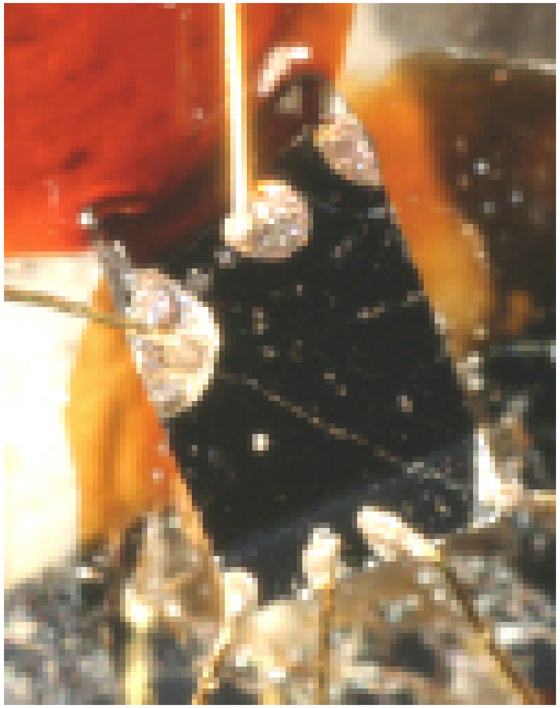
Sr_2RuO_4: Chiral p-wave superconductor?



Catherine Kallin, McMaster

- Brief introduction to p+ip SC
- Early evidence for p+ip
- More recent experiments probing TRSB or OP symmetry
- Putting it all together

SC discovered in SRO
by Maeno in 1994

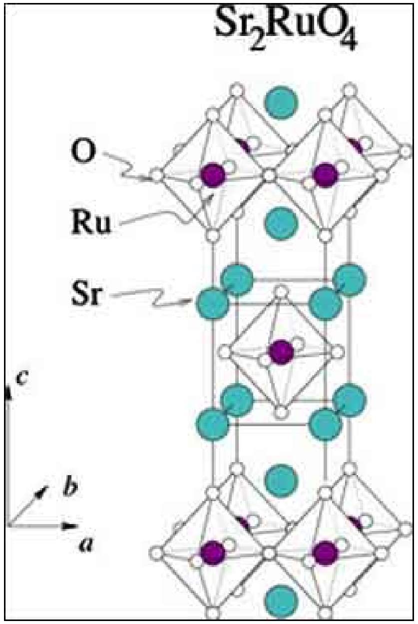
KITP, April 20, 2007

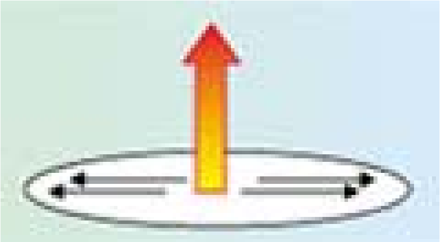
Brief introduction to p_x+ip_y SC

$$\Delta(\mathbf{k}) = i\{\mathbf{d}(\mathbf{k})\cdot\boldsymbol{\sigma}\}\sigma_y$$

[2x2 matrix in s,s'. Analogous to A phase of He-3]

$$\mathbf{d}(\mathbf{k}) = \Delta_0\hat{\mathbf{z}}(k_x \pm ik_y)$$
$$= \hat{\mathbf{z}}|\eta_0|(u,v)$$





d-vector aligned along c-axis due to spin-orbit coupling

k_x+ik_y degenerate with k_x-ik_y → can have domains

Defects and surfaces are pair-breaking, in general, because of p-symmetry, and this causes supercurrents to flow at surfaces, defects, and domain walls, due to the spatial variation of the 2-component order parameter.

Brief introduction to p_x+ip_y SC

Ginzburg-Landau Free energy:

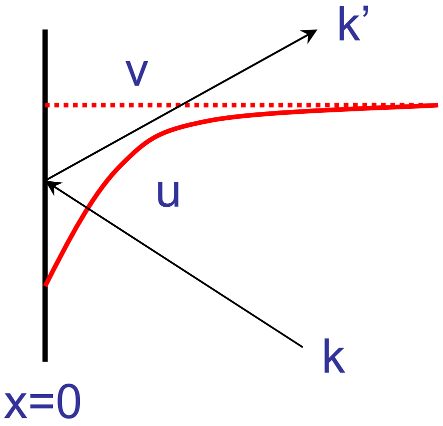
$$F=\frac{1}{4\pi}H_c^2\xi^3\int d^3r\Big[-\tfrac{1}{2}(|u|^2+|v|^2)+(\tfrac{1}{8}+\tfrac{1}{2}\tilde{\beta}_2)(|u|^2+|v|^2)^2+\tfrac{1}{2}\tilde{\beta}_2(u^*v-uv^*)^2$$

$$-\frac{\tilde{\beta}_3}{8}(|u|^2-|v|^2)^2+k_1(|d_xu|^2+|d_yv|^2)+k_2(|d_yu|^2+d_xv|^2)$$

$$+\tilde{k}[(d_xu)^*(d_yv)+(d_xv)^*(d_yu)+\text{c.c.}]+\Delta\tilde{k}[(d_xu)^*(d_yv)-(d_xv)^*(d_yu)+\text{c.c.}]$$

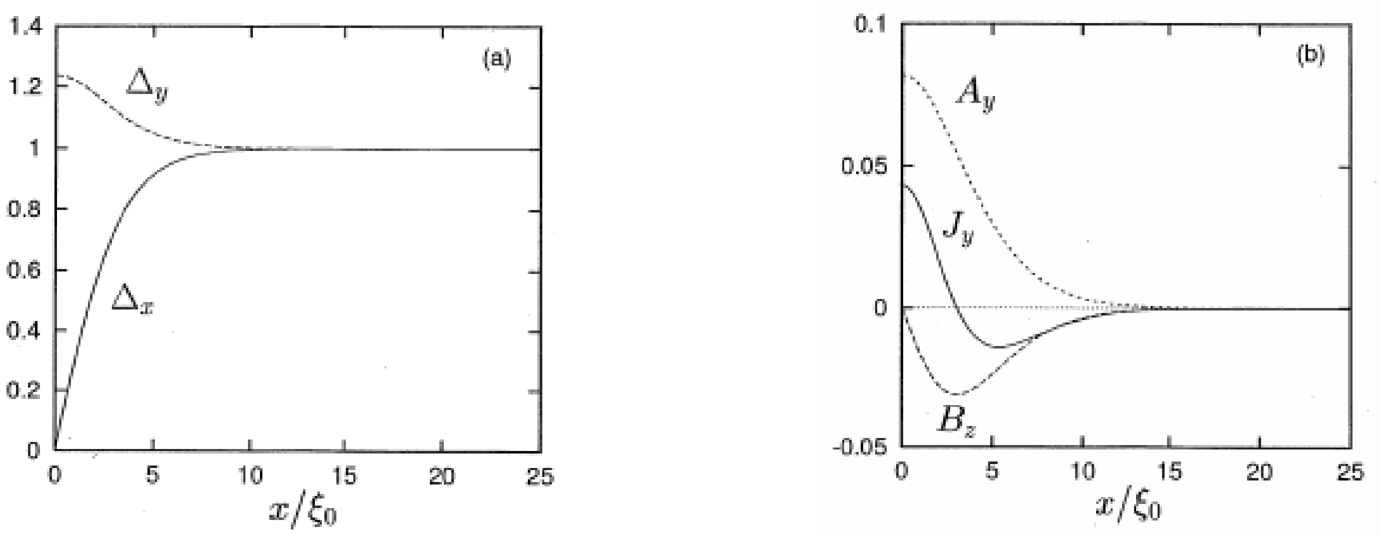
$$+k_5(|d_zu|^2+|d_zv|^2)+\kappa^2\mathbf{b}^2\Big],$$

This implies that a surface at x=0 will cause a supercurrent to flow along y.



$$j_y=\frac{1}{\kappa^2}\mathrm{Im}[k_2u^*\partial_yu+k_1v^*\partial_yv+\tilde{k}(u^*\partial_xv+v^*\partial_xu)$$

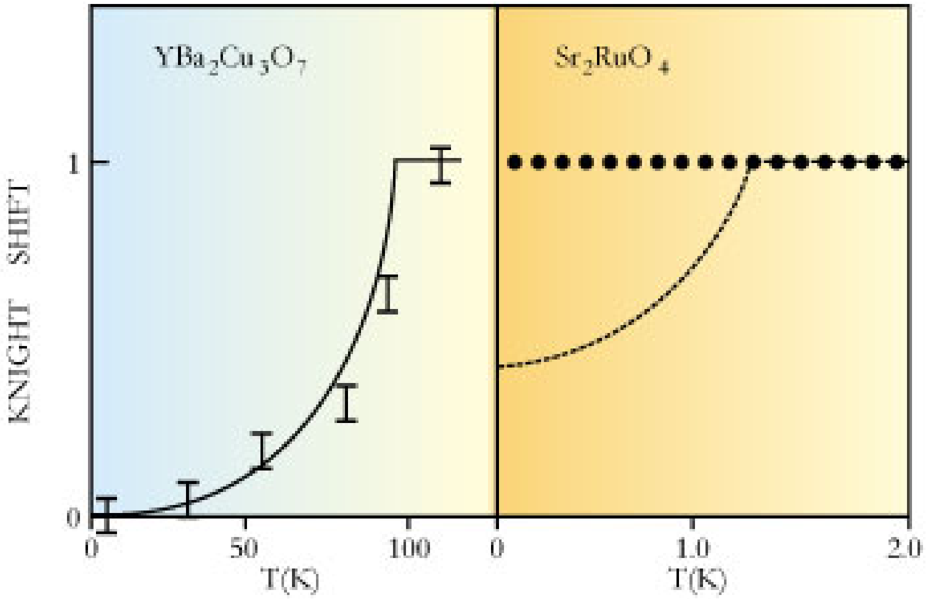
$$-\Delta\tilde{k}(u^*\partial_xv-v^*\partial_xu)]\quad-\frac{1}{\kappa^2}\mathrm{Re}[(k_1|v|^2+k_2|u|^2)a_y+\tilde{k}u^*va_x].$$



Matsumoto and Sigrist, J. Phys. Soc. Jap. 68, 994 (1999).

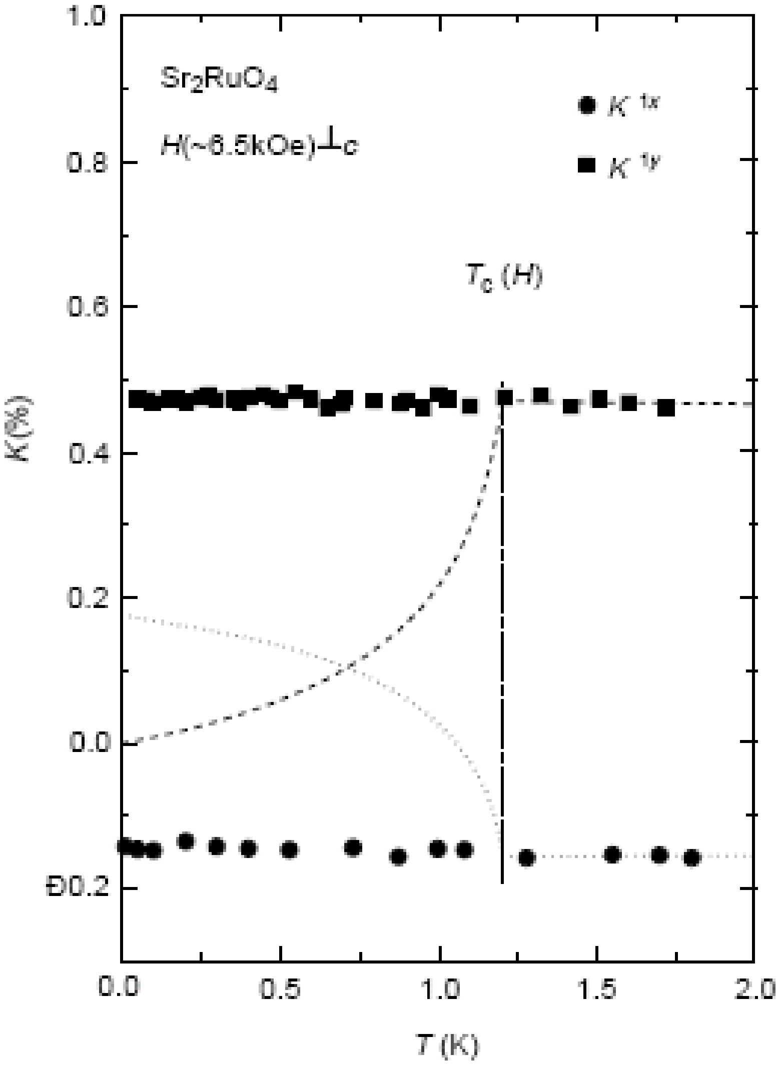
Domain wall similar to two edges put together, with opposite sign field on each side and a current flowing along domain wall with compensating currents on each side. In this case, the field maximum is ~20 G (whereas the maximum field at an edge is ~10 G).

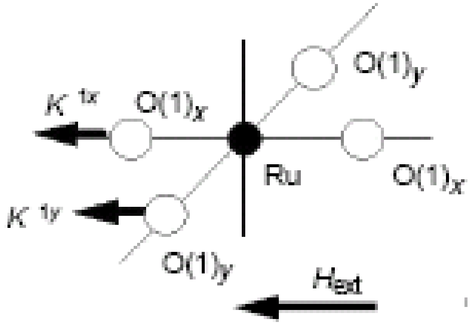
Early evidence for p+ip SC



- Sensitivity of Tc to disorder → not s-wave pairing
- Knight shift → triplet pairing
- p-wave symmetry most likely

The Knight shift for oxygen-17 in YBCO (left) and SRO (right). For spin-singlet Cooper pairing, Knight-shift data exhibit a drop in the spin susceptibility in the superconducting state. Such a drop occurs in YBa2Cu3O7, but not in Sr2RuO4, whose superconductivity is most likely mediated by spin-triplet Cooper pairs. From K. Ishida et al., *Nature* **396**, 658 (1998).

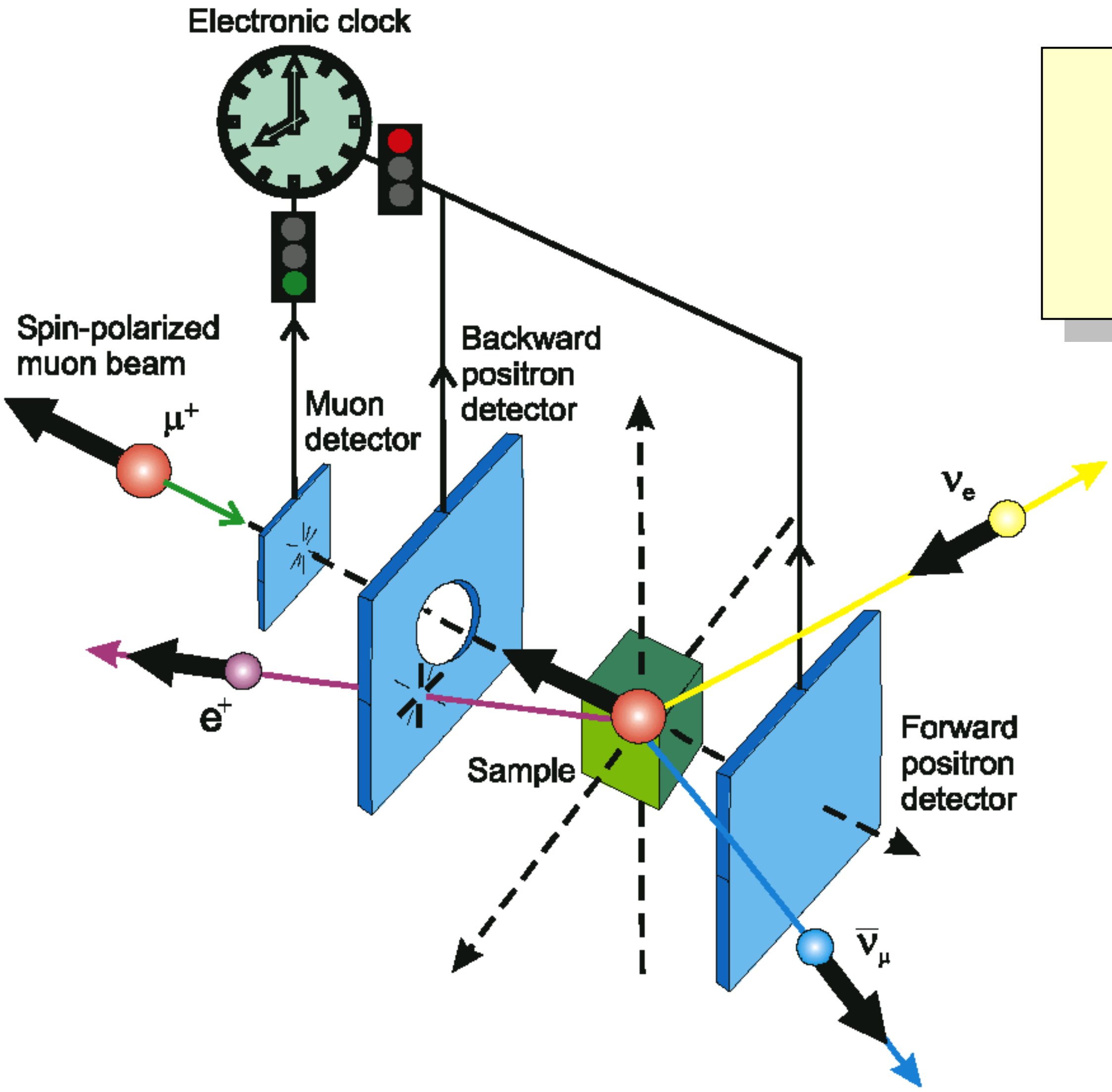




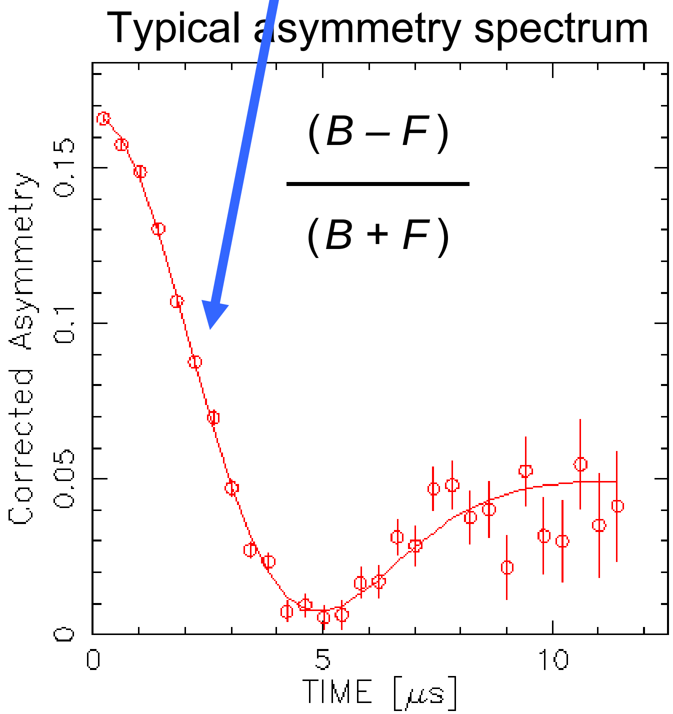
Actual data from Ishida et al. Nature (1998).

More recent NMR data less clear.

Zero Field (ZF)-μSR



Kubo-Toyabe lineshape due to dense array of local moments (nuclear spins)



$$\frac{(B-F)}{(B+F)}$$

Sr_2RuO_4 ZF-μSR

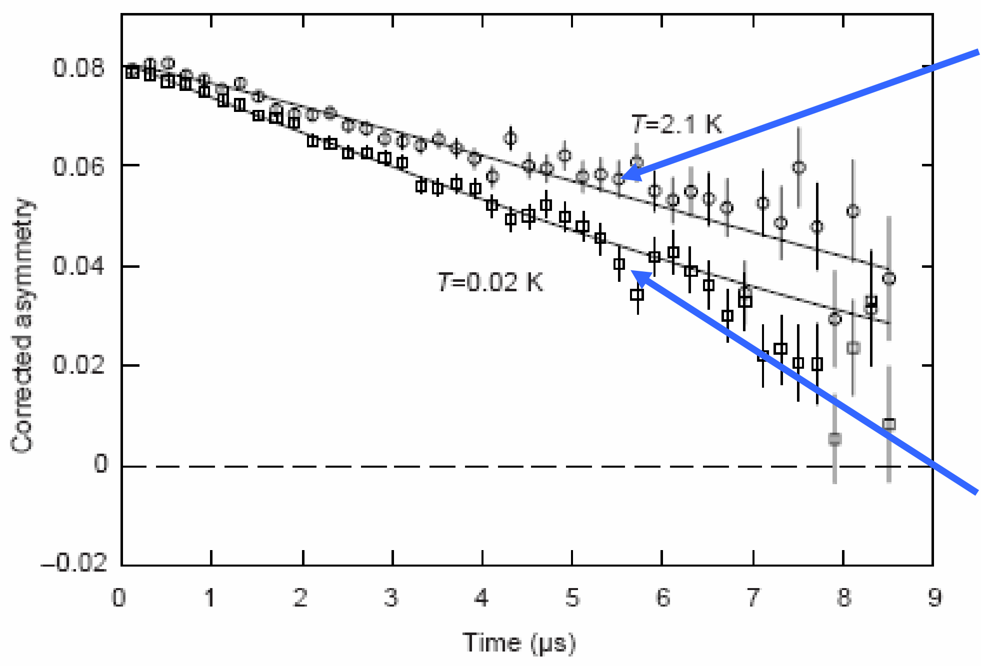


Figure 1 Zero-field μSR spectra measured with $P_\mu \perp c$ in Sr_2RuO_4 at $T = 2.1$ K (circles) and $T = 0.02$ K (squares). Curves are fits to the product of equation (1) and $\exp(-\Lambda t)$ as described in the text.

Decay for T > Tc: $K(t)e^{-\Lambda t}$

Kubo-Toyabe

dilute fields: Λ(T)

Decay for T < Tc: $K(t)e^{-\Lambda t}$

G. M. Luke[*], Y. Fudamoto[*], K. M. Kojima[*], M. I. Larkin[*], J. Merrin[*], B. Nachumi[*], Y. J. Uemura[*], Y. Maeno[†], Z. Q. Mao[†], Y. Mori[†], H. Nakamura[‡] & M. Sigrist[§]

Nature 394, 558 (1998).

Sr_2RuO_4 ZF-μSR Decay Rate vs. T

Fields in ab plane

Λ vs T for $P_\mu \parallel c$

Λ vs T for $P_\mu \perp c$

Shows fields << 50G. Characteristic field ~ 0.5G

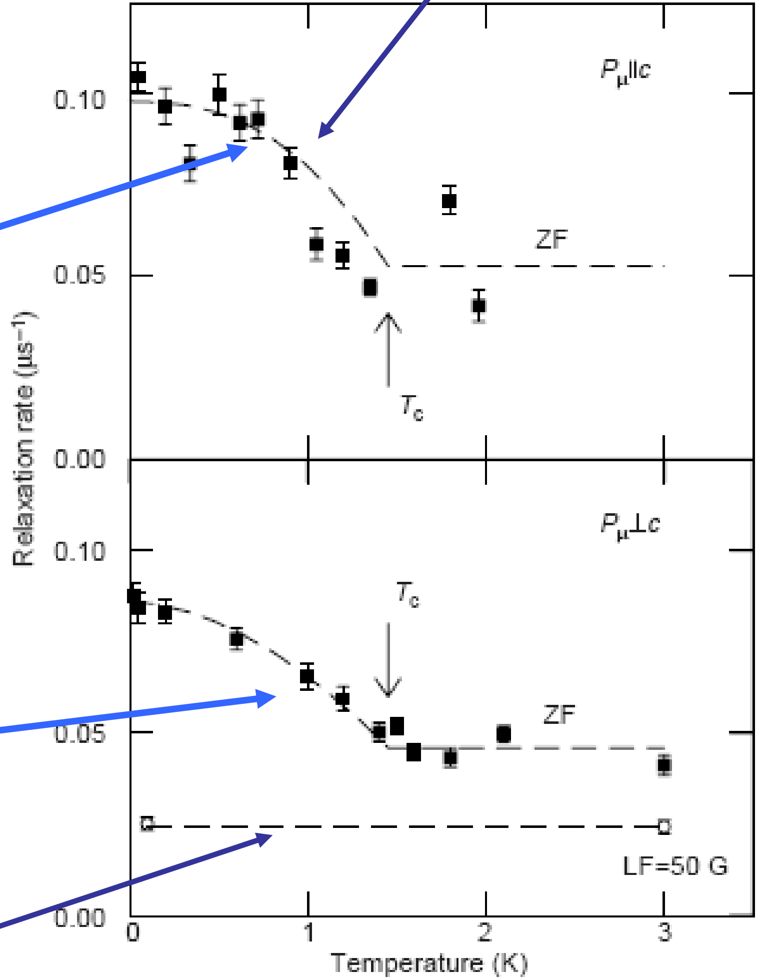


Figure 2 Zero-field (ZF) relaxation rate Λ for the initial muon spin polarization ∥c (top) and ⊥c (bottom). T_c from a.c.-susceptibility indicated by arrows. Circles in bottom figure give relaxation rate in $B_{LF} = 50\,G \perp c$. Curves are guides to the eye.

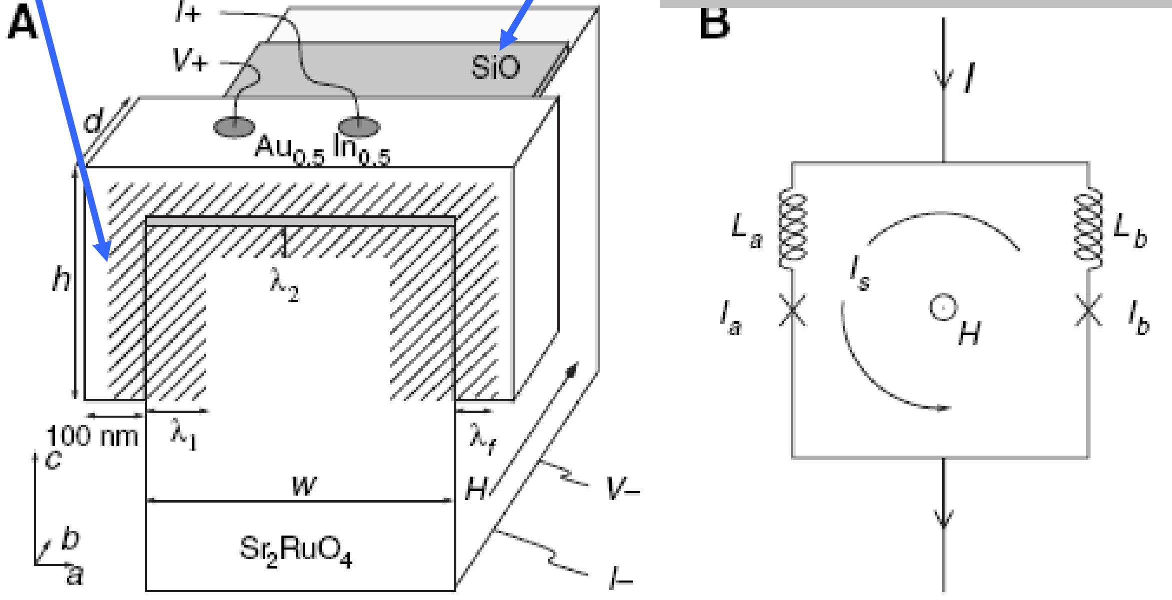
Phase sensitive measurements

AuIn-Sr_2RuO_4 SQUID – Nelson et al, Science (2004)

S-Wave Superconductor

Insulating layer

Equivalent Circuit



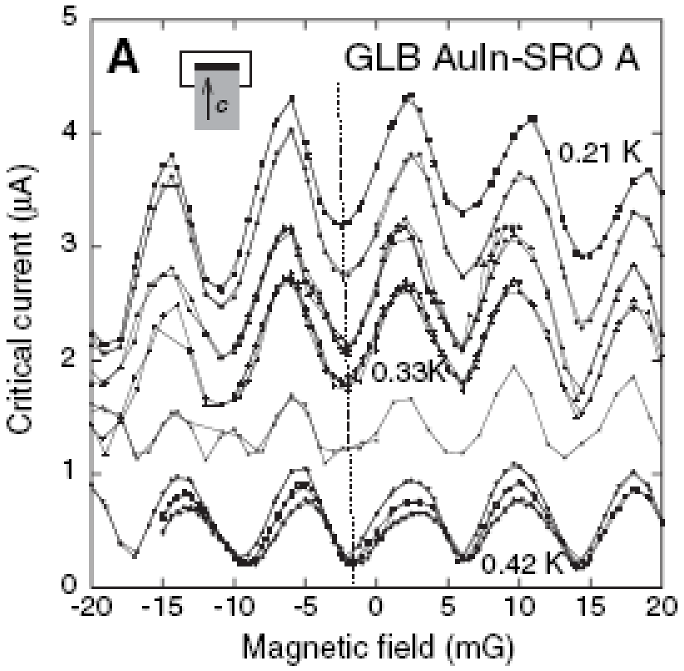
GLB
geometry

Tunneling from singlet to triplet allowed by spin-orbit coupling Geshkenbein, Larkin, Barone (GLB) geometry

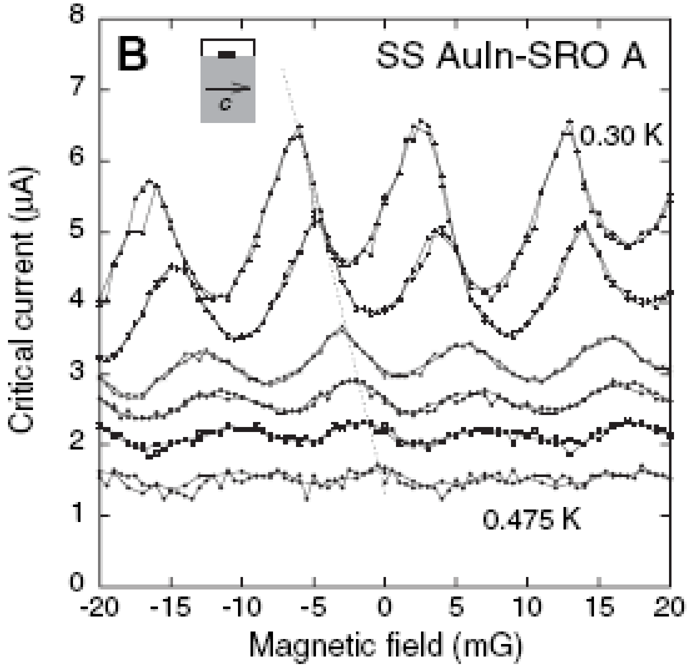
$$j_s \propto \langle \mathrm{Re}(c_{21}s_{21}^{*})\ \mathrm{Im}[\Psi^{*}\mathbf{d}\cdot(\mathbf{n}\times\mathbf{k})]\rangle_{\mathrm{FS}}$$

Phase ~ **d·(n x k)**
gives π for opposite b-c faces (GLB)
and zero for same b-c faces (SS)

GLB Geometry



SS geometry



Dashed lines show zero field corrected for induced flux which varies with T

Polar Kerr effect

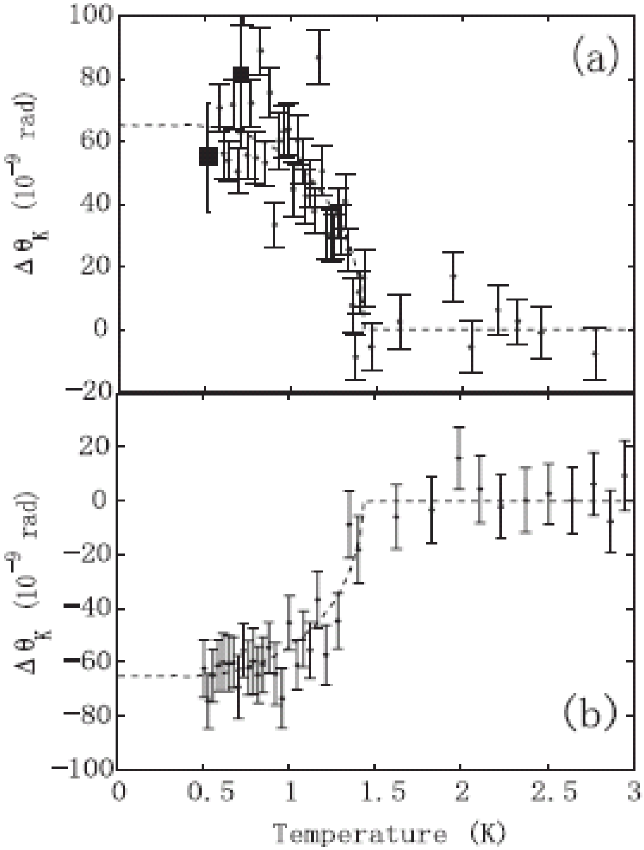
$$\theta_K \propto \sigma''_{xy}(\Omega)$$

From V.M. Yakovenko, PRL (2007):

$$\sigma''_{xy}(\Omega) = \frac{e^2}{2\hbar}\left(\frac{\Delta_0}{\hbar\Omega}\right)^2$$

→230 nanorads

BUT neglected supercurrent which exactly cancels this term!



Cooled in (a) 93 G (b) -43 G

J. Xia, Y. Maeno, P.T. Beyersdorf, M.M. Fejer, A. Kapitulnik, PRL 97, 167002 (2006).

Scanning SQUID microscopy: search for edge and domain currents

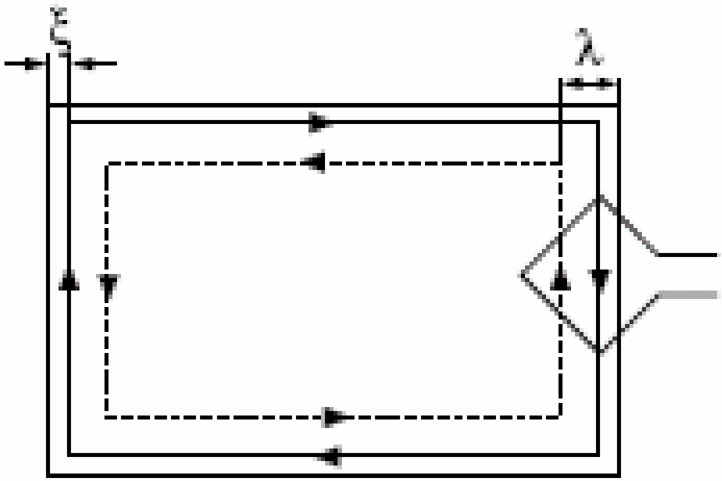
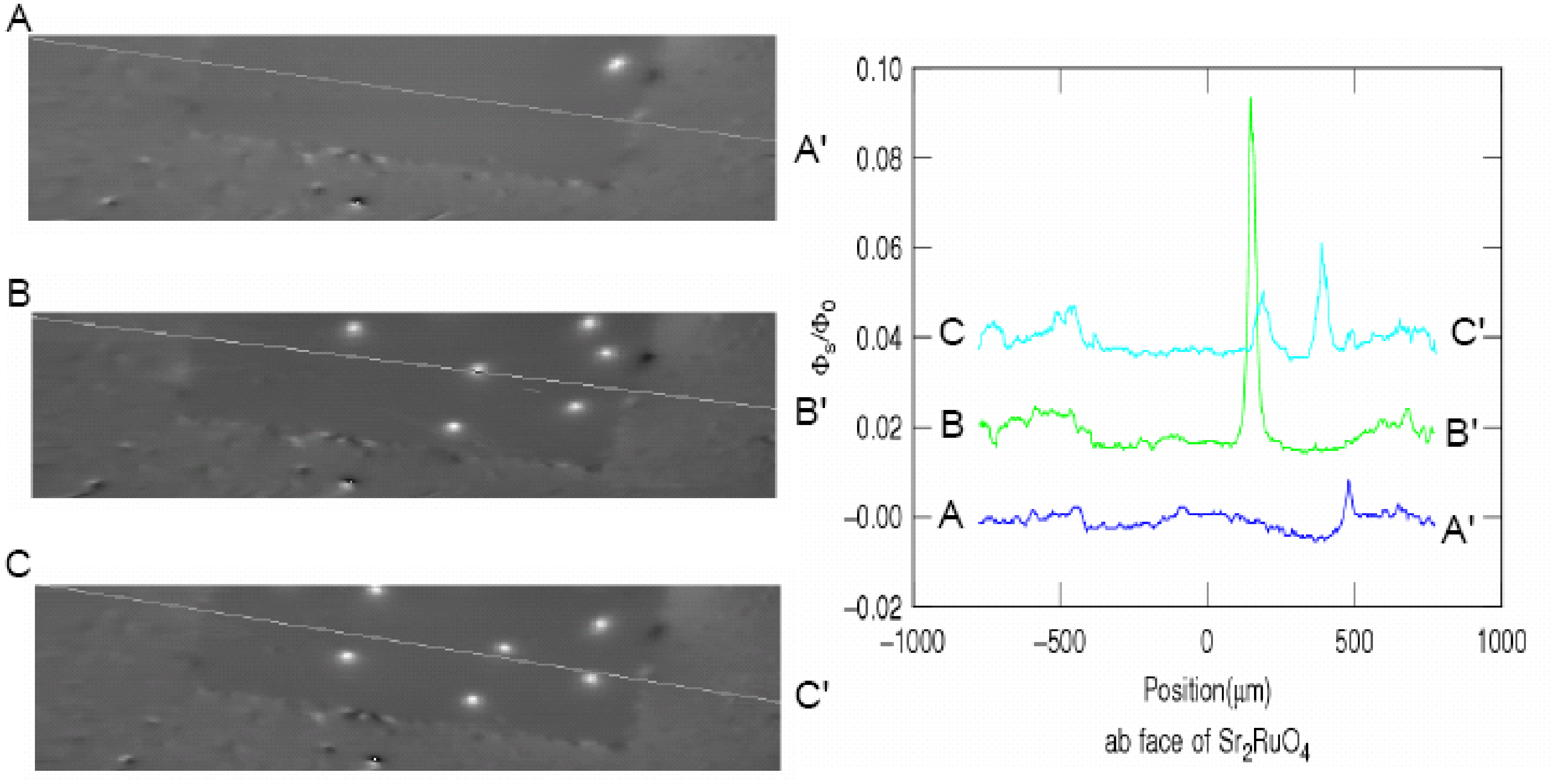


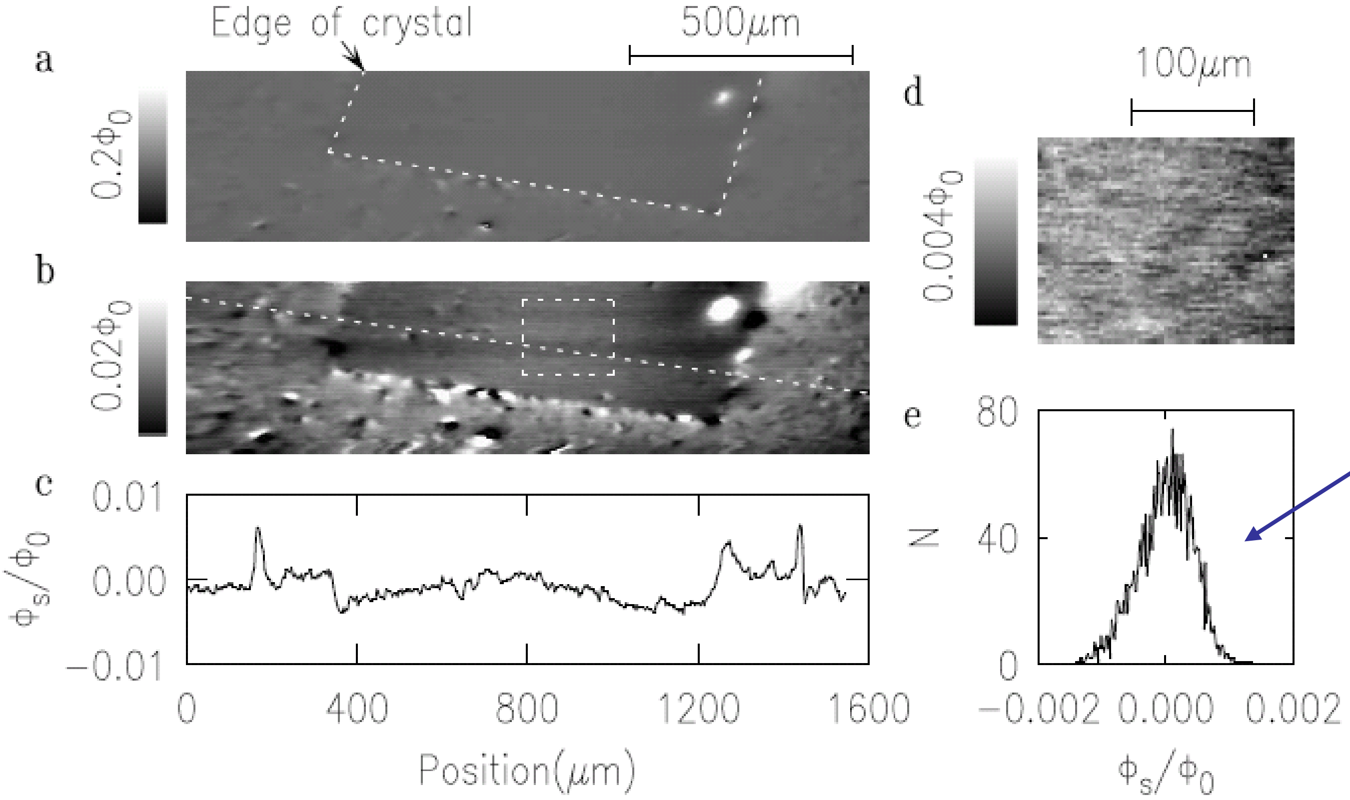
Fig. 5. Electric currents (solid lines) of the chiral edge states along the inner and outer edges of Sr_2RuO_4. The dashed lines show superfluid counterflow. The rectangular coil on the right represents a SQUID pickup loop.

Scanning SQUID microscopy: search for edge and domain currents

J.R. Kirtley, C. Kallin, C. Hicks, E.A. Kim, Y. Liu, K.A. Moler, Y. Maeno (preprint).

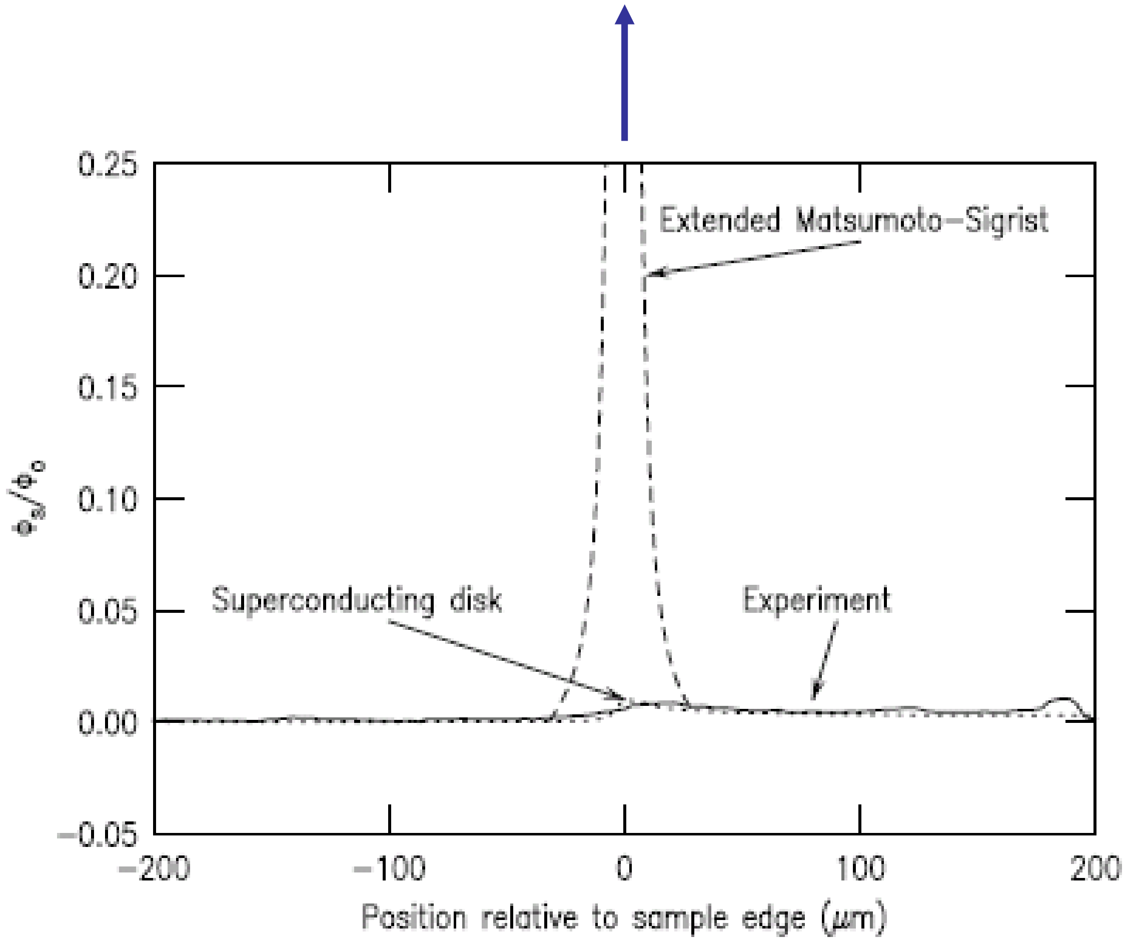


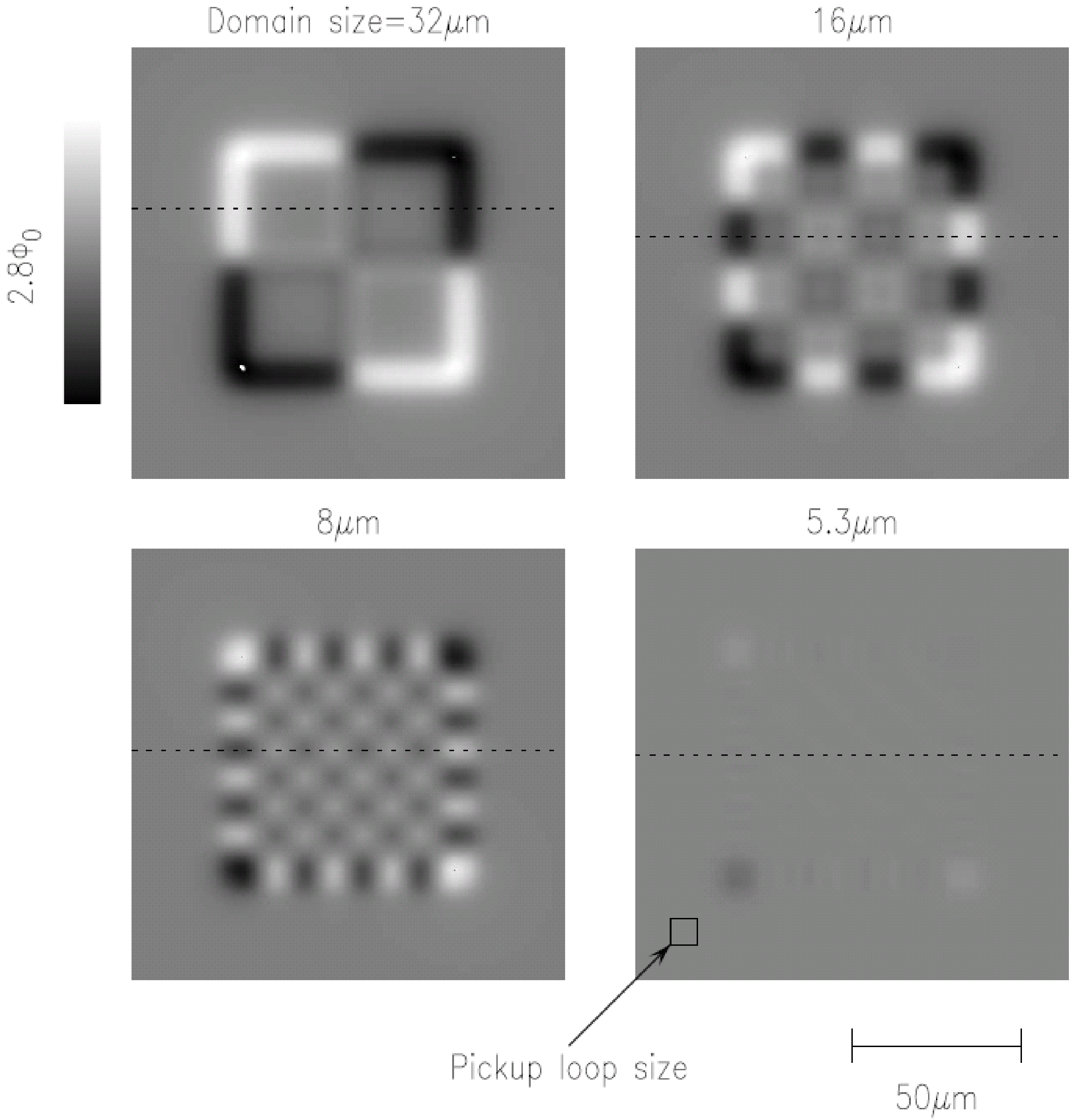
ab face of Sr_2RuO_4



Flux distribution in highlighted square

goes to 1


0.25
0.20
0.15
0.10
0.05
0.00
−0.05
Φ_s/Φ_0
Extended Matsumoto−Sigrist
Superconducting disk
Experiment
−200
−100
0
100
200
Position relative to sample edge (μm)


Domain size=32μm
16μm
8μm
5.3μm
2.8Φ0
Pickup loop size
50μm

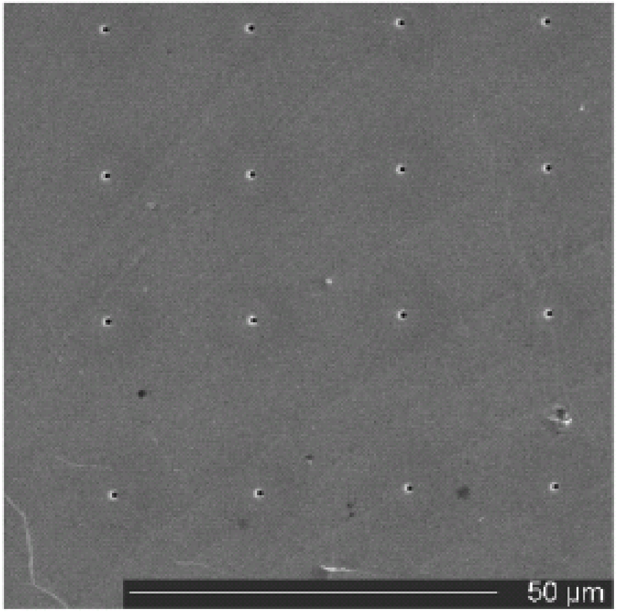


FIG. 1. A SEM image of the Sr_2RuO_4 crystal used for the Hall probe imaging. An array of holes was milled in the sample using a FIB. The hole spacing is 20 μm.

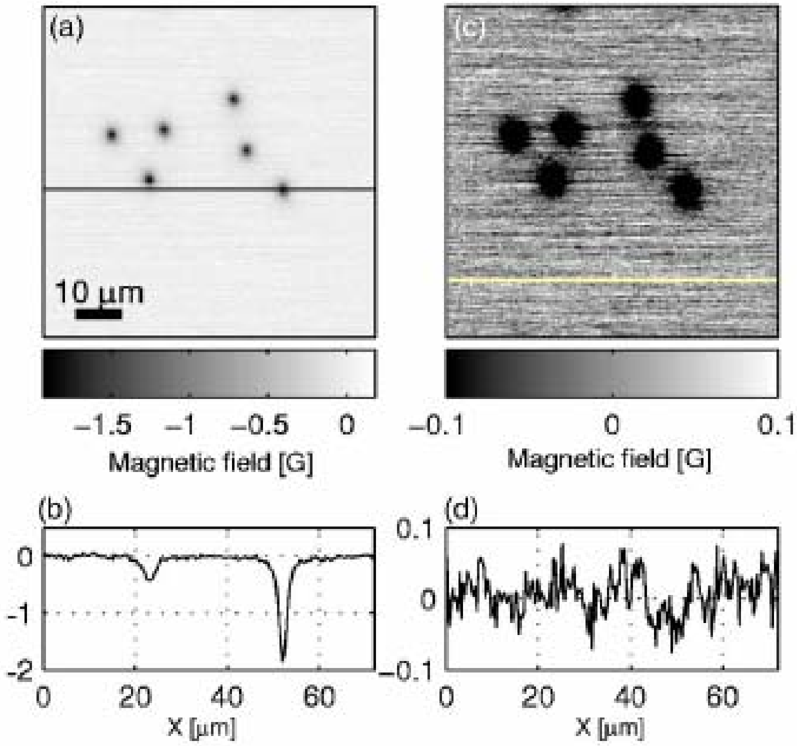
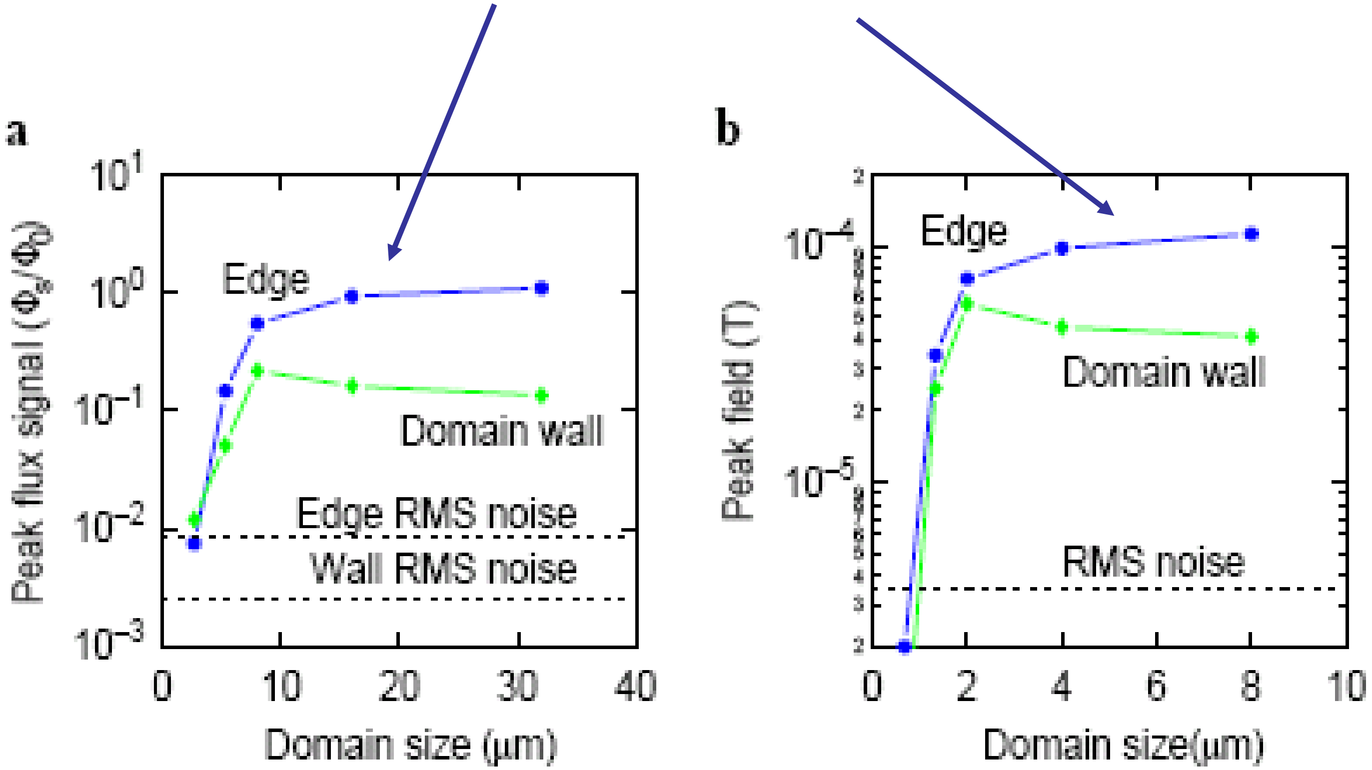


FIG. 2. (Color online) Scanning Hall probe image at $T=100$ mK of the sample shown in Fig. 1, cooled in a background field of ~25 mG. The background has been line normalized to remove $1/f$ noise. (a) Image with a color scale showing the full measured magnetic field range. Isolated trapped vortices dominate the image. (b) Cross section taken along the darkened line in (a). (c) Image with an expanded color scale, showing that there are no obvious features in the noise. (d) Cross section taken along the lightened line in (c).

Scanning Hall probe measurements (K.A. Moler's group)

Predicted signals from Matsumoto & Sigrist plus modelling for expt. setup



8µm SQUID pickup loop z=3µm

0.5µm Hall bar z=1.2µm

Latest phase-sensitive measurements

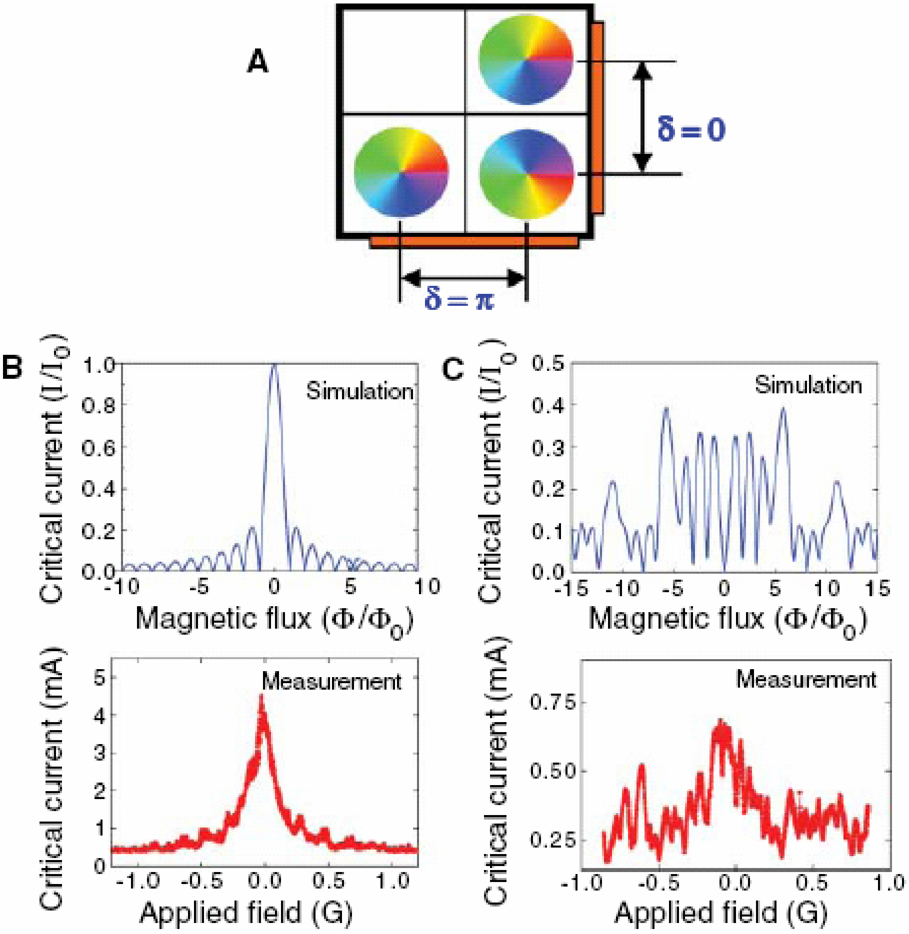
SRO single crystal (black) with 4 Josephson junctions. Gray ribbons are Pb thin film counterelectrodes. A field B is applied along c-axis.

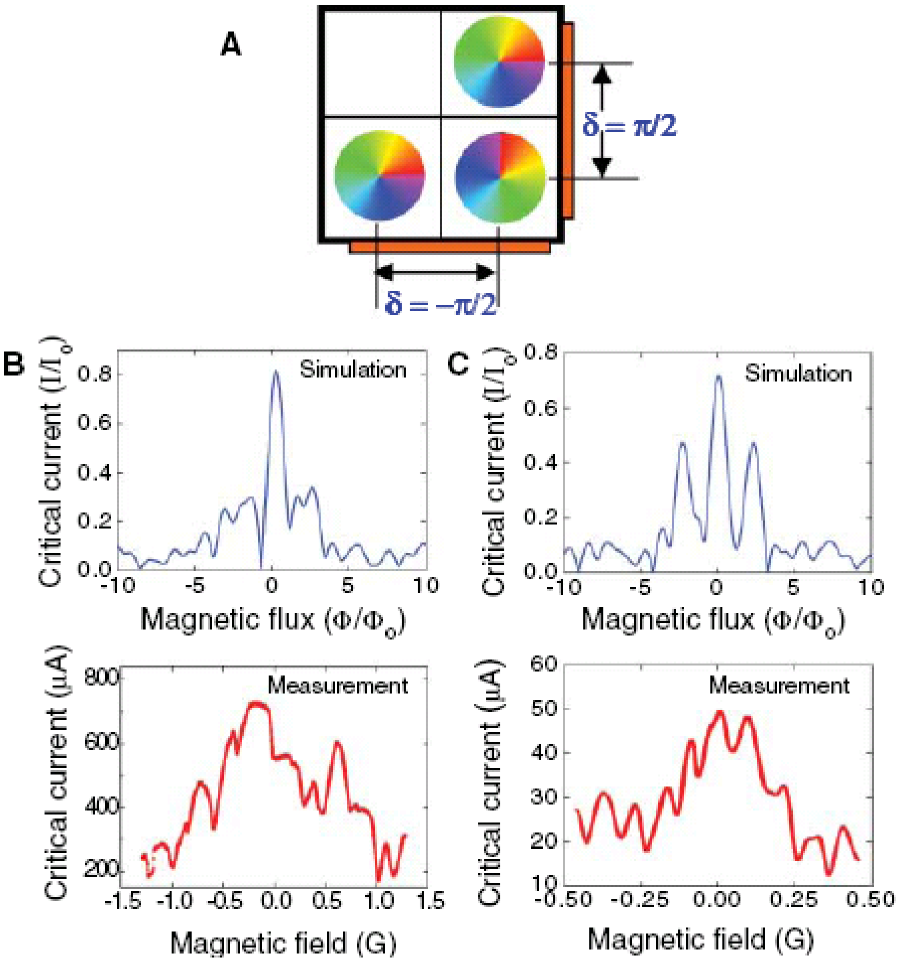
Ideal junction of area A gives Fraunhofer pattern:

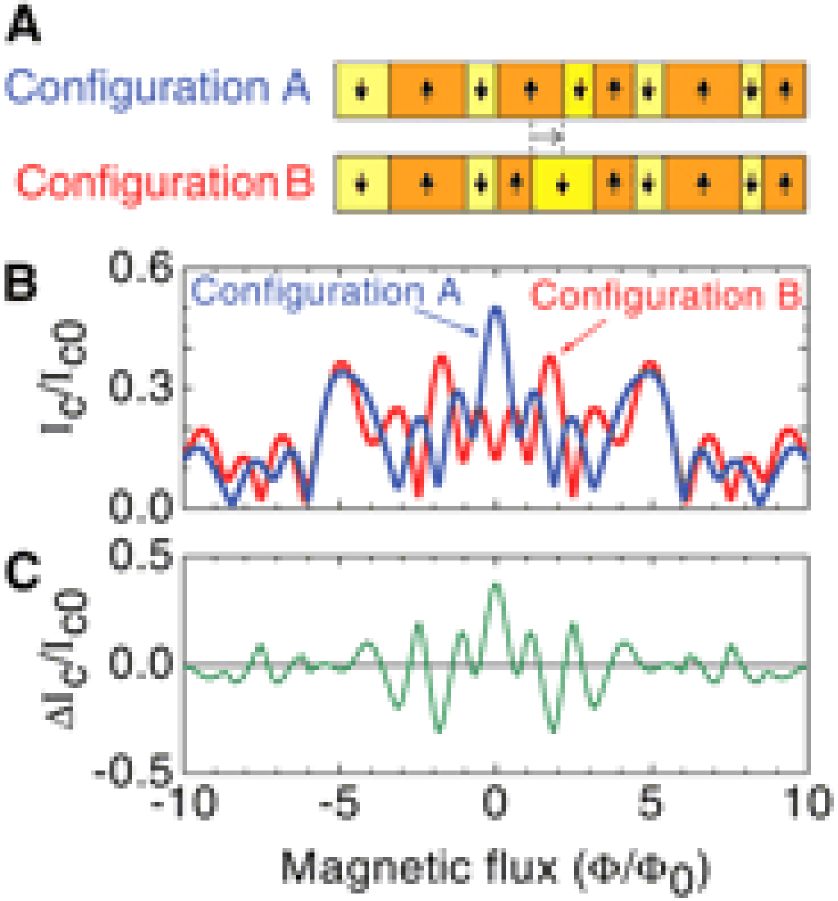
$$I_c(\Phi) = J_c A \frac{\sin(\pi\Phi/\Phi_0)}{\pi\Phi/\Phi_0}$$

Observe “Fraunhofer-type patterns” which they compare to currents expected from domains of $p_x \pm ip_y$, $p_y \pm ip_x$. They conclude one needs all four types of domains to best model the data. Also see dynamics, which they model as dynamic domains with average size of ~1 micron.

F. Kidwingira, J.D. Strand, D.J. Van Harlingen, and Y. Maeno, Science 314, 1271 (2006).


A
δ = 0
δ = π
B
Simulation
Critical current (I/I$_0$)
Magnetic flux (Φ/Φ$_0$)
1.0
0.8
0.6
0.4
0.2
0.0
-10
-5
0
5
10
Measurement
Critical current (mA)
Applied field (G)
5
4
3
2
1
0
-1.0
-0.5
0.0
0.5
1.0
C
Simulation
Critical current (I/I$_0$)
Magnetic flux (Φ/Φ$_0$)
0.5
0.4
0.3
0.2
0.1
0.0
-15
-10
-5
0
5
10
15
Measurement
Critical current (mA)
Applied field (G)
0.75
0.50
0.25
-1.0
-0.5
0.0
0.5
1.0


A
δ = π/2
δ = −π/2
B
Simulation
Critical current (I/I$_0$)
Magnetic flux (Φ/Φ$_0$)
0.8
0.6
0.4
0.2
0.0
-10
-5
0
5
10
Measurement
Critical current (μA)
Magnetic field (G)
800
600
400
200
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
C
Simulation
Critical current (I/I$_0$)
Magnetic flux (Φ/Φ$_0$)
0.8
0.6
0.4
0.2
0.0
-10
-5
0
5
10
Measurement
Critical current (μA)
Magnetic field (G)
60
50
40
30
20
10
-0.50
-0.25
0.00
0.25
0.50



Observed “complicated modulations characteristic of interference between regions with different phase and size, distinctly different behavior in different crystals and even in different junctions on the same crystal, asymmetry with respect to field direction, abrupt jumps in the critical current, telegraph switching noise.”

Argue that this is captured in the modeling of dynamic p±ip domains.

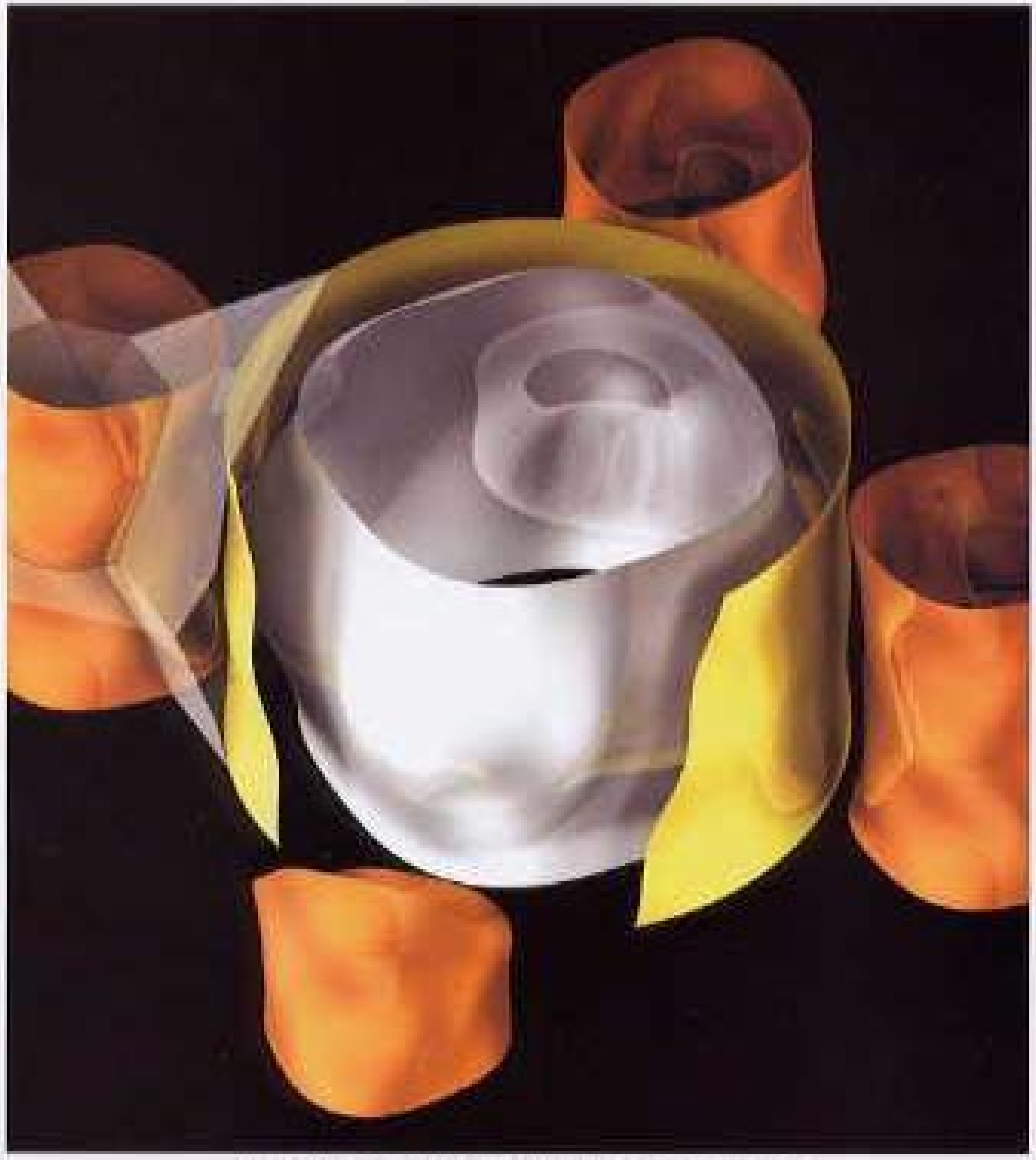
F. Kidwingira, J.D. Strand, D.J. Van Harlingen, and Y. Maeno, Science 314, 1271 (2006).

Putting it all together

- SRO is an unconventional SC
- Probably triplet pairing, but even this is not certain
- Evidence for TRSB from muSR, polar Kerr effect, but neither is explained by simple p_x+ip_y
- No evidence of spontaneous supercurrents at edges or domain boundaries → problematic for TRSB SC
- One JJ experiment points to odd-parity (e.g. p-wave) and another is interpreted in terms of $k_x \pm ik_y$ and $k_y \pm ik_x$ domains.

- EXPERIMENT: slow muons or beta-NMR to look for edge currents; more detailed muSR; smaller SQUID/Hall bar probe
- THEORY: polar Kerr effect needs explanation, analyze existing data for other possible order parameters, proposals for more definitive experiments; may need to deal with 3 Fermi surfaces, crystal anisotropy and c-axis pairing

JANUARY 2001



AN INTRIGUING SUPERCONDUCTOR