Novel Quantum Phenomena Characteristic of Spin-Triplet Superconductivity

U of Tokyo, Dec. 15, 2005

Kyoto University Y. Maeno

計画研究: A04班 「異方的超流動・超伝導」

group キ: 「異方的超伝導に特有の新量子現象」

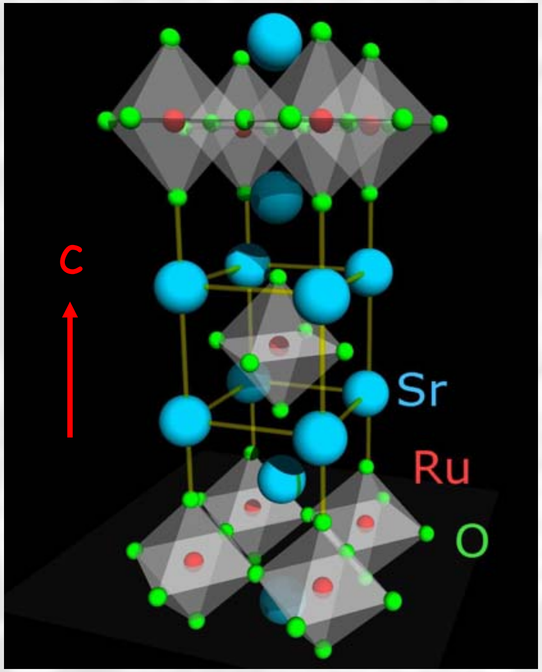
前野(京大)、石田(京大)、三宅(阪大)、
田仲(名大)、神原(東大)

内部自由度を持った超伝導状態に特有の新量子現象

スピン自由度、スピンの超流動性、

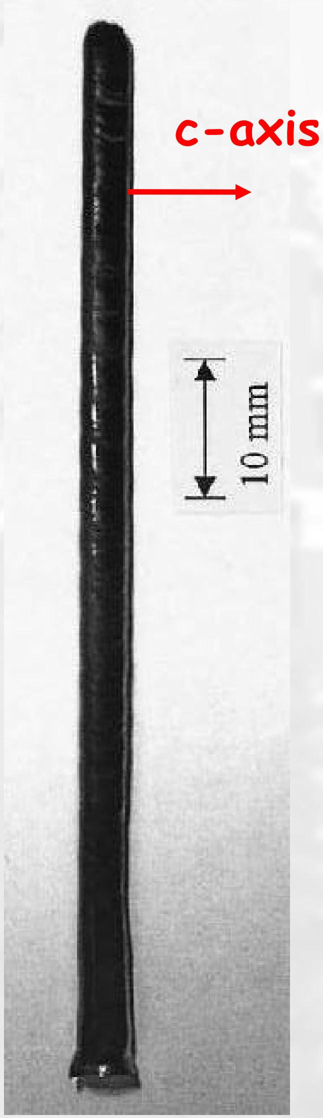
時間反転対称性の破れ(カイラル状態)

Sr_2RuO_4



K_2NiF_4 structure

without distortion



T_c = 1.5 K

Coherence length:

$\xi_{ab}(0)$ = 66 nm

Residual resistivity :

$\rho_0 < 100$ nΩcm

Mean-free-path

$\ell \approx 1\ \mu m$

"Superclean material in the low temperature limit"

Candidate Spin-Triplet Superconductors
$S = 1$ Cooper pairing

(0) Superfluid ^3He *p*-wave

"Superfluidity of CHARGE and SPIN"

(1) Heavy fermion sc. UPt_3

UNi_2Al_3 ⟷ UPd_2Al_3 is clearly singlet.

(2) Ruthenate sc. Sr_2RuO_4

(3) Ferromagnetic sc. UGe_2, URhGe, UIr

$ZrZn_2$??

(4) Q1D organic sc. $(TMTSF)_2PF_6$?

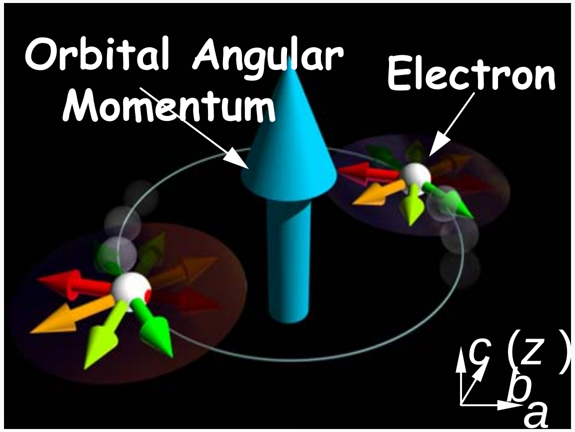
(5) others $PrOs_4Sb_{12}$?? , $Na_xCoO_2 \cdot yH_2O$??, $CePt_3Si$?, etc.

Arguably, Sr_2RuO_4 is the first example for which details of the spin-triplet superconductivity are quantitatively characterized.

Sr_2RuO_4: The spin-triplet order parameter has been "determined".

Order parameter:

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



Spin part: $\mathbf{z}$ ($S_z = 0$):

NMR Knight shift Ishida, Kitaoka *et al.*

polarized neutron Duffy, Hayden *et al.*

pair tunnenling into s-wave sc (selection rule) Liu *et al.*

Orbital part: $k_x + ik_y$ (TRS broken, "chiral")

μSR (internal field) Luke, Uemura *et al.*, Higemoto *et al.*

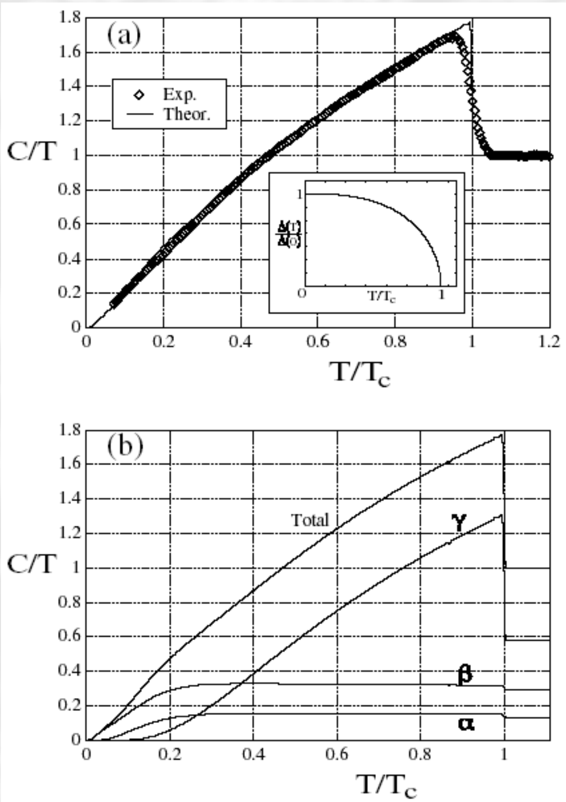
flux-line lattice (field distribution) Keakey *et al.*

jump in the transverse US velocity

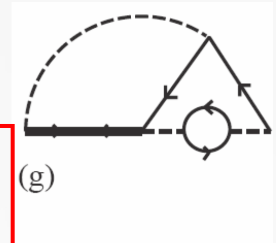
Lupien; Walker; Sigrist; Okuda *et al.*

π-Junction SQUID Nelson, Liu *et al.*

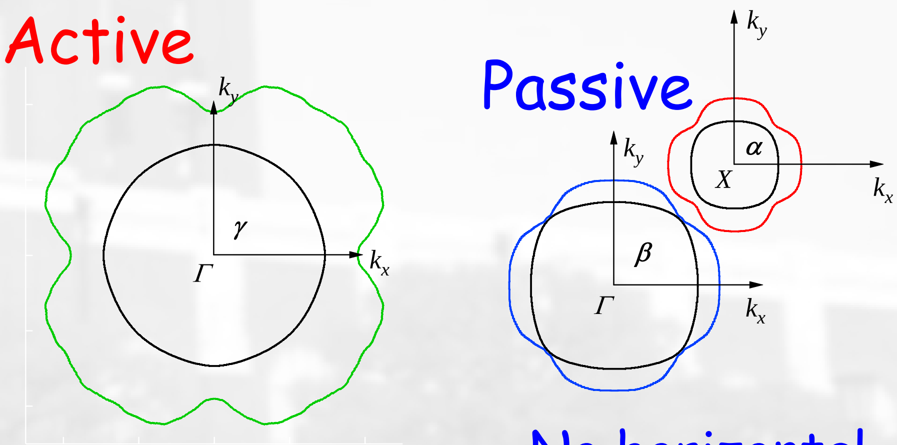
Success of Microscopic Mechanism Theory Based on Realistic Fermi Surfaces



Third-Order Perturbation Theory



Coulomb repulsion
beyond the spin fluctuations



No horizontal line nodes

T. Nomura and K. Yamada,
J. Phys. Soc. Jpn. **71**, 404 (2002).

Also by Kuroki, Aoki *et al.*;
Yanase, Ogata *et al.*

cf. Hoshihara, Miyake *et al.*,

Research Objectives; Two Approaches

Explore novel superconducting phenomena specific to the spin-triplet superconductivity.

1. Control the order parameter by *H*, *P*, etc.

⇒ •Rotation of the d-vector

•Collective motion of the Cooper pairs

•Superconducting multiple phases

2. Explore new superconducting phenomena in the **eutectic crystals**.

⇒ •Surface bound states (Andreev bound states)

•Proximity effects

•Chiral edge current, etc.

Organization

内部自由度をもつ超伝導の新量子現象

実験

石田　神原

前野

三宅　田仲

理論

1. 超伝導秩序パラメターの制御による新量子現象

- 集団励起運動
- 超伝導多相現象
- ベクトル秩序変数制御

公募研究

2. 共晶接合系などでの新量子現象

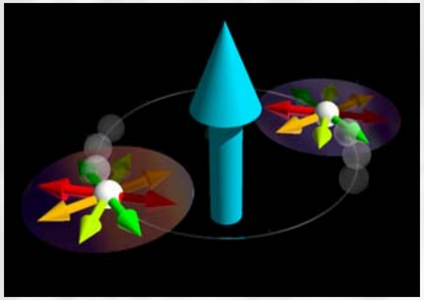
- ゼロエネルギー束縛状態
- 特異な近接効果
- カイラリティー観測

公募研究

内部自由度をもつ超流動液体

内部自由度をもつボーズ凝縮原子気体

Superconductivity in Sr_2RuO_4: Recent Progress

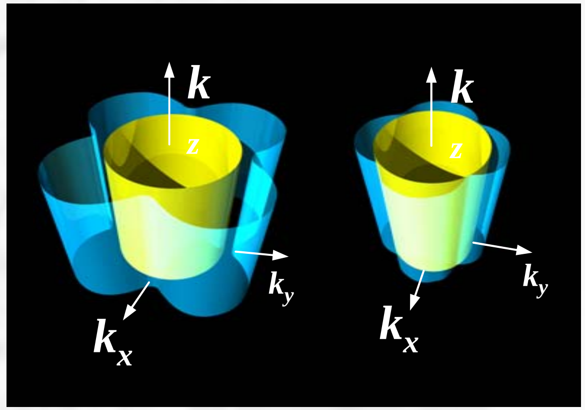


Spin-triplet SC and *d*-vector

d-vector may rotate under *H*, such that $d \perp H$.

π-junction SQUID:

Demonstration of ODD PARITY



Gap structure

γ (d_{xy}): **Active** band.

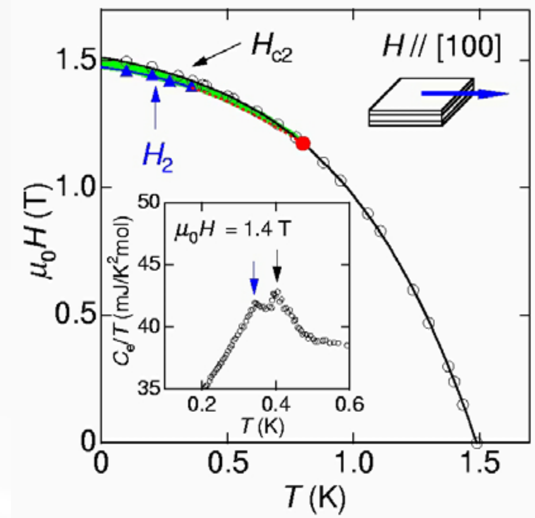
Gap min. along ⟨100⟩

α, β (d_{yz}, d_{zx}):

Passive bands.

Gap "zero" along ⟨110⟩

Deguchi *et al.* (Kyoto)



Double transitions

Mechanism is unknown.

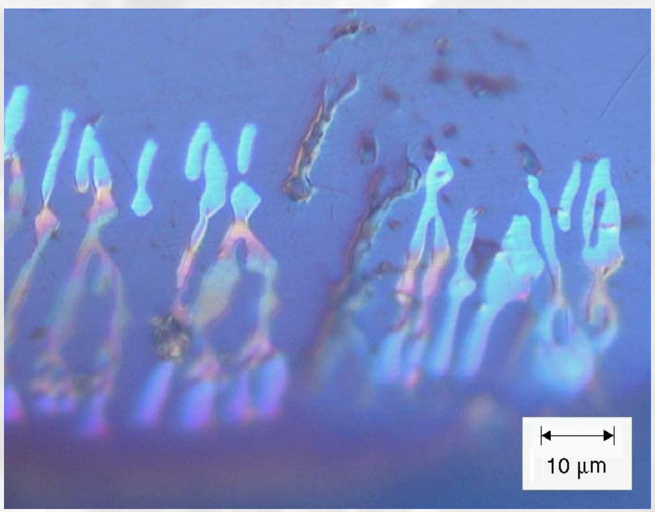
Further theoretical studies are needed.

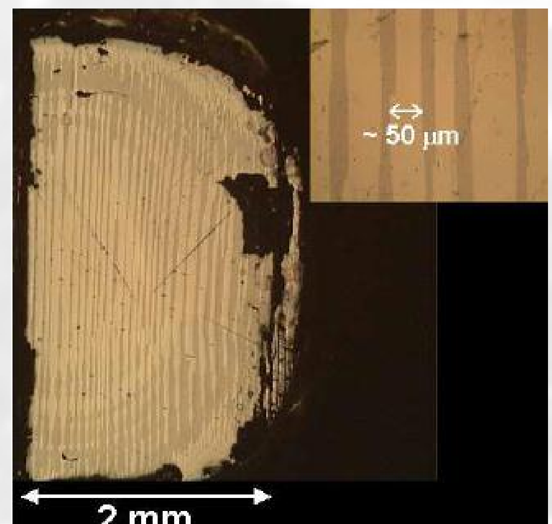
Novel Quantum Phenomena in the Eutectics containing Sr_2RuO_4

京都大学　房登真司，橋高俊一郎，矢口宏，前野悦輝
Univ. of Salerno R. Fittipaldi, A. Vecchione

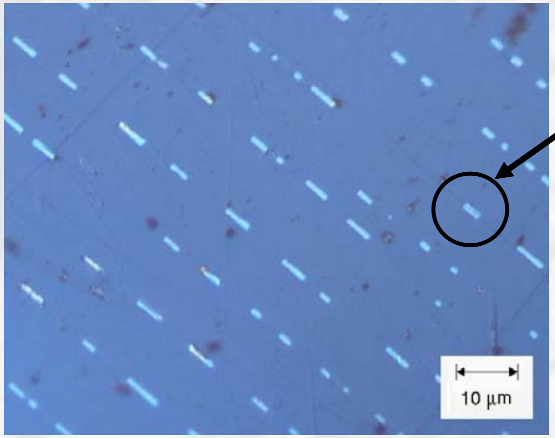
1.Ruとの共晶：3-K相
圧力下での増強超伝導
ポスター　**P45**（矢口）

2.$Sr_3Ru_2O_7$との共晶：
超伝導近接ネットワーク
ポスター　**P38**（房登·橋高)





Sr_2RuO_4-Ru Eutectic (3-K Phase)

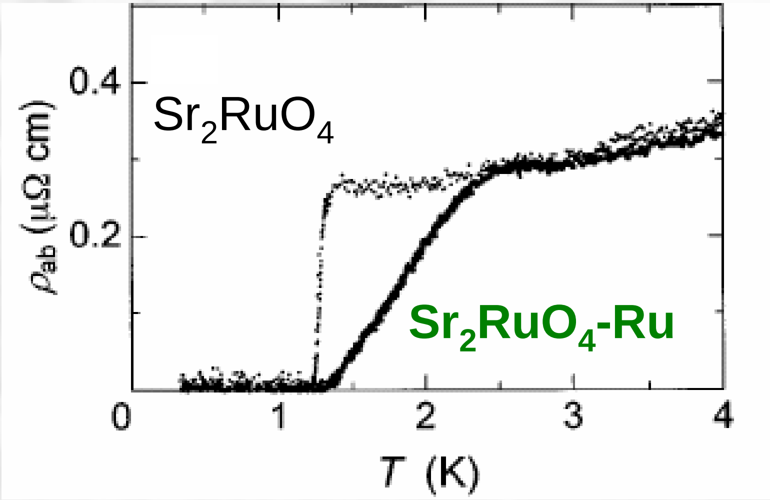


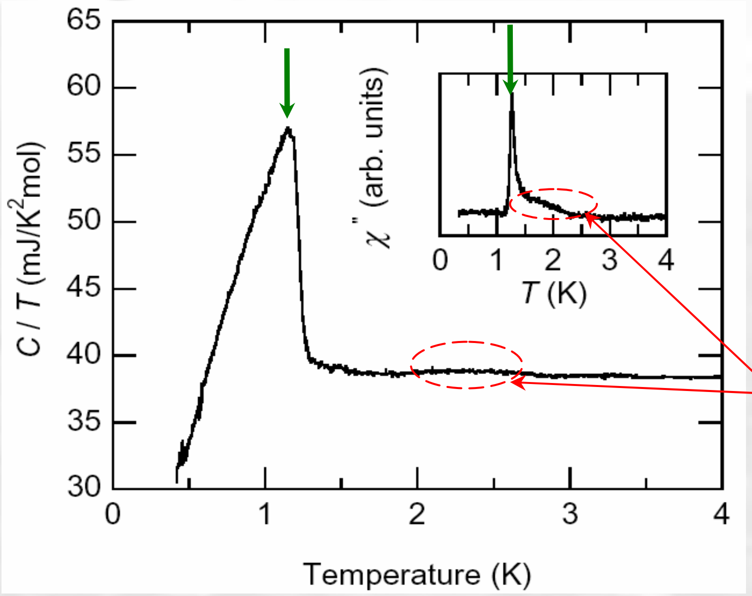
Sr_2RuO_4-Ru T_c ~ 3 K (3-K 相)

Sr_2RuO_4 (T_c = 1.5 K; 1.5-K相)

cf. Ru (T_c = 0.5 K)

Interfacial superconductivity around Ru





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

Yaguchi

Enhancement of Superconductivity by Uniaxial Pressure

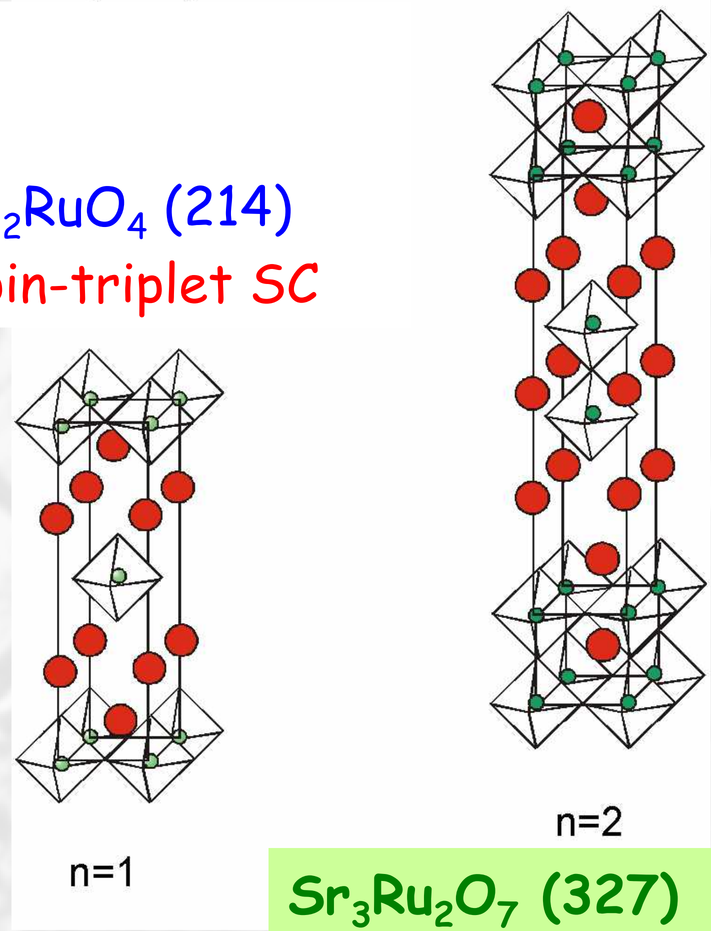
Meissner volume fractions (ZFC) at 1.8 K and 0.5 GPa:
38% (*P*//[100]), 4% (*P*//[001])

Superconductivity above 1.5 K is induced in Sr_2RuO_4.

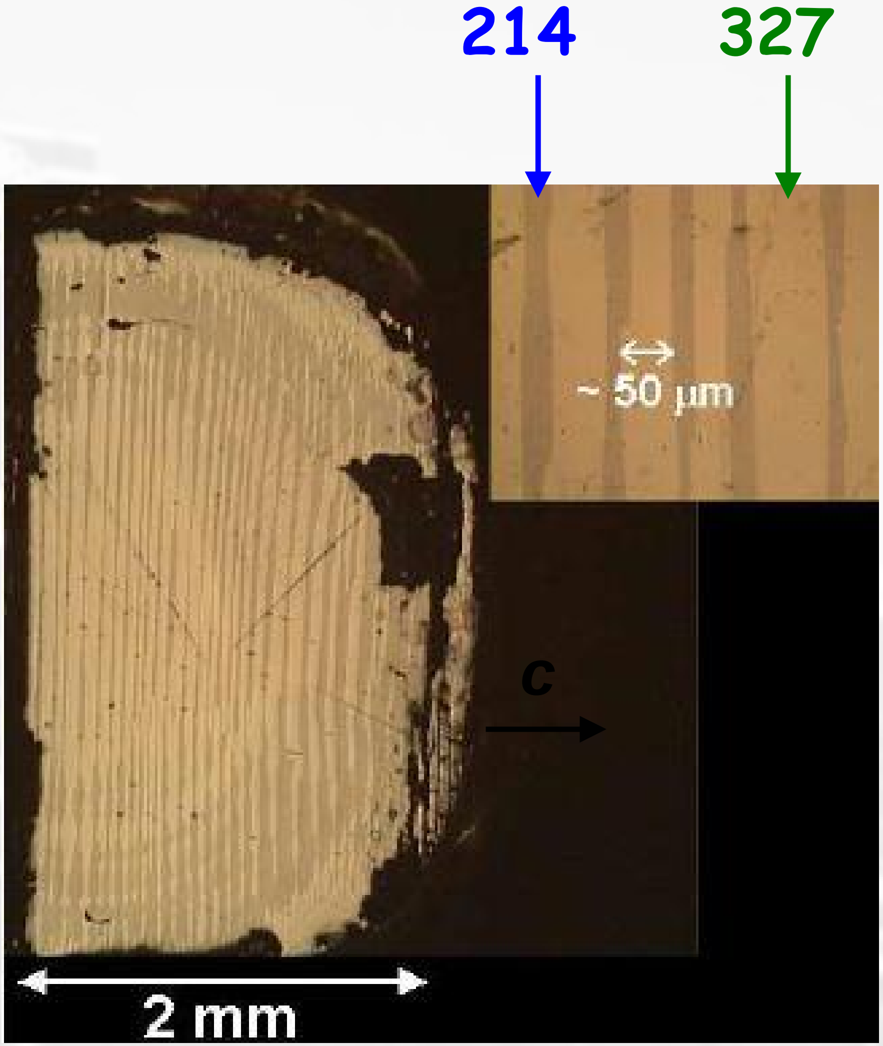
Mechanism is NOT known. Cf. $dT_c/dP_c = -0.8$ K/GPa

Eutectic Crystals of 214 and 327

Sr_2RuO_4 (214)
Spin-triplet SC

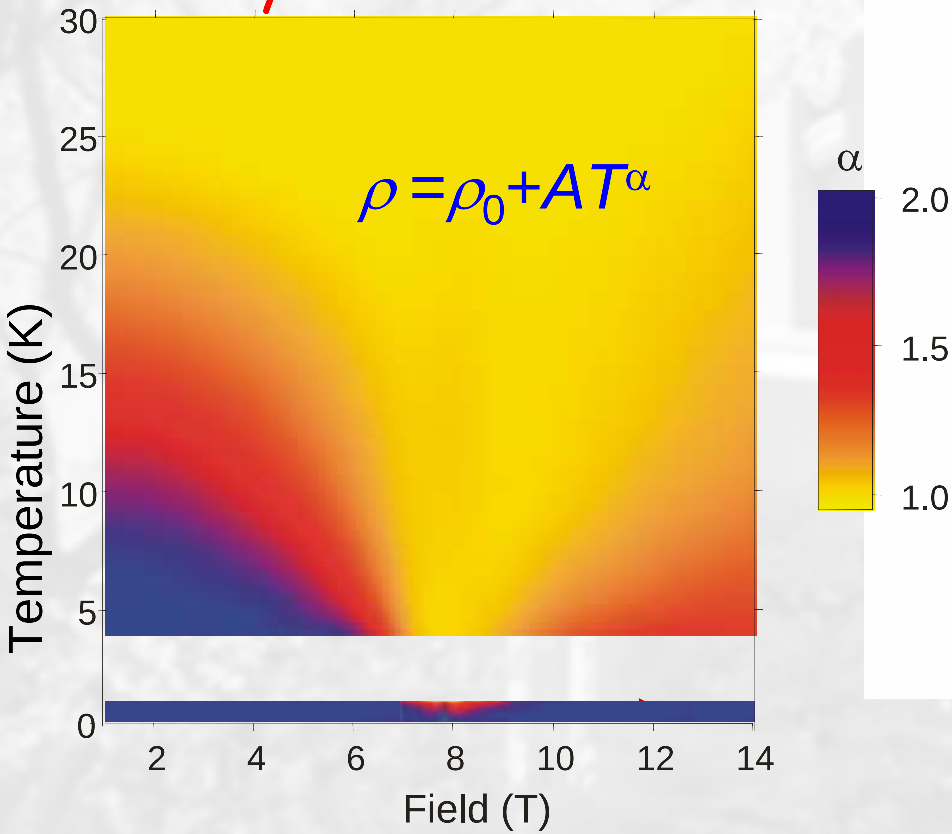


$Sr_3Ru_2O_7$ (327)
Enhanced paramagnet,
FM under pressure

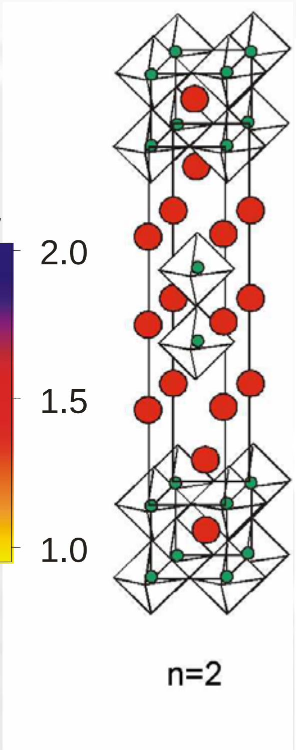


Properties of $Sr_3Ru_2O_7$

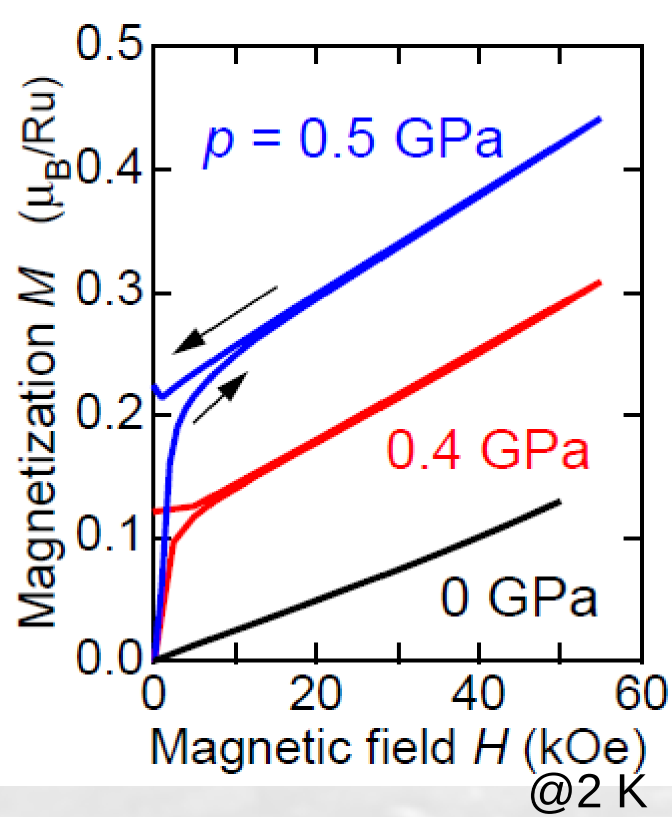
Metamagnetic quantum criticality



S.A.Grigera, et al., Science **294**, 329 (2001).

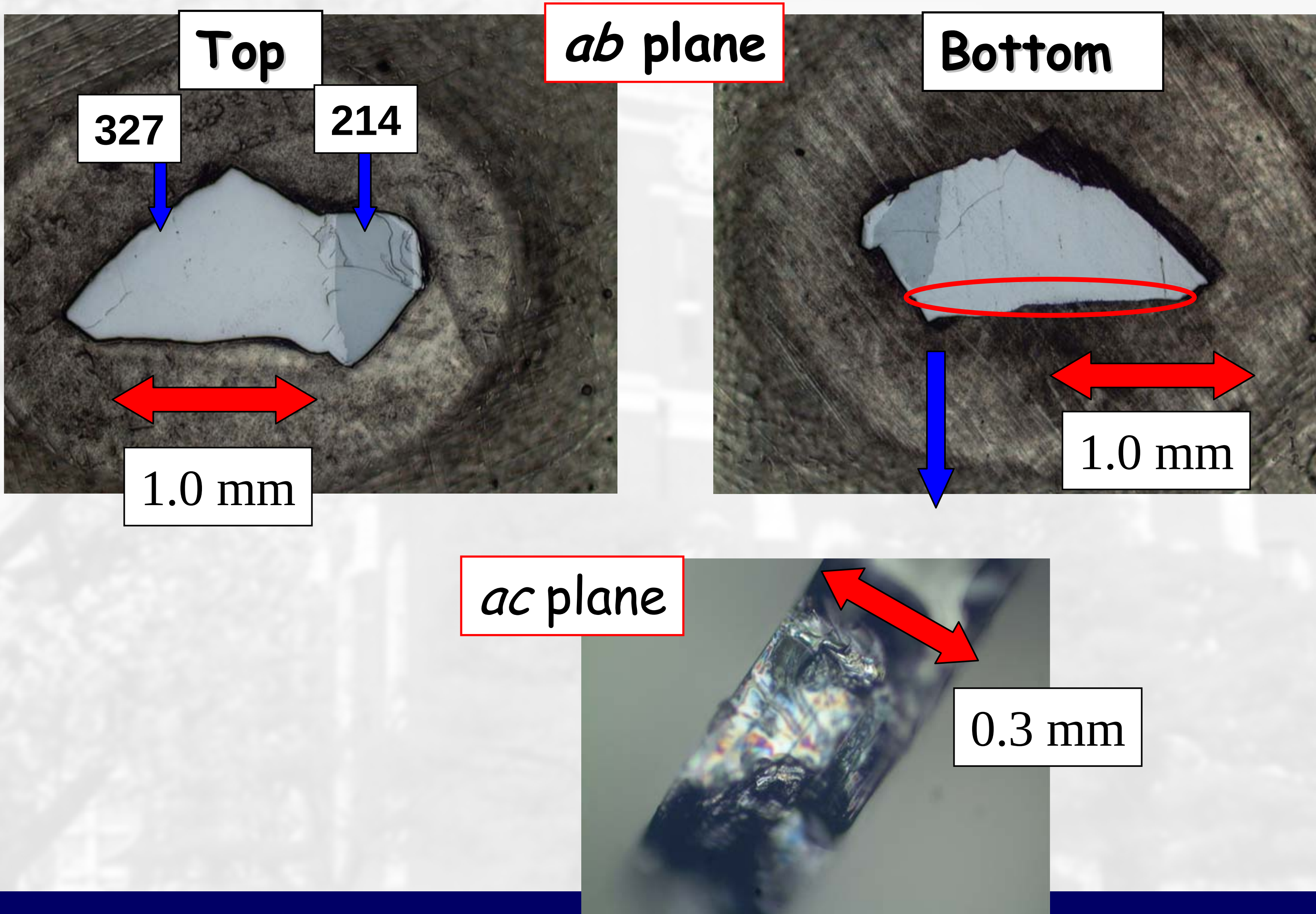


Pressure-induced FM ordering



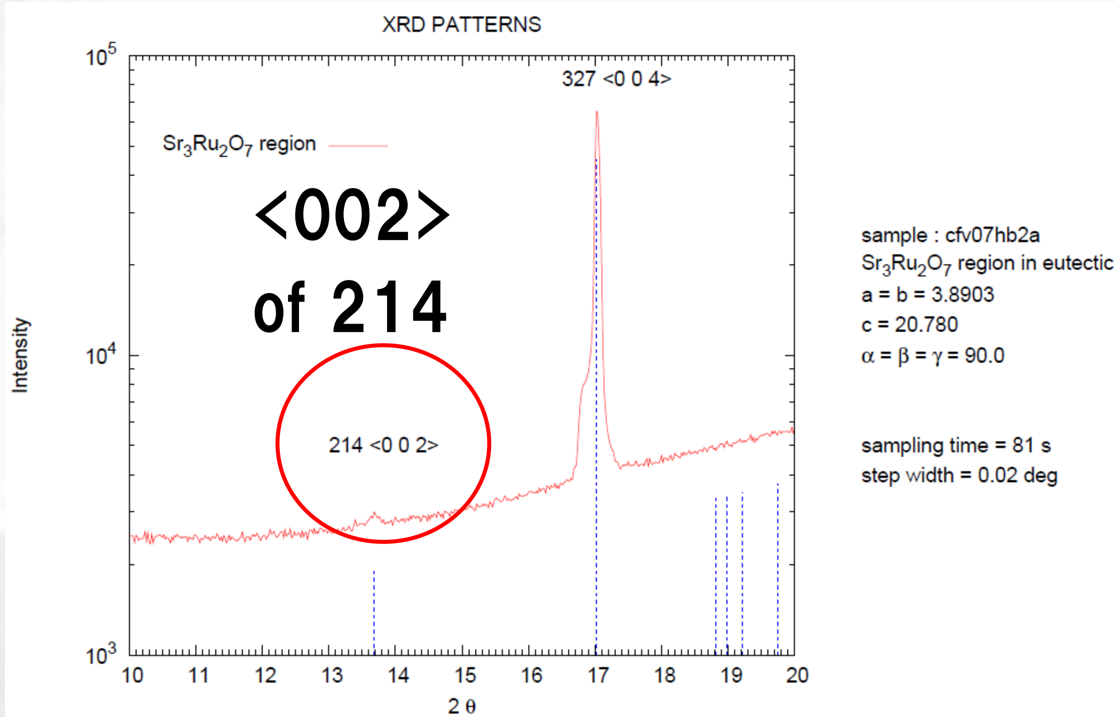
S. Ikeda *et al.*, J. Phys. Soc. Jpn., (2004).

Eutectic crystal of Sr_2RuO_4 and $Sr_3Ru_2O_7$



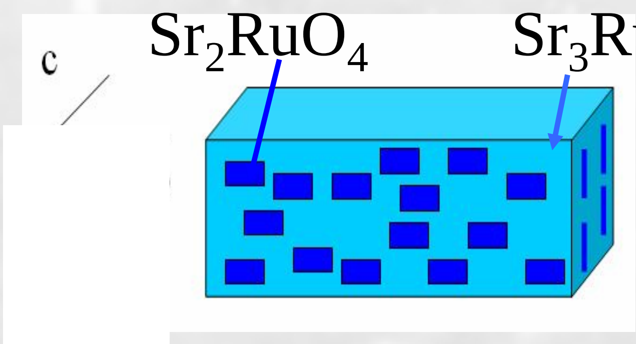
X-ray spectrum of a “327” piece cut from the 214-327 Eutectic

sample No. 7-β



見た目は327のみだが、

X線回折の結果から214の含有が明らかになった。



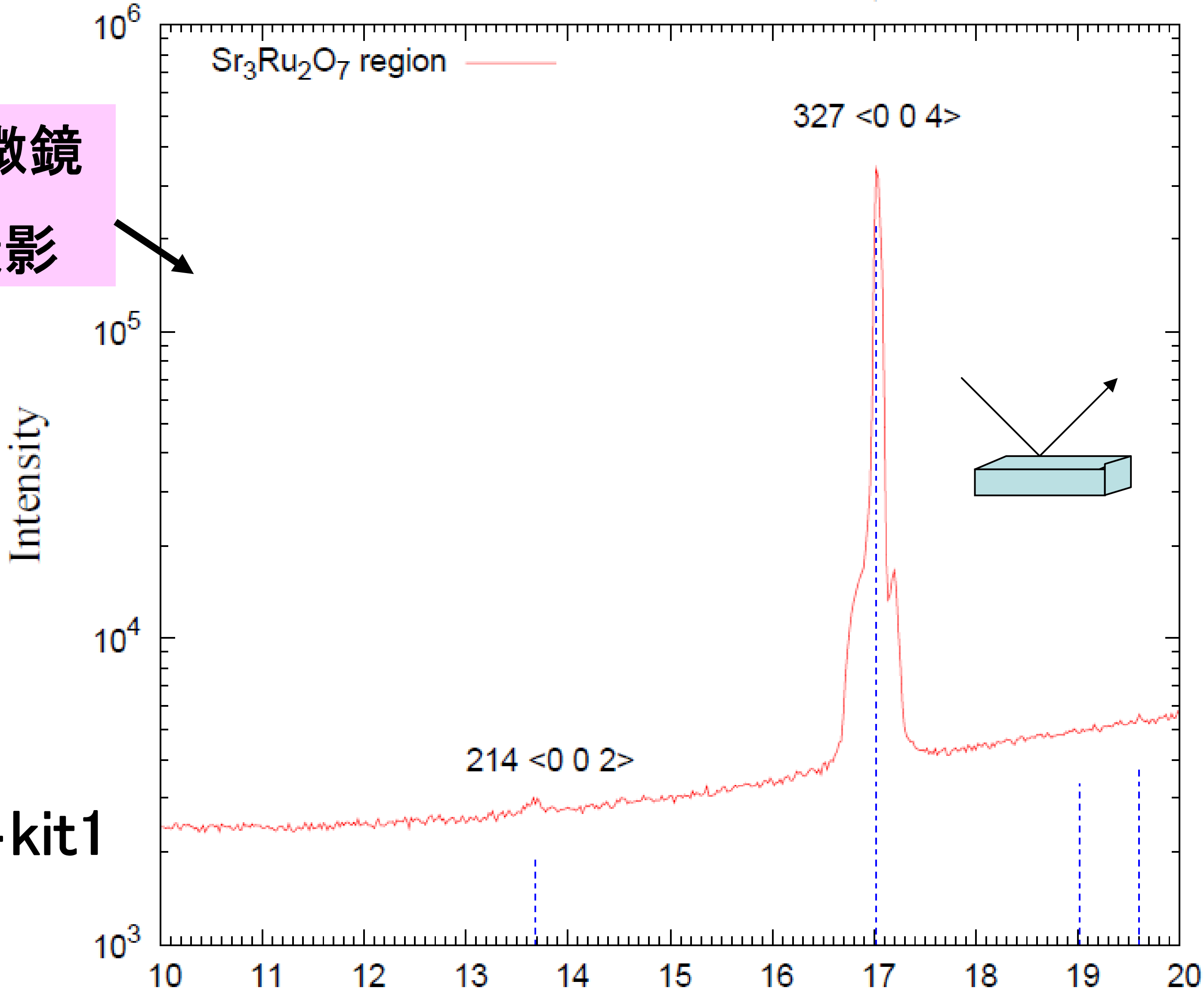
327中に214の小さな領域が存在すると考えられる。

実際、顕微鏡観察で確認した。

$Sr_3Ru_2O_7$領域の表面写真とX線回折パターン

光学顕微鏡

により撮影



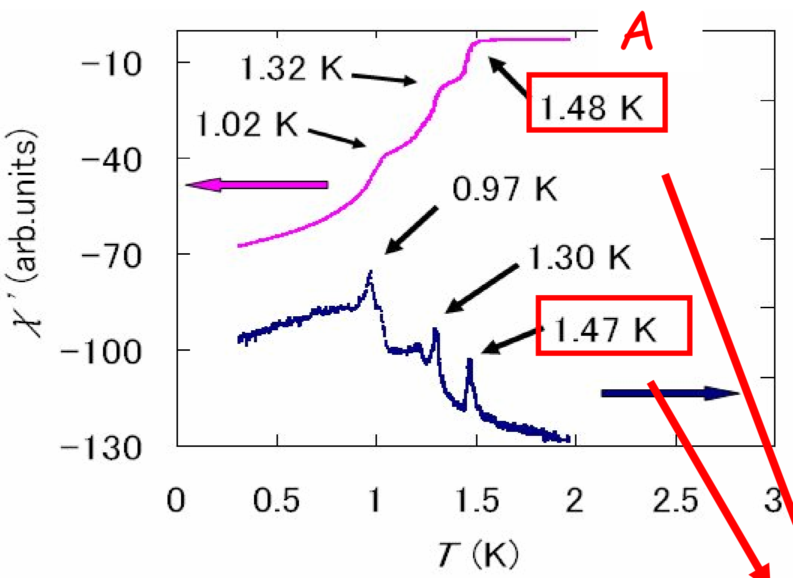
Sample

Cfv07f-kit1

表面を観察するとμmオーダーのSr_2RuO_4が見える。

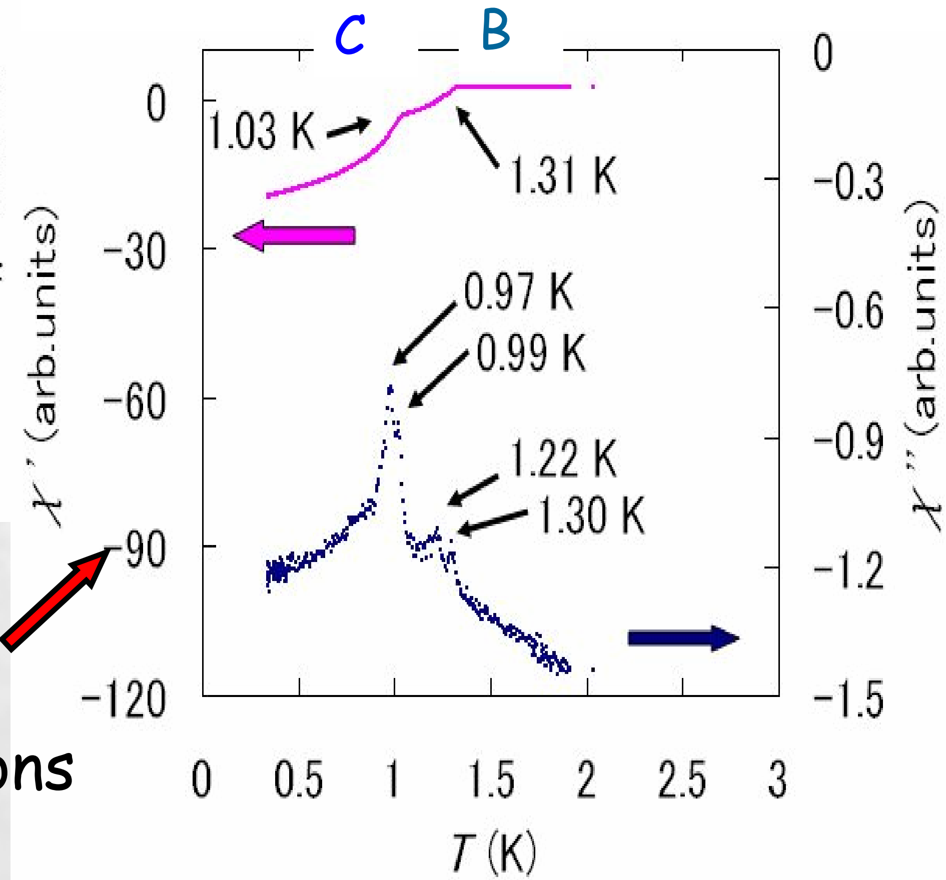
Before and After the bulk 214 is removed

Both 214 and 327



"327" only:

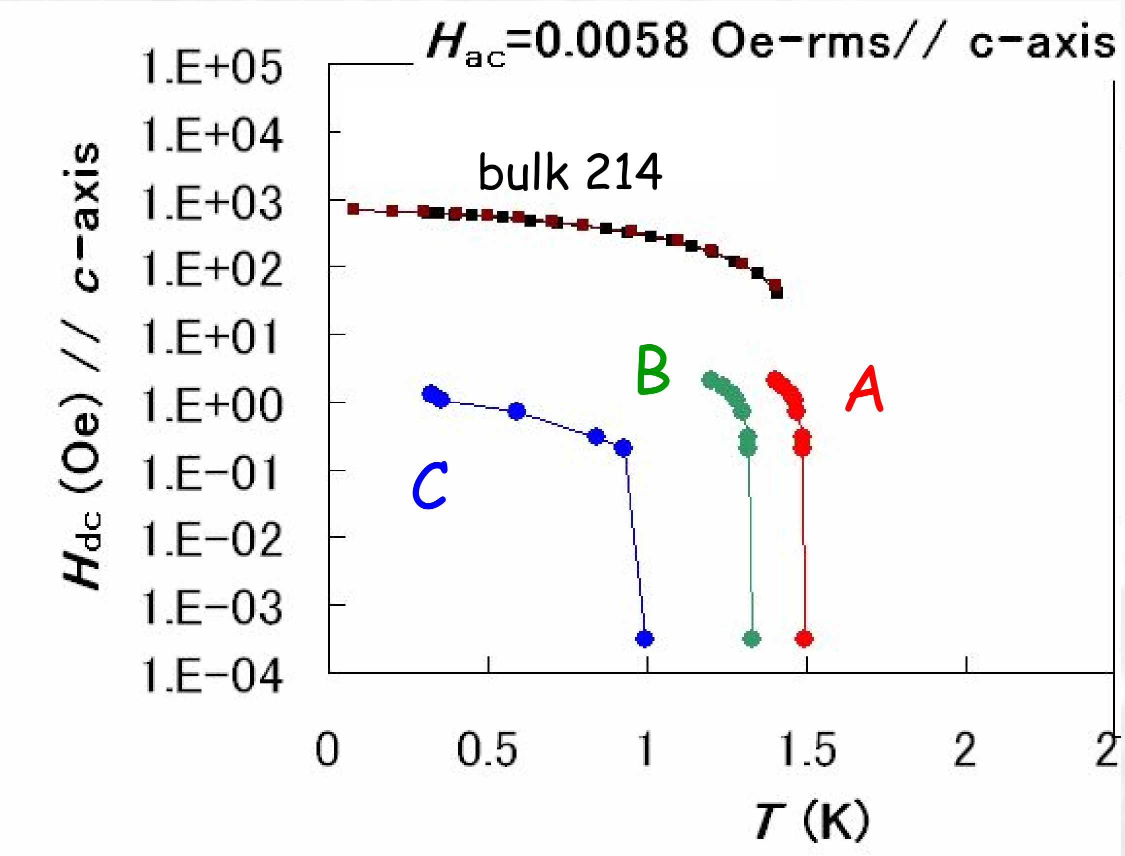
still contains two weak sc



No contribution from the bulk 214

Two superconducting transitions remain in the "327" .

H-T Phase Diagram of the 214-327 Eutectic



For weak links:

$H_c S \sim \Phi_0$

For C:

Area $S \sim 20\ (\mu m)^2$

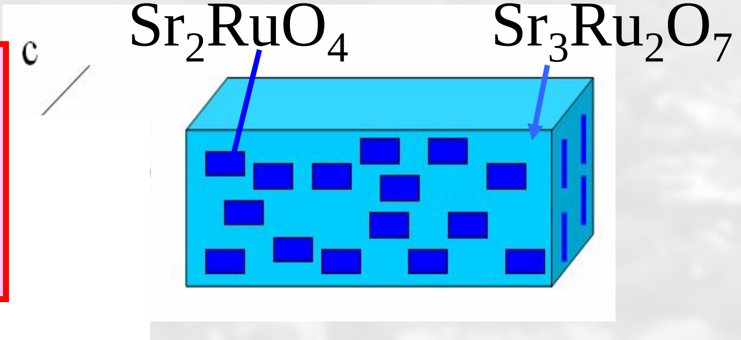
A: bulk Sr_2RuO_4,

C: very weak superconductivity

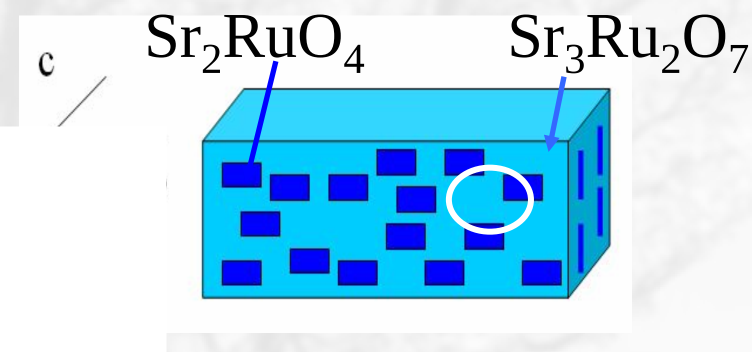
Estimate of volume fraction

Sample	*H*// ab-plane	*H*// c-axis
"327" from 214-327 eutectic (No.7-β)	5 %	**81 %**
Higher quality 327 (C642a1a1)	6 %	5 %
Lower quality 327 (C632b1)	0.8 %	3 %

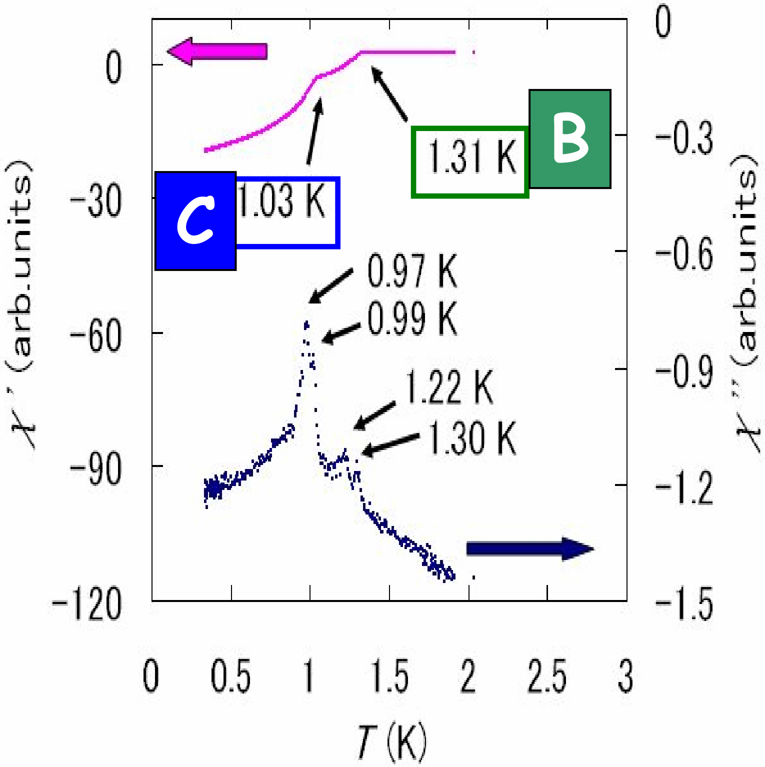
Apparent "327" from the eutectic exhibits an anomalous diamagnetic shielding.



Speculations



ac susceptibility



Two well-separated weak sc signatures:

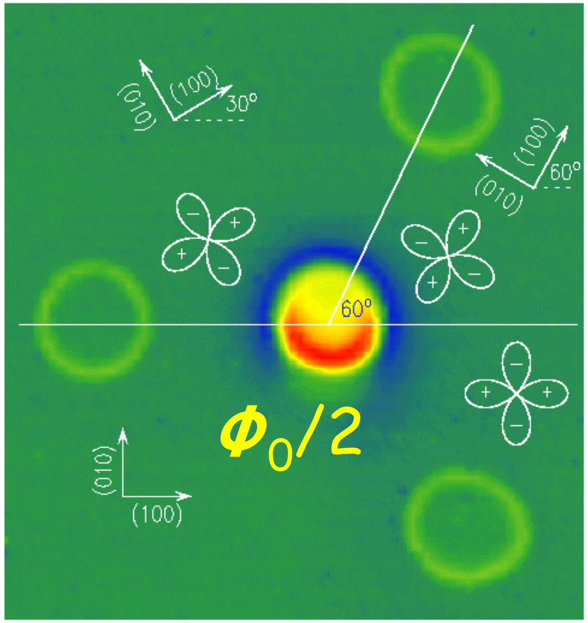
"B": properties of **214 micro-domains**?

Robust against H_{DC}, very sensitive to H_{AC}

"C": properties of **proximity-junction network**?

Very sensitive to both H_{DC} and H_{AC}

For d-wave:
π -junction loop in high- T_c cuprates



Tricrystal Ring of YBCO
Tsuei, Kirtley *et al.*,
PRL **73**, 593(1994).

Braunisch et al., PRL (1992)

Sigrist and Rice, JPSJ (1992).

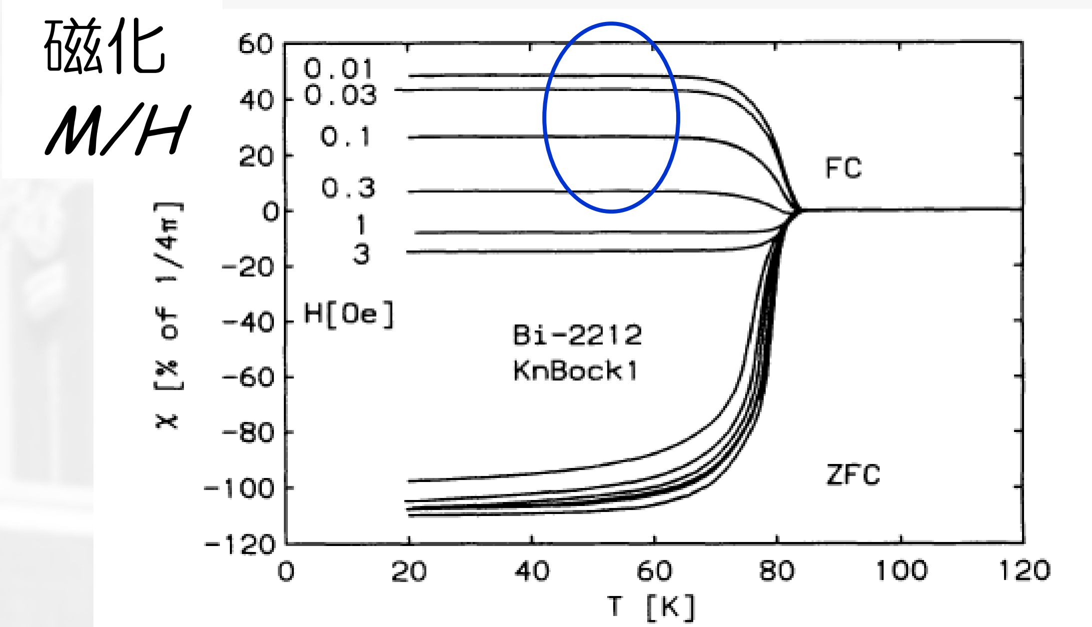


FIG. 2. ZFC and FC signals of a ceramic Bi-2:2:1:2 sample exhibiting the paramagnetic Meissner effect (PME).

Wohlleben effect :
positive susceptibility
due to π -junction loops
among randomly-oriented grains.

Eutectic Systems: Conclusions

1. Ruとの共晶：**3-K相**

圧力下での増強超伝導

● 1.8 K (>bulk T_c) での体積分率が**40%**にも達する。

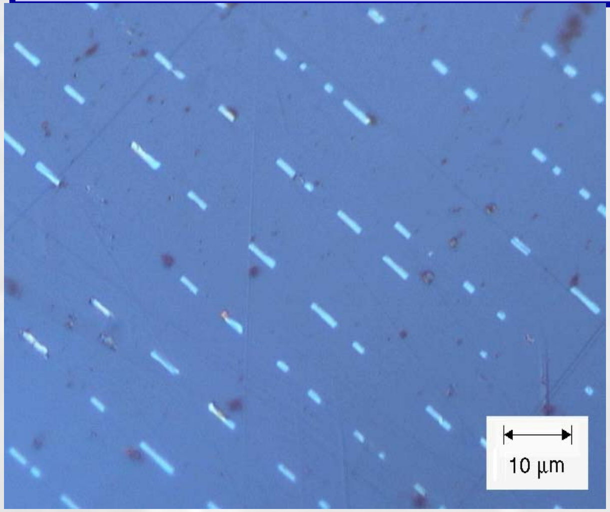
機構未解明

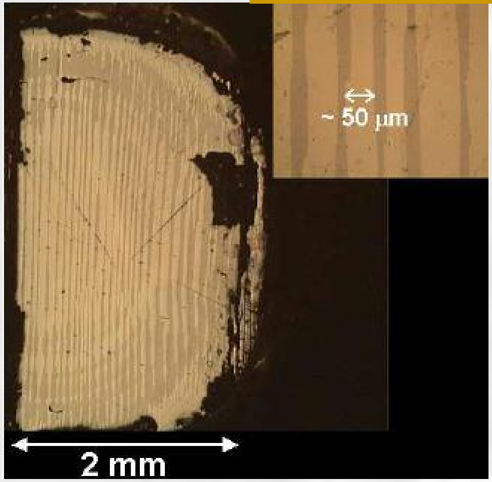
2. $Sr_3Ru_2O_7$との共晶：

超伝導近接ネットワーク

●見かけ**$Sr_3Ru_2O_7$**の領域でも弱磁場では**80%**の反磁性遮蔽

おそらくSr_2RuO_4のグレイン結合0-junctionsのループ





これらを舞台に
スピン三重項の
特性を引き出せるか?