The Superheating Field of Niobium: Theory and Experiment

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• Critical Fields of Superconductors
• Survey of Previous Work
• New Results from Cornell on the Superheating Field
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• New Results from Cornell on the Superheating Field
• Type-I: Meissner State below applied field $H_c$, normal above

• Type-II: Meissner State below $H_{c1}$. Energetically favorable to enter mixed state below $H_{c2}$. Normal above $H_{c2}$.

• $H_{c3}$ is a surface effect: bulk is normal, but surface layer ($\sim \xi$) superconducting.
<table>
<thead>
<tr>
<th>Critical Field</th>
<th>Value at 0K (mT)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bc</td>
<td>200</td>
<td>Finnemore; Casalbuoni</td>
</tr>
<tr>
<td>Bc1</td>
<td>174</td>
<td>Finnemore</td>
</tr>
<tr>
<td>Bc1</td>
<td>190</td>
<td>C. Vallet</td>
</tr>
<tr>
<td>Bc2</td>
<td>390</td>
<td>Casalbuoni</td>
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<tr>
<td>Bc2</td>
<td>400</td>
<td>Finnemore</td>
</tr>
<tr>
<td>Bc2</td>
<td>410</td>
<td>Saito</td>
</tr>
<tr>
<td>Bc2</td>
<td>450</td>
<td>C. Vallet</td>
</tr>
</tbody>
</table>
Raindrops: the Liquid-Gas Transition

“Superheating” like 110% humidity

Metastable
energy barrier $B$
droplet nucleation
$R^2$ surface tension cost
$R^3$ bulk energy gain

J. Sethna, Cornell University
Can we calculate the phase diagram for $H_{sh}$?

J. Sethna, Cornell University
Why is there a barrier to vortex penetration?

Why a superheating field?

Costly core $\xi$ enters first; gain from field $\Lambda$ later

Coherence length: $\xi$

Decay of $\Psi$

Energy cost

Penetration depth: $\Lambda$

Decay of $H$

J. Sethna, Cornell University
Motivation

• Why do we care?
  – $H_{sh}$ sets the ultimate physical limit for surface fields
  – $H_{sh}$ can be effected by surface treatments
  – Metastability is an interesting phenomenon to study
• Critical Fields of Superconductors
• Survey of Previous Work
• New Results from Cornell on the Superheating Field
$H_{sh}(T) = c(\kappa)H_c \left(1 - \left(\frac{T}{T_c}\right)^2\right)$

- Most $H_{sh}$ work based on Ginzburg-Landau Theory

- GL solved in 1D case

$$H_{sh} \approx \frac{0.89}{\sqrt{\kappa_{GL}}} H_c$$  
for $\kappa_{GL} \ll 1$

$$H_{sh} \approx 1.2H_c$$  
for $\kappa_{GL} \approx 1$

$$H_{sh} \approx 0.75H_c$$  
for $\kappa_{GL} \gg 1$.

- Asymptotic expansion (Dolgert et. al.)
We present experimental evidences of superheating in pure niobium: our results are in agreement with a superheating field larger than $H_c$.

Magnetization curves of Nb cylinders at 4.2K showing $H_{sh} > H_c$
Type-I and Type-II superconducting spheres near $T_c$. Yogi (1976)
H_{sh}: First measurement of Temperature Dependence

Hays Measurement of H_{sh}(T) for Nb (1995)
• Critical Fields of Superconductors
• Survey of Previous Work
• New Results from Cornell on the Superheating Field
Validity versus complexity

**Ginzburg-Landau (GL)**
- $\psi(r), H(r)$ order parameters
- Spatial dependence OK
- **Valid only near $T_c$**

**Bardeen Cooper Schrieffer (BCS) theory**
- Pairing $k, -k$ within vibration energy
- Excellent for traditional superconductors
- $H_{c1}(T), H_{c2}(T)$ done
- $H_{sh}(T)$ hard (spatial dependence)

*J. Sethna, Cornell University*
Validity versus complexity

Eilenberger Equations
- Valid at all temperatures
- Assumes $\Delta(r)$, $H(r)$ vary slowly

Eliashberg equations
- Needs electronic structure
- Never done before for $H_{sh}$

J. Sethna, Cornell University
Ginzburg-Landau

Eilenberger near $T_c$ – Mark Transtrum
$H_{sh}(T)$, Large $\kappa$

Eilenberger Eqns, $\kappa >> 1$.
Sethna, Catelani
• Solving the Eilenberger equations are hard, especially for moderate or small $\kappa$

• Experimental measurements are necessary to help guide theory

Hsh($\kappa \sim 1$), convergence
LR1-3 to measure Superheating Field
Hsh(T) Measurement

Re-entrant cavity prep:
• Vertical EP
• 2 hr HPR, clean assembly
• 120C bake for 48 hr

LR1-3 to measure Superheating Field
Boeing Klystron supplies high power pulses

- $P_f \sim 1.5\ \text{MW}$
- $Q_{\text{ext}} \sim 6 \times 10^6$
- Ramp up power quickly (100 $\mu$s) to minimize thermal effects
• Following Hays we can write:

\[
P_f = P_r + \frac{\omega U}{Q_0} + \frac{dU}{dt} \quad \text{and} \quad \sqrt{P_r} = \sqrt{P_f} - \sqrt{\frac{\omega U}{Q_{\text{ext}}}}
\]

which gives

\[
\frac{\omega U}{Q_0} = 2\sqrt{\frac{\omega U P_f}{Q_{\text{ext}}}} - \frac{dU}{dt} - \frac{\omega U}{Q_{\text{ext}}}
\]

or

\[
\frac{1}{Q_0} = \frac{2}{\omega \sqrt{U}} \left( \sqrt{\frac{\omega P_f}{Q_{\text{ext}}}} - \frac{d\sqrt{U}}{dt} \right) - \frac{1}{Q_{\text{ext}}}
\]
Measuring Hsh

Surface Magnetic Field [mT]

Time [µs]

Klystron Power [MW]

Intrinsic Quality Factor

Time [µs]
Measuring Hsh

Surface Magnetic Field [mT] vs. Time [µs]

Klystron Power [MW] vs. Intrinsic Quality Factor vs. Time [µs]

90% SC
Determining $\kappa$ in CW

SRIMP Fit: MFP = 27 nm. $\kappa = 3.5$
$H_{sh}(T) = c(\kappa)H_c\left(1 - \left(\frac{T}{T_c}\right)^2\right)$

**Fit:** $c(\kappa) = 1.04 \pm 0.01$
Transtrum: $H_{sh}(\kappa)$

The graph shows the function $H_{sh}/H_c$ as a function of $\kappa$, with $\kappa = 3.5$ indicated by the arrow on the graph.

The equation $\kappa = 3.5$ is also provided in the text.
Possibility for 20% increase by changing $\kappa$
Baking lowers mean free path (and thus $\kappa$) by introducing surface impurities.

$$
\kappa(\ell) = \frac{\lambda_L}{\xi_0} \left( \frac{\xi_0 + \ell}{\ell} \right)^{3/2}
$$
Re-entrant cavity prep:
• 800 C bake, 2 hr
• Vertical EP
• 2 hr HPR, clean assembly
• NO 120C bake

LR1-3 to measure Superheating Field
Severe Q drop at low fields.
Small radiation, no quenches
$H_{sh}(T) = c(\kappa)H_c \left(1 - \left(\frac{T}{T_c}\right)^2\right)$

c(\kappa) = 1.28 \pm 0.06

(Theory predicts 1.30) \kappa clearly changed!
Conclusions

• We now have a measurement showing the full temperature dependence of $H_{sh}$

• GL theory is surprisingly accurate over the full temperature range

• Surface treatments strongly influence $H_{sh}$

• There appears to be a trade-off between removing high field $Q$-slope and high superheating field

  – Alternative to 120C bake?
• Eilenberger theory appears to give a small increase to $H_{sh}$ at low temperatures
• $H_{sh}$ measurements are a place where experiment can really drive theory
• More work needs to be done to ensure the convergence of the Eilenberger eqns for $T \ll T_c$
• Can we reproduce these results for new materials such as Nb$_3$Sn or MgB$_2$?
Eilenberger theory appears to give a small increase to $H_{sh}$ at low temperatures.

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More work needs to be done to ensure the convergence of the Eilenberger eqns for $T << T_c$.

Can we reproduce these results for new materials such as Nb$_3$Sn or MgB$_2$?

Sam Posen at Cornell is currently making Nb$_3$Sn. THPO066

$H_{sh}$ measurements to follow.
• Special thanks:
  – Matthias Liepe, Hasan Padamsee, and Zachary Conway for great help with experimental measurements
  – James Sethna and Mark Transtrom for temperature dependence from Eilenberger Theory
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