Plan of the Study of Superconducting Sr_2RuO_4 by Resonance Experiments

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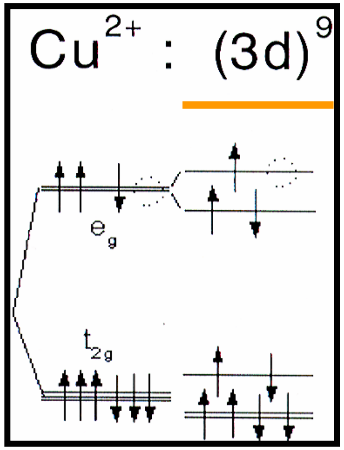
Superconductivity in Sr_2RuO_4 ($T_c \sim 1.5$ K)

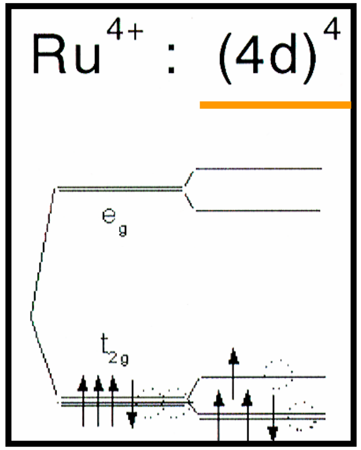
Maeno *et al.* Nature 372, 532 ('94)

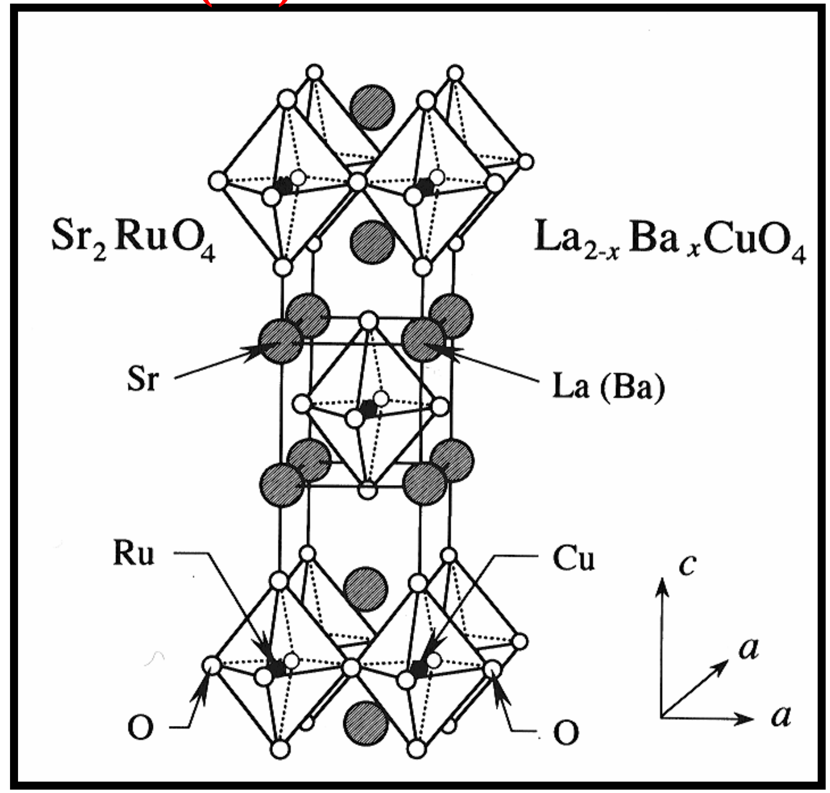
- 2-D proveskite structure

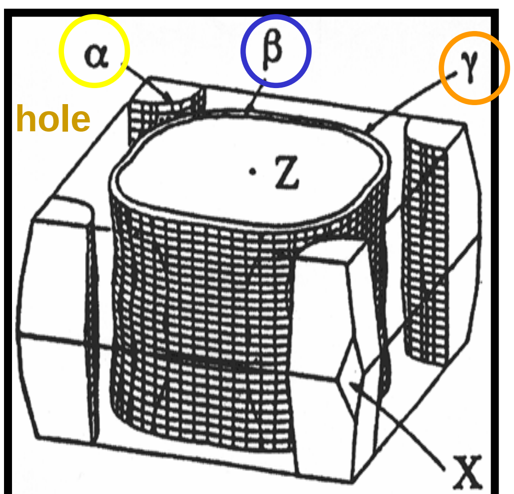
  Same as high-T_c cuprate (La_2CuO_4)

- CuO_2 → RuO_2









α,β : 1-D d_{xz}, d_{yz} character

γ :2-D d_{xy} character

57% Main-band

Electronic state

- Quasi-2D Fermi liquid : $\rho \propto T^2$ at Low-T
- Strongly Correlated Electron system

  $\gamma \sim 37.5$ mJ/K²mol $\chi_{obs} / \chi_{band} \sim 5.5$,
- Multi-band character

Possibility of Spin-Triplet Superconductivity

T.M.Rice and M. Sigrist, J. Phys, Condens. Matter7 ('95)

Related compounds : $SrRuO_3$ (FM: T_C ~ 160 K), $Sr_3Ru_2O_7$ (Metamagnetism)

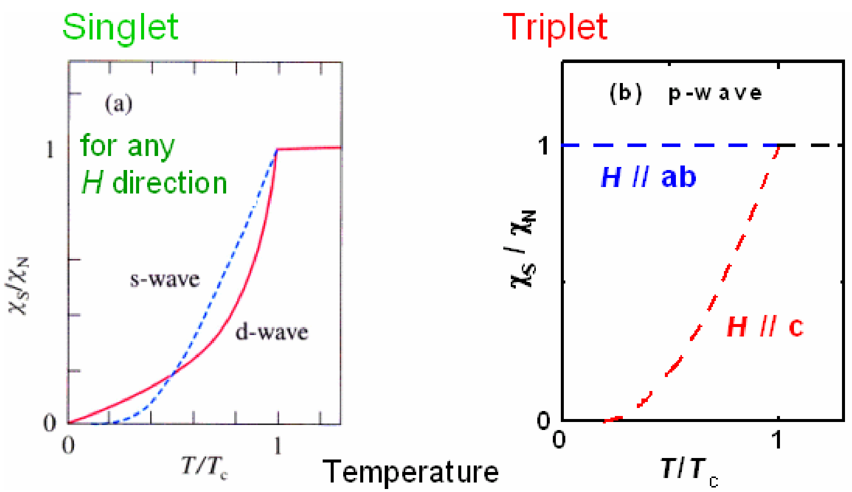
Importance of ferromagnetic fluctuations for the superconductivity and analogy of superfluid ^{3}He were pointed out.

Symmetry of SC Gap function

SC wave function

$$\Psi(r_1, \sigma_1: r_2, \sigma_2) = \chi(\sigma_1, \sigma_2)\ \ \psi(r_1, r_2)$$

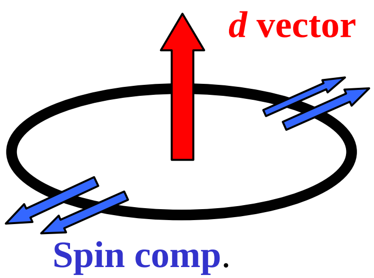
Spin part **Orbital part**



NMR gives important information about both parts.

Knight shift measurements : Spin susceptibility

Nuclear spin-lattice relaxation rate $1/T_1$: Gap structure



Spin susceptibility in the SC state

K.Ishida *et al.* Phys. Rev. B 63, 060507(R)

K-χ plot : Estimation of K_{spin}

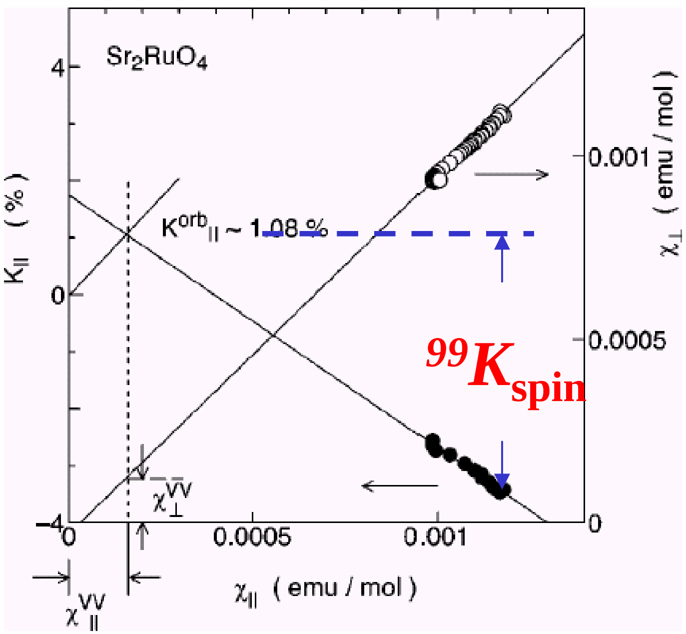


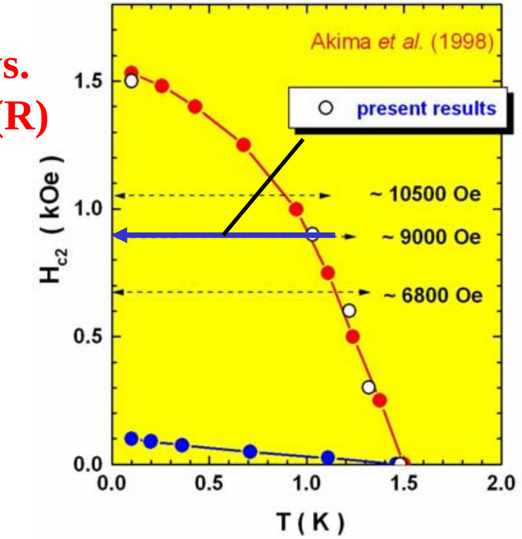
FIG. 2. Plot of $^{99}K_{\|}$ (Ref. 18) against $\chi_{\|}$ (left scale). The relation between $\chi_{\perp}$ and $\chi_{\|}$ are also plotted (right scale).

$K = A\chi$

$^{Ru}A \sim -250$ kOe / μ_B

(Core polarization by 4d)

Ru site : $K_{spin}^{ab} \sim -3.6$ %



Ru NMR

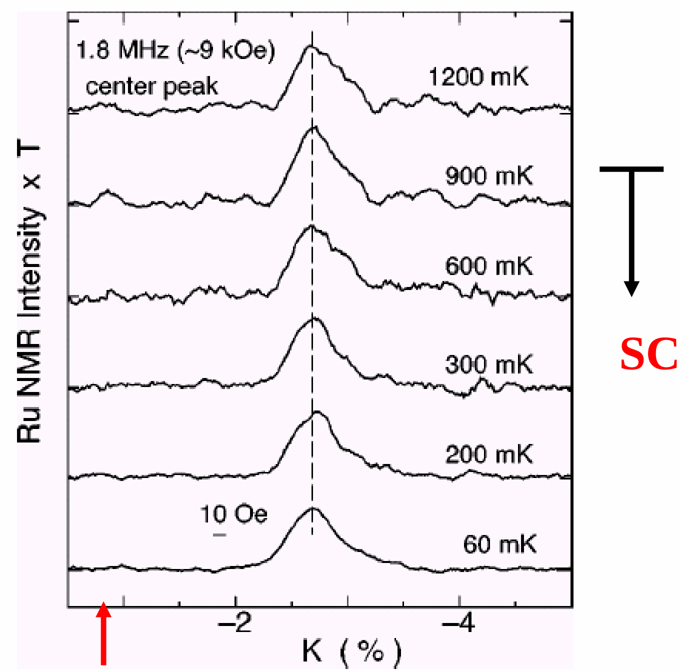


FIG. 5. ^{99}Ru-NMR spectra of the $1/2 \leftrightarrow -1/2$ central transition at various temperatures. T_c (9 kOe) is ~ 1.0 K. Signal intensity was multiplied by T. In the bottom spectrum, the scale of 10 Oe is shown.

^{17}O Knight Shift measurement

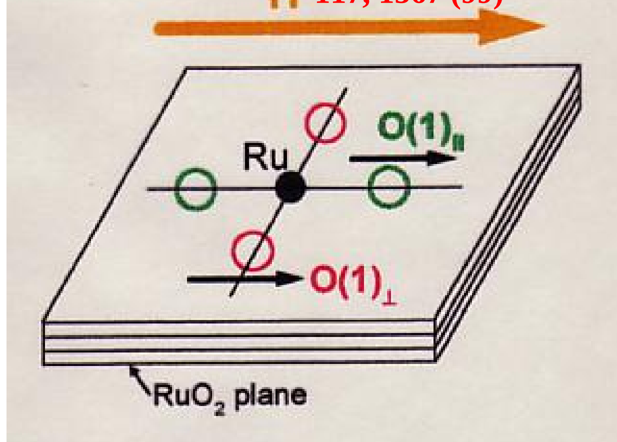
K. Ishida *et al.* Nature 395, 658 (98)

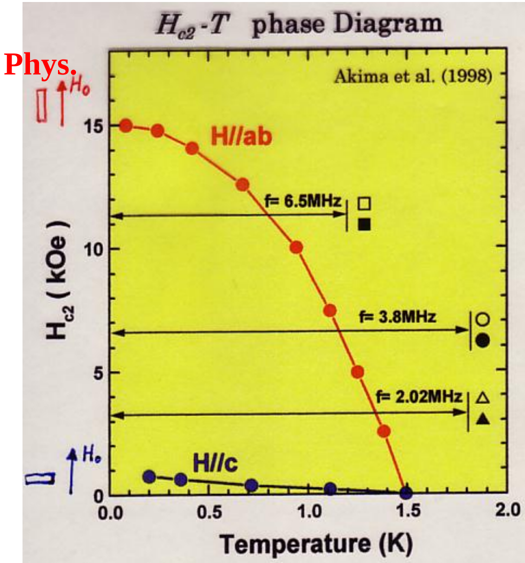
Mukuda *et al.* J. Low Temp. Phys. 117, 1567 (99)

Spin part in *K*

$K = 0.5$ %

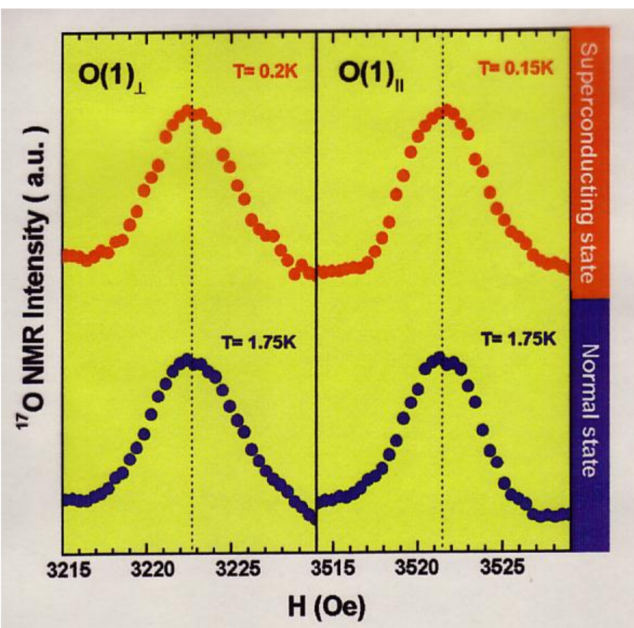
$K_{\|} = -0.3$ %

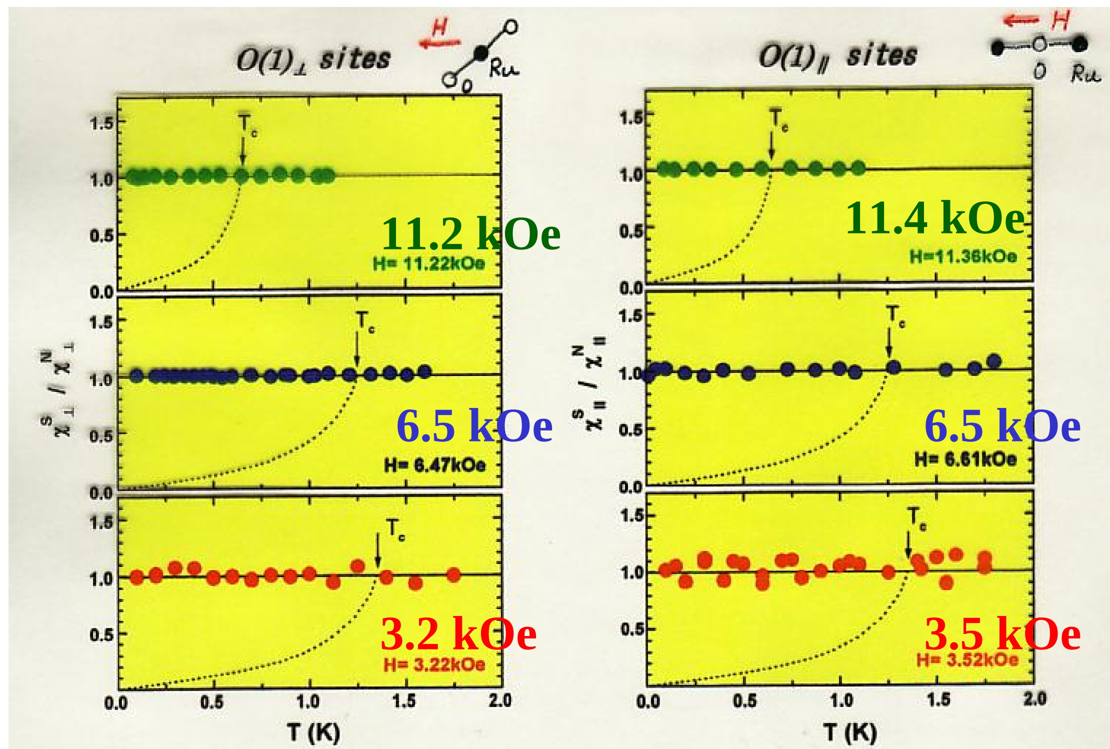




H // ab ~ 3.5 kOe

FWHM ~ 5Oe



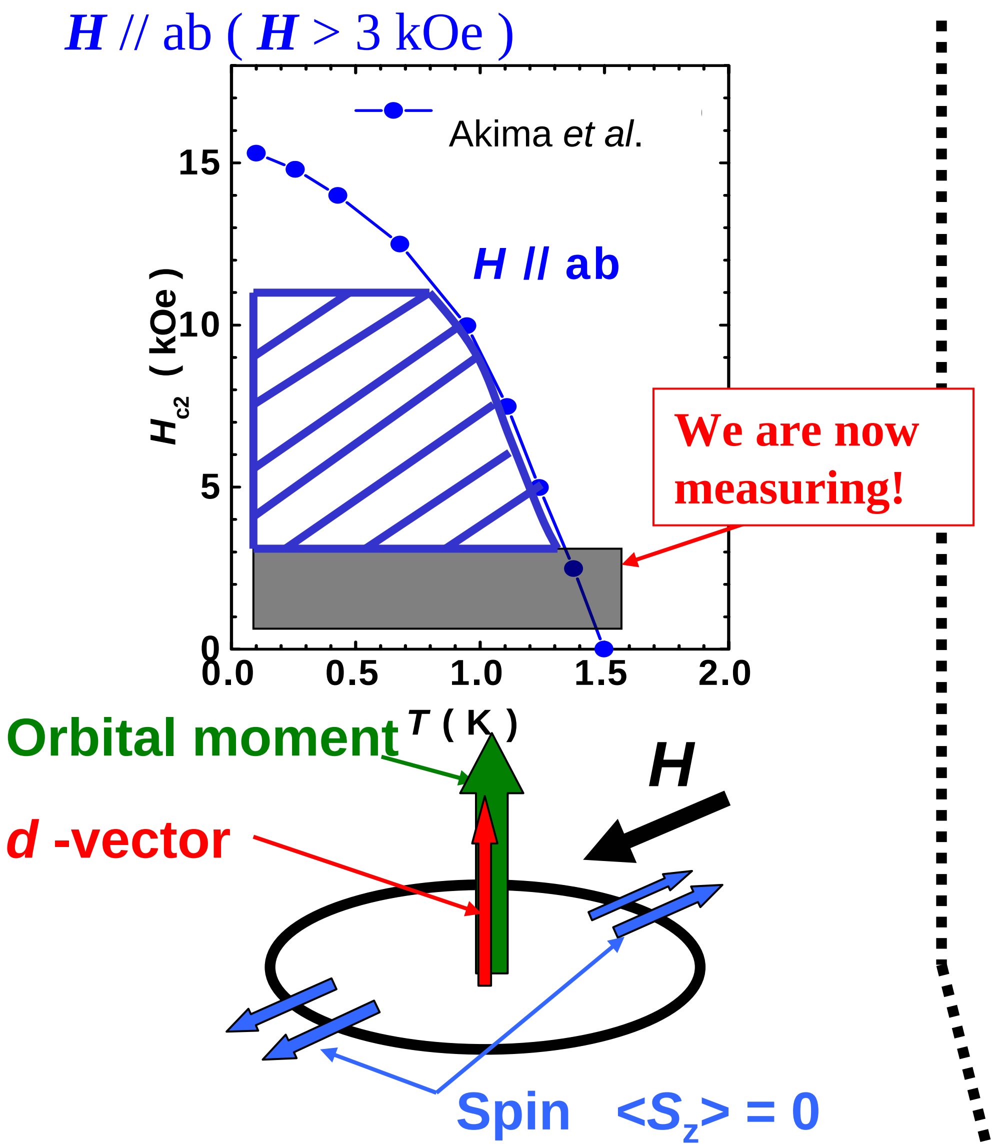


Issues to be clarified

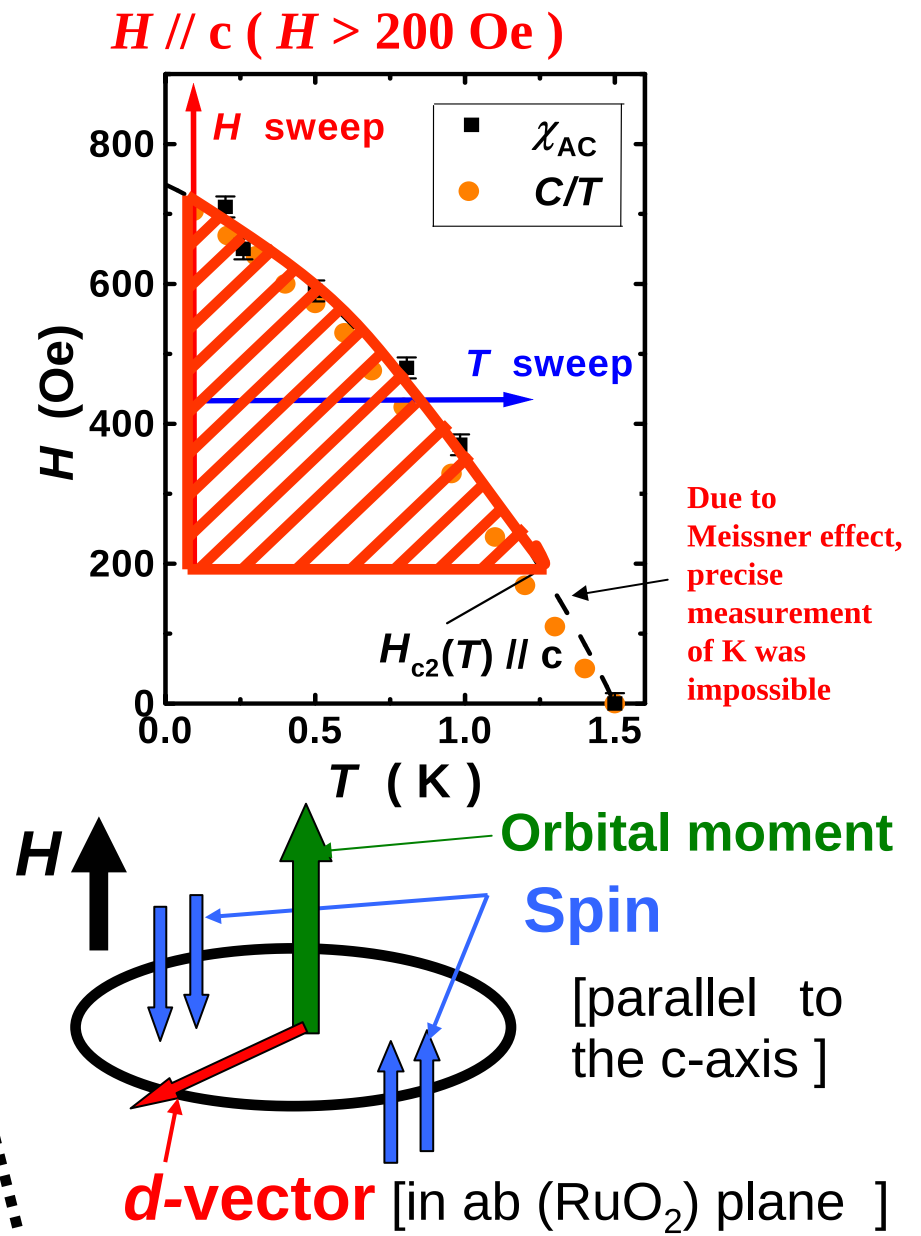
1) Determination of ***d*-**vector at zero field and the pinning interaction of the Cooper pairs

Knight shift measurements under small field

Possible *d*-vector state suggested by *KS* measurements



$d = z\Delta_0(\sin k_x + i \sin k_y)$ (A state)



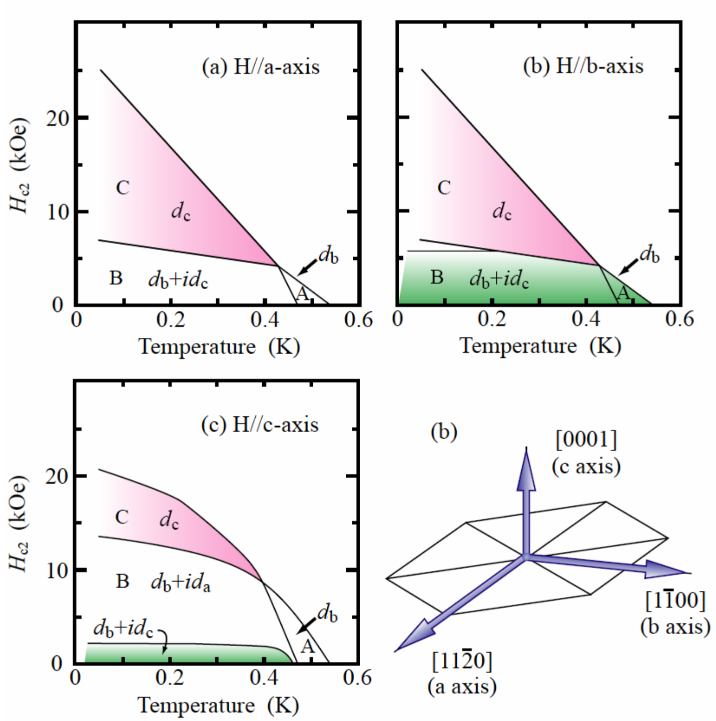
Knight Shift Measurements in Triplet Superconductor UPt_3

UPt_3: Heavy Fermion Superconductor

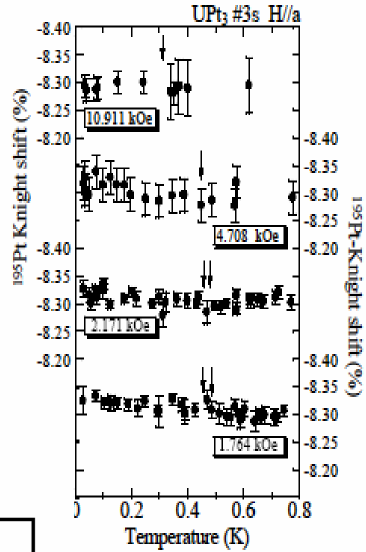
T_{c1} ~ 0.58 K,

T_{c2} ~ 0.53 K

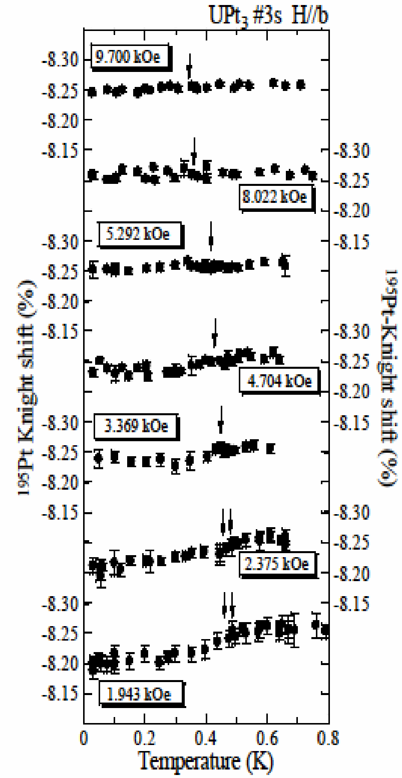
Multi-SC phase



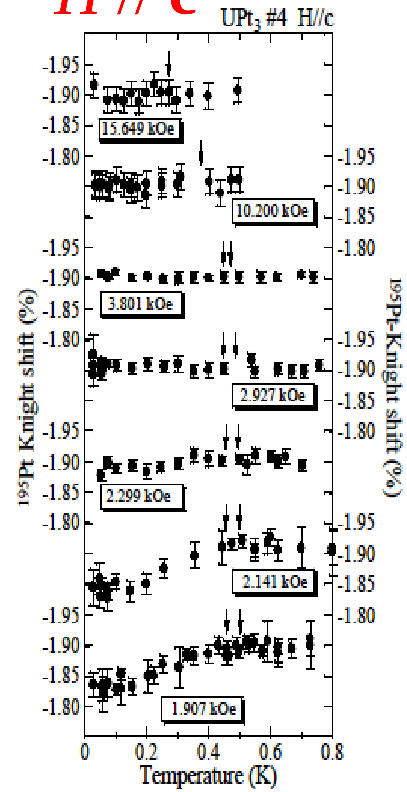
H // **a**



H // **b**



H // **c**



Tou *et al.*

PRL 80, 3132

KS decreases when

H < 5 kOe // **b**, *H* < 2.2 kOe //**c** are applied.

***KS* shows anisotropic behavior**

Pinning interaction is small.

^{101}Ru-NMR in Sr_2RuO_4

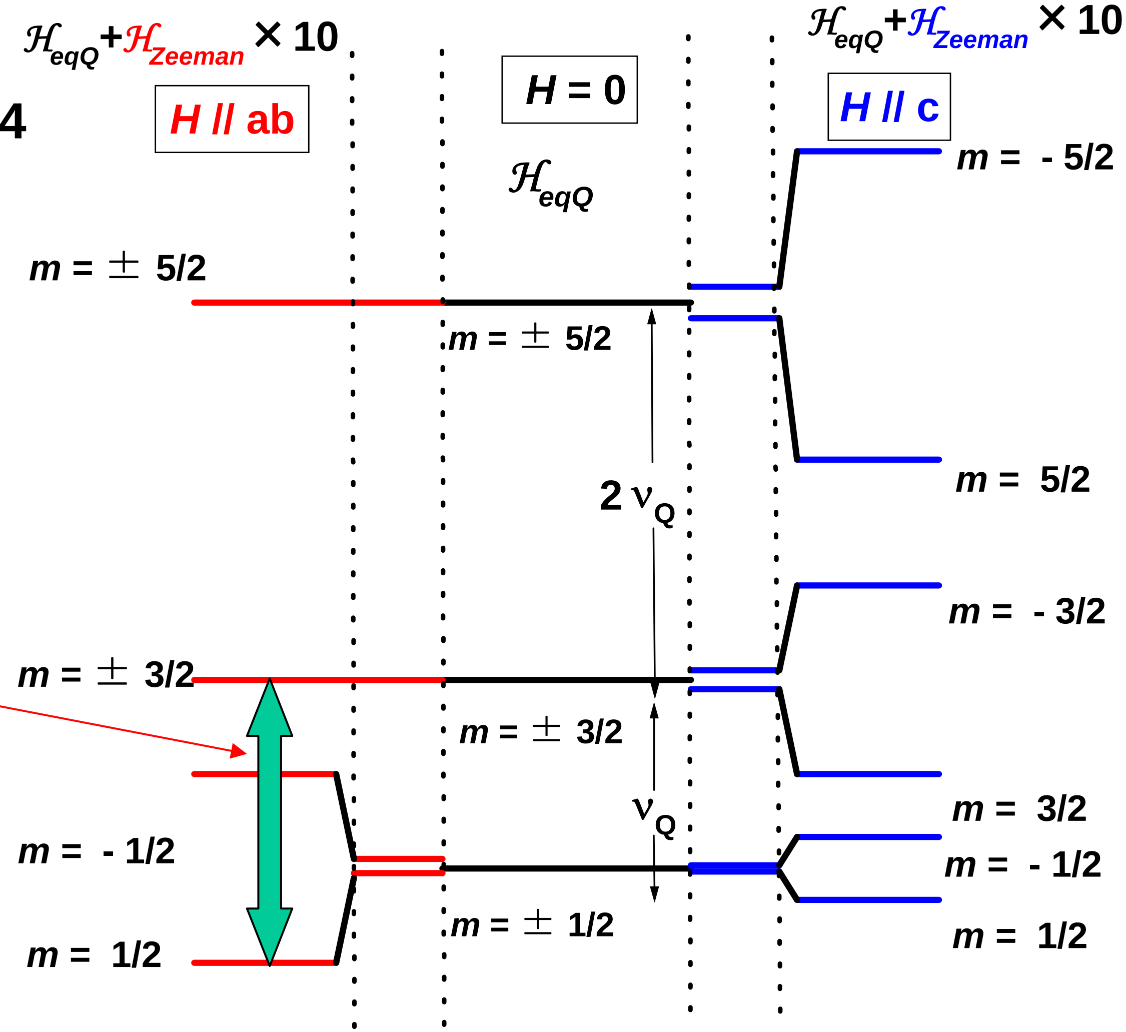
$^{101}\gamma/2\pi \sim 0.2$ MHz / kOe

$K_{spin} \sim -4$ %

N.A. ~ 17 %

Observed Transition

$\Delta\omega = 2\gamma_n H(1+K)$



Nuclear Spin Hamiltonian

$$\mathcal{H} = \mathcal{H}_{eqQ} + \mathcal{H}_z = A\{3I_z^2 - m(m+1)\} - \gamma\hbar H_0(I_z\cos\theta + I_x\sin\theta)$$

$$= A\{3I_z^2 - m(m+1)\} - \gamma\hbar H_0\{I_z\cos\theta + \tfrac{1}{2}(I_+ + I_-)\sin\theta\}$$

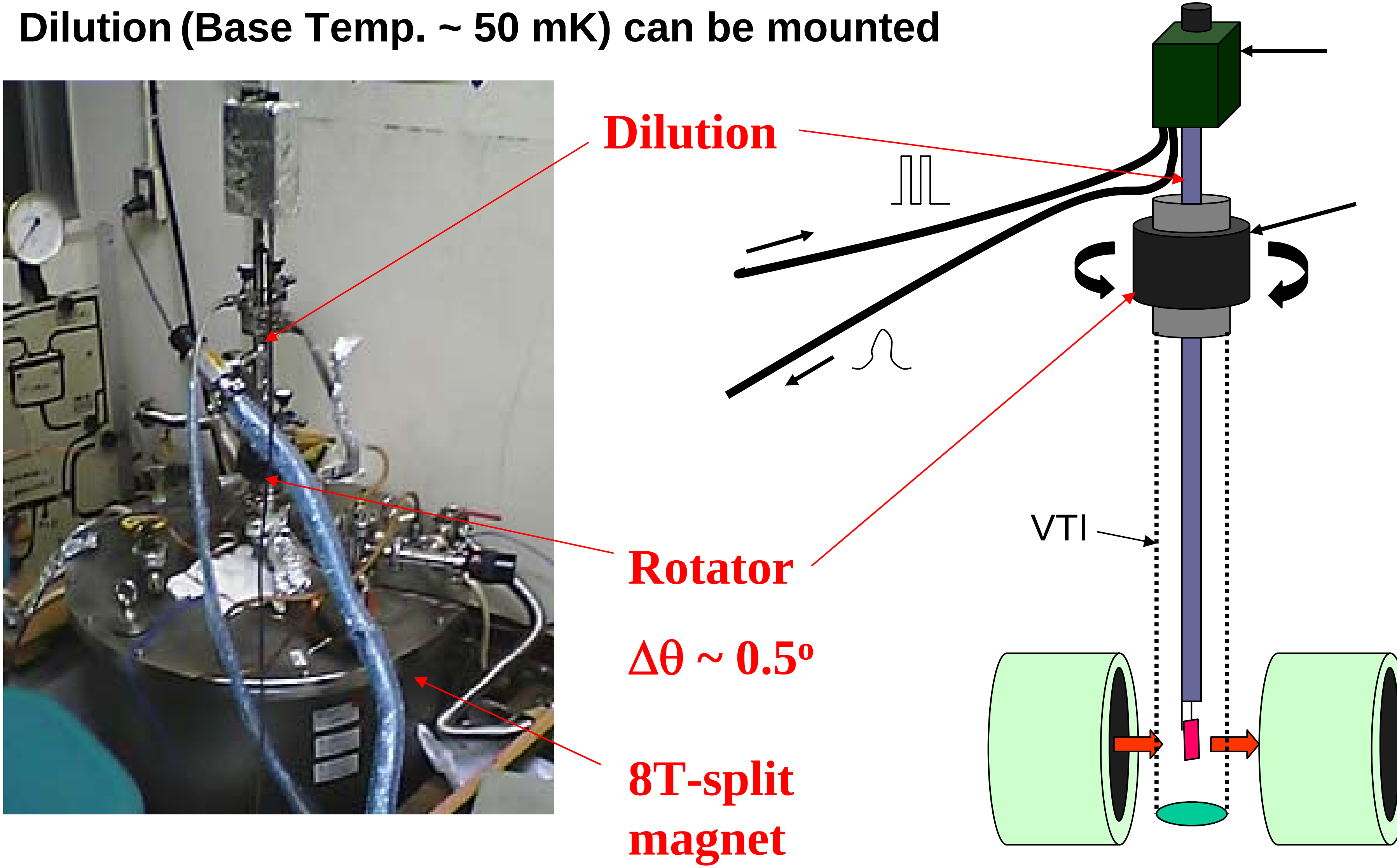
$$E_{\pm m}(H_0) = E_{\pm m}(0) \mp \frac{\gamma\hbar H_0}{2}[\cos^2\theta + (I+\tfrac{1}{2})^2\sin^2\theta]^{\frac{1}{2}} \qquad (m = \pm\tfrac{1}{2})$$

$$E_{\pm m}(H_0) = E_{\pm m}(0) \mp \gamma\hbar H_0 m\cos\theta \qquad (m \neq \pm\tfrac{1}{2})$$

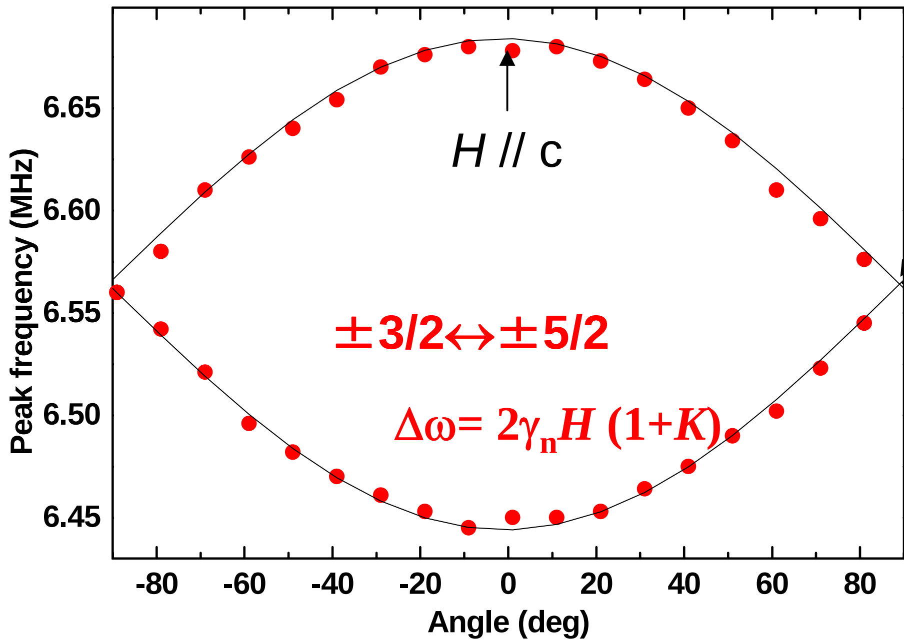
Equipment （8 T-split Magnet + Dilution）

Magnetic field homogeneity : 5×10^{-5} / cm^3

Dilution (Base Temp. ~ 50 mK) can be mounted



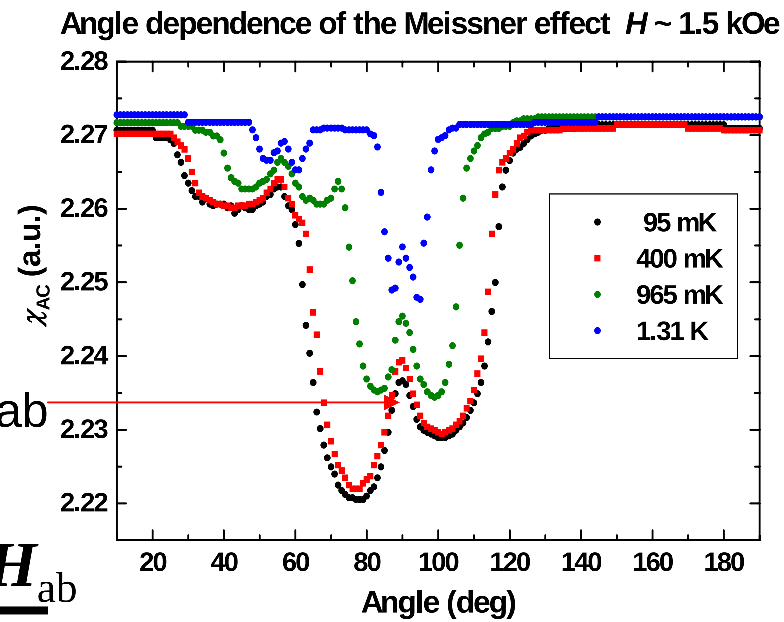
Angle dependence of ^{101}Ru NQR Spectra under 500 Oe

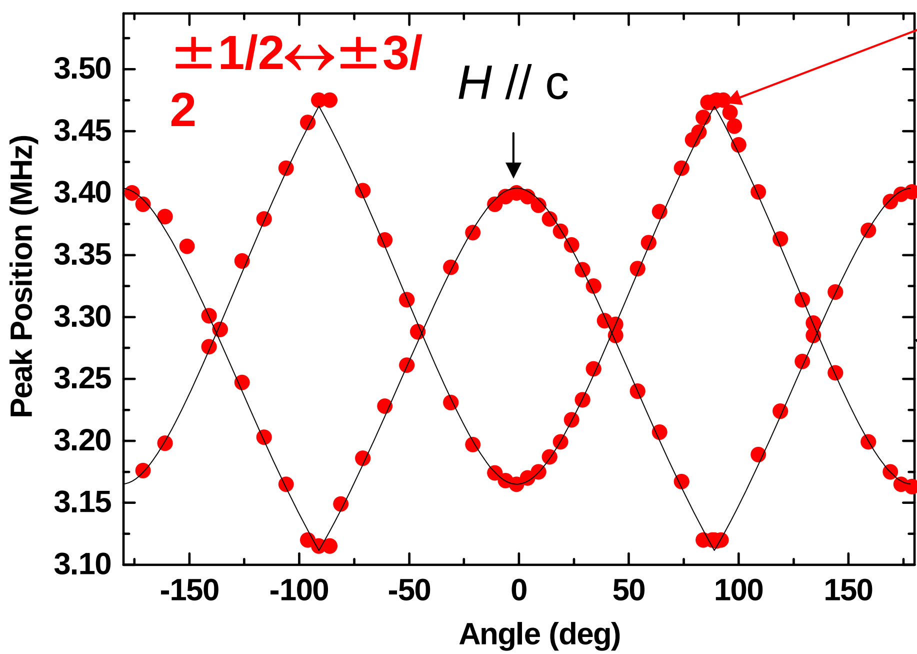


No splitting when *H // ab*

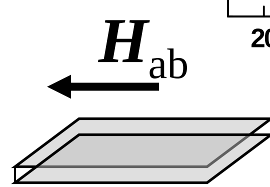
ν_Q = **6.564 MHz**

Meissner





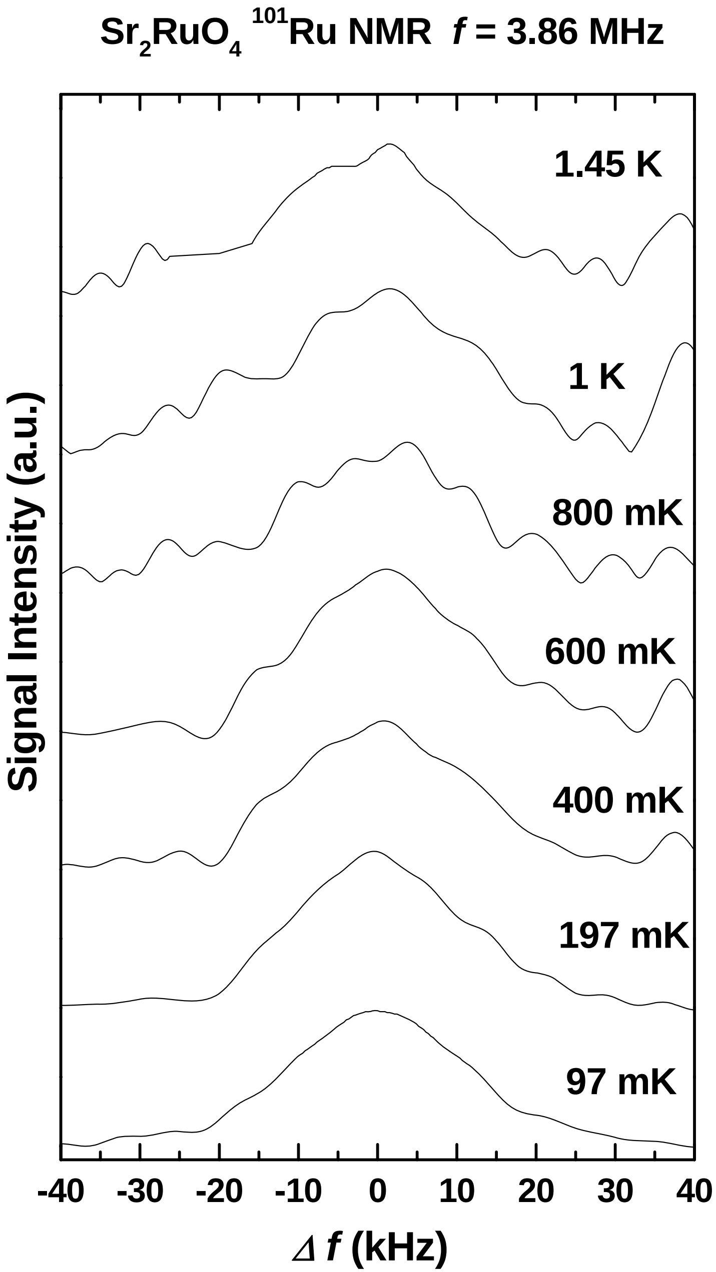
H // ab



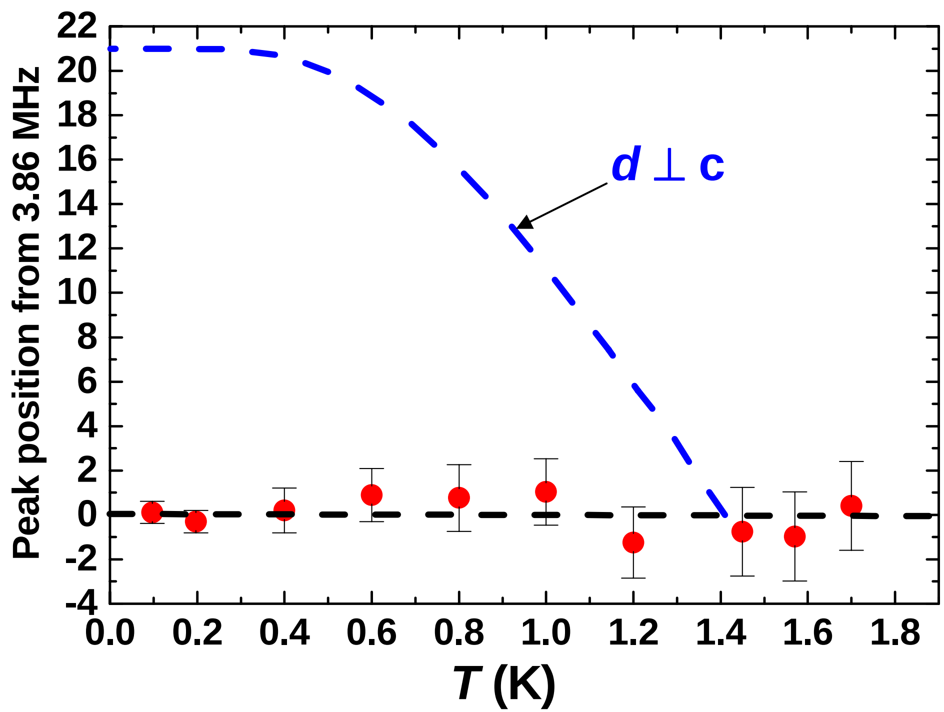
ν_Q = 3.282 MHz

Poster P-49 Murakawa

NMR spectra by dilution under H = 1.5 kOe



The peak positions of the NMR spectra is invariant with temperature.

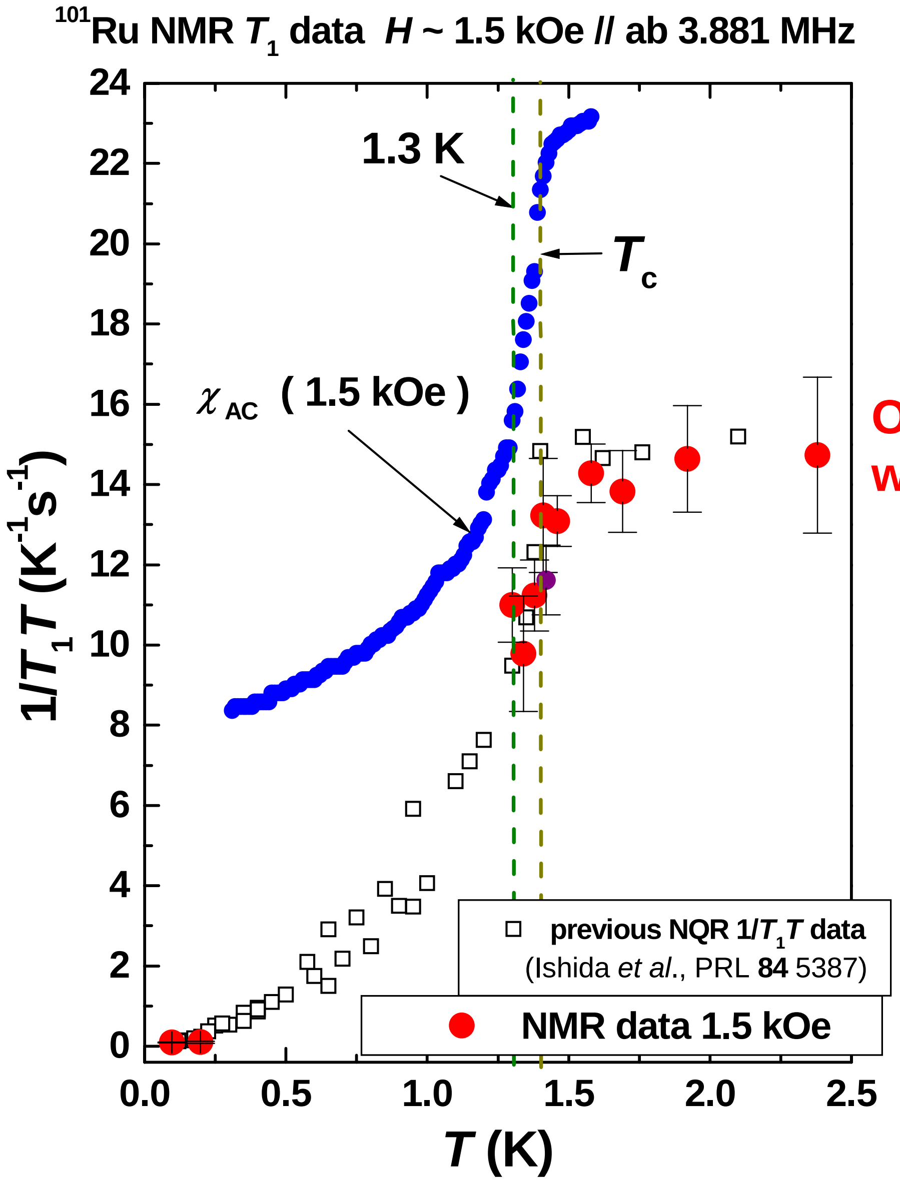


^{101}Ru NMR signal is very weak and intensity is proportional to the inverse of the temperature.

Around T_c, it is difficult to get clear signal as 100 mK.

Confirmation of the SC transition

（Measurement of the spin lattice relaxation time (T_1)）



$1/T_1T$ decreases abruptly below T_c (~ 1.4 K at 1.5 kOe) .

Our T_1 data strongly suggest that the signals we observed arise from the SC region.

$1/T_1T \propto N(E)^2$

（ $N(E)$; density of states ）

$1/T_1T$ (at 100 mK) ~ 8 × 10^{-5} ($ms^{-1}K^{-1}$)

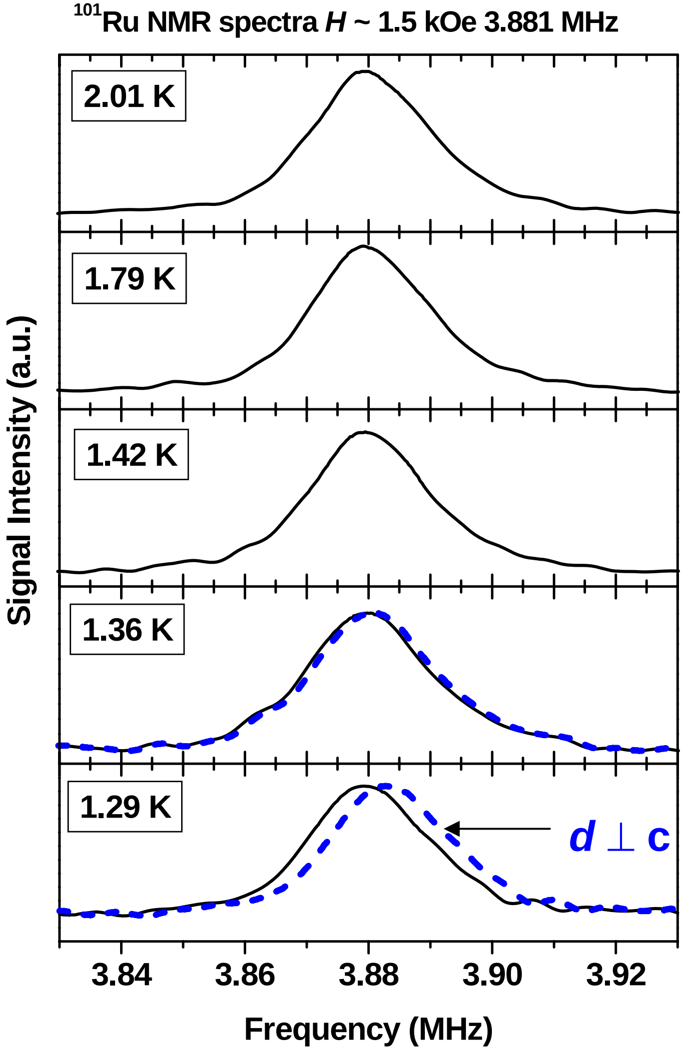
< 10^{-5} $1/T_1T$ (normal state) ~ 15 ($ms^{-1}K^{-1}$)

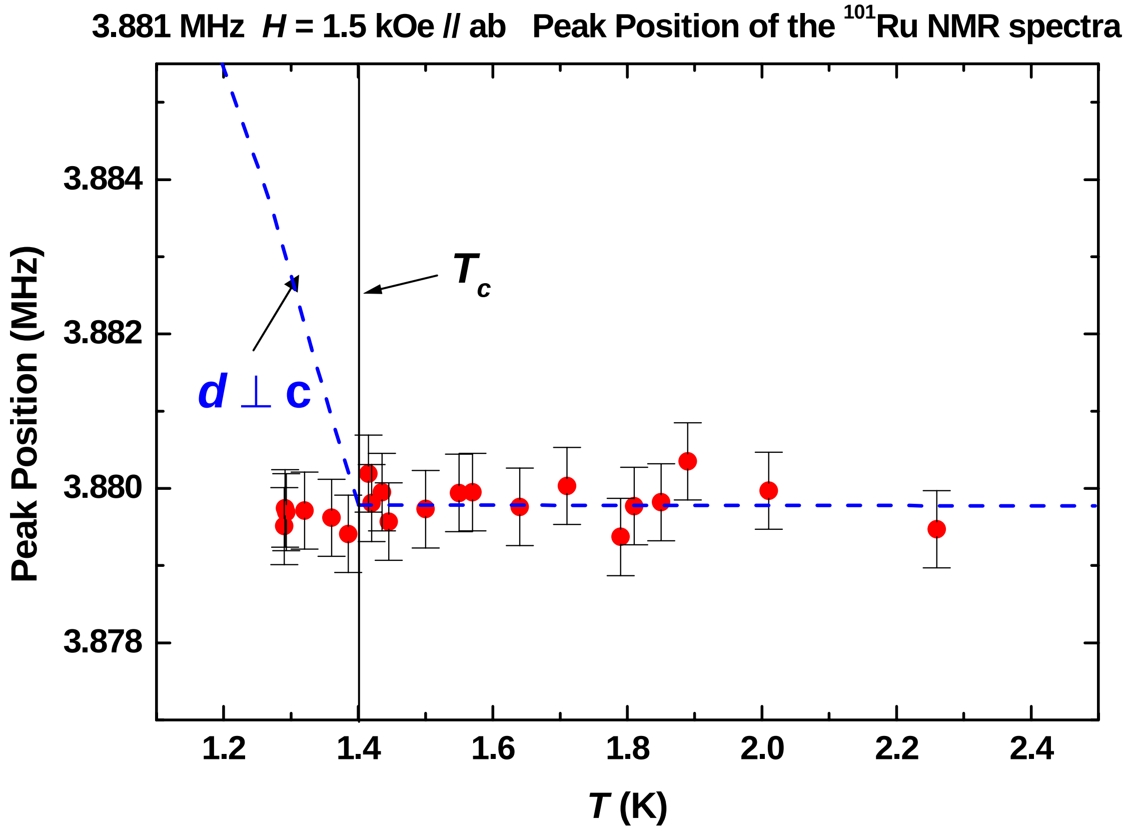
More than 90 % decrease of the density of states at 100 mK.

Precise measurement of the spectra around T_c

Just below T_c, the density of states rapidly changes with temperature.

We performed the previous Knight shift measurement just below T_c.





***K* is invariant with *T*.**

Issues to be clarified

1) Determination of ***d*-**vector at zero field and the pinning interaction of the Cooper pairs

Poster - 49 Murakawa *et al.*

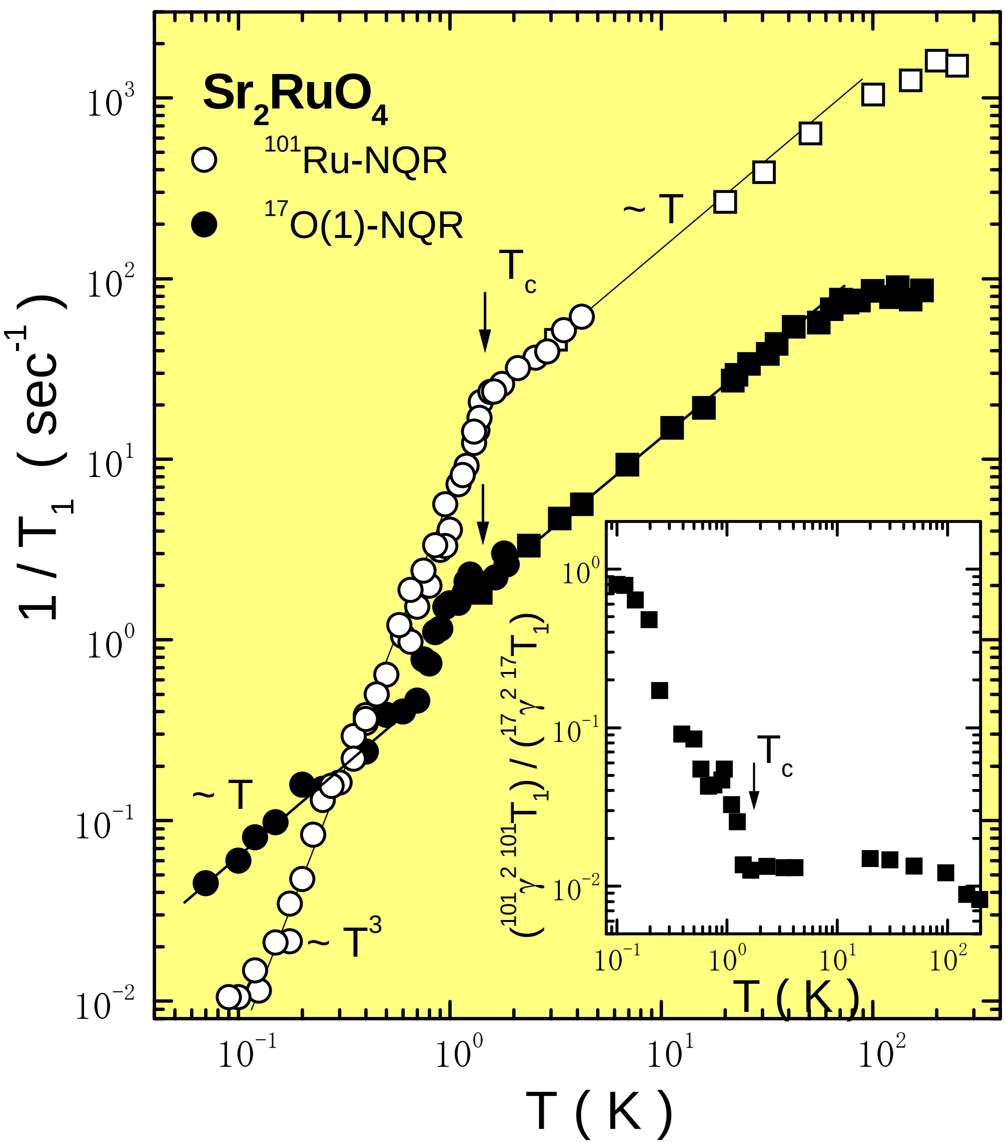
2) Collective mode in the SC state

Nuclear spin-lattice relaxation rate $1/T_1$ in the SC state

$1/T_1$ at Ru and O sites in Sr_2RuO_4

H. Mukuda *et al.*

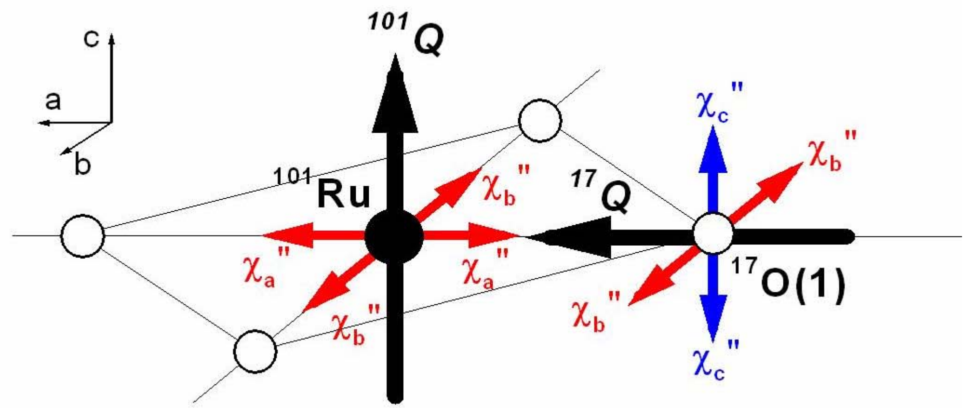
Phys. Rev. B 65, 132507



In the normal state, $1/T_1$'s at both sites show similar T dependence

T dependence of $1/T_1$ becomes different between Ru and O sites below T_c.

Analyses



^{101}Ru

$$^{101}(T_1T)_{NQR}^{-1} \sim \Sigma\, |^{101}A_{ab}|^2\, {}^{101}\chi_a''(\mathbf{q},\omega_n)/\omega_n + \Sigma\, |^{101}A_{ab}|^2\, {}^{101}\chi_b''(\mathbf{q},\omega_n)/\omega_n$$

^{17}O(1)

$$^{17}(T_1T)_{NQR}^{-1} \sim \Sigma\, |^{17}A_b|^2\, {}^{17}\chi_b''(\mathbf{q},\omega_n)/\omega_n + \Sigma\, |^{17}A_c|^2\, {}^{17}\chi_c''(\mathbf{q},\omega_n)/\omega_n$$

$^{101}A_{ab} \sim -220\ kOe/\mu_B$

$^{17}A_b \sim +26.8\ kOe/\mu_B$

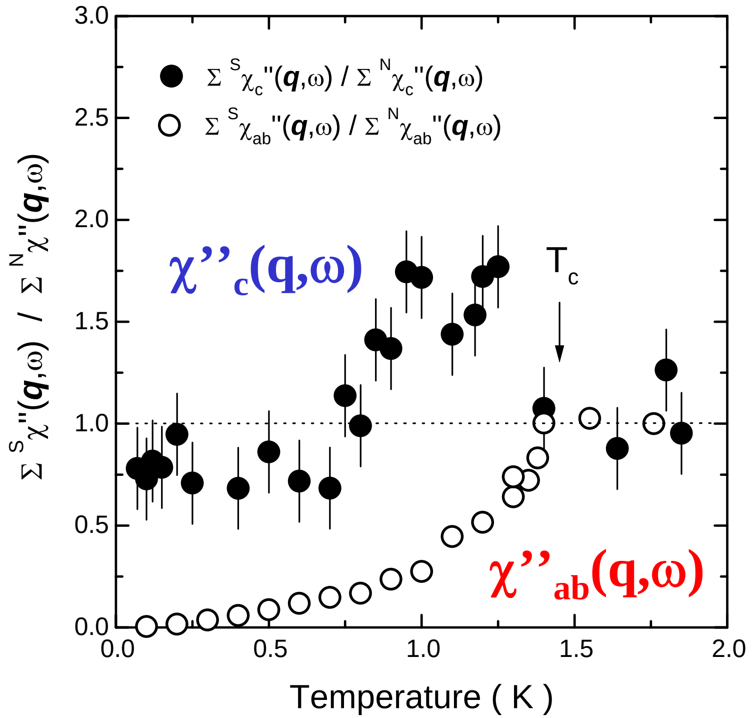
$^{17}A_c \sim -8.3\ kOe/\mu_B$

Imai *et al* : *Phys. Rev. Lett.* 81, 3006 (00),

"same *T*-dependence between $^{101}(1/T_1T)_c$ and $^{17}(1/T_1T)_c$"

$\Rightarrow |^{101}A_{a,b}| / |^{17}A_{a,b}| \sim 11.3$

$\Rightarrow \Sigma\, {}^{101}\chi_{a,b}''(\mathbf{q},\omega_n) \sim \Sigma\, {}^{17}\chi_{a,b}''(\mathbf{q},\omega_n)$



Some dynamics show up below T_c.

Gapless excitations along the c-axis.

Collective mode?

Issues to be clarified

1) Determination of ***d*-**vector at zero field and the pinning interaction of the Cooper pairs

Poster - 49 Murakawa *et al.*

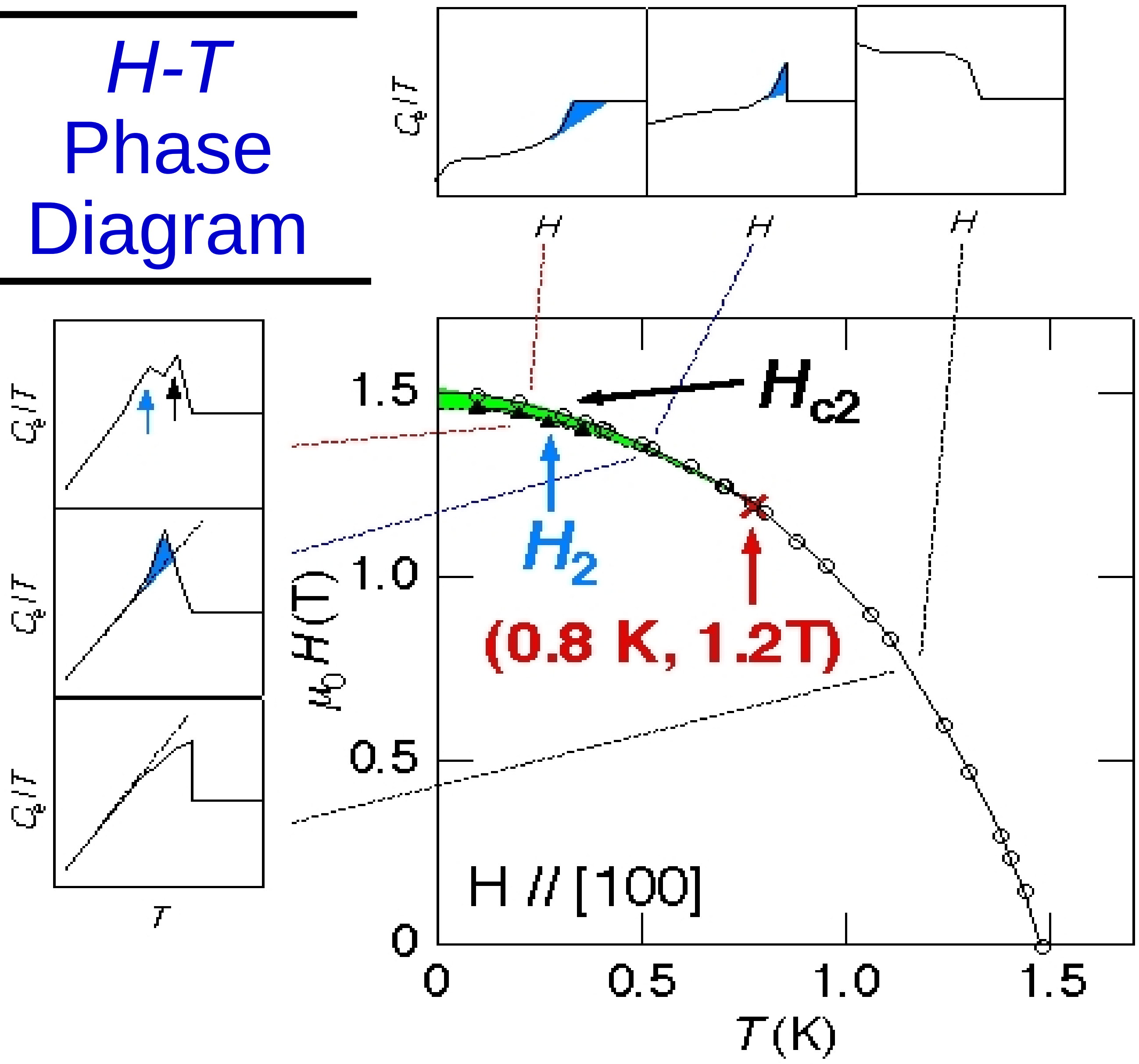
2) Collective modes in the SC state

$1/T_1$ at O sites

3) Multi-SC phase behavior

$1/T_1$ and KS measurements in various field

H-T Phase Diagram



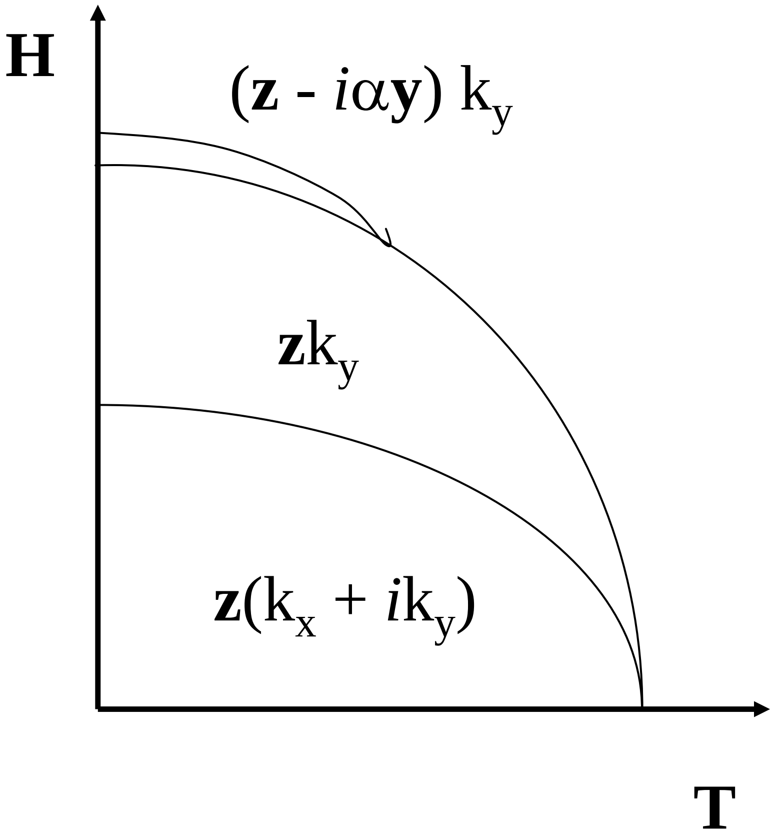
Deguchi, Maeno, JPSJ.

Formation of non-unitary state near the upper-critical field of Sr_2RuO_4

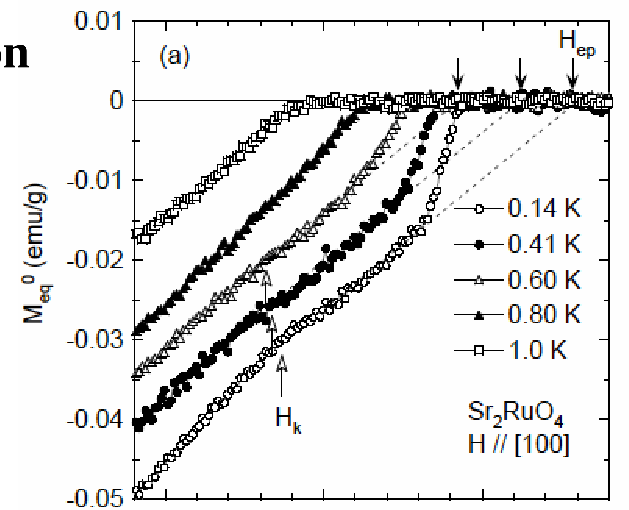
Masafumi Udagawa, Youichi Yanase, and Masao Ogata

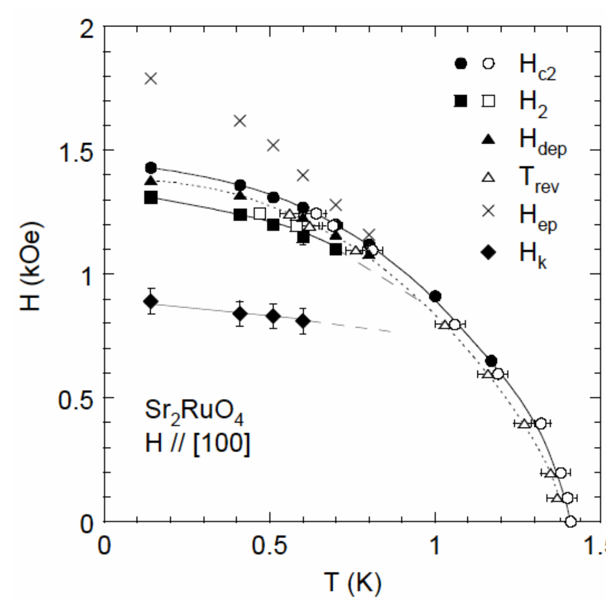
Department of Physics, University of Tokyo, Hongo, Tokyo 113-0033, Japan

Udagawa P-43



Magnetization





Tenya *et al.*

to be published in JPSJ

Issues to be clarified

1) Determination of ***d*-**vector at zero field and the pinning interaction of the Cooper pairs

Poster - 49 Murakawa *et al.*

2) Collective modes in the SC state

$1/T_1$ at O sites

3) Multi-SC phase behavior

$1/T_1$ and KS measurements in various field

4) Properties of the spontaneous field in the SC state

μSR experiments

Spontaneous field in the SC state

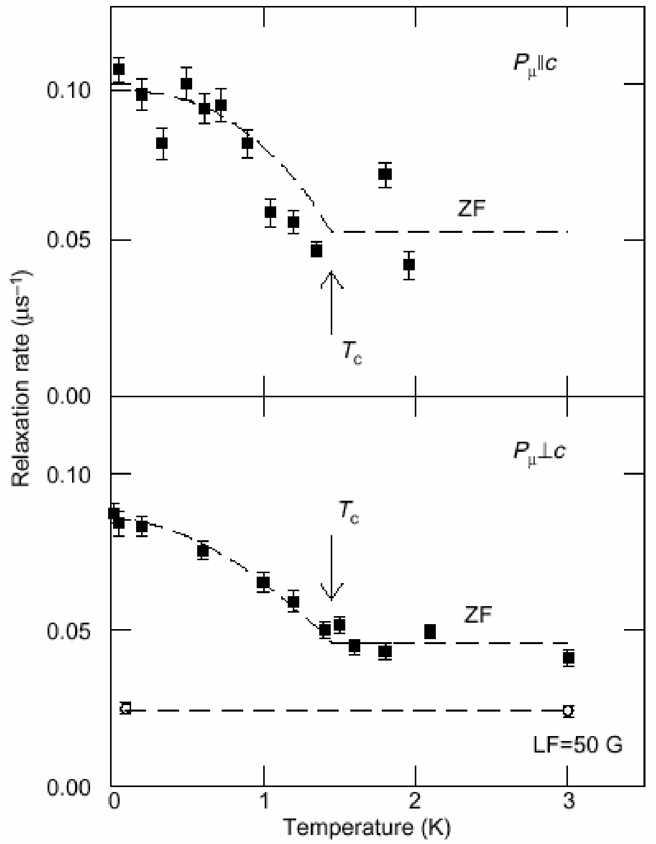


Figure 2 Zero-field (ZF) relaxation rate Λ for the initial muon spin polarization $\parallel c$ (top) and $\perp c$ (bottom). T_c from a.c.-susceptibility indicated by arrows. Circles in bottom figure give relaxation rate in $B_{LF} = 50$ G$\perp c$. Curves are guides to the eye.

G.M.Luke *et al*.

Nature 394, 558 (98)

Spontaneous magnetization below T_c

⇒*Broken TRS*

(orbital magnetization)

Measurements on samples with artificial defect.

(3 K –phase, Ti-dope, heavy ion irradiation)

Collaboration with Dr. Higemoto