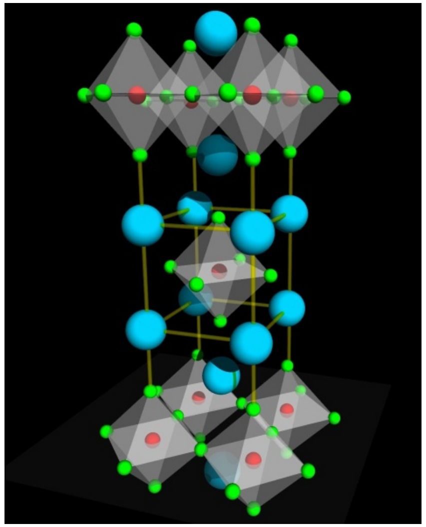


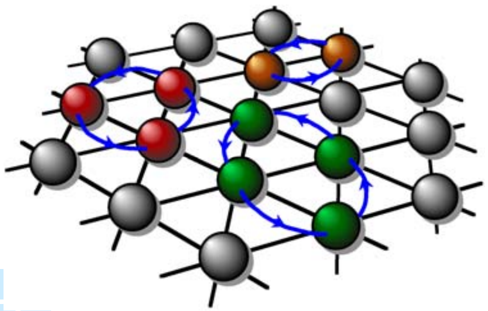
Novel Quantum Phenomena
in Superconducting Sr_2RuO_4

Interference between *s*-wave superconductor and Sr_2RuO_4

Y. Maeno, R. Nakagawa, T. Nakamura,

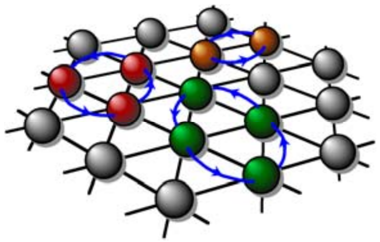
T. Yamagishi, S. Yonezawa, T. Terashima

Kyoto University



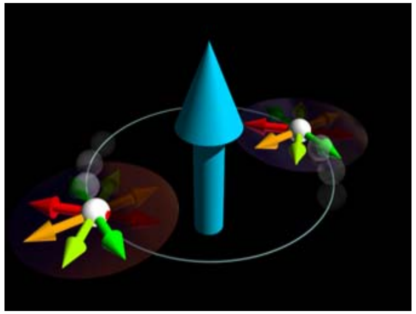
The "Superclean" Project (FY2005-2009)

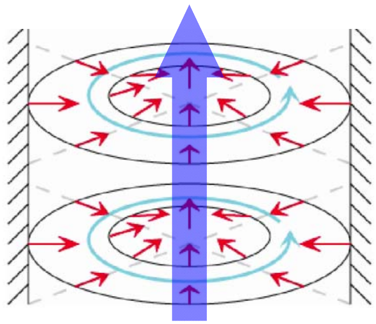
A04: Anisotropic Superconductors and Superfluids



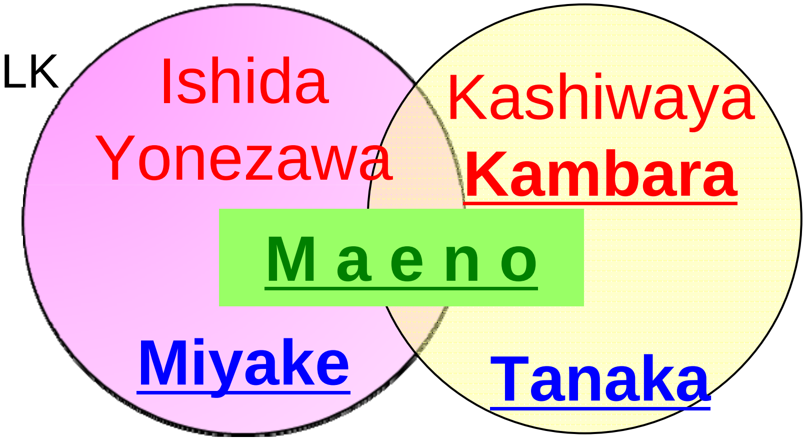
Sr_2RuO_4	(1.5 K)	^{3}He-A, B
Sr_2RuO_4-Ru	(3 K)	^{3}He-A-like

A04g: Maeno (Kyoto) A04h: Ishikawa (Osaka City)





BULK



EUTECTICS
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INTERFACES

Posters on Ruthenate SupeC

P121 Kittaka: T_c of *pure* Sr_2RuO_4 can be as high as 3.2 K *!*

P123 Nakagawa: Pb/Ru/Sr_2RuO_4 proximity junctions

P 116 Karaki, P118 Tenya: Magnetization curves

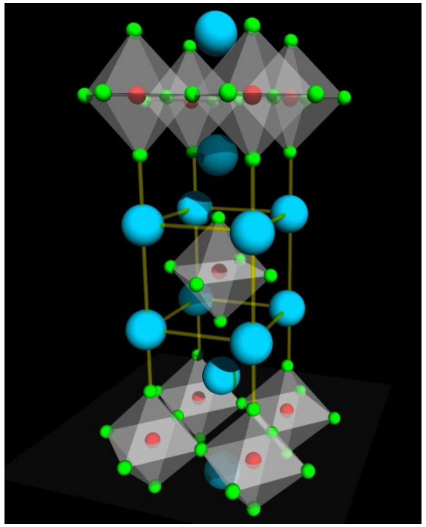
P119 Ishida: NMR review

P139 Kashiwaya: Microdevices

P117 Nomura, P120 H.Ikeda, P124 Yanase:

d-vector orientation (theories)

P138 Sakaki: ***E***-induced M-I transition in Ca_2RuO_4



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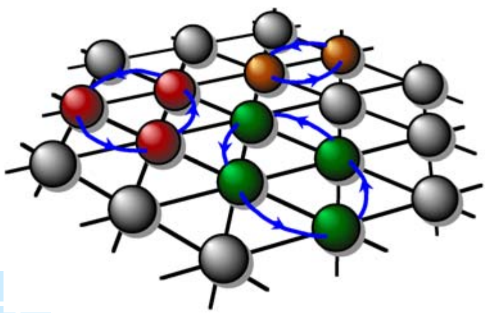
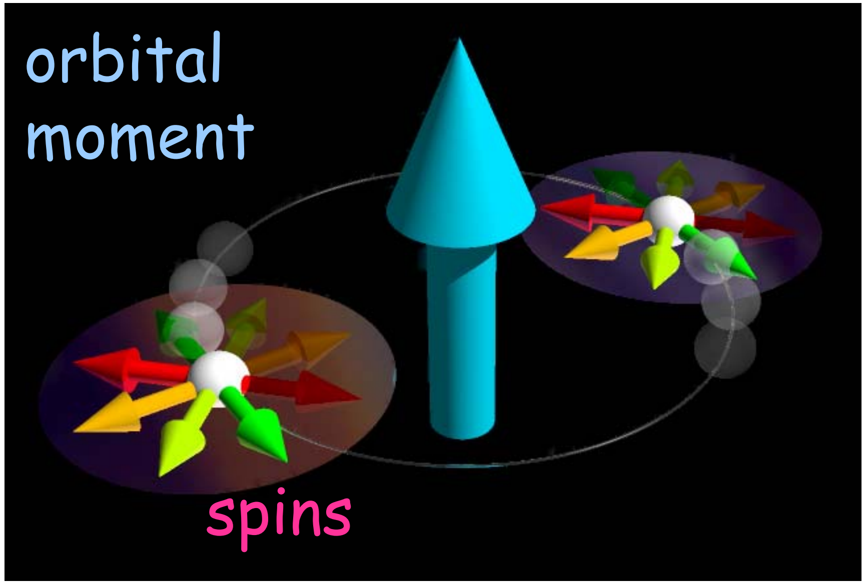


Kyoto University

Pairing Symmetry of Sr_2RuO_4



$$\boldsymbol{d} = \boldsymbol{z}\,\Delta_0(k_x + ik_y)$$

A.P. Mackenzie and Y. Maeno, Rev. Mod. Phys. **75**, 657 (2003).

Spins: $S = 1$, $S_z = 0$ → **?**

Spin

- **NMR Knight shifts**
- Polarized neutrons

➜ **Spin Triplet Pairing**

Orbital moment: $L = 1$, $L_z = 1$

Orbital

Broken T

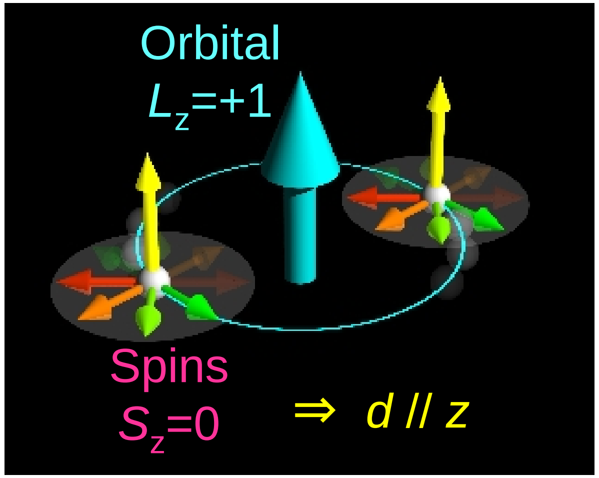
- μSR
- Vortex lattice
- Kerr effect

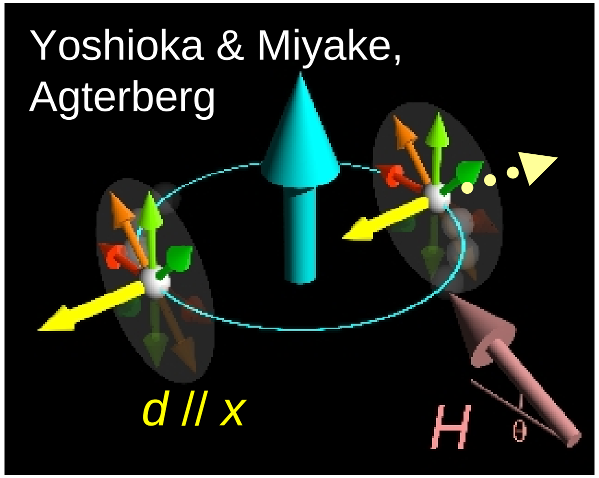
➜ **Broken Time Reversal Symmetry**

- **Josephson effect**
- **chiral domains**

➜ **Odd Parity (*p*-wave)**

Spin Orientation (*d*-vector) in Sr_2RuO_4





Both spin states are compatible with NMR experiments.

Murakawa, Ishida *et al.*

Half-quantum vortex (HQV) is possible,

with the rotation of the *d*-vector (spin) by π,

and the orbital phase winding of π.

↓

HQV

d //*x* is preferred energetically.

S.B. Chung, Bluhm, Kim, PRL **99**, 197002 (2007).

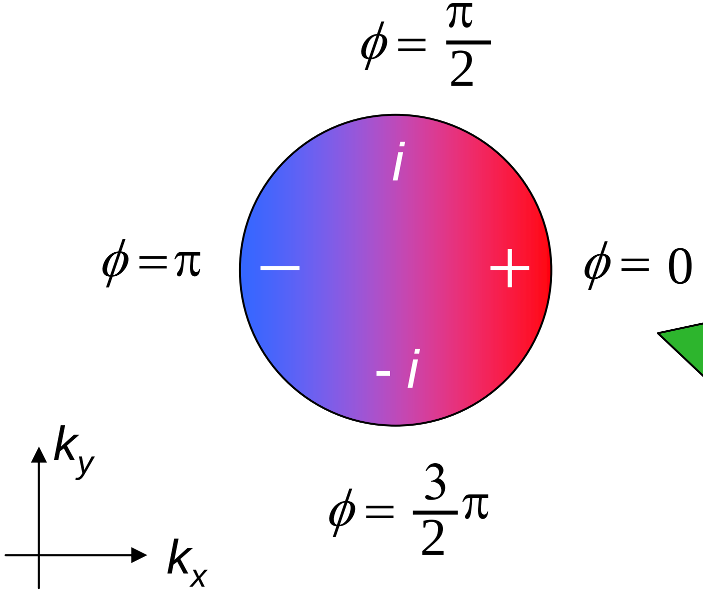
Vakaryuk, **Leggett,** PRL **103,** 057003 (2009).

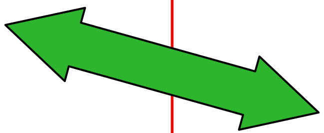
Chiral p-wave state of Sr_2RuO_4

Chiral *p*-wave

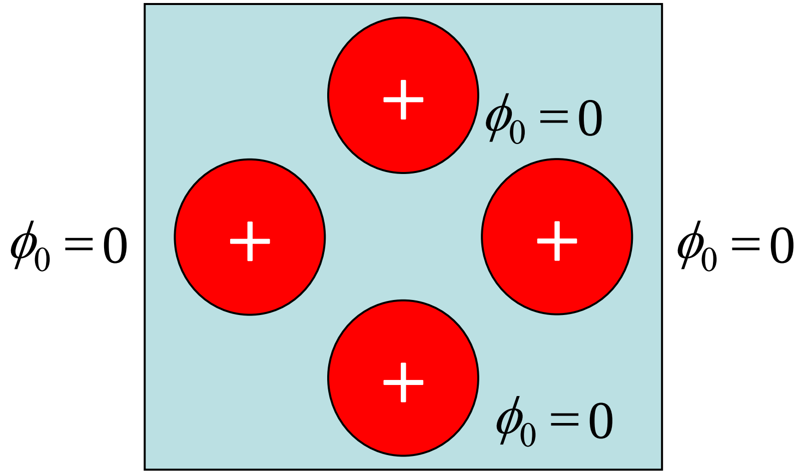
$$\Delta(k) \propto k_x + ik_y$$
$$\propto e^{i\theta_k}$$

Thus ϕ (phase) = θ_k (direction)

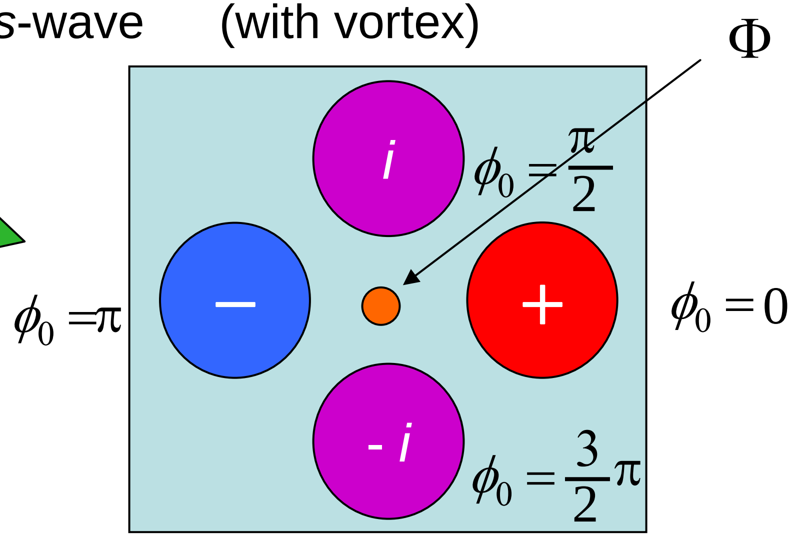




cf.) *s*-wave

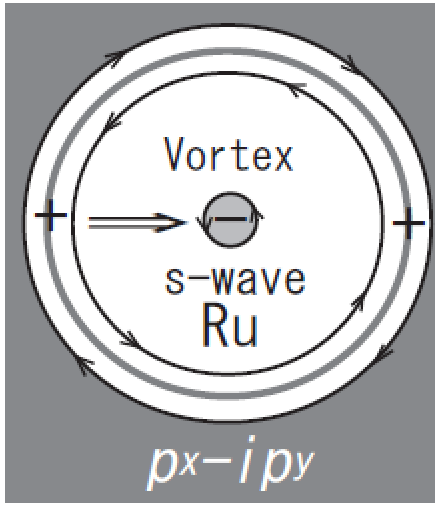


s-wave (with vortex)



Nucleation of Vortex State in Ru-inclusion in Eutectic Ruthenium Oxide Sr_2RuO_4-Ru

H. Kaneyasu and M. Sigrist, arXiv: 1002.4793v2.



T_c (Sr_2RuO_4) = 1.5 K

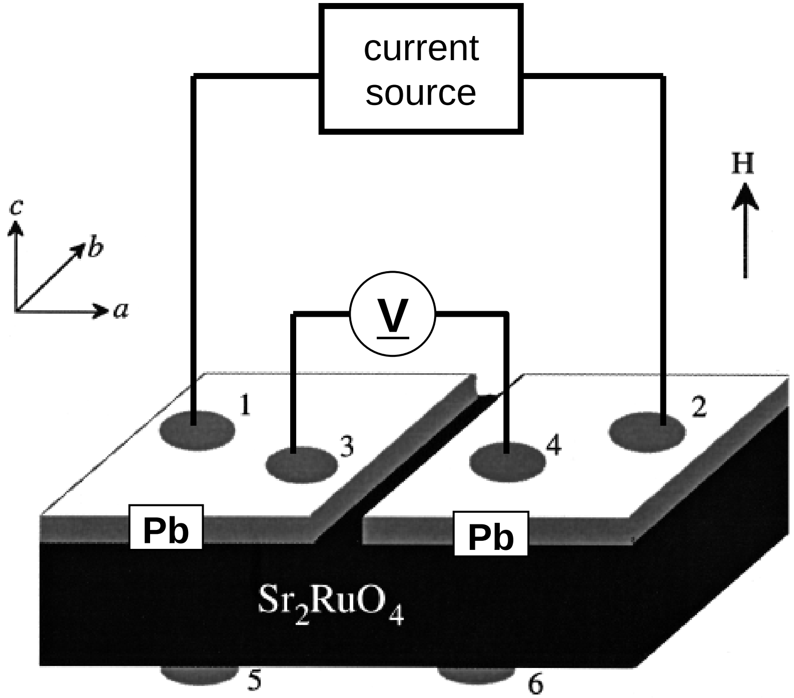
T_c (Ru) = 0.49 K

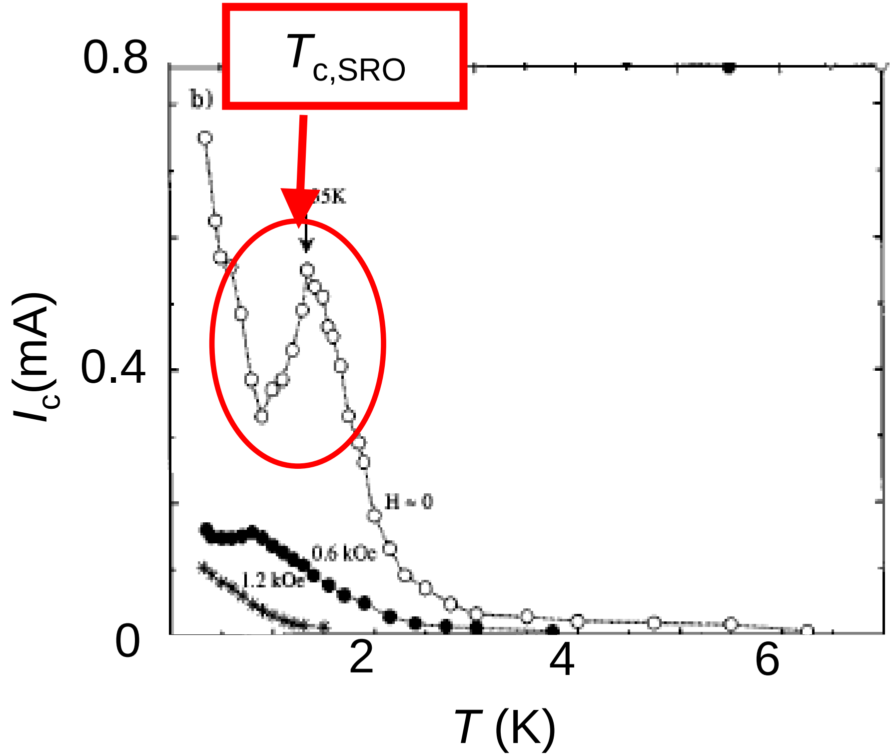
At lower T, a vortex should be induced in Ru.

Anomalous I_c–T of Pb/Sr_2RuO_4/Pb junction

■ Experimental study

R. Jin *et al.*, PRB **55**, 4433 (1999). PSU





The critical current I_c is suppressed just below $T_{c.SRO}$

Interference between the superconductivities of Pb and Sr_2RuO_4

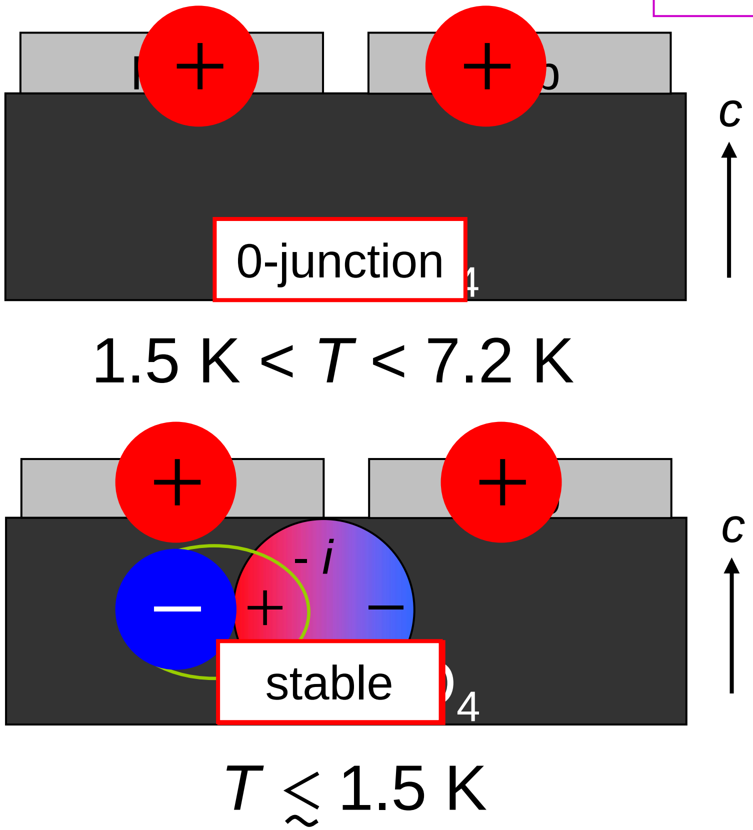
Proximity effect in Pb/Sr_2RuO_4/Pb junction

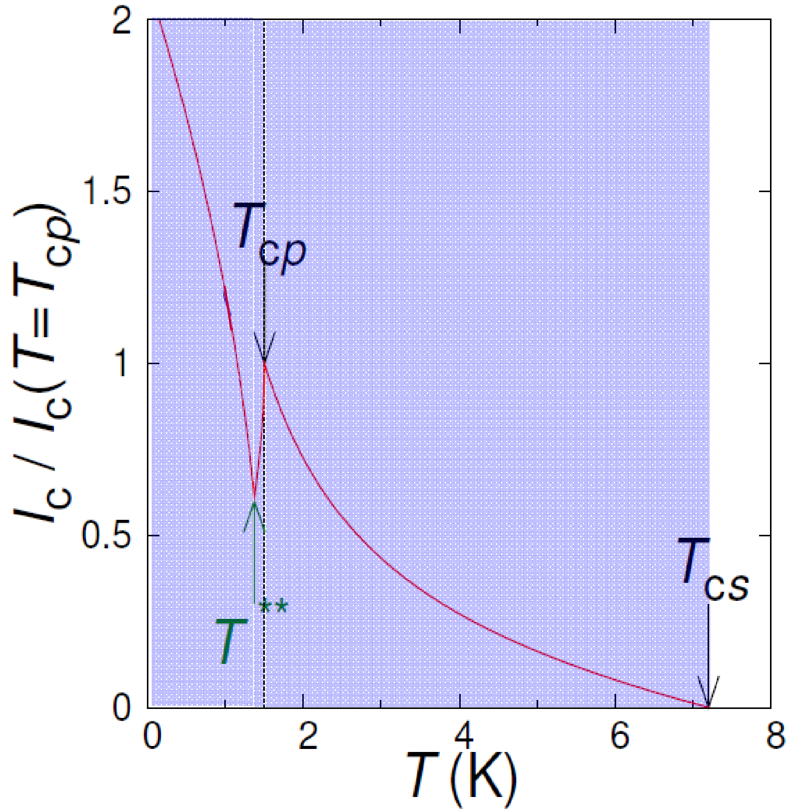
■ Theoretical study

- Pb : *s*-wave SC (T_c = 7.2 K)

Honerkamp & Sigrist
Prog. Theor. Phys. **100**, 53 (1998).

Also by Yamashiro, Kashiwaya, and Tanaka.





➡ **Phase difference between the TWO Pb electrodes changes from 0 to π.**

Important roles of Ru

In Jin's experiments,

the crystals were not *pure* Sr_2RuO_4

but Sr_2RuO_4-Ru eutectic crystal.

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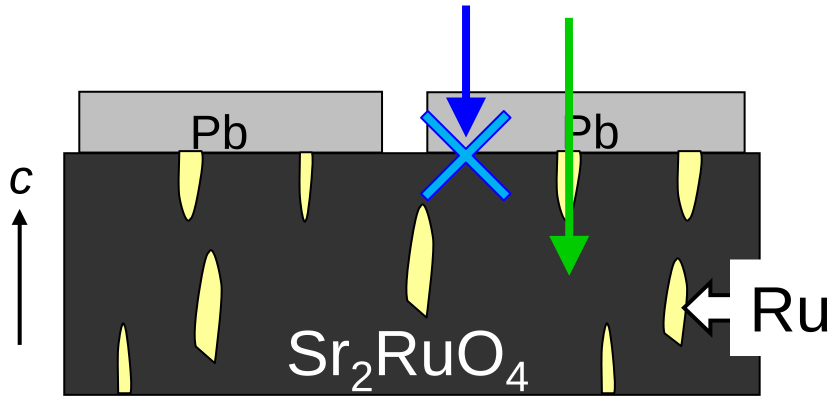


Low contact resistance

between Pb and Ru allows

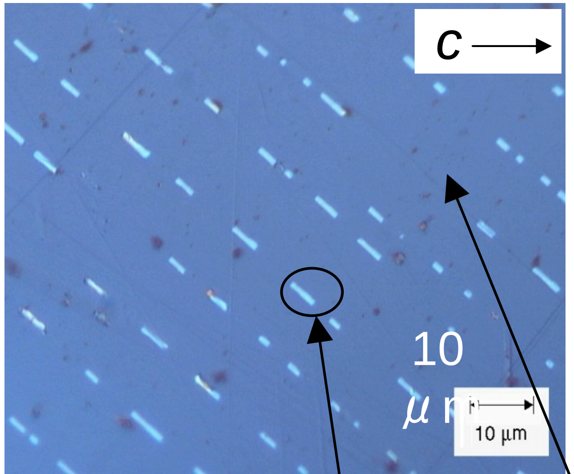
the penetration of *s*-wave SC (Pb) into Ru,

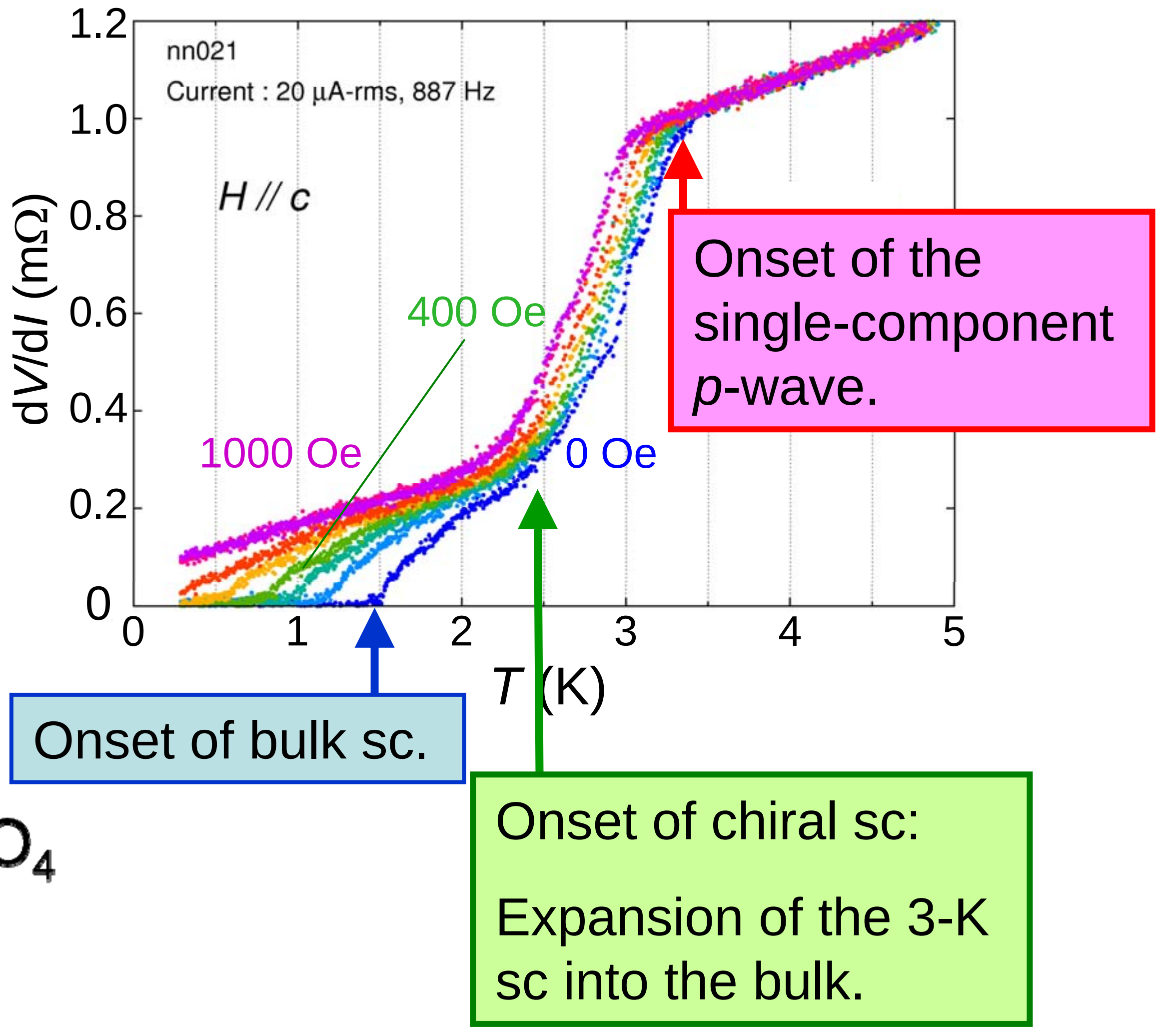
and then into Sr_2RuO_4

A complication: the 3-K superconductivity.

3-K phase superconductivity

Sr_2RuO_4-Ru eutectic system (3-K phase)





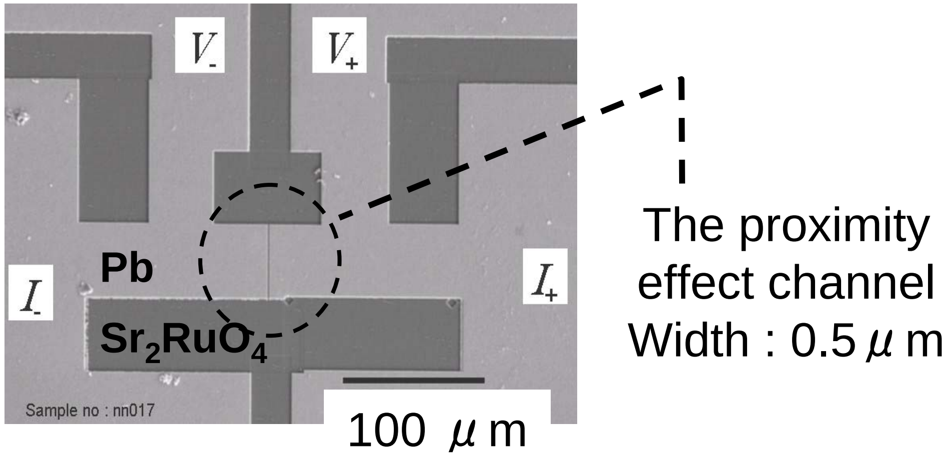
1.5 K < T < 3.3 K:

Proximity length into the NORMAL Sr_2RuO_4

$$\xi_n \sim \frac{1}{\sqrt{T - T_c}}$$

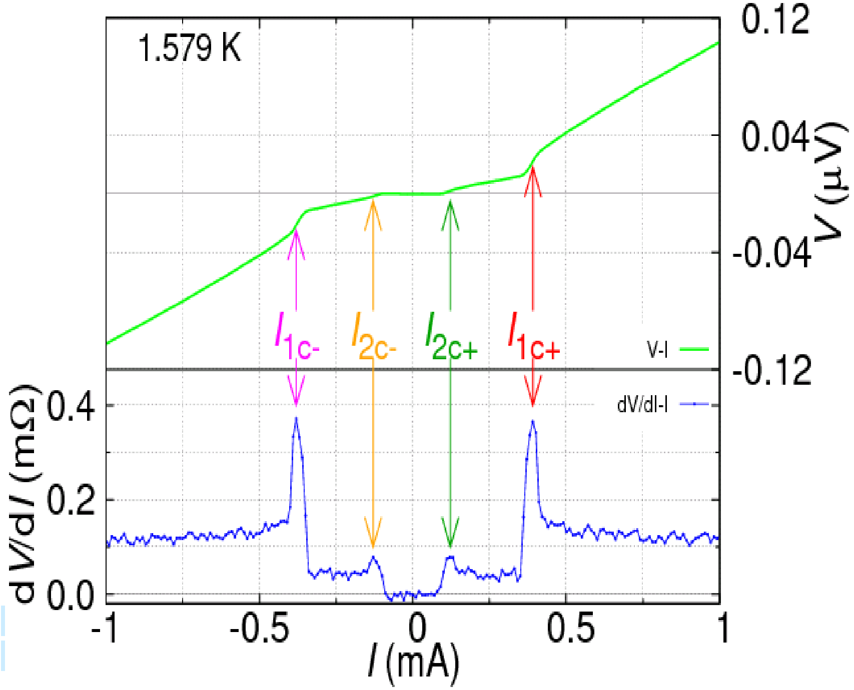
Diverges towards T_c(SRO). (Kittaka *et al.*)

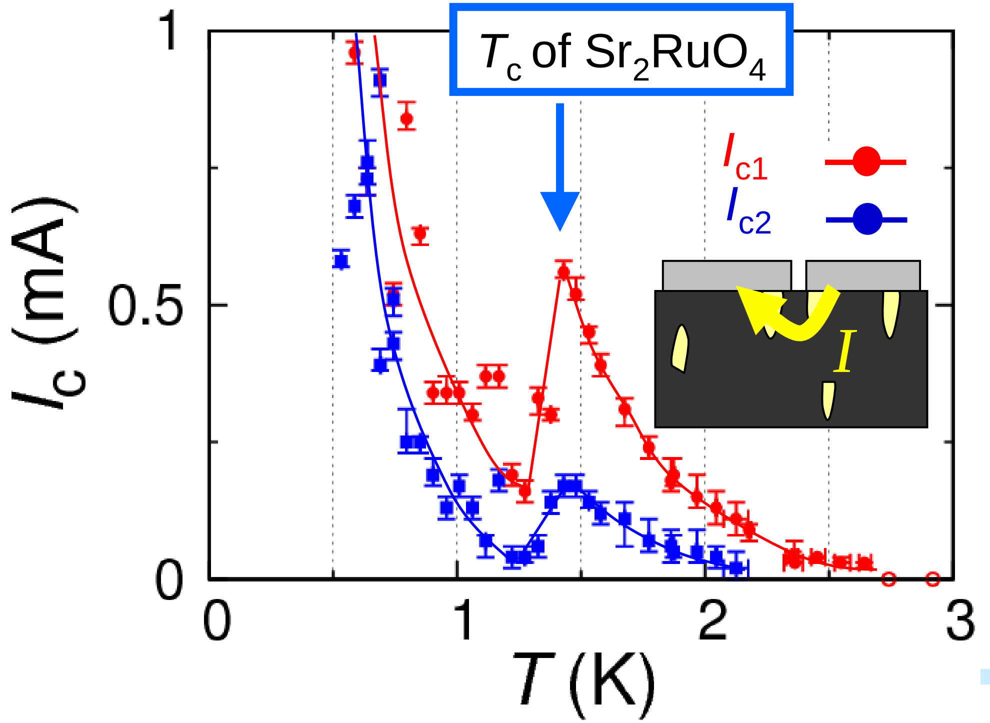
Interference well-reproduced in micro-fabricated junctions



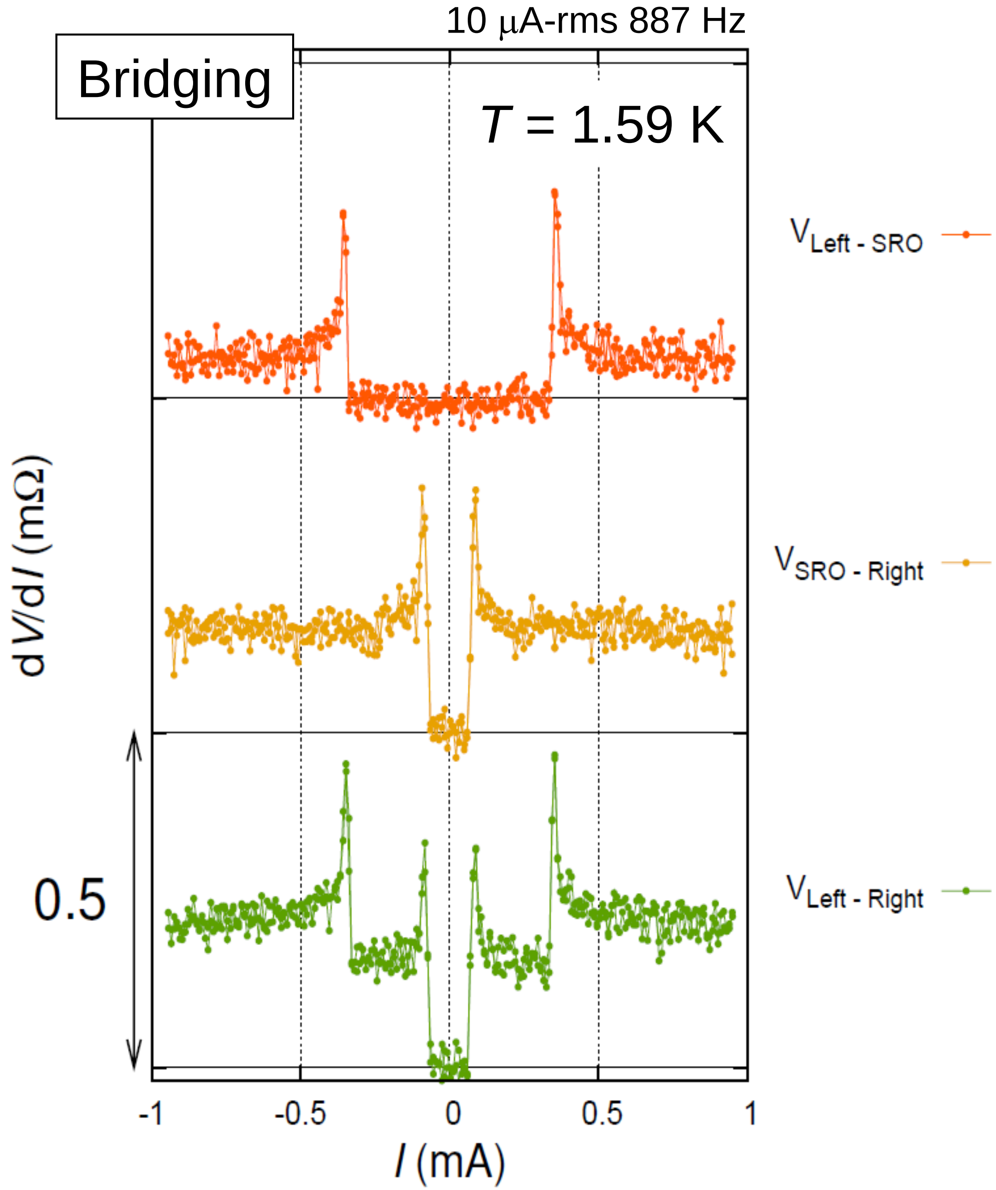
The location of a pair of Ru inclusions are precisely known.

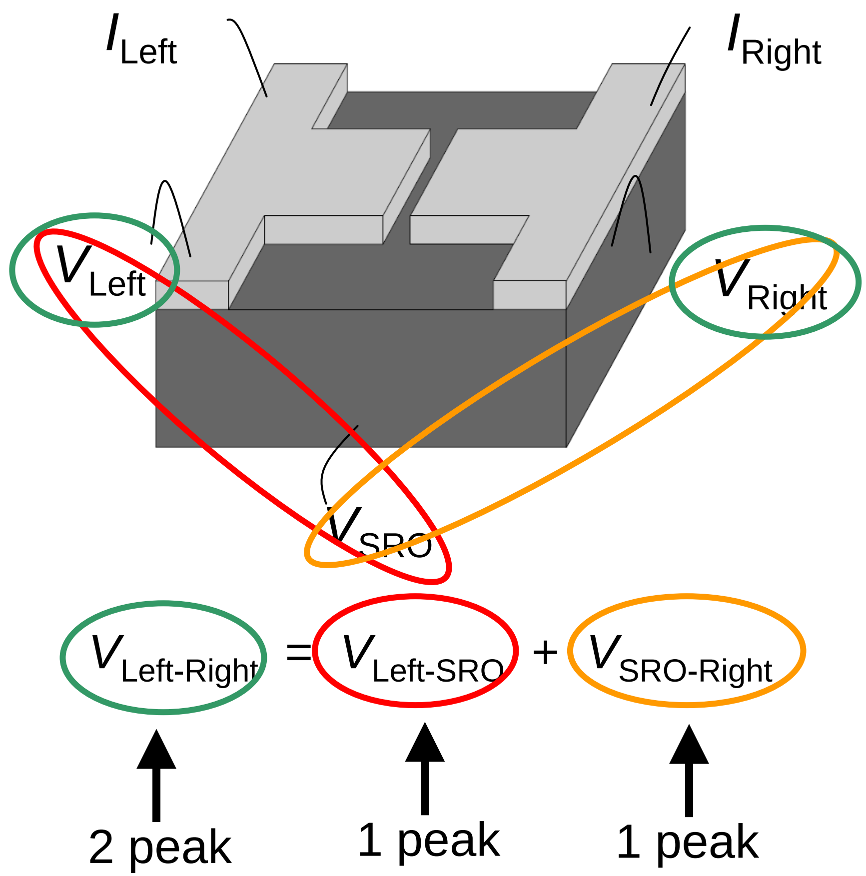
Nakamura, Nakagawa *et al.*





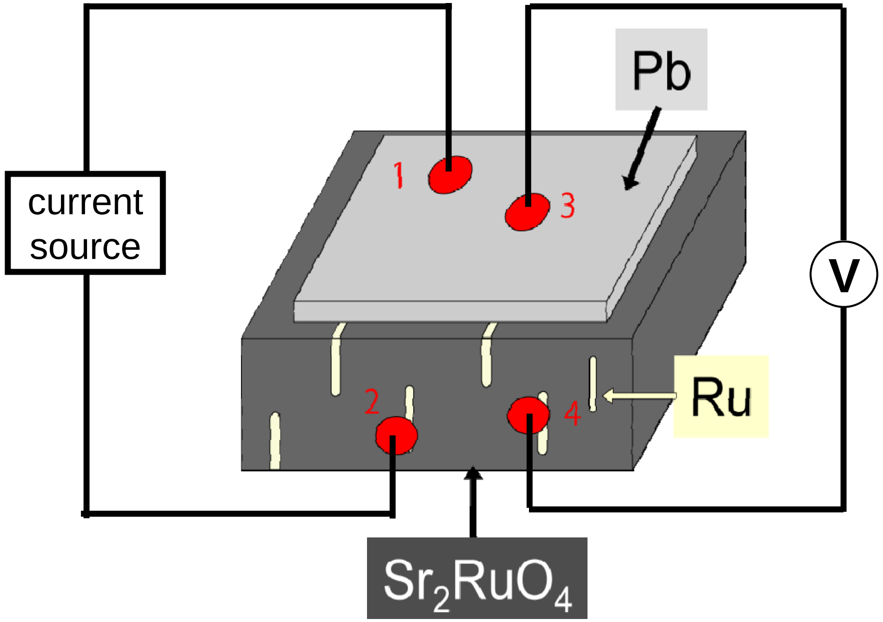
Two I_c's: Only one Pb is sufficient !

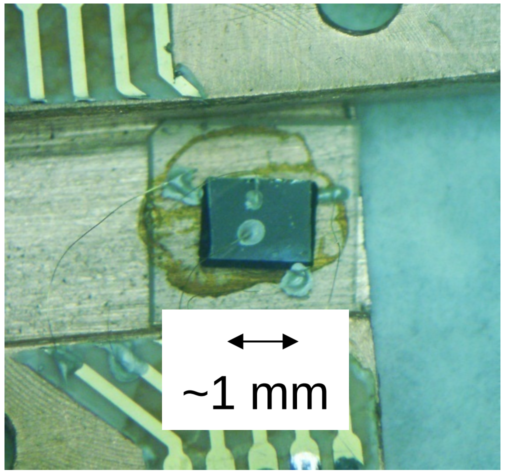




We need to re-consider the previous interpretation, since only one Pb is needed.

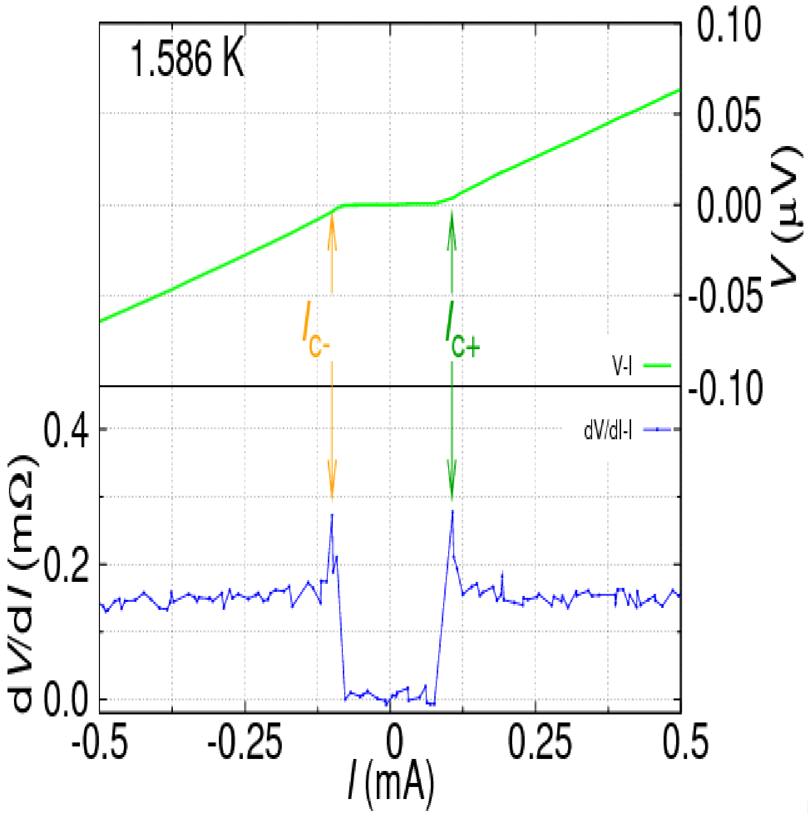
Pb/Ru/Sr_2RuO_4 junction



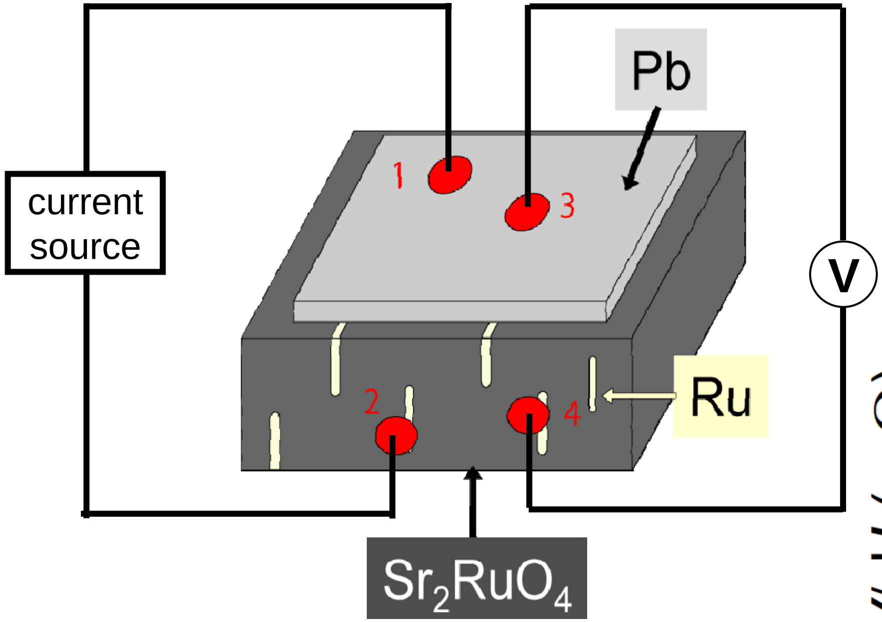


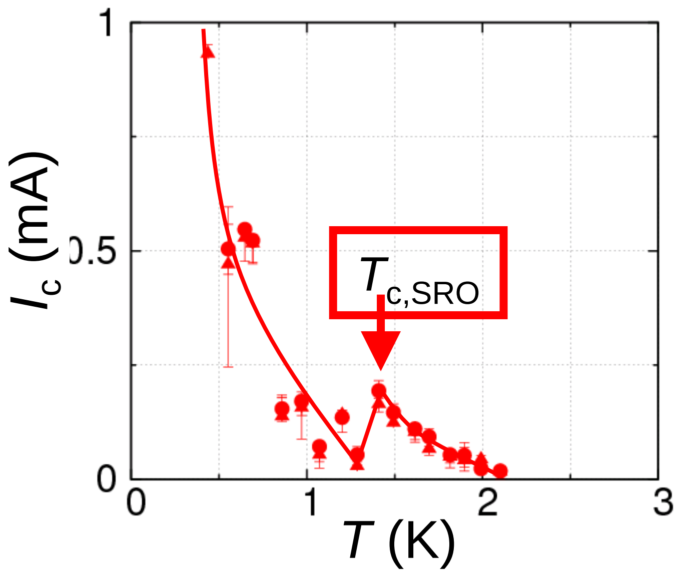
Measurement

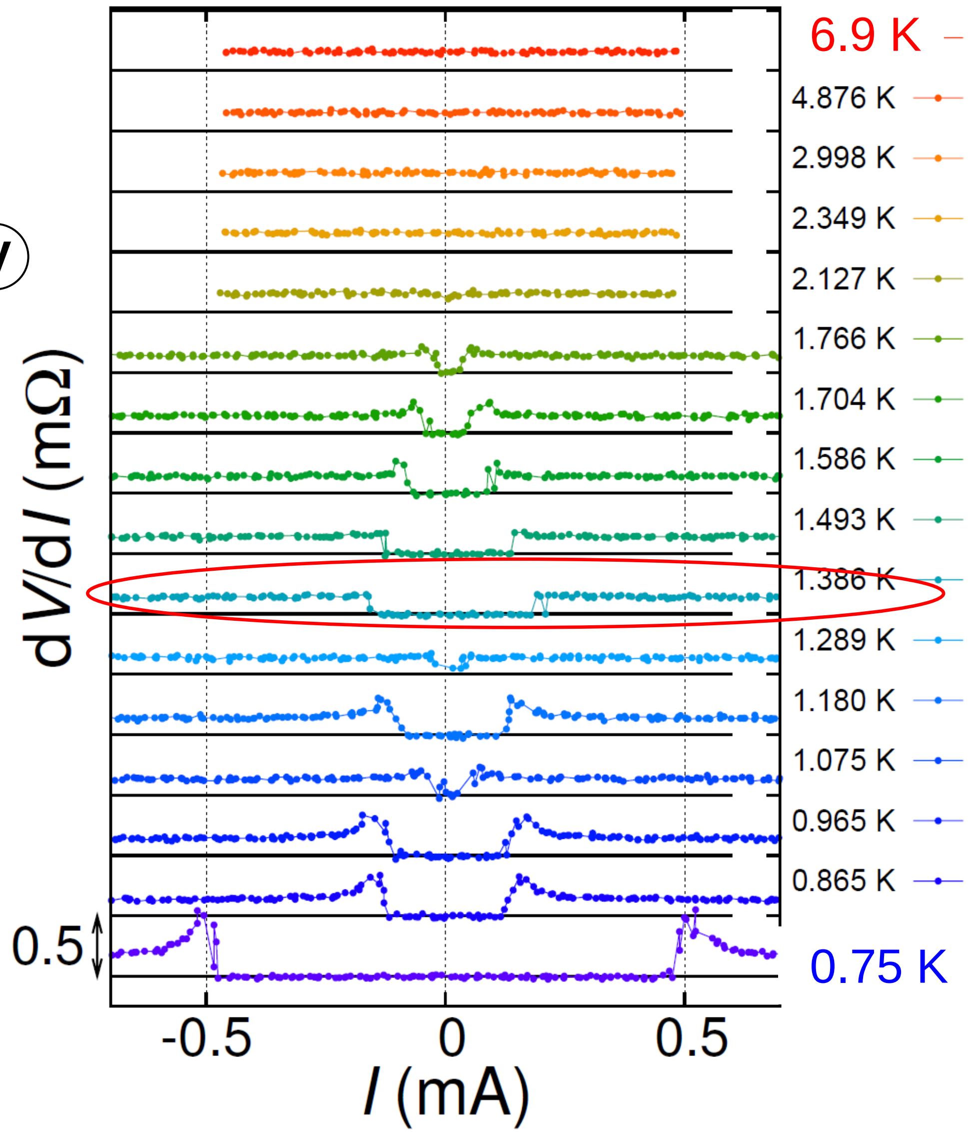
Apply: $I = I_{DC} + I_{AC}$ ($I_{DC} >> I_{AC}$) ⇨ Measure: $V = V_{AC}$



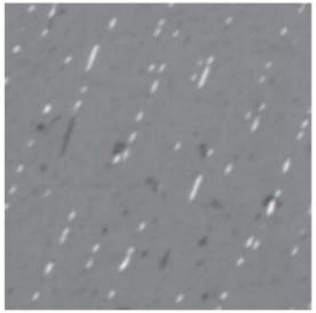
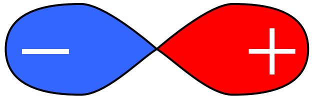
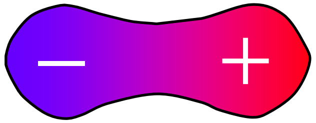
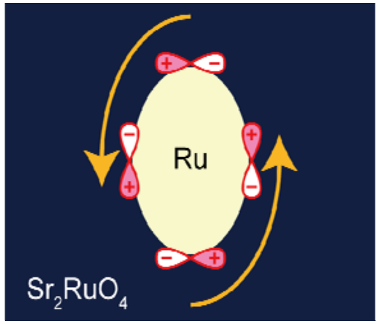
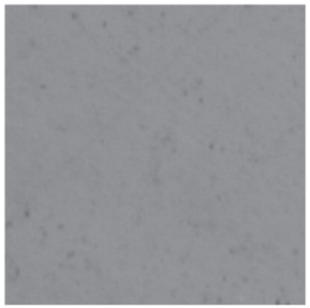
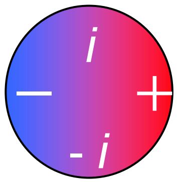
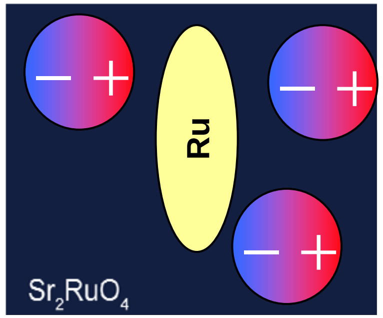
Pb/Ru/Sr_2RuO_4 junction



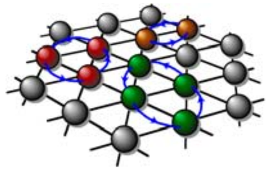




Sr_2RuO_4 and the 3-K phase

	k-dependence	spatial dependence
Sr_2RuO_4-Ru eutectic system 	non chiral *p*-wave k_x ($T < 3$ K)  chiral *p*-wave $k_x + \varepsilon i k_y$ ($T < 2.4$ K) 	 Around the Sr_2RuO_4-Ru interface Phase winding: $N = 0$
Sr_2RuO_4 	chiral *p*-wave $k_x + i k_y$ 	 homogeneous in bulk Sr_2RuO_4 Phase winding: $N = 1$

Conclusions



1. Pb/Ru/Sr_2RuO_4 proximity junctions reveal the interference between *s*-SC and Sr_2RuO_4.

2. The unusual $I_c(T)$ is ascribable to the change in the phase windings around Ru.

"Topological quantum phenomenon"

3. Further tests needed to prove **Odd Parity** of Sr_2RuO_4 :

◆ Direct observation of induced vortex in Ru.