Transport and noise properties of YBCO nanowire based nanoSQUIDs

Thilo Bauch
Intriguing puzzle in solid state physics: High critical Temperature Superconductors (HTS)
Towards a complete theory of high-\(T_c\)

Given the successes of the microscopic theory of conventional superconductors, it seems natural to expect a similar all-encompassing theory for high-temperature superconductivity. But is it the best approach? Where are we heading?

It is high-temperature superconductivity (high-\(T_c\)) on the list of the most profound physics problems, or is it a collective illusion rooted in sociological developments in the late 1980s? It is not an illusion — I perceive high-\(T_c\) on a par with dark energy, extra dimensions and the secret of life.

High-\(T_c\) is a graveyard of theories. However, this has had the beneficial effect of causing a state of mind not dissimilar from the goal of Zen Buddhism: think nothingness, in order to reach enlightenment. Rid the mind from textbook wisdoms, such as the conventional theory of Bardeen, Cooper and Schrieffer (BCS), the Fermi gas and even resonating valence bonds (RVBs), and the essence of high-\(T_c\) comes into view. The metallic state at optimal doping embodies the enlightenment. Rather than being complicated, this ‘bad’ metal shows a sacred simplicity — symbolized, for example, by its linear resistivity as a function of temperature, up to the melting point of the crystal. This reveals principle at work, of a quality of Einstein’s principle of equivalence.

I am convinced that this principle cannot be found by merely thinking hard — the reason I stopped designing theories. It requires experiments to give away the clue, and there are reasons to be optimistic. A group of experimentalists are providing further evidence that phonons play an important, albeit quite unusual, microscopic role. Even if this does not lead to the magic bullet, it has at least the effect of discredit the influential religious dogma that the electronic toy models invented by Anderson and Hubbard will solve all problems.
Charge Density Wave (CDW) order

Static CDW:
Competing order to superconductivity, well established in 214 compounds

Dynamic/fluctuating CDWs:
Possible mechanism for HTS??
Looking into the superconducting dome from different perspectives

**Nano scale ordering**
Transport Anisotropy in nanowires

**Excitation spectrum**
Single Electron Transistor

**2e or not 2e**
Little-Parks ring, nanoSQUID

**Noise properties**
nanoSQUID
Doping and temperature dependence: new insights about HTS

Nano scale ordering
Transport Anisotropy in nanowires

Excitation spectrum
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Noise properties
nanoSQUID

Correlation between properties: Invaluable for microscopic modeling of HTS
Nano-patterning of HTS films: wires, nano-rings, nanoSQUIDs, SET ...

The challenge

From literature

- Evidence of damage during \( \text{Ar}^+ \)-ion etching

(\text{Papari et al. SuST 25, 035011 (2012)})

Our achievement:

- Depairing critical current measured in YBCO nanowires with cross section 50x50 nm\(^2\)

Josephson-like behavior of nanowires

**Origin of Current Phase Relation**
(Likharev, RMP 51, 101 (1971))

\[ L = f_2 - f_1 \]

**Current Phase Relation**
(Likharev, Yakobson, Zh. Tekhn. Fiz. 45, 1503 (1975))

\[ \frac{L}{\xi(T)} < p = \frac{2}{L/t} \]

(Kupriyanov et al., LT14 T027, 104 (1975))
Current Voltage Characteristic

See talk by Riccardo Arpaia
3EO2-02 @ 16:20 on Wednesday
Key feature of superconductivity: Fluxoid quantization

Total flux through the loop = INTEGER * FLUX QUANTUM

\[ \varphi + \mu_0 \int \lambda_L^2 j_s \cdot d\vec{r} = n \cdot \frac{h}{2e} \]

Superconducting loop keeps total flux always at an integer multiple of h/2e
Superconducting QUantum Interference Device (SQUID)

Superconducting loop keeps total flux always at an integer multiple of $\hbar/2e$

YBCO nanoSQUID implementing nanowires

Demonstration of critical current modulations in the full temperature range below the transition temperature $T_c$.

YBCO nanoSQUID: sub-$\mu \Phi_0/\text{Hz}^{1/2}$ sensitivity

• White noise level **better than** $1 \, \mu \Phi_0/\text{Hz}^{1/2}$ at 8K!

  White Flux Noise $S_\Phi(f) \sim 4k_B T L^2/R$ (?)

• Detection of magnetic nanoparticles in high magnetic fields and wide temperature range.
• Single spin detection?

Improving white flux noise

Flux noise limited by amplifier input noise

- Large voltage modulation depth is needed.
- One possibility is to increase normal state resistance of the wire.

$$S^{1/2} = S_{V}^{1/2} \frac{V}{\cdot}$$

Arpaia, Arzeo, Baghdadi, Trabaldo Lombardi, Bauch, SuST 30, 014008 (2017)
Improving white flux noise

White flux noise limited by amplifier input noise

Increasing normal state resistance by:
- Removing gold capping
- Using thinner YBCO films

\[ 1 \, \mu \Phi_0/Hz^{1/2} \rightarrow 0.6 \, \mu \Phi_0/Hz^{1/2} \]
\[ 0.6 \, \mu \Phi_0/Hz^{1/2} \rightarrow 0.45 \, \mu \Phi_0/Hz^{1/2} \]

@ 18 K
Towards field sensitivity

Improving white flux noise

Flux noise \( \propto \) loop area

Implications on:

- Single spin detection.
- Detection of magnetic nanoparticles in high magnetic fields.

Magnetic Field noise = Flux noise / magnetic pickup area

Arzeo, Arpaia, Baghdadi, Lombardi, Bauch, JAP 119, 174501 (2016)
Towards field sensitivity

Magnetic Field noise = Flux noise / magnetic pickup area

Relevant inductances (per unit length)

$$L'_{loop} = \frac{\mu_0 L \coth \left( \frac{t}{\lambda_L} \right)}{w} + \frac{\mu_0}{2\pi} \left[ \ln \left( \frac{16r}{w} \right) - 2 \right]$$

$$L'_{c} = \frac{\mu_0 \lambda_L}{w_c} \coth \left( \frac{t}{\lambda_L} \right) + k/2$$

$$k \approx 0.3 \text{ pH/\mu m}$$

Kinetic inductance

Superconducting strip of width $w$, thickness $t$

$$L_k = \frac{2}{\sqrt{wt}}$$

($T$): London penetration depth

Arzeo, Arpaia, Baghdadi, Lombardi, Bauch, JAP 119, 174501 (2016)
Towards field sensitivity

**Effective area vs. pick up loop diameter**

For $T = 150\, \text{nm}$:
- 70% of flux coupling occurs via kinetic inductance

For $T = 400\, \text{nm}$:
- 94% of flux coupling occurs via kinetic inductance

Arzeo, Arpaia, Baghdadi, Lombardi, Bauch, JAP 119, 174501 (2016)
Towards field sensitivity

Summary of nanoSQUIDs w/ pickup loop

<table>
<thead>
<tr>
<th>Device</th>
<th>$d_w$ ($\mu m$)</th>
<th>l (nm)</th>
<th>w (nm)</th>
<th>d ($\mu m$)</th>
<th>$A_{\text{eff}}$ ($\mu m^2$)</th>
<th>$I_C$ (mA)</th>
<th>$\delta R$ ($\Omega$)</th>
<th>$V_\Phi$ (mV/$\Phi_0$)</th>
<th>$S_{\Phi,w}^{1/2} (\mu \Phi_0/\sqrt{Hz})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSQ1</td>
<td>1</td>
<td>200</td>
<td>65</td>
<td>100</td>
<td>24</td>
<td>1.7</td>
<td>0.8</td>
<td>2.4</td>
<td>&lt;1</td>
</tr>
<tr>
<td>NSQ2</td>
<td>1</td>
<td>200</td>
<td>65</td>
<td>400</td>
<td>62</td>
<td>2.4</td>
<td>2.4</td>
<td>0.75</td>
<td>&lt;2</td>
</tr>
<tr>
<td>NSQR</td>
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<td>100</td>
<td>65</td>
<td>-</td>
<td>2.8</td>
<td>1.75</td>
<td>0.2</td>
<td>1.5</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

- Flux noise independent of pick up loop.
- Magnetic field noise properties improve with pick up loop size.
- Coupling mainly via kinetic inductance.

Arzeo, Arpaia, Baghdadi, Lombardi, Bauch, JAP 119, 174501 (2016)
Increasing further effective area

\[ T = 77 \text{ K} \]

Xie, Chukharkin, Ruffieux, Schneiderman, Kalabukhov, Arzeo, TB, Lombardi, Winkler, submitted to SuST
50 nm YBCO:
- no Au capping
- no pick up loop
- $V_\phi \sim 15 \ \mu V/\phi_0$
- Amp: $S_{\nu}^{1/2} \sim 0.4 \ nV/Hz^{1/2}$

Expected field noise taking achieved effective area $A_{\text{eff}} \sim 0.1 \ mm^2$:

$$S_{\phi}^{1/2} \sim 500 \ fT/Hz^{1/2}$$

For HTS MEG applications: $S_{\phi}^{1/2} < 50 \ fT/Hz^{1/2}$ needed

⇒ SQUID electronics with lower input noise (Cryoton)
\[ \delta V = \left( \frac{\partial V}{\partial R} \right) \delta R + \left( \frac{\partial V}{\partial I_c} \right) \delta I_c \]
Resistance and critical current 1/f noise

Hooge’s law for 1/f noise

\[ S_V = \frac{V^2}{f \times n \times Vol} \]

Critical current 1/f noise is roughly 10 times larger

\[ g \approx 3.4 \times 10^{-4} \] (Hooge’s parameter)

Vol = 3w^2t
\[ t = 50 \text{ nm}, \ w = 65 \text{ nm}, \ldots, \ 1 \text{ \textmu m} \]
High critical temperature superconductor nanodevices

- Nanoscale devices beyond state-of-the-art
- Vision: obtain groundbreaking information about the microscopic mechanism of HTS
- Quantum limited detectors
  - Nanomagnetism
  - HTS MEG systems
Transport anisotropy and noise

Finite correlation length of charge density waves (CDW): 10-40 nm

Alignment of CDW along a- or b-direction in CuO$_2$ planes

Equivalent resistor network

Fluctuating CDW:

Resistance fluctuations as a function of:

- Doping
- Temperature
- Substrate
- Magnetic field

Similar effects expected for superfluid density: critical current fluctuations

Probing the AC-Josephson-like behavior: Detection of Shapiro-like steps under microwave irradiation

- Phase locking of driving microwave field at frequency $\omega_d$ and Abrikosov vortex motion across the wire.

$$V_n = n \times \frac{d}{2}$$

- Shapiro steps observable to the 160$^{th}$ order

Probing the AC-Josephson-like behavior: Detection of Shapiro-like steps under microwave irradiation

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\[ V_n = n \times \frac{d}{2} \]

- Shapiro steps observable to the 160th order

- Modulation of Shapiro-like steps indicates the existence of a periodic Current Phase Relation

Critical current density $J_C$ vs wire width $w$: a quality check

Transition from zero voltage state to finite voltage state of a wire:

Transition from the zero voltage state to the finite voltage state when the **LOCAL** current density $j_y$ (typically at the edge of the wire) is close to the Ginzburg Landau depairing current density $j_y \sim j_{dp}$ (nucleation of vortices)

$$J_{C} = \frac{I_{\text{max}}}{tw}$$

$$J_{dp} = \begin{pmatrix} 0 \\ 3\sqrt{3} \\ 0 \end{pmatrix} \frac{2}{L} \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} = 1.5 \times 10^8 \text{ A/cm}^2$$
dc SQUIDs based upon YBa$_2$Cu$_3$O$_7$ nanobridges

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(Received 6 April 1994; accepted for publication 30 August 1994)

$100 \text{nm}^3 (l,w,d)$. Even for a calculated $\beta_L \approx 1$, no significant modulation of the critical current was observed for our HTS SQUIDS, i.e., $\Delta I_c/I_c \ll 1$. The relatively high volt-

Superconducting quantum interference devices based on YBaCuO nanobridges

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for weak link SQUIDs. To explain this phenomenon, we considered degradation of superconductor in the nanobridge area, which leads to a local suppression of $T_c$ and to a transition from SNS to SS’S-type junctions with decreasing temperature. This approach allows us to explain the experimen-

See also Supercond. Sci. Technol. 22 (2009) 064001

“Why NanoSQUIDs are important: an introduction to the focus issue”
by C. P. Foley and H. Hilgenkamp
Doping dependence: thin films

Variation of hole doping through proper annealing

(unpublished)