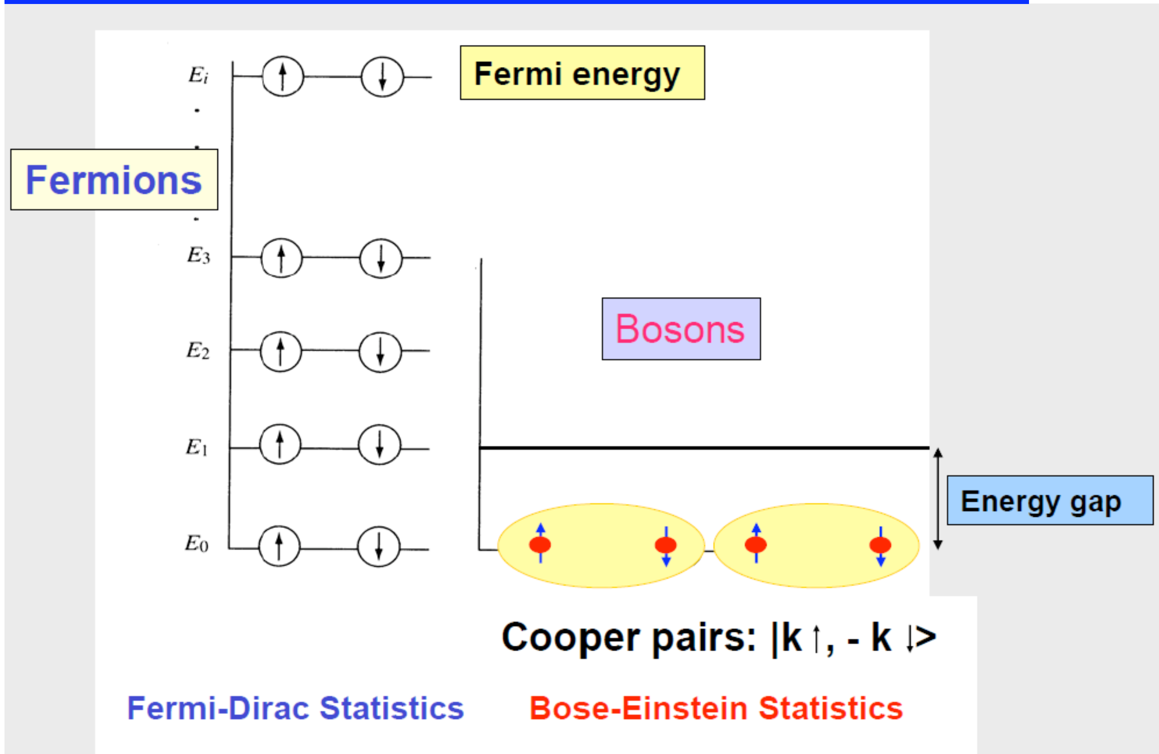
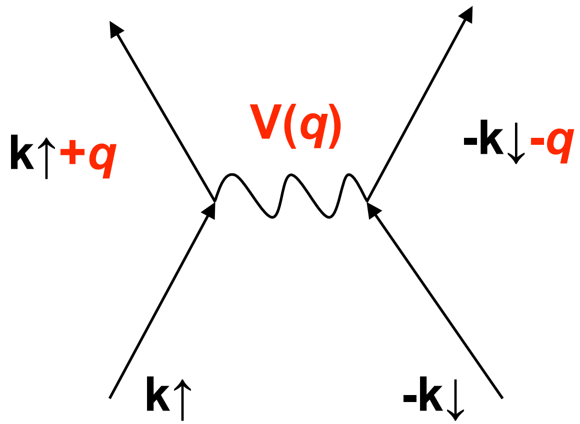
超伝導(BCS理論)の概念



2電子｜k ↑, -k ↓〉間

の引力



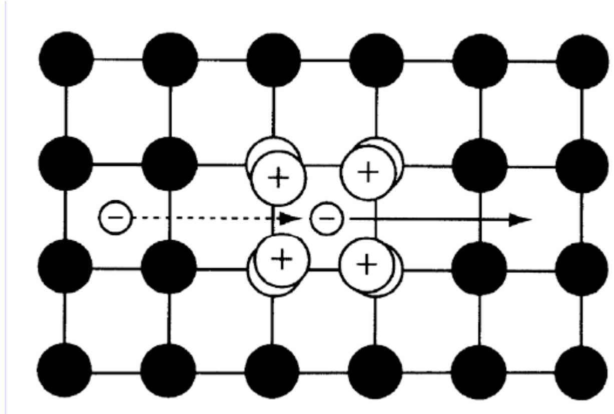
2電子間に働く引力の概念図

常伝導状態

電子は基底状態からフェルミ統計に従い状態を占めていく

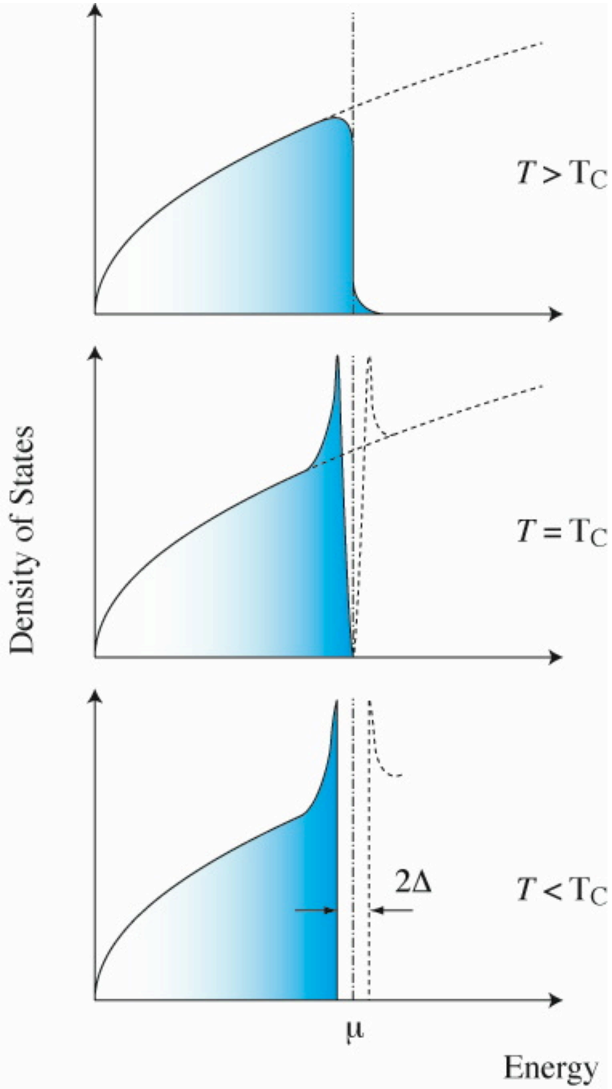
超伝導状態

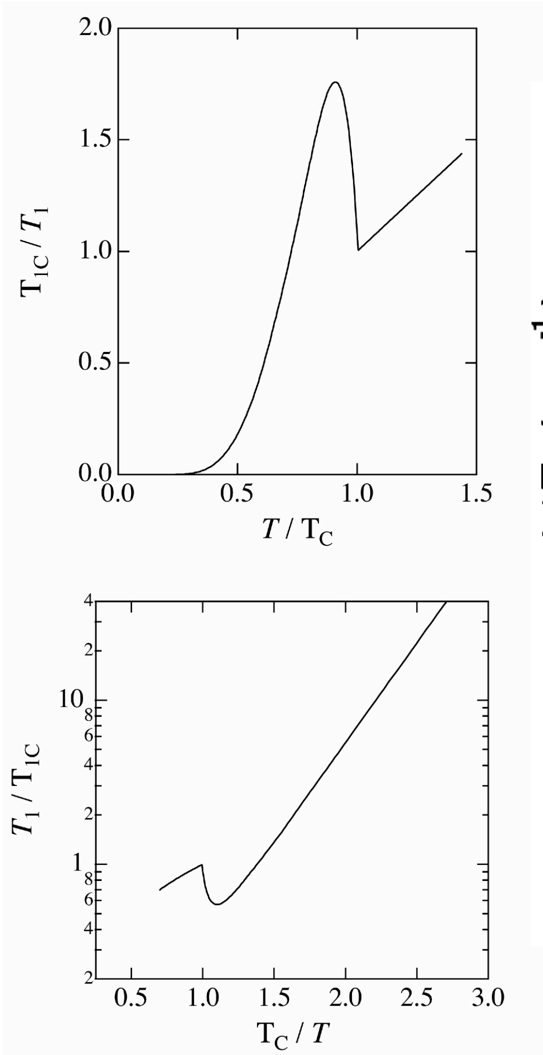
k↑と-k↓がボーズ粒子となる対を組み基底状態に落ち込む

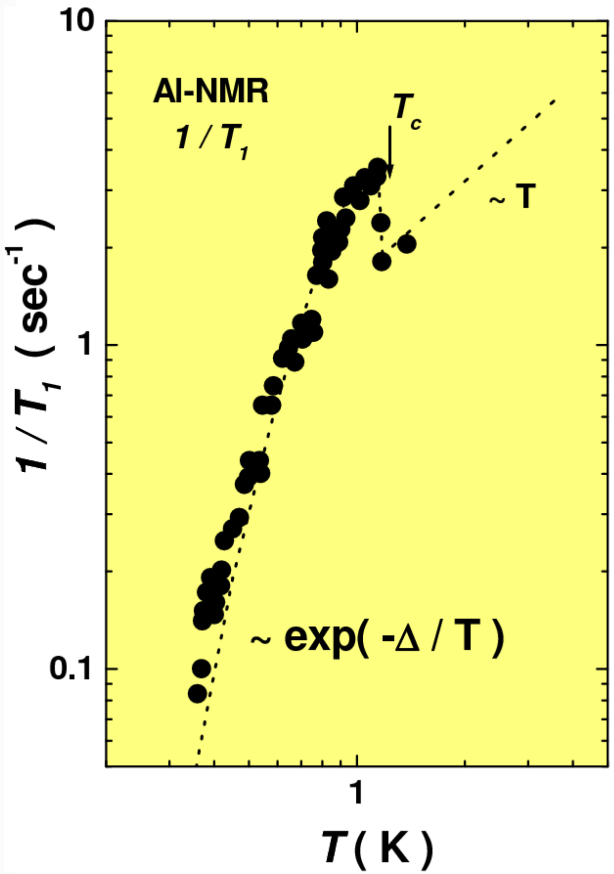


量子化された格子振動(フォノン)

BCS-Type



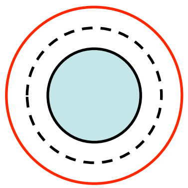




Y. Masuda and A. Redfield, Phys. Rev. 133 A944 ('64)

$$T << T_c: \quad 1/T_1 \propto \exp\left(-\frac{2\Delta_0(0)}{k_B T}\right)$$

$$2\Delta_0(0) \cong 3.5 k_B T_c$$



Uniform gap formation
Isotropic gap

→ **s-wave super-conductor**

超伝導対の波動関数

P.W. Anderson and P. Morel, *PR* 123 1911('61) "Generalized BCS State…"

$$\Psi(\mathbf{r}_1,\sigma_1;\mathbf{r}_2,\sigma_2) = \chi(\sigma_1,\sigma_2)\cdot\psi(\mathbf{r}_1,\mathbf{r}_2)$$

Spin part　Orbital part

Spin part : $S = 0$　スピン一重項　$\chi^{S=0} = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$

$S = 1$　三重項　$\chi^{S=1} = |\uparrow\uparrow\rangle,\ \left(1/\sqrt{2}\right)\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right),\ |\downarrow\downarrow\rangle$

スピン三重項超伝導

Orbital part : $\psi(\boldsymbol{r}_1,\boldsymbol{r}_2)$　$\boldsymbol{r} = \boldsymbol{r}_1 - \boldsymbol{r}_2$　$\psi(\boldsymbol{r})$

$$\left(-\frac{\hbar^2}{m}\nabla^2 + V(\mathbf{r})\right)\psi(\mathbf{r}) = E\psi(\mathbf{r})$$

V(r) **が異方的な場合、超伝導対の波動関数も異方的になる**

$$\psi(r) \propto Y_l^m(\theta,\varphi)$$

球面調和関数

$l = 0,$	$l = 1,$	$l = 2,$	$l = 3,$ ……..
s -波,	*p* -波,	*d* -波,	*f* -波

$$\Delta_l = \Delta_0 \sum_{m=-l}^{l} \lambda_{lm} Y_l^m(\theta,\varphi)$$

異方的な超伝導ギャップ

異方的超伝導対

原点に振幅を持たない

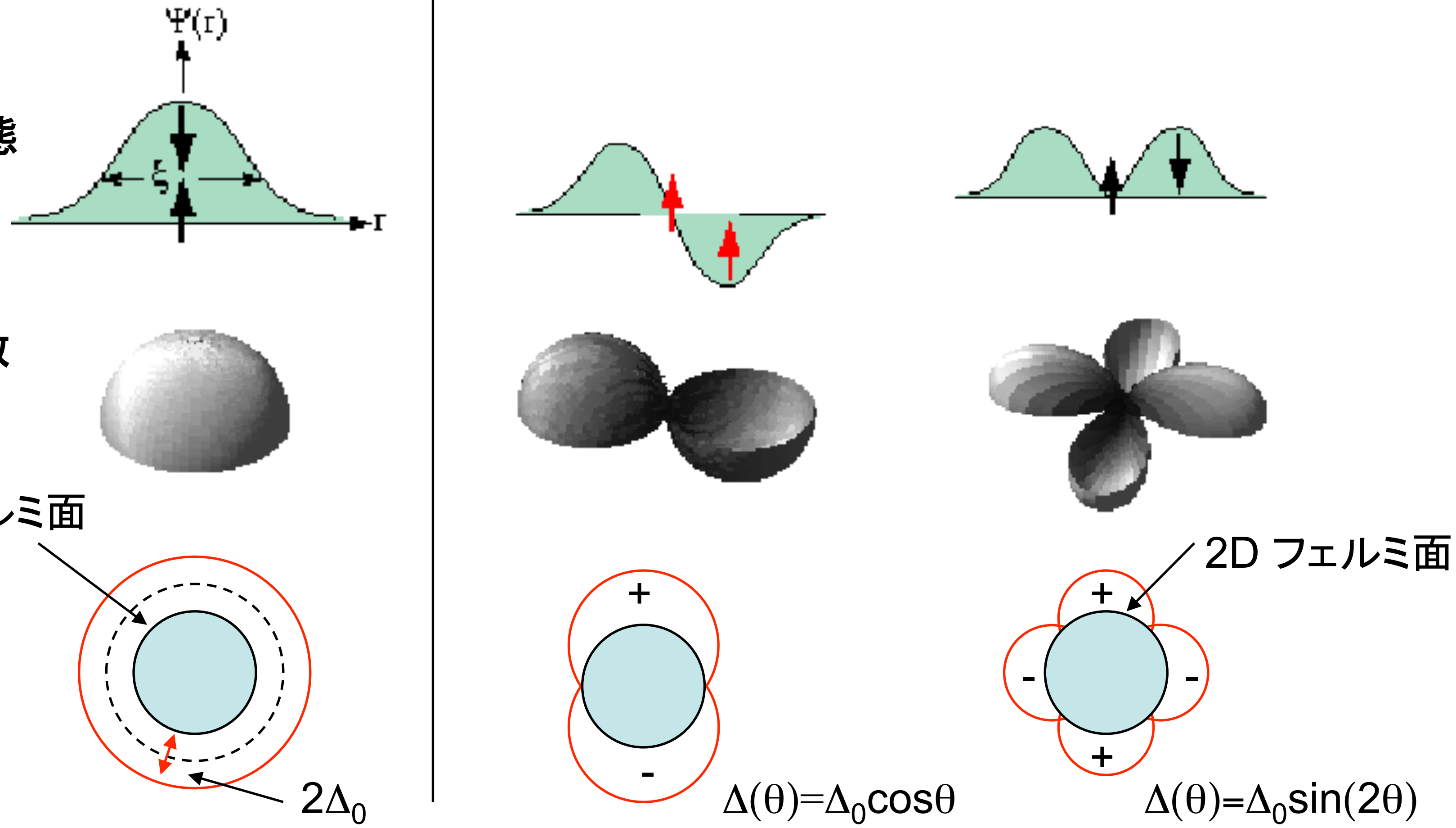
強相関電子系の特徴

スピン状態	一重項	三重項	一重項
軌道状態	s 波	p 波	d 波

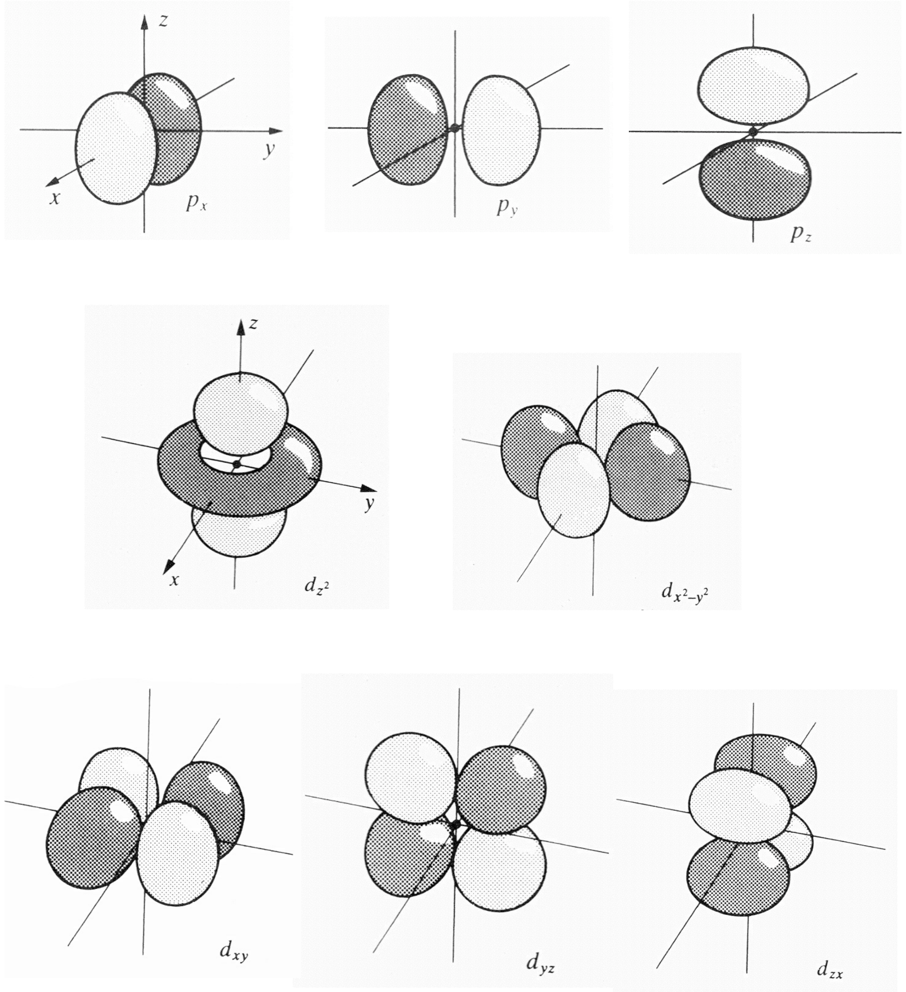
スピン状態

波動関数の広がり

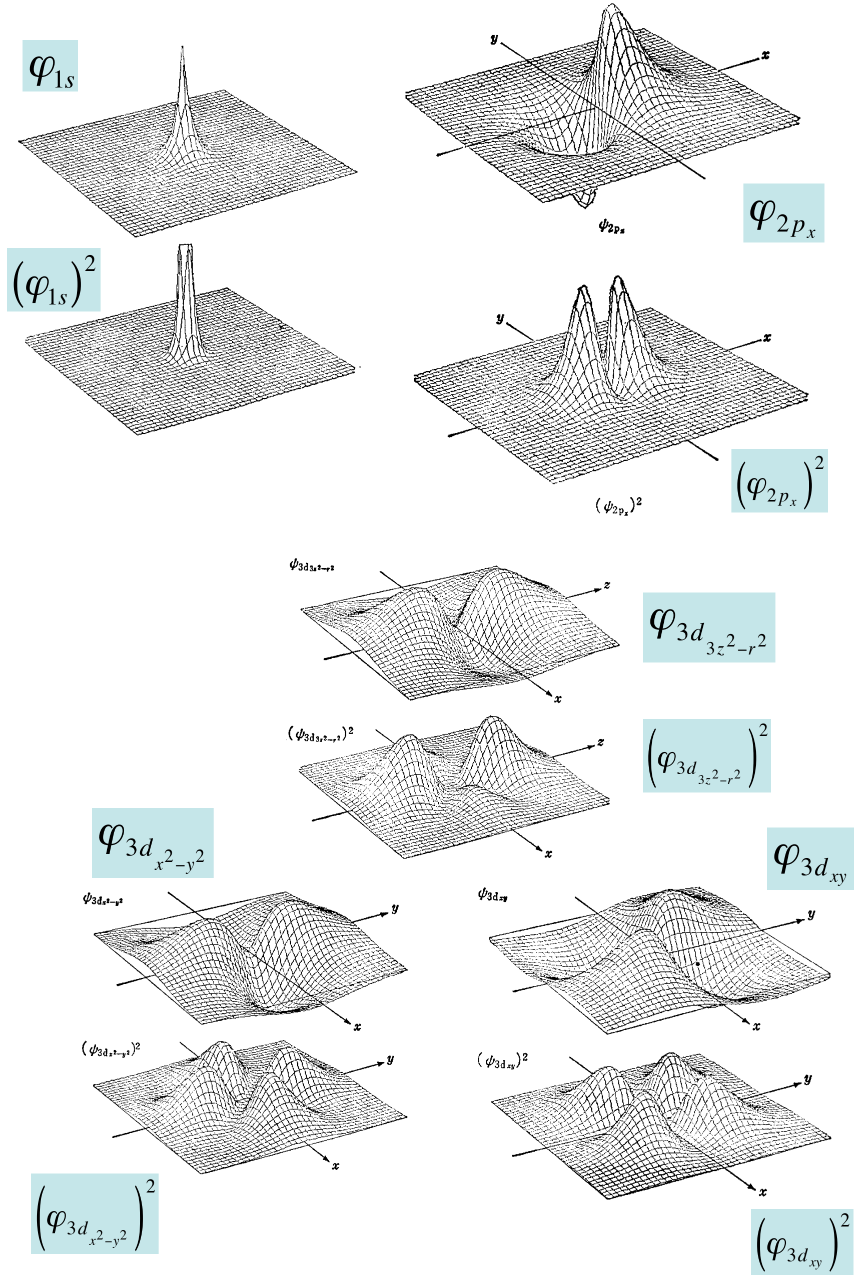
ギャップ関数



電子軌道

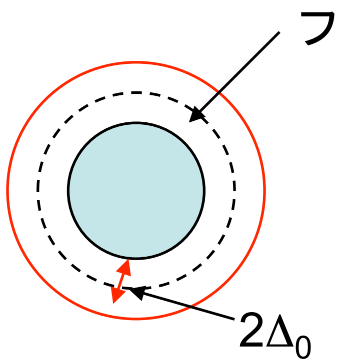


波動関数の角度依存



波動関数の形

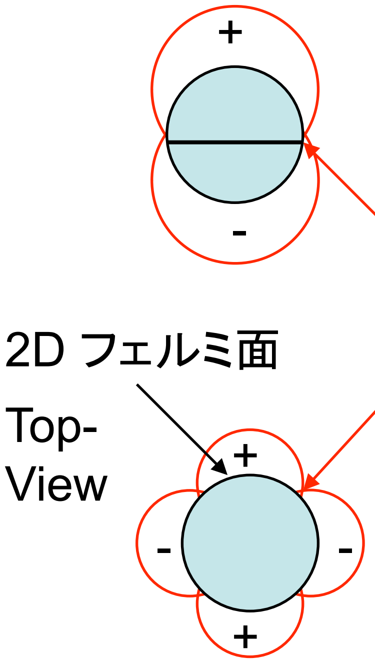
異方的超伝導ギャップ



(a) $l = 0$ (s 波)

$\Delta(\theta) = \Delta_0$

等方的なギャップ



(b) $l = 1$ (p 波)

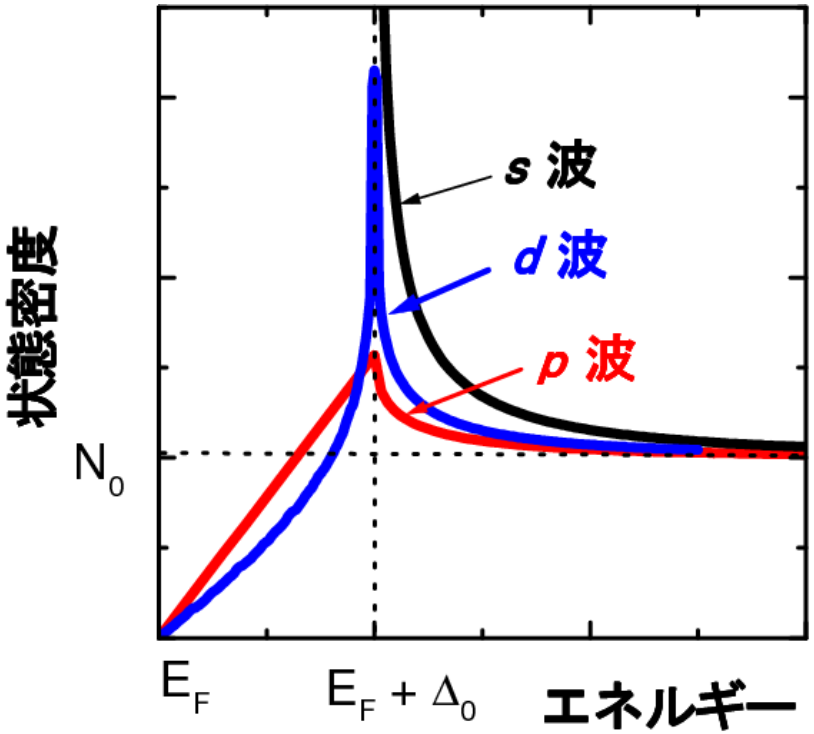
$\Delta(\theta) = \Delta_0 \cos\theta$

線状にギャップ
ゼロが存在する

(c) $l = 2$ (d 波)

$\Delta(\theta) = \Delta_0 \sin(2\theta)$

超伝導状態状態の状態密度



異方的超伝導ギャップの特徴

超伝導ギャップ内に連続的に状態を持つ　$N(E) \propto E$

➡ 超伝導状態の物理量が温度のベキ乗となる。

強相関電子系超伝導の相図

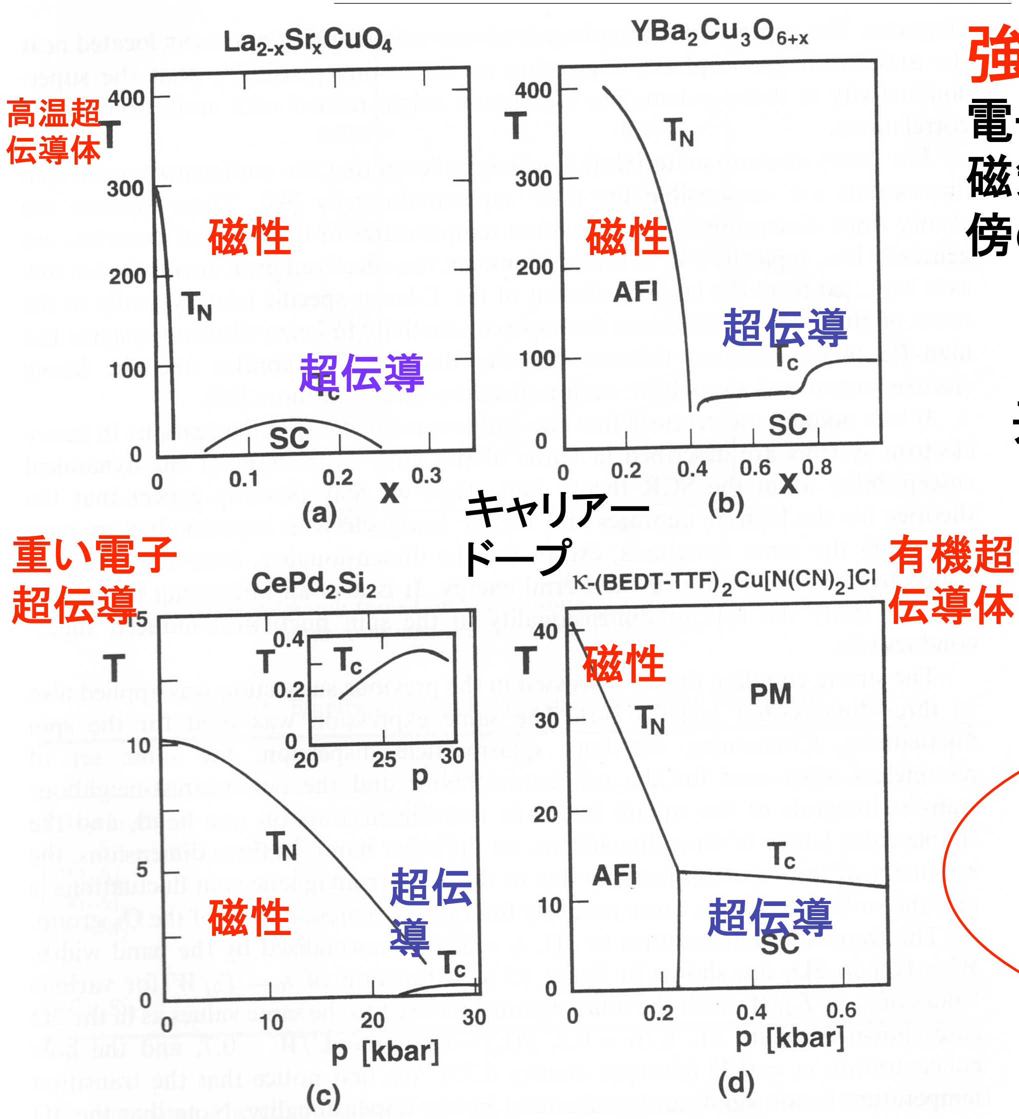


Figure 14. Phase diagrams of high-T_c cuprates, (*a*) $La_{2-x}Sr_xCuO_4$ and (*b*) $YBa_2Cu_3O_{6+x}$, (*c*) a heavy electron superconductor $CePd_2Si_2$ under pressure *p* and (*d*) an organic superconductor κ-(ET)$_2$Cu[N(CN)$_2$]Cl under pressure. T_N: Néel temperature, AFI: antiferromagnetic insulator, SC: superconductor, PM: paramagnetic metal.

強相関電子系物質

電子間のクーロン相互作用が強い系
磁気転移、モット転移(金属-絶縁体転移)近傍の電子状態

共通点

- 異方的超伝導体である。

超伝導対の対称性(性質)が従来の BCS超伝導体と性質を異にする

- 磁気相と超伝導が競合(共存)している。

磁性と超伝導が密接に関係

$Na_x(H_3O)_zCoO_2\ yH_2O$の超伝導

“磁気的Frustration”

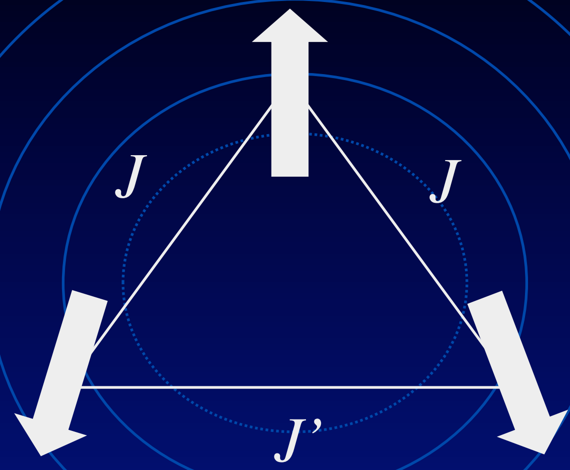
Pyrochlore Oxide ($A_2B_2O_7$),
Spinel Oxide (AB_2O_4),
C15 Laves Phase (AB_2)

Geometrical Frustration
Spin Frustration
Charge Frustration

Magnetite Fe_3O_4 (Fe^{2+} and Fe^{3+})
Spinel Oxide AlV_2O_4
($V^{2.5-\delta}$ and $V^{2.5+3\delta}$)

High Degeneracy

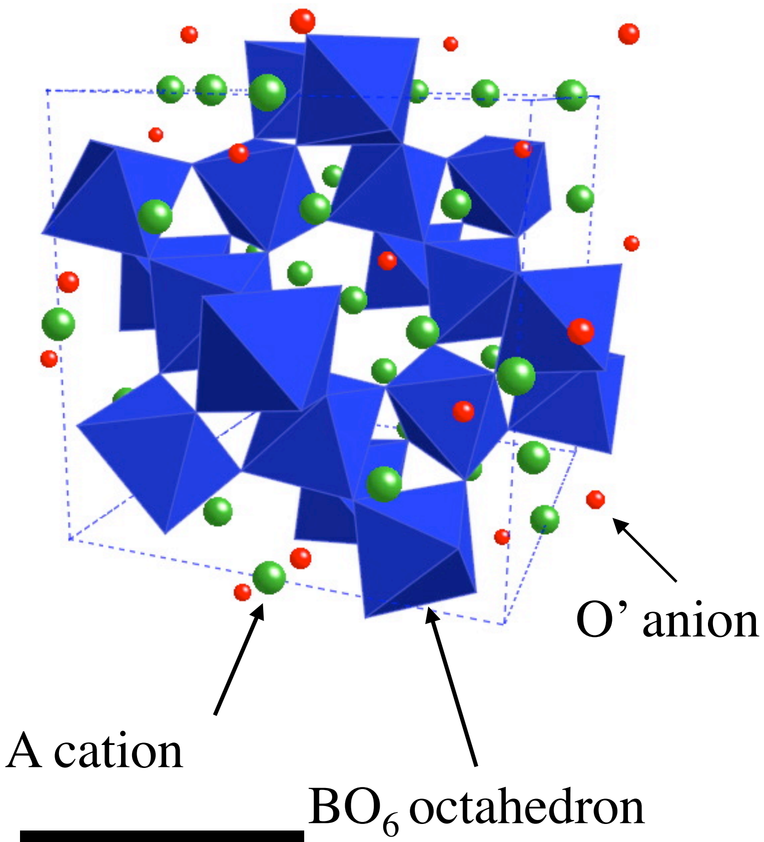
Lattice Distortion, Spin-Ice, Spin-Singlet,
Heavy Fermion



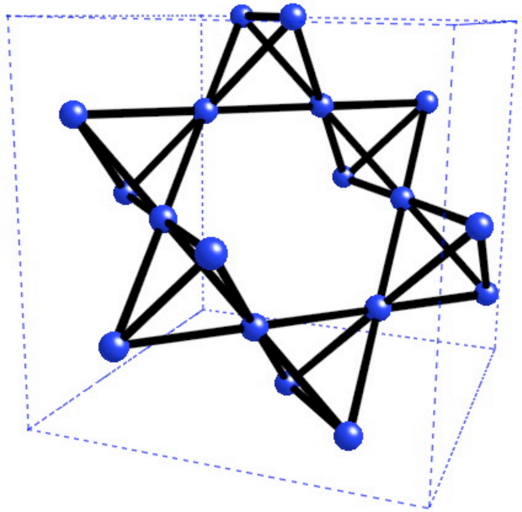
P. Laccore (1987)
AF Triangular platelet < AF Pyrochlore

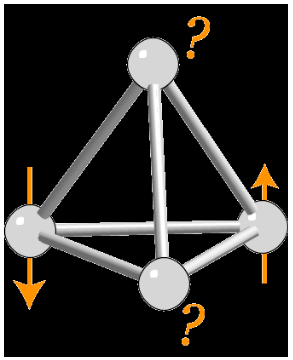
“低次元性(Low Dimensionality)”

Pyrochlore $A_2B_2O_6O'$

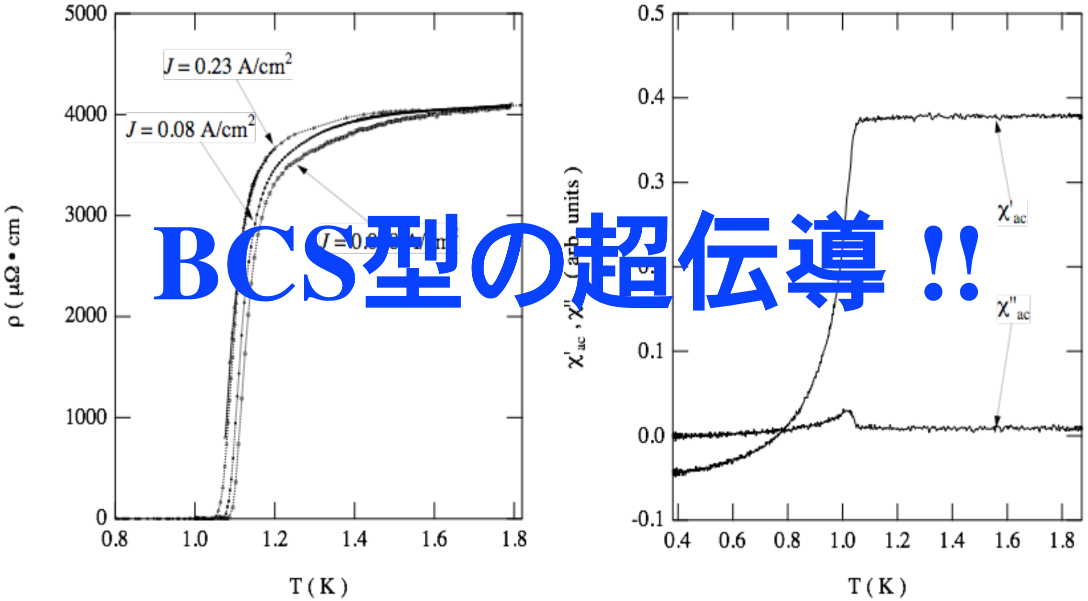


"Pyrochlore Lattice"
of B Cation





$Cd_2Re_2O_7$ の超伝導



BCS型の超伝導 !!

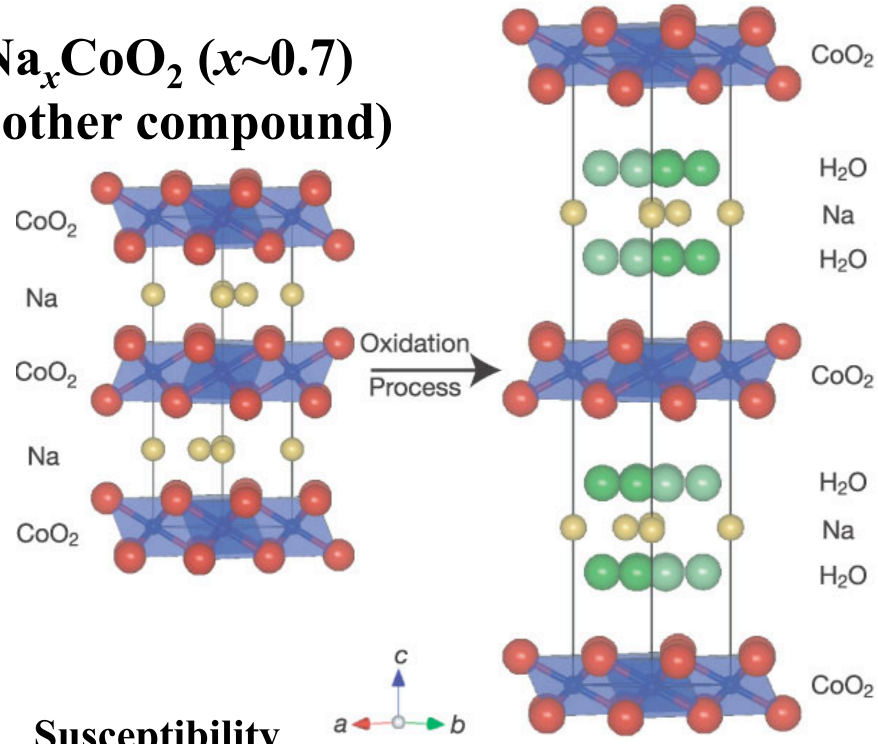
H. Sakai, K. Yoshimura et al., J. Phys. Condens. Matter 13 (2001) L785.

Introduction Takada, Sakurai *et al.* Nature **422** (2003) 53

BLH-$Na_xCoO_2 \cdot yH_2O$

Bulk Superconductivity in **Layered structure** with CoO_2 layer, double H_2O layers and partially occupied Na layer

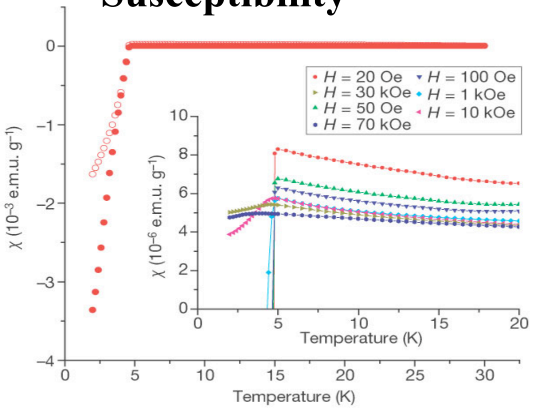
Na_xCoO_2 (x~0.7) (mother compound)

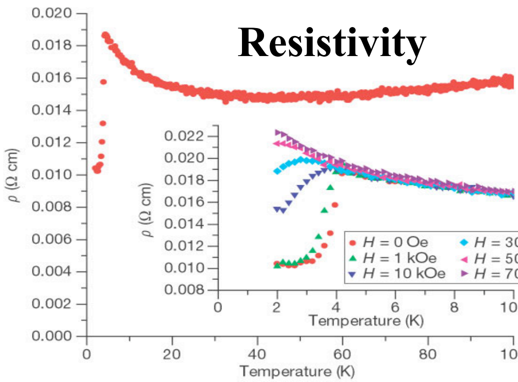


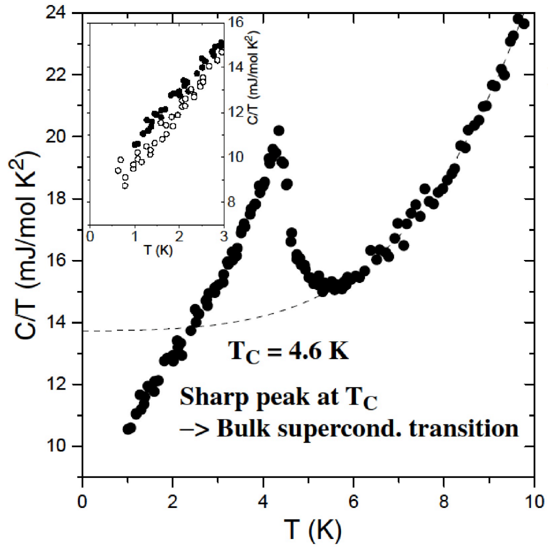
Co ions form **triangular lattice** in CoO_2 layer.

Crystal structure is different from Cuprate and Ruthenate superconductors.

Susceptibility



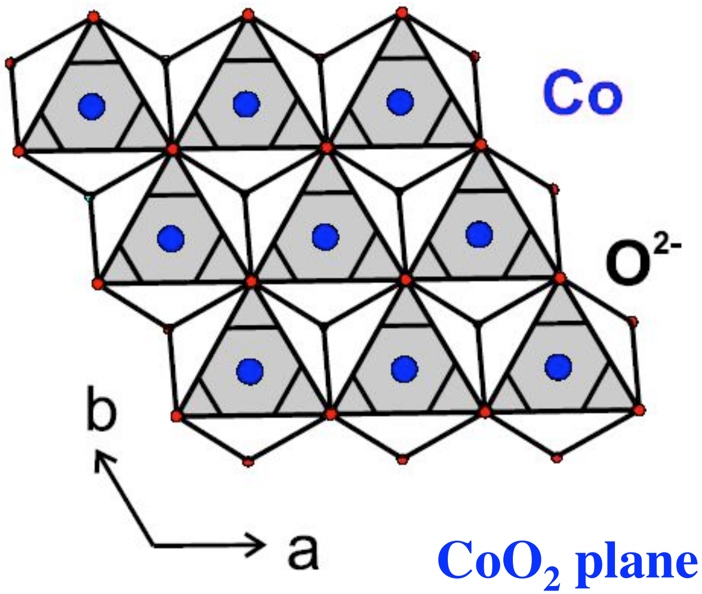




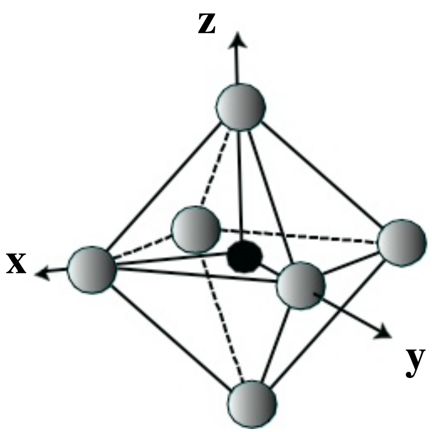
Specific Heat

Cobaltate Superconductor

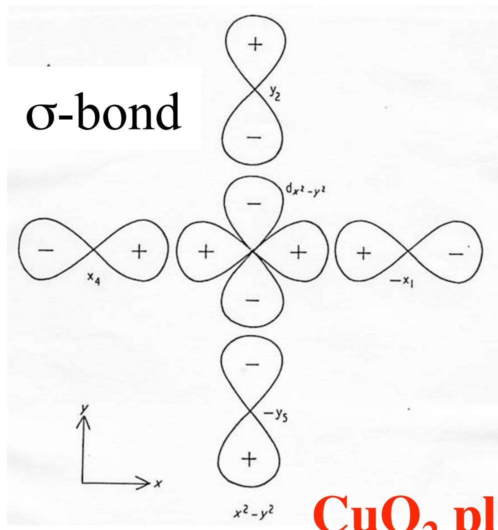
Cuprate Superconductor



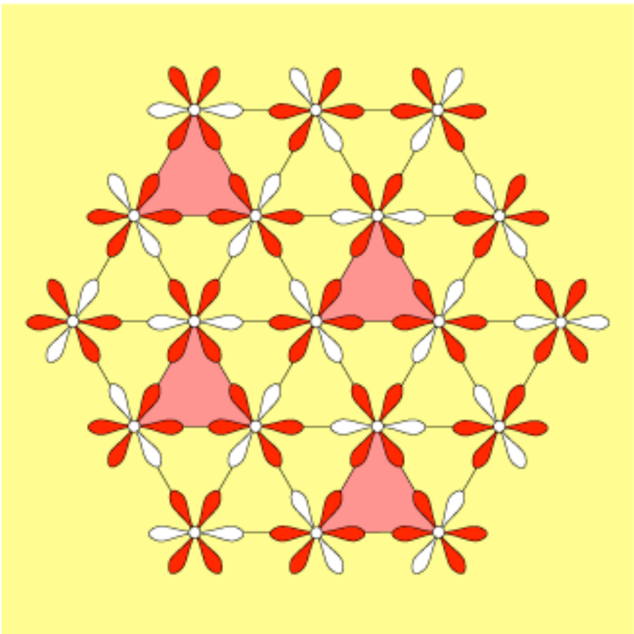
CoO_2 plane

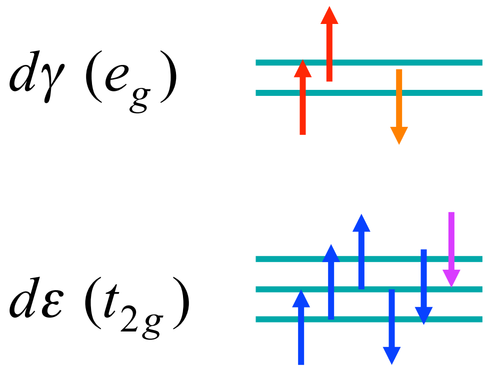


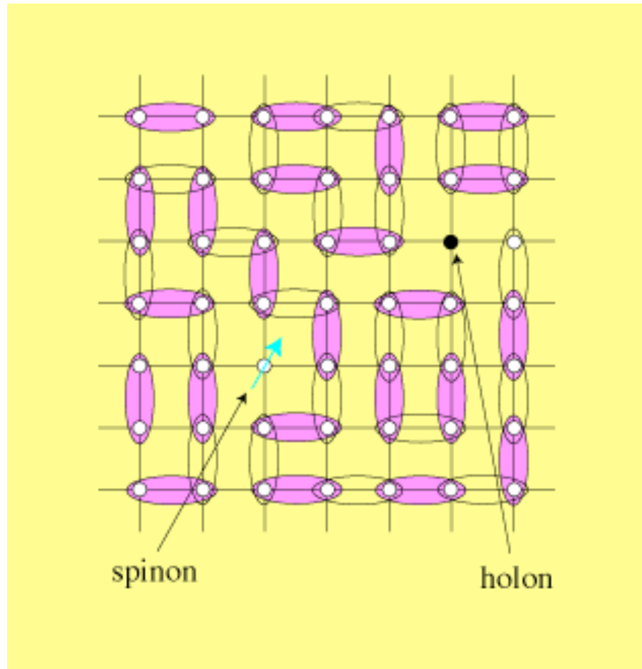
Superconductivity in the strongly correlated electron system



CuO_2 plane





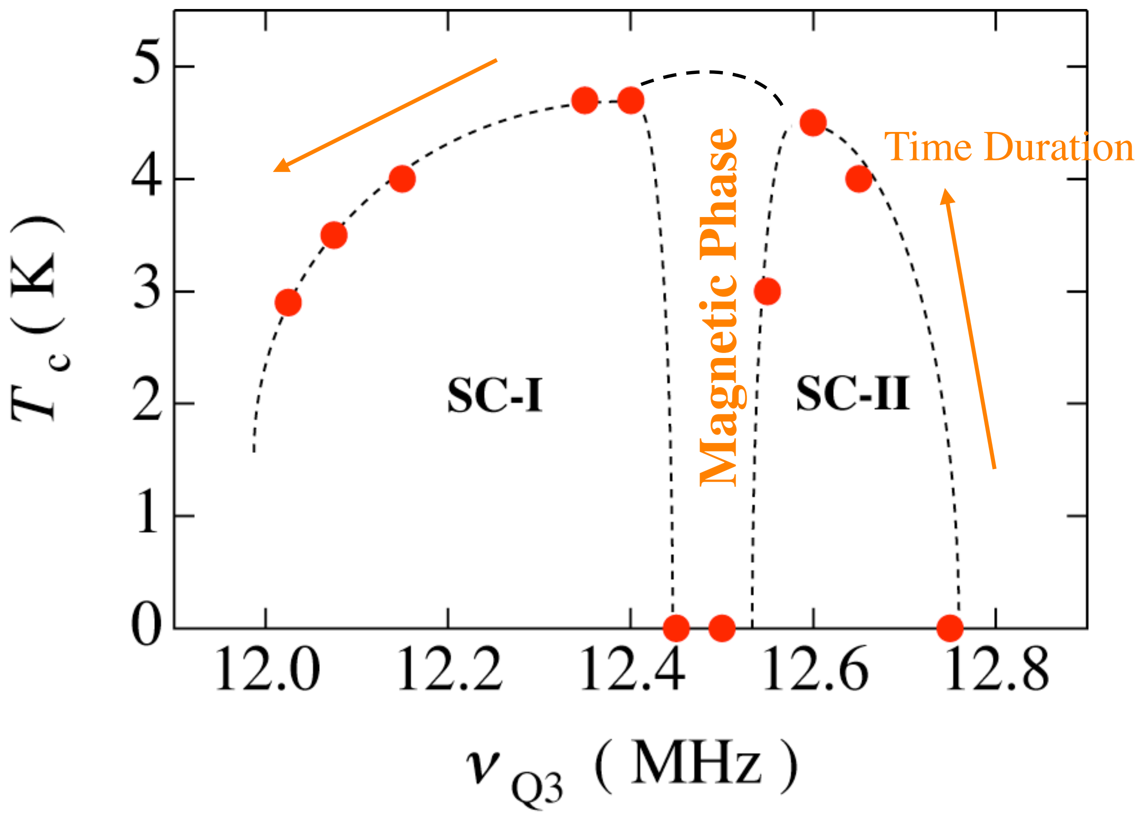


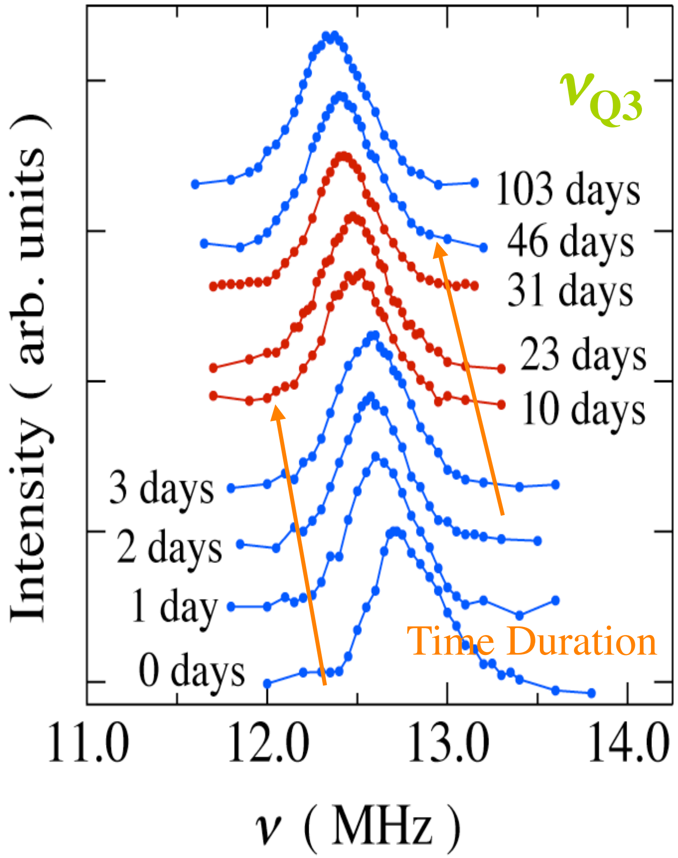
Co^{4+}: $3d^5$
Co^{3+}: $3d^6$

Cu^{3+}: $3d^8$
Cu^{2+}: $3d^9$

T_c vs. ν_{Q3} Phase Diagram of $Na_xCoO_2 \cdot yH_2O$

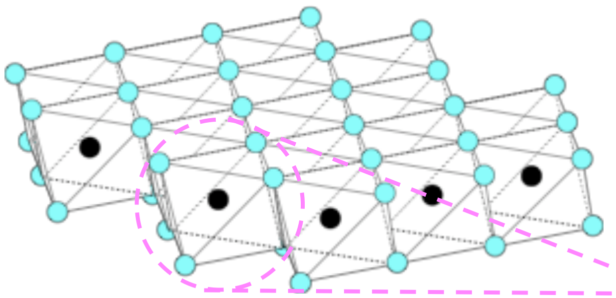
Reentrant Behavior of Superconductivity

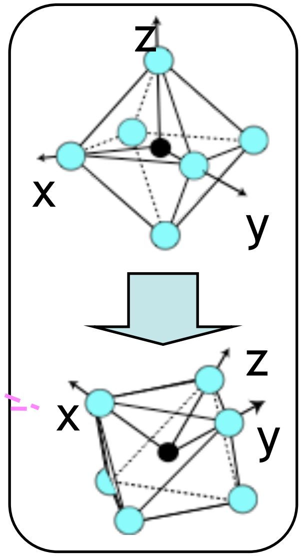




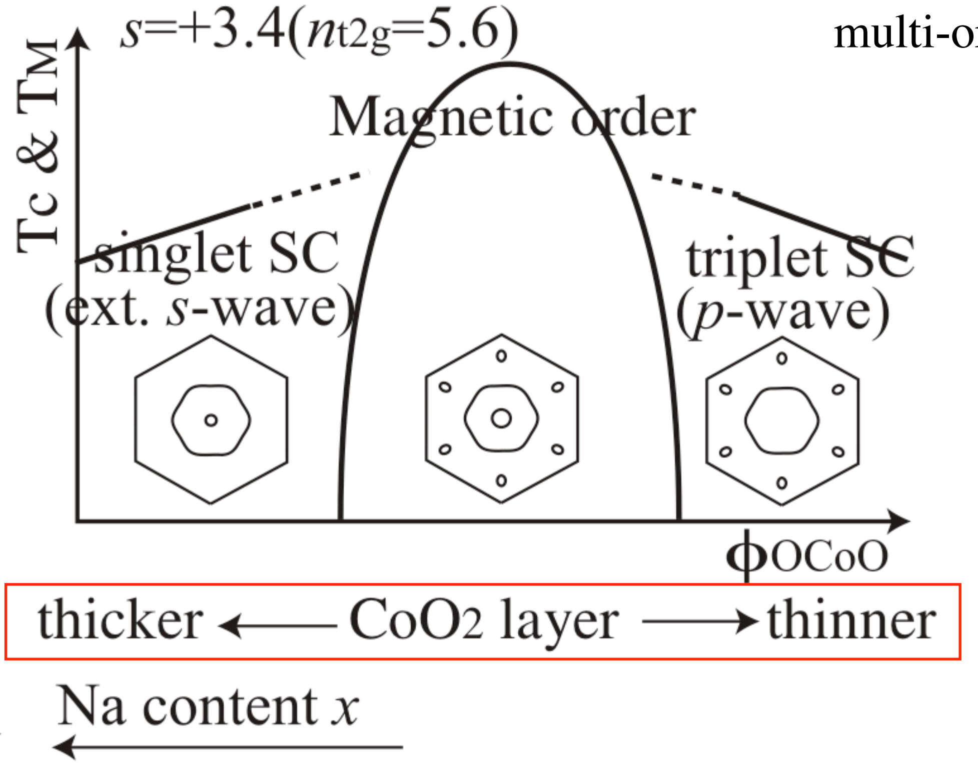
^{59}Co NQR Spectra at 77K

The Phase Diagram of $Na_xCoO_2{\cdot}yH_2O$

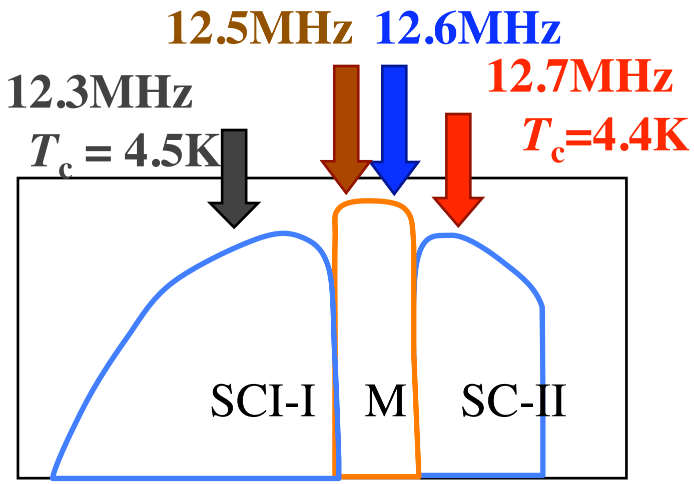




Recently, Mochizuki & Ogata proposed new theoretical phase diagram in order to explain our phase diagram. Their calculation is based upon the multi-orbital model and RPA.



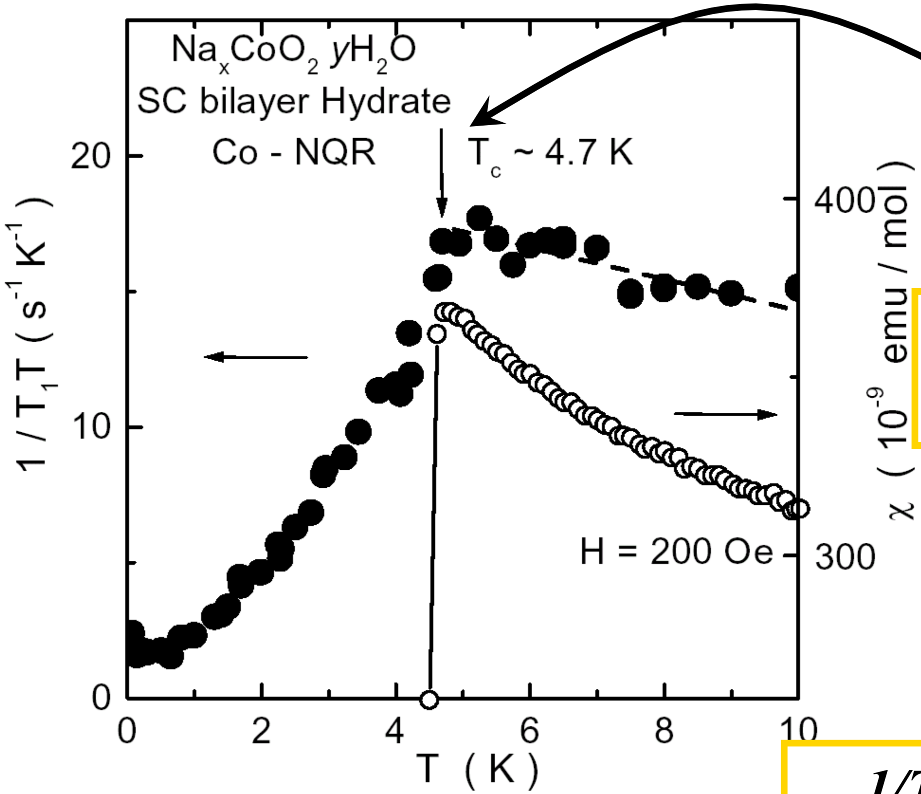
It is important to compare to the real phase diagram.



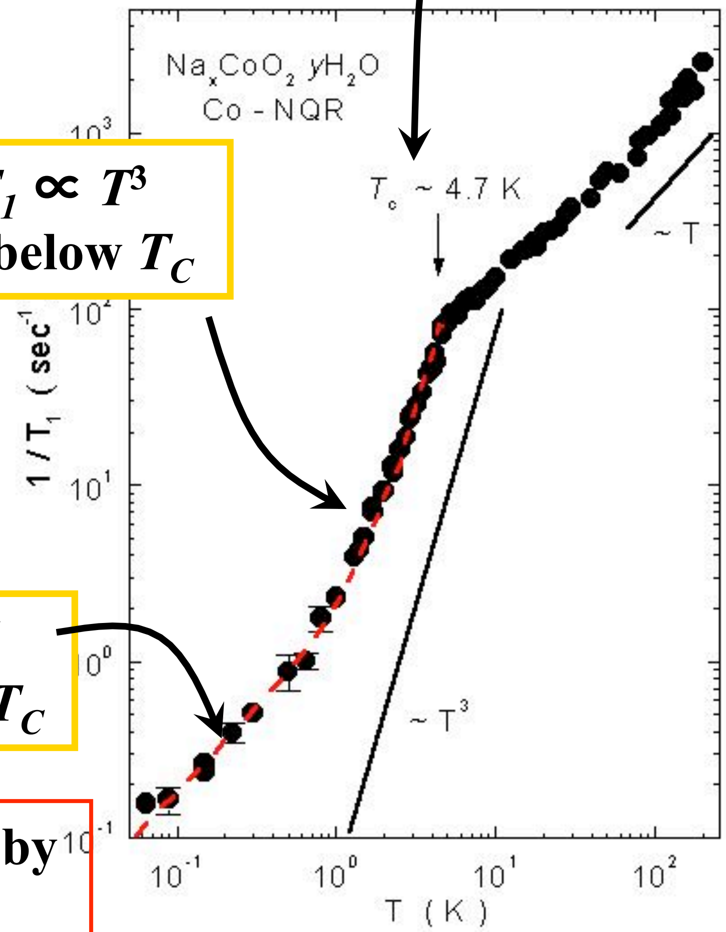
M. Mochizuki & M. Ogata: JPSJ 76 (2007) 013704.

Nuclear Spin-Lattice Relaxation Rate $1/T_1$: SC state

K. Ishida *et al.* J. Phys. Soc. Jpn 72 3041 (2003)



Coherence peak is absent.



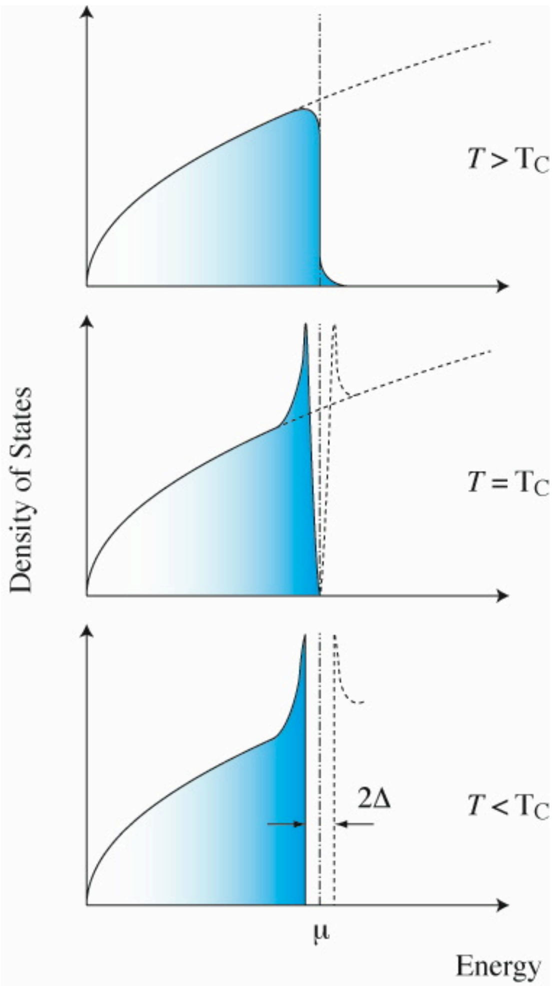
$1/T_1 \propto T^3$
Just below T_C

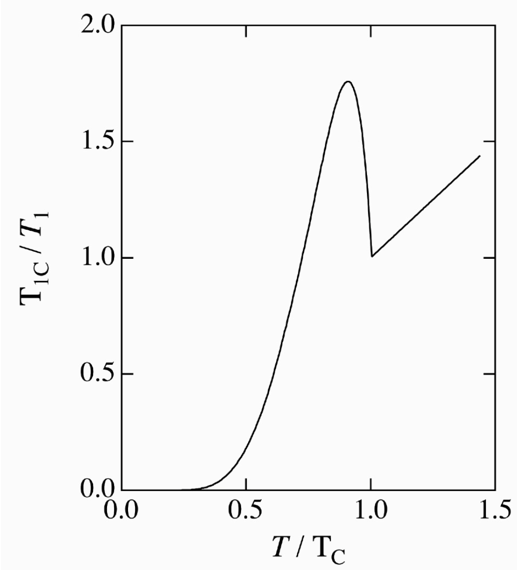
$1/T_1 \propto T$
Far below T_C

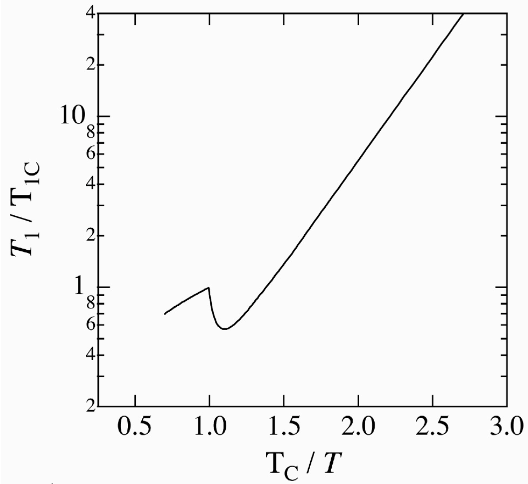
$1/T_1$ in $Na_xCoO_2 \cdot yH_2O$ cannot be understood by an s-wave superconductor with isotropic gap

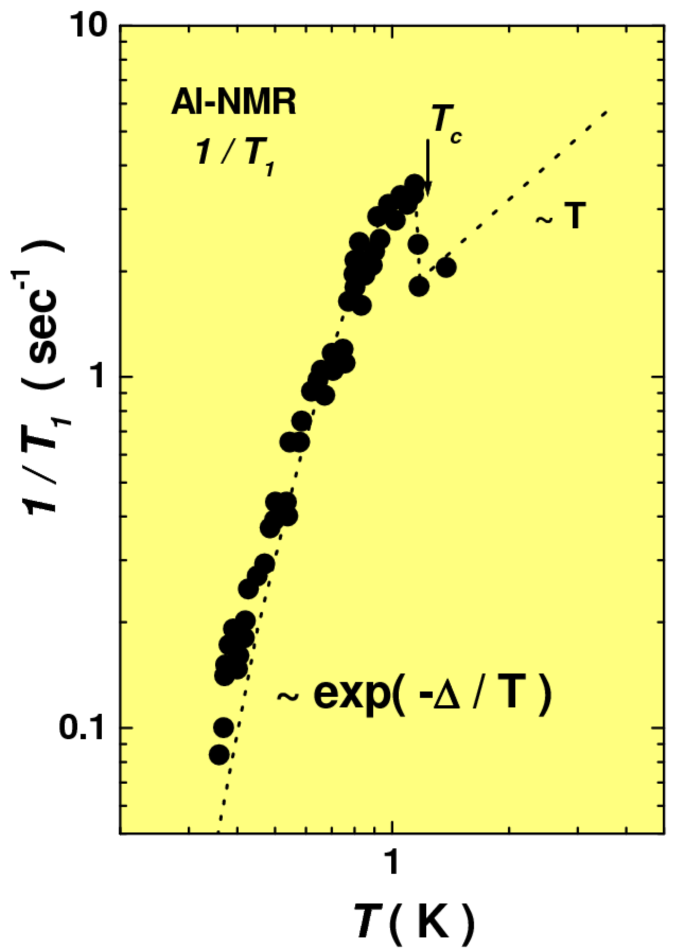
the same conclusion by Fujimoto *et al.* PRL 97 047004 (2004)

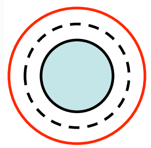
BCS-Type











Y. Masuda and A. Redfield,
Phys. Rev. 133 A944 ('64)

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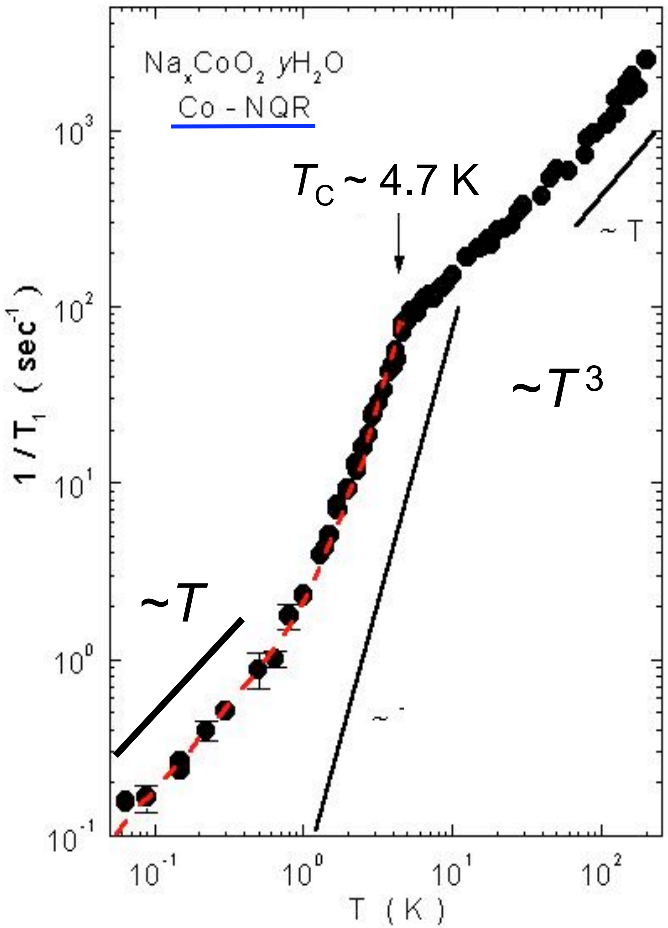
Uniform gap formation
Isotropic gap → **s-wave super-conductor**

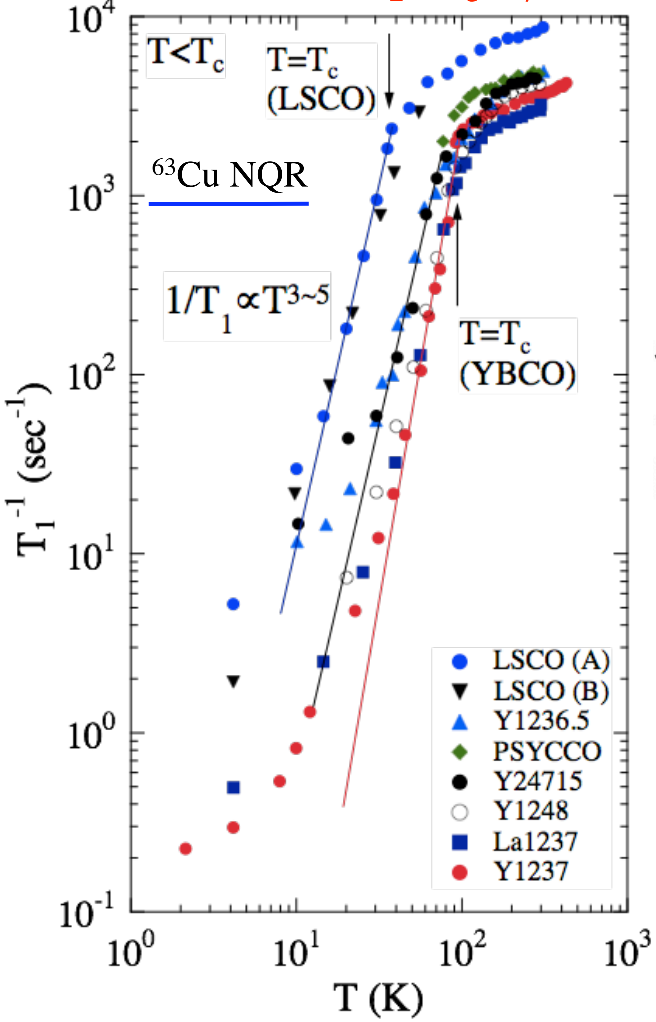
Nuclear Spin-Lattice Relaxation Rate $1/T_1$: SC state

BLH Cobaltate

$Na_xCoO_2 \cdot yH_2O$

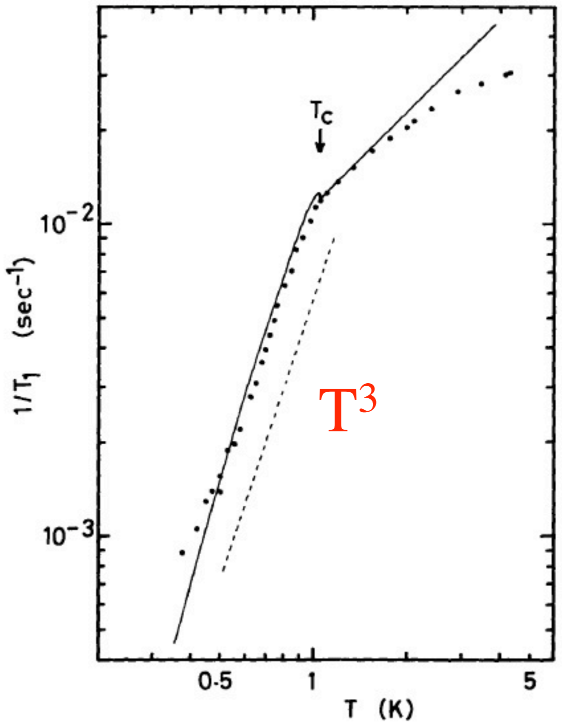


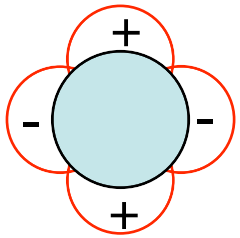
Cuprate $YBa_2Cu_3O_7$



Organic System

TMTSF ^{1}H NMR



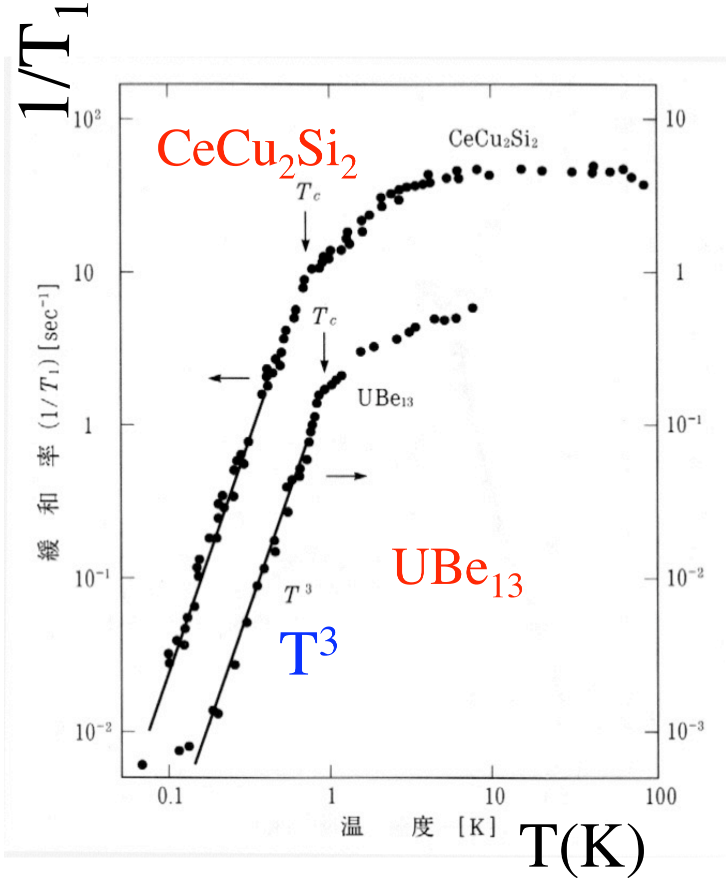


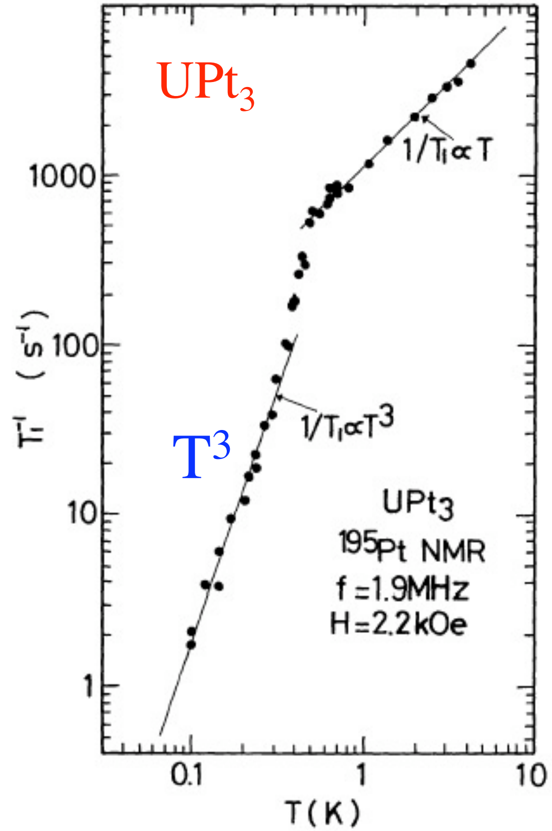
K. Ishida, Y. Ihara, K. Yoshimrua *et al.*
JPSJ 72 3041 (2003)
Fujimoto *et al.* PRL 97 047004 (2004)

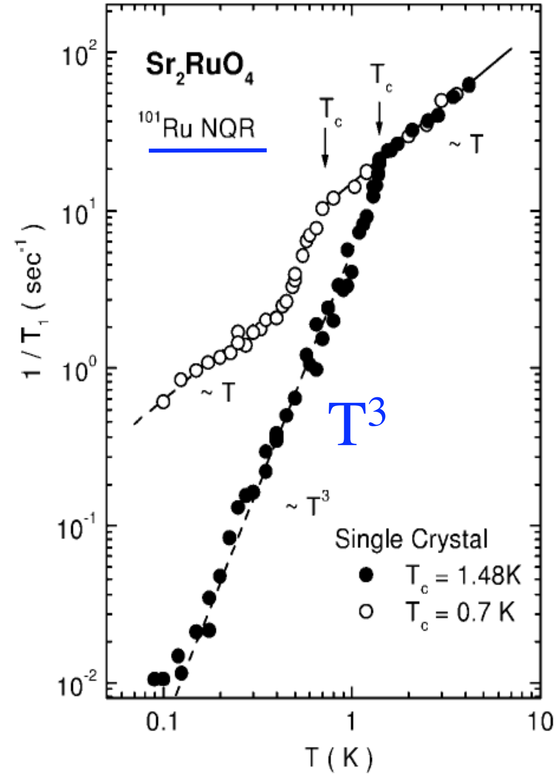
$Na_xCoO_2 \cdot yH_2O$ is classified to be an **unconventional superconductor.**

Heavy-Fermion Superconductors

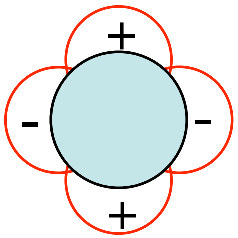
Ruthenate Sr_2RuO_4







K. Ishida *et al.*
PRL 84 5387 (2000)



$Na_xCoO_2 \cdot yH_2O$ is classified to be
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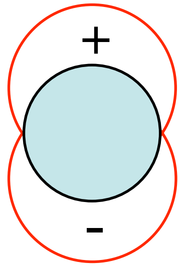


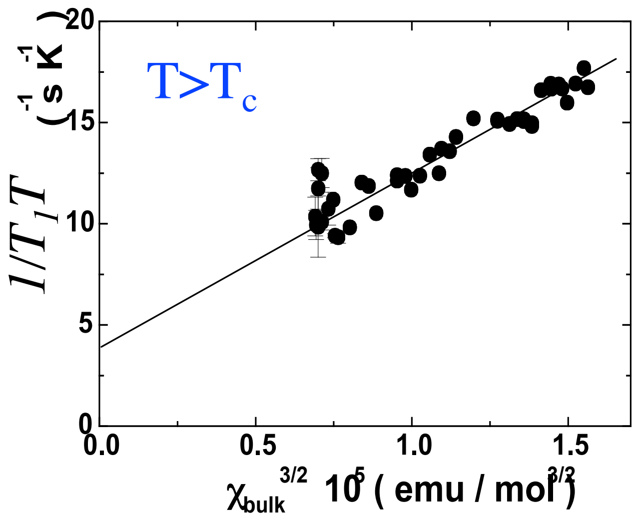
Magnetic Excitations in BLH, MLH and Unhydrated

Magnetic fluctuations above 100 K are similar in these cobaltate.

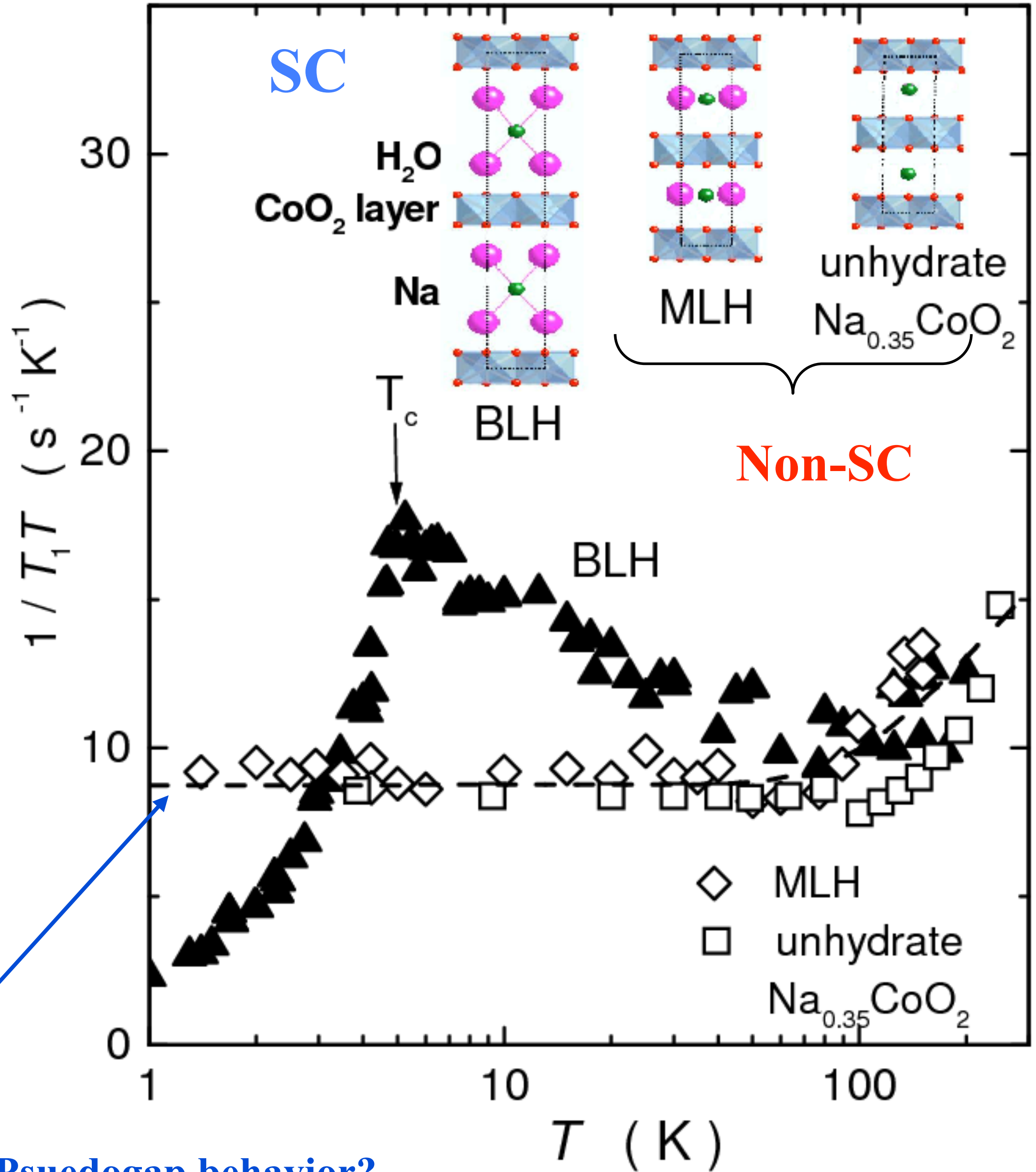
SC BLH shows the increase of $1/T_1T$ below 70 K

Two kinds of magnetic fluctuations in BLH

Ferromaganetic Fluctuation (q∼0)

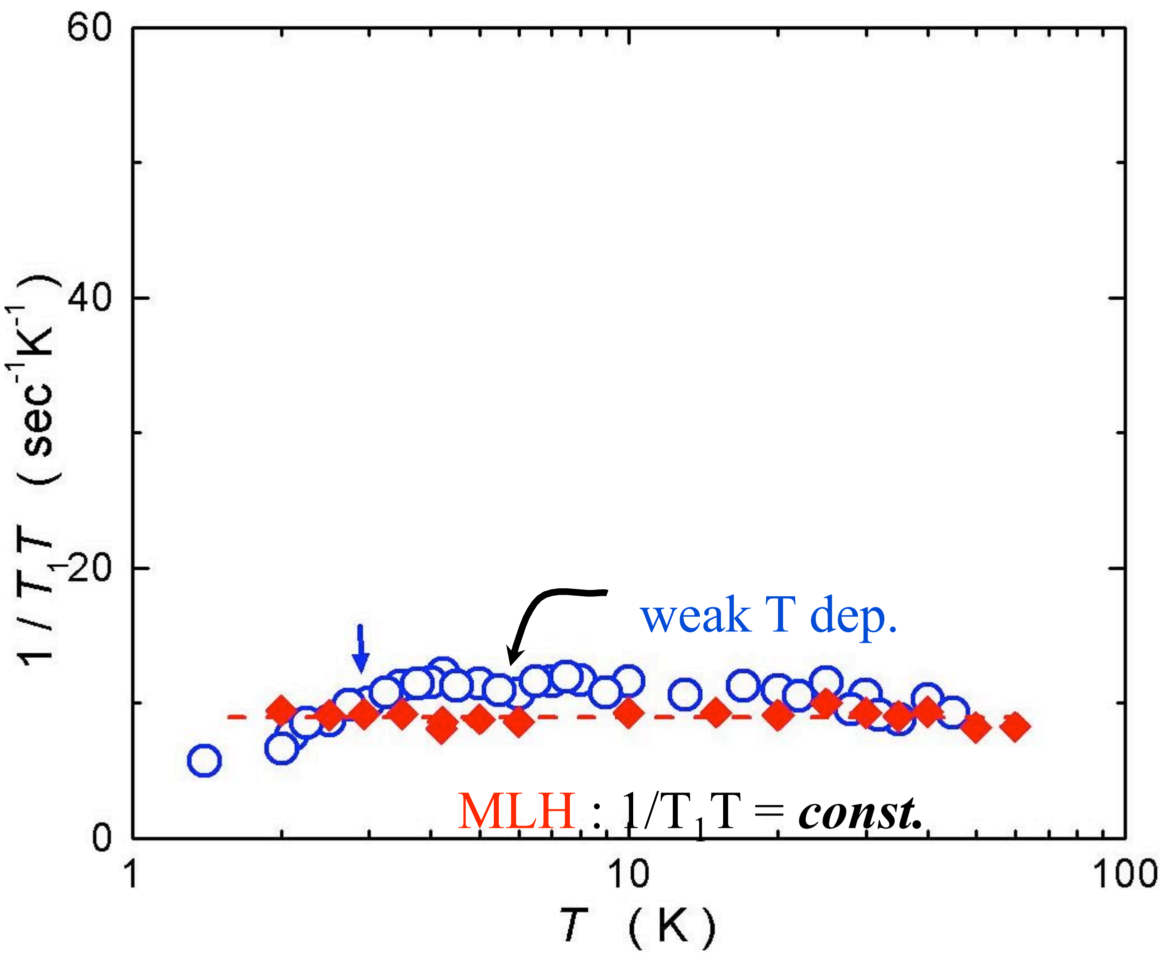


$$\left(\frac{1}{T_1T}\right)_{MLH} = 8.75 + 15\exp\left(-\frac{\Delta}{T}\right) \quad (\mathrm{sec}^{-1}\mathrm{K}^{-1})$$

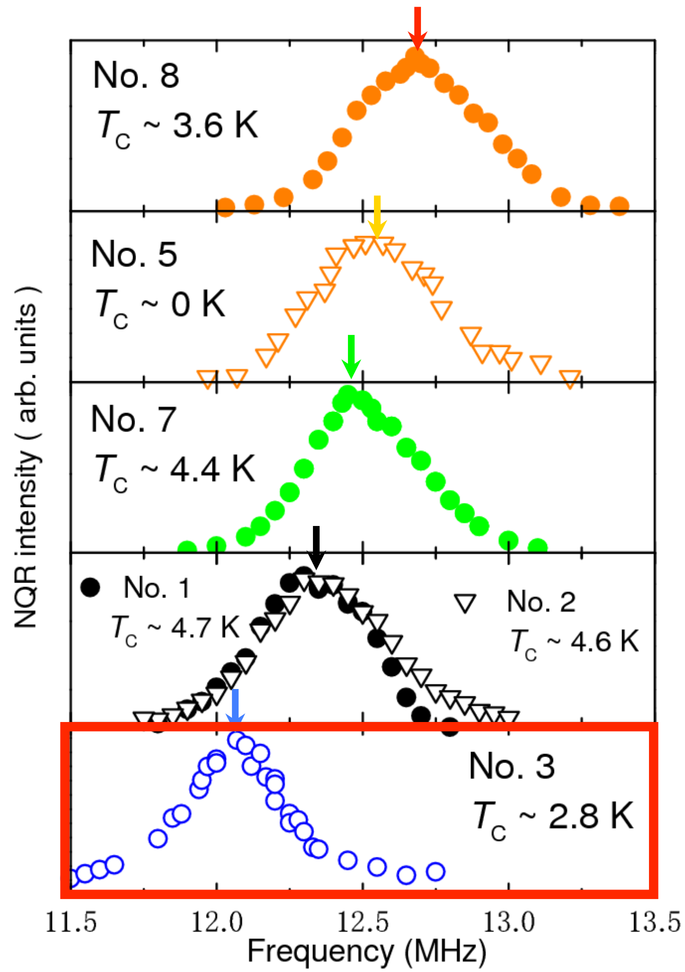


Psuedogap behavior?

$1/T_1T$: Nuclear spin-Lattice relaxation Rate



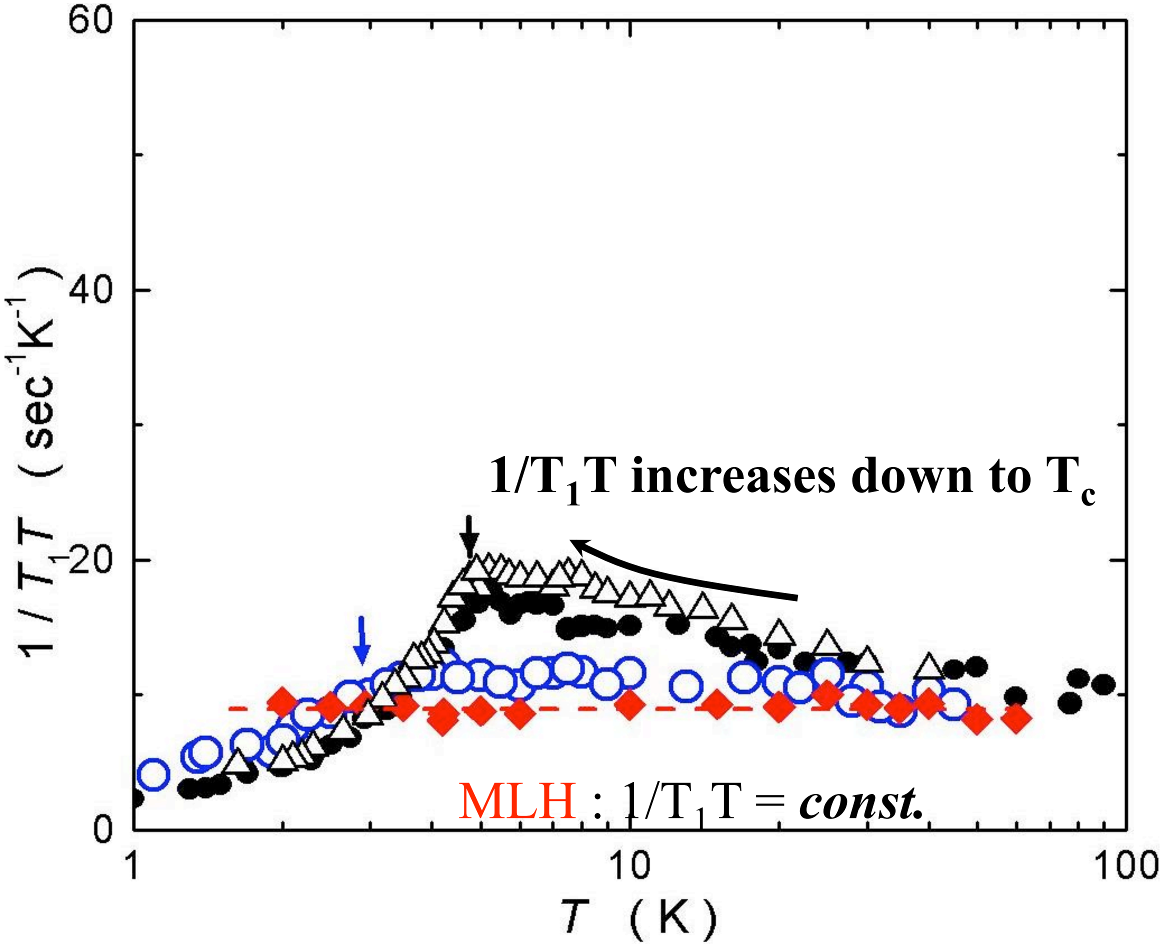
NQR Spectrum



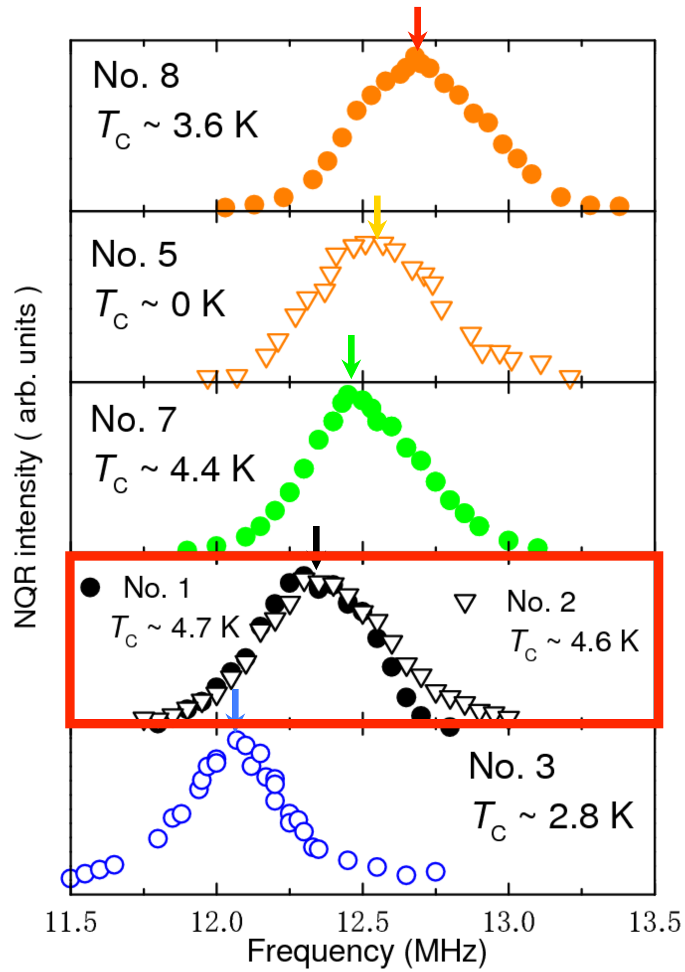
MLH $Na_{0.3}CoO_2 \cdot 0.7H_2O$ → non-SC down to 1.5 K

$1/T_1T$ is constant below 100 K

$1/T_1T$: Nuclear spin-Lattice relaxation Rate



NQR Spectrum



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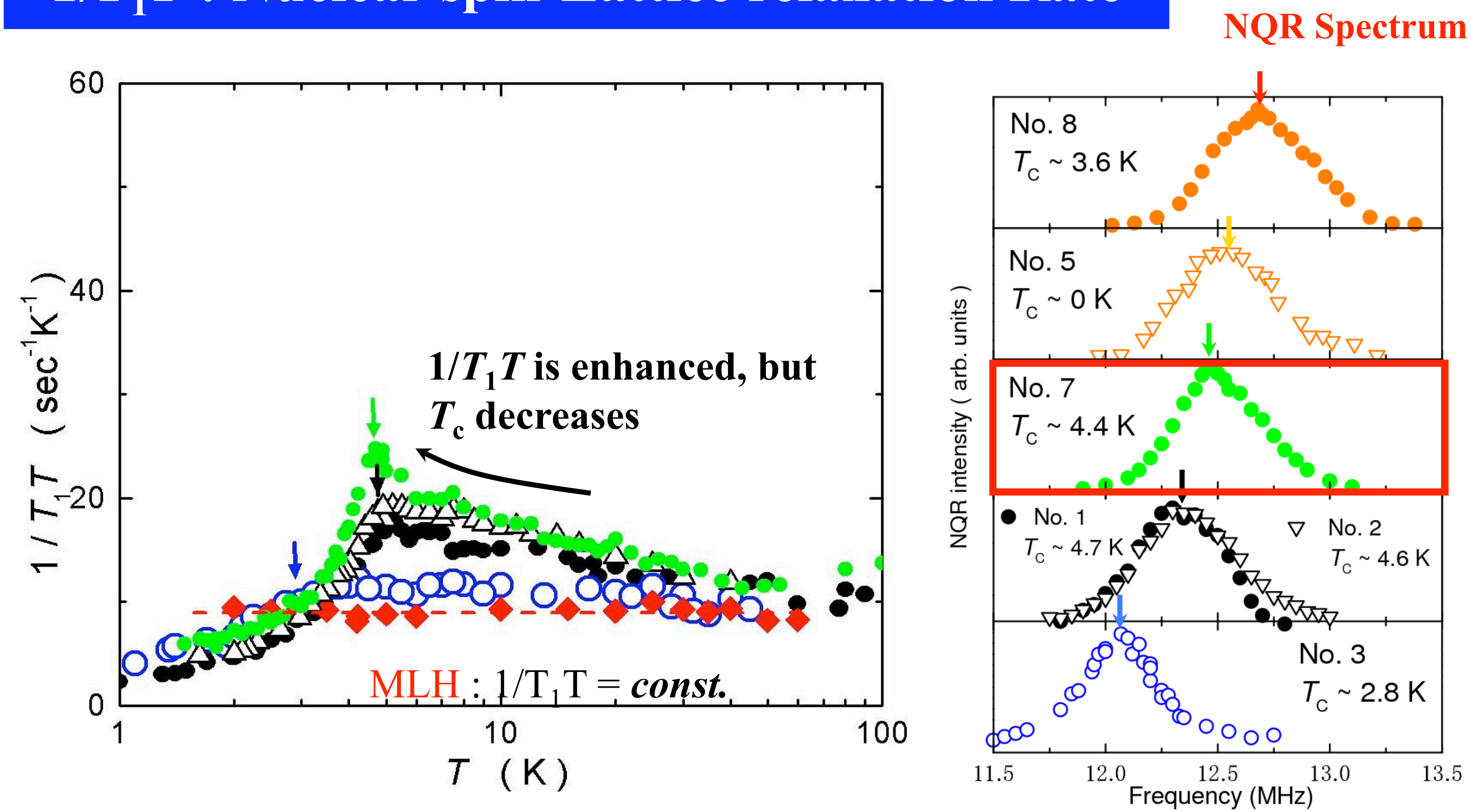

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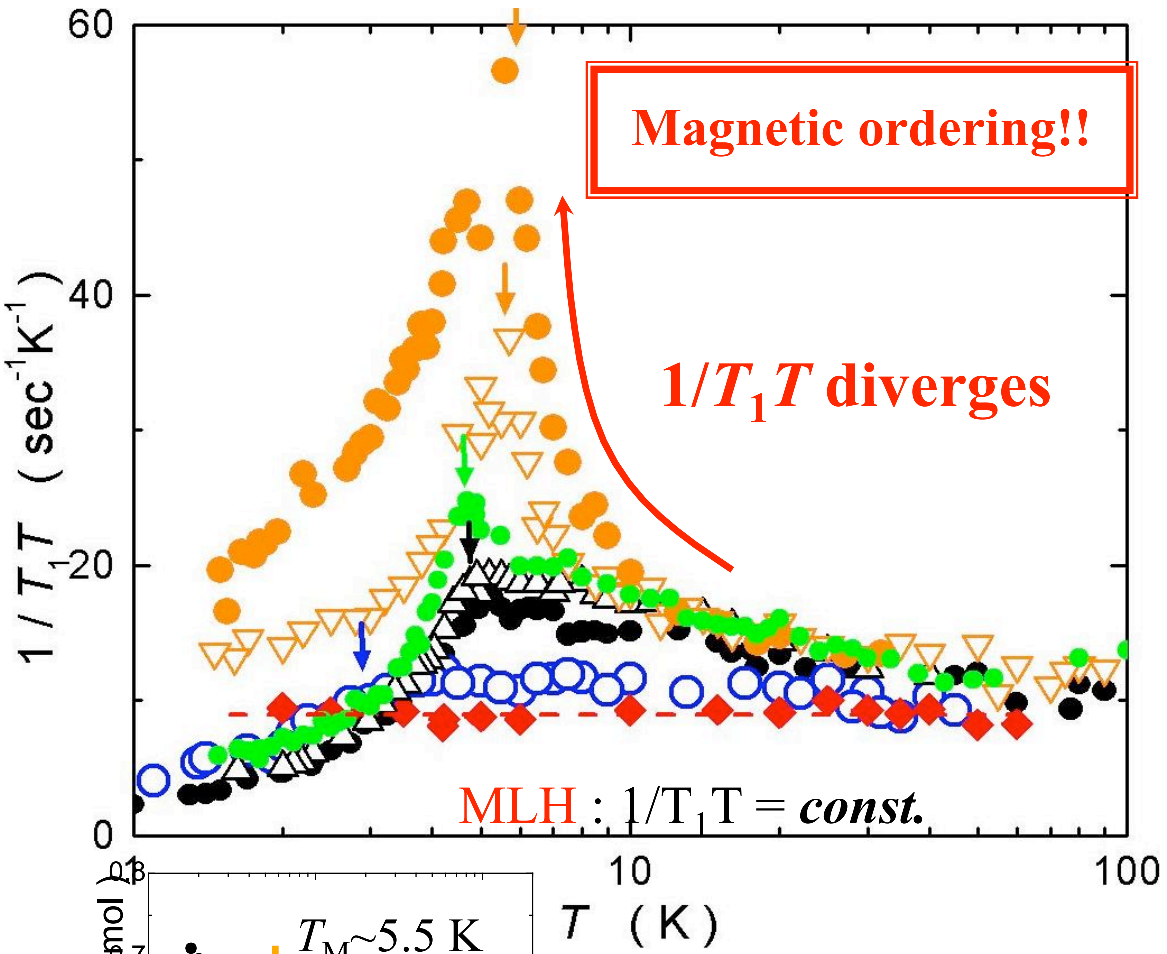
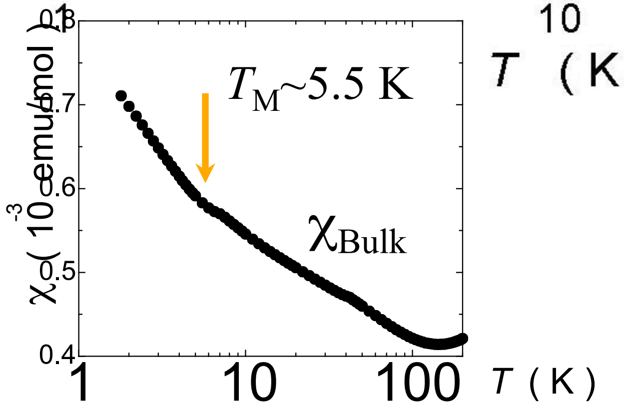
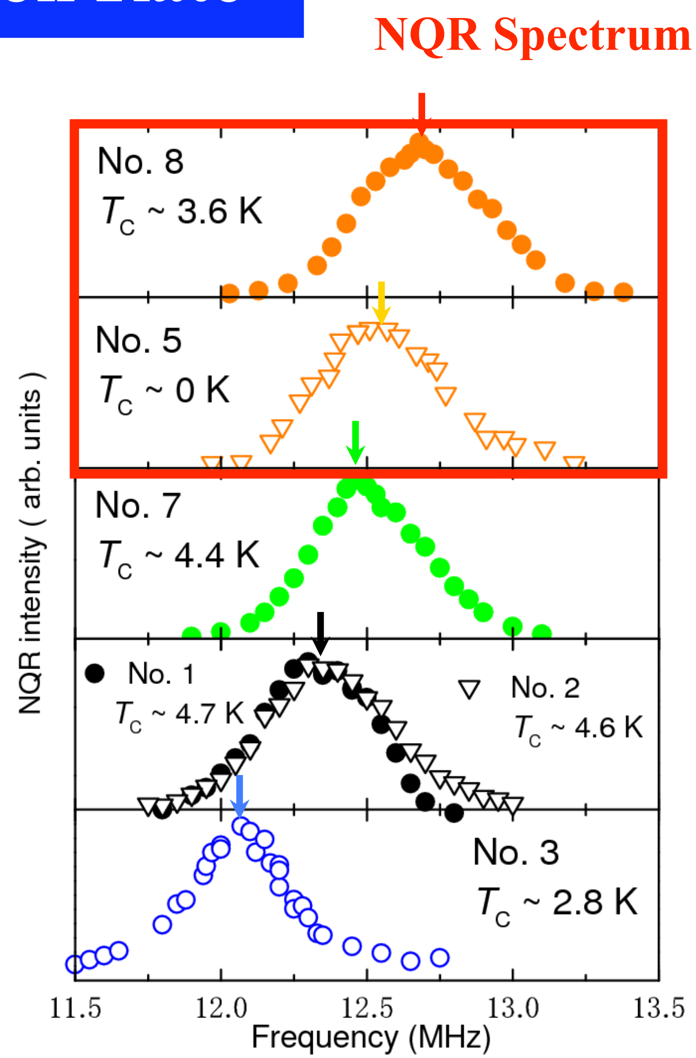
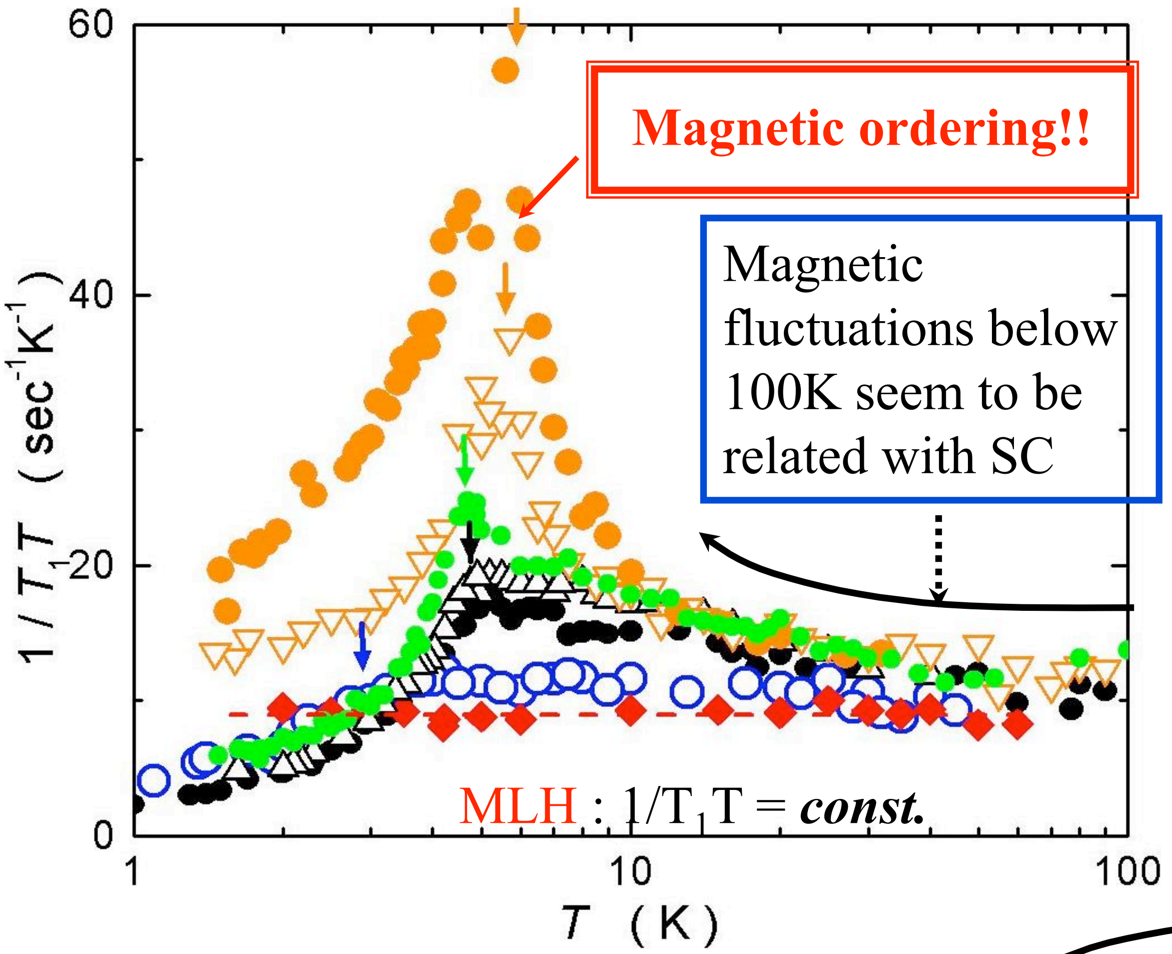


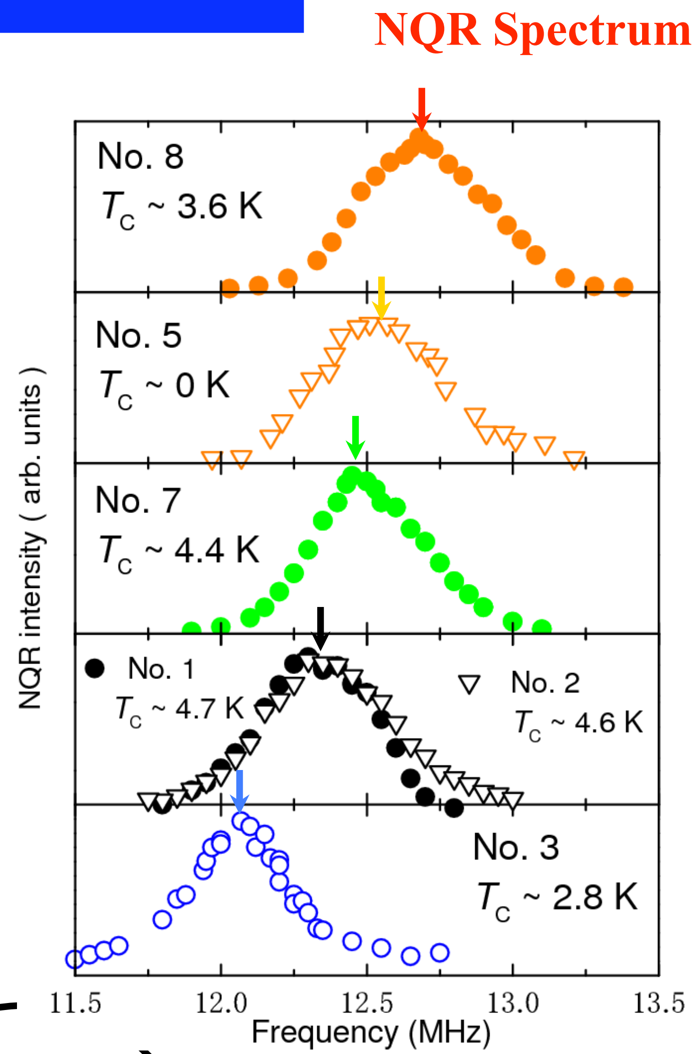




The samples with higher ν_Q show magnetic ordering.

$1/T_1T$: Nuclear spin-Lattice relaxation Rate



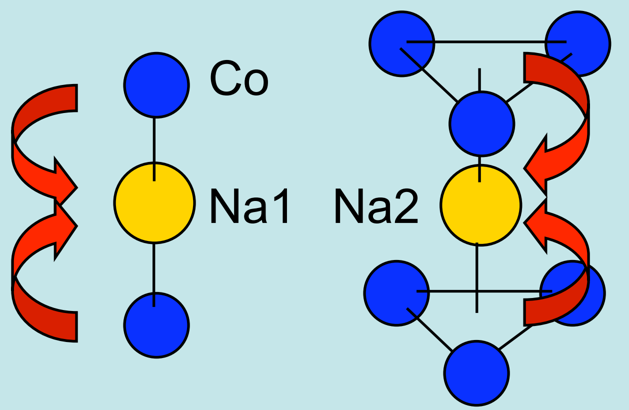


SC is observed in the vicinity of QCP of magnetic fluctuations.

NQR frequency has relation with S.F.

Magnetic fluctuation in BLH

Superconductivity
in the vicinit of QCP
of A-type fluctuation ?

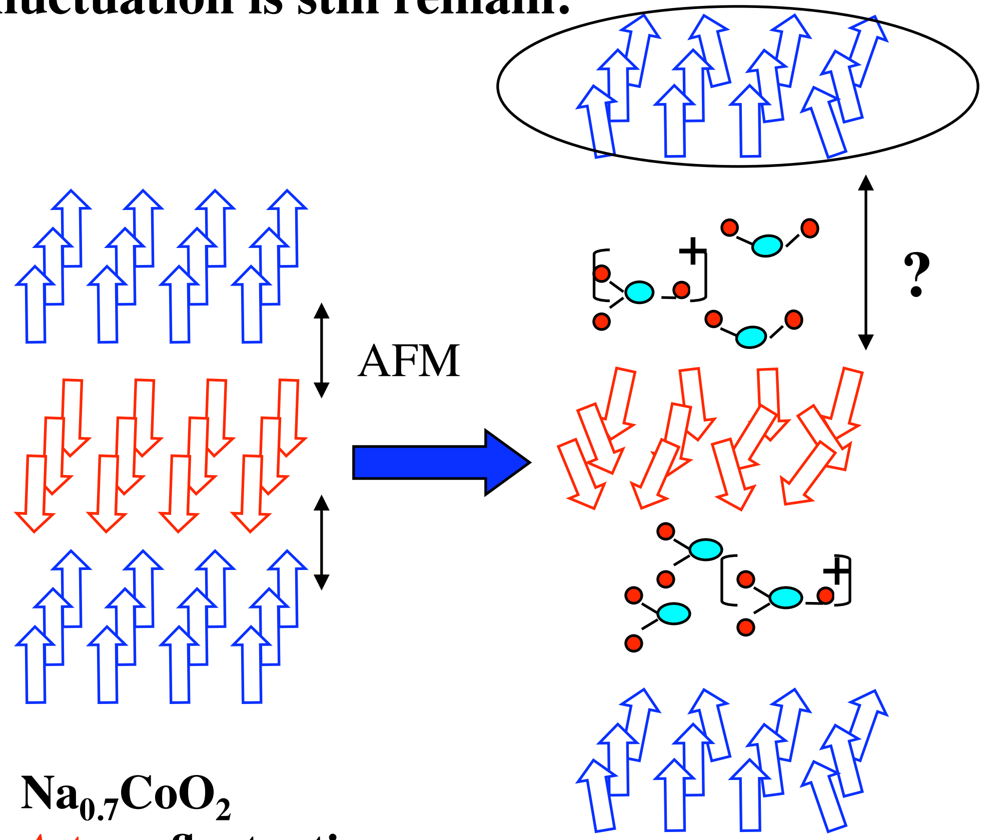


The inter-plane AFM fluctuation is canceled at Na site.

The T^n relation seen in $^{23}1/T_1$ of **$Na_{0.7}CoO_2$** below 40K is due to FM spin fluctuations. **($\rightarrow Co^{3.3+}$)**

Similar relation seen in $^{23}1/T_1$ of **$Na_{0.35}CoO_2 \cdot 1.7H_2O$** indicates the existence of FM spin fluctuations in the SC $Na_xCoO_2 \cdot yH_2O$.
($\rightarrow Co^{3.65+}$? $\rightarrow$ $Co^{3.4+}$ in the presence of **H_3O^+**)

In-plane ferromagnetic fluctuation is still remain.



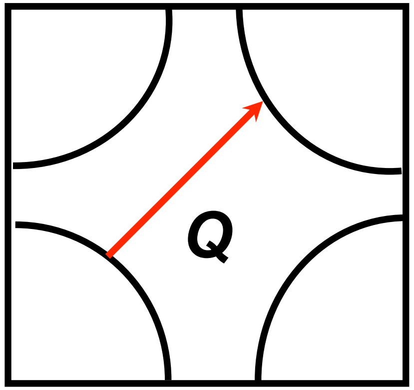
$Na_{0.7}CoO_2$
***A*-type fluctuation**

BLH $Na_{0.35}CoO_2 \cdot 1.7H_2O$

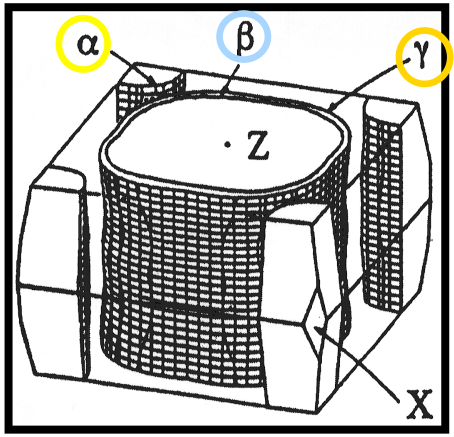
Neutron Scattering: Boothroyd *et al.*, PRL **92** (2004) 197201.

Comparison

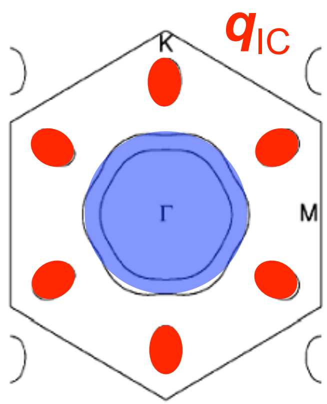
Cuprate



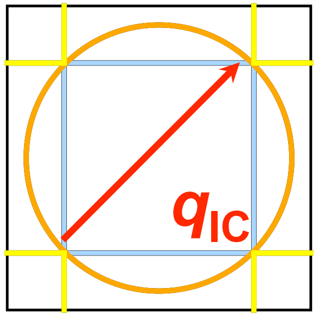
Ruthenate



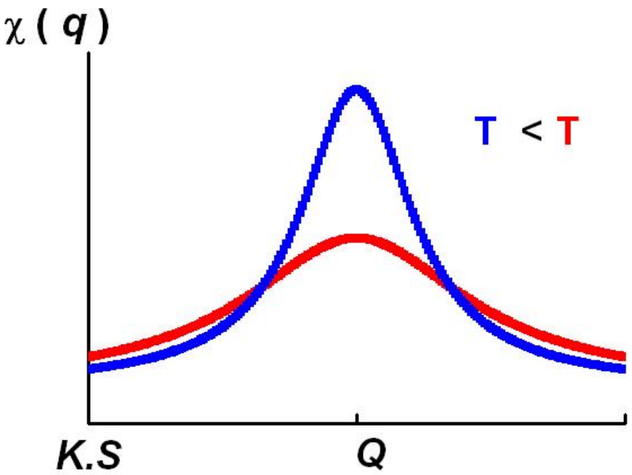
Cobaltate

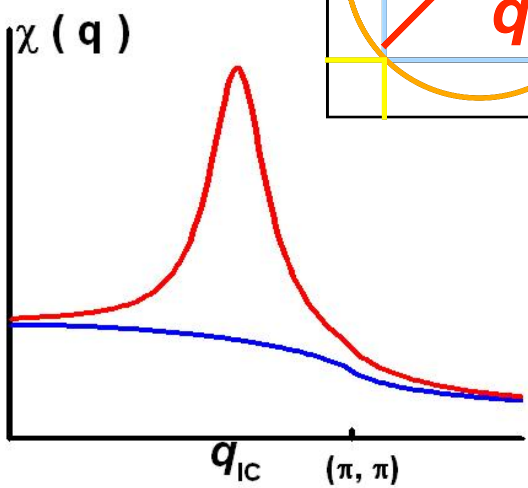


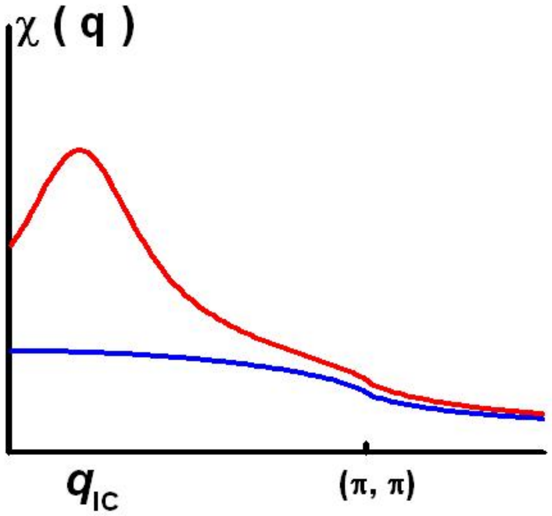
One component



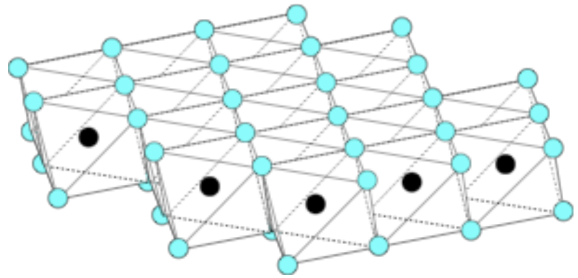
Multi bands







Conclusion ($Na_xCoO_2 \cdot yH_2O$)



1. **Universal Phase Diagram: T_c vs. ν_Q of ^{59}Co NQR**
   → Superconducting Phases appear in both sides of Magnetic Phase !
   → Strong Relation between Superconducting and Magnetic Phases

2. **Magnetic Correlation: $Na_xCoO_2 \cdot yH_2O$ is Unconventional Superconductor**
   ← $1/T_1$ of ^{59}Co NQR
   Superconductivity appears in the vicinity of
   ***Unconventional* Quantum Critical Point !**

3. **Only SC BLH has spin fluctuations at q~0! ← ^{59}Co NQR**
   The *A-type* spin fluctuation is important ! ← ^{23}Na NMR