Muon Spin Rotation/Relaxation Studies of Niobium for SRF Applications
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Superconductivity

Muon Spin Rotation/Relaxation Studies of Niobium for SRF Applications
Q-slopes in Nb cavities

- Degradation of quality factor with the applied RF field
- Medium field Q-slope: gradual decrease in range $H_{pk} \approx 20-100$ mT
- High field Q-drop: sharp losses above peak field $\approx 80-100$ mT
- $120^\circ C$ bake 48 hrs UHV improves/removes HFQS

Huge number of models in the history of SRF to explain Q-slopes
None so far unconfutably proves causes or mechanisms
### Models for HFQS

**Theories / Experiments Confrontation**


<table>
<thead>
<tr>
<th></th>
<th>Q-Slope Fit</th>
<th>Q-Slope before baking (EF = BCP)</th>
<th>Q-Slope after baking (EF &lt; BCP)</th>
<th>No change after 4 y. air exposure</th>
<th>Exceptional Results (BCP)</th>
<th>Q-Slope unchanged after HIF chemistry</th>
<th>TEM1 Q-Slope before baking</th>
<th>Quench EP &gt; BCP</th>
<th>SCP Quench unchanged after baking</th>
<th>Argument Validity</th>
<th>Fundamentally Disagree with Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnetic Field Enhancement</strong></td>
<td>Y simult. code</td>
<td>N ( B_{c2}^3 \neq )</td>
<td>Y ( B_{c2}^3 \uparrow )</td>
<td>Y lower ( \beta_m )</td>
<td>Y high ( \beta_m )</td>
<td>-</td>
<td>-</td>
<td>Y lower ( \beta_m )</td>
<td>N ( B_{c2}^3 \uparrow )</td>
<td>Y</td>
<td>D1</td>
</tr>
<tr>
<td><strong>Interface Tunnel Exchange</strong></td>
<td>Y ( E^\parallel )</td>
<td>N ( Nb_{2}O_{6-y} \downarrow )</td>
<td>Y ( Nb_{2}O_{6-y} \uparrow )</td>
<td>N ( \beta = )</td>
<td>N ( \beta = )</td>
<td>Y ( )</td>
<td>-</td>
<td>Y</td>
<td>-</td>
<td>Y</td>
<td>D2</td>
</tr>
<tr>
<td><strong>Thermal Feedback</strong></td>
<td>Y parabolic</td>
<td>( R_{BCS} ) ( R_{th} )</td>
<td>Y ( )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>N ( C )</td>
<td>-</td>
</tr>
<tr>
<td><strong>Magnetic Field Dependence of ( \Delta )</strong></td>
<td>Y ( \exp^{\text{gas}} )</td>
<td>( B_{c2}^3 \neq )</td>
<td>Y ( B_{c2}^3 \uparrow )</td>
<td>Y higher ( B_{c2}^3 )</td>
<td>Y</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>N ( \text{thin film} )</td>
<td>D1</td>
</tr>
<tr>
<td><strong>Segregation of Impurities</strong></td>
<td>? segregation</td>
<td>only O diffusion</td>
<td>Y surface</td>
<td>Y good cleaning</td>
<td>Y chemistry</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Y</td>
<td>-</td>
</tr>
<tr>
<td><strong>Bad S.C. Layer Interstitial Oxygen ( Nb_{2}O_{6} )</strong></td>
<td>? NC layer</td>
<td>O diffusion</td>
<td>Y interstitial re-appears</td>
<td>-</td>
<td>Y new bad layer</td>
<td>-</td>
<td>-</td>
<td>Y ( B_{c2}^3 \downarrow )</td>
<td>B2 ( )</td>
<td>-</td>
<td>D1</td>
</tr>
</tbody>
</table>

**Y / N = theory in agreement / contradiction with experimental observation**

\(/ = \) = undiscutable disagreement with experiment

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5/26/11
Muon Spin Rotation/Relaxation Studies of Niobium for SRF Applications
• ‘Weaker’ superconducting regions allow ‘premature’ magnetic flux entry

• Cutout samples studies: decrease in average dislocation density observed by EBSD after 120C baking (which removes the HFQS in cavities)

• Working hypothesis – surface dislocations provide sites for early flux penetration (below bulk Hc1)
HFQS: early flux penetration?

- **GOAL**: Design an experiment to prove magnetic flux entry as the right or wrong mechanism behind HFQS
- Study field of flux entry (and other superconducting properties) in **HFQS limited cutout samples**:
  - Hot vs cold
  - **Baked vs unbaked**
- Need of local, sensitive magnetic field probe: Muon Spin Rotation
- First time in SRF we attempt to measure superconducting parameters of Nb cut out of cavities with muSR
Cutout samples: large grain, small grain BCP

LE1-37 large grain BCP cavity

RF Side

Outer Side

Muon Spin Rotation/Relaxation Studies of Niobium for SRF Applications

A. Romanenko Ph.D. thesis
RF characterization of samples studied
(A.Romanenko)
**LOCAL probe of magnetism: muSR**

<table>
<thead>
<tr>
<th></th>
<th>Conventional Methods</th>
<th>Nuclear Beam Methods</th>
</tr>
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<tbody>
<tr>
<td><strong>Probe:</strong></td>
<td>host nuclei</td>
<td>muons</td>
</tr>
<tr>
<td></td>
<td>host electrons</td>
<td>radioactive nuclei</td>
</tr>
<tr>
<td><strong>Lifetime:</strong></td>
<td>infinite</td>
<td>2.2 µs</td>
</tr>
<tr>
<td></td>
<td>infinite</td>
<td>100 ms - hours</td>
</tr>
<tr>
<td><strong>Polarization Method:</strong></td>
<td>apply large field</td>
<td>natural</td>
</tr>
<tr>
<td></td>
<td>apply large field</td>
<td>optical pumping</td>
</tr>
<tr>
<td><strong>Polarization (max.):</strong></td>
<td>&lt;&lt; 1 %</td>
<td>100 %</td>
</tr>
<tr>
<td></td>
<td>&lt;&lt; 1 %</td>
<td>80 %</td>
</tr>
<tr>
<td><strong>Detection:</strong></td>
<td>absorbed RF radiation</td>
<td>anisotropic decay of</td>
</tr>
<tr>
<td></td>
<td>absorbed microwave</td>
<td>muon</td>
</tr>
<tr>
<td></td>
<td>radiation</td>
<td>anisotropic decay of</td>
</tr>
<tr>
<td></td>
<td></td>
<td>nucleus</td>
</tr>
<tr>
<td><strong>Sensitivity:</strong></td>
<td>$10^{17}$ spins</td>
<td>$10^{7}$ spins</td>
</tr>
<tr>
<td></td>
<td>$10^{17}$ spins</td>
<td>$10^{7}$ spins</td>
</tr>
</tbody>
</table>
TRIUMF

ISIS

PSI

KEK

\( \mu \text{SR} \) facilities of the world.
Muon Spin Rotation/Relaxation Studies of Niobium for SRF Applications
Pion Decay: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

A pion resting on the downstream side of the primary production target has zero linear momentum and zero angular momentum.

**Conservation of Linear Momentum:** $\mu^+$ emitted with momentum equal and opposite to that of the $\nu_\mu$.

**Conservation of Angular Momentum:** $\mu^+$ and the $\nu_\mu$ have equal and opposite spin.

**Weak Interaction:** only "left-handed" $\nu_\mu$ are created. Therefore the emerging $\mu^+$ has its spin pointing antiparallel to its momentum direction.

$\rightarrow$ 100% spin polarized!
Angular distribution of positrons from the $\mu^+$-decay. The asymmetry is $a = 1/3$ when all positron energies are sampled with equal probability.
The muon is sensitive to the vector sum of the local magnetic fields at its stopping site. The local fields consist of:

- those from nuclear magnetic moments
- those from electronic moments (100-1000 times larger than from nuclear moments)
- external magnetic fields

As a local probe, $\mu$SR can be used to deduce Magnetic volume fractions.

\[ \omega = \gamma_\mu B \]
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Courtesy of Jess Brewer, TRIUMF
Transverse-Field $\mu$SR: vortex lattice studies, measurement of $\lambda$, $\xi$, G-L parameter $k$

The time evolution of the muon spin polarization is described by:

$$P(t) = G(t)\cos(\gamma_\mu B_\mu t + \phi)$$

where $G(t)$ is a relaxation function describing the envelope of the TF-$\mu$SR signal that is sensitive to the width of the static field distribution or temporal fluctuations.
The count rates for opposing $e^+$ detectors:

$$N_B(t) = N_0 e^{-t/\tau_\mu} \left[ 1 + a_0 G(t) \cos(\gamma \mu B_\mu t + \Phi) \right]$$

$$N_F(t) = N_0 e^{-t/\tau_\mu} \left[ 1 - a_0 G(t) \cos(\gamma \mu B_\mu t + \Phi) \right]$$

Forming the $B$-$F$ count rate ratio:

$$\frac{N_B(t) - N_F(t)}{N_B(t) + N_F(t)} = a_0 G(t) \cos(\gamma \mu B_\mu t + \Phi)$$

$$= a_0 P(t) \equiv A(t)$$

$\mu$SR asymmetry spectrum
Zero-Field $\mu$SR: internal field distribution, magnetic impurities, trapped flux

The count rates for opposing $e^+$ detectors:

$$N_B(t) = N_0 e^{-t/\tau_{\mu}} \left[ 1 + a_0 G(t) \cos(\gamma_{\mu} B_{\mu} t + \Phi) \right]$$

$$N_F(t) = N_0 e^{-t/\tau_{\mu}} \left[ 1 - a_0 G(t) \cos(\gamma_{\mu} B_{\mu} t + \Phi) \right]$$

The corresponding $\mu^+$ spin relaxation function is known as the *Kubo-Toyabe function*

$$G_z(t) = \frac{1}{3} + \frac{2}{3} (1 - \Delta^2 t^2) \exp \left( -\frac{1}{2} \Delta^2 t^2 \right)$$
Magnetic field distribution of a vortex lattice

Asymmetry spectrum plotted in a rotating reference frame

V\textsubscript{3}Si
H = 50 kOe
T = 3.8 K

Fourier transform
TF-muSR on cutout samples

- DC field perpendicular to sample, T=2.3K (and measurements at 4.5K up to 8K), full scan in field 0-270mT

Muon stopping depth ~300µm
(a) Representative ZF-$\mu$SR spectra of sample H1 at different temperatures.
(b) Temperature dependence of the muon hop rate in sample H1 before and after baking.

Results consistent with what observed in $\mu$SR experiments on nitrogen doped Nb
Asymmetry signals, 30 and 120mT, 2.3K

C1 - cold spot large grain cutout,

H1 – hot spot large grain cutout

H1 after 48 hours UHV 120C baking

H1 after 48 hours UHV 120C baking plus 5µm BCP
Fast Fourier transforms for sample H1 at 2.3K and respectively field levels: zero, 30mT, 120mT (peak of flux appearing at ~50mT), 270mT (peak of flux ~260mT) → Suggests an inhomogeneous surface with preferential sites for flux entry
Volume fraction of sample **NOT** containing flux

- The part of the asymmetry signal corresponding to the muons which do not see field in the sample is fitted to a dynamic Gaussian zero-field Kubo-Toyabe.
- The fraction corresponding to the muons that see field is assumed to relax fast.
Strong correlation fraction of sample containing flux vs RF cavity performance

- Onset of flux entry measured with muSR strongly correlates with onset of RF HF losses as for thermometry characterization
- Measurements consistent among all 6 samples tested
Hot vs Cold sample

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In conclusion

• Muon spin rotation used for SRF applications for the first time
• Experiment results strongly suggest early magnetic flux entry at ‘weaker spots’ as losses mechanism in SRF Nb cavities
• Invaluable tool for studying superconducting parameters
• Field dependent losses can be studied designing experiments with cavities, however it’s vital to gain an understanding of the ‘microscopic’ world
• It’s vital to keep working in close contact with the condensed matter world
Future direction

- First establish **baseline**: study **ultrapure Nb** single crystal (field of entry, superconducting parameters)
- Understand **which step of Nb processing for cavities causes early flux entry**: systematic study of field of entry for niobium with different treatments, degree of cold work, RRR…
- **$Q_0$ and medium field losses** studies: design apparatus for parallel field measurements
- Study **quench** spots
- **Thin films and multilayer**: accurate tool for field of entry
- Beamtime already approved for these studies, to be scheduled in fall
- LEM for penetration depth and role of hydrogen in surface
Thanks for your attention!
Back up slides
Thermometry characterization of losses

Fine grain

Large grain

Example of T-map system, G.Ciovati
Ph.D. thesis

Thermometry maps, courtesy of Cornell

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$H_{en}^{strip}/H_{c1} = \tanh \sqrt{0.36b/a}$,

$H_{en}^{disk}/H_{c1} = \tanh \sqrt{0.67b/a}$.

Ernst Helmut Brandt
Irreversible magnetization of pin-free type-II superconductors
PHYSICAL REVIEW B VOLUME 60, NUMBER 17
RF characterization of samples studied (A. Romanenko)
Center vs Annular mask

![Graph showing magnetic flux free asymmetry vs field strength (H, mT) with data points for C1 baked and C1 baked annular mask.]
All samples results

Muon Spin Rotation/Relaxation Studies of Niobium for SRF Applications
Upper critical field measurement

FFTs for sample H10 respectively for temperature and fields: (2.3K, 130mT), (4.5K, 200mT), (7.5K, 100mT), (7.5K, 140mT), (7.5K, 170mT), (7.5K, 200mT)
Coexistence of different ‘superconducting’ regions?

2821: H1 Large Grain T=2K TF B=123.4mT [1vs2] ASY

2822: H1 Large Grain T=2K TF B=150.6mT [1vs2] ASY

2835: H1 Large Grain T=2K TF axial field B=200mT [1vs2] ASY

2836: H1 Large Grain T=2K TF axial field B=245mT [1vs2] ASY
Coexistence of different ‘superconducting’ regions?

2890: H6 Small Grain T=2.5K, TF, B=135mT [1vs2] ASY

2891: H6 Small Grain T=2.5K, TF, B=140mT [1vs2] ASY

2892: H6 Small Grain T=2.5K, TF, B=150mT [1vs2] ASY

2897: H6 Small Grain T=2.5K, TF, B=160mT [1vs2] ASY
Nuclear Dipolar Relaxation

Nuclei with electric quadrupole moments (such as Cu and Y in YBa$_2$Cu$_3$O$_{6+x}$) exert an effective dipolar field $B_{\text{dip}}$ on the $\mu^+$. The static (in the $\mu^+$SR time window) internal fields are Gaussian distributed in their values and randomly oriented

$$n(B_i) = \frac{1}{\sqrt{2\pi} \Delta} \gamma_\mu \exp \left( -\frac{1}{2} \frac{\gamma_\mu^2 B_i^2}{\Delta^2} \right)$$

(i = x, y, z)

where $\Delta^2/\gamma_\mu^2$ is the second moment of the field distribution

The corresponding $\mu^+$ spin relaxation function is known as the *Kubo-Toyabe function*

$$G_z(t) = \frac{1}{3} + \frac{2}{3} \left( 1 - \Delta^2 t^2 \right) \exp \left( -\frac{1}{2} \Delta^2 t^2 \right)$$
“Effective” Magnetic Penetration Depth: Magnetic Field Dependence

- $V_3Si$ fully gapped
- $LuNi_2B_2C$ anisotropic gap
- $YBa_2Cu_3O_{6.95}$ $d_{x^2-y^2}$-wave gap
- $NbSe_2$ multiband

Choice of Niobium

- High critical temperature
- High critical field
- Low surface resistance
  - Small penetration depth
  - Large coherence length
- Mechanical properties, cost, availability

\[ R_S = \frac{A}{T} \cdot \sigma_n \cdot \omega^2 \cdot \lambda^3 \cdot e^{-B \cdot T_c / T} + R_{\text{residual}} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>( T_c ) (K)</th>
<th>( \lambda ) (nm)</th>
<th>( \xi_0 ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb</td>
<td>7.2</td>
<td>39</td>
<td>83-92</td>
</tr>
<tr>
<td>TYPE I ↑</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TYPE II ↓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td>9.2</td>
<td>32-44</td>
<td>30-60</td>
</tr>
<tr>
<td>Nb(<em>{0.6})Ti(</em>{0.4})</td>
<td>9.8</td>
<td>250-320</td>
<td>4</td>
</tr>
<tr>
<td>NbN</td>
<td>15-17</td>
<td>200-350</td>
<td>3-5</td>
</tr>
<tr>
<td>Nb(_3)Sn</td>
<td>18</td>
<td>110-170</td>
<td>3-6</td>
</tr>
<tr>
<td>YBCO</td>
<td>94</td>
<td>140</td>
<td>0.2-1.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Regime</th>
<th>( H_c )</th>
<th>( H_{c2} )</th>
<th>( J_c )</th>
<th>( R_s )</th>
<th>( T_c )</th>
<th>( \xi )</th>
<th>( \lambda )</th>
<th>Material</th>
</tr>
</thead>
</table>
| DC     | -          | large        | large    | high     | small    | large | (pinning is needed) | Nb/Ti
|        |            |              |          |          |          |       | (bulk current)   | Nb\(_3\)Sn |
| RF     | large      | -            | small    | high     | large    | small | (R_s depends on \( T/T_c \)) | Nb       |
|        |            |              |          |          |          |       | (to give little sensitivity to structure defects) | Nb(Ti)N
|        |            |              |          |          |          |       | R_s \( \lambda \) | Nb\(_3\)Sn? |
|        |            |              |          |          |          |       |                       | YBCO?    |
Detection in a cryogenic environment

Muon Spin Rotation/Relaxation Studies of Niobium for SRF Applications
Mechanism to prove right or wrong: HFQS caused by flux entry?

- Measure $H_p$, $H_{c2}$, $T_c$ in samples: S1 (pristine as received by vendor), S2 (BCP+10h 600C), S3 (S2 plus 10h 120C)
- But these samples are different from what final Nb is in our cavities
- And they lack RF characterization