Chiral p-wave superconductivity and Sr_2RuO_4

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SC discovered in SRO
by Maeno in 1994

ICMR Summer School on Novel Superconductors
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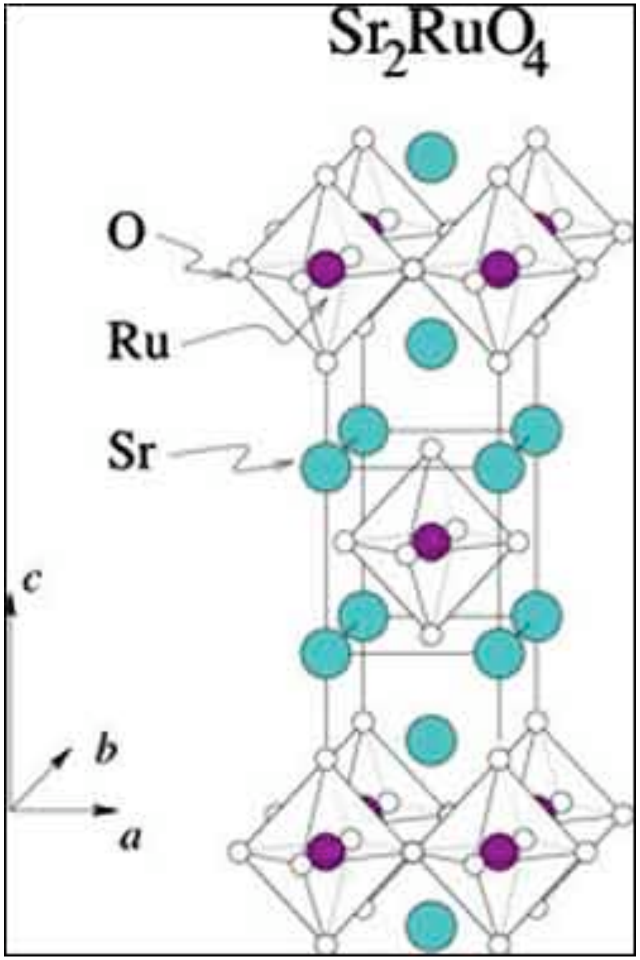
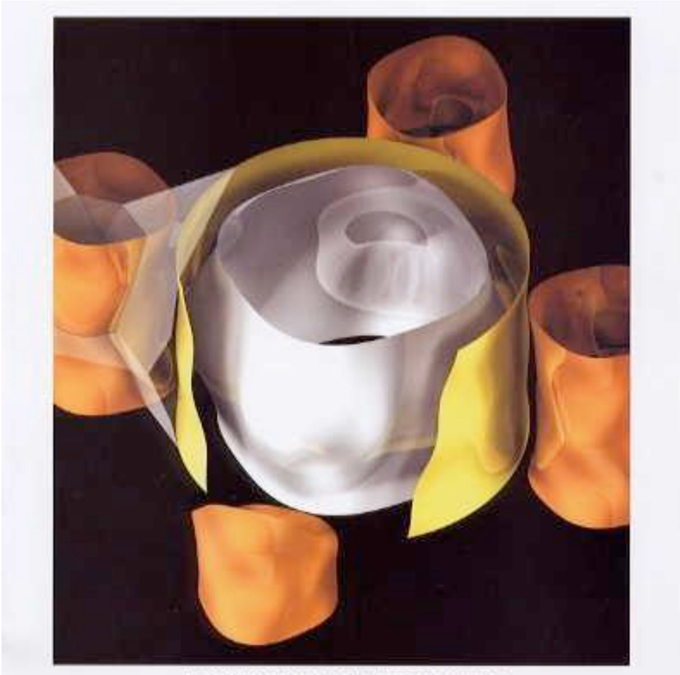
Chiral p–wave & SRO Outline

- Introduction to SRO and early evidence for chiral p-wave superconductivity
- Chiral p-wave SC order
  - triplet pairing
  - topological order & Majorana fermions
  - spontaneous supercurrents
- Search for spontaneous supercurrents & attempts to reconcile with theory
- Polar Kerr effect experiments & theory
- Phase sensitive measurements
- Putting it all together

Strontium Ruthenate





- Same structure as La2CuO4 cuprate
- Quasi-two-dimensional; multiband
- $T_c \leq 1.5$K, strongly disorder dependent

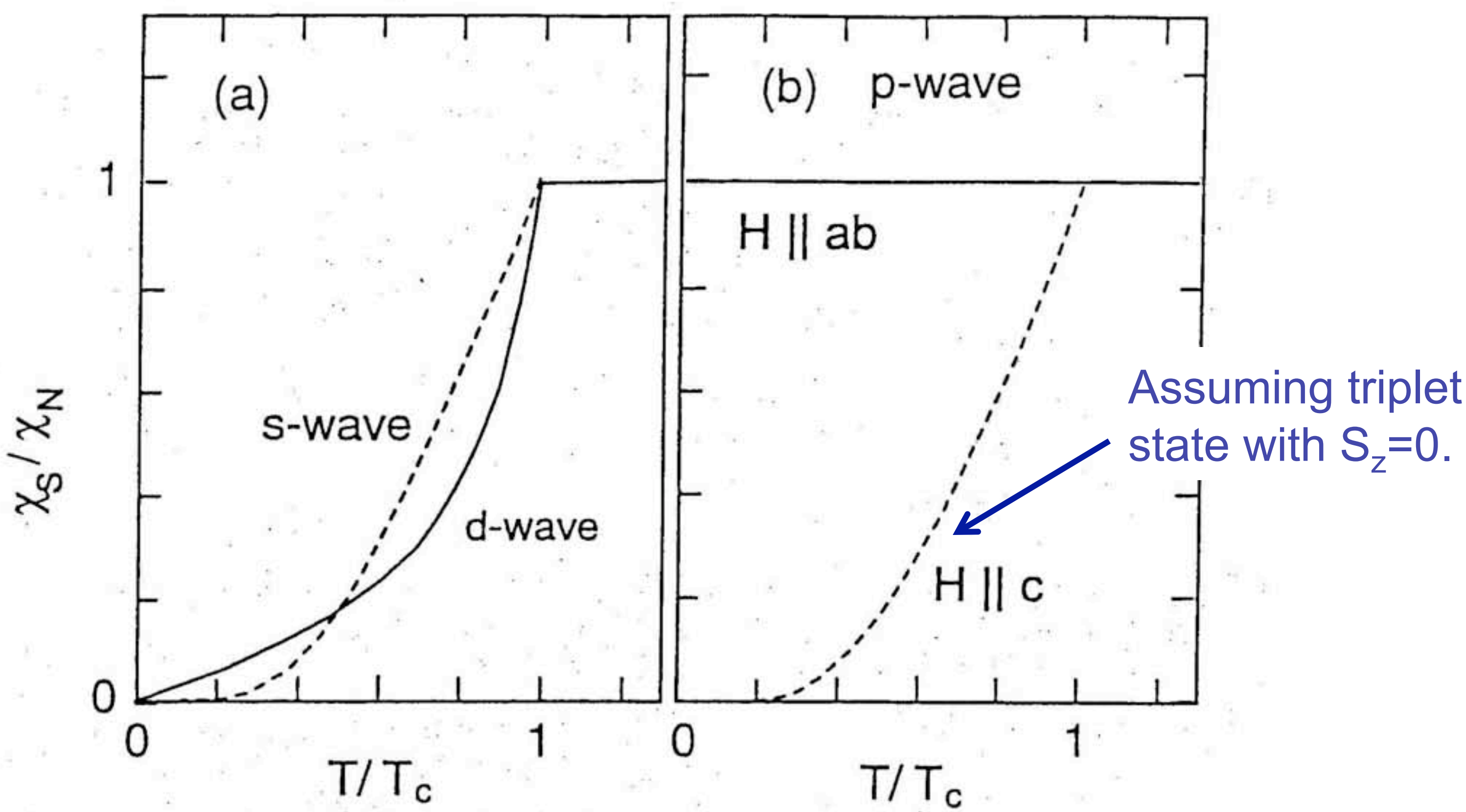
  → unconventional pairing

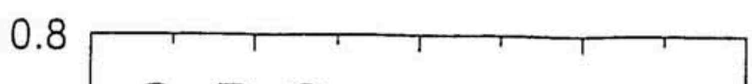
Singlet or Triplet?

Spin susceptibility measurement can distinquish between singlet and triplet superconductivity. For spin singlet pairing:

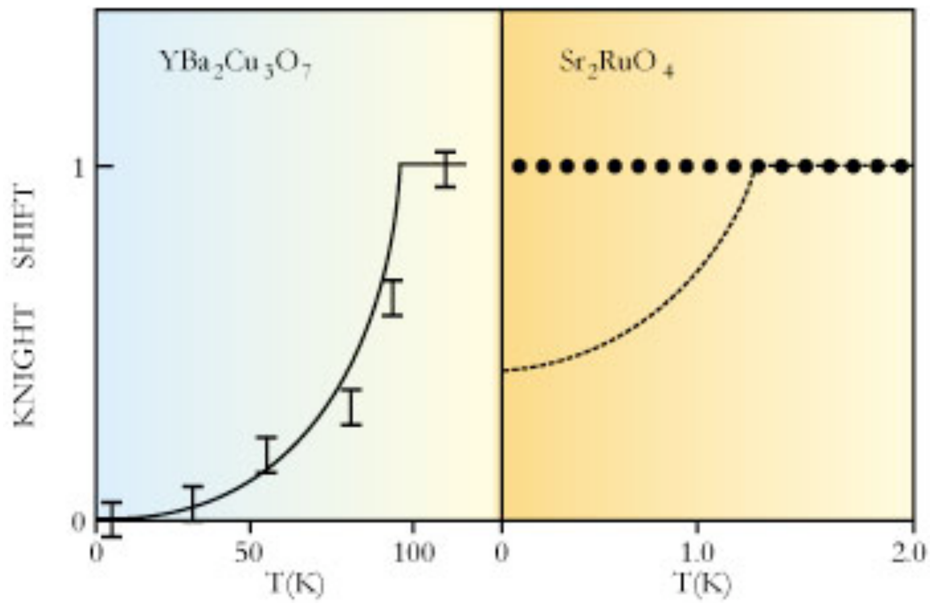
$$\chi_s / \chi_N = -\frac{2}{N}\int_0^{\infty} dE \, \frac{\partial f(E)}{\partial E} N_S(E) \rightarrow e^{-\Delta / k_B T} \quad \text{at low T for s-wave}$$

Theoretical curves





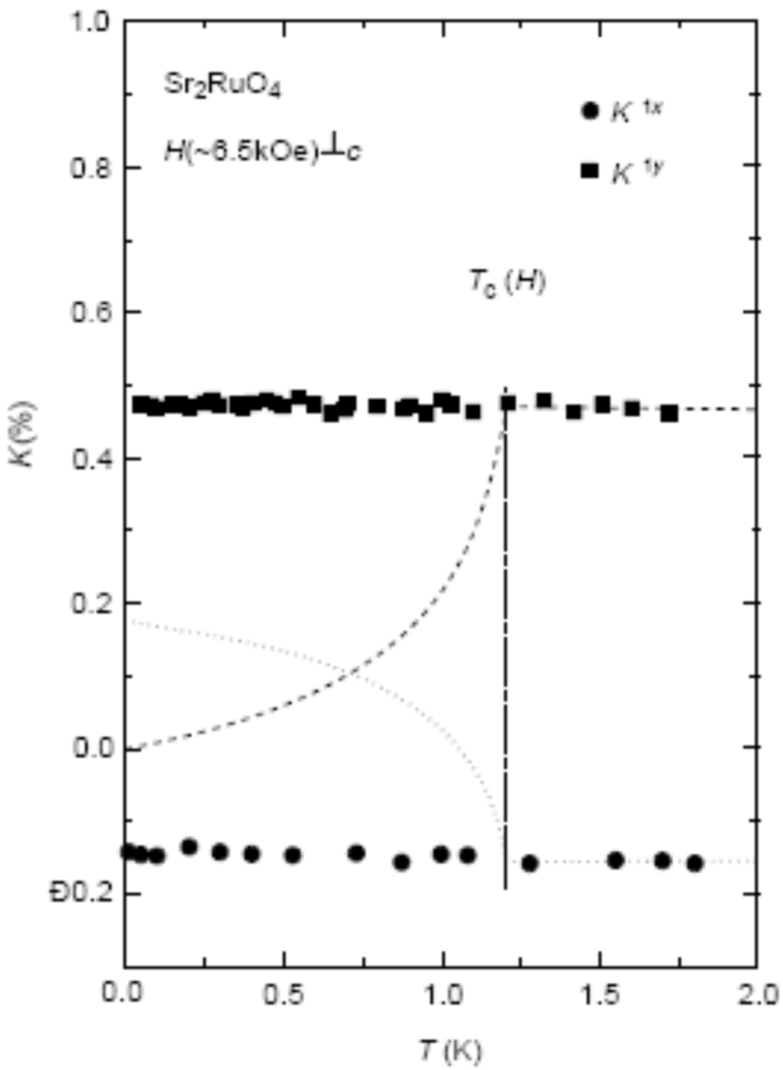
NMR evidence for triplet pairing in SRO

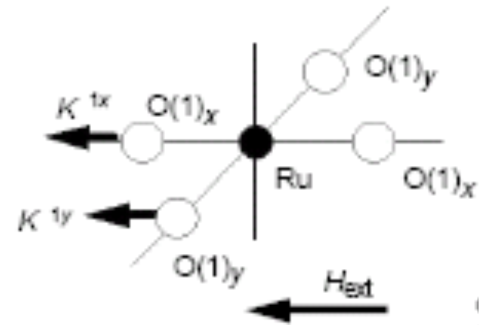


Knight shift → triplet pairing

[B || ab]

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).



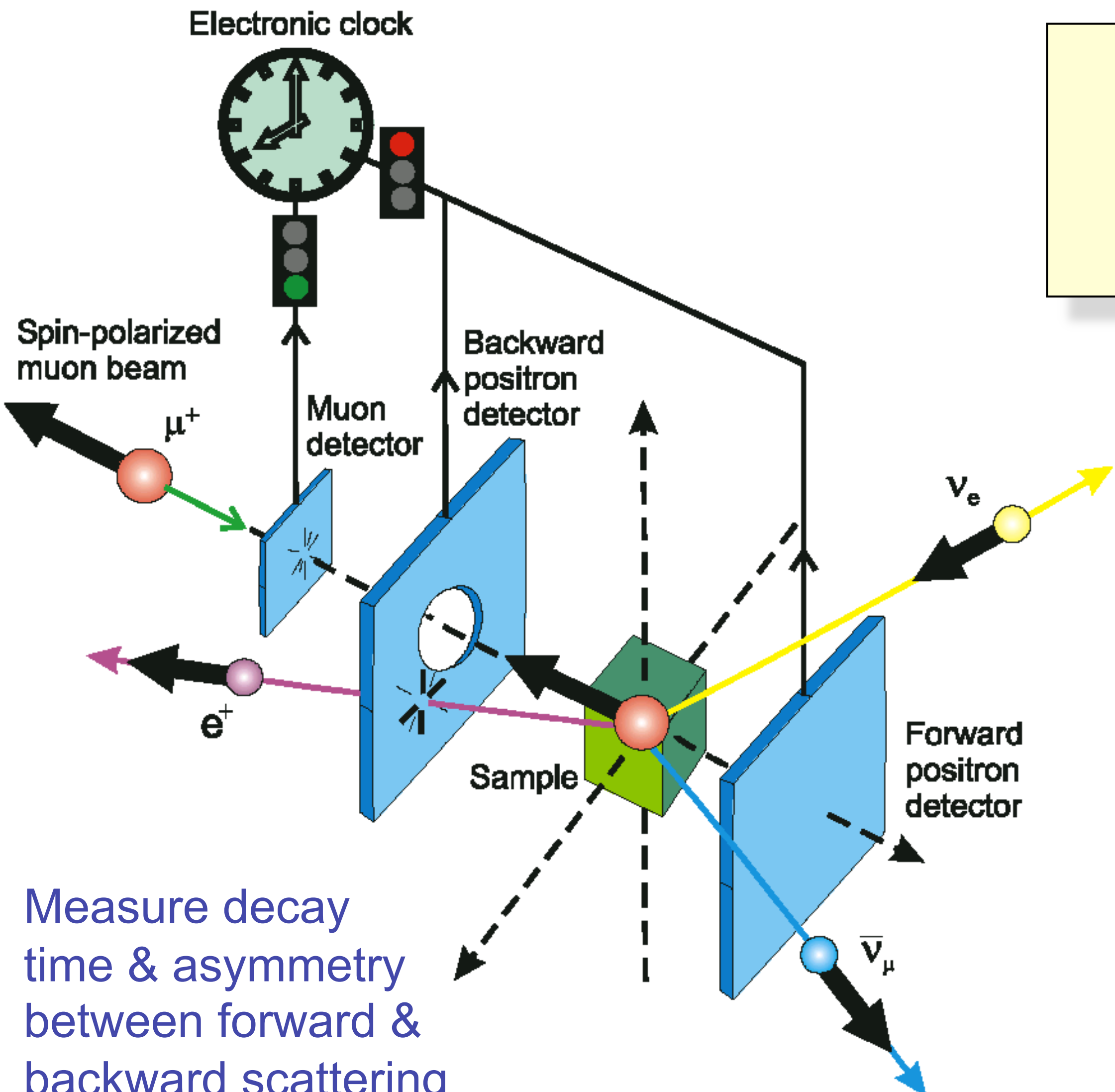


Actual data from Ishida et al. Nature (1998).

Triplet→ p-wave pairing most likely/simplest possibility

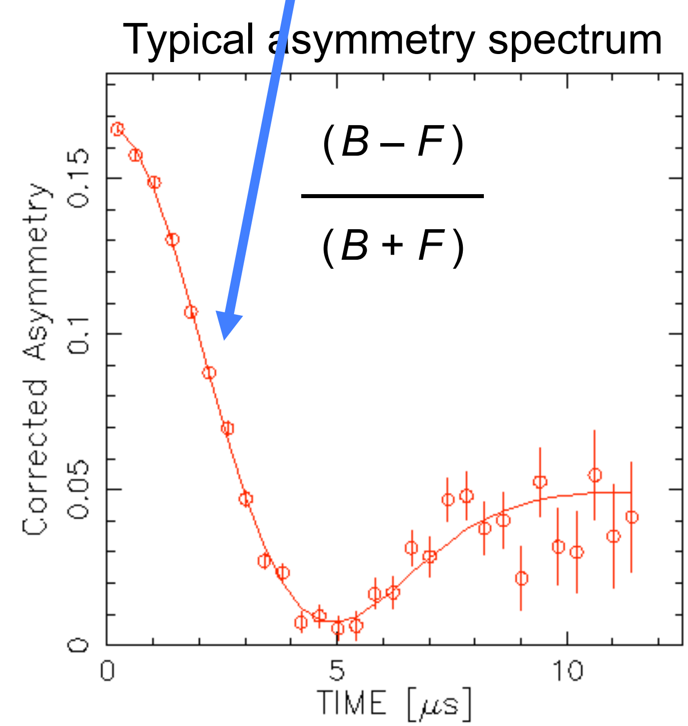
More recent NMR data less clear.

Zero Field (ZF)-μSR



Measure decay time & asymmetry between forward & backward scattering

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



Sr_2RuO_4 ZF-μSR

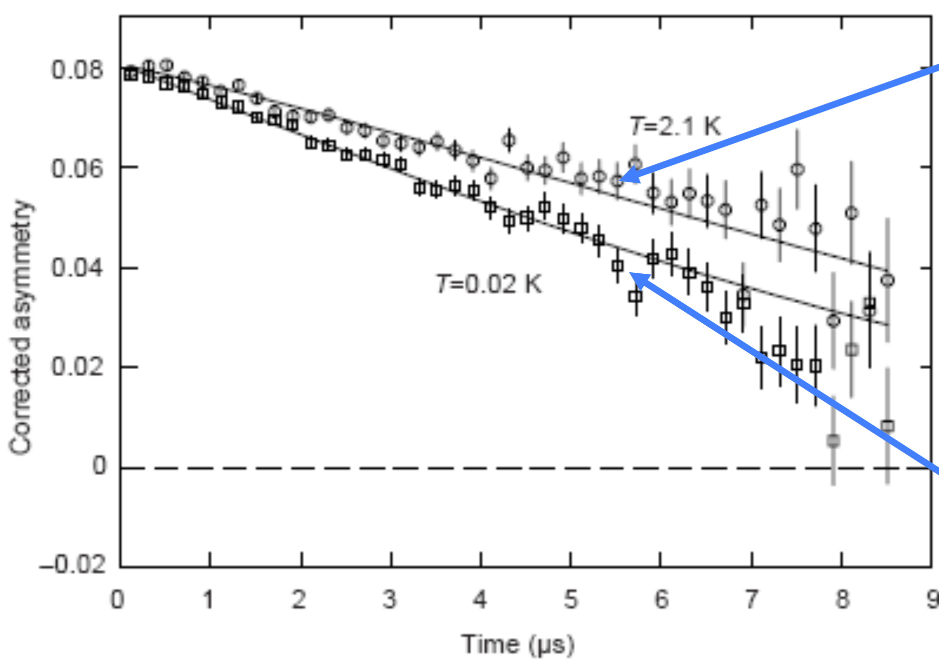


Figure 1 Zero-field μSR spectra measured with $P_\mu \perp c$ in Sr_2RuO_4 at $T = 2.1$ K (circles) and $T = 0.02$ K (squares). Curves are fits to the product of equation (1) and $\exp(-\Lambda t)$ as described in the text.

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

Kubo-Toyabe

dilute fields: $\Lambda(T)$

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_μ || c

Λ vs T for $P_\mu \perp$ c

Shows fields << 50G. Characteristic field ~ 1G

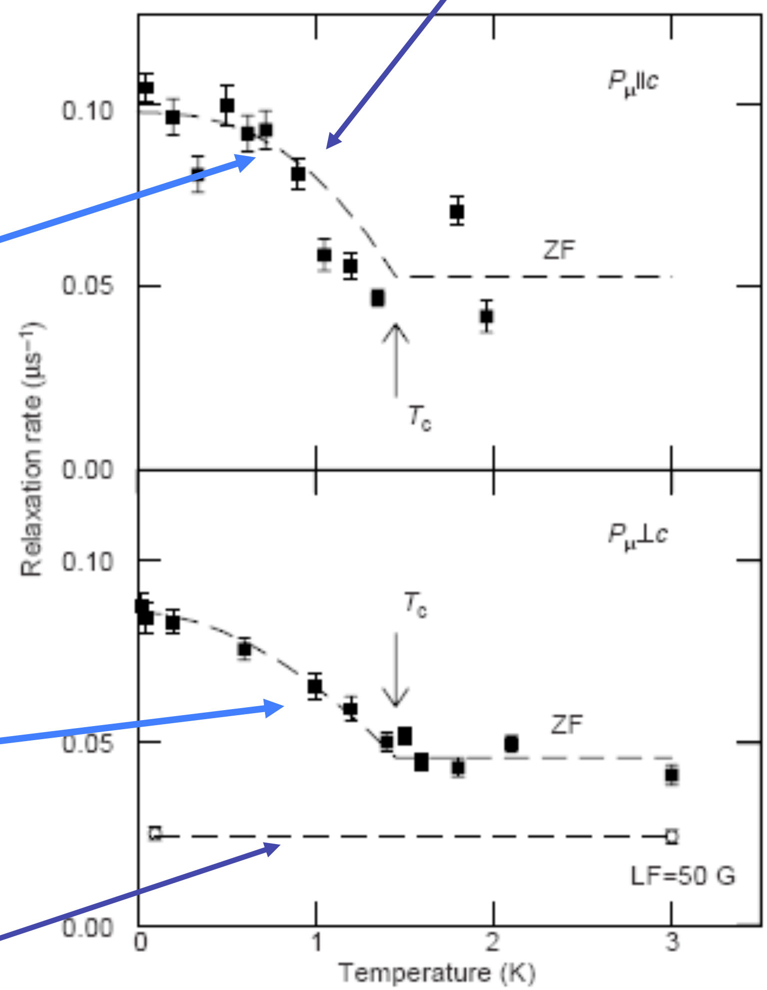


Figure 2 Zero-field (ZF) relaxation rate Λ for the initial muon spin polarization $\parallel c$ (top) and $\perp c$ (bottom). T_c from a.c.-susceptibility indicated by arrows. Circles in bottom figure give relaxation rate in $B_{LF} = 50\,G \perp c$. Curves are guides to the eye.

muSR sees internal fields (as one would see in a ferromagnet or antiferromagnet – but dilute in this case) which turn on with superconducting order. This is a signature of broken time reversal symmetry

$$\mathcal{T}\Psi_{\sigma} \rightarrow \Psi^{*}_{-\sigma}$$

Can break TRS with spin order or with orbital order.

Early expts pointed toward triplet (simplest case is p-wave) with TRSB.

Singlet SC

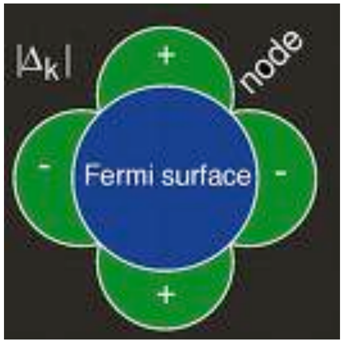
$$S = 0 \Rightarrow \chi_{s=0} = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

symmetric

order parameter: $\psi = \Delta(\vec{k})\chi_{s=0}$

s – wave: $\Delta(\vec{k}) = \Delta_0$ (simplest case; may have k - dependence)

d - wave: $\Delta(\vec{k}) = \begin{cases} [k_x^2 - k_y^2]/k_F^2 \\ [(k_x^2 - k_y^2) + ik_x k_y]/k_F^2 \end{cases}$ (for example)



Triplet SC

$$S = 1 \Rightarrow |\uparrow\uparrow\rangle, \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right), |\downarrow\downarrow\rangle \Rightarrow \text{must specify pairing amplitude}$$

for each triplet state

Triplet SC

$$\boxed{S=1 \Rightarrow |\uparrow\uparrow\rangle, \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right), |\downarrow\downarrow\rangle}$$

order parameter: $\psi = \Delta_{\uparrow\uparrow}(\vec{k})\chi_{\uparrow\uparrow} + \Delta_{\downarrow\downarrow}(\vec{k})\chi_{\downarrow\downarrow} + \Delta_{\uparrow\downarrow}(\vec{k})(\chi_{\uparrow\downarrow} + \chi_{\downarrow\uparrow})$

can organize this into a 2x2 matrix form: $\psi = (\uparrow,\downarrow)_1 \begin{pmatrix} \Delta_{\uparrow\uparrow} & \Delta_{\uparrow\downarrow} \\ \Delta_{\uparrow\downarrow} & \Delta_{\downarrow\downarrow} \end{pmatrix} \begin{pmatrix} \uparrow \\ \downarrow \end{pmatrix}_2$

or can organize into 3-component vector (Balian-Werthamer, 1963):

$\psi = i\{\vec{d}(\vec{k}) \cdot \vec{\sigma}\}\sigma_y$ where $\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

$$\psi = i\{d_x\sigma_x + d_y\sigma_y + d_z\sigma_z\}\sigma_y = \begin{pmatrix} -d_x + id_y & d_z \\ d_z & d_x + id_y \end{pmatrix}$$

Triplet SC continued

$$\psi = i\{\vec{d}(\vec{k})\cdot\vec{\sigma}\}\sigma_y \quad = \begin{pmatrix} -d_x + id_y & d_z \\ d_z & d_x + id_y \end{pmatrix}$$

$$\text{If } \vec{d} = d_z\hat{z} \Rightarrow \psi = d_z(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) \Rightarrow S_z = 0$$

If $\vec{d}$ is a real vector except for a k - dependent phase, i.e. $\vec{d}\times\vec{d}^* = 0$ (unitary) then the component of S along $\vec{d}$ is zero.

What d-vector is compatible with experiments on SRO?

What p-wave states are allowed for SRO by symmetry?

TABLE IV. Allowed *p*-wave states on a cylindrical Fermi surface for a tetragonal crystal. References to ^{3}He are for the analogous three-dimensional states.

$\mathbf{d}/\Delta_0$	Δ/Δ_0	Node	Time-reversal symmetry	^{3}He
Unitary states				
$\hat{x}k_x+\hat{y}k_y$	$\sqrt{k_x^2+k_y^2}$			BW
$\hat{x}k_y-\hat{y}k_x$	$\sqrt{k_x^2+k_y^2}$			
$\hat{x}k_x-\hat{y}k_y$	$\sqrt{k_x^2+k_y^2}$			
$\hat{x}k_y+\hat{y}k_x$	$\sqrt{k_x^2+k_y^2}$			
$\hat{z}k_x$	$\lvert k_x\rvert$	line		
$\hat{z}(k_x+k_y)$	$\lvert k_x+k_y\rvert$	line		
$\hat{z}(k_x\pm ik_y)$	$\sqrt{k_x^2+k_y^2}$		broken	ABM
Nonunitary states				
$\hat{x}k_x+i\hat{y}k_y$	$\lvert k_x+k_y\rvert\uparrow\uparrow$ $\lvert k_x-k_y\rvert\downarrow\downarrow$		broken	
$\hat{x}k_y-i\hat{y}k_x$	$\lvert k_y-k_x\rvert\uparrow\uparrow$ $\lvert k_x+k_y\rvert\downarrow\downarrow$		broken	
$\hat{x}k_x-i\hat{y}k_y$	$\lvert k_y-k_x\rvert\uparrow\uparrow$ $\lvert k_x+k_y\rvert\downarrow\downarrow$		broken	
$\hat{x}k_y+i\hat{y}k_x$	$\lvert k_x+k_y\rvert\uparrow\uparrow$ $\lvert k_y-k_x\rvert\downarrow\downarrow$		broken	
$(\hat{x}+i\hat{y})(k_x+k_y)$	$2(\lvert k_x+k_y\rvert)\uparrow\uparrow$ $0\downarrow\downarrow$	line	broken	
$(\hat{x}+i\hat{y})(k_x+ik_y)$	$2\sqrt{k_x^2+k_y^2}\uparrow\uparrow$ $0\downarrow\downarrow$		broken	A1

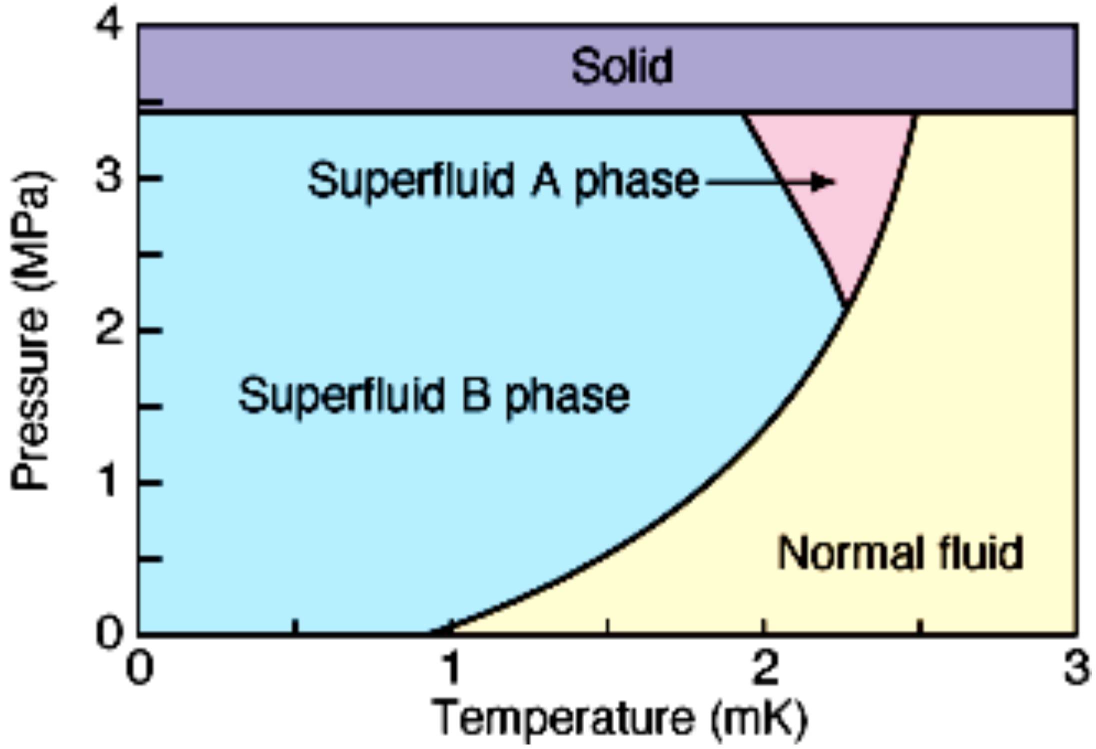
unitary & gapped & TRSB

(unitary: $d\times d^*=0$)

[from Mackenzie & Maeno, RMP (2003).]

Superfluid ^{3}He

Lee, Osheroff & Richardson (1971)



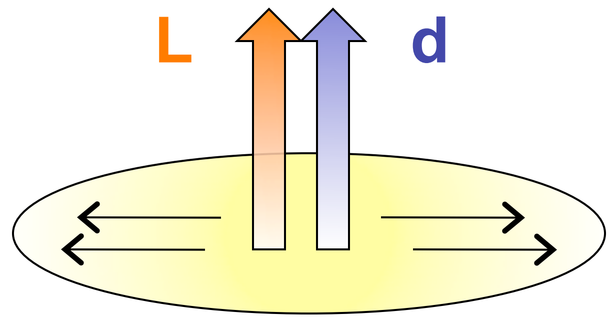
Chiral p-wave Superconductivity

$$\mathbf{d}(\mathbf{k}) = \Delta_0 \hat{\mathbf{z}}(k_x \pm i k_y)$$

Breaks time-reversal symmetry

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

$$\vec{L} = \hbar \hat{\mathbf{z}}$$



Both d-vector and L aligned
along c-axis
equal spin pairing in ab-plane

Each Cooper pair carries angular momentum ħ and the BCS SC state carries $\langle L_z \rangle = \hbar N/2$ (Stone & Roy, PRB 2004.)

Zero modes & Majorana Fermions

The chiral p-wave state is equivalent to the Moore-Read quantum Hall 5/2 state → topological state with special Majorana fermion edge modes (also in vortex cores). See Read & Green, PRB (2000); Gurarie & Radzihovsky, Ann. Phys. (2007).

Consider mean field Hamiltonian for superconductivity:

$$H_{MF} = \sum_{ij} \left\{ h_{ij} a_i^+ a_j + h_{ji} a_j^+ a_i \right\} + \Delta_{ij} a_i^+ a_j^+ + \Delta_{ij}^+ a_i a_j$$

$$= \sum_{ij} \begin{pmatrix} a_i^+ & a_i \end{pmatrix} \underbrace{\begin{pmatrix} h_{ij} & \Delta_{ij} \\ \Delta_{ij}^+ & -h_{ij}^T \end{pmatrix}}_{\mathrm{H}} \begin{pmatrix} a_j \\ a_j^+ \end{pmatrix} \qquad \text{where } \Delta_{ji} = -\Delta_{ij}$$

The Bogoliubov-de Gennes equations are: $H\psi_n = E_n \psi_n$

$$H\psi_n = E_n\psi_n \quad \text{where} \quad H = \begin{pmatrix} h_{ij} & \Delta_{ij} \\ \Delta^+_{ij} & -h^T_{ij} \end{pmatrix}. \quad \text{Let} \quad \sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

$$\text{Note: } \sigma_1 H \sigma_1 = -H^* \Rightarrow \text{ if } H\psi_n = E_n\psi_n$$

$$\text{then} \quad H\sigma_1\psi^*_n = \sigma_1^2 H\sigma_1\psi^*_n = -\sigma_1 H^*\psi^*_n = -E_n\sigma_1\psi^*_n$$

$$\psi_n = \begin{pmatrix} u_n \\ v_n \end{pmatrix} \quad \Rightarrow \quad \sigma_1\psi^*_n = \begin{pmatrix} v^*_n \\ u^*_n \end{pmatrix}$$

$$\text{Bogoliubov qps: } \quad \gamma^+_{\mathrm{n}} = \sum_i \left(u_{ni} a^+_i + v_{ni} a_i \right) \text{ and } H = \sum_n E_n \gamma^+_{\mathrm{n}} \gamma_{\mathrm{n}}.$$

$$\text{If } H\psi = 0, \text{ then } H\sigma_1\psi^* = 0. \text{ Let } \psi_0 = \psi + \sigma_1\psi^* \Rightarrow H\psi_0 = 0$$

$$\text{Then } \sigma_1\psi^*_0 = \psi_0 \Rightarrow \psi_0 = \begin{pmatrix} u_0 \\ u^*_0 \end{pmatrix} \Rightarrow \gamma^+ = \sum_{\mathrm{i}} u_{0i} a^+_i + u^*_{0i} a_i = \gamma.$$

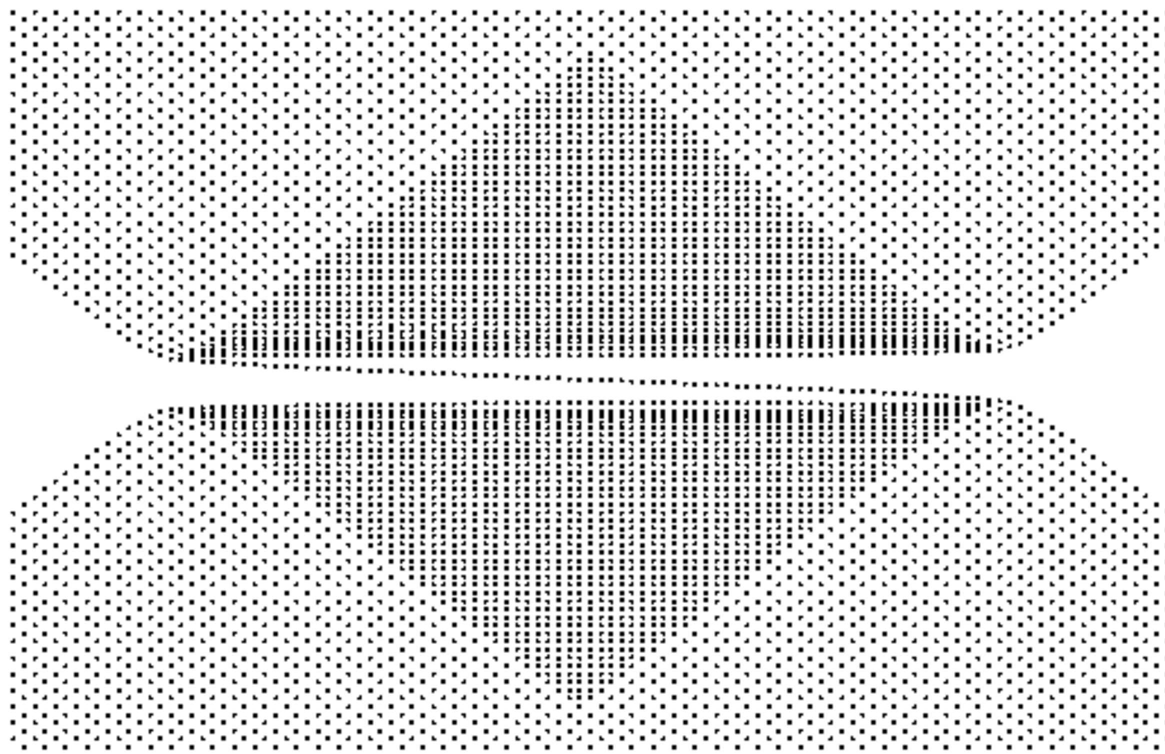
$$\gamma = \gamma^{+} \Rightarrow \text{ its own antiparticle}$$

need 2 to make 1 fermion

$$\mathrm{c} = \gamma_{01} + i\gamma_{02} \quad c^{+} = \gamma_{01} - i\gamma_{02} \qquad \{\mathrm{c},\mathrm{c}^{+}\} = 1$$

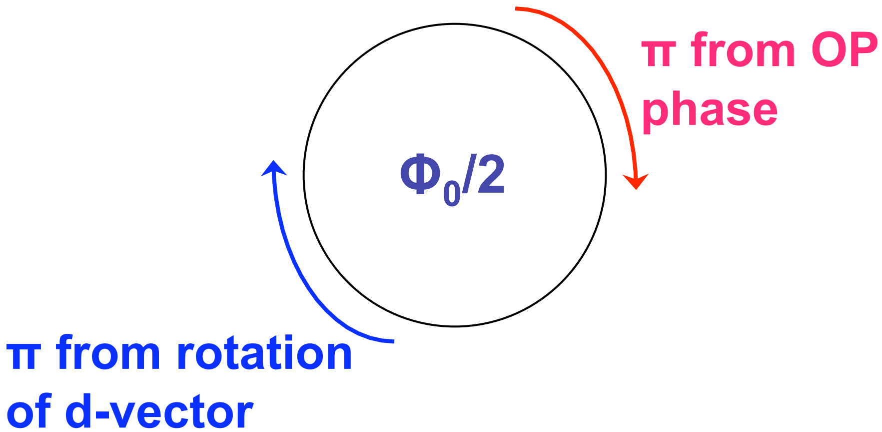
These zero modes are **Majorana fermions** and must come in pairs.

chiral p-wave: a single Majorana fermion can exist at a vortex core or an edge and, if well separated, are protected by the bulk gap. Need to analyze spatially varying BdG eqs for chiral p-wave. See, for example, Gurarie & Radzihovsky, Ann. Phys. (2007). Need conditions for half-quantum vortices to isolate single Majorana fermions.



From Stone & Anduaga, PRB (2007). Energy levels as function of angular momentum for chiral p-wave in harmonic trap.

Exotic physics from chiral p-wave



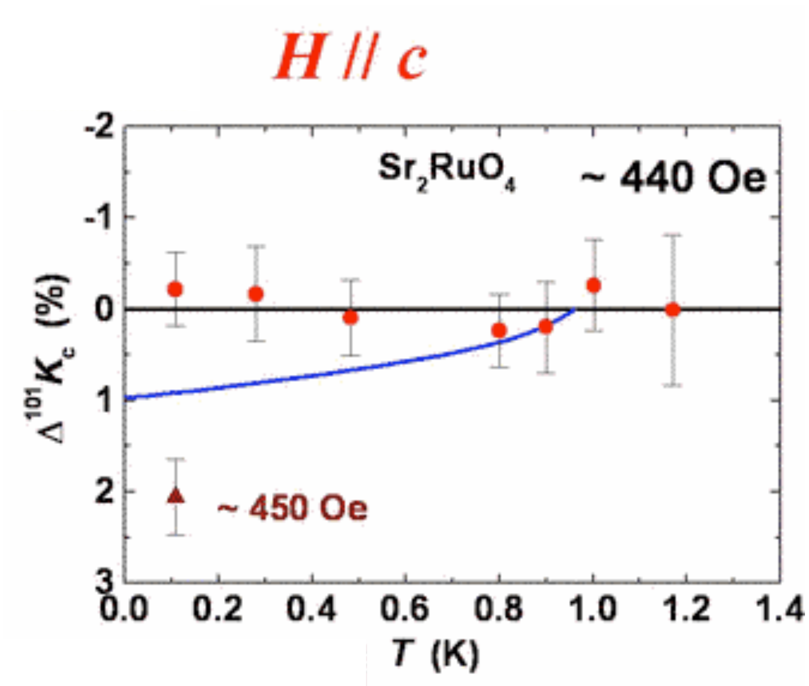
d-vector perpendicular to z

→ may have half-quantum vortices with a single Majorana zero mode bound at the core

→ non-Abelian statistics.

→ useful for quantum computing because of the topological stability and non-trivial winding

NMR for H||z **may** be explained by rotating d-vector



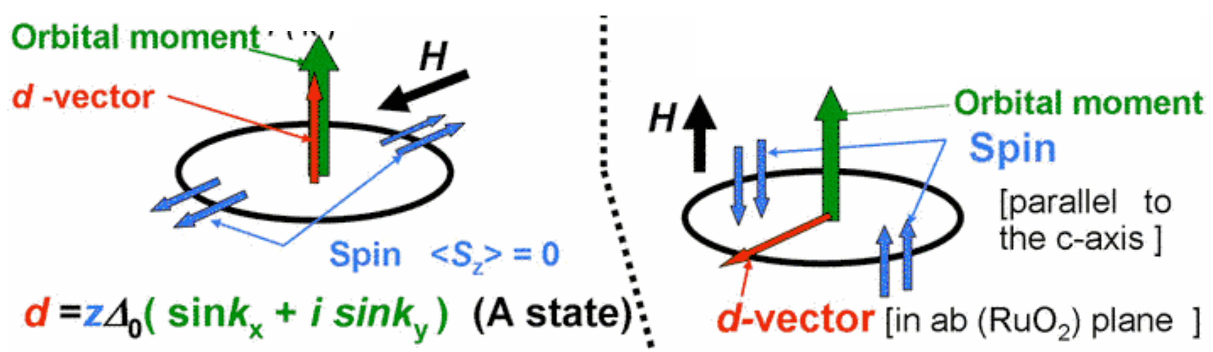
[From Ishida (KITP 2007)]

More recent NMR with H‖c also found no supression of Knight shift below Tc

→ triplet with spins along c ?

→ not necessarily same orbital state

→ NMR lineshapes broader



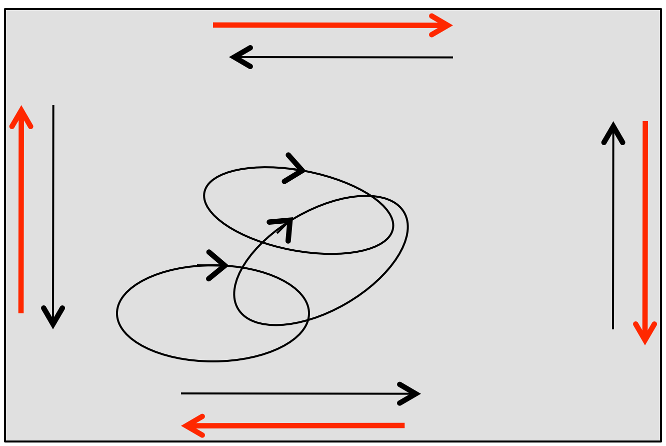
Spontaneous supercurrents

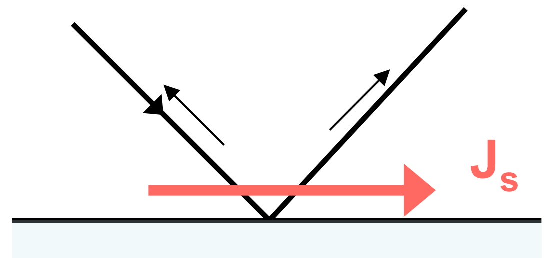
$$\mathbf{d}(\mathbf{k}) = \Delta_0 \hat{\mathbf{z}}(k_x \pm i k_y)$$

p-wave → defects and surfaces are pair-breaking

Chiral p-wave → disturbances cause supercurrents

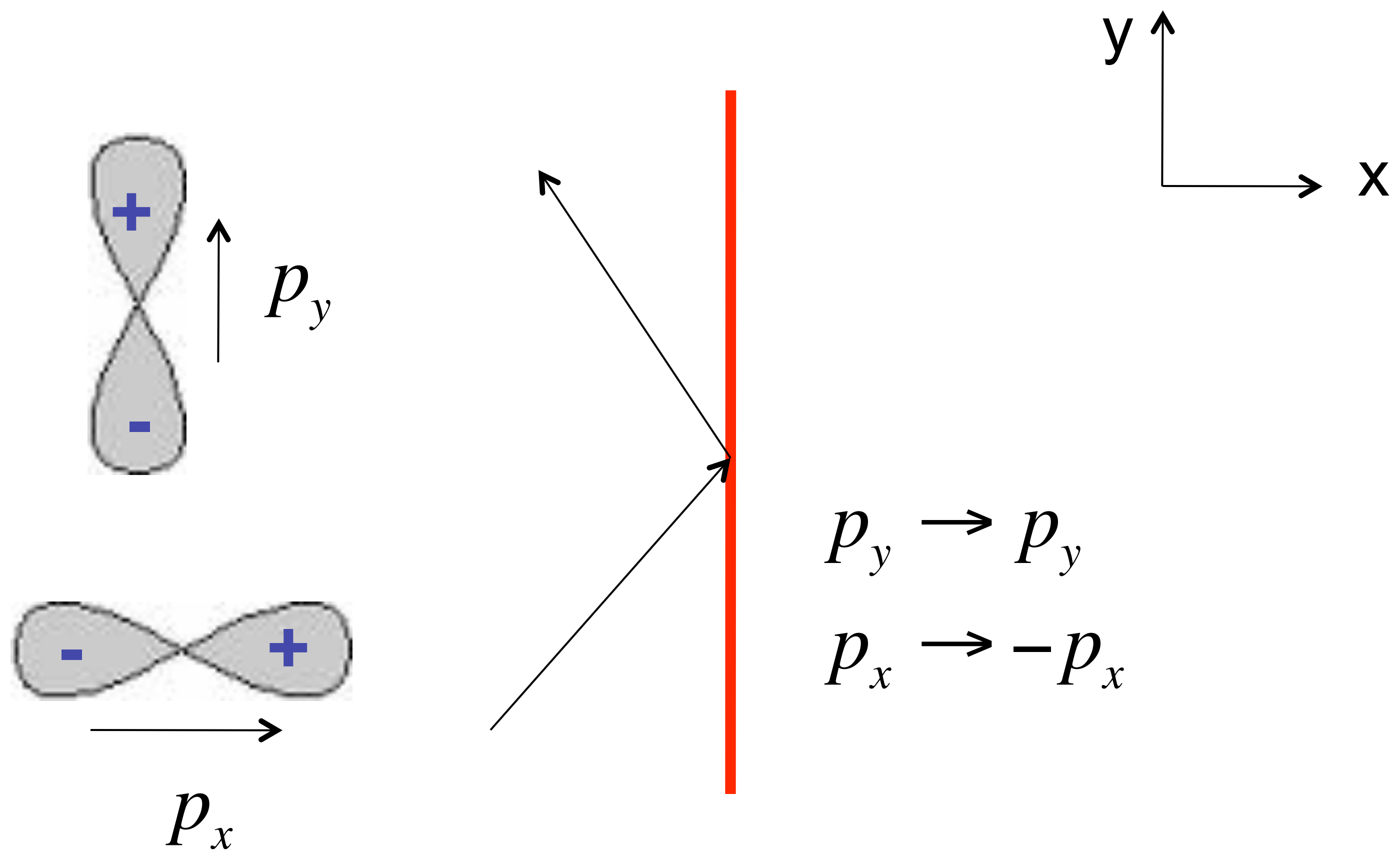
$$\langle L_z \rangle = \hbar N / 2$$





Stone and Roy (2004)
Matsumato and Sigrist (1999)

Mid-gap bound states plus scattering states give a large supercurrent within ξ of surface, which is screened within λ of surface



Any surface is pair-breaking for some component of p_x+ip_y

$\vec{j} \propto \mathrm{Im}(\psi^* \vec{\nabla} \psi) \Rightarrow$ Supercurrents flow at defects
→ local magnetic fields

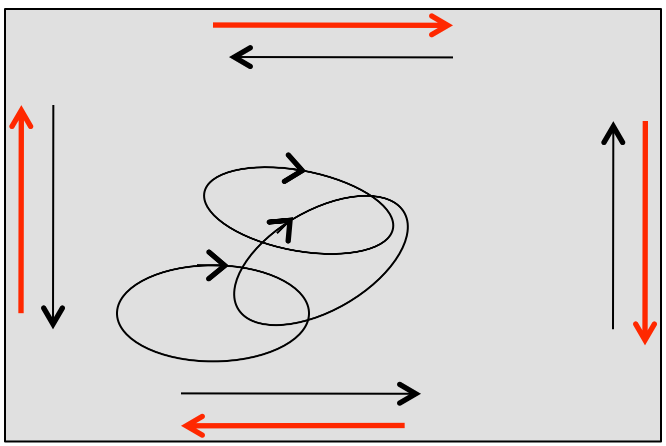
Spontaneous supercurrents

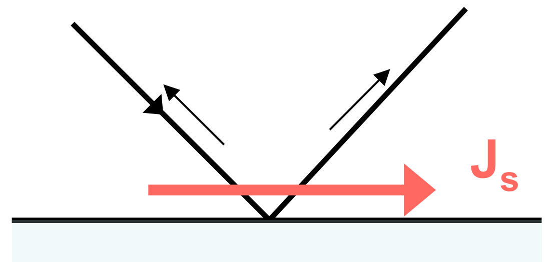
$$\mathbf{d}(\mathbf{k}) = \Delta_0 \hat{\mathbf{z}}(k_x \pm ik_y)$$

p-wave → defects and surfaces are pair-breaking

Order parameter is complex (carries angular momentum) → disturbances cause supercurrents

$$\langle L_z \rangle = \hbar N / 2$$





Stone and Roy (2004)
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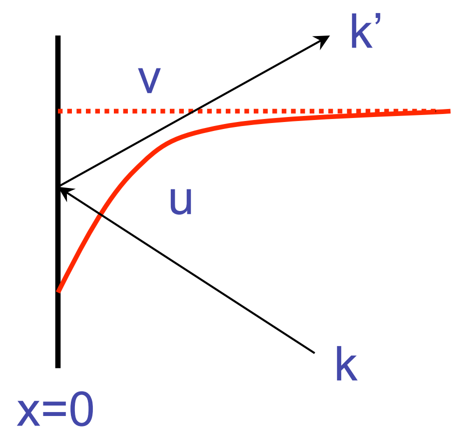
Supercurrents in p_x+ip_y SC from GL theory

Ginzburg-Landau Free energy:

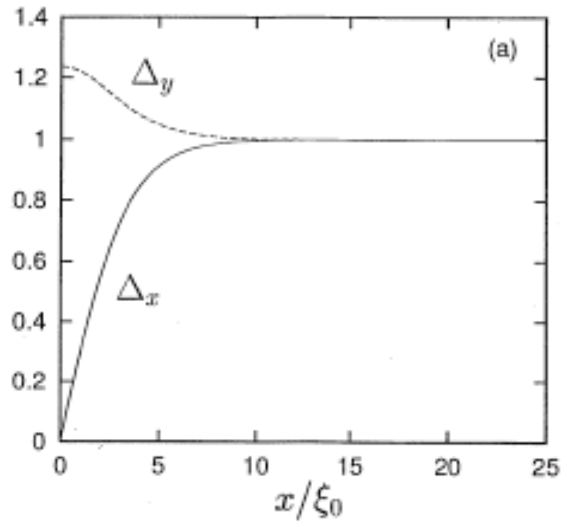
$$\mathbf{d(k)} = \hat{z}|\Delta_0|(u,v)$$

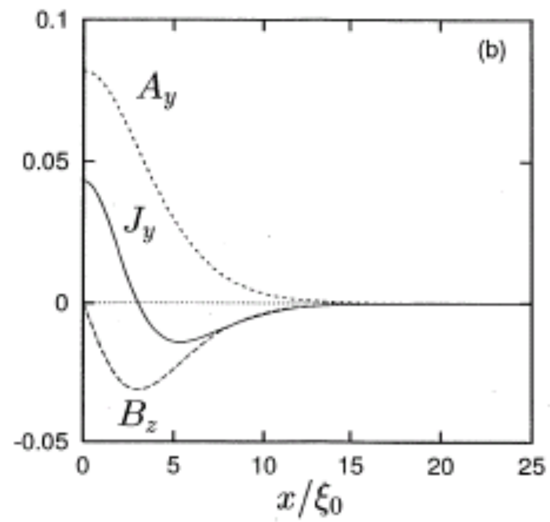
$$F=\frac{1}{4\pi}H_c^2\xi^3\int d^3r\Big[-\tfrac{1}{2}(|u|^2+|v|^2)+(\tfrac{1}{8}+\tfrac{1}{2}\tilde{\beta}_2)(|u|^2+|v|^2)^2+\tfrac{1}{2}\tilde{\beta}_2(u^*v-uv^*)^2$$
$$-\frac{\tilde{\beta}_3}{8}(|u|^2-|v|^2)^2+k_1(|d_xu|^2+|d_yv|^2)+k_2(|d_yu|^2+d_xv|^2)$$
$$+\tilde{k}[(d_xu)^*(d_yv)+(d_xv)^*(d_yu)+\text{c.c.}]+\Delta\tilde{k}[(d_xu)^*(d_yv)-(d_xv)^*(d_yu)+\text{c.c.}]$$
$$+k_5(|d_zu|^2+|d_zv|^2)+\kappa^2\mathbf{b}^2\Big],$$

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



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





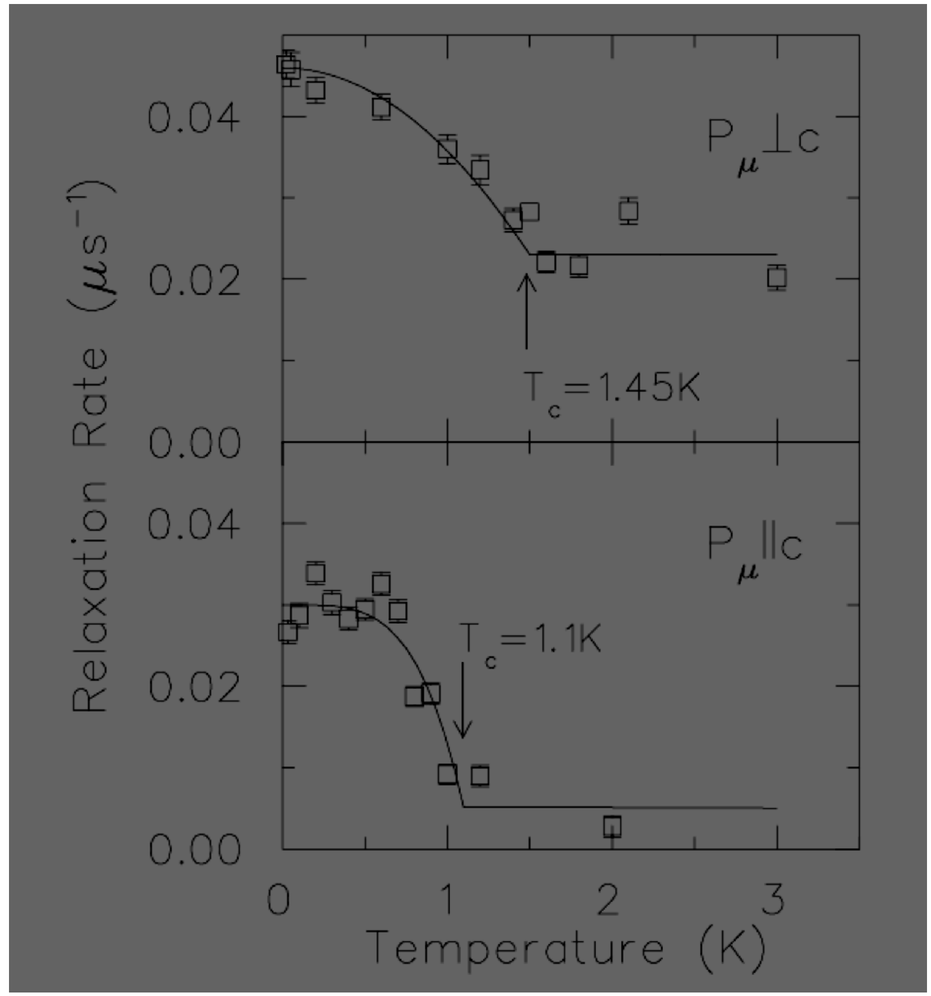
Matsumoto and Sigrist, J. Phys. Soc. Jap. 68, 994 (1999).

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).

ZF-muSR Decay Rate vs Temperature

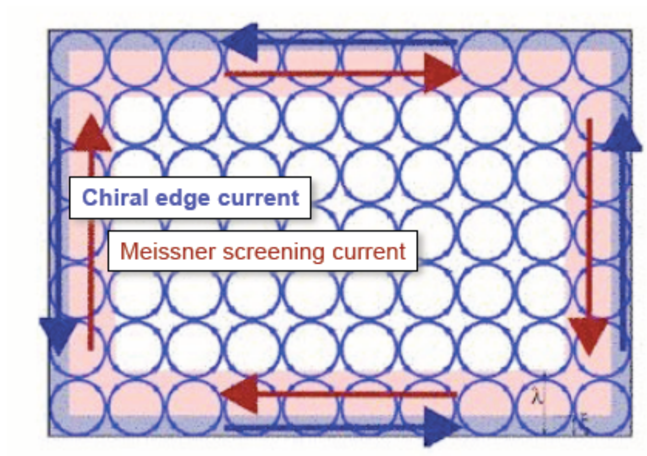
- Spontaneous field seen below T_c, for P_m//c, //a
- B_{loc}~1G
- Follows T_c

- Fit with Lorentzian; no evidence of same field at each muon



Luke et al. to be published

Scanning SQUID microscopy: search for edge and domain currents



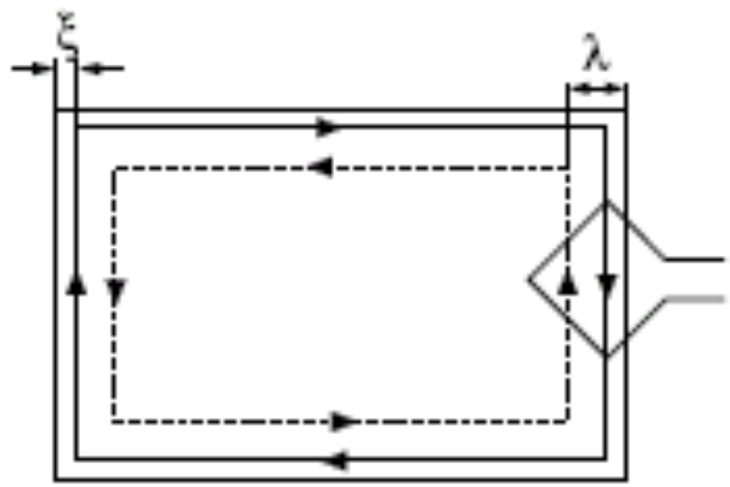
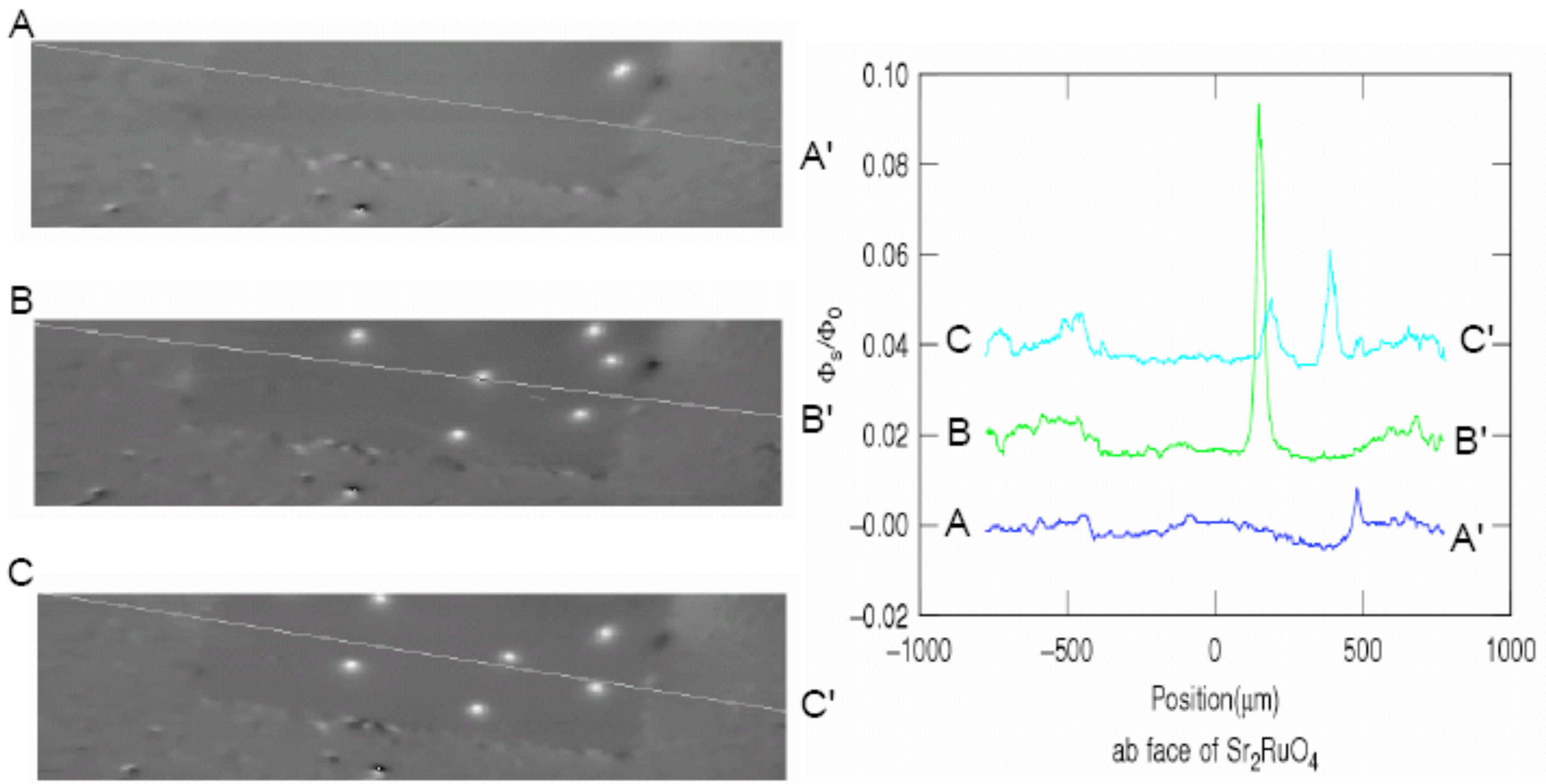
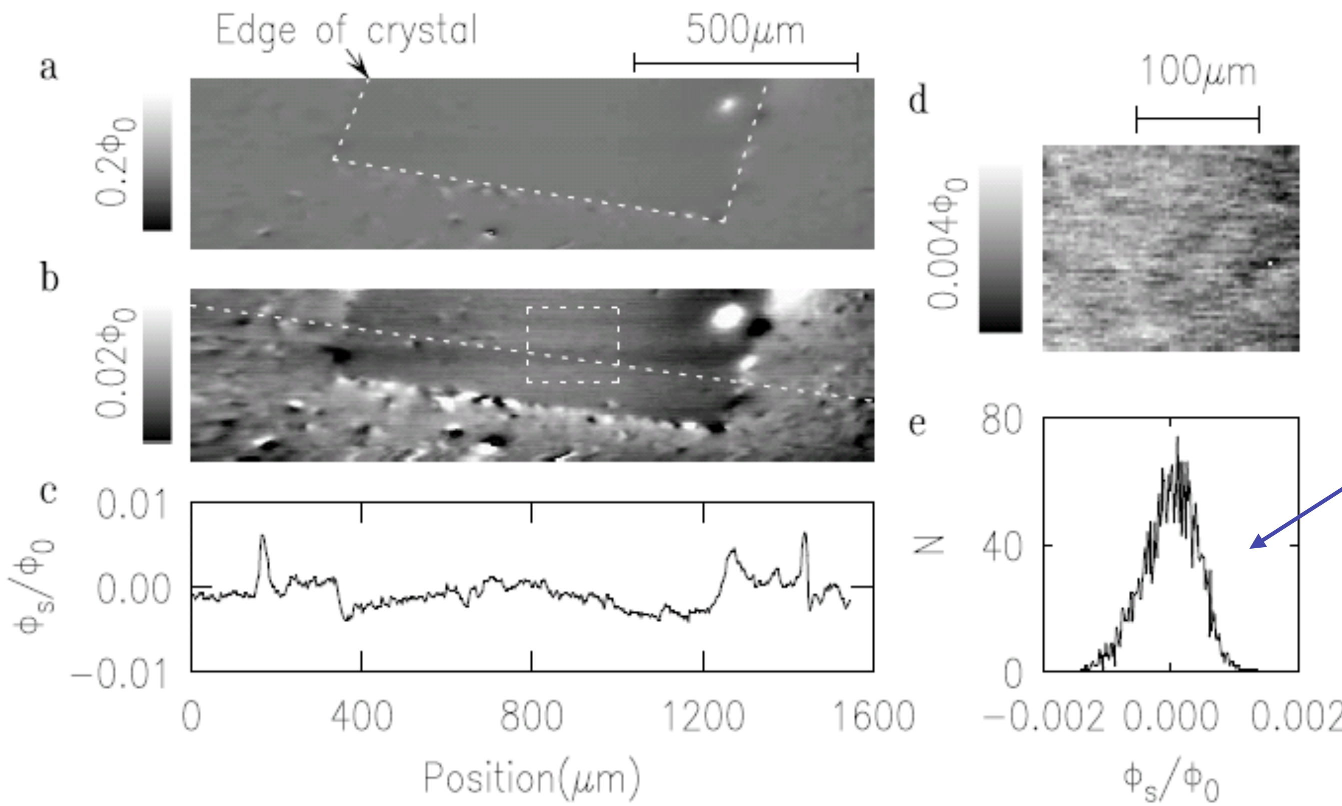


Fig. 5. Electric currents (solid lines) of the chiral edge states along the inner and outer edges of Sr_2RuO_4. The dashed lines show superfluid counterflow. The rectangular coil on the right represents a SQUID pickup loop.

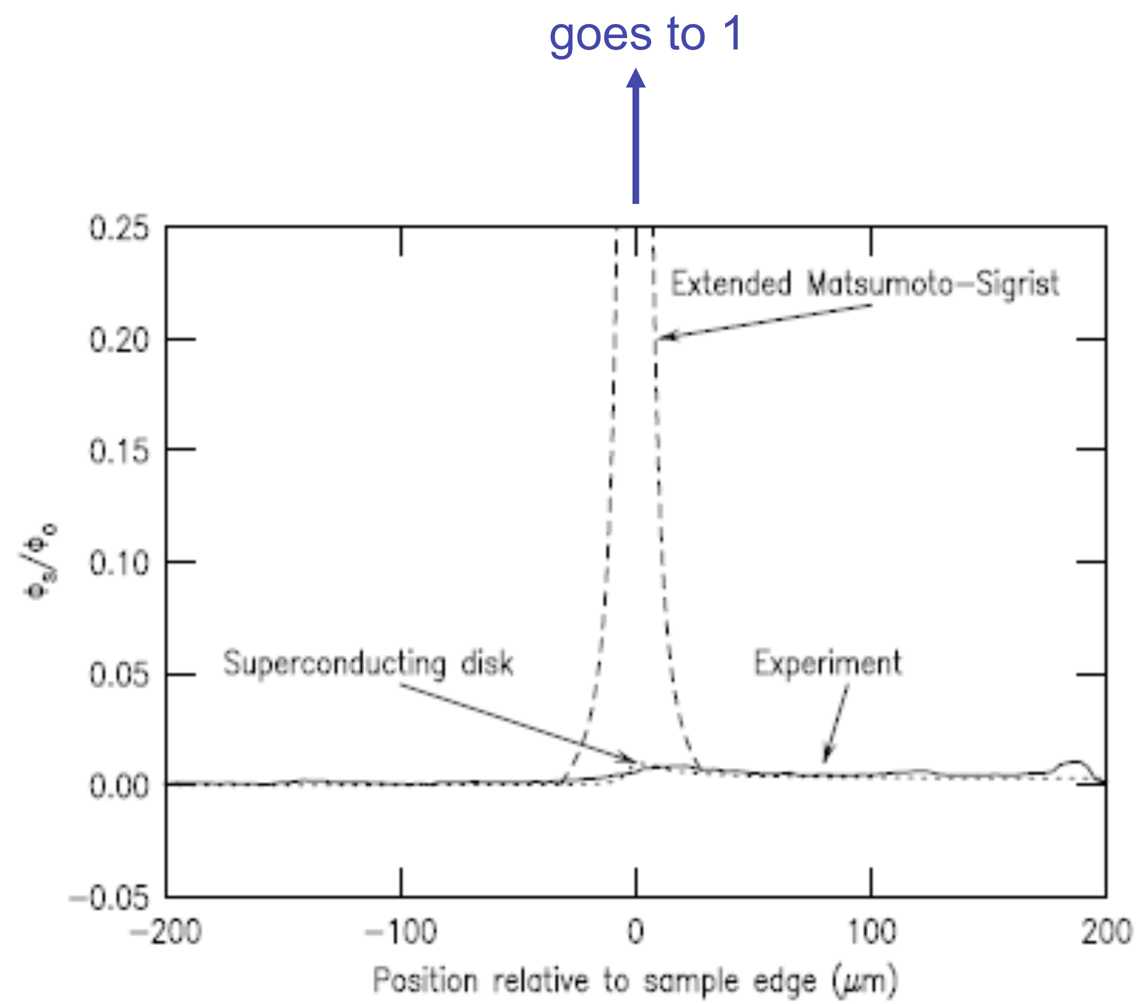
Scanning SQUID microscopy: search for edge and domain currents

J.R. Kirtley, C. Kallin, C. Hicks, E.A. Kim, Y. Liu, K.A. Moler, Y. Maeno, PRB (2007).

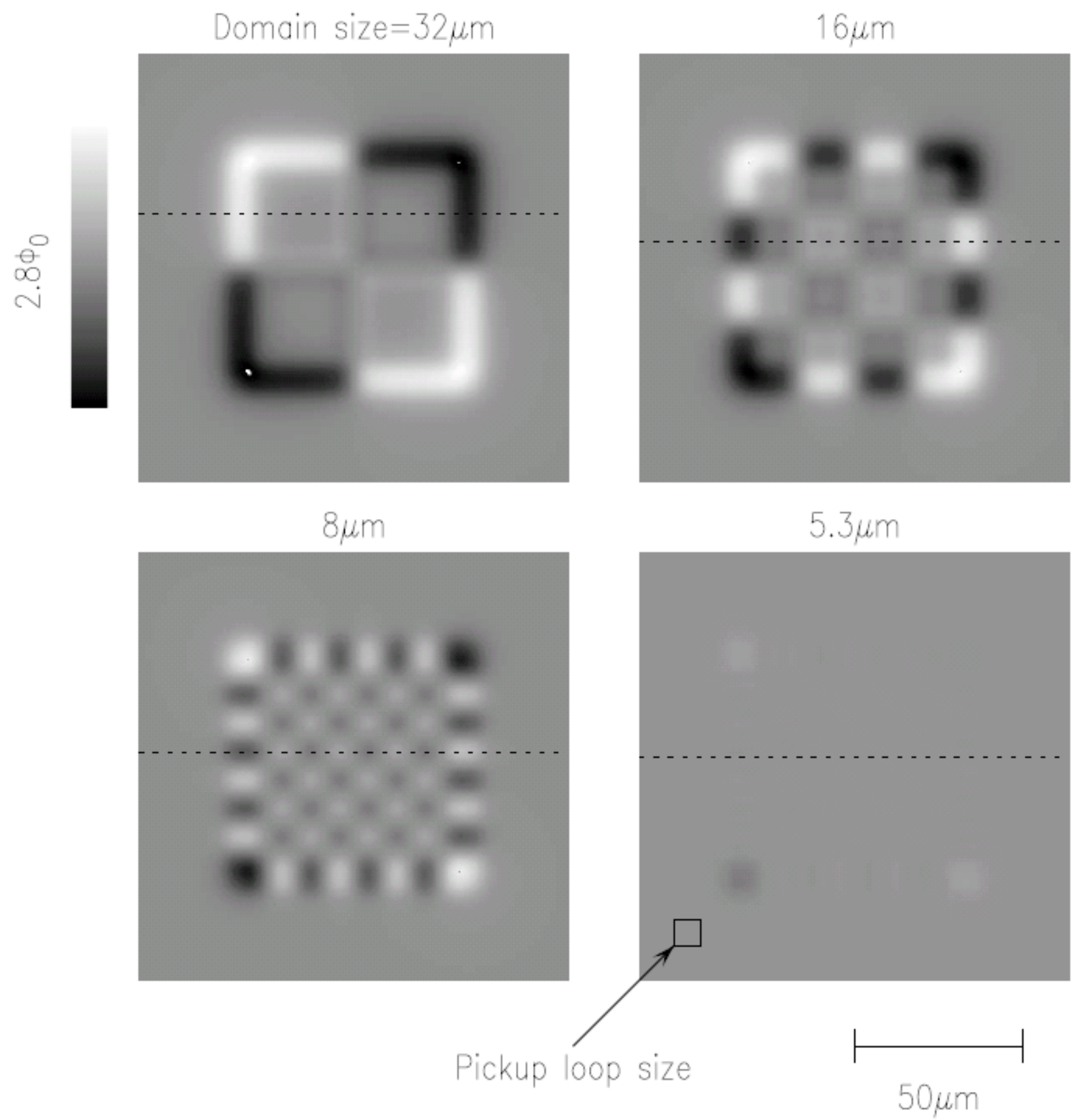




Flux distribution in highlighted square



goes to 1
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
−200
−100
0
100
200
Extended Matsumoto–Sigrist
Superconducting disk
Experiment
Φ_s/Φ_0
Position relative to sample edge (μm)



Domain size=32μm
16μm
8μm
5.3μm
2.8Φ_0
Pickup loop size
50μm

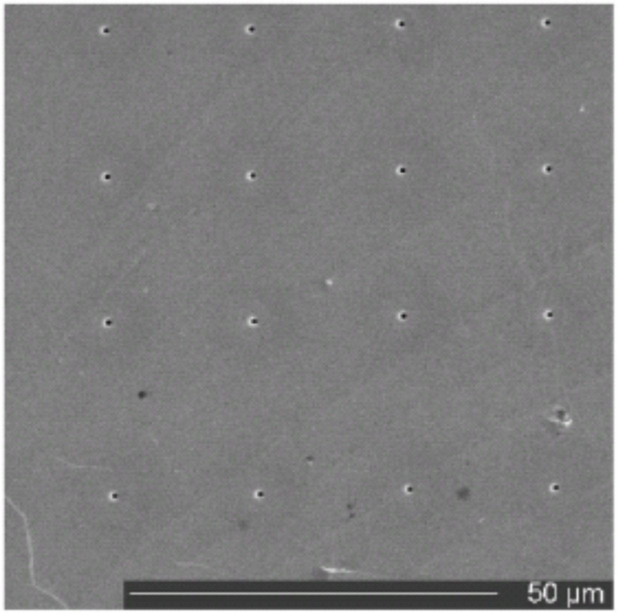


FIG. 1. A SEM image of the Sr_2RuO_4 crystal used for the Hall probe imaging. An array of holes was milled in the sample using a FIB. The hole spacing is 20 μm.

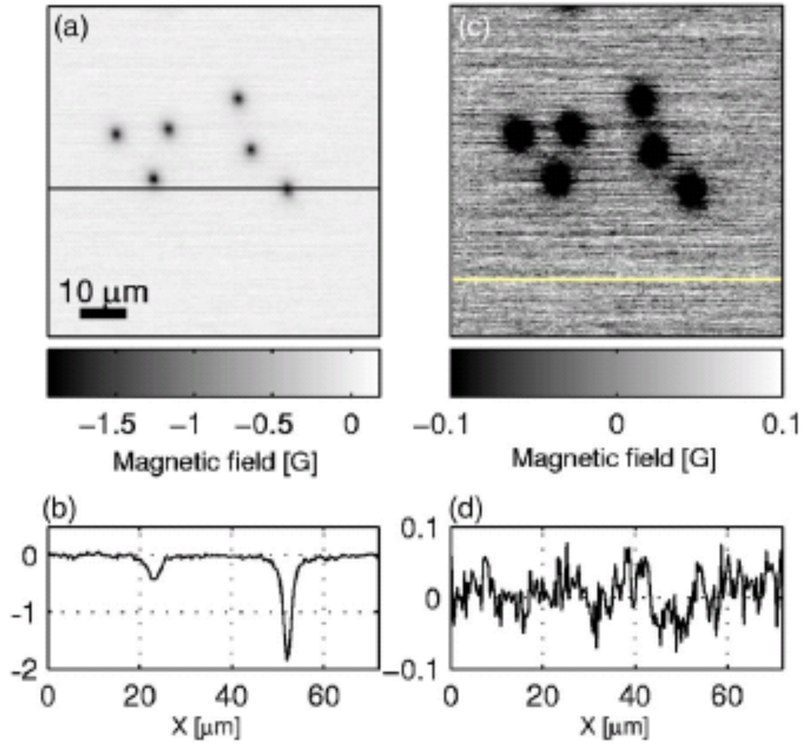
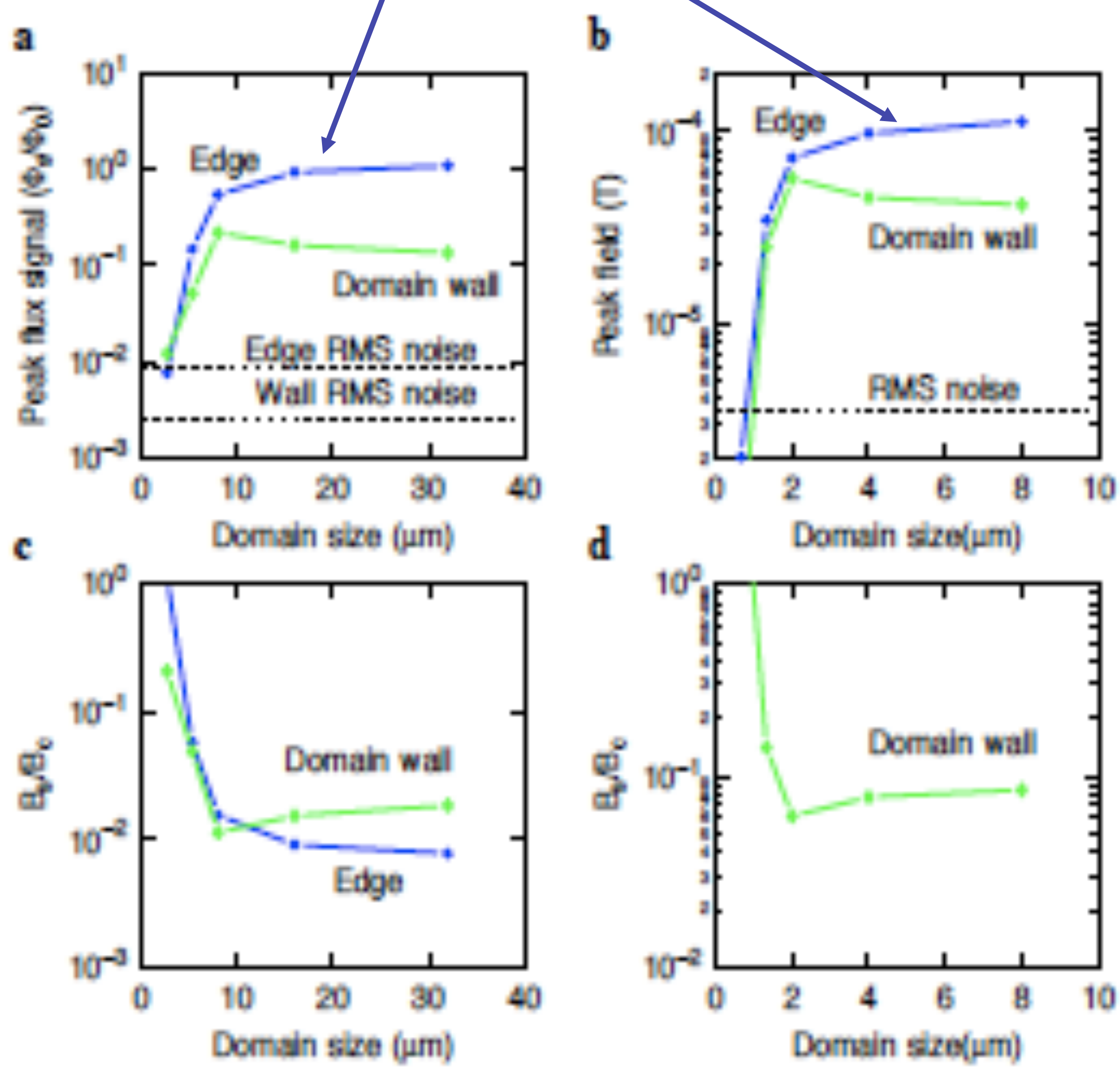


FIG. 2. (Color online) Scanning Hall probe image at $T = 100$ mK of the sample shown in Fig. 1, cooled in a background field of ~25 mG. The background has been line normalized to remove $1/f$ noise. (a) Image with a color scale showing the full measured magnetic field range. Isolated trapped vortices 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

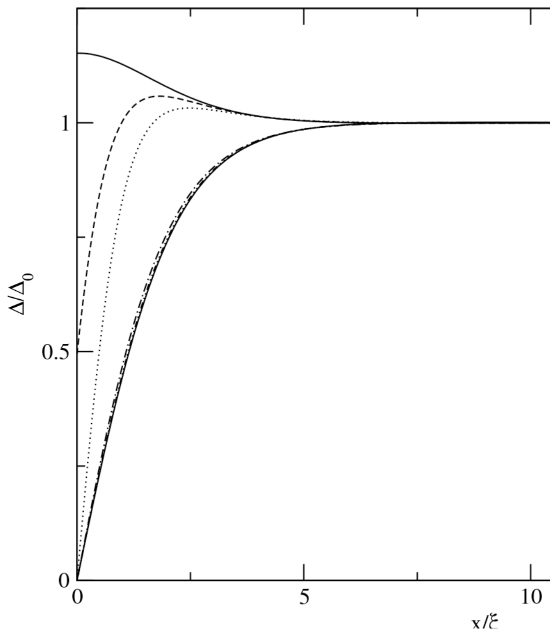
Effects on supercurrents

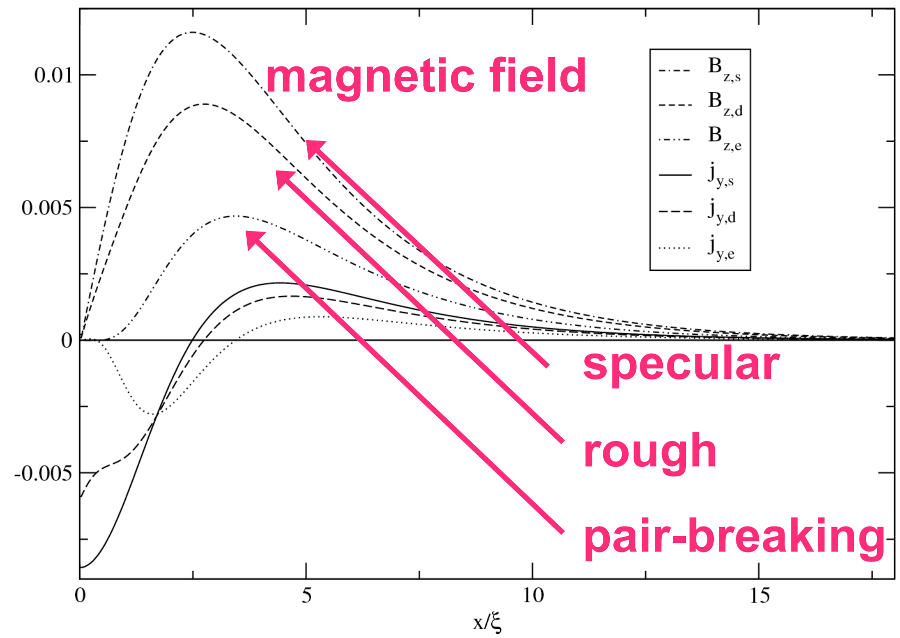
- Multibands
- Anisotropy (mixing in higher harmonics to p-wave)
- Disorder
- Leggett's wavefunction. $<L_z>$ reduced

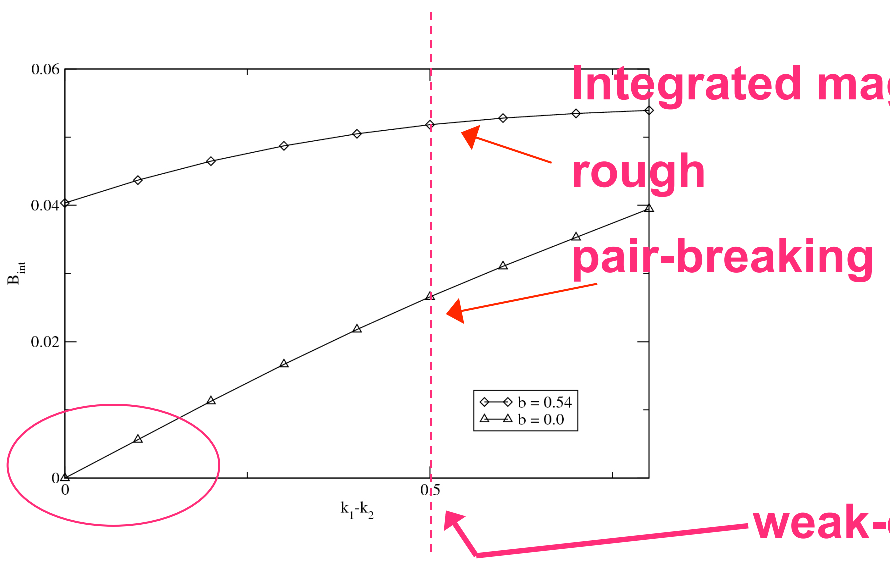
All of the above will reduce all supercurrents (domain walls, impurities) and so would reduce expected muSR signature as well

- Need to look for surface effects such as roughness, pairbreaking, nucleating other order parameters. Considerations not the same for edge currents and for observing domain walls intersecting ab surface.

EFFECTS OF SURFACE ROUGHNESS, PAIRBREAKING, GL PARAMETERS

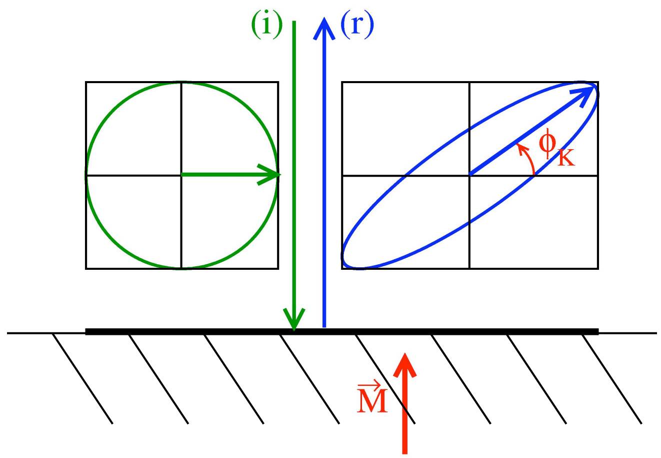






If one forces $\partial_x u \approx \partial_x v$ and considers pair-breaking surface, then supercurrents greatly suppressed.

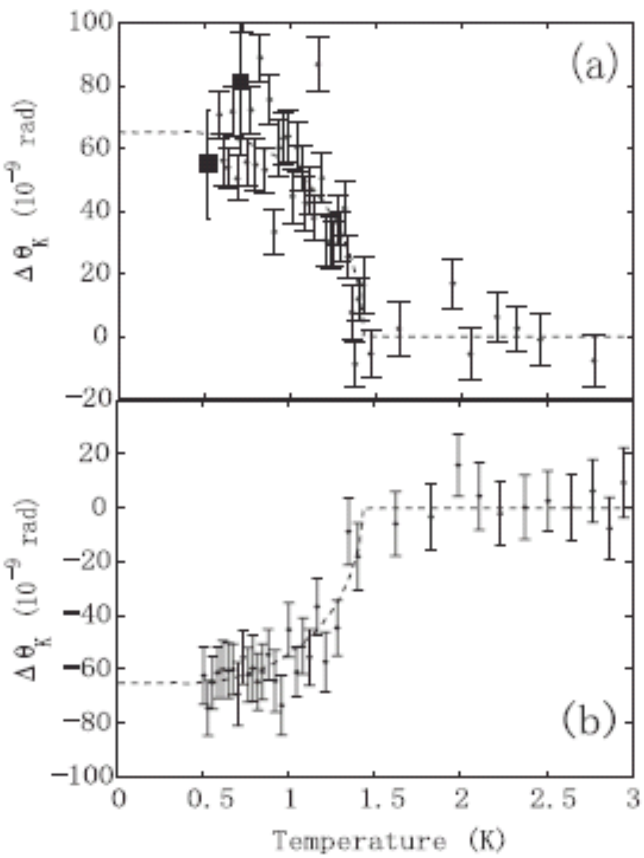
Polar Kerr effect



Linearly polarized light is reflected as elliptically polarized light, with rotation of polarization axis by Kerr angle

Measure magnetization perpendicular to surface in FM

Requires broken time-reversal symmetry



Cooled in (a) 93 G (b) -43 G
[ω=0.8ev; Θ=60 nanorads]

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

Polar Kerr effect

$$\theta_K = \frac{4\pi\sigma''_{xy}(\omega)}{n(n^2-1)\omega} \propto \sigma''_{xy}(\omega)$$ (for $\omega > \omega_p$)

Absorptive part of σ_{xy} → system absorbs either right or left circularly polarized light preferentially

However, in the absence of disorder $$\vec{j}_s = \frac{ie^2\rho_s/m}{\omega + i\delta}\vec{E} \Rightarrow \sigma_{xy} = 0$$

This follows from translational symmetry (clean limit). Uniform field couples only to COM momentum and cannot depend on e-e interactions.

In the clean limit, e-e interactions can enter through

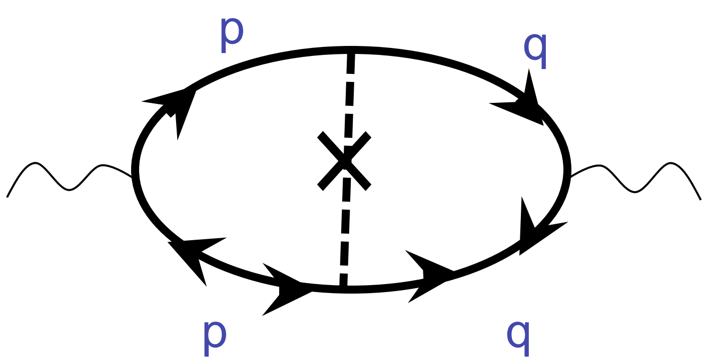
(i) Finite size effects (small spontaneous dc Hall effect due to edges)

(ii) probing system at finite wavelength q

In 2D limit, Goryo and Ishikawa (1999), found $\sigma_{xy} = c_{xy} \frac{c_s^2 k^2}{\omega^2 - c_s^2 k^2}$

3D case: Lutchyn, Nagornykh, Yakovenko and Roy, Kallin, PRB (2008).

With disorder, translational invariance is broken and relative and COM degrees of freedom couple → nonzero Kerr effect is allowed.



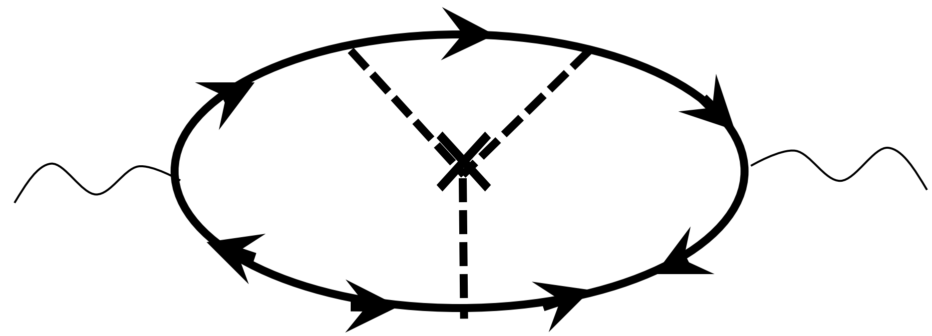
External vertices give $\sigma_{ij}p_iq_j$
→$p \times q = pq\sin\theta$
Angular integral averages to zero

Goryo identified diagrams of order n_iU^3 (skew scattering) which contribute.

$\mathrm{Tr}[\tau_3 G(p)G(k)]=2i\Delta^2\sin\theta$
→$\sin^2\theta$ → **nonzero, only for l=1 !**

~ comparable to experiment; a bit small & likely to be reduced

Explanation? Test by studying disorder and frequency dependence of Kerr effect.



$$\sigma_{xy}^{(v)}(\omega) = \gamma_{BCS}^2\left(1-\frac{T}{T_c}\right)\frac{l_\parallel}{\xi_0}\left(\frac{\epsilon_F}{\pi\tau_0}\right)^{3/2}\frac{\sigma_{xy}^{(0)}}{(\omega+i/\tau_0)^3}$$

Jun Goryo, PRB (2008).

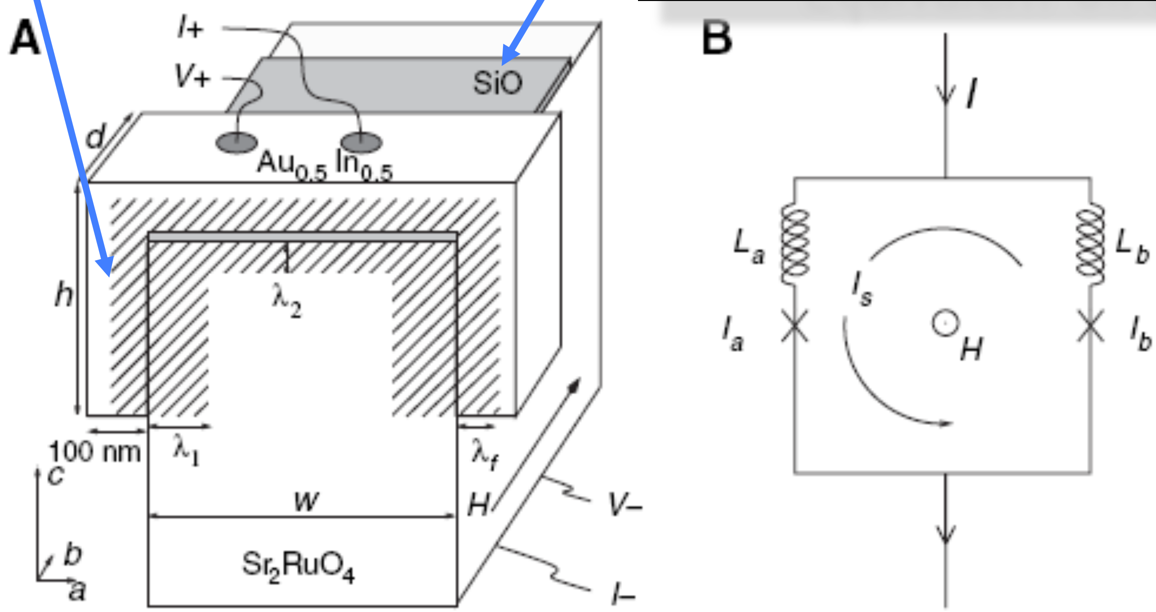
Phase sensitive measurements

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

S-Wave Superconductor

Insulating layer

Equivalent Circuit



GLB geometry

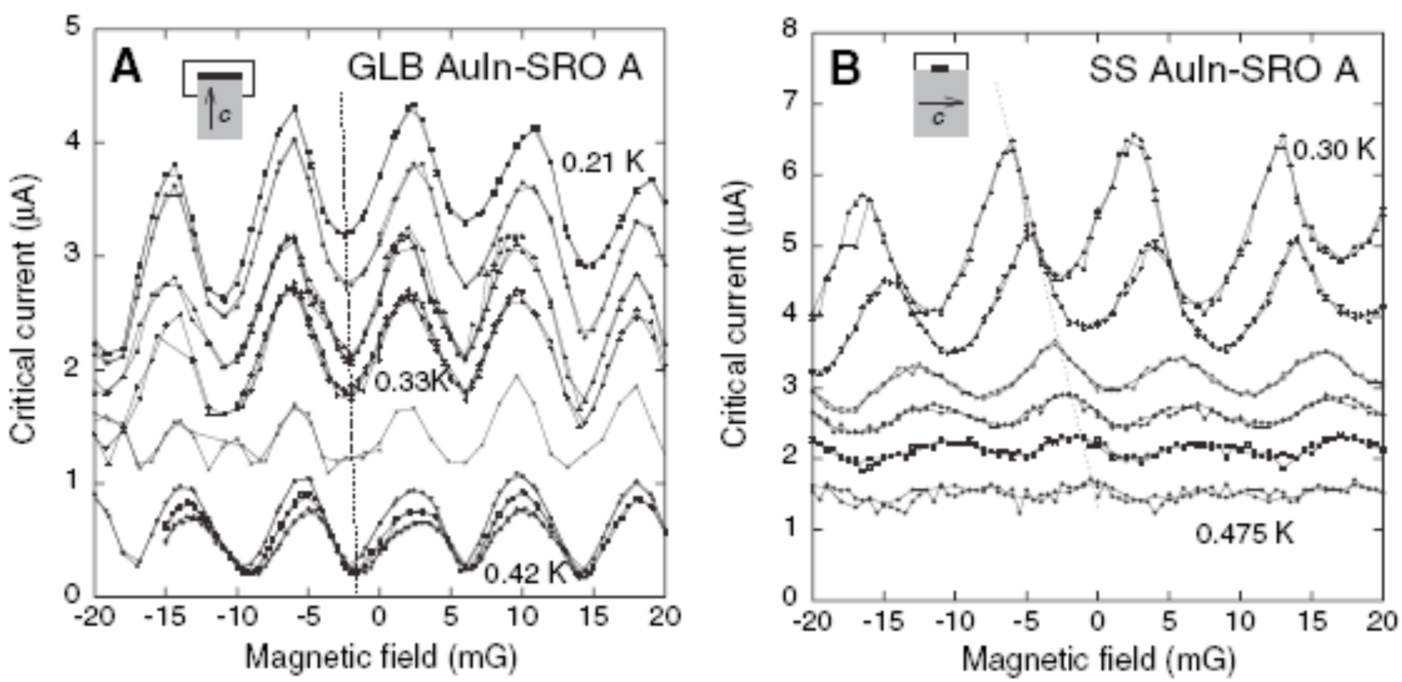
Tunneling from singlet to triplet allowed by spin-orbit coupling
Geshkenbein, Larkin, Barone (GLB) geometry

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

Phase ~ $\mathbf{d}\cdot(\mathbf{n}\times\mathbf{k})$
gives π for opposite b-c faces (GLB)
and zero for same b-c faces (SS)

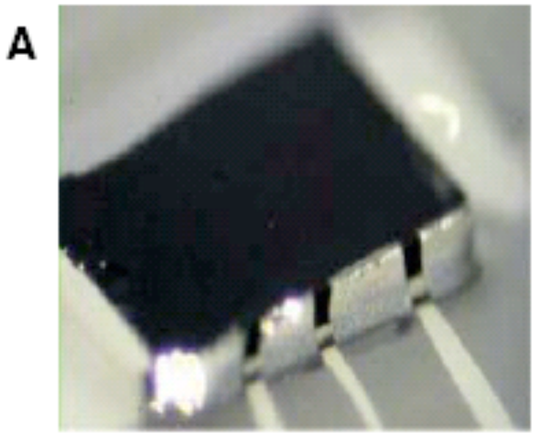
GLB Geometry

SS geometry



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

Recent phase-sensitive measurements



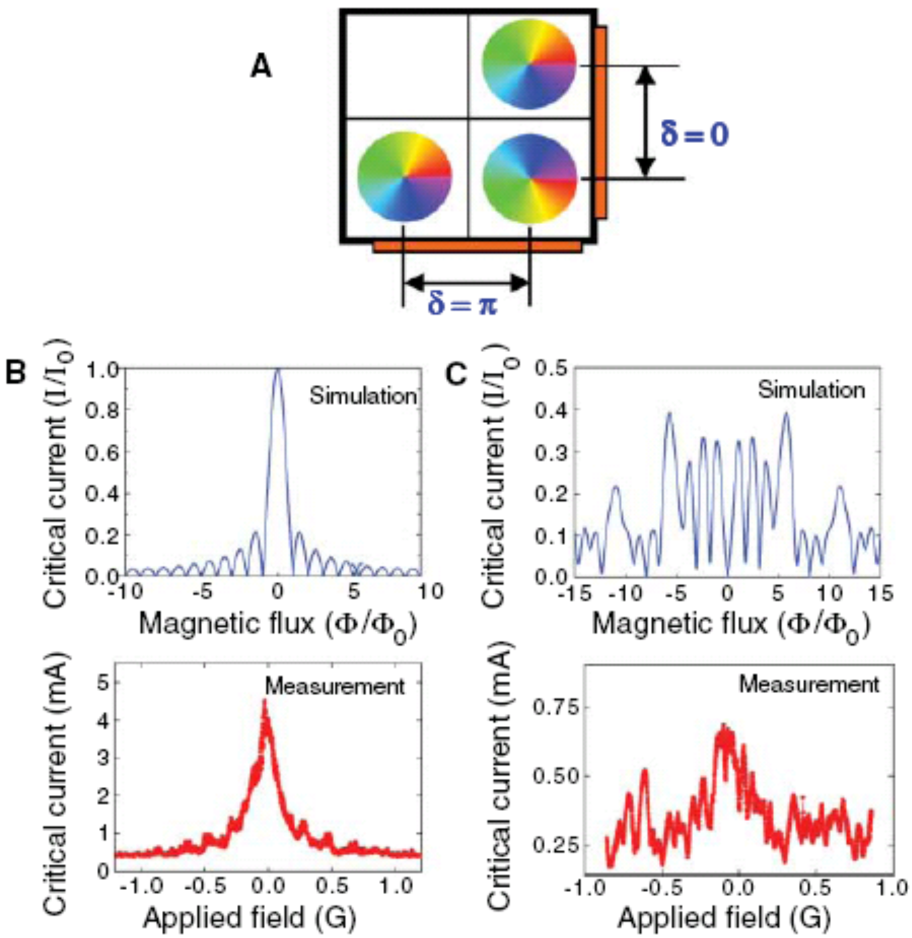
SRO single crystal (black) with 4 Josephson junctions. Gray ribbons are Pb thin film counterelectrodes. A field B is applied along c-axis.

Ideal junction of area A gives Fraunhofer pattern:

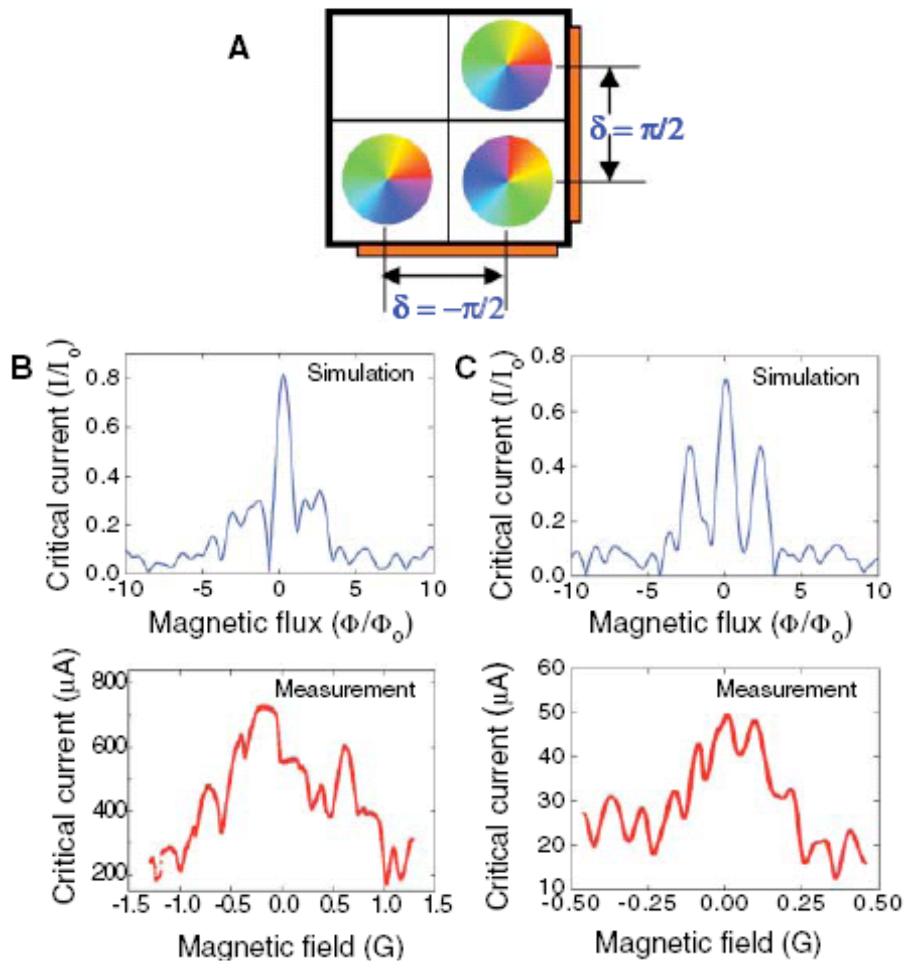
$$I_c(\Phi) = J_c A \frac{\sin(\pi\Phi/\Phi_0)}{\pi\Phi/\Phi_0}$$

Observe "Fraunhofer-type patterns" which they compare to currents expected from relative phases of 0, π, ±π/2. They conclude one needs all four relative phase factors to best model the data. Also see dynamics, which they model as dynamic domains with average size of ~1 micron.

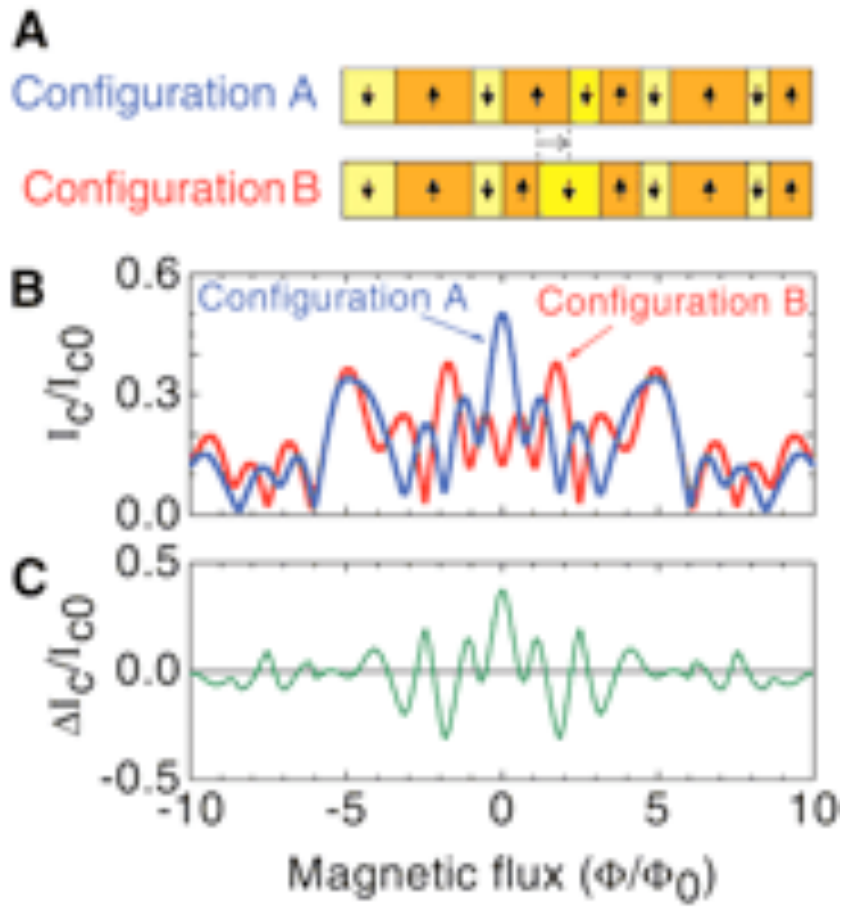
F. Kidwingira, J.D. Strand, D.J. Van Harlingen, and Y. Maeno, Science 314, 1271 (2006).



A
δ = 0
δ = π
B
Simulation
Critical current (I/I0)
Magnetic flux (Φ/Φ0)
Measurement
Critical current (mA)
Applied field (G)
C
Simulation
Critical current (I/I0)
Magnetic flux (Φ/Φ0)
Measurement
Critical current (mA)
Applied field (G)



A
δ = π/2
δ = −π/2
B
Simulation
Critical current (I/Io)
Magnetic flux (Φ/Φo)
Measurement
Critical current (μA)
Magnetic field (G)
C
Simulation
Critical current (I/Io)
Magnetic flux (Φ/Φo)
Measurement
Critical current (μA)
Magnetic field (G)



Observed “complicated modulations characteristic of interference between regions with different phase and size...”

Data is best captured in the modeling of dynamic ±p±ip domains.

Domain walls which intersect surface at an angle (not π/2) can give rise to phase shifts other than ± 1. (Sigrist)

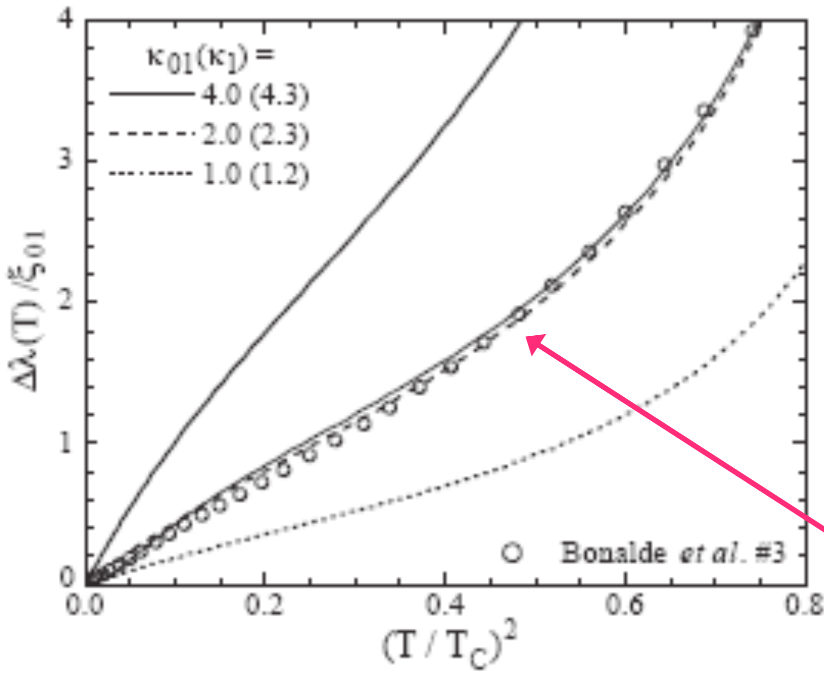
F. Kidwingira, J.D. Strand, D.J. Van Harlingen, and Y. Maeno, Science 314, 1271 (2006).

Time Reversal Symmetry Breaking

Experiment	TRSB?	Domain size [limit >0.3μ]
muSR (Luke & Ishida)	Yes	< 2 μ
Kerr rotation (Kapitulnik)	Yes	> 50 μ with field cooling ~ > 15-20 μ in ZFC
Scanning Hall Probe (Moler)	No	< 1 μ
SQUID (Kirtley)	No	< 2 μ
Tunneling (van Harlingen)	Yes	< 1 μ ~0.5 μ dynamic
Tunneling (Liu) Corner junctions	Parity Yes	>10-50 μ

Are there nodes?

Penetration Depth



Low T data shows power law behaviour → nodes?

Analysis complicated by multi-band effects which give power-law-like behaviour down to relatively low T. Need very low T data (below 0.05K) to resolve differences.

Data is inconclusive.

Comparison of data, fit with line nodes, fit with no nodes

From Kusunose & Sigrist Euro Phys Lett (2002);
Data from Bonalde et al. PRL (2000)

Putting it all together

- SRO is an unconventional SC; likely triplet pairing (JJ expt also points to triplet) but NMR data with B along c-axis is not explained.
- Substantial evidence of time-reversal symmetry breaking, but all require assumptions about domain walls and/or disorder, and absence of observable edge currents remains a puzzle.
- Need direct evidence of domain walls (if they exist!)
- Other order parameters?

The end