to Hexatic fluid transition point remains fairly temperature independent below 2 K.
Acknowledgement and Reference

The project was conceived and supervised by Prof. Pratap Raychaudhuri.

Transport data were taken and analyzed by Surajit Dutta, Aditya N. Roy Choudhury and Somak Basistha.

STM data were taken and analyzed with help from Soumyajit Mandal’s help.

Sample was prepared by Aditya N. Roy Choudhury, John Jesudasan and Vivas Bagwe.

Physical picture was refined through discussions with Ilaria Maccari, Claudio Castellani and Lara Benfatto.

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Thank you
Observation of a BKTHNY-type melting.

- Two-step melting is observed in vortex lattice in NbSe$_2$ single crystals, which is a 3-D system.
- But the Hexatic Phase observed here has no dynamics, hence it is a Hexatic Glass Phase, and hence not a true-BKTHNY melting.
Penetration Depth Measurement

\[
\frac{\lambda_L^{-2}(T)}{\lambda_L^{-2}(0)} = \frac{\Delta(T)}{\Delta(0)} \tanh \left( \frac{\Delta(T)}{k_B T} \right)
\]

Sample parameters

\( T_c = 7.05 \text{ K} \)
\( \Delta(0) = 1.36 \text{ meV} \)
\( \lambda_L(0) = 534 \text{ nm} \)

Thickness= 20 nm
1 kOe Vortex Movements
$G_6$ as a function of $r$

$$G_6(r) = \langle g_6(0)g_6^*(r) \rangle |r|$$

where, $g_6(r) = \exp[6i\theta(r)]$

$\theta(r)$: angle of a bond between two nearest-neighbor points on the lattice located at position $r$ with respect to an arbitrary reference axis.

Ideal hexagonal lattice: $G_6(r) = 1$

Hexatic fluid (Orientational order is quasi long-range): $G_6(r)$ decays slowly as a power-law with $r$.

Vortex liquid (Orientational order is short range): $G_6(r)$ decays exponentially.

Decay lengths: (70 kOe) 6.2 $a_0$ and (85 kOe) 2.2 $a_0$
Vortex Core spectroscopy in NbSe$_2$ at 0.7 kOe at 450 mK

NbSe$_2$ is a BCS superconductor and has a $H_{c2} \sim 40$ kOe in clean case.

Vortex cores in NbSe$_2$ shows Andreev bound states, known as Caroli-De Gennes-Matricon bound states.
Vortex Core spectroscopy in MoGe at 5 kOe at 450 mK

MoGe, although is a BCS superconductor and in its clean limit, the vortex core here shows superconducting gap in all fields.

The reason behind observing a gapped vortex core is suspected to be due to very fast vortex movements.