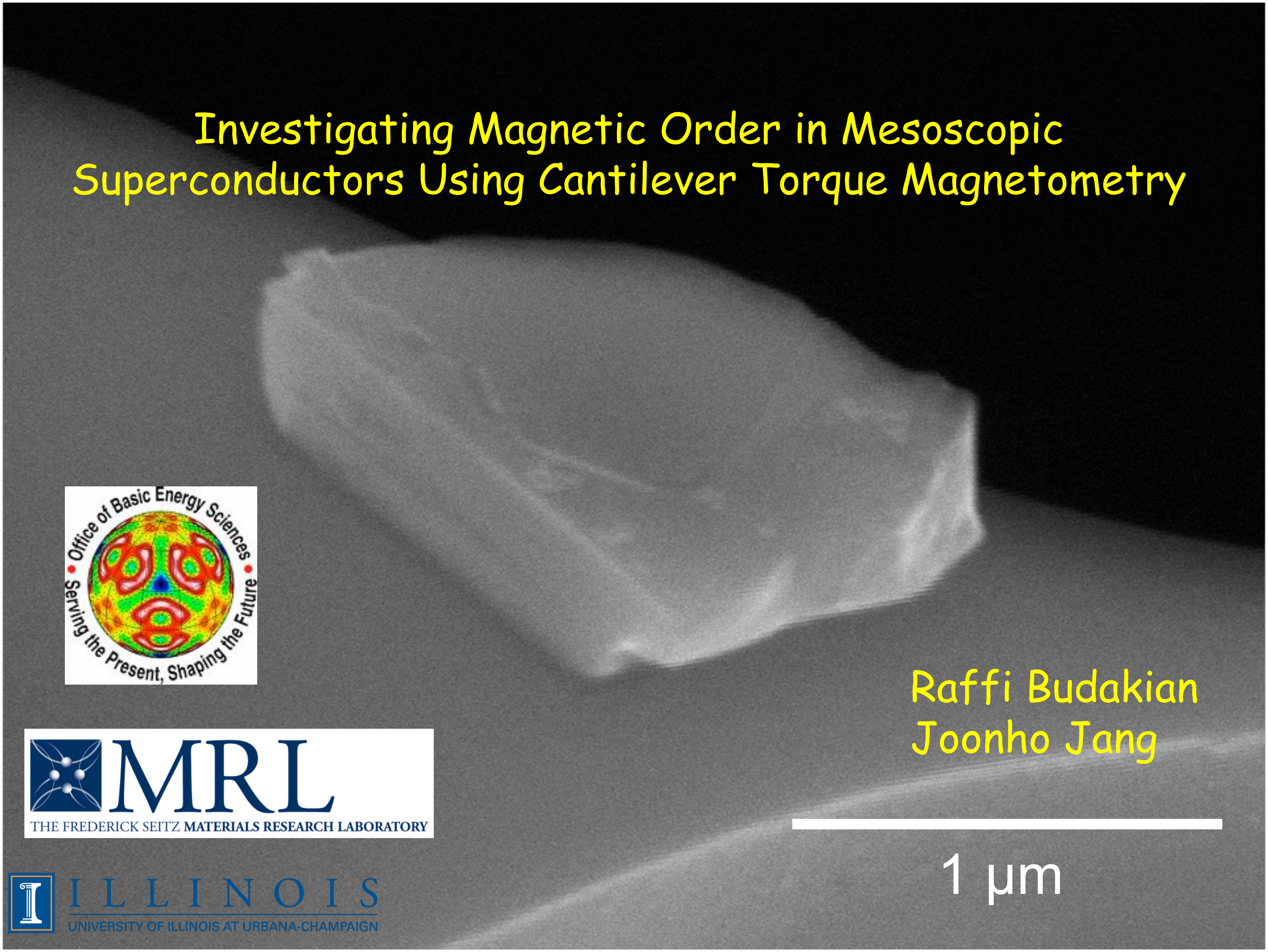
Investigating Magnetic Order in Mesoscopic Superconductors Using Cantilever Torque Magnetometry



Raffi Budakian
Joonho Jang

Office of Basic Energy Sciences
Serving the Present, Shaping the Future

MRL
THE FREDERICK SEITZ MATERIALS RESEARCH LABORATORY

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

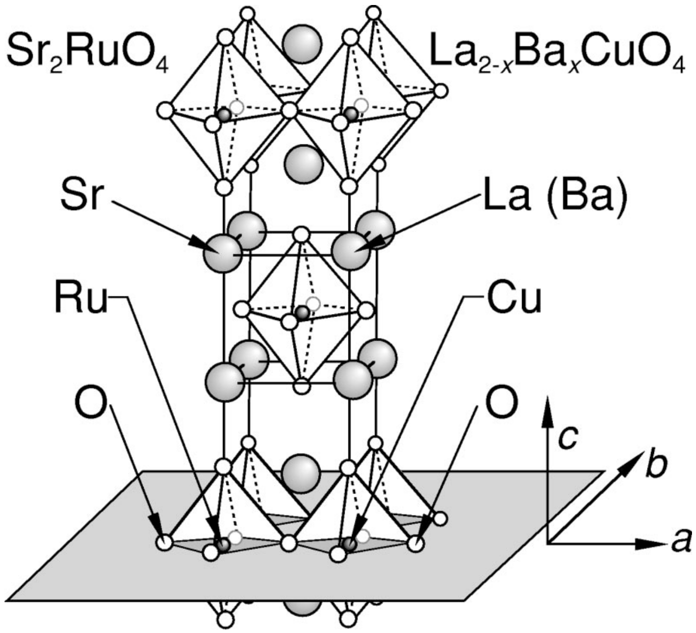
Outline

- Introduction to superconductivity in Sr_2RuO_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_2RuO_4



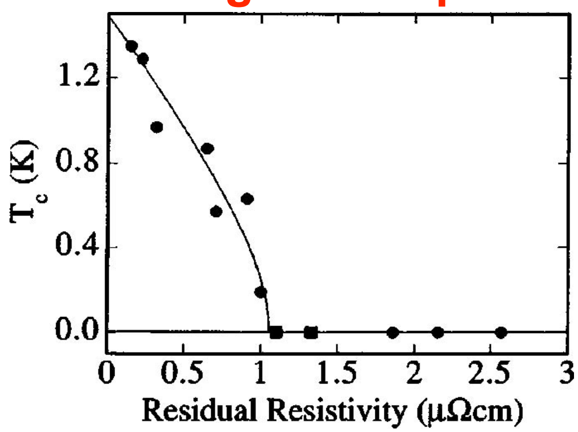
$$a, b = 0.38\ nm$$
$$c = 1.27\ nm$$

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

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

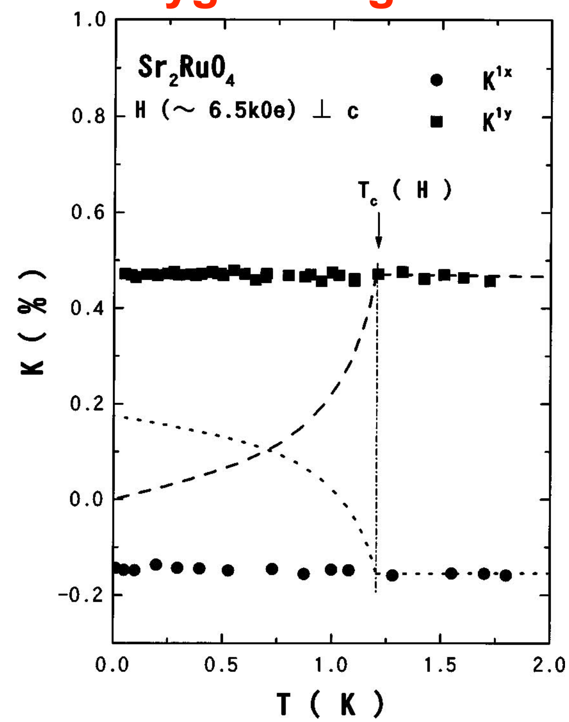
Evidence for Unconventional Superconductivity

Suppression of T_c from non-magnetic impurities



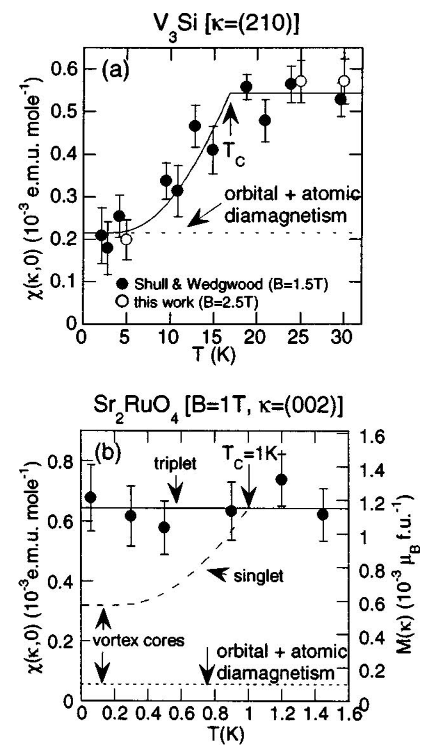
Mackenzie *et al.* (1998)

(NMR) Oxygen Knight shift



Ishida *et al.* (1998)

Spin-polarized neutron scattering



Duffy *et al.* (2000)

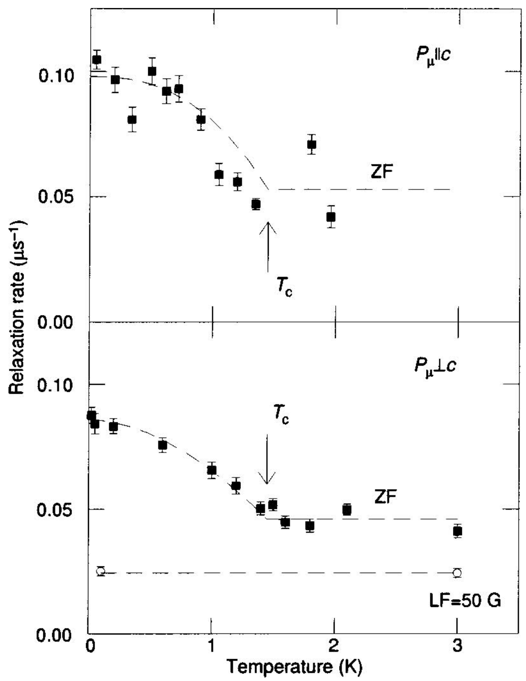
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

$$\vec{S} = 1$$

Spin component of wavefunction is even parity

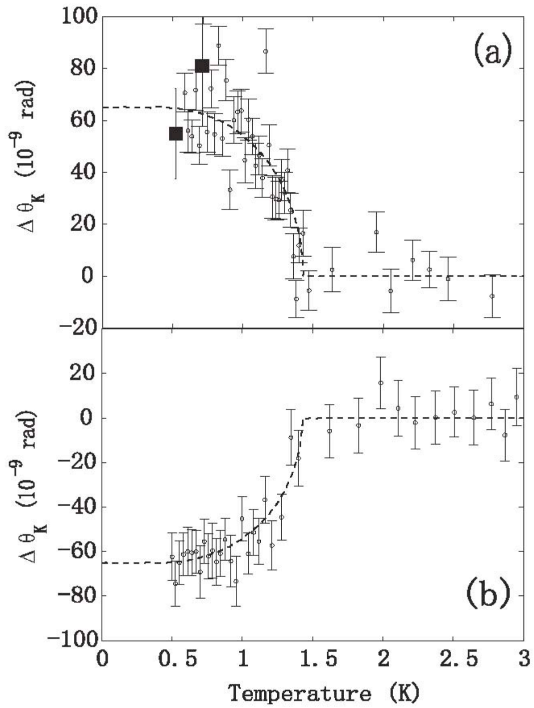
Evidence for Time Reversal Symmetry Breaking

μSR



Luke *et al.* (1998)

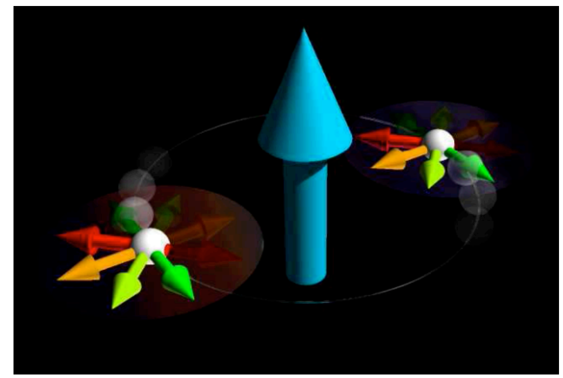
Kerr Rotation



Xia *et al.* (2006)

$p_x \pm ip_y$

Complex order parameter

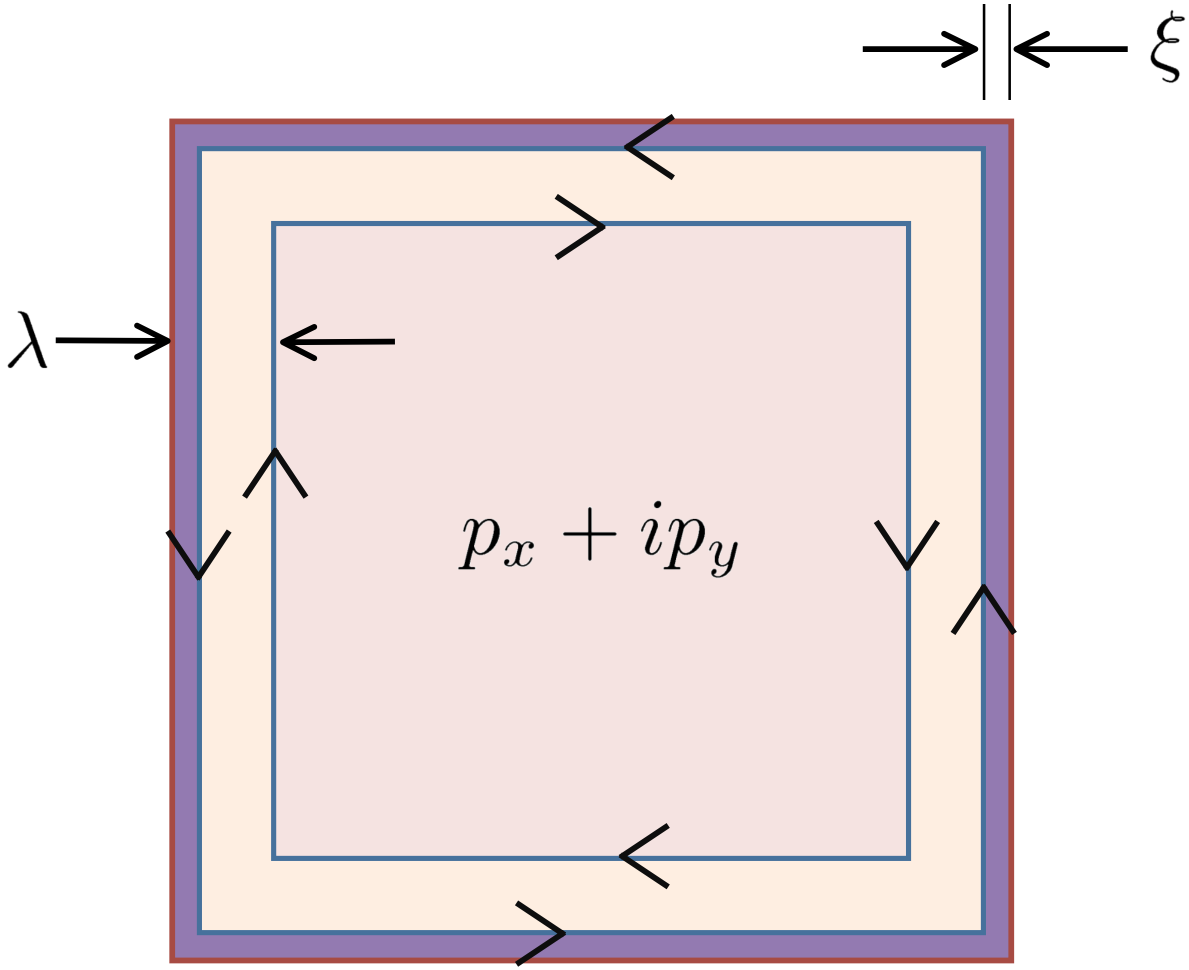


$\vec{L} = 1,\ \vec{S} = 1$

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

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Screening Currents Around Chiral Domains



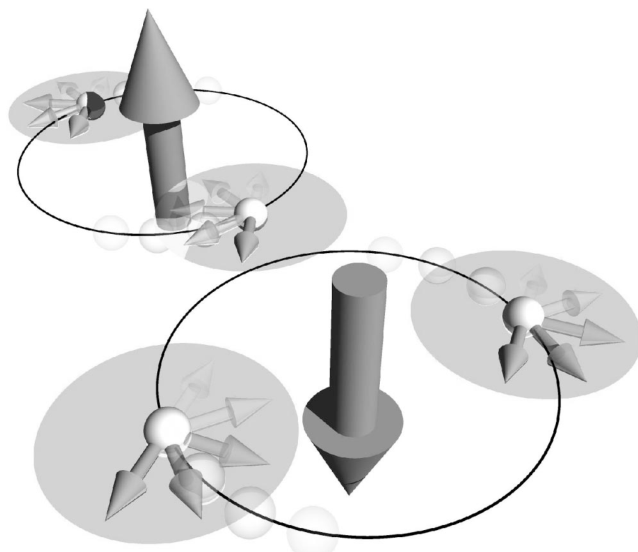
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

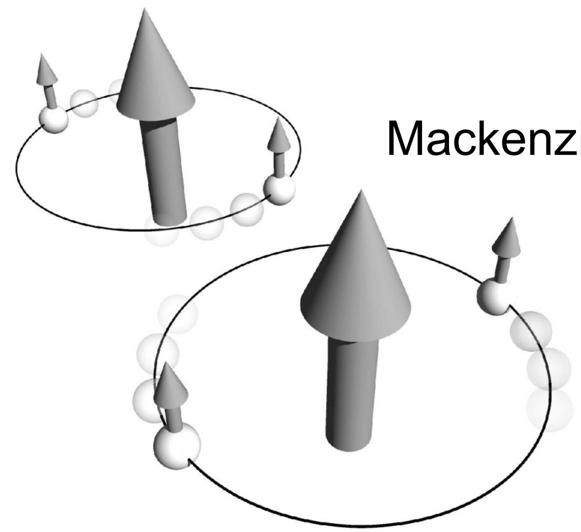
Experimental Evidence for TRS Breaking

Experiment	Status	Domain Size
μSR	●	-----
Josephson tunneling	●	< 1 μm
Kerr Rotation	●	~ 50 – 100 μm
SQUID Imaging	⊘	< 2 μm
Hall probe Imaging	⊘	< 1 μm

Vortex Matter in Chiral Superconductors

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





Mackenzie (2003)

$$\vec{d} \parallel \vec{L}$$

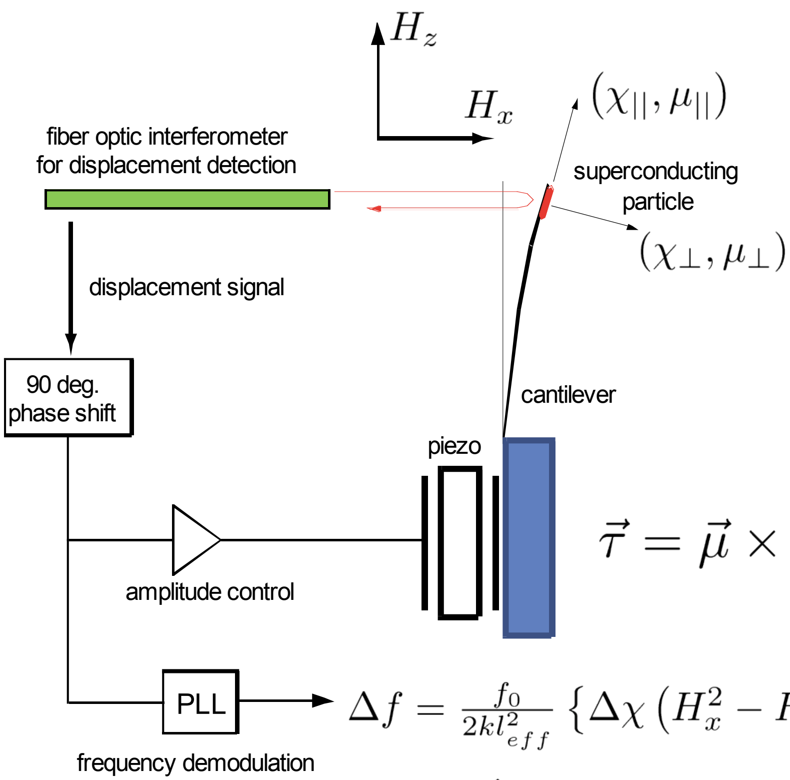
Integer quantum vortex:
Orbital phase winds by 2π
d-vector is stationary

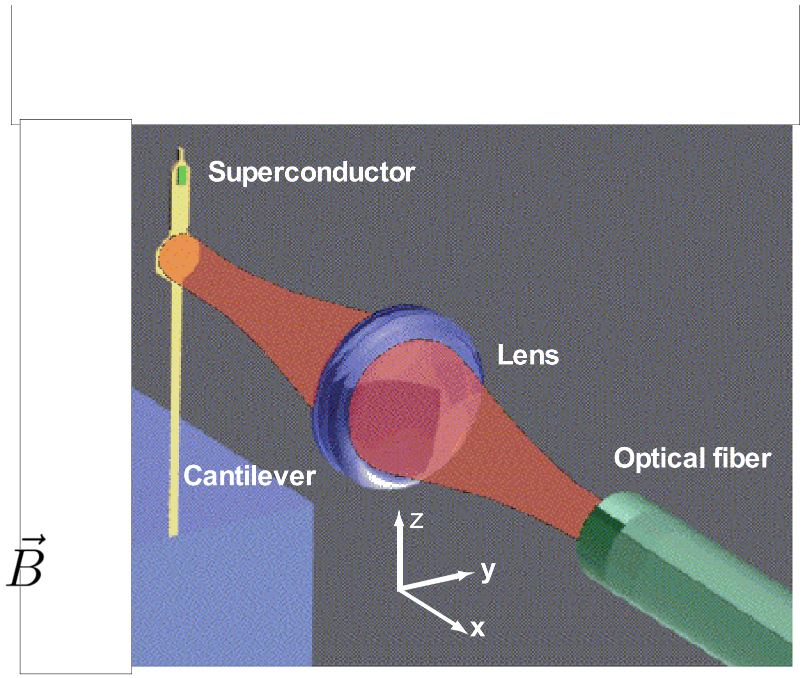
$$\vec{d} \perp \vec{L}$$

Half-integer quantum vortex:
Orbital phase winds by π
d-vector winds by ± π

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Cantilever Torque Magnetometry Measurements





$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

$$\Delta f = \frac{f_0}{2kl_{eff}^2}\left\{\Delta\chi\left(H_x^2 - H_z^2\right) - \mu_{||}H_z - \mu_{\perp}H_x\right\}$$

$$\Delta\chi = \chi_{||} - \chi_{\perp}$$

$$f_0 = 5.3\ kHz$$

$$k = 3 \times 10^{-4} N/m$$

$$Q = 60,000$$

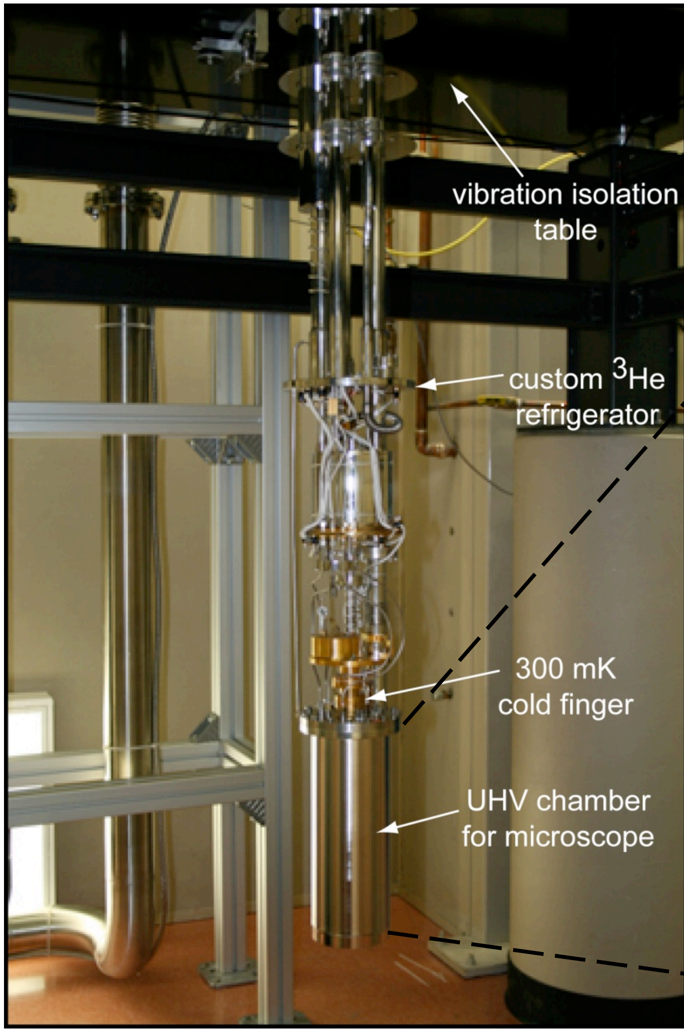
$$l_{eff} = 63\ \mu m$$

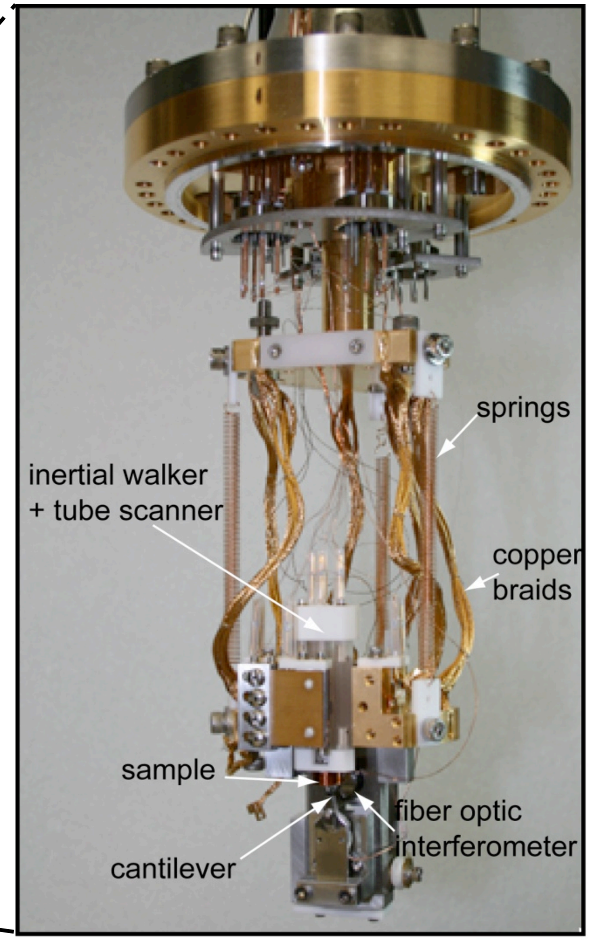
$$S_{\mu}^{1/2} = 3.3 \times 10^{4}\ \mu_B/\sqrt{Hz}\ T$$

$$T = 4.2\ K$$

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

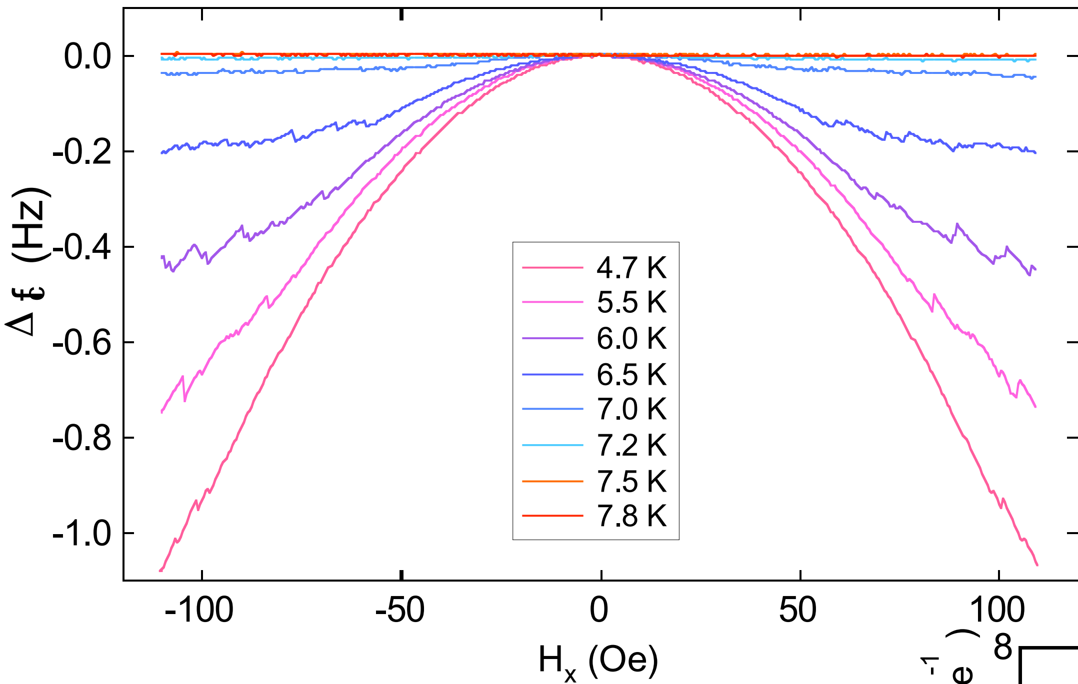
300 mK Force Microscope

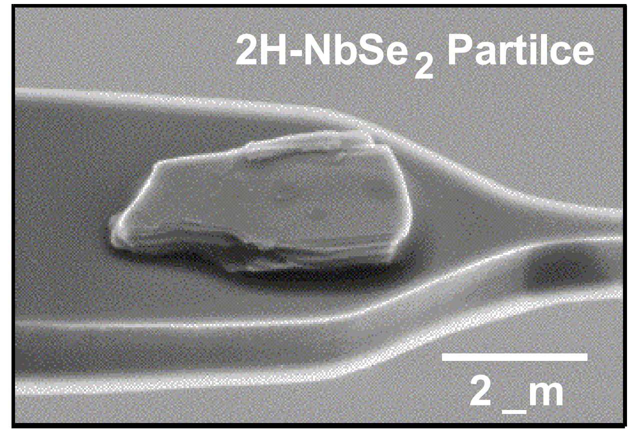




ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

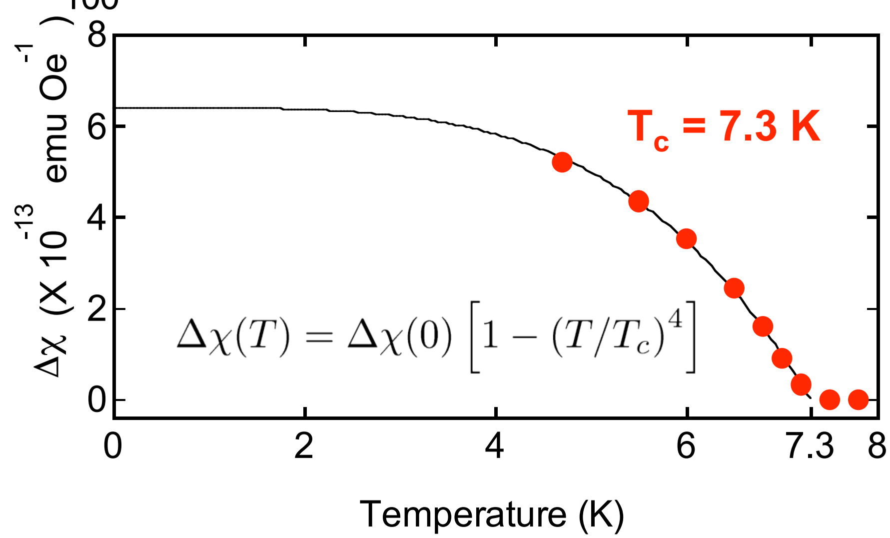
Micron-Size Superconducting $NbSe_2$ Particles





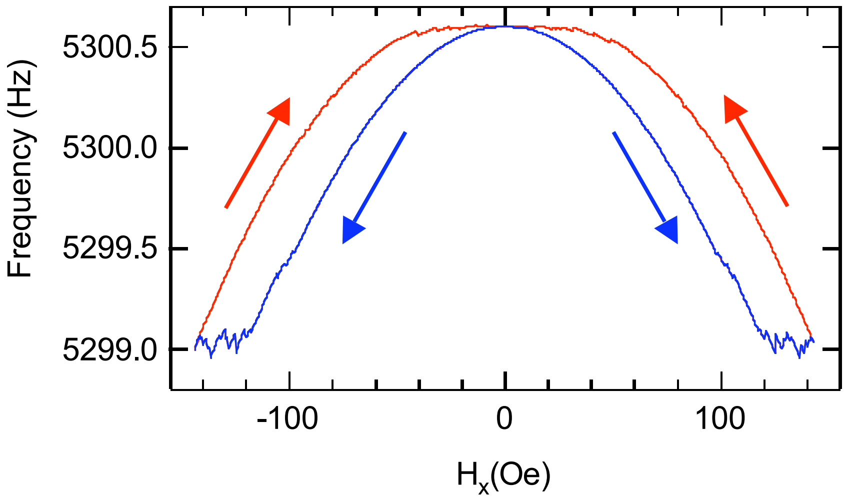
$$\lambda_c(0) = 230\ nm$$

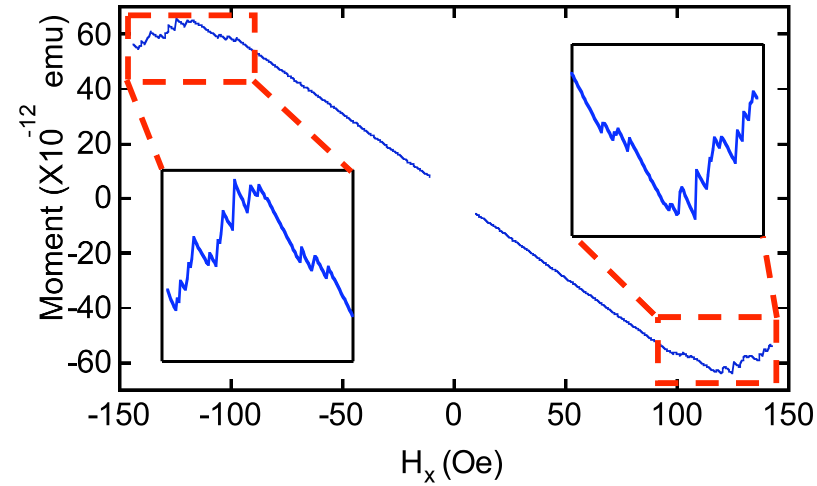
$$\lambda_{ab}(0) = 69\ nm$$

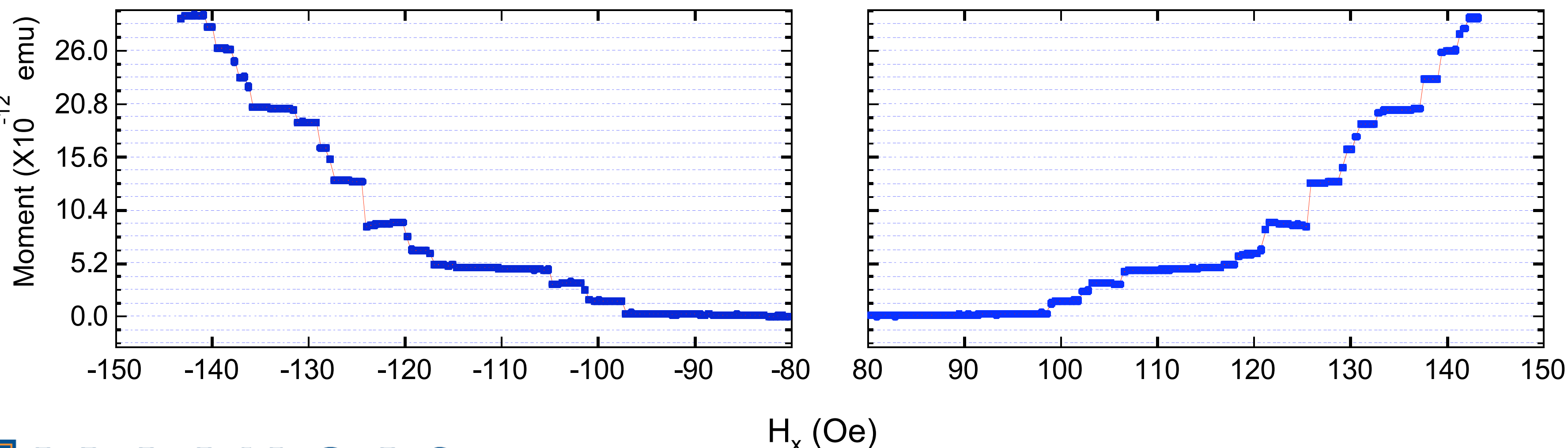


ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Vortex State in Mesoscopic $NbSe_2$ Samples

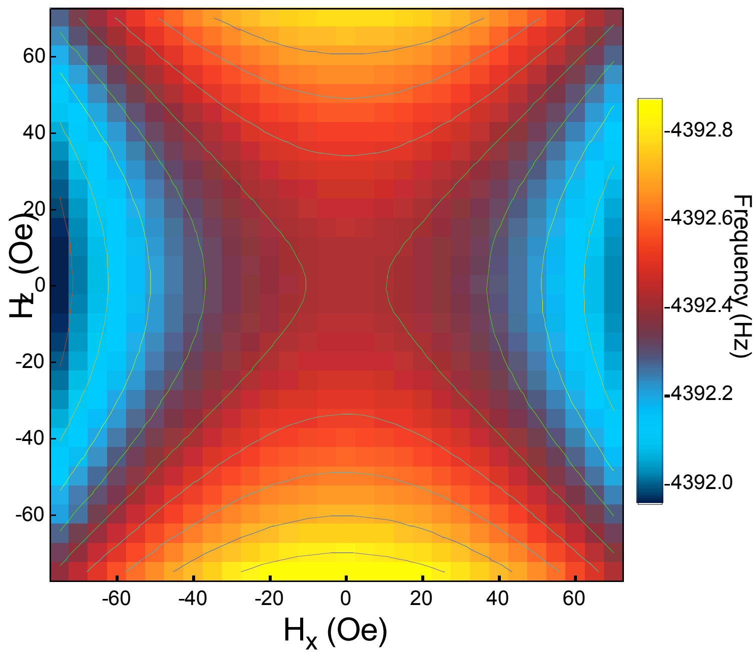


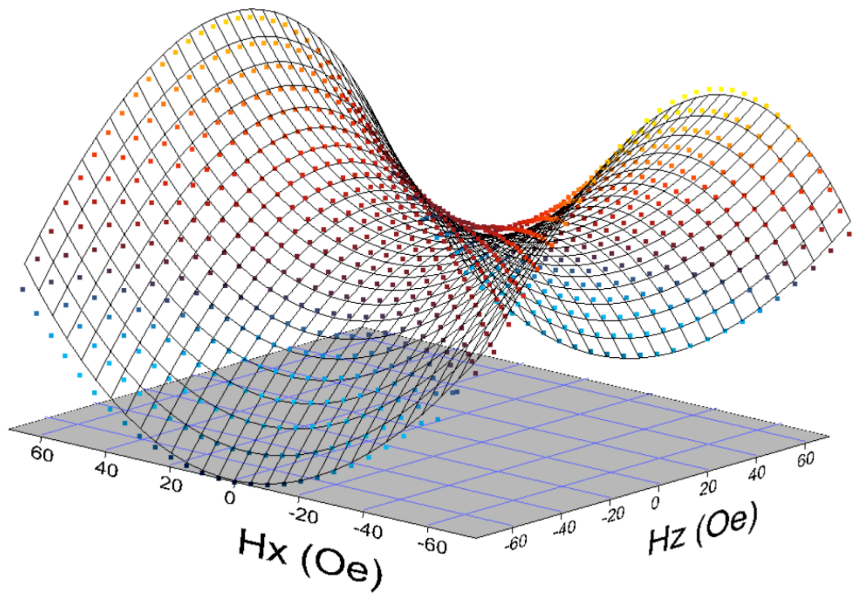




ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Diamagnetic Susceptibility of $NbSe_2$

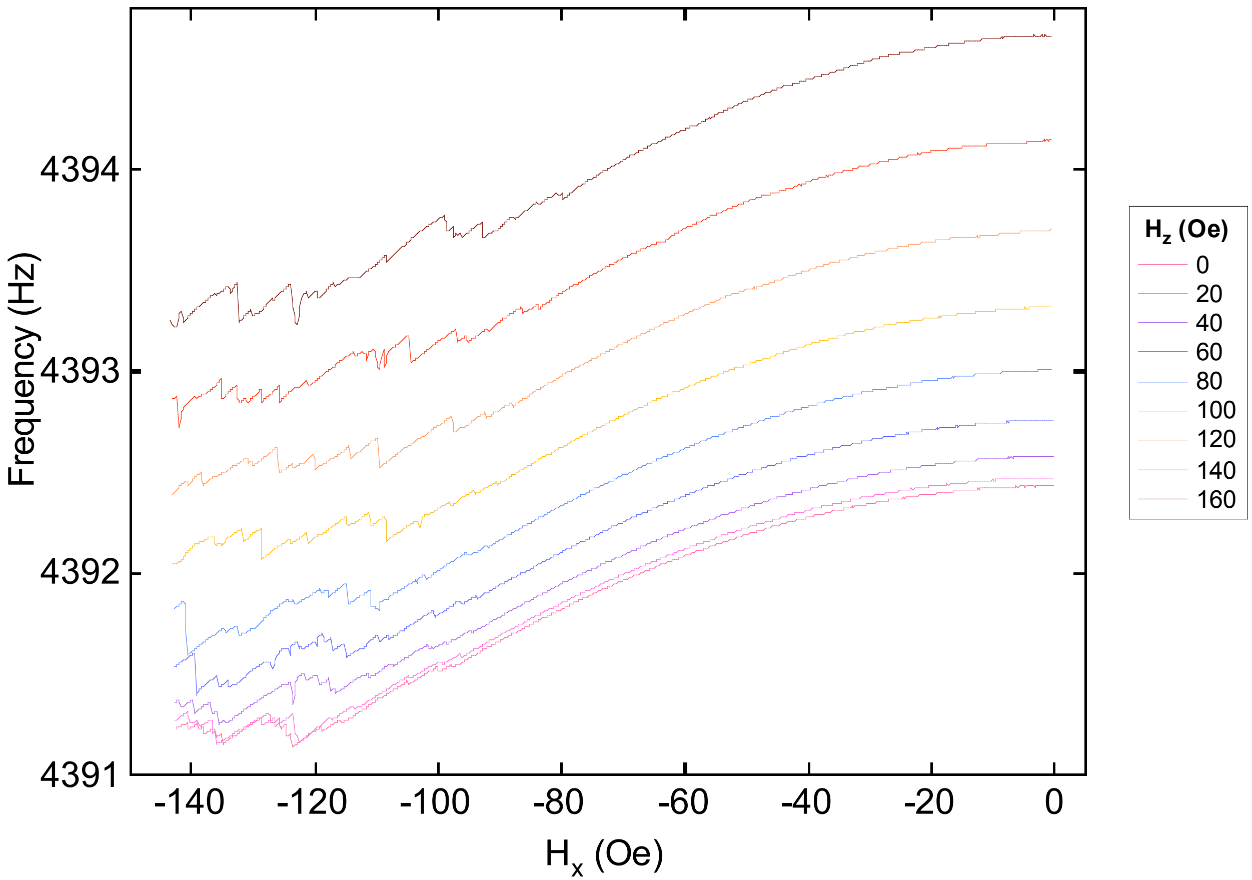




$$\Delta f = \frac{f_0}{2kl_{eff}^2}\Delta\chi\left(H_x^2 - H_z^2\right)$$

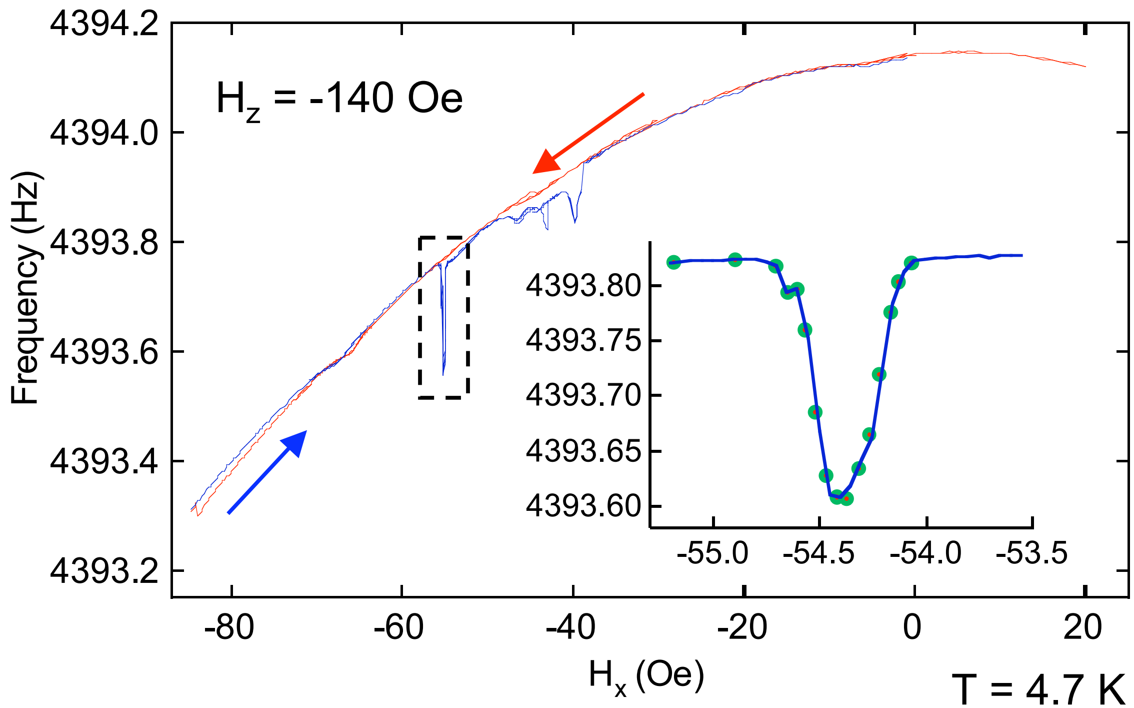
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

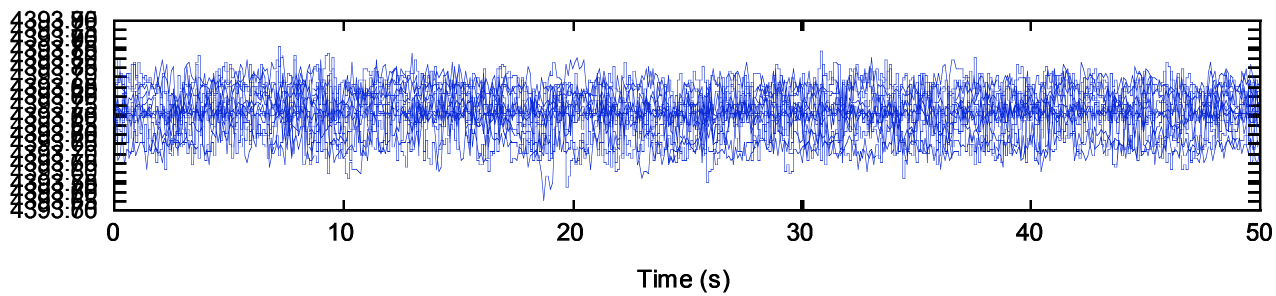
Response to ab-Plane Field



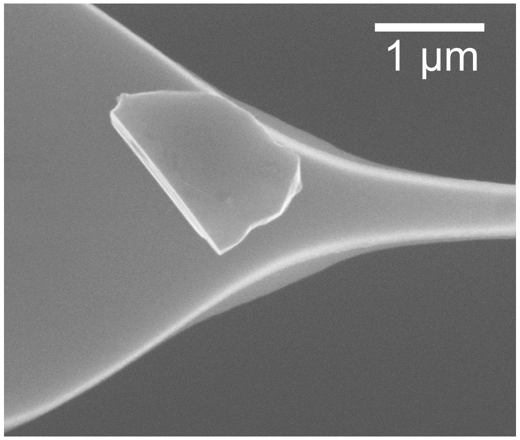
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

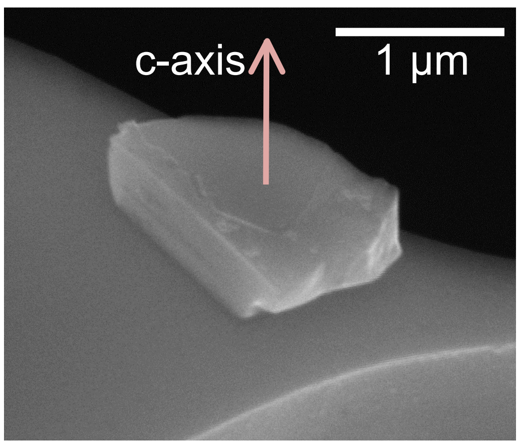
Switching Noise in Vortex Dynamics



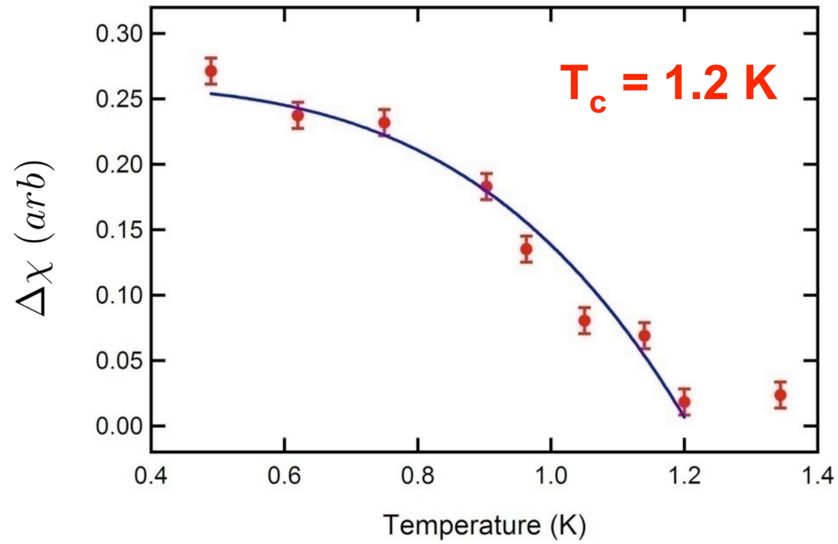


Torque Magnetometry of Micron-Size Sr_2RuO_4 Particles





Samples grown by Y. Maeno



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

Parameter		*ab*	*c*
$\mu_0 H_{c2\parallel c}(0)$ (T)	0.075		
$\mu_0 H_{c2\parallel ab}(0)$ (T)	1.50		
$\mu_0 H_c(0)$ (T)	0.023		
$\xi(0)$ (Å)		660	33
$\lambda(0)$ (Å)		1520	3.0×10^4
$\kappa(0)$		2.3	46
$\gamma_s = \xi_{ab}(0)/\xi_c(0)$	20		

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Zero-Field Magnetization Measruements

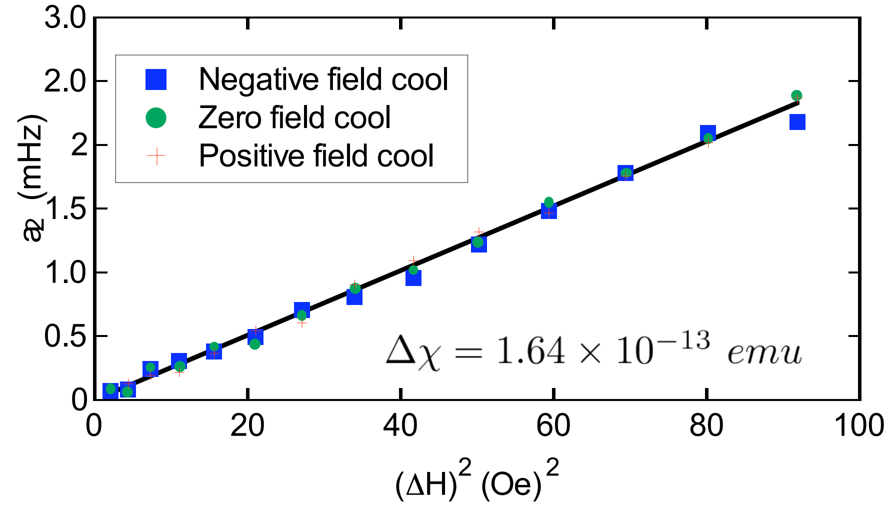
$$H_x = H_0 + \Delta H \ cos\left(\omega_m t\right)$$

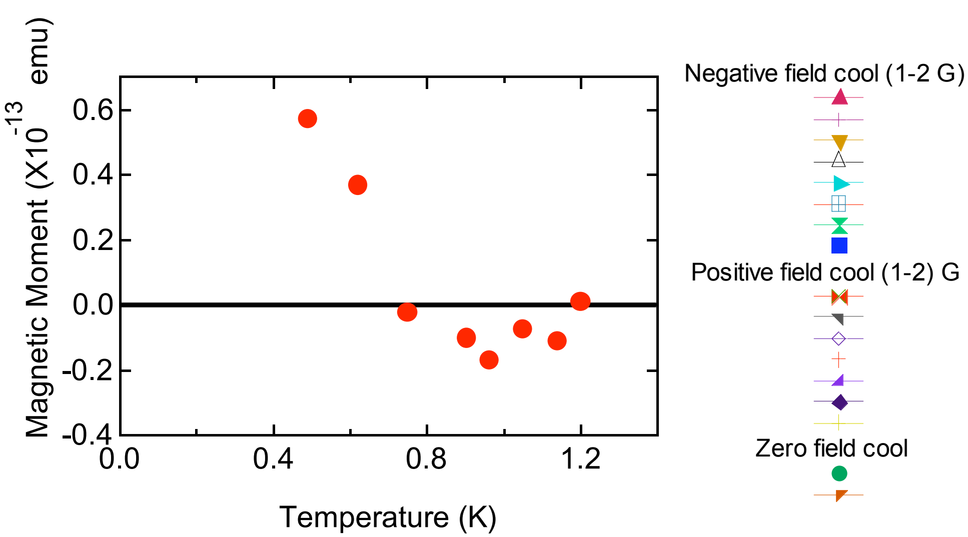
$$H_z = 0 \qquad H_x^{min} = 1.25 \ Oe$$

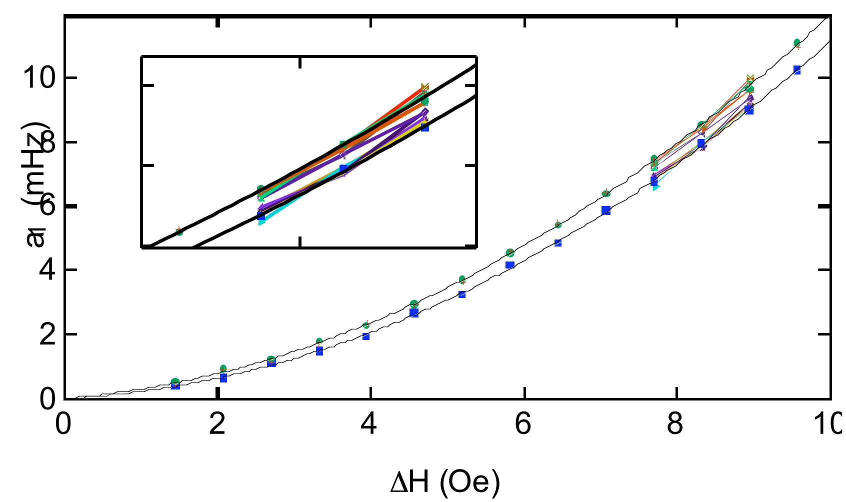
$$\Delta f = a_1 \ cos\left(\omega_m t\right) + a_2 \ cos\left(2\omega_m t\right) + const.$$

$$a_1 = \frac{f_0 \Delta H}{2kl_{eff}^2}\left(2H_0\Delta\chi + \mu_x\right)$$

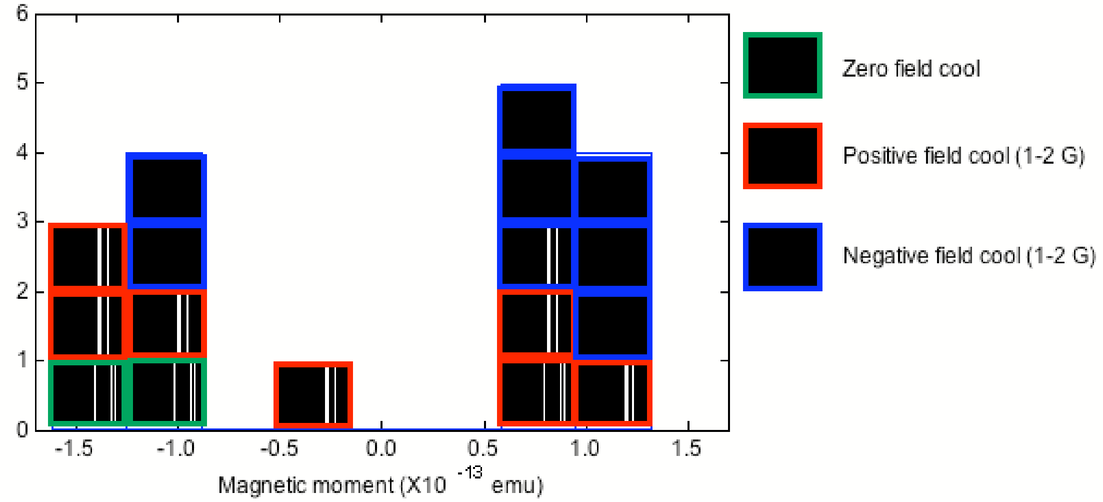
$$a_2 = \frac{f_0}{4kl_{eff}^2}\Delta\chi \ \left(\Delta H\right)^2$$



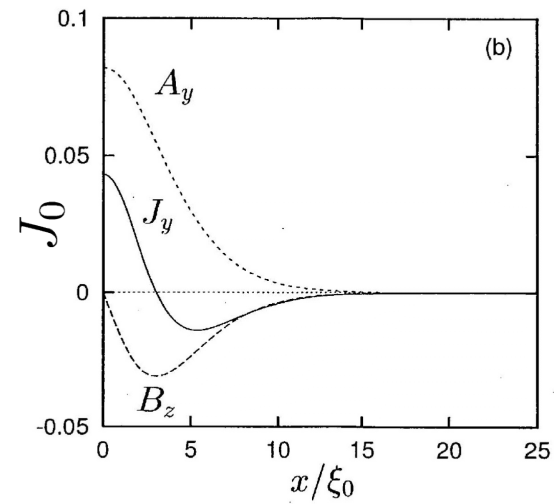




ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

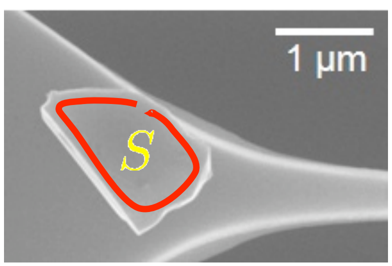


$$m_0 \approx (1.1 \pm 0.2) \times 10^{-13}\ emu$$



M. Matsumoto & M. Sigrist
J. Phys. Soc. Jpn. ***994*** *(1999)*

Assume the particle is a single chiral domain



perimeter: $S \approx 4\ \mu m$

thickness: $h = 440\ \mu m$

$$m_0 \approx (0.5 - 1.0) \times 10^{-13}\ emu$$

$\xi_0 = 66\ nm$

$v_F = 5.5 \times 10^4 m\ s^{-1}$

$N(E_F) = 4.36\ states/eV\ cell$

$T_c = 1.5\ K$

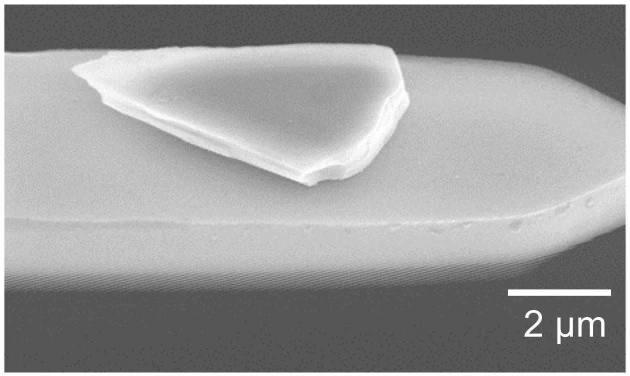
$J_0 = ev_F N(E_F) k_B T_c$

$J_0 = 2.6 \times 10^{10}\ A\ m^{-2}$

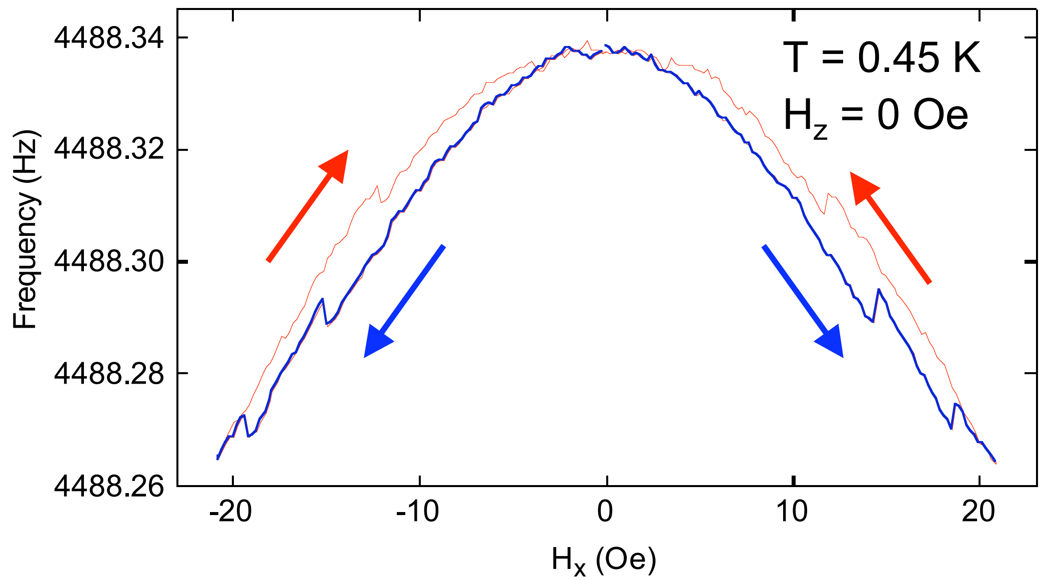
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

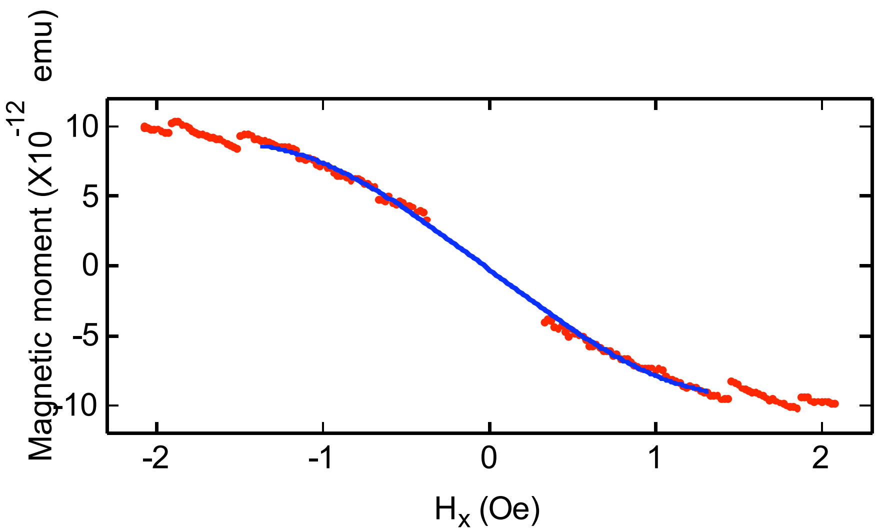
Diamagnetic Susceptibility Measurements in Sr_2RuO_4

Sr_2RuO_4



Particle dimensions: 3 µm × 4 µm × 0.5 µm



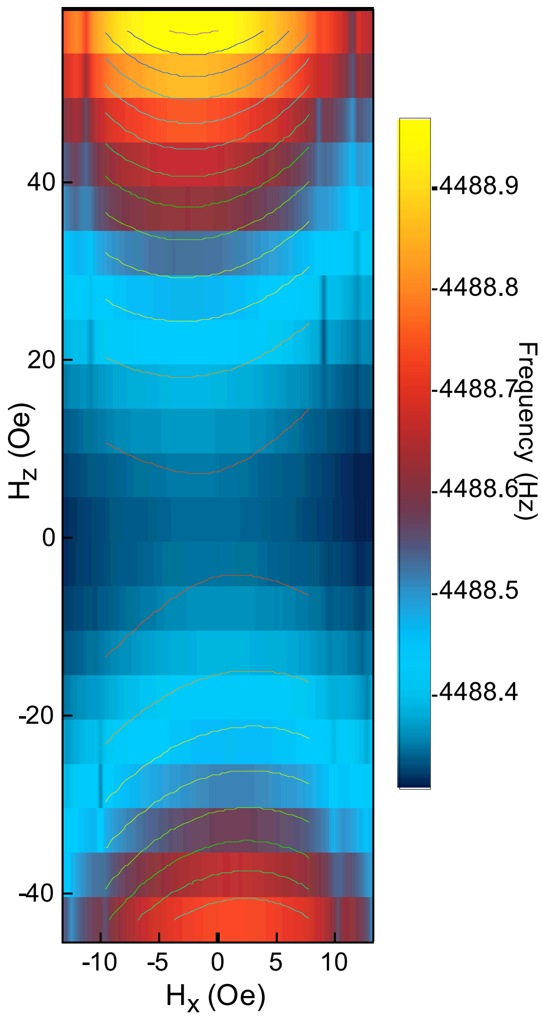


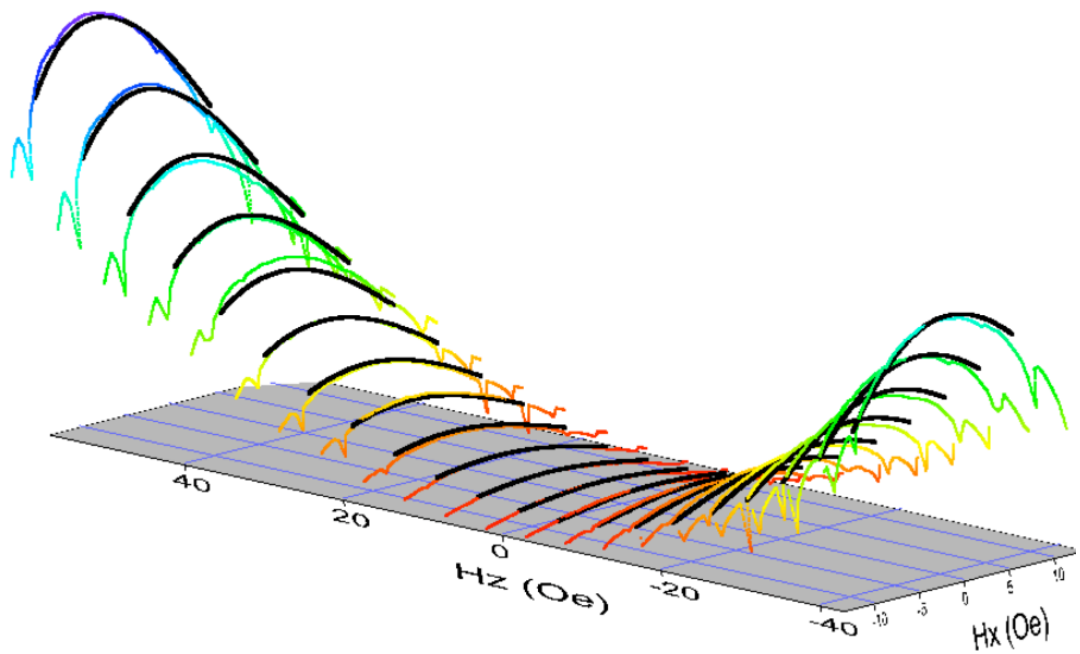
$$\Delta f \propto \Delta\chi_0 \left(1 - \frac{H_x^2}{H_0^2}\right) H_x^2$$

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

$$H_0 = 26.7\ Oe$$

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN





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

$$\Delta\chi_0 = -5.5 \times 10^{-13}\ emu$$

$$H_0 = 20.0\ Oe$$

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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 ?