特定領域研究
「スーパークリーン物質で実現する
新しい量子相の物理」
A03,A04班　合同研究会

19th April, ‘09
Hotel Hakone Powell

Ferromagnetic Superconductor UCoGe
Co NMR/NQR

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Ferromagnetic Superconductor

Ferromagnetism & Superconductivity

(with a spin-singlet pairing)

Mutually exclusive ?!

Coexistence of ferromagnetism and superconductivity has been known.

Examples

$(Ce_{1-x}Gd_x)Ru_2$ ('58)

x=0.12 T_{SC} ~ 5K

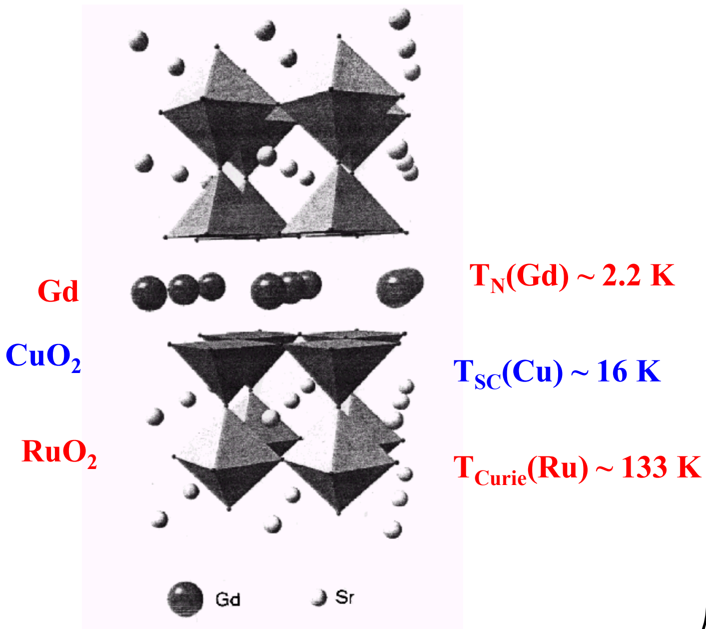
T_{Curie} ~ 4 K

$RuSr_2GdCu_2O_8$ ('96)

magnetic ordering $T_{Curie}(Ru)$ ~ 133 K,

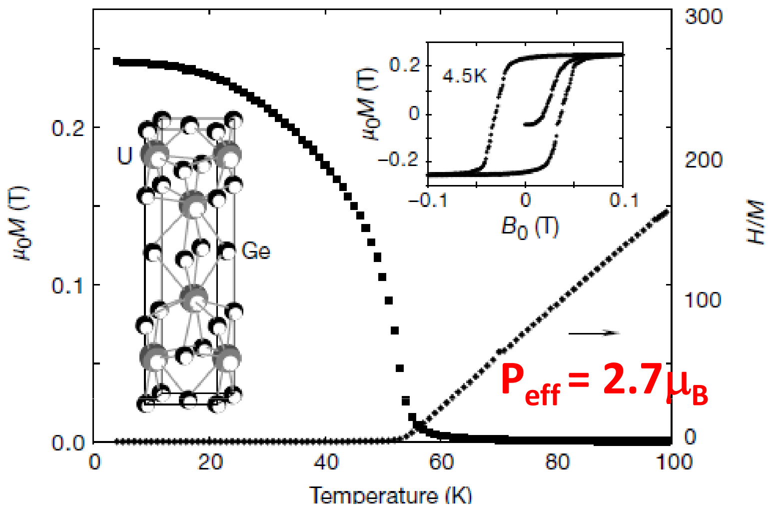
$T_N(Gd)$ ~ 2.2 K

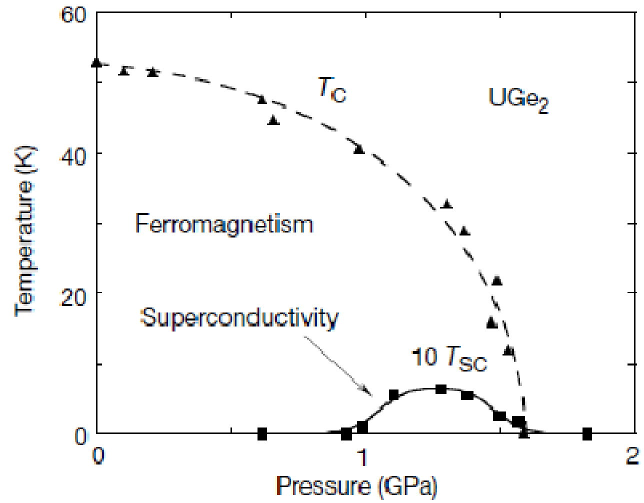
SC transition $T_S(Cu)$ ~ 16 K,

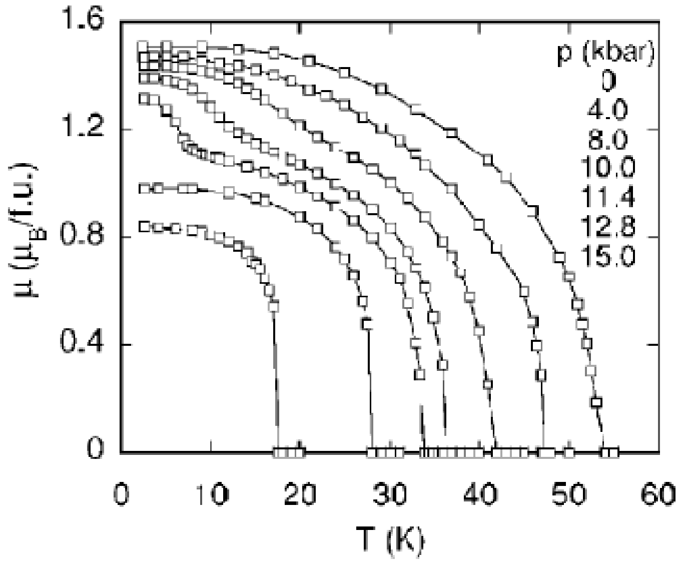


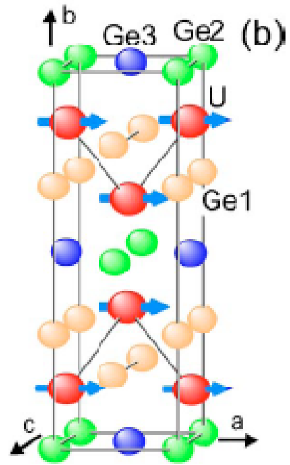
Break Through (S.S. Saxena *et al.* Nature '00)

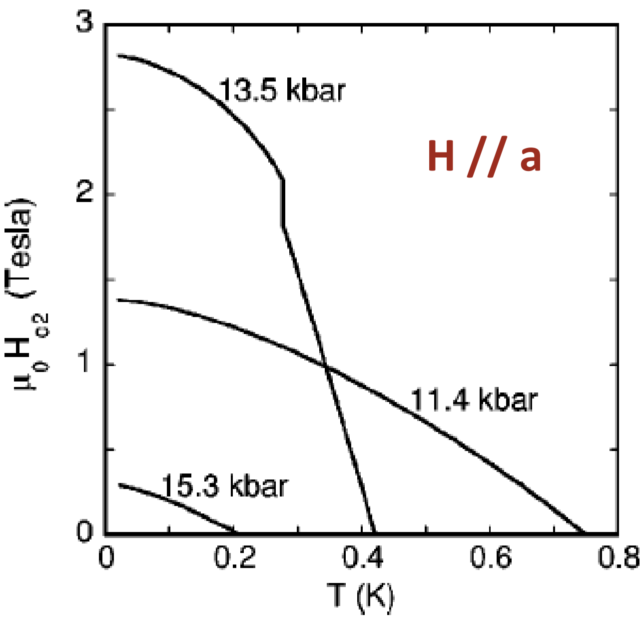
UGe_2











Sheikin *et al.*

Coexistence of superconductivity and ferromagnetism in URhGe

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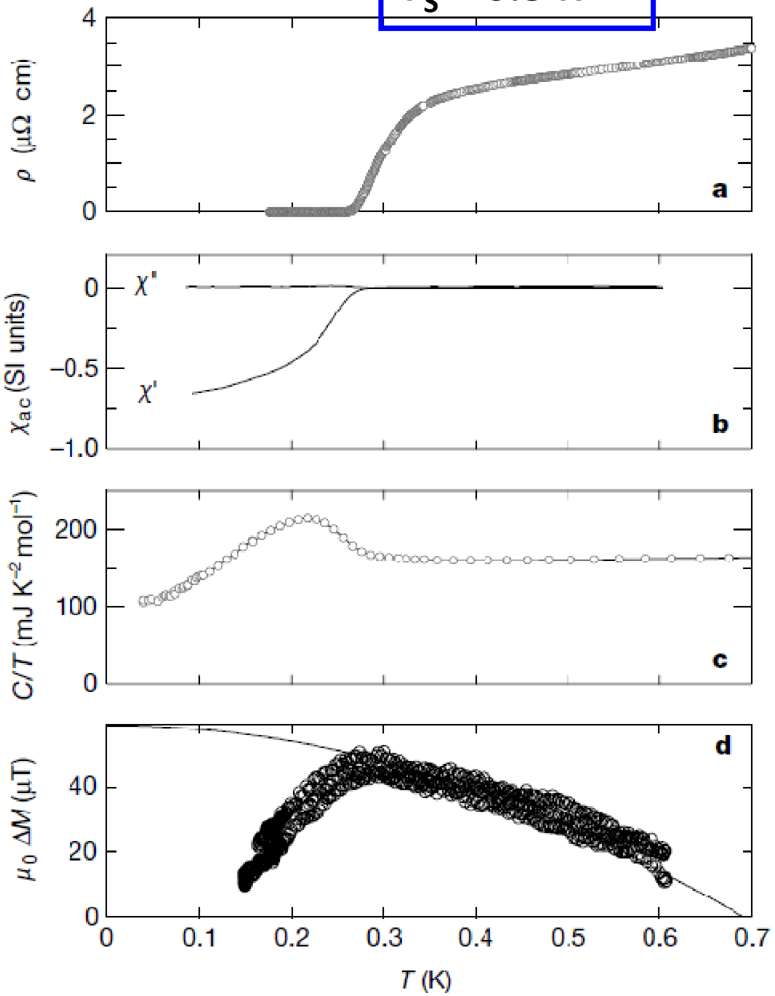
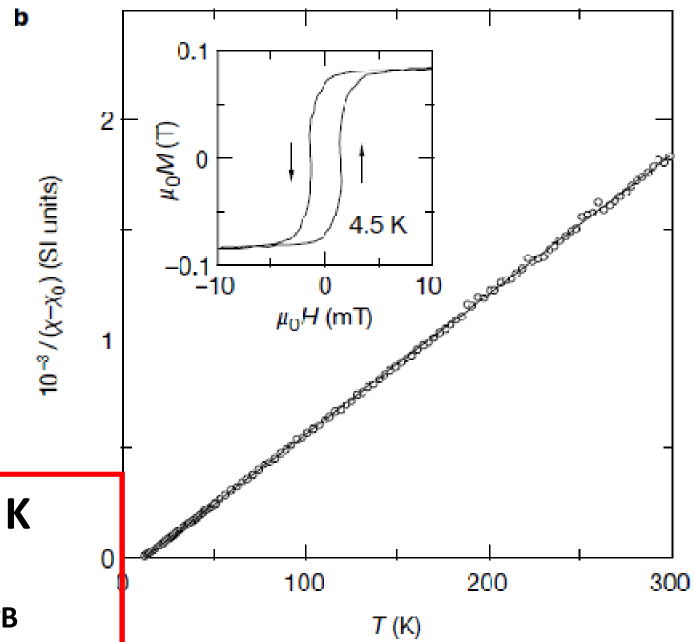
T_S ~ 0.3 K

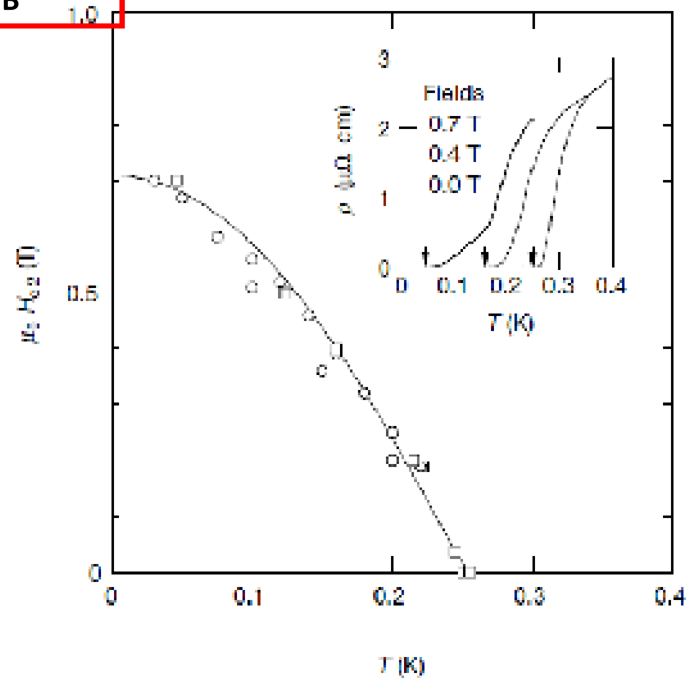


T_{Curie} = 9.5 K

P_{eff} = 1.8 μ_B

P_s = 0.42 μ_B





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Superconductivity on the Border of Weak Itinerant Ferromagnetism in UCoGe

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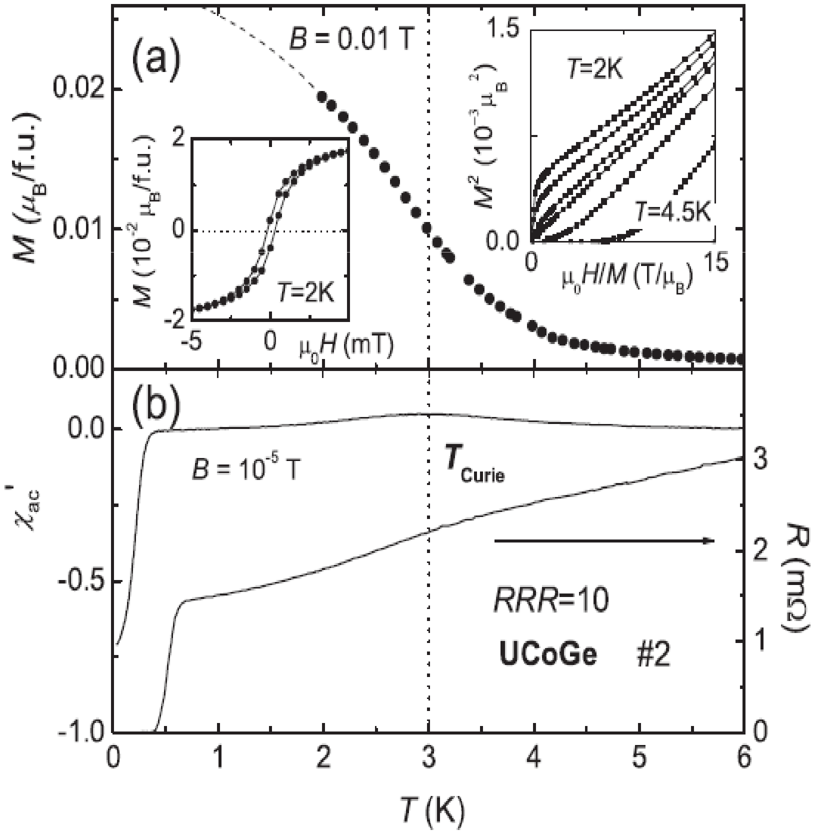
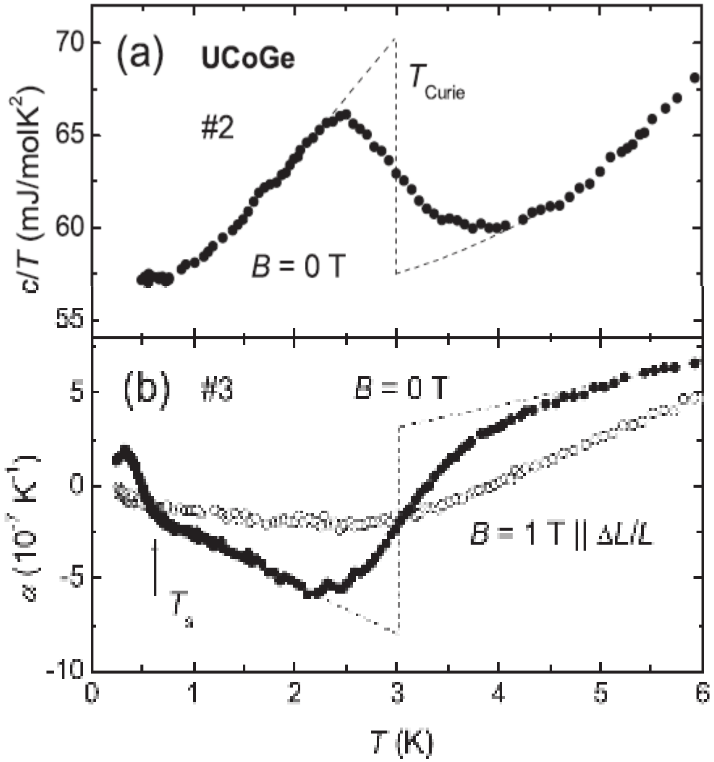
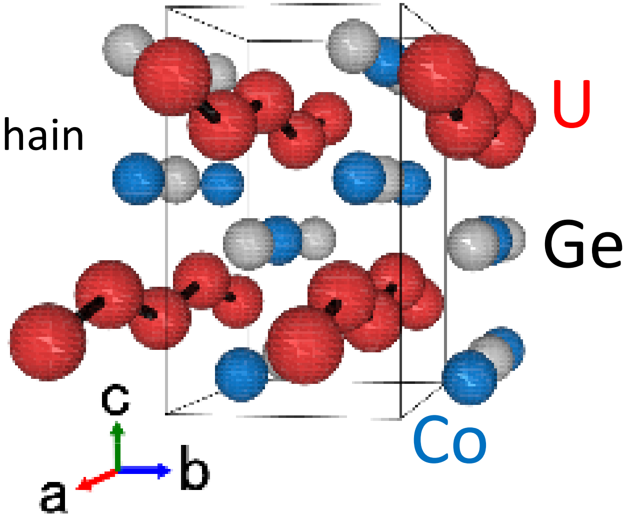


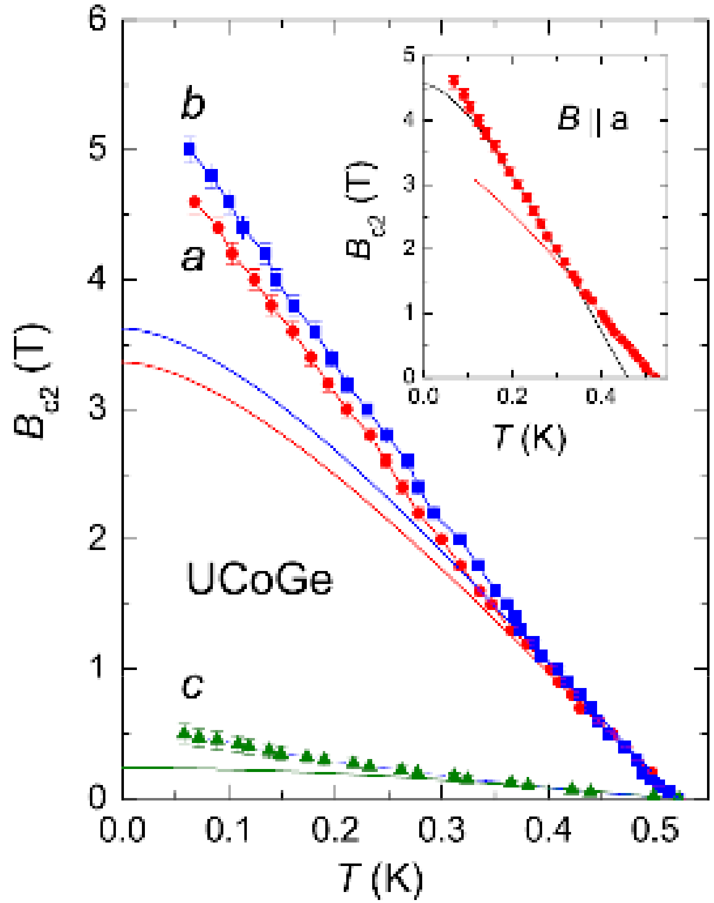


T_C=3K
T_S=0.8K (best sample)
m_0=0.03μ_B : weak itinerant FM

Introduction 2

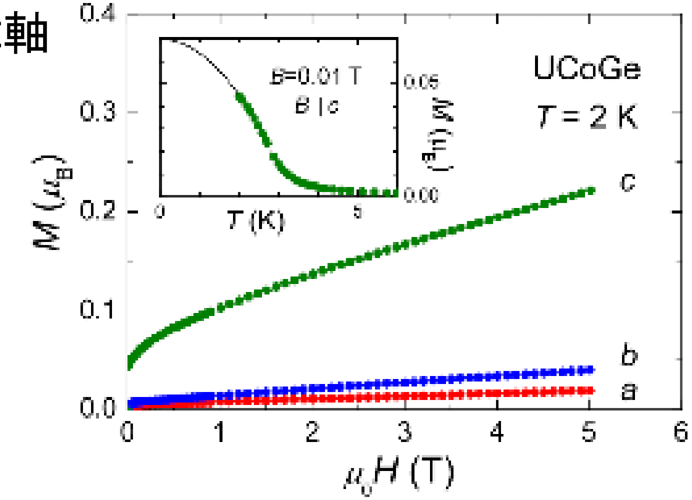
- Othorhombic
- **U** forms zigzag chain





N. T. Huy, *et al.*, Phys. Rev. Lett. 100 077002 (2008)

Easy axis: C軸



Large Upper Critical Field:
Greater than Pauli-Limit field (that is an expected Hc2 in the spin-singlet SC)

$$\left(B_{c2}^{\rm Pauli}(0K) = 1.83T_{\rm SC} \sim 1{\rm T}\right)$$

Spin-triplet superconductivity?

Motivation

- By using Co-nuclear quadrupole resonance_(NQR), we have investigated magnetic and SC properties in UCoGe.
  - Whether SC and FM states coexist microscopically or not?

  ⇒Microscopic measurements are crucial.

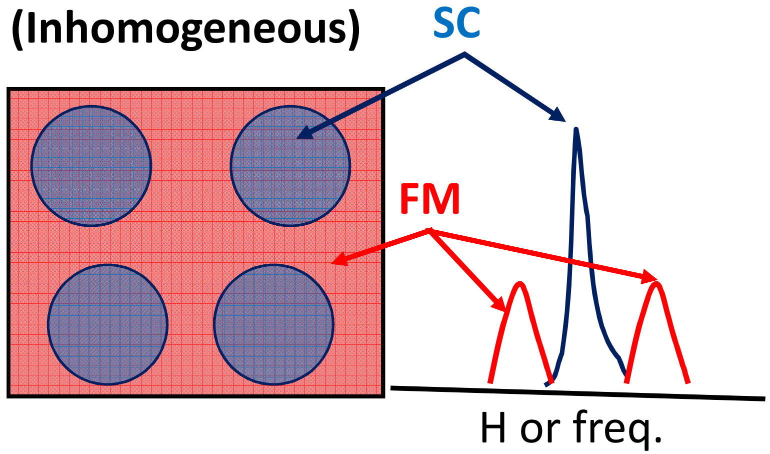
Sample: Provided by

佐藤憲昭, 出口和彦 @名古屋大学理学研究科

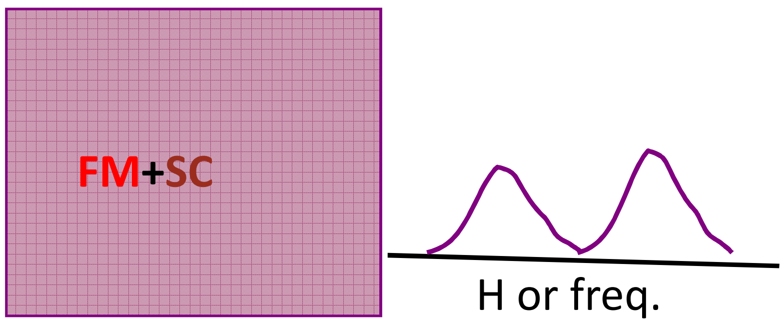
佐藤伊佐務 @東北大学金属材料研究所

$T_{curie} > T_{SC} > T$

Compete (Inhomogeneous)



Coexistence (homogeneous)



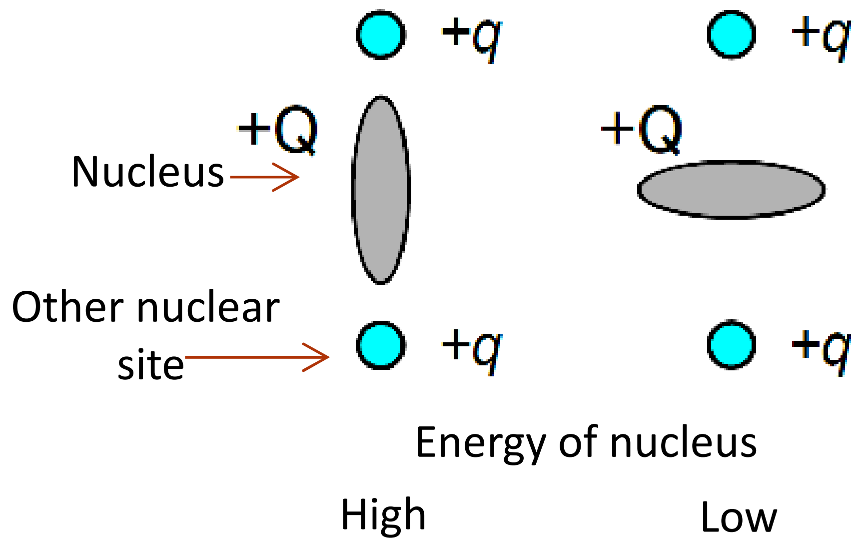
Nuclear Quadrupole Resonance (NQR)

When nuclear Spin ($I \geqq 1$)
Electric quadrupole moment (eQ) is present

Electric field gradient: V_{zz}

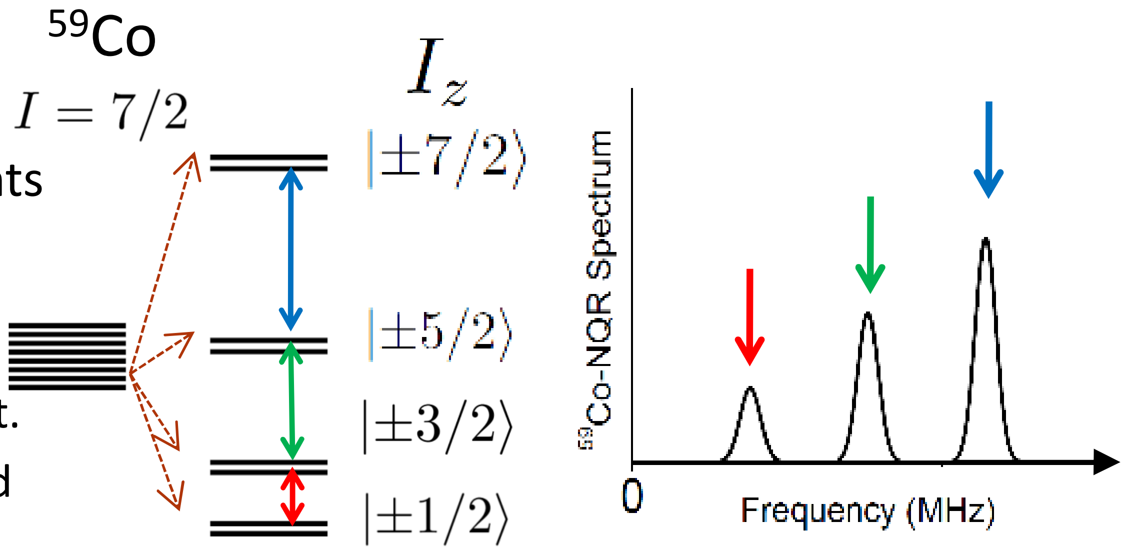
Energy Levels are split.

When RF fields corresponding to the energy splitting are applied, resonance is observed.



Advantage of NQR Measurements

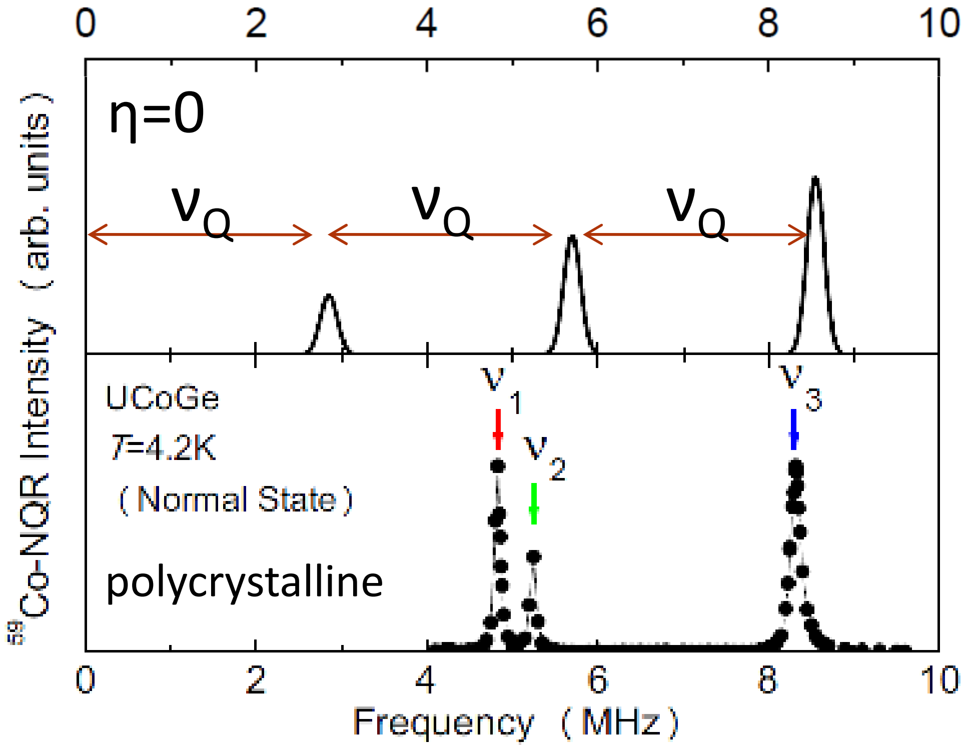
- Zero external fields
  ⇒SC is not suppressed
- Signal from electric quadrupole Int.
  ⇒Microscopic information around nuclear site



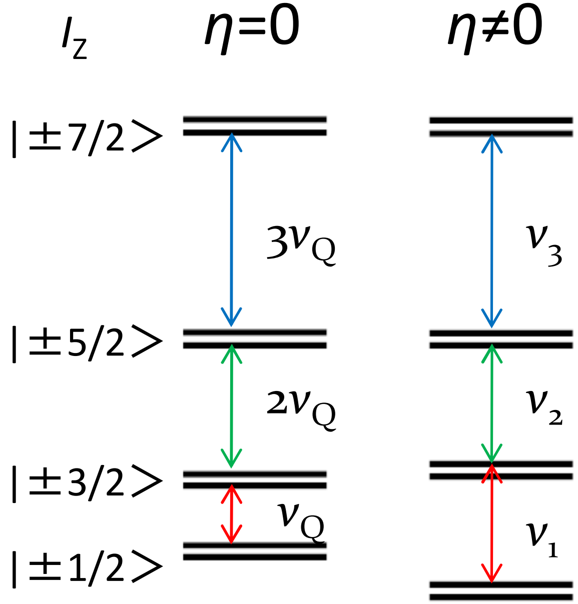
^{59}Co-NQR spectrum 1

$$\hat{H}_Q = \frac{\nu_Q}{6}\left\{\left(3\hat{I}_Z^2 - \hat{I}^2\right) + \frac{1}{2}\eta\left(\hat{I}_+^2 + \hat{I}_-^2\right)\right\}$$

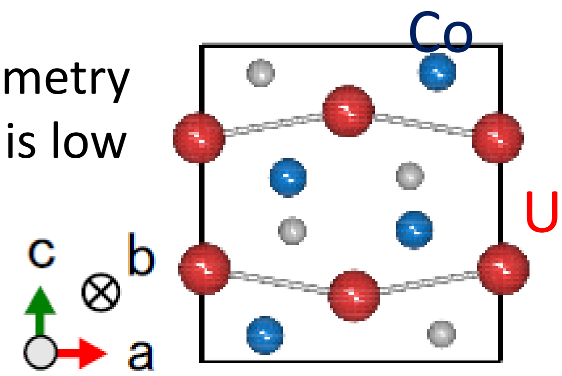
Asymmetric parameter $\eta = \dfrac{V_{XX} - V_{YY}}{V_{ZZ}}$



^{59}Co (nuclear spin I = 7/2)



Local symmetry at Co site is low $\Rightarrow \eta \neq 0$



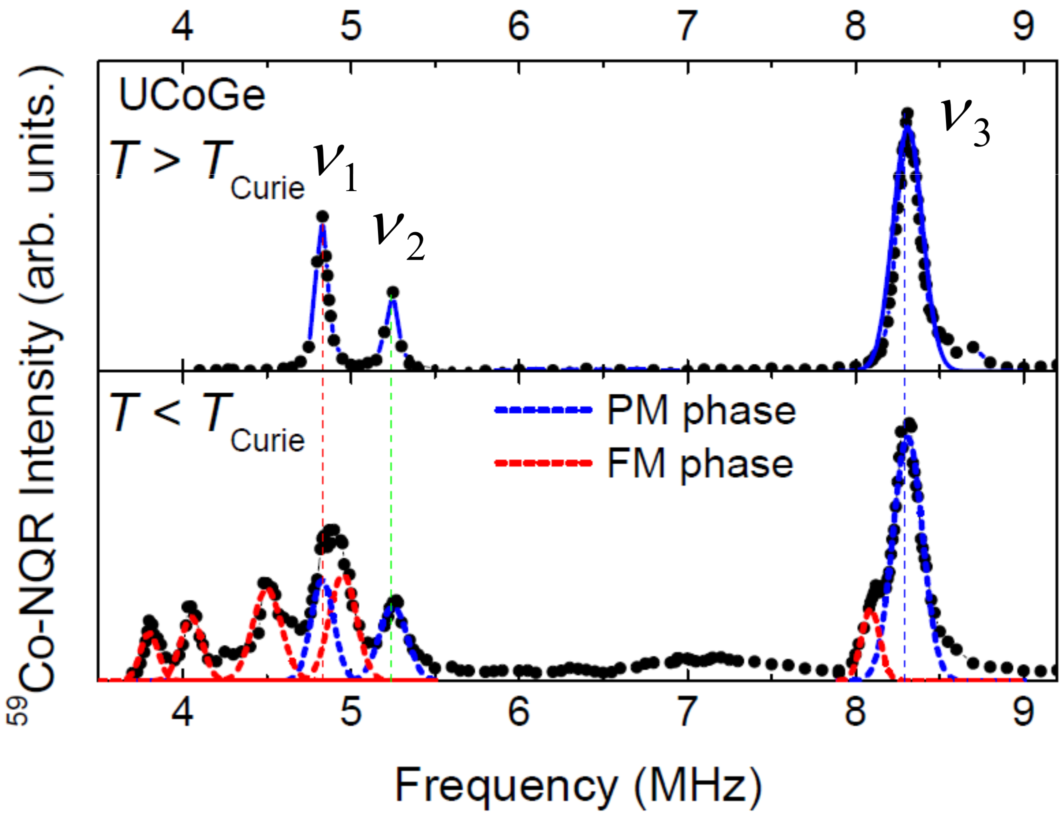
ν_Q=2.85MHz, η=0.52

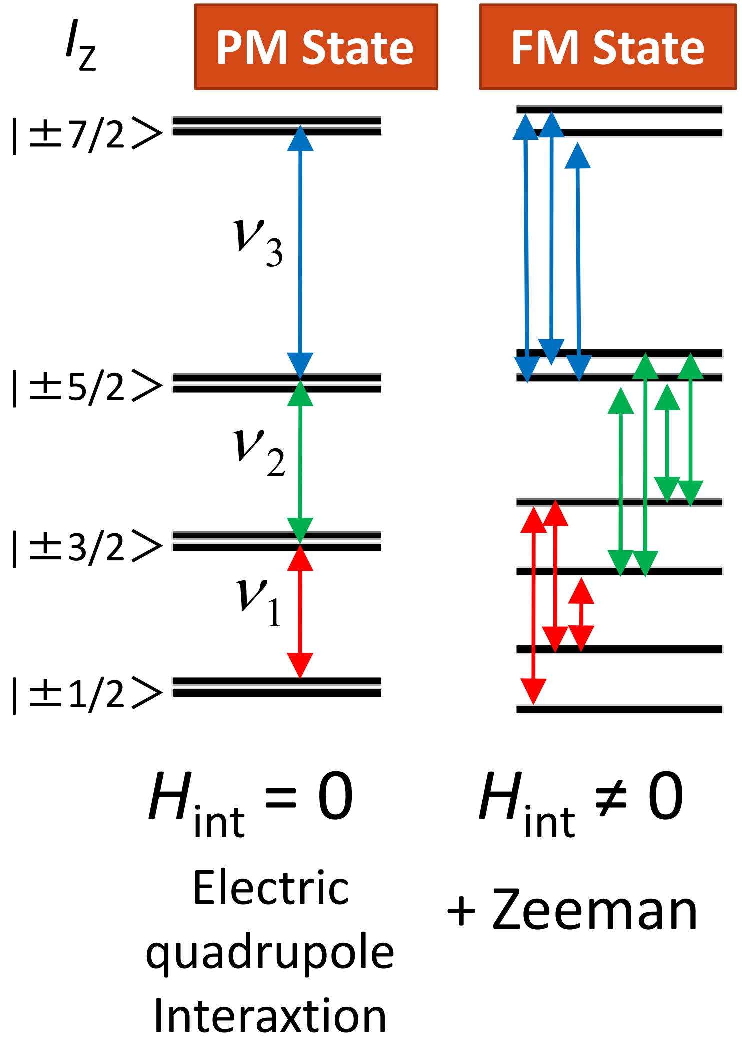
^{59}Co-NQR spectrum 2

FM state

$$\mathscr{H} = \mathscr{H}_Q - \underline{\gamma \hbar \boldsymbol{I} \cdot \boldsymbol{H}_0}$$

Zeeman Interaction by internal field

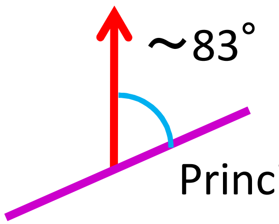




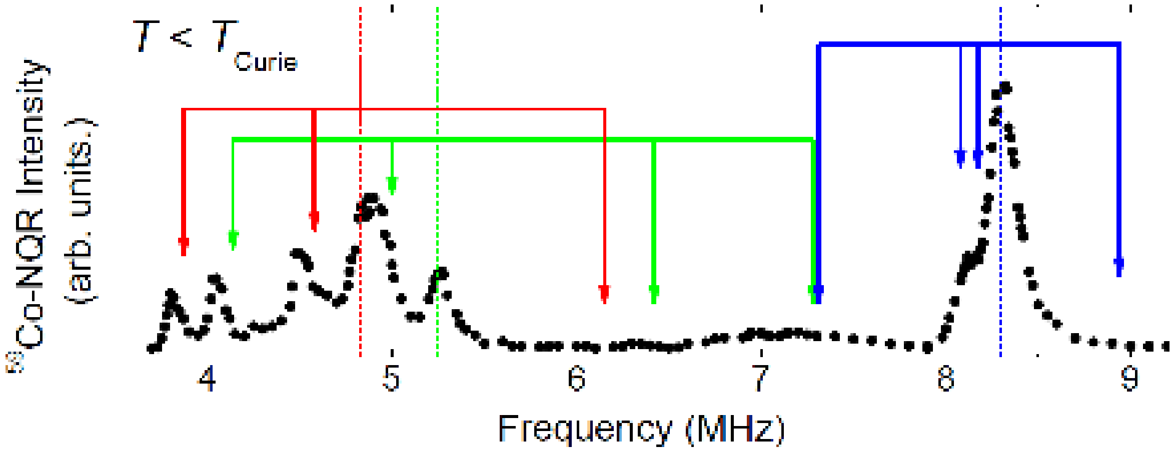
Internal Field

NQR spectrum

H_{int} at ^{59}Co(～900 Oe)

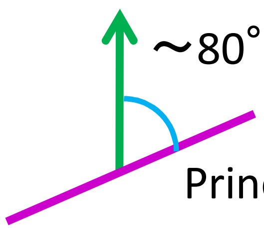


Principal axis of NQR



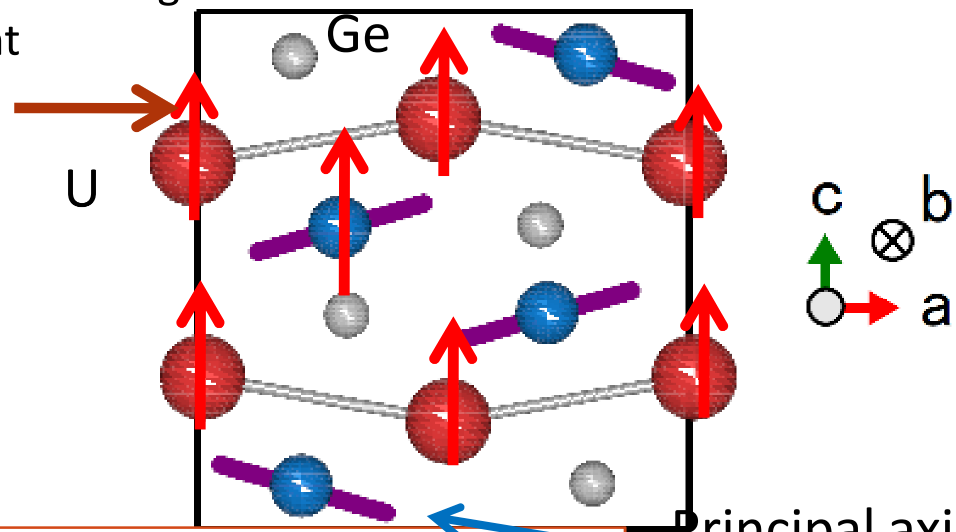
Band Cal. (by. H. Harima)

C軸



Principal axis of NQR

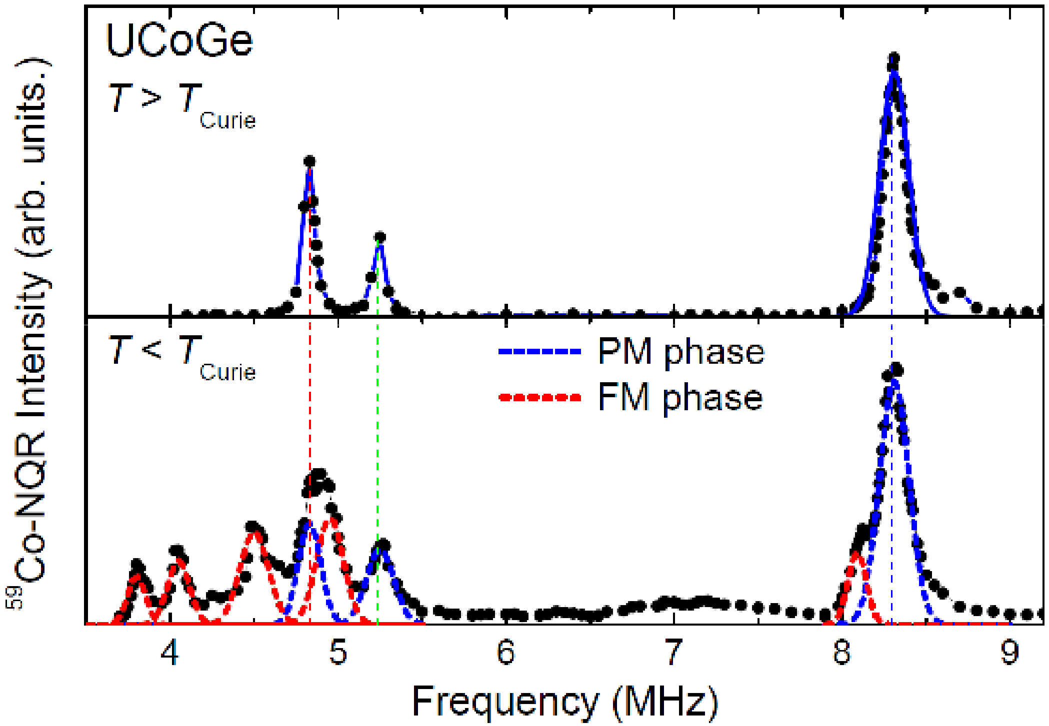
Direction of Magnetic moment



Principal axis of NQR

U ordered moments produce the Internal field at the Co site.

^{59}Co-NQR spectrum



FM state ($T < T_{Curie}$) Two Co signal

- Co signal with internal field

  Co signal from FM region

- Co signal without internal field

  Co signal from PM region

Phase separation

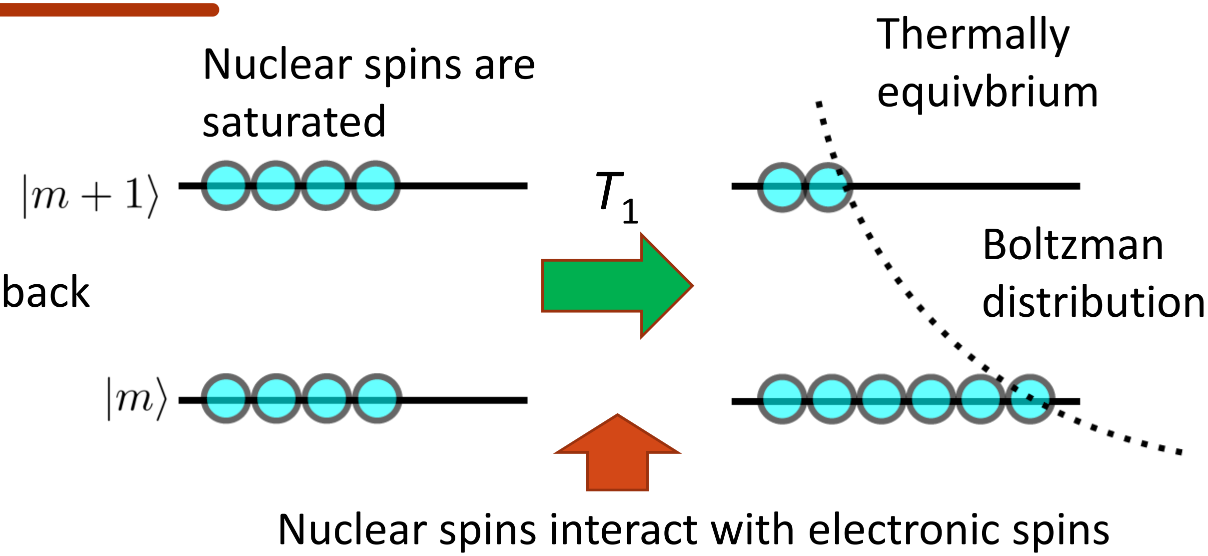
FM region **PM region**

From the measurement of 1/T1, we can know which region is responsible for superconductivity.

Spin-lattice relaxation time : T_1

Nuclear Spin-lattice relaxation Time : T_1

Characteristic time for going back to the thermal equivbrium after thermally excited state



$$\frac{1}{T_1} = \frac{2\gamma_n^2 k_B T}{(\gamma_e \hbar)^2} \sum_{\boldsymbol{q}} A_{\boldsymbol{q}} A_{-\boldsymbol{q}} \frac{\chi_\perp{}''(\boldsymbol{q}, \omega_0)}{\omega_0}$$

$$\cong \frac{4\pi}{\hbar} (\gamma_n \hbar H_{hf}^s)^2 \frac{N^2(E_F)}{N^2} k_B T$$

In a conventional metal, $1/T_1$ is proportional to T and $N(E_F)^2$

Dynamical information surrounding the nuclear spins (e.g. Electrons around EF and spin dynamics)

Superconducting state

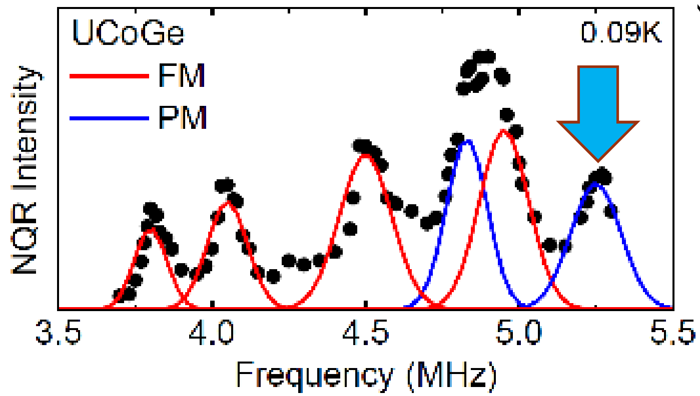
⇒quasiparticle decreases due to opening SC gap

⇒T_1: longer (1/T_1: smaller)

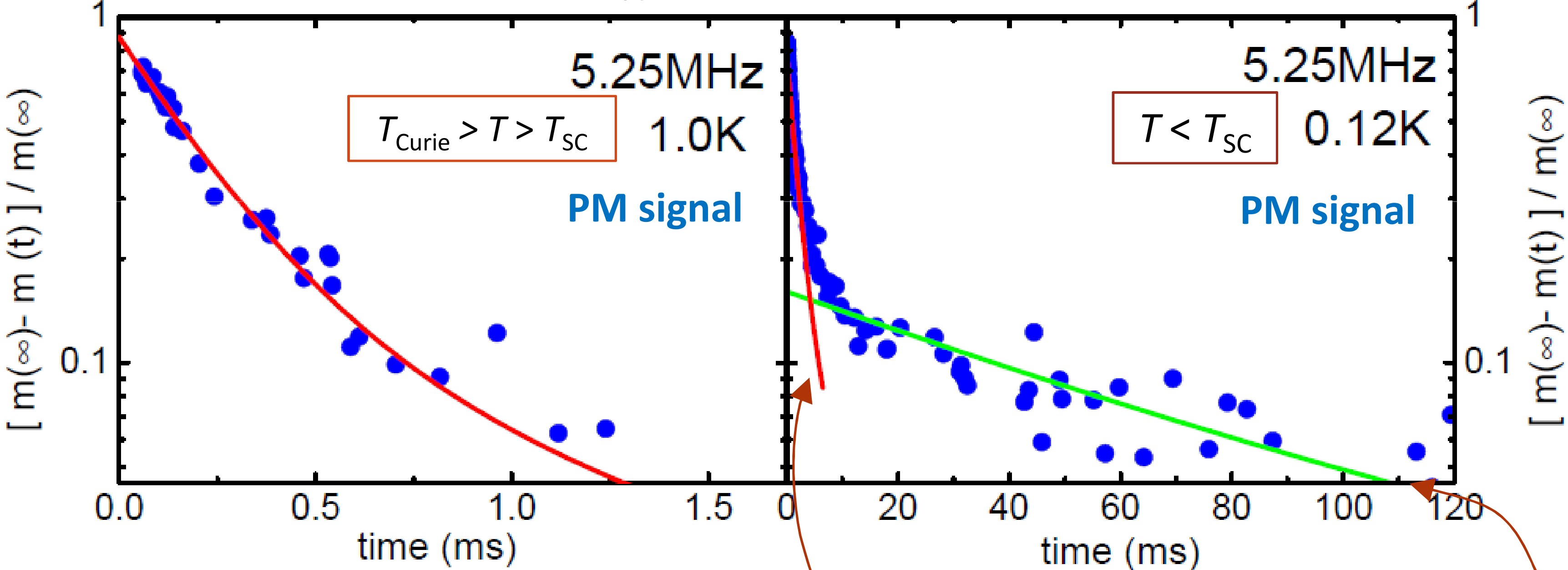
Relaxation Curve @ PM

Relaxation behavior : ($m = \pm 5/2 \leftrightarrow \pm 3/2$)

$$\frac{M_\infty - M_z(t)}{M_\infty} \propto \frac{2}{21}\exp\left(-\frac{3t}{T_1}\right) + \frac{25}{154}\exp\left(-\frac{10t}{T_1}\right) + \frac{49}{66}\exp\left(-\frac{21t}{T_1}\right)$$



T_{SC}~ 0.7 K



Single relaxation process

Relaxation process: Two components

Fast relax.
⇒ non-super state

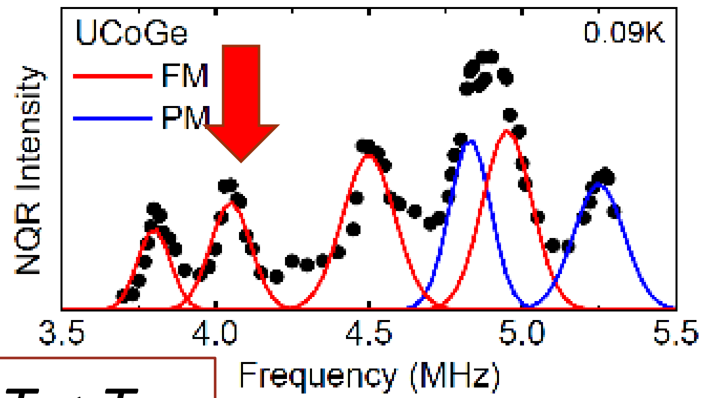
Slow Relax.
⇒ Super state

SC state: Decrease of quasiparticle due to opening SC gap

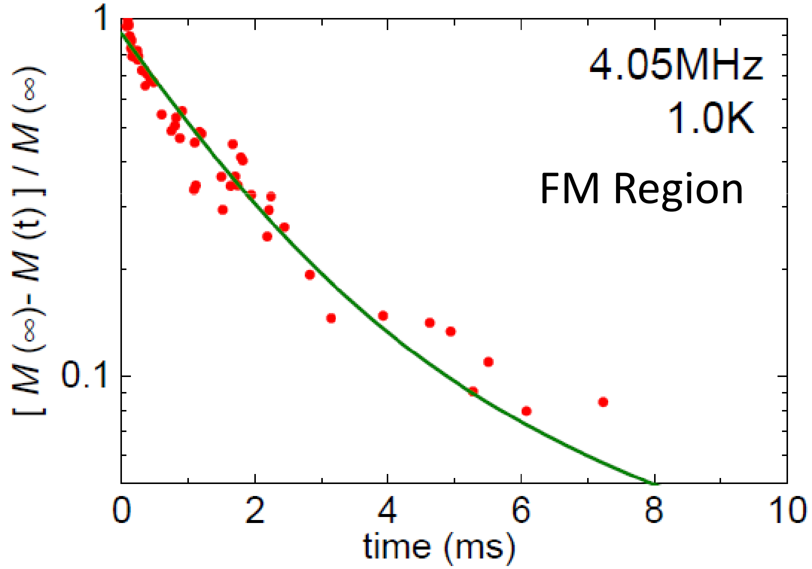
⇒relaxation time is long below T_{SC}

PM region: SC anomaly was observed

Relaxation Curve @ FM

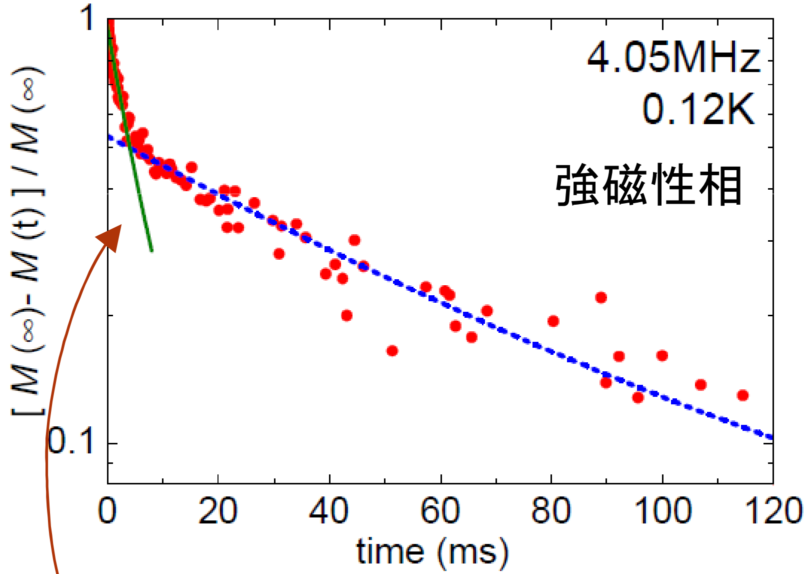


$T > T_{SC}$



Single Relax. Process

$T < T_{SC}$



Relax. Process : Two Comp.

Non-SC state　　SC state

Microscopic Coexistence of FM and SC ?

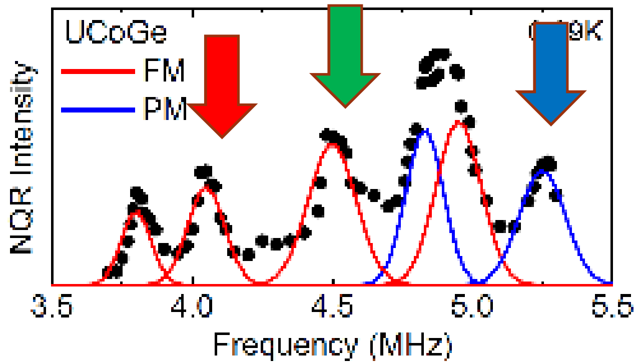
Volume fraction of SC

Fraction of SC-state relax. comp. @0.12K

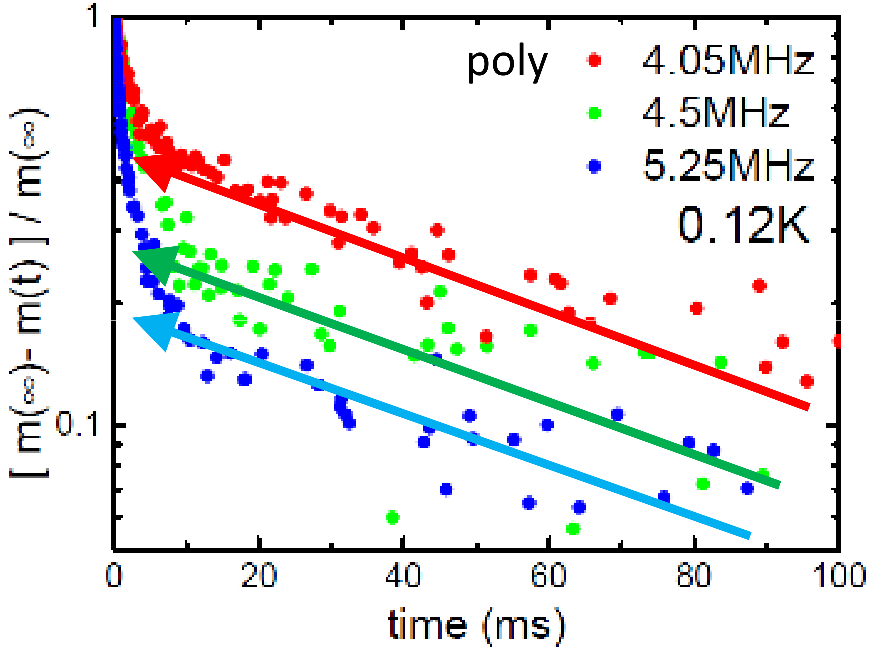
FM ● 4.05MHz ~50%

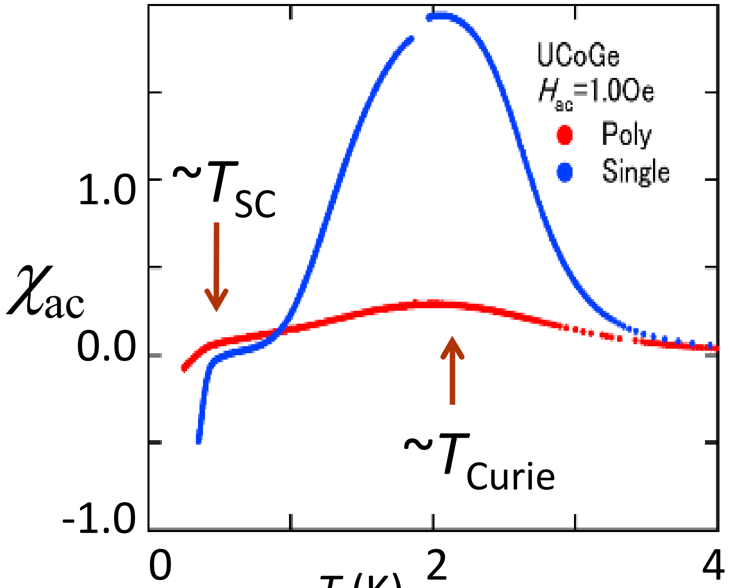
● 4.5MHz ~30%

PM ● 5.25MHz ~20%



Fraction of SC state SC comp. at the FM signal is larger than that at the PM signal





S. Ban, *et al.*,

Anomaly at T_{curie} is obvious

⇒Anomaly at T_{SC} is sharp

Intimate relation between FM and SC states