Anomalous Transport Characteristics in Sr_2RuO_4-Ru eutectic junction

AIST

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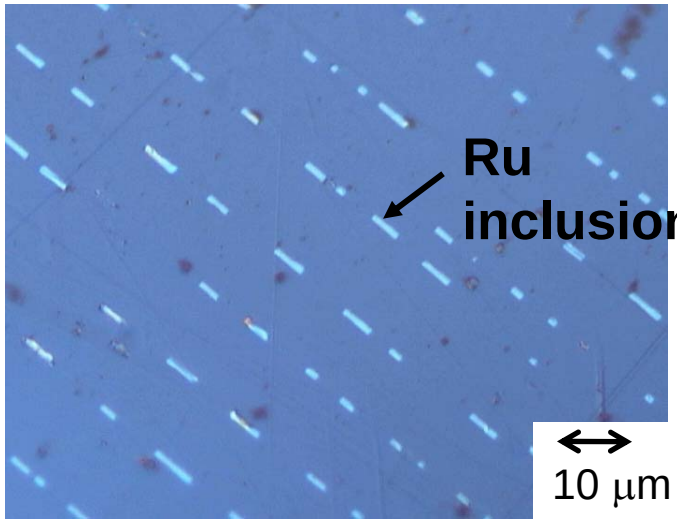
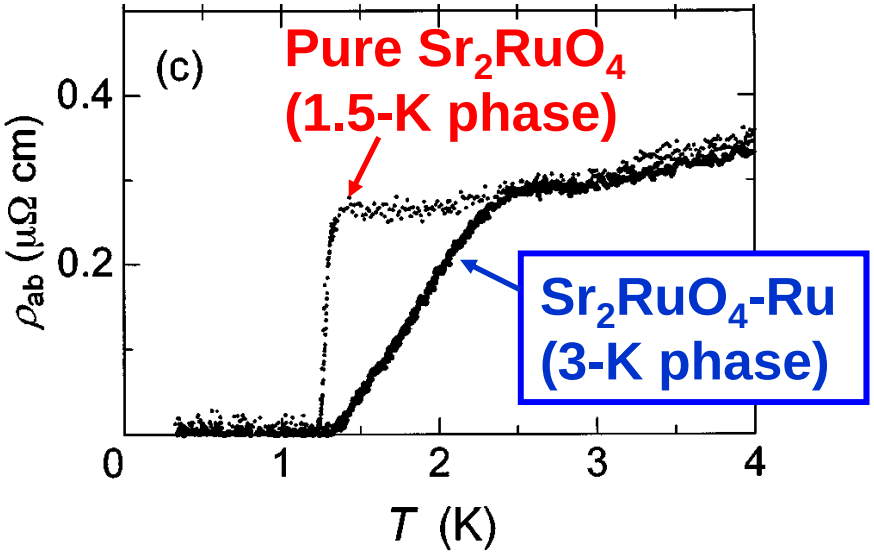
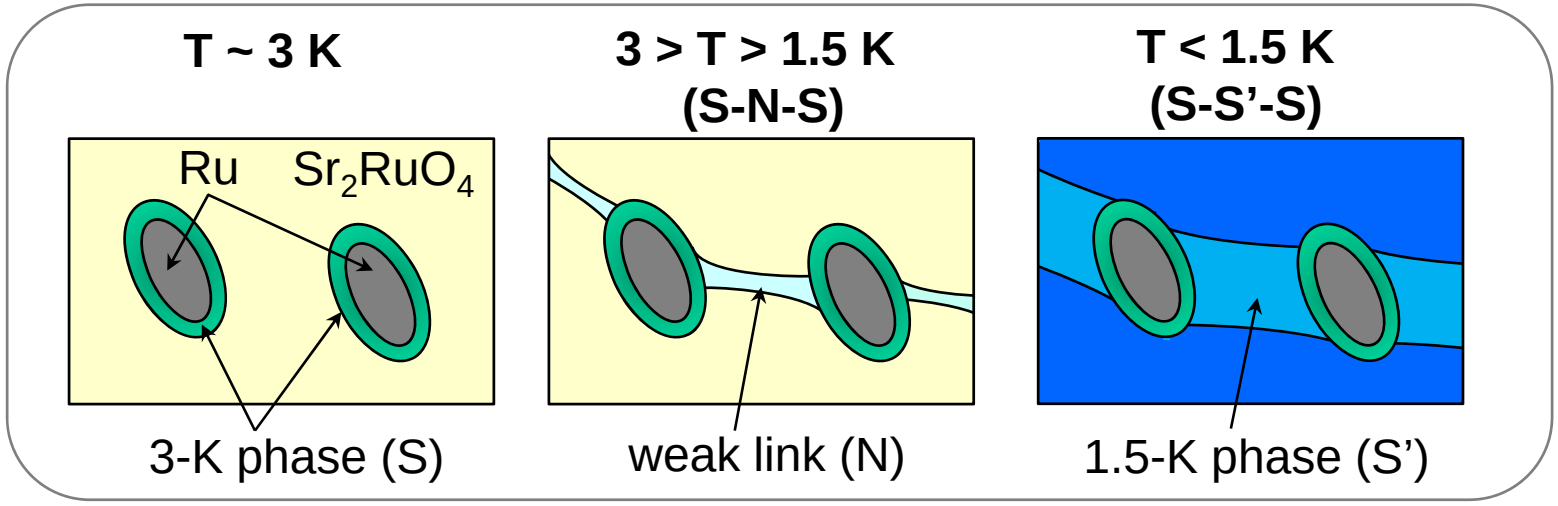
Introduction ~3-K phase superconductivity~

Sr_2RuO_4 - Ru eutectics





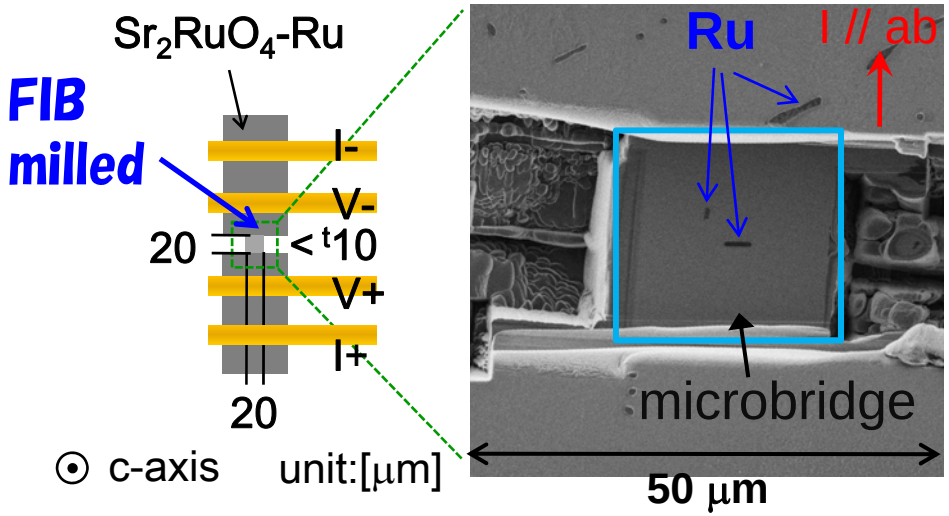
Maeno *et al.*, PRL **81**, 3765 (1998).



How is a local transport of the p-wave Josephson junction?

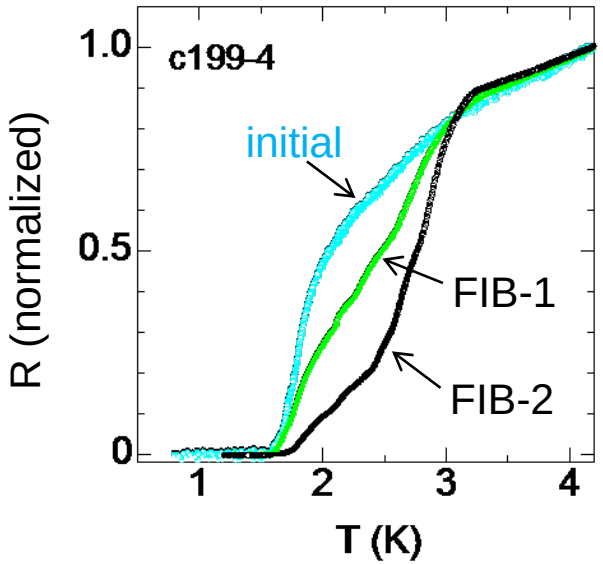
Extract a channel of Sr_2RuO_4-Ru junction

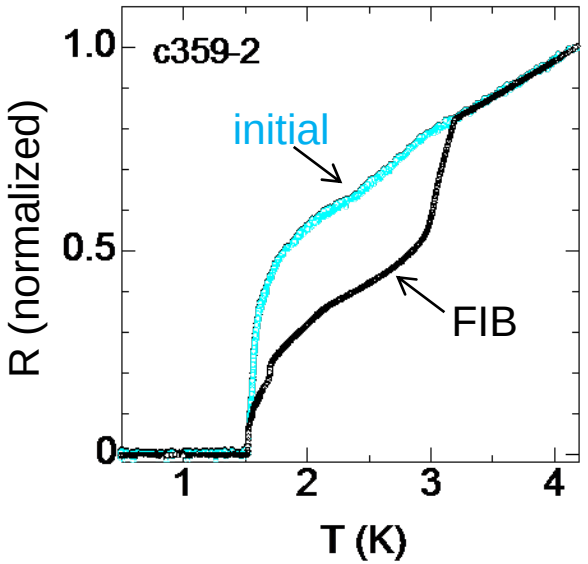
Focusing on the local superconducting channel by controlling the number of Ru-inclusions



$$R_{total} \approx R_{bridge}$$

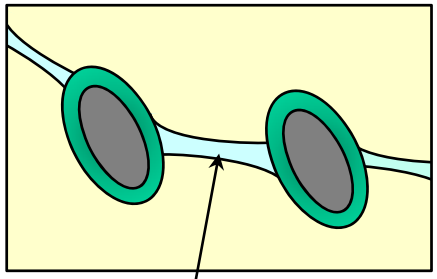
Kink structures appear after FIB milling because only a few channels are left.





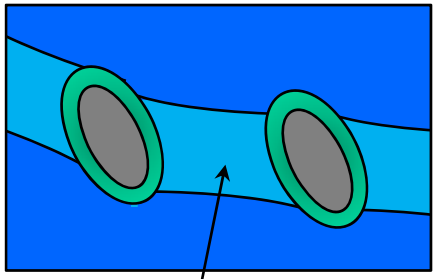
dV/dI-I characteristics

3 > T > 1.5 K
(S-N-S)



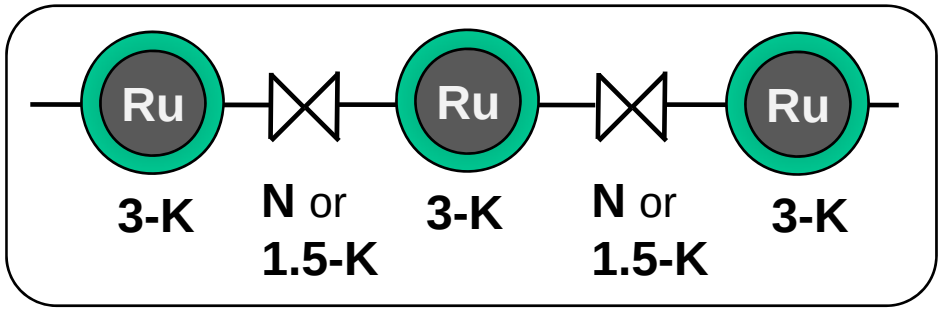
weak link (N)

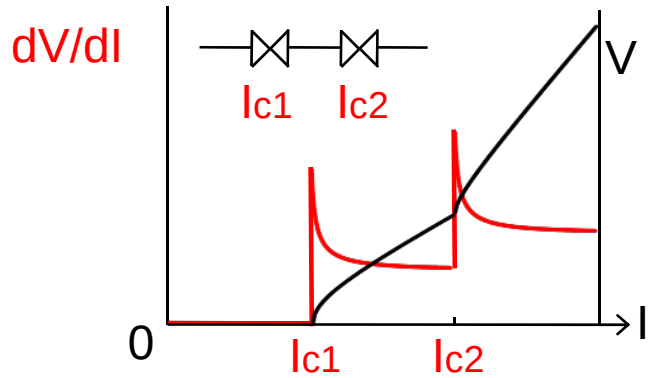
T < 1.5 K
(S-S'-S)

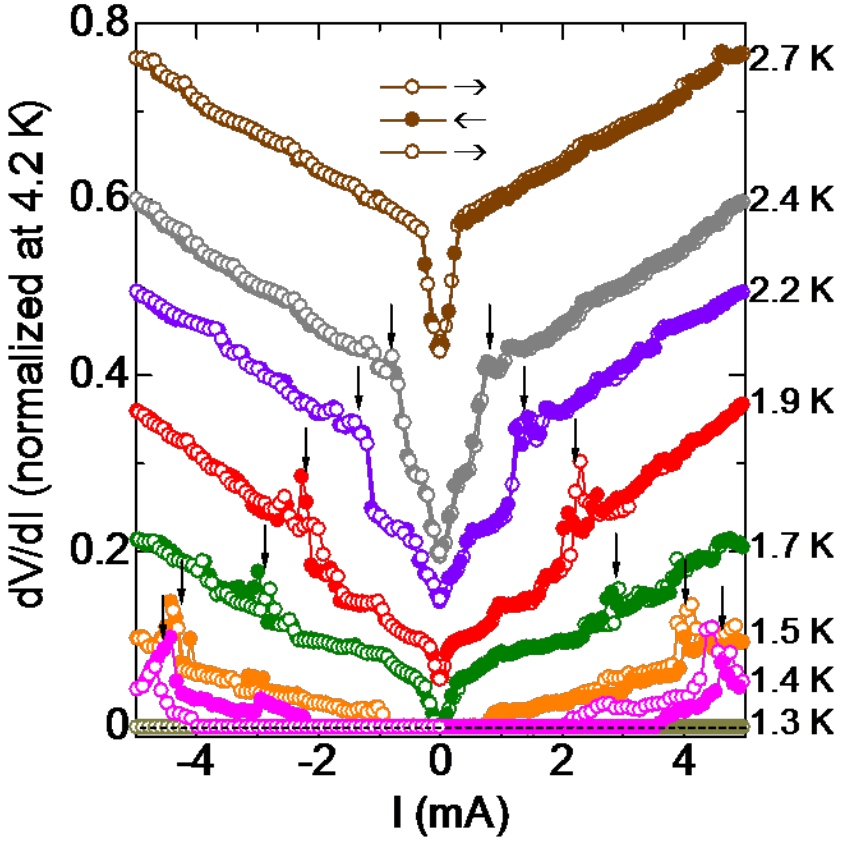


1.5-K phase (S')

Model of Josephson junctions in series

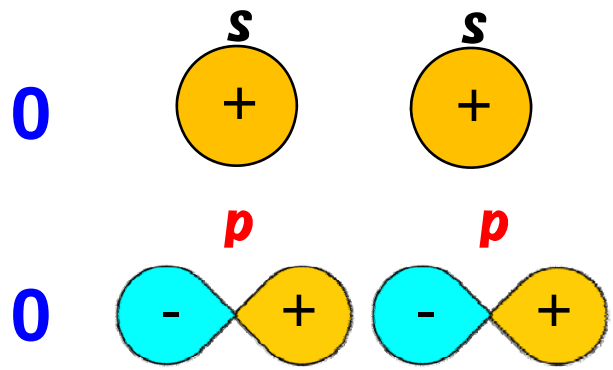


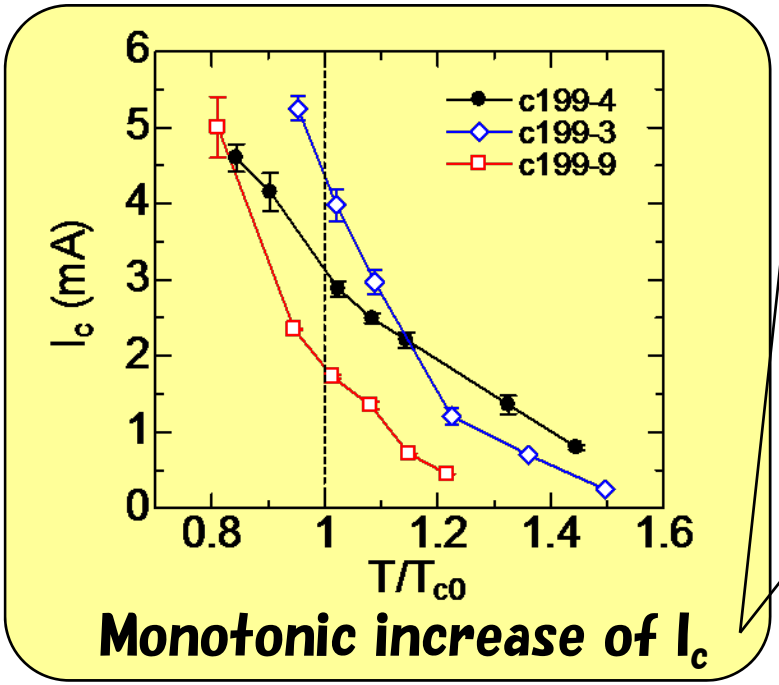


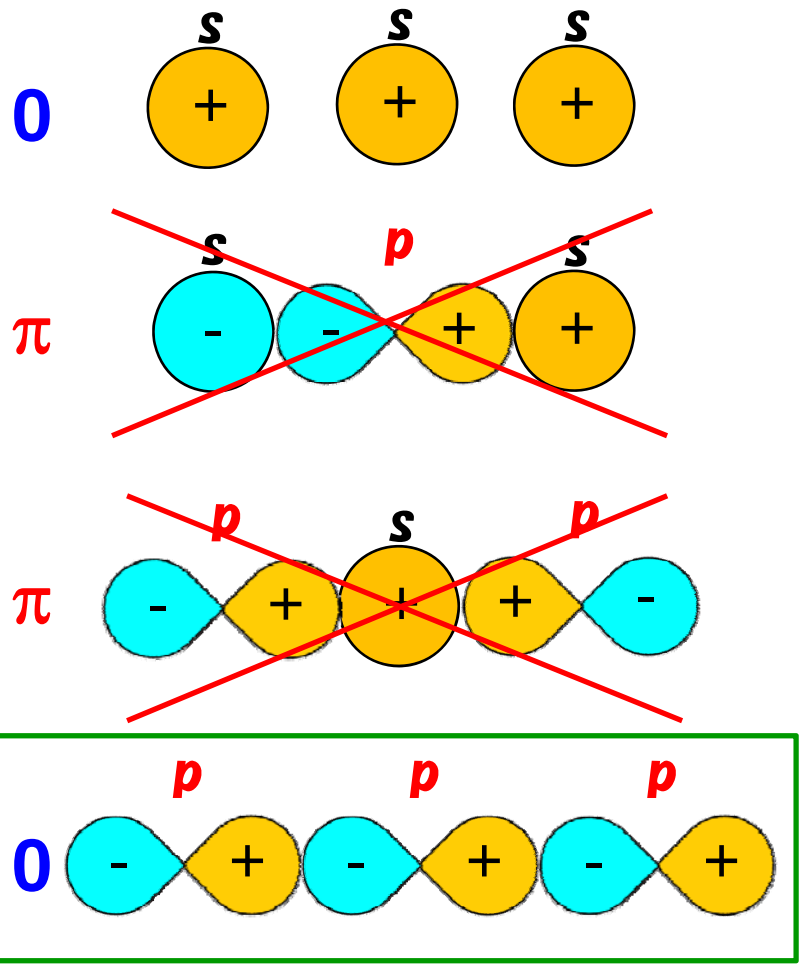


1. Parity of the 3-K phase is the same as 1.5-K phase.
2. Anomalous hysteresis is observed T < 1.9 K.

Parity of the 3-K phase



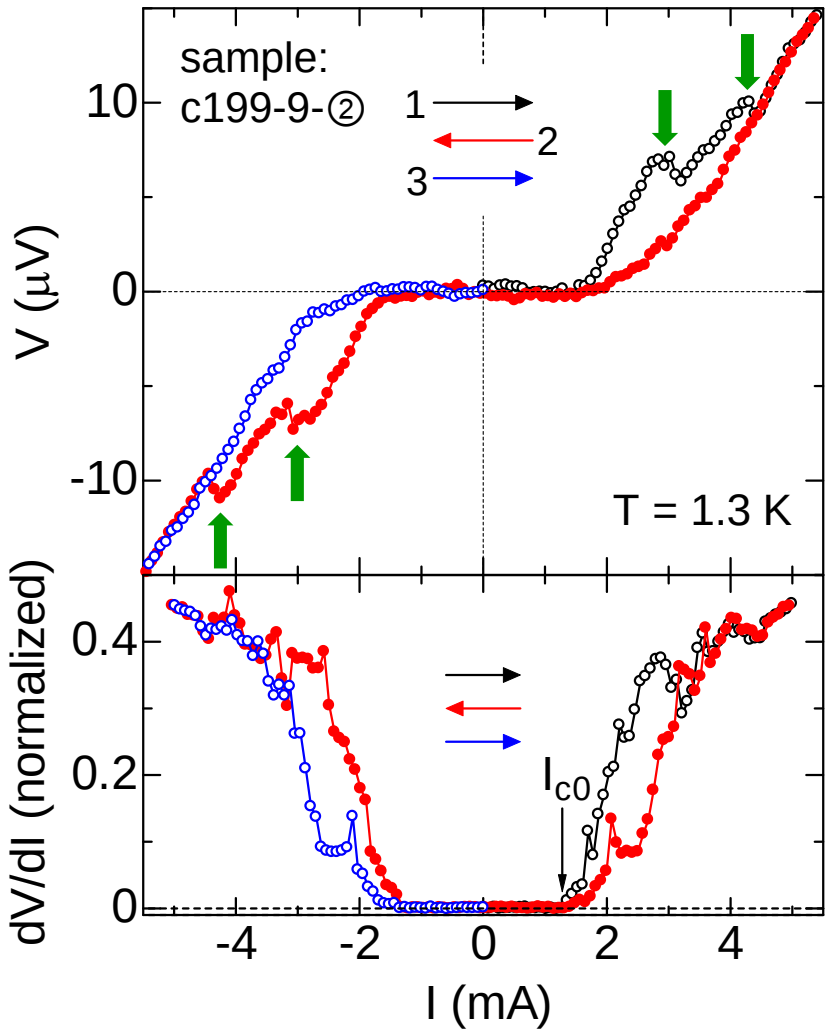




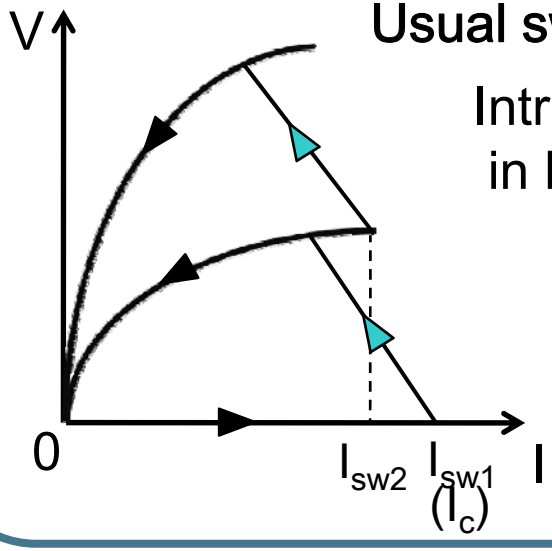
p-wave for 3-K phase

(∵ p-wave for 1.5-K phase)

Anomalous V-I characteristics (I // ab)



NOT usual JJs!



Anomalous features

(1) Voltage **decreases** at I_{th}.

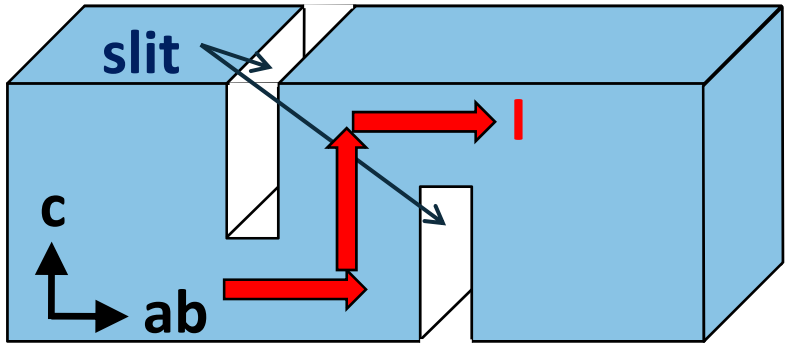
(2) It switches to a **lower** R_n (normal resistance) branch with larger I_c.

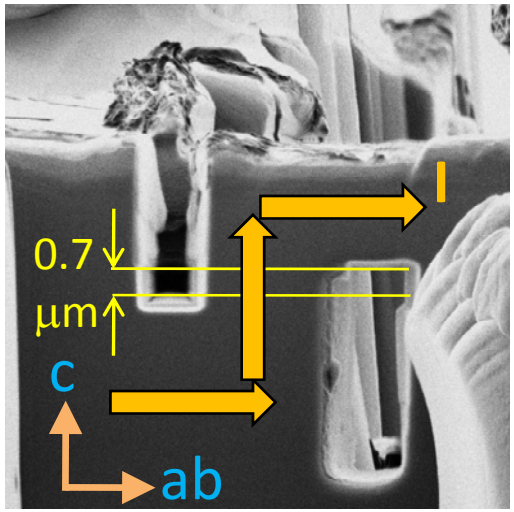
(3) **Opposite** hysteresis loop compared to typical Josephson junction (JJ) s.

Transport along c-axis

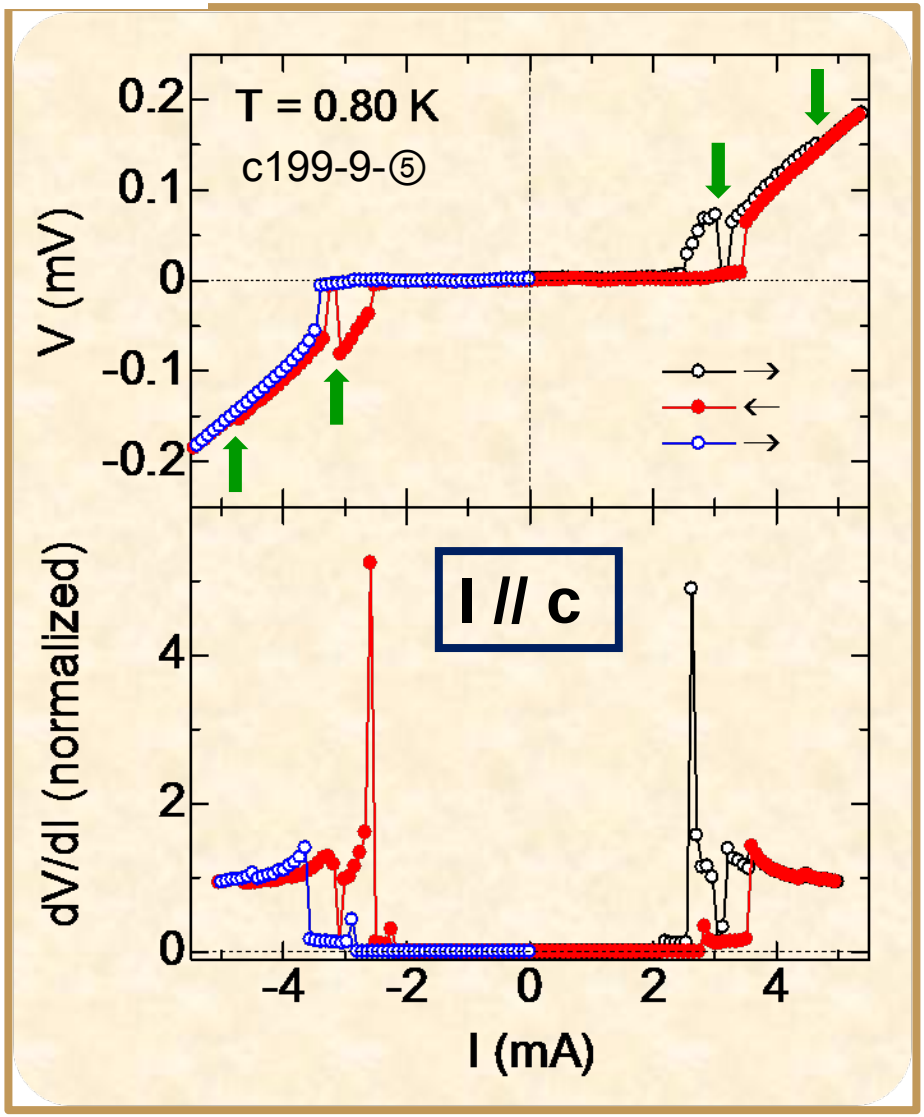
How is the c-axis local transport ?

Is anomalous hysteresis observed ? ➡ **Yes!** (clearer)

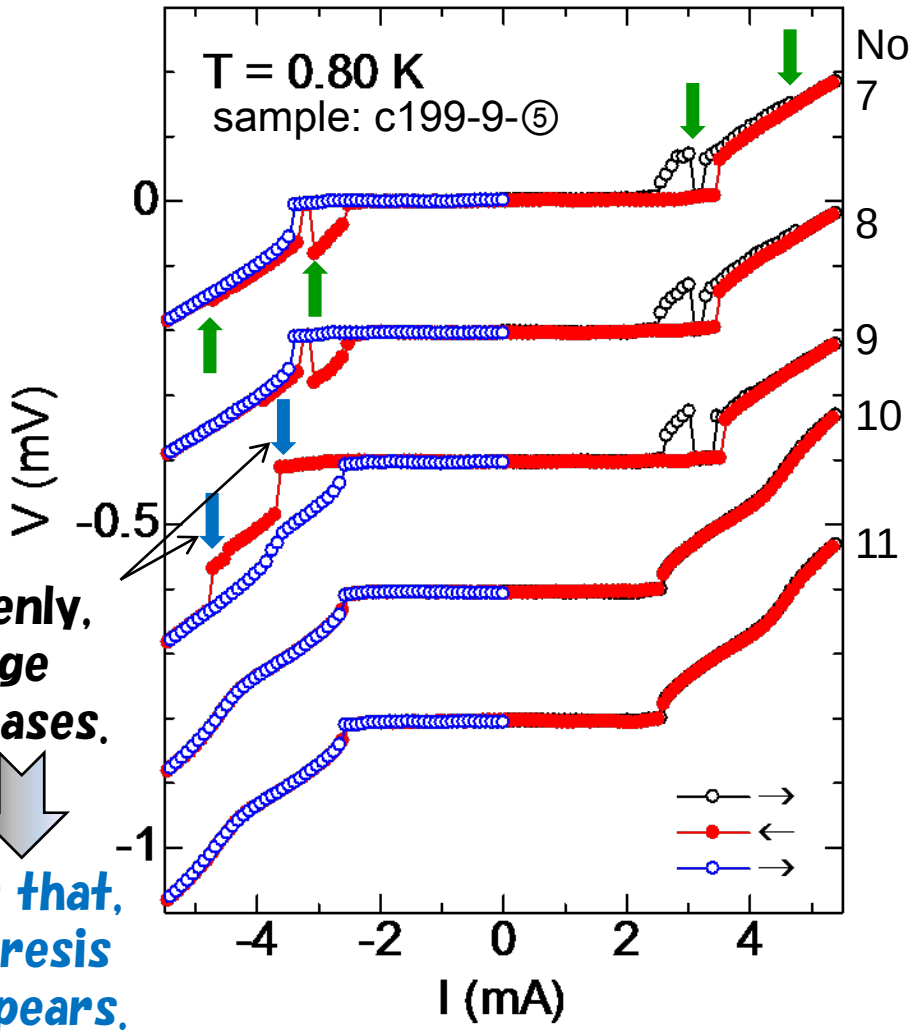




sample: c199-9-⑤



Disappearance of hysteresis (I//c)



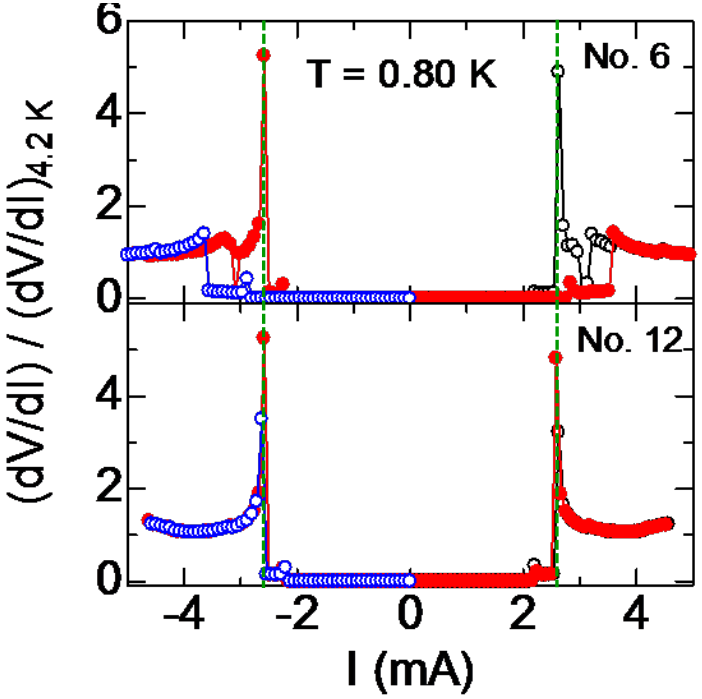
Suddenly, voltage increases.

After that, hysteresis disappears.

The curves are offset by -0.2 mV.

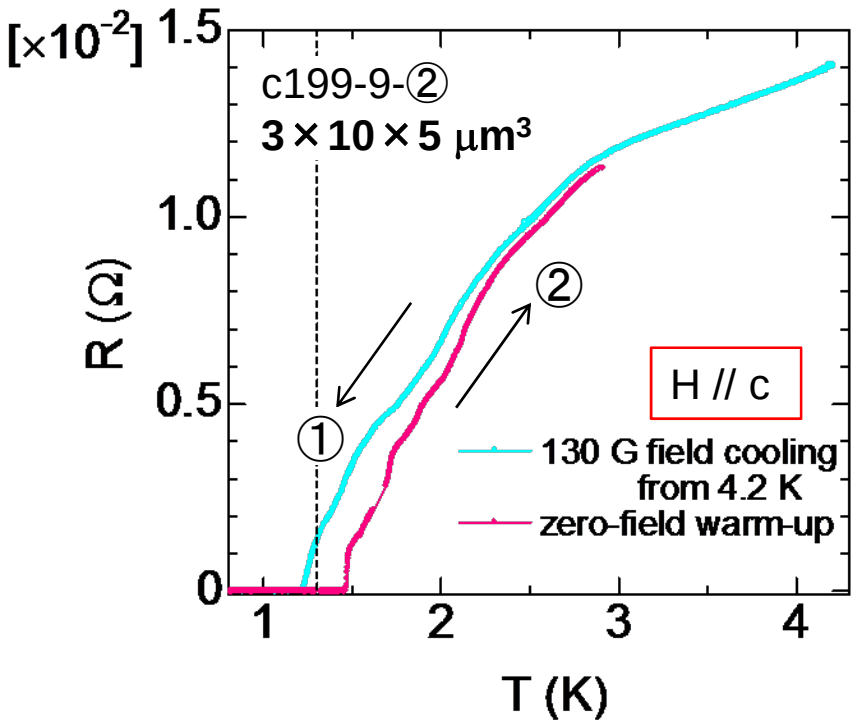
Hysteresis disappears during many dc bias current sweeps (~10-20 times).

Finally, the lower I_c is stabilized.
(same as for I_c//ab)



※ **Hysteresis disappears through temperature variation under finite dc bias current.**

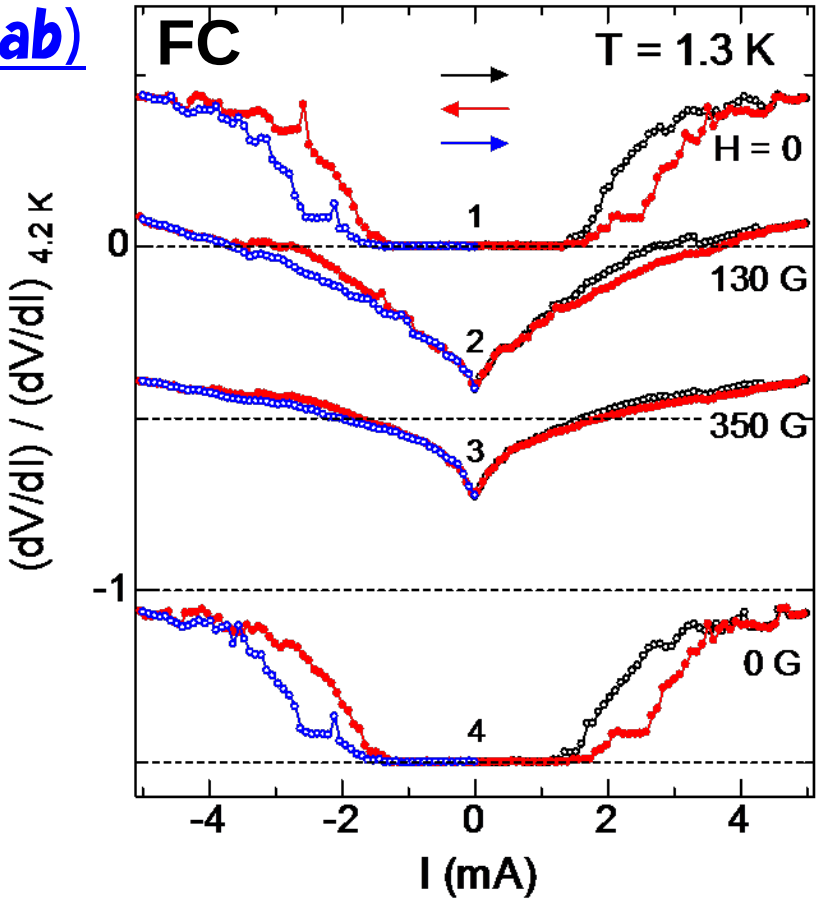
Field cooling experiment (I // ab)



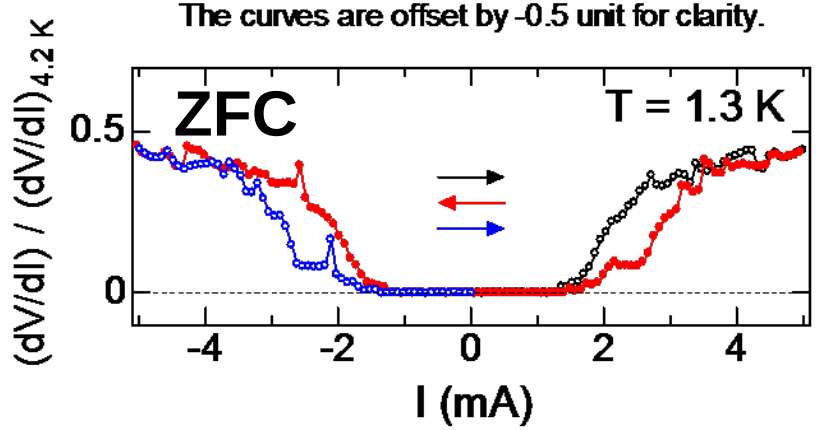
cf) $H_{c1}(0) \cong 70$ G (1.5-K phase)
Deguchi, Mao, Maeno, JPSJ(2004).

No change in the hysteresis between FC and ZFC.

NO influence of vortices !



The curves are offset by -0.5 unit for clarity.



Possible origin of the hysteresis

Experimental results

- Anomalous hysteresis appears in both directions.
- Hysteresis disappears during many dc bias current sweeps.
- The lower I_c state is stabilized after the hysteresis disappears.
- Hysteresis is stable against magnetic field.

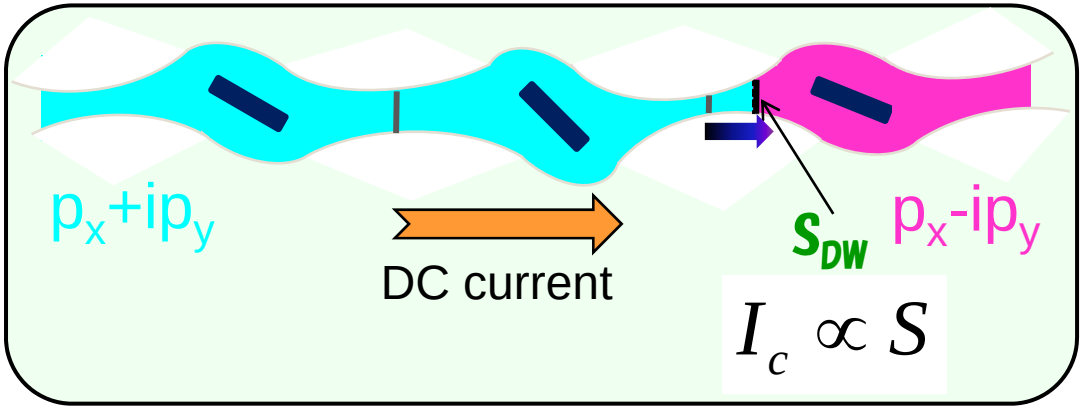
All features are common in I//ab, I//c.

Possible origin of the hysteresis
(What is the degree of freedom of I_c ?)

→
- (a) **Chiral domain**
- (b) **3-K phase**(p_x or p_y) + **1.5-K phase**($p_x \pm ip_y$)
- (c) **Others**

Possible origin of the hysteresis

(a) Chiral domain



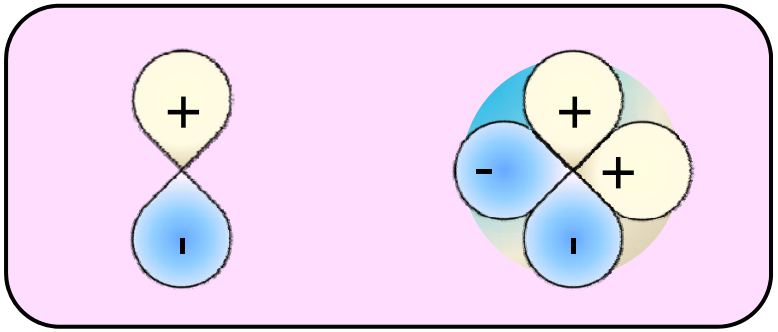
〈problems〉

- **Reproducibility of the hysteresis (appearance and shape) is quite high.**
  → Antiparallel domain always forms in the same position? (pinning at lattice defects ?)
- **Hysteresis survives after magnetic field cooling.**
  → Is it hard to interact with external field ?

Possible origin of the hysteresis

(b) 3-K phase + 1.5-K phase

(p_x or p_y) ($p_x \pm ip_y$)



3-K phase symmetry (p_x) is stabilized along the edge due to broken translational symmetry?

Hysteresis may appear due to interference between (p_x) and ($p_x \pm ip_y$).

<problems>

- **Hysteresis exists along l//c.**
  → Spatial variation in the order parameter along c-axis should be small.
- **Switch occurs from the lower I_c path to the larger I_c path (anomalous hysteresis).**
  → Why is the larger I_c path NOT chosen at first?

Summary of the hysteresis

Model	Hysteresis		Sudden dis-appearance	Final lower-I_c state	No-magnetic field effect	**total**
	I // ab	I // c				
Chiral domain	○	○	△	△	**?**	**?**
3-K + 1.5-K	○	**?**	△	△	△	**?**
~~**Vortex**~~	○	○	**?**	△	✕	✕

○…OK!　△…probably OK　?…question　✕…contrary

Summary

- Local transport measurements have been done (I//ab, I//c) for Sr_2RuO_4-Ru eutectic samples made by FIB process.

(1) p-wave Josephson junctions are formed (3-K / 1.5-K / 3-K).

(2) Anomalous hysteresis was observed for both current directions.
(voltage drop, opposite hysteresis loop)
Hysteresis disappears during many dc bias current sweeps, and then the lower I_c state is stabilized.

Origin of the hysteresis (internal degrees of freedom)
- Chiral domain?
- 3-K phase+1.5-K phase?
- Others?

(3) Symmetry of the 3-K phase (p_x or p_y) tends to be enhanced for microfabricated (~μm) samples.