Unusual Vortex Interactions and Dynamics in SNS Arrays

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Vortices in superconductors
→ New device structures: Strong competition between pinning and interactions
→ Current-driven: Interesting non-equilibrium behavior

Focus on De-pinning dynamics:
1) Low fields: New understanding of dissipation
2) High fields: Unusual de-pinning due to interactions
Vortices in Type II Superconductors

$H > 0$

- Vortex interactions over scale of penetration depth $\lambda \sim 1/\sqrt{T_c}$ (~ 2 µm, our sample)
- Dominate transport below $T_c$

Vortices

$\Phi_0 = \hbar/2e$

Equilibrium vortex phases — can be interacting, many-body systems

Experimental phase diagram of LaSCO (Rev. Mod. Phys. 82, 109, 2010)
Non-equilibrium vortex phases

Thermally-driven transitions: de-pinning & melting

Current-driven de-pinning & critical phenomena

*pinning & interactions stronger than thermal fluctuations

Science (2015)
SNS Island arrays as model 2D superconductors

Standard long-junction behavior at \( T_c \) (array transition)

- Undergoes Berezinskii-Kosterlitz-Thouless transition at \( T_2 \) (jumps in \( a \) for \( V = I^a \)): signifies 2D superconducting behavior
- \( I_c \) vs \( T \) fits well for single, diffusive SNS junction
  - \( T_{\text{BKT}} \sim E_{\text{Thouless}} \sim 1/d^2 \)

- Strong pinning potential
- Interactions controlled by vortex density, island spacing

Vortex Pinning Behavior

- At finite field, vortices populate array
- Periodic potential
- Lowest energy at center of triangle
- Highest energy between islands

Rich features due to competition between periodic potential and vortex repulsion

Filling characterized by frustration parameter, $f$

$f = \frac{\Phi}{\Phi_0}$ or $\Phi_0$ per plaquette

$f=1/4$  
$1/4$ filled

![Graph showing resistance vs. $f$ for different temperatures]
**$I$-$V$ Measurements to focus on De-pinning**

- Current provides Lorentz Force, driving vortices
- Vortex motion measured as voltage across sample

**d$V$/d$I$ vs $I$**

**$IV$ in vortex-dominant region**

- Vortex flow
- Pinned vortices
Transition from pinned to flux flow

Flux flow: Vortices move at terminal velocity (linear $IV$, flat $dV/dI$)

Why isn’t there a peak in the data?

Commonly absent in SNS array studies.


Dynamic Vortex Models

RCSJ Array


Molecular Vortex Models


Driving Force

Potential used by Mondragon, Hughes

Equations of motion of a Vortex

\[ m \ddot{x}_i = -\partial{x}_i V(x_i) - \sum_j \partial{x}_i U(x_i - x_j) + \epsilon_i(t) - \eta \dot{x}_i \]

- Mass term (\( \to 0 \) for small R, C, i.e. overdamped)
- Effective potential (array geometry)
- Vortex-vortex interactions
- Thermal fluctuations
- Dissipation (1/R)

Models produce similar dynamic behavior in low filling regime...
Dynamic Vortex Models

Dilute Vortex Population Predictions

- Extrapolate $V=0 \rightarrow V \propto I$
- Necessitates $dV/dI$ peak

Rapid increase in $V$ is damped: consider modifying damping term...

- Linear $IV$
- Nonzero $I$ intercept
- Does not converge with $V \propto I$
Data fit by including history dependent dissipation

Only velocity-dependent forces can change concavity of $dV/dI$
\[\Rightarrow\] Need to add “delayed” drag term

$$F_d = -\eta \dot{x}_i(t)$$

$$F_d = -\int_0^t \chi(t-\tau) \dot{x}_i(\tau) d\tau$$

Correlates system at different times

Example: Exponential Response

$$\chi(t) = \eta_1 \delta(t) + \eta_2 \tau_\beta^{-1} e^{-t/\tau_\beta}$$

Effects of history dependent dissipation

Long relaxation time limit is similar to our data.

$$V \propto \sqrt{I^2 - I_d^2}$$

$$V \propto I - I_d$$
Only velocity-dependent forces can change concavity of \( \frac{dV}{dl} \)

\[ F_d = -\eta \dot{x}_i(t) \]

\( \rightarrow \) Need to add “delayed” drag term

Simplest approximation:

\[ F_d = \eta_1 \dot{x}(t) + \eta_2 \frac{x(t) - x(t - t_c)}{t_c} \]

Possible origin:
Time-dependent quasiparticle scattering from moving vortices

Microscopic origin: ??
Re-forming of superfluid around vortex cores? Quasiparticle diffusion?

\( \rightarrow \) Time-dependent dissipation relevant to understanding typical signatures of vortex depinning dynamics

Agreement between theory and experiment

Data fit by including history dependent dissipation

\[ F_d = -\int_0^t \chi(t - \tau) \dot{x}_i(\tau) d\tau \]

Correlates system at different times
Conclusions

Current-driven vortices with strong competition between pinning and interactions → Interesting non-equilibrium behavior

- For vortex de-pinning & phase transitions in low fields, need to consider history-dependent dissipation to obtain correct dynamics
- For vortex de-pinning in high fields, unusual incommensurate → commensurate transition

Future Work: Scaling of transitions, effects of point disorder

Acknowledgements

- Malcolm Durkin, Rita Garrido-Menacho
- Ian Mondragon-Shem (UIUC/Yale), Taylor Hughes (UIUC)
- Sarang Gopalakrishnan (Caltech/CUNY)

Work supported by the DOE under DE-FG02-07ER46453 through the Frederick Seitz Materials Research Laboratory