The Paramagnetic Meissner Effect in Josephson Junction Arrays

Aaron P. Nielsen, A. B. Cawthorne, P. Barbara, F. C. Wellstood, C. J. Lobb

Center for Superconductivity Research
University of Maryland
College Park, MD 20742

F. M. Araujo-Moreira

UFSCar, Sao Paulo, Brazil

R. S. Newrock

Department of Physics, University of Cincinnati

M. G. Forrester

Northrop-Grumman Corporation

Support: AFOSR Grant F49620-98-1-0072,
Center for Superconductivity Research, UMD
Outline

• Paramagnetic Meissner effect.
• Arrays.
• Bulk susceptibility.
• Single-loop model.
• Scanning SQUID measurements.
• Single loop revisited.
• Possible explanations.
Field cooled BSCCO$^{1,2}$

1. W. Braunisch et al. PRL 68 1908 (1992)

π-junctions in d-wave ceramics?
PME observations

Nb - D.J. Thompson et al. PRL 75 529 (1995)
P. Kostic et al. PRB 53 791 (1996)


BSCCO - W. Braunisch et al. PRL 68 1908 (1992)

YBCO - S. Reidling et al. PRB 49 13283 (1994)


Proposed causes

- $\pi$-junctions
- Surface effects
- Random pinning
- Non-equilibrium
Bulk susceptibility

\[ H_{\text{EXT}} = h_{AC} \cos(\omega t) \]

\[ M(t) = h_{AC} \sum [\chi'_m \cos(m\omega t) + \chi''_m \sin(m\omega t)] \]

\[ M_1(t) = h_{AC} [\chi'_1 \cos(\omega t) + \chi''_1 \sin(\omega t)] \]
Data

(a) $h_{AC} = 96$ mOe, array.
(b) $h_{AC} = 7$ mOe, array.
(c) $h_{AC} = 10$ mOe, Nb film
Data, loops only

(Nb background subtracted)
Single-loop simulation

\[ M(t) = h_{AC} \sum [\chi'_m \cos(m\omega t) + \chi''_m \sin(m\omega t)] \]

\[ M_1(t) = h_{AC} [\chi'_1 \cos(\omega t) + \chi''_1 \sin(\omega t)] \]
(a) $h_{AC} = 5 \text{ mOe}, \text{ loop.}$
(b) $h_{AC} = 29 \text{ mOe}, \text{ loop.}$
(c) $h_{AC} = 69 \text{ mOe}, \text{ loop.}$
(d) $h_{AC} = 118 \text{ mOe}, \text{ loop.}$
Single-loop simulation

Temperature Dependence of the Total Magnetic Flux Density ($\Phi_{\text{TOT}}$) vs. the Extensive Magnetic Flux Density ($\Phi_{\text{ext}}$) for Three Different Temperatures:

- T = 7.6 K
- T = 6.0 K
- T = 4.0 K

The figure shows the transition between the PARA and DIA states with temperature. The plots indicate a phase transition at each temperature, with the boundary between PARA and DIA states shifting with temperature.
Susceptibility summary

- Nb-AlOx-Nb arrays are paramagnetic
- No $\pi$ junctions
- Little disorder
- Single-loop: paramagnetic and diamagnetic states
- Is single-loop model enough?

Scanning SQUID Experiment

Unshunted Array
Nb - AlOx - Nb

30 x 100 junctions

$$\beta_l = \frac{2\pi LI_c}{\Phi_0} = 30$$

Sample is field cooled
Measured with field turned on
Paramagnetic Image of JJ Array

\[ \Phi_{\text{external}} = 4.8 \Phi_0 \]

\[
\frac{(\Phi_{\text{total}} - \Phi_{\text{external}})}{\Phi_0}
\]

5 mm
M = B - H
Histogram of Flux Values for JJ Array

\[ \Phi_{\text{external}} = 4.8\Phi_0 \]
Diamagnetic

$\Phi_{\text{external}} = 1.2 \Phi_0$

$(\Phi_{\text{total}} - \Phi_{\text{external}}) / \Phi_0$
Histogram of Flux Values for JJ Array

\[ \Phi_{\text{external}} = 1.2 \Phi_0 \]
Array Exhibits Paramagnetism For Some Cooling Fields!

$M$ vs. $H$

$\frac{\Phi_{\text{tot}} - \Phi_{\text{ext}}}{\Phi_0}$ vs. $\frac{\Phi_{\text{ext}}}{\Phi_0}$

- **Paramagnetic**
- **Diamagnetic**
Four Junction Loop

\[ I = I_c \sin \gamma \]

\[ \gamma_i = \theta_k - \theta_{k-1} - \frac{2\pi}{\Phi_0} \int_k A \cdot dl \]

\[ L = \text{self- inductance of loop} \]

\[ \sum_i \gamma_i = 2\pi n - \frac{2\pi}{\Phi_0} \Phi_{\text{total}} \]

\[ \Phi_{\text{total}} = \Phi_{\text{external}} + LI \]

By symmetry: \[ \gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_i \]

\[ \gamma_i = \frac{\pi}{2} n - \frac{\pi}{2} \frac{\Phi_{\text{total}}}{\Phi_0} \]

**Equation:**

\[ \frac{\Phi_{\text{tot}}}{\Phi_0} = \frac{\Phi_{\text{ext}}}{\Phi_0} + \frac{LI_c}{\Phi_0} \sin\left(\frac{\pi}{2} n - \frac{\pi}{2} \frac{\Phi_{\text{tot}}}{\Phi_0}\right) \]
Four Junction Loop

\[ \frac{\Phi_{\text{tot}}}{\Phi_0} = \frac{\Phi_{\text{ext}}}{\Phi_0} + \frac{LI_c}{\Phi_0} \sin\left(\frac{\pi}{2} n - \frac{\pi}{2} \frac{\Phi_{\text{tot}}}{\Phi_0}\right) \]
Single Loop Magnetization

\[
\frac{(\Phi_{\text{tot}} - \Phi_{\text{ext}})}{\Phi_0}
\]

\[
\frac{\Phi_{\text{ext}}}{\Phi_0}
\]

- Paramagnetic
- Diamagnetic
\( \frac{(\Phi_{\text{tot}} - \Phi_{\text{ext}})}{\Phi_0} \) vs. \( \Phi_{\text{ext}}/\Phi_0 \)

- **Paramagnetic**
- **Diamagnetic**

- **Single Loop**
- **Array Data**
Conclusions

Conventional Josephson junction arrays can be paramagnetic

\(\pi\)-junctions are not necessary for paramagnetism

The 4-junction loop can be paramagnetic

Arrays more likely to be paramagnetic than diamagnetic; single loop nearly equally likely.

What are the differences with \(\pi\)-junction arrays?