Investigating Magnetic Order in Mesoscopic Superconductors Using Cantilever Torque Magnetometry

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Introduction to superconductivity in Sr$_2$RuO$_4$

Describe torque magnetometry measurements to detect moments from edge currents in mesoscopic SRO samples

Measurements in NbSe$_2$ (Model system that is layered and s-wave)

SRO Measurements

- Preliminary evidence of moment due to edge currents
- Nonlinear diamagnetic susceptibility
- Concluding Remarks
Superconductivity in Sr$_2$RuO$_4$

- Layered perovskite structure similar to high $T_c$ cuprates
- Normal state is metallic
- $T_c = 1.5$ K

$a, b = 0.38 \text{ nm} \quad c = 1.27 \text{ nm}$
Evidence for Unconventional Superconductivity

Suppression of $T_c$ from non-magnetic impurities

Mackenzie et al. (1998)

(NMR) Oxygen Knight shift

Ishida et al. (1998)

Spin-polarized neutron scattering

Duffy et al. (2000)

\[ \vec{S} = 1 \]

Spin component of wavefunction is even parity
Evidence for Time Reversal Symmetry Breaking

µSR

Kerr Rotation

\[ p_x \pm ip_y \]

Complex order parameter

\[ \vec{L} = 1, \vec{S} = 1 \]

- Domains with orbital order have a net magnetic moment.
- Magnetic fields from domains are screened by the collective motion of CP.
Screening Currents Around Chiral Domains

\[ p_x + i p_y \]
### Experimental Evidence for TRS Breaking

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Status</th>
<th>Domain Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>µSR</td>
<td>⬤</td>
<td>-----</td>
</tr>
<tr>
<td>Josephson tunneling</td>
<td>⬤</td>
<td>&lt; 1 µm</td>
</tr>
<tr>
<td>Kerr Rotation</td>
<td>⬤</td>
<td>~ 50 – 100 µm</td>
</tr>
<tr>
<td>SQUID Imaging</td>
<td>⬤</td>
<td>&lt; 2 µm</td>
</tr>
<tr>
<td>Hall probe Imaging</td>
<td>⬤</td>
<td>&lt; 1 µm</td>
</tr>
</tbody>
</table>
Vortex Matter in Chiral Superconductors

- 2 Vectors are needed to describe the SC order
  - (1) $\mathbf{d}$-vector - direction normal to the spin polarization
  - (2) $\mathbf{L}$-vector - the angular momentum

**Integer quantum vortex:**
- Orbital phase winds by $2\pi$
- $\mathbf{d}$-vector is stationary

**Half-integer quantum vortex:**
- Orbital phase winds by $\pi$
- $\mathbf{d}$-vector winds by $\pm \pi$

Mackenzie (2003)
Cantilever Torque Magnetometry Measurements

\[ \Delta f = \frac{f_0}{2k l_{eff}} \left\{ \Delta \chi \left( H_x^2 - H_z^2 \right) - \mu_{||} H_z - \mu_{\perp} H_x \right\} \]

\[ \Delta \chi = \chi_{||} - \chi_{\perp} \]

\[ f_0 = 5.3 \ kHz \]
\[ k = 3 \times 10^{-4} N/m \]
\[ Q = 60,000 \]
\[ l_{eff} = 63 \ \mu m \]

\[ S_{\mu}^{1/2} = 3.3 \times 10^4 \ \mu_B/\sqrt{Hz} \ T \]
\[ T = 4.2 \ K \]
300 mK Force Microscope
Micron-Size Superconducting NbSe$_2$ Particles

$\lambda_c(0) = 230 \text{ nm}$

$\lambda_{ab}(0) = 69 \text{ nm}$

$\Delta \chi(T) = \Delta \chi(0) \left[ 1 - \left( \frac{T}{T_c} \right)^4 \right]$
Vortex State in Mesoscopic NbSe$_2$ Samples
Diamagnetic Susceptibility of NbSe$_2$

\[
\Delta f = \frac{f_0}{2\hbar c \, 2} \Delta \chi \left( H_x^2 - H_z^2 \right)
\]
Response to ab-Plane Field

Frequency (Hz)

$H_x$ (Oe)

$H_z$ (Oe)

0
20
40
60
80
100
120
140
160

$H_x$ (Oe)

-140 -120 -100 -80 -60 -40 -20 0

Frequency (Hz)

4391
4392
4393
4394

$H_x$ (Oe)
Switching Noise in Vortex Dynamics

$H_z = -140 \text{ Oe}$

$T = 4.7 \text{ K}$

Time (s)
Torque Magnetometry of Micron-Size Sr$_2$RuO$_4$ Particles

Samples grown by Y. Maeno

$T_c = 1.2$ K

- Samples are cleaved from bulk crystals and glued to the cantilever with the c-axis normal to the cantilever face.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$ab$</th>
<th>$c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_0 H_{c2\parallel c}(0)$ (T)</td>
<td>0.075</td>
<td></td>
</tr>
<tr>
<td>$\mu_0 H_{c2\parallel ab}(0)$ (T)</td>
<td>1.50</td>
<td></td>
</tr>
<tr>
<td>$\mu_0 H_{c}(0)$ (T)</td>
<td>0.023</td>
<td></td>
</tr>
<tr>
<td>$\xi(0)$ (Å)</td>
<td>660</td>
<td>33</td>
</tr>
<tr>
<td>$\lambda(0)$ (Å)</td>
<td>1520</td>
<td>$3.0 \times 10^4$</td>
</tr>
<tr>
<td>$\kappa(0)$</td>
<td>2.3</td>
<td>46</td>
</tr>
<tr>
<td>$\gamma_\parallel = \xi_{ab}(0)/\xi_c(0)$</td>
<td>20</td>
<td></td>
</tr>
</tbody>
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Zero-Field Magnetization Measurements

\[ H_x = H_0 + \Delta H \cos(\omega_m t) \]
\[ H_z = 0 \quad H_x^{min} = 1.25 \text{ Oe} \]
\[ \Delta f = a_1 \cos(\omega_m t) + a_2 \cos(2\omega_m t) + \text{const.} \]
\[ a_1 = \frac{f_0 \Delta H}{2kT_{eff}} (2H_0 \Delta \chi + \mu_x) \]
\[ a_2 = \frac{f_0^2}{4kT_{eff}} \Delta \chi (\Delta H)^2 \]

\( \Delta \chi = 1.64 \times 10^{-13} \text{ emu} \)
Assume the particle is a single chiral domain

\[ m_0 \approx (1.1 \pm 0.2) \times 10^{-13} \text{ emu} \]

perimeter: \( S \approx 4 \mu m \)
thickness: \( h = 440 \mu m \)

\[ m_0 \approx (0.5 - 1.0) \times 10^{-13} \text{ emu} \]

\[ \xi_0 = 66 \text{ nm} \]
\[ v_F = 5.5 \times 10^4 m \text{ s}^{-1} \]
\[ N(E_F) = 4.36 \text{ states/eV cell} \]
\[ T_c = 1.5 \text{ K} \]
\[ J_0 = e v_F N(E_F) k_B T_c \]
\[ J_0 = 2.6 \times 10^{10} A \text{ m}^{-2} \]
Diamagnetic Susceptibility Measurements in $\text{Sr}_2\text{RuO}_4$

Particle dimensions: $3 \mu m \times 4 \mu m \times 0.5 \mu m$

$\Delta f \propto \Delta \chi_0 \left(1 - \frac{H_x^2}{H_0^2}\right) H_x^2$

$\Delta \chi_0 = -8.8 \times 10^{-13} \text{ emu}$

$H_0 = 26.7 \text{ Oe}$
\[ \Delta f \propto \left(1 - \frac{H_x^2}{H_0^2}\right) \Delta \chi_0 \left(H_x^2 - H_z^2\right) \]

\[ \Delta \chi_0 = -5.5 \times 10^{-13} \text{ emu} \]

\[ H_0 = 20.0 \text{ Oe} \]
Remarks

- Torque magnetometry measurements of mesoscopic samples is a promising technique for detection of edge currents

- Mesoscopic anular geometry might be useful in stabilizing fractional vortices

Questions

- Why do we not observe training effects in the zero-field magnetization?

- What is the origin of the nonlinear diamagnetic susceptibility?