Superconducting pairing symmetries in the 3-K phase of Sr_2RuO_4

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KITP, UCSB. December 12, 2007

Acknowledgement

Penn State

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Collaborators

Single crystal growth

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Low-temperature scanning SQUID measurements

J.R. Kirtley (IBM), K. Moler (Stanford), K. Hasselbach (CNRS)

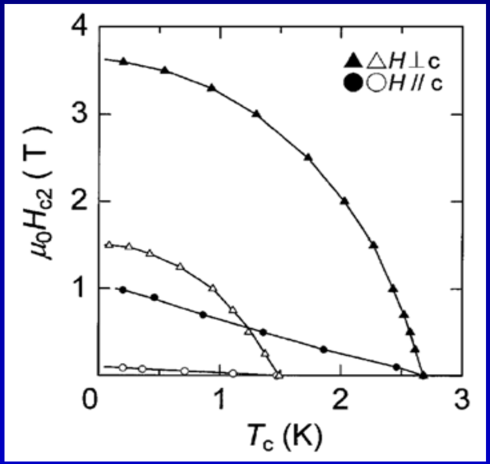
Work supported by DOE

Ru in Sr_2RuO_4: The 3-K phase

Y. Maeno *et al.*, Phys. Rev. Lett. 81, 3765 (1998).

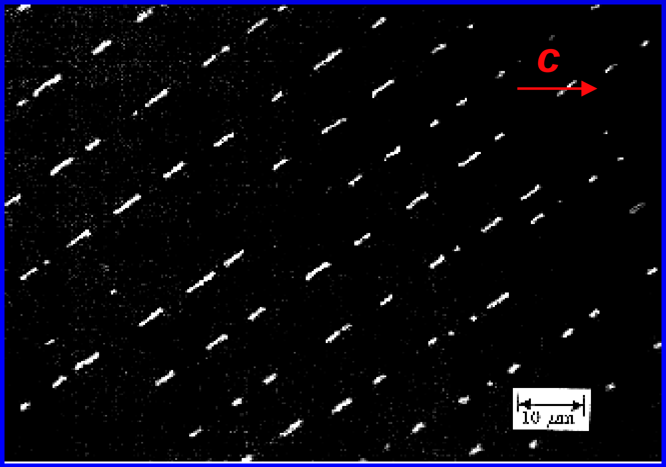
Surprising enhancement of T_c!

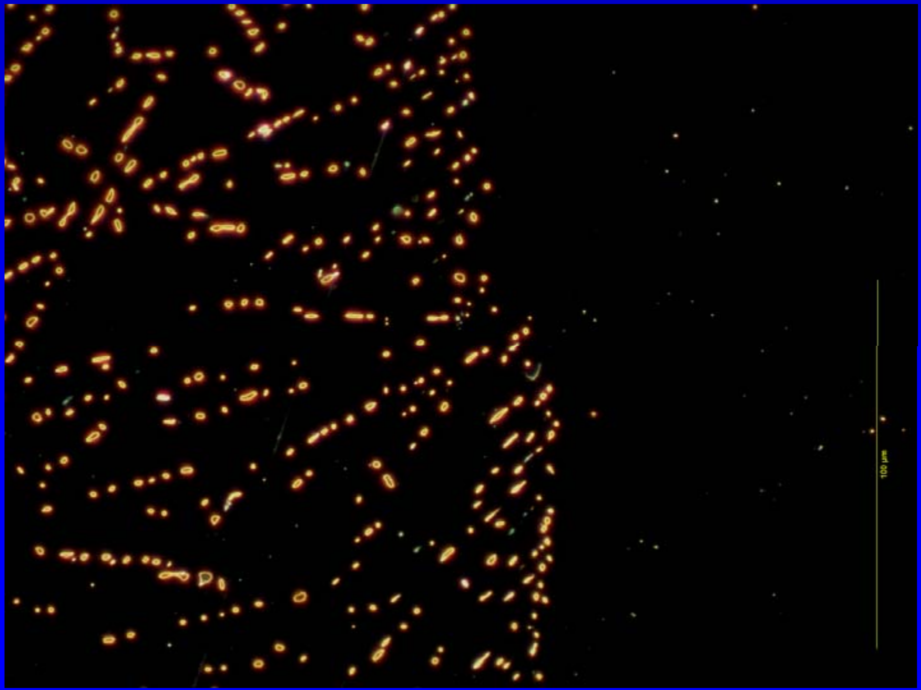
$T_c^{bulk} = 1.5K$	$T_c^{Ru} = 0.5K$	$T_c^* \leq 3K$
$H_{c2}^{c} = 0.075T$	$H_c = 69G$	$H_{c2}^{c} = 1.0T$
$H_{c2}^{ab} = 1.5T$		$H_{c2}^{ab} = 3.6T$



Early interests:

- Insight into the mechanism of superconductivity in Sr_2RuO_4?
- Phenomenology of interfacial unconventional superconductivity.

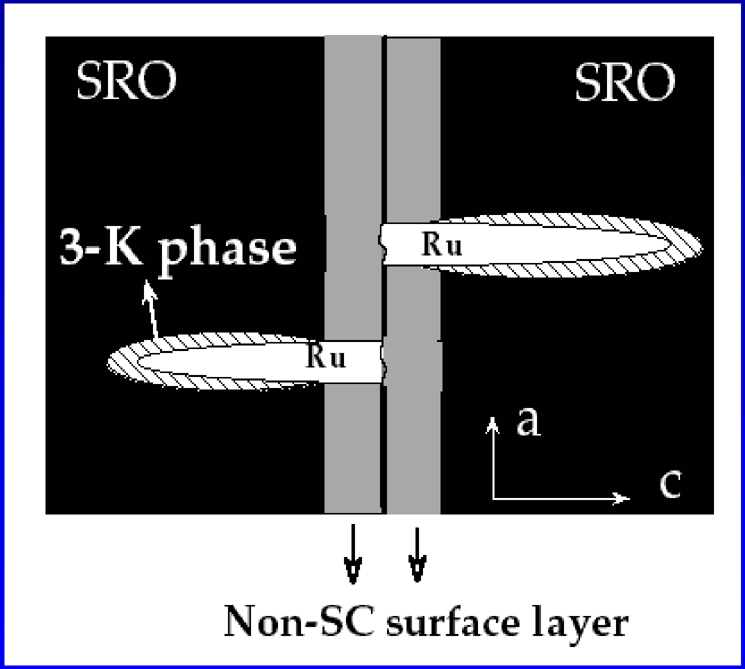


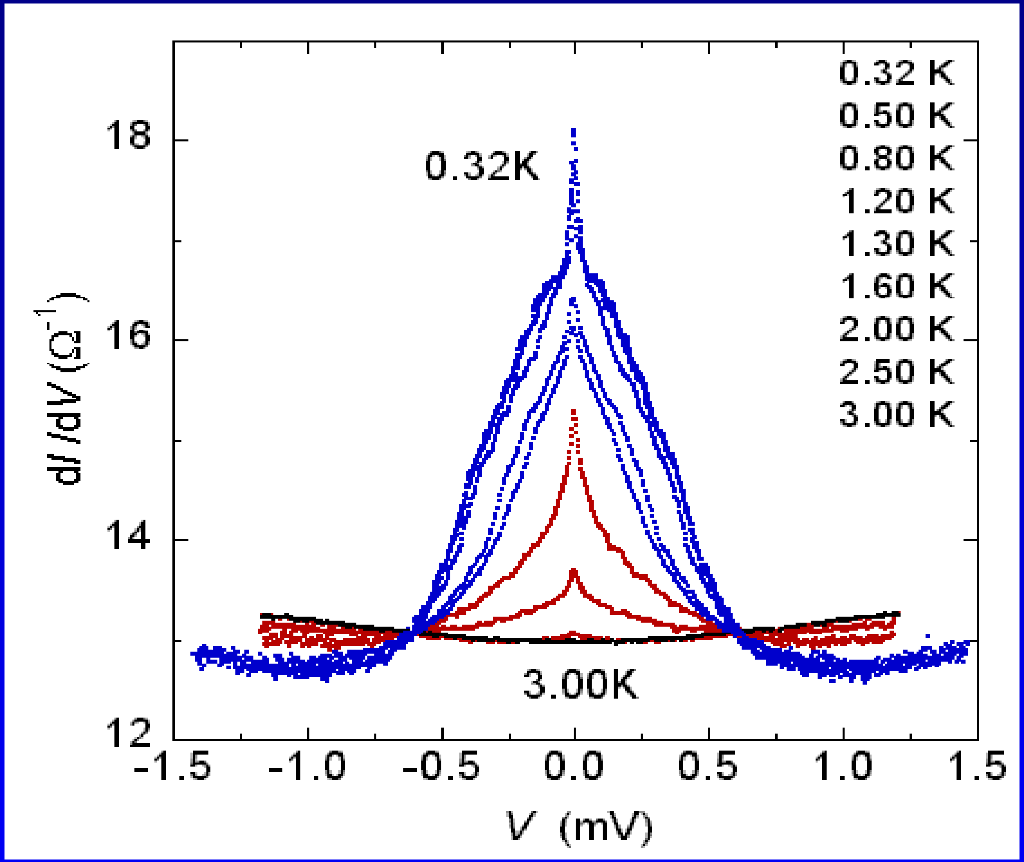


Andreev surface bound states in the 3K phase

Z. Q. Mao, K.D. Nelson, R. Jin, Y. Liu, and Y.Maeno, PRL 87, 037003 (2001).

Single-crystal cleave (break) tunnel junctions





Superconductivity in the 3-K phase is also unconventional!

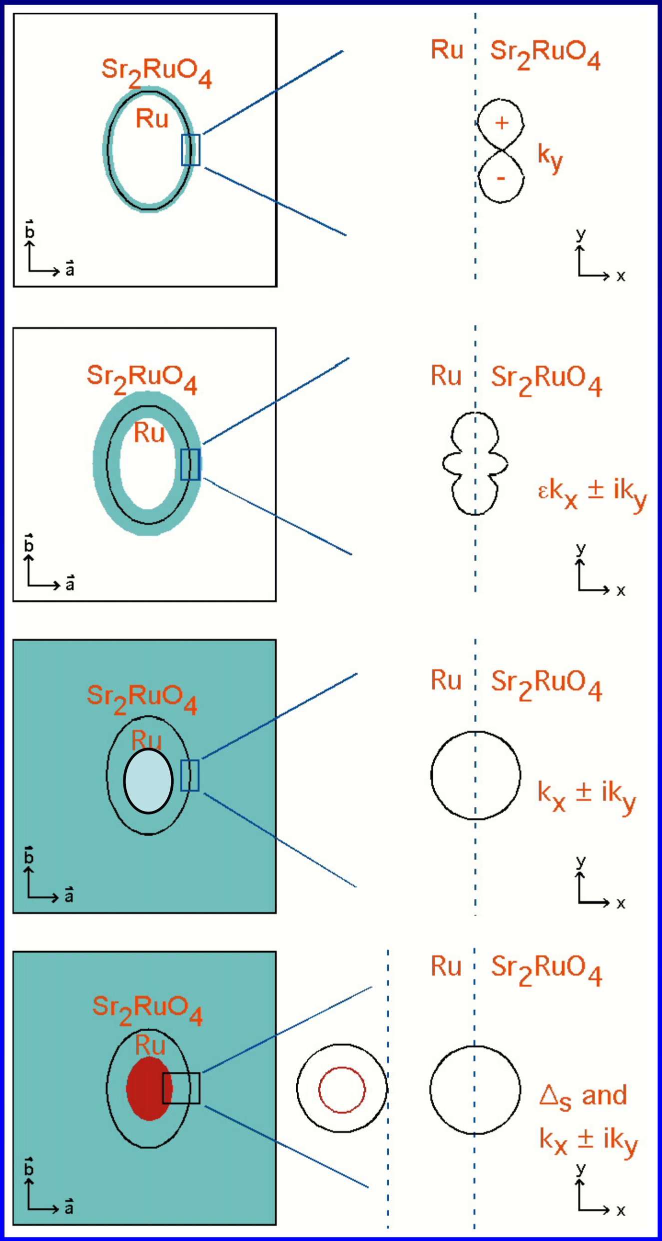
Pairing symmetries of Ru embedded in Sr_2RuO_4

An unconventional mesocopic superconducting system that that gives rise to some unique physical phenomena not available in conventiona mesoscopic superconductors.

Mixed pairing state at the lowest temperatures?

Ru microdomains do remember that it is an *s*-wave superconductor to begin with:

$V_{l=0} > V_{l=1}$



$T_0 < T < T_c^{3K}$

$T_c^{bulk} < T < T_0$

$T_c^{Ru} < T < T_c^{bulk}$

$T < T_c^{Ru}$

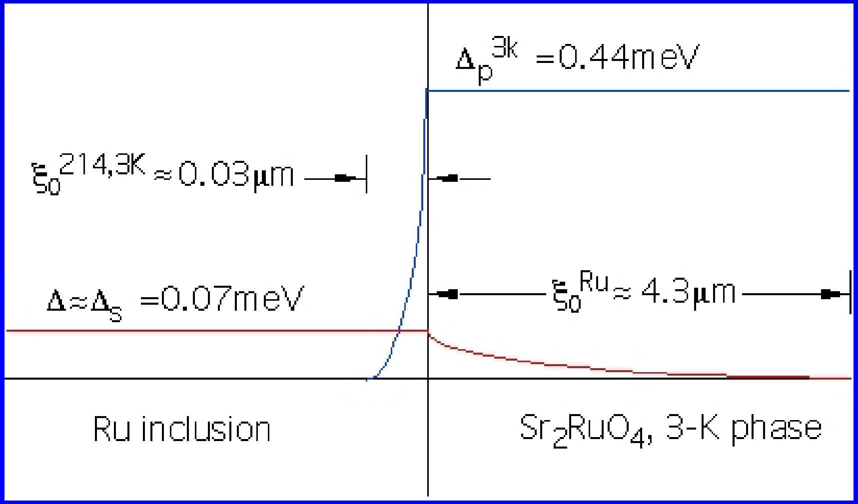
Mixing of two pairing states!

Proximity effect at an *s*- and *p*-wave interface at zero temperature

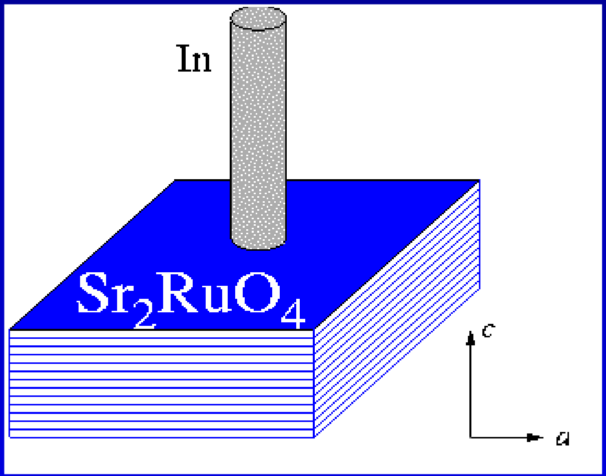
Theoretical work

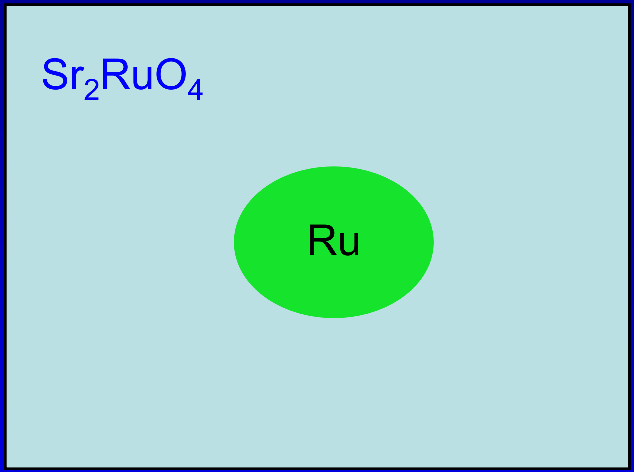
Millis, 1985.
Millis, Rainer, Sauls, 1988.
Yip, De Alcantara Bonfim, Kumar, 1990.

In the T = 0 limit, physics is similar to conventional superconductors.



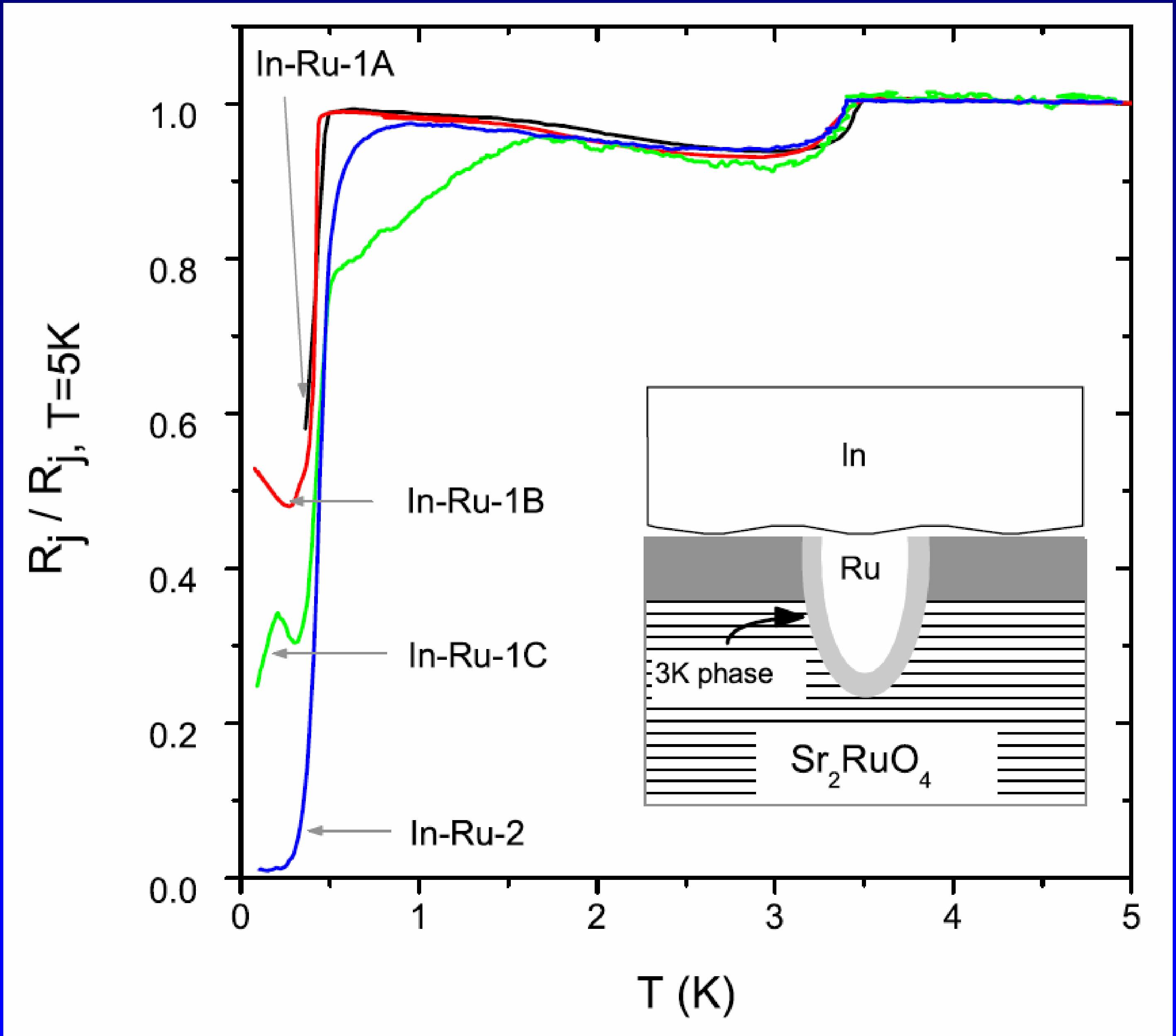
Experiment I: Pressed In on almost pure Sr_2RuO_4 crystal (*ab* face)



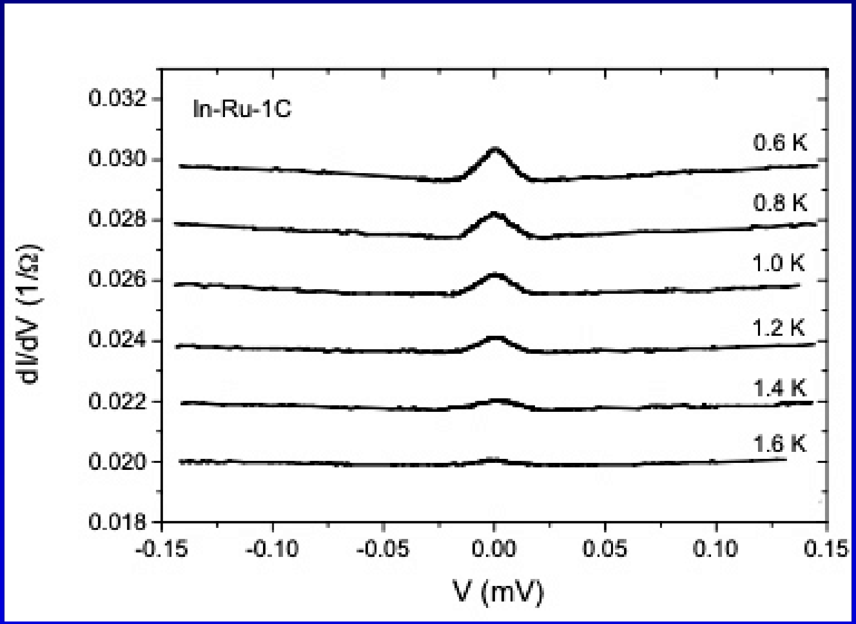


Ru microdomains involved in the pressed In junction will be small in size. Only few of them will be present at the junction.

Temperature dependent tunneling resistance



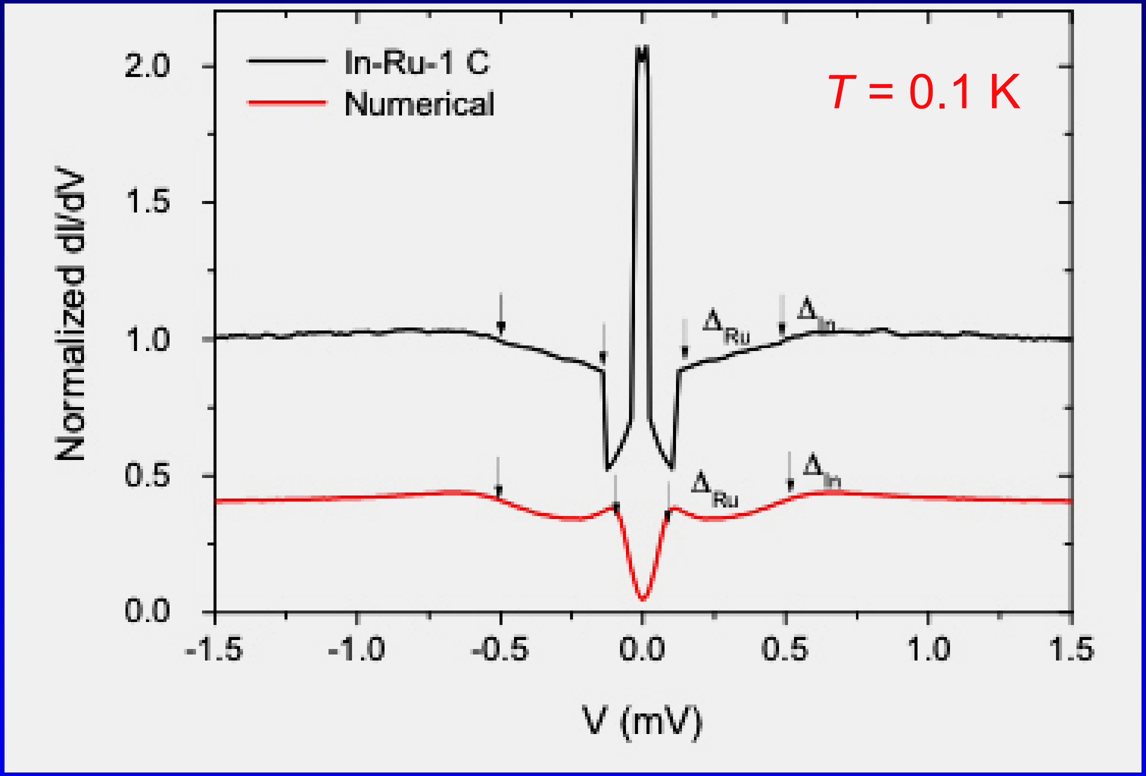
Behavior above the intrinsic T_c of Ru



Observation of a zero-bias conductance peak (ZBCP)

$\Rightarrow$ Andreev surface bound states
$\Rightarrow$ proximity induced, small unconventional pairing in Ru

Opening of a superconducting energy gap in Ru

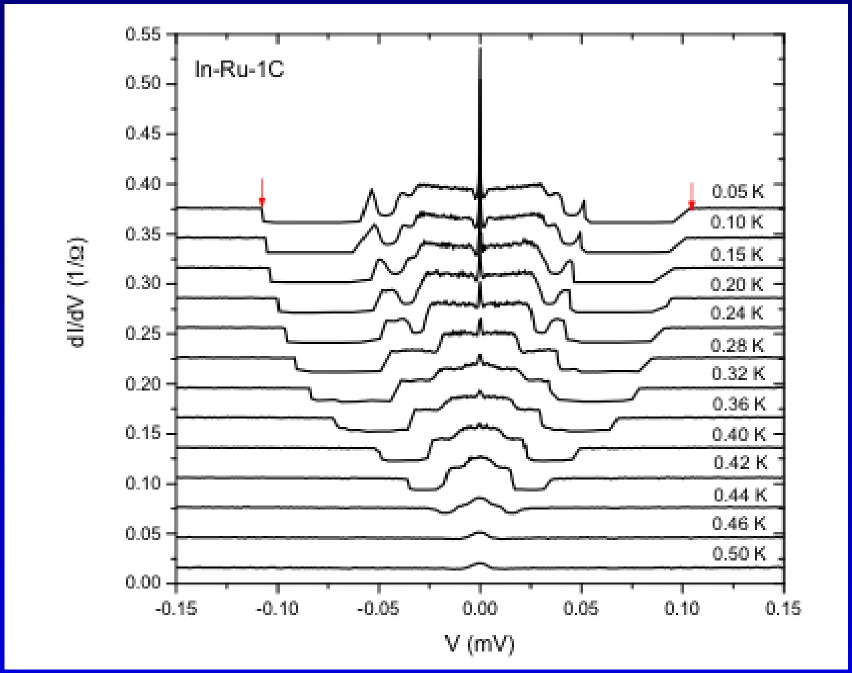


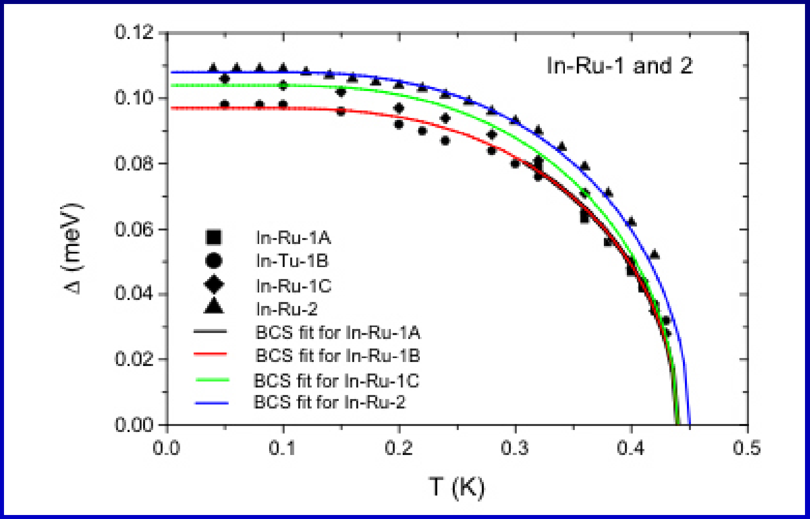
$$I(V) = \int_{-\infty}^{+\infty} N(E)N'(E+eV)\left[f(E) - f(E+eV)\right]dE$$

$$N(E) = \mathrm{Re}\left[\frac{|E| + i\Gamma}{\sqrt{(|E| + i\Gamma)^2 - \Delta^2}}\right]$$

$\Delta_{Ru}(0) = 0.1\mathrm{meV}$?

Temperature dependence of the energy gap





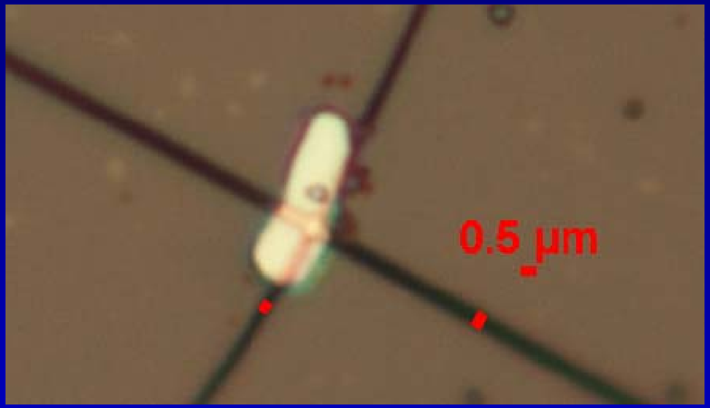
BCS *T*-dependence fits well.
□□□ Δ(0) ≈ 0.1meV!

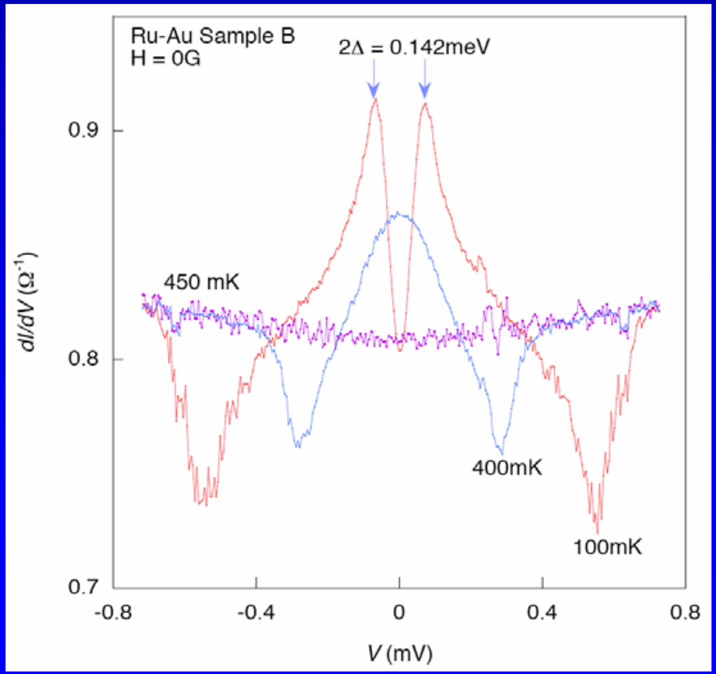
If Ru is a BCS weak-coupling superconductor, we expect

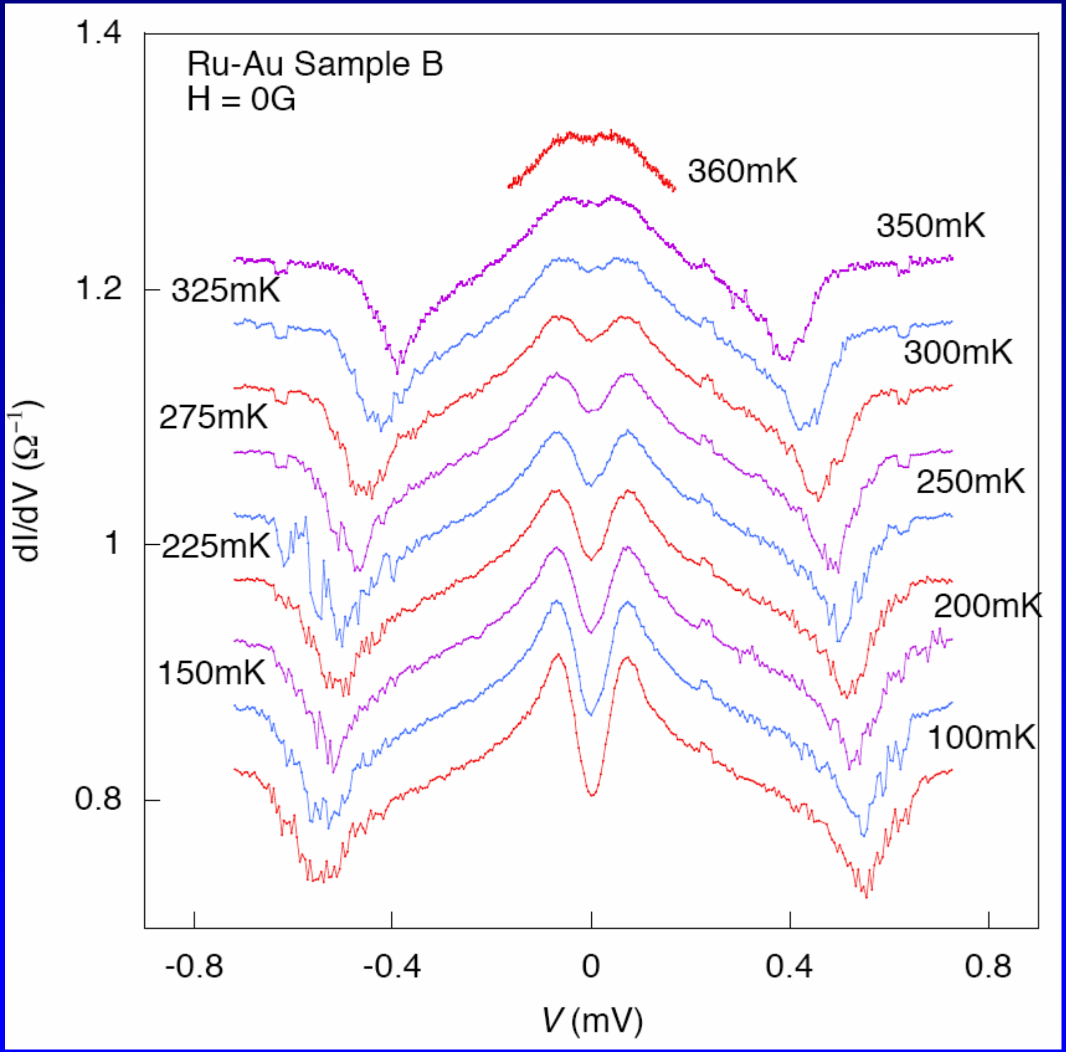
$$\Delta = 1.76 k_B T_C = 1.76 k_B (0.5K) \approx 0.072 meV$$

Is Ru weak coupling superconductor?
Ru gap has never been determined before!

Experiment II: Tunneling into a single Ru domain



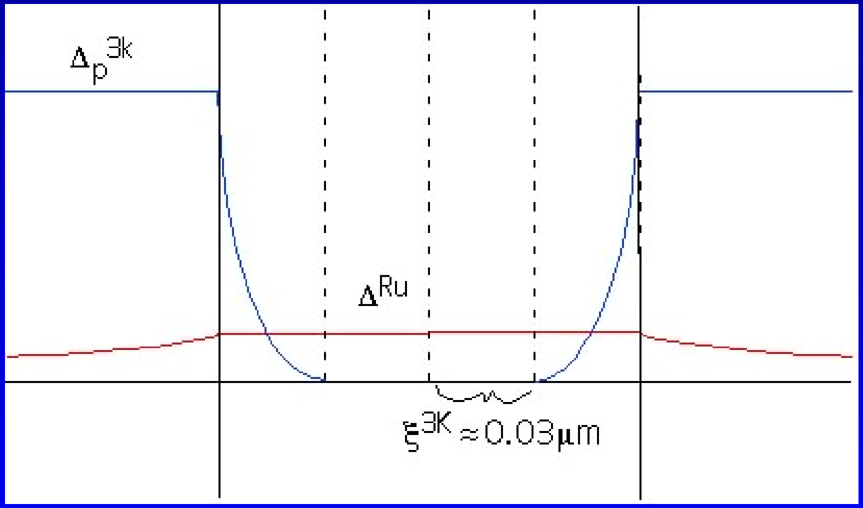




The Ru microdomain is large compared with $\xi^{214}(0) \approx 0.066$ μm

Origin of the anomalously large energy gap

For Ru inclusion of a size only several times larger than the T = 0 coherence length of the 3K phase, the interplay between the condensation energy and the kinetic energy due to gradient of the order parameter becomes important.



If $\Delta_{Ru} = \Delta_s + i\Delta_p$ $\quad |\Delta_s| \approx |\Delta_p| \approx 0.072 meV$

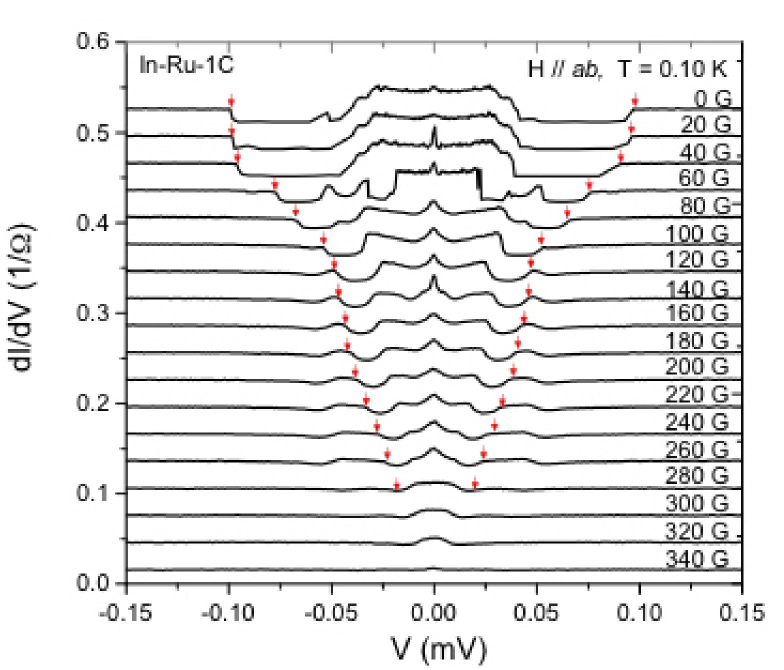
$\Rightarrow \Delta_{Ru}(0) = 0.102$ meV!

A chiral mixed pairing state? Not forbidden by symmetry Consideration because this occures in a mesoscopic sample.

Different critical field for the *s*- and *p*-wave pairing?

H // ab (along the junction plan)

Therefore the field can penetrate the Ru surface into which tunneling occurs easily.

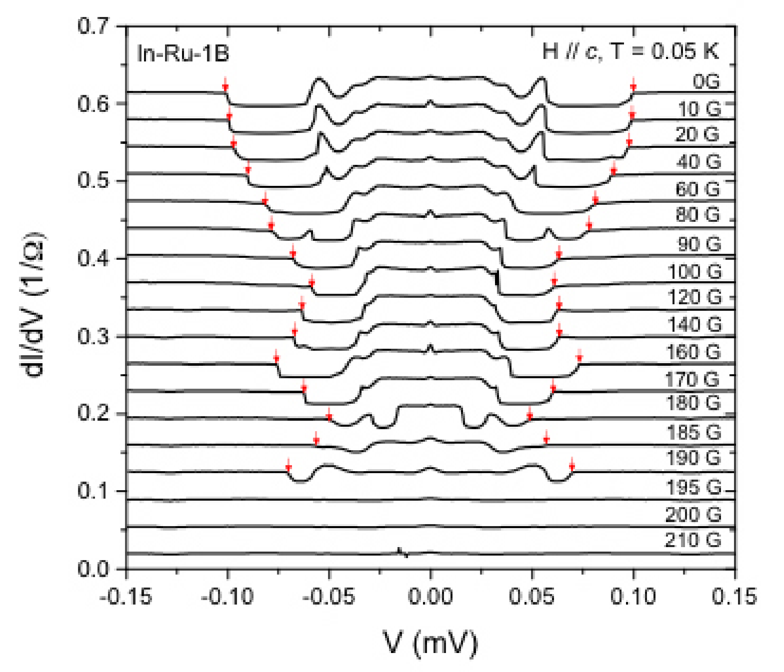


Field suppresses the gap at $H = H_c^{Ru} = 69$ G, making.

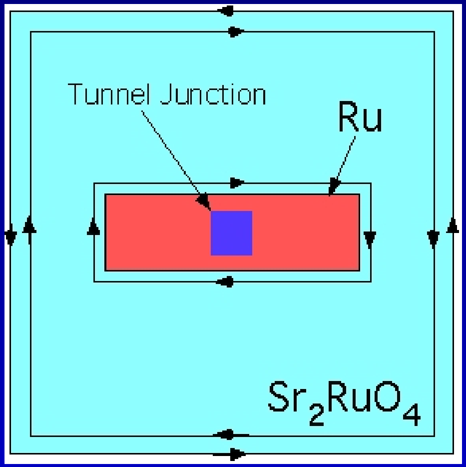
$$\Delta_{Ru} = \Delta_p \approx 0.072 meV$$

Results were reproduced in another sample.

Effects of a perpendicular magnetic field



1) Interplay between The chiral and Field-induced current near the Ru/Sr_2RuO_4 interface?



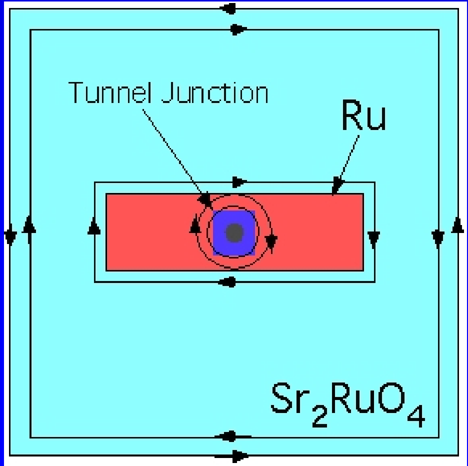
How is the current induced?

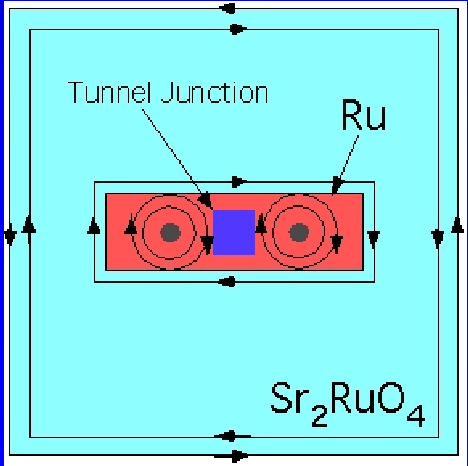
2) Vortex physics?

$H \perp ab$

Field modulates the gap in a non-monotonic way!

Physical origin?





Conclusion

- In a Ru microdomain embedded in Sr_2RuO_4, there may be a mixed pairing state below 0.45 K.

- Ru-Sr_2RuO_4 provides a fascinating arena for studying the physics of unconventional, odd-parity superconductivity!