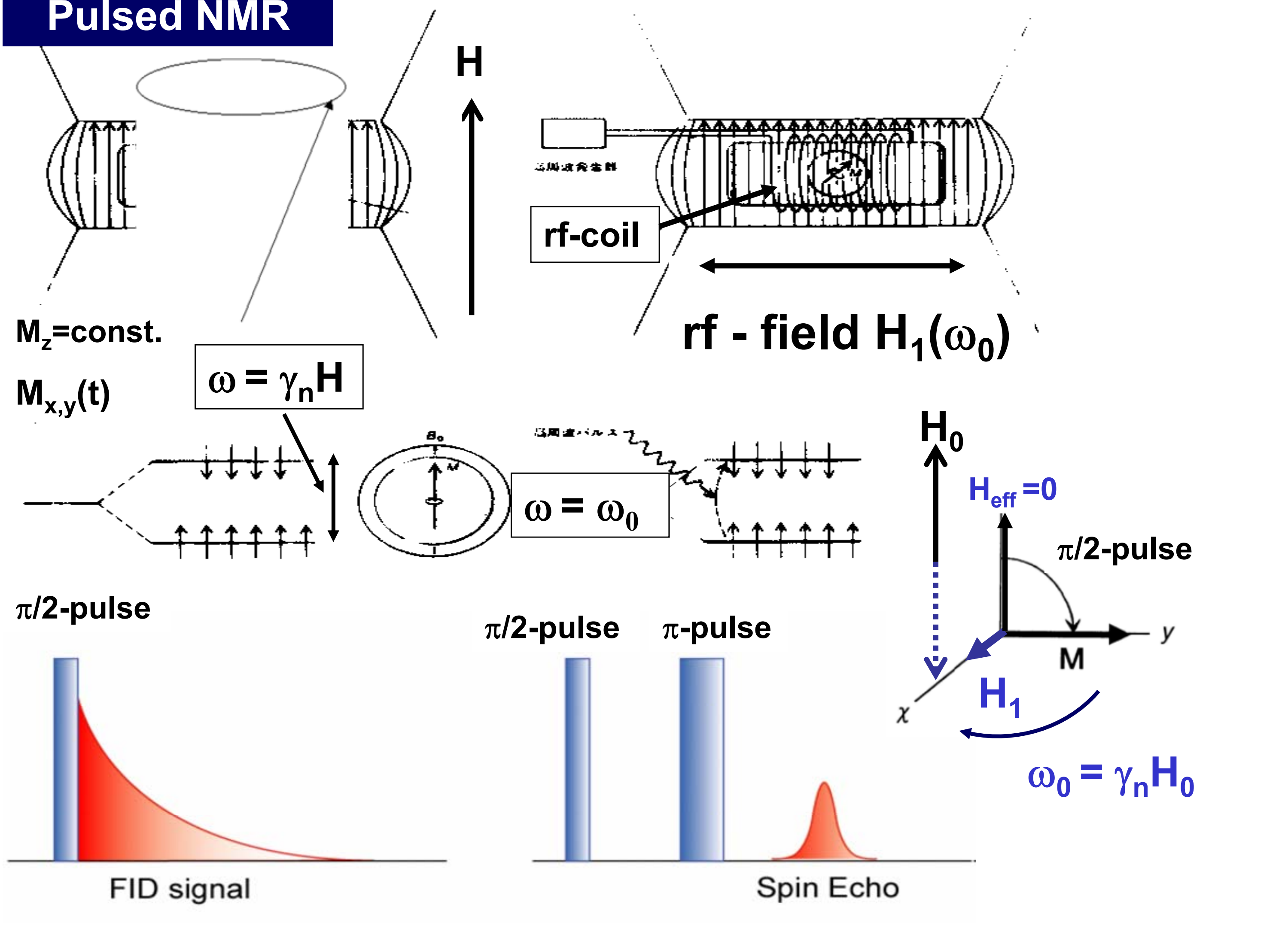
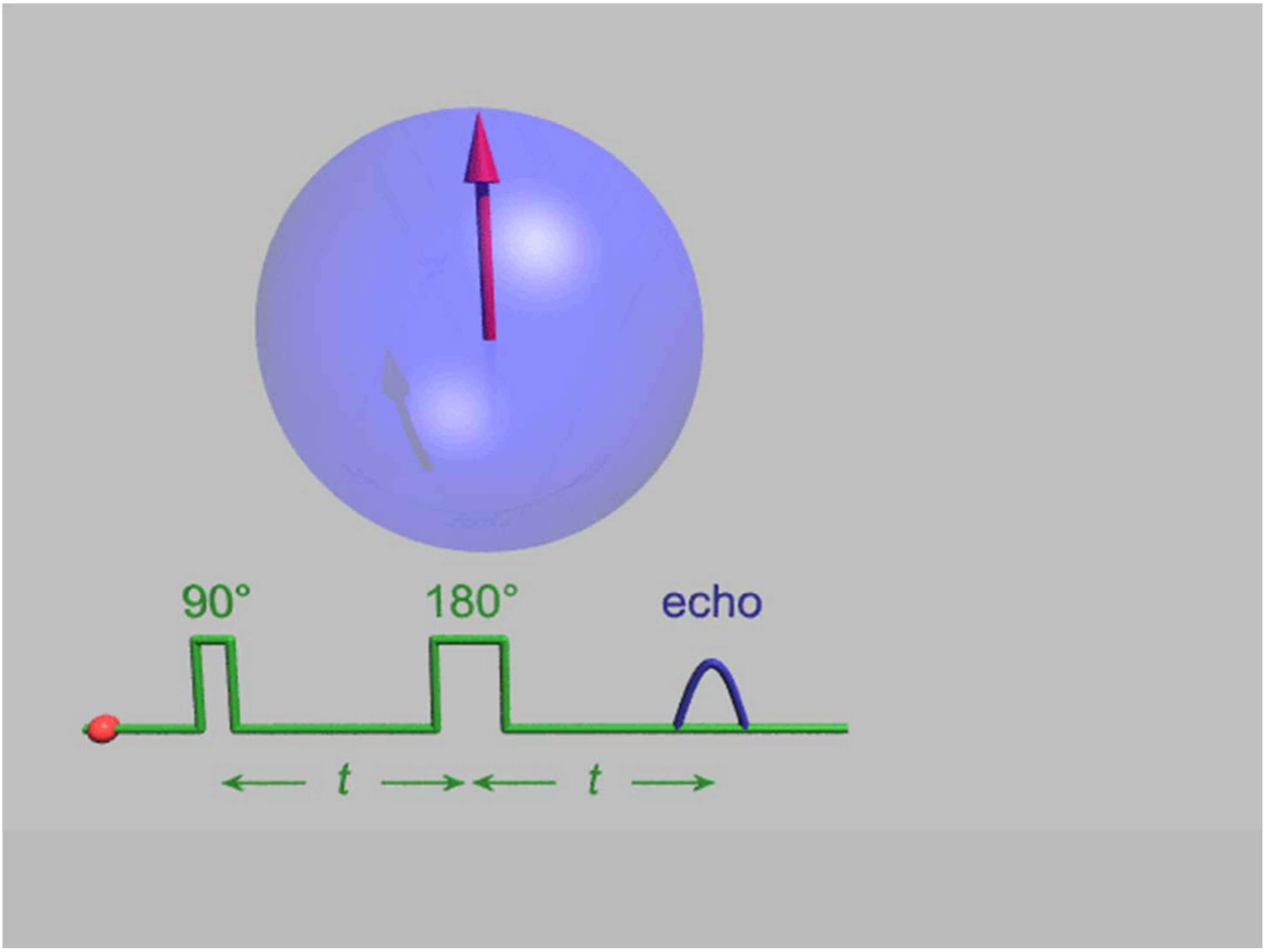
核磁気共鳴法（NMR）および核電気四極子共鳴法（NQR）の基礎　および　強相関電子系への応用

NMR/NQR probes of emergent properties in correlated-electron superconductors

- Symmetry of the Cooper pair of either spin-singlet or spin-triplet
- SC gap with either isotropic or nodal structure
- Characters of spin fluctuations

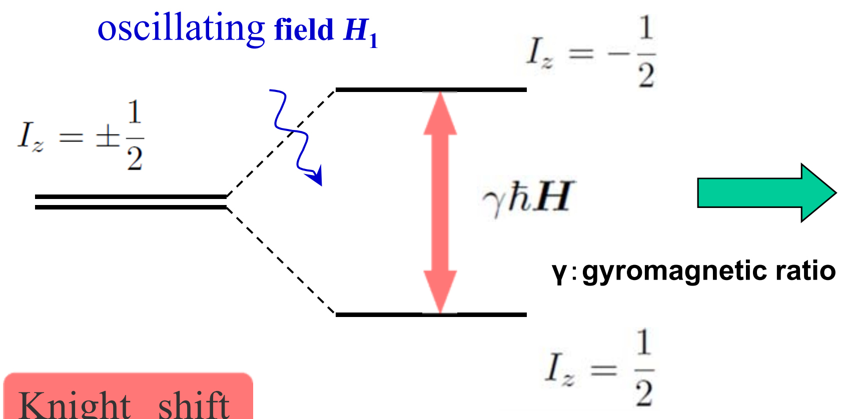
Pulsed NMR

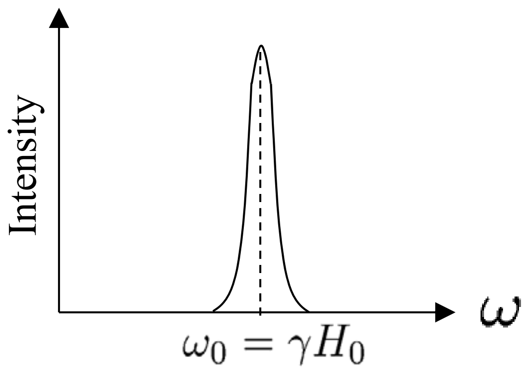




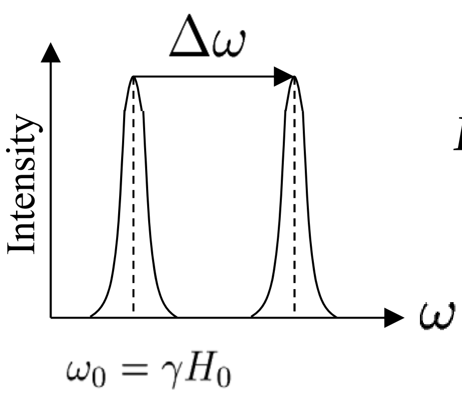
NMR – Nuclear Magnetic Resonance –

Zeeman splitting



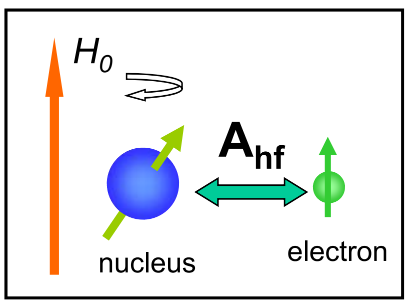


Knight shift



$$K = \frac{\Delta\omega}{\omega_0} = K_{spin} + K_{orb}$$

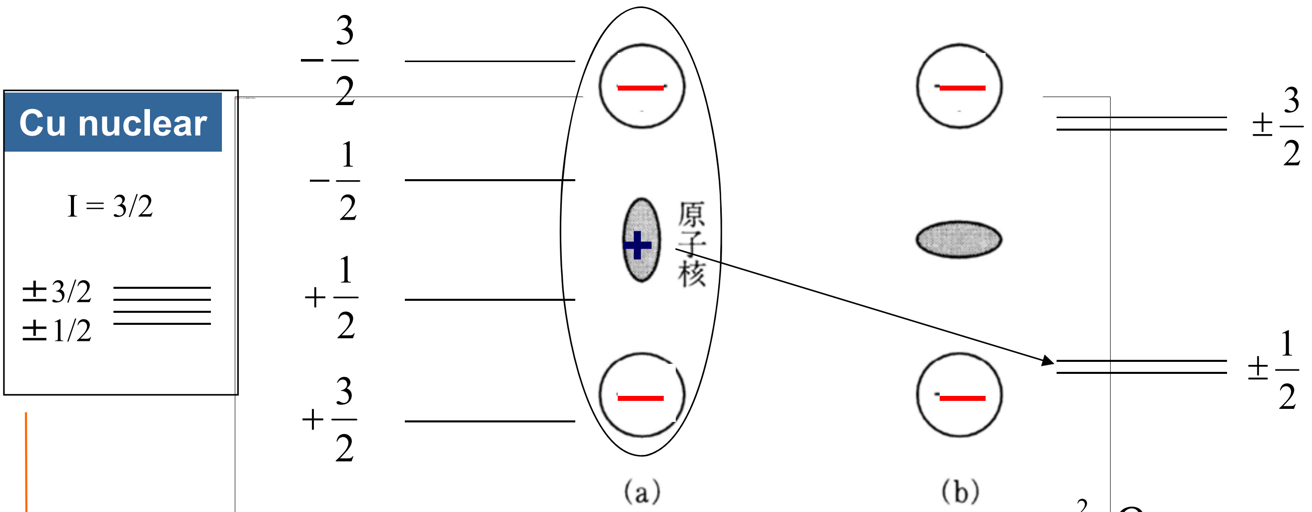
$$K_{spin} = A_{hf}\,\chi_{spin}$$



核電気四極子共鳴の原理

Principle of Nuclear Electric Quadrupole Resonance

Nuclear Magnetic Resonance（NMR) and Nuclear Quadrupole Resonance (NQR）



$$\mathscr{H} = -\gamma\hbar I \cdot H$$

$$\mathscr{H}_Q = \frac{e^2qQ}{4I(2I-1)}(3I_Z^2 - I^2)$$

Zeeman Interaction

Nuclear electric quadrupole Interaction

- **NMR at magnetic field**
- **Zero-Field NMR probing onset of magnetism**

- **NQR at zero field**

$$\omega = \gamma_n H$$

$$f \equiv \nu_Q = \frac{3e^2qQ}{2I(2I-1)h}$$

NQR and Zero-field NMR for nuclear spin I ≥ 1

Nuclear Hamiltonian of Internal Zeeman interaction and electric quadrupole interaction

$$\mathscr{H} = -\gamma_N \hbar I \cdot H_{int} + \frac{e^2 qQ}{4I(2I-1)}(3I_Z^2 - I^2)$$

i) In the case of non-magnetic state

NQR at zero field → To characterize samples

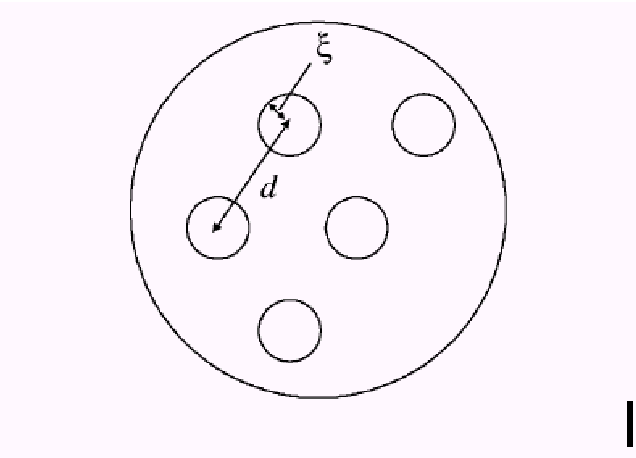
ii) In the case of antiferromagnetically ordered state

Observation of Zero-field NMR provides evidence for an onset of AFM and enables to estimate of AFM moments

超伝導状態のNMRによる研究から分かること

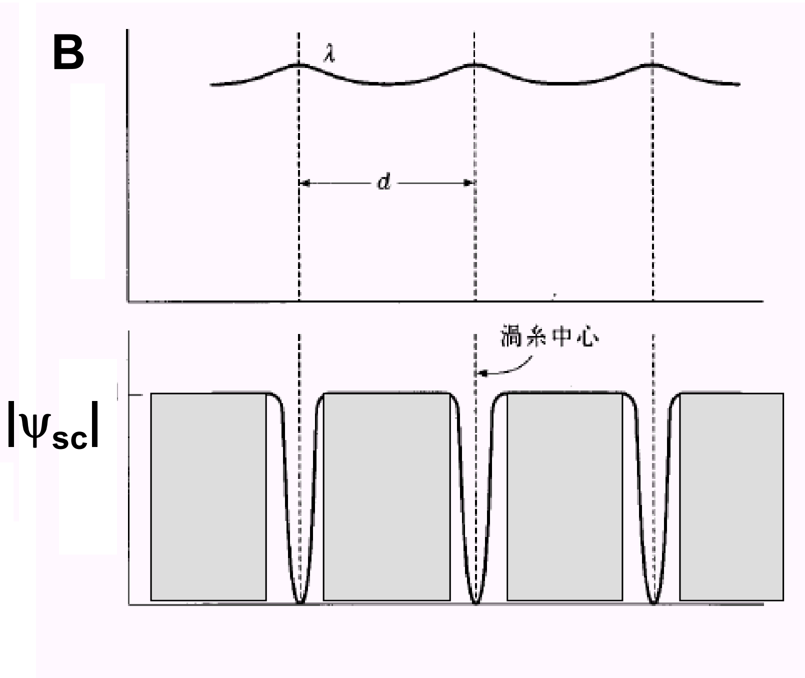
・ナイトシフト
・T_1測定

NMR in superconducting state under magnetic field



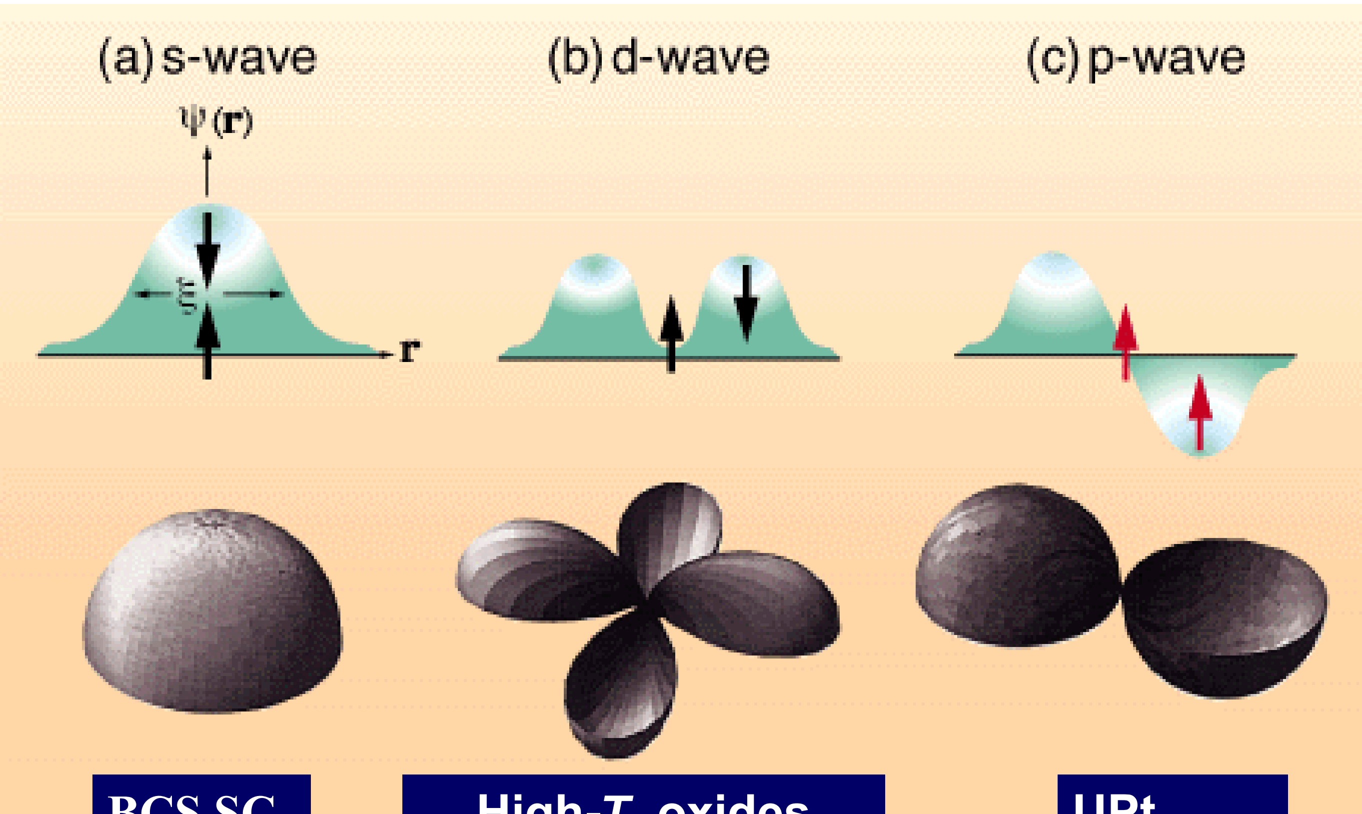
Distribution of Vortexes

$\xi \ll d \leq \lambda$



Knight-shift can measure the spin susceptibility below T_c, regardless of bulk-susceptibility being dominant by SC diamagnetism

Possible SC order parameters and their spin-state



BCS SC

High-T_c oxides

$CeCu_2Si_2$ UPd_2Al_3, $CeRIn_5$

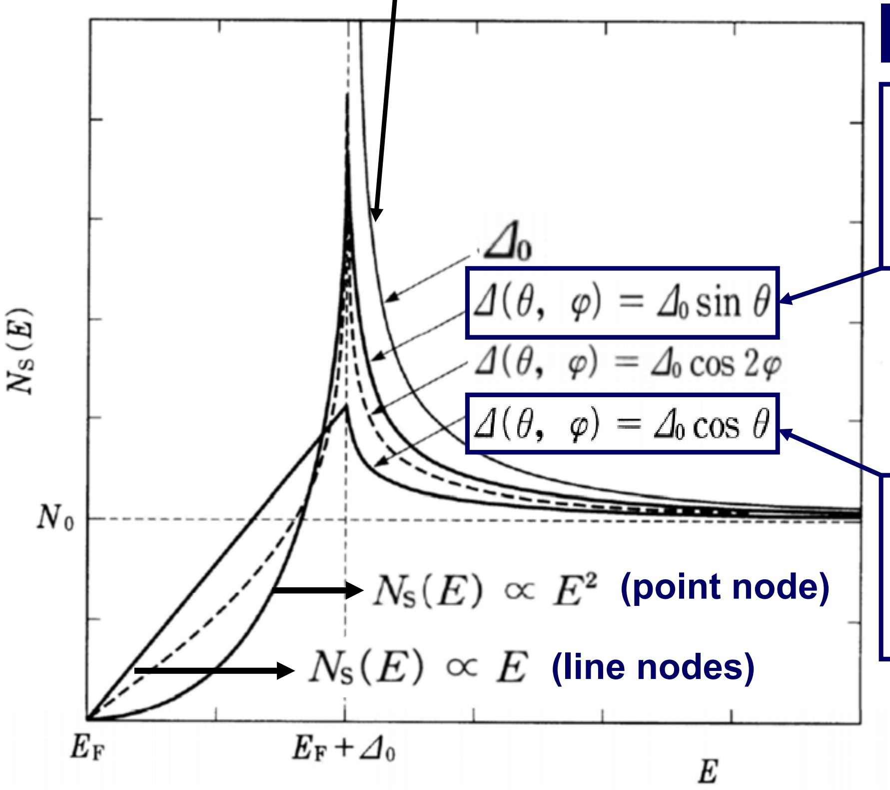
UPt_3

Sr_2RuO_4

Quasi-particle DOS in SC state

s-wave with isotropic gap

$N_s(E)=N_0E/(E^2 - \Delta^2)^{1/2}$



p-wave with point–node gap

$$N_S(E) = \frac{N_0E}{4\pi}\int_0^{2\pi}\int_0^{\pi}\frac{\sin\theta\, d\theta\, d\varphi}{\sqrt{E^2-\Delta_0^2\sin^2\theta}} = \frac{N_0E}{2\Delta_0}\ln\left|\frac{E+\Delta_0}{E-\Delta_0}\right|$$

p-wave with line–node gap

$$N_S(E) = \frac{N_0E}{4\pi}\int_0^{2\pi}\int_0^{\pi}\frac{\sin\theta\, d\theta\, d\varphi}{\sqrt{E^2-\Delta_0^2\cos^2\theta}} = \frac{\pi}{2}\frac{N_0E}{\Delta_0} \qquad (E < \Delta_0)$$

Spin susceptibility

Spin polarization in superconducting phase

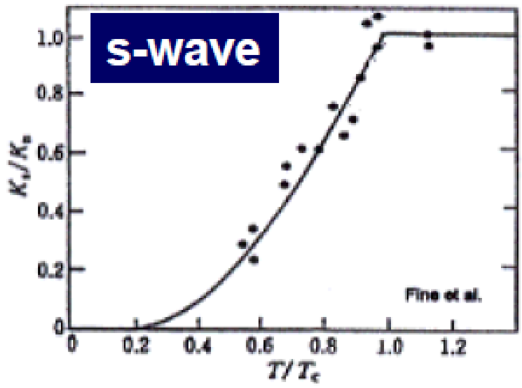
Spin singlet pairing:

- breaking up of Cooper pairs
- decrease of spin susceptibility
- vanishing susceptibility at T=0

$$\chi_s = 2\mu_B^2 N_0 Y(T),$$

where $Y(T)$ is the *Yosida function* defined by[38]

$$Y(T) = -\frac{2}{N_0}\int_0^{\infty} N_{BCS}(\varepsilon)\frac{df(\varepsilon)}{d\varepsilon}\,d\varepsilon,$$

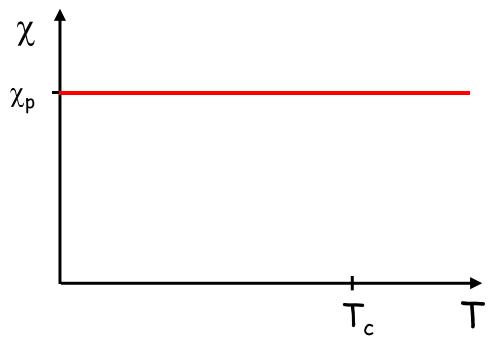


^{27}Al Knight shift

Spin triplet pairing:

- polarization without pair breaking
- no reduction of spin susceptibility for equal-spin pairing

$$\chi = \text{const.}\ \text{ for }\ \vec{d}(\vec{k})\cdot\vec{H} = 0$$



Spin susceptibility

Spin polarization in superconducting phase

Spin triplet pairing:

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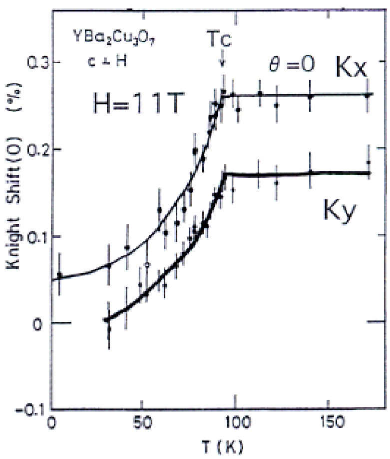
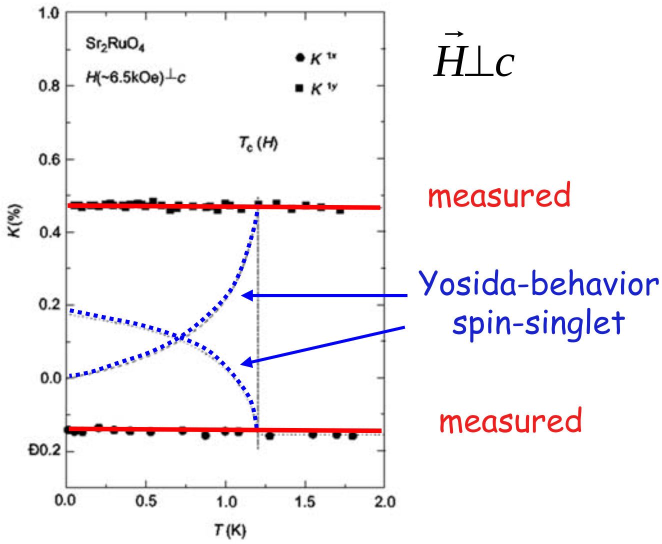
$\chi = \text{const.}$ for $\vec{d}(\vec{k}) \cdot \vec{H} = 0$

^{17}O-Knight shift (High-T_c oxides)



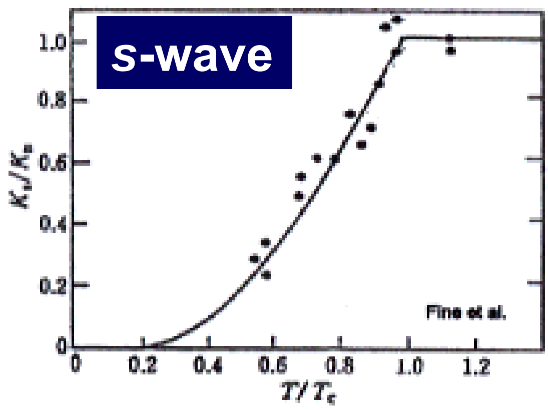
^{17}O-Knight shift In Sr_2RuO_4



Ishida et al., Nature 396, 242 (1998)

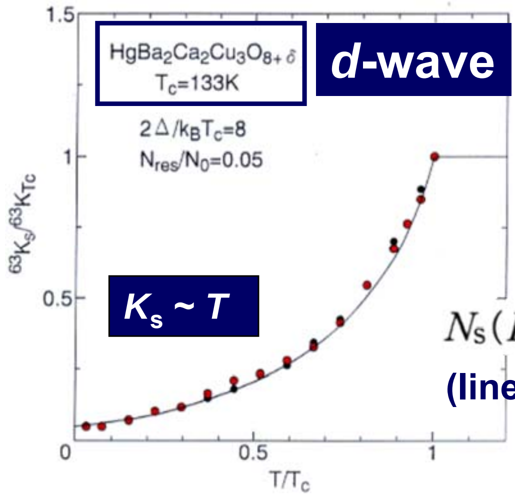
inplane equal-spin pairing $\vec{d} \parallel \hat{z}$

Summary1 : Knight shift



^{27}Al Knight shift

High-T_c SC : ^{63}Cu-NMR

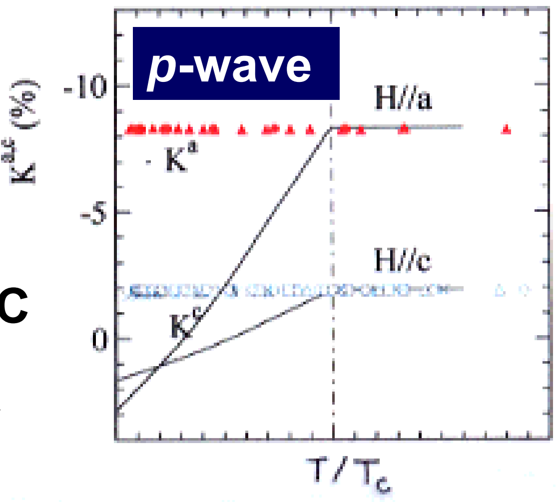


$N_s(E) \propto E$

(line nodes)

Heavy-electrons SC

UPt_3 : ^{195}Pt-NMR

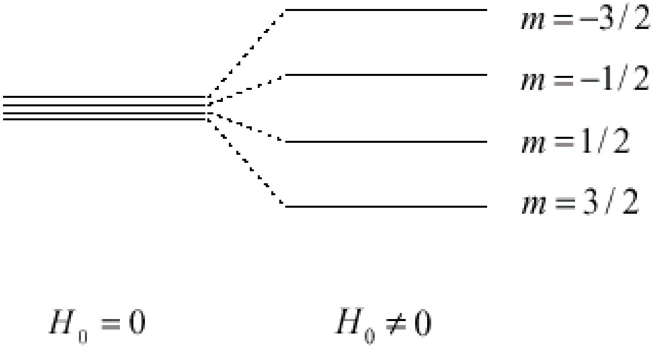


Nuclear Magnetism

$$\vec{\mu} = g_N \mu_N \vec{I} = \gamma\hbar\vec{I}$$

$$\mathcal{H}_0 = -\vec{\mu}\cdot\vec{H}_0 = -\gamma\hbar\vec{I}\cdot\vec{H}_0$$

$$E_m = -\gamma\hbar H_0 m$$

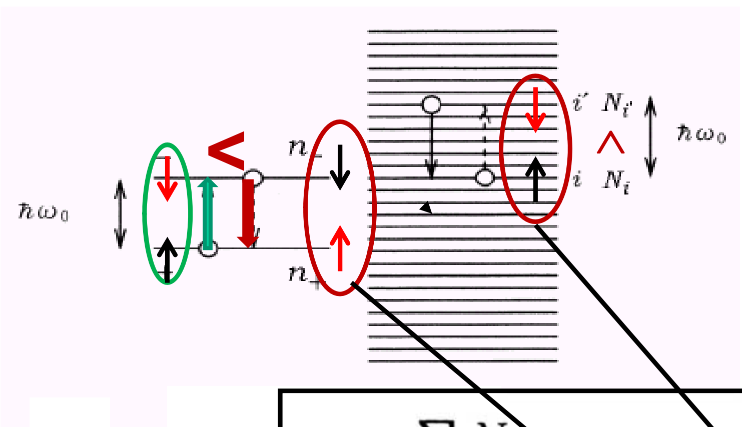


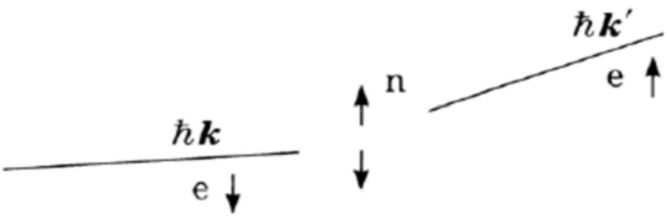
$$M(T,H) = \frac{N_0\gamma\hbar \sum_{m=-I}^{I} m \exp\left(\frac{\gamma\hbar H_0 m}{k_B T}\right)}{\sum_{m=-I}^{I} \exp\left(\frac{\gamma\hbar H_0 m}{k_B T}\right)} = N_0\gamma\hbar I B_I(Ix)$$

$$B_I(y) = \frac{2I+1}{2I}\coth\left(\frac{2I+1}{2I}y\right) - \frac{1}{2I}\coth\left(\frac{y}{2I}\right)$$

$$\chi_0(T) = \frac{M}{H} = \frac{N_0\gamma^2\hbar^2}{3k_BT} I(I+1)$$

Nuclear-spin relaxation ($1/T_1$) process





$$|\psi_i\rangle = u_k(\boldsymbol{r})\, e^{i\boldsymbol{k}\cdot\boldsymbol{r}}\,|+,\ -\rangle = |\boldsymbol{k},\ +,\ -\rangle$$
$$|\psi_f\rangle = u_{k'}(\boldsymbol{r})\, e^{i\boldsymbol{k}'\cdot\boldsymbol{r}}\,|-,\ +\rangle = |\boldsymbol{k}',\ -,\ +\rangle$$

$$\frac{n_-}{n_+} = 1 \;\longrightarrow\; \frac{n_-^0}{n_+^0} = \frac{\sum_{i'} N_{i'}}{\sum_i N_i} = e^{-\hbar\omega_0/k_BT}$$

T_1

Thermal equilibrium state

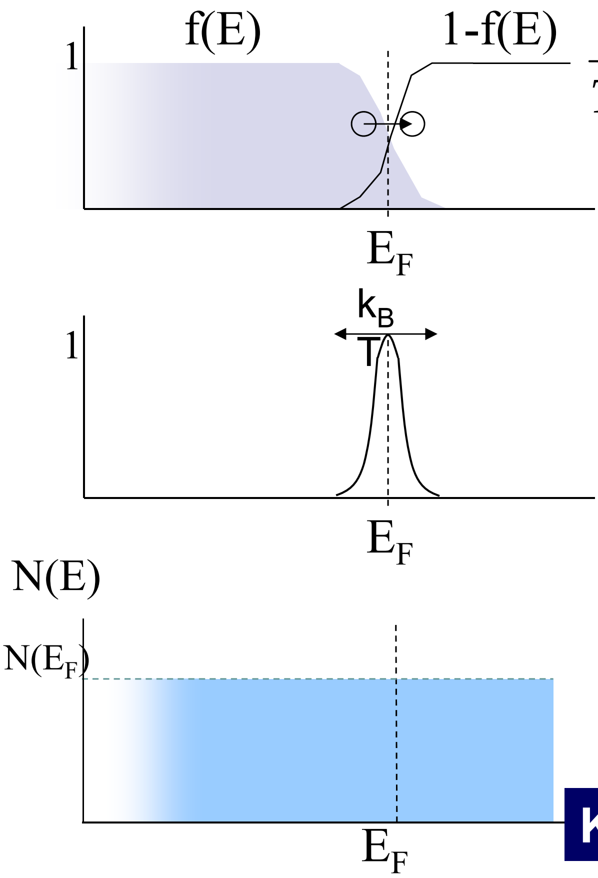
$$\mathcal{H}_{\mathrm{hf}} = A\boldsymbol{I}\cdot\boldsymbol{S}$$

A **: Fermi-contact hyperfine interaction (s-electrons)**

$$\mathcal{H}_{\mathrm{F}} = \frac{8\pi}{3}\gamma_n\gamma_e\hbar^2\delta(\boldsymbol{r})\left\{I_zS_z + \frac{1}{2}(I_+S_- + I_-S_+)\right\}$$

NMR – 1 / T_1 –

T_1 in normal state of metals



$$\frac{1}{T_1} = \frac{\pi}{\hbar} A^2 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} N(E)N(E') f(E)(1-f(E'))dEdE'$$

$$= \frac{\pi}{h} A^2 N^2(E_F) k_B T$$

Pauli paramagnetism ⇨ $\chi_S = 2\mu_B^2 N(E_F)$

Knight Shift ⇨ $K_S = A\chi_S \propto N(E)$

$$\frac{1}{T_1} \propto K_s^2 k_B T \Rightarrow \frac{1}{T_1 T} \propto K^2$$

Korringa Relation: $T_1 T K_s^2 = \frac{\hbar}{4\pi k_B}\left(\frac{\gamma_e}{\gamma_n}\right)^2$

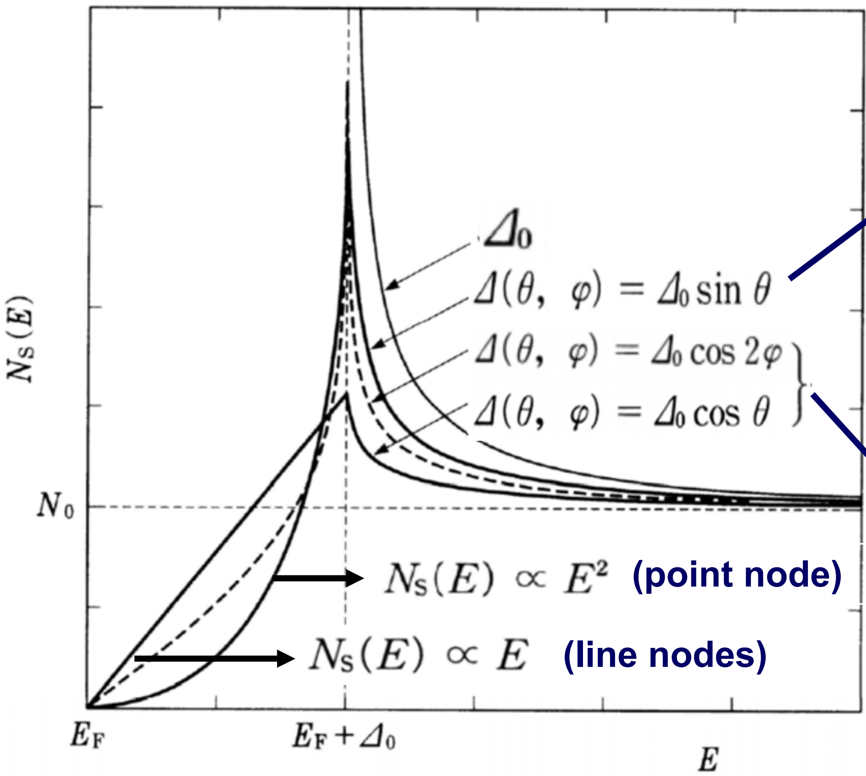
1/T_1 in superconducting state

$$\frac{1}{T_1} = \frac{\pi}{\hbar}\frac{A^2}{N^2}\int_0^{\infty}\int_0^{\infty}\left\{\left(1+\frac{\Delta^2}{EE'}\right)N_s(E)N_s(E')\right\} \times f(E)(1-f(E'))\delta(E-E')\, dE\, dE'$$

s-wave with isotropic gap

$$\left(1+\frac{\Delta^2}{E^2}\right)N_s^2(E) = N_s^2(E) + M_s^2(E)$$

$$M_s(E) = \frac{\Delta}{\sqrt{E^2-\Delta^2}}$$



p-wave with point–node gap

$$N_S(E) \propto E^2$$

SC with line–node gap

$$N_S(E) \propto E$$

BCS *s*-wave superconductors:

$$\left(1+\frac{\Delta^2}{E^2}\right) N_s^2(E) = N_s^2(E) + M_s^2(E)$$

$$M_s(E) = \frac{\Delta}{\sqrt{E^2-\Delta^2}}$$

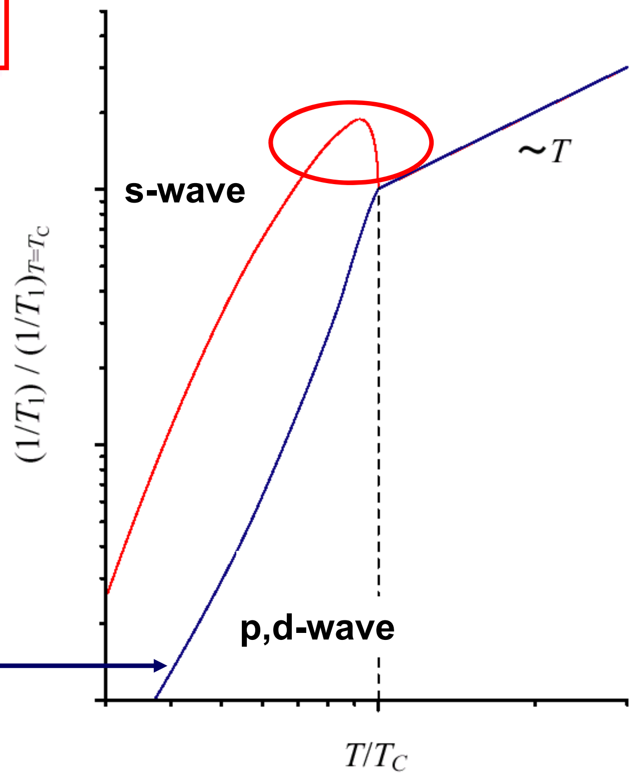
Unconventional SC in most correlated-electrons systems

$$E \to 0$$

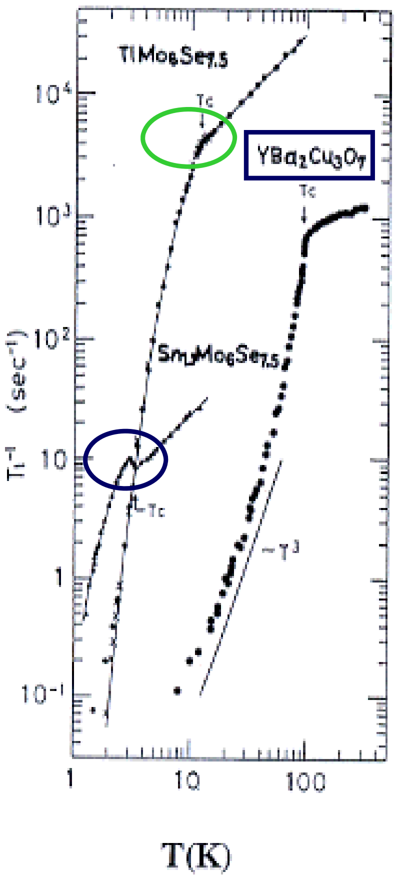
$$N_S(E) \propto E \quad [\int M_s(E,\theta)\, d\theta = 0]$$

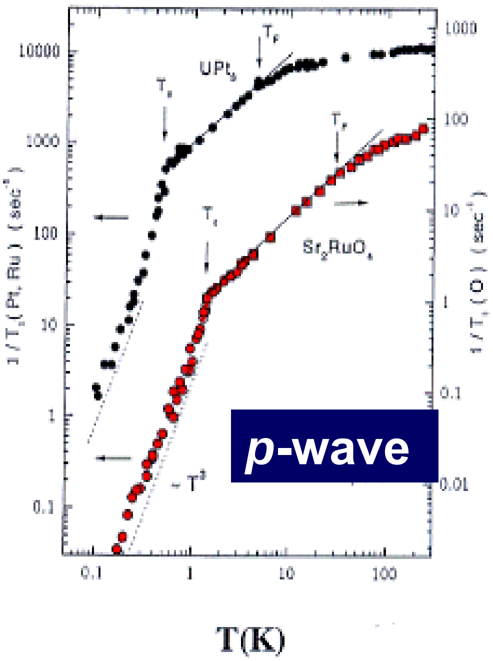
(line nodes)

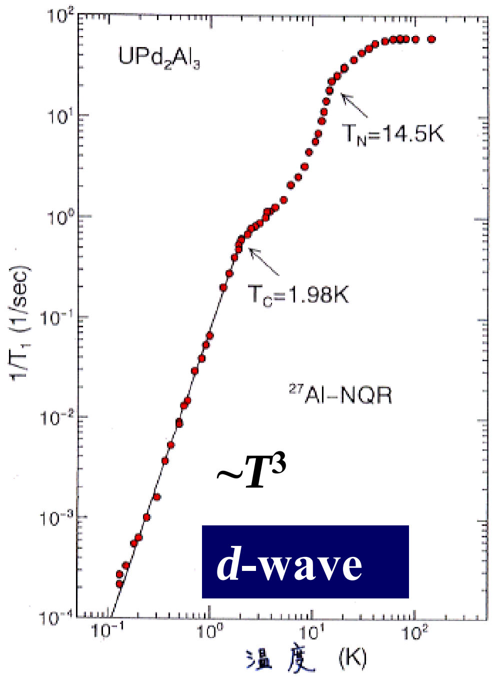
$$\frac{1}{T_1} \propto \int_0^\infty E^2 e^{-E/k_BT} dE = T^3 \int_0^\infty x^2 e^{-x} dx$$



Line-nodes gap SC in correlated electrons SC







***s*-wave**

Strong-coupling effect

***d*-wave**

***p*-wave**

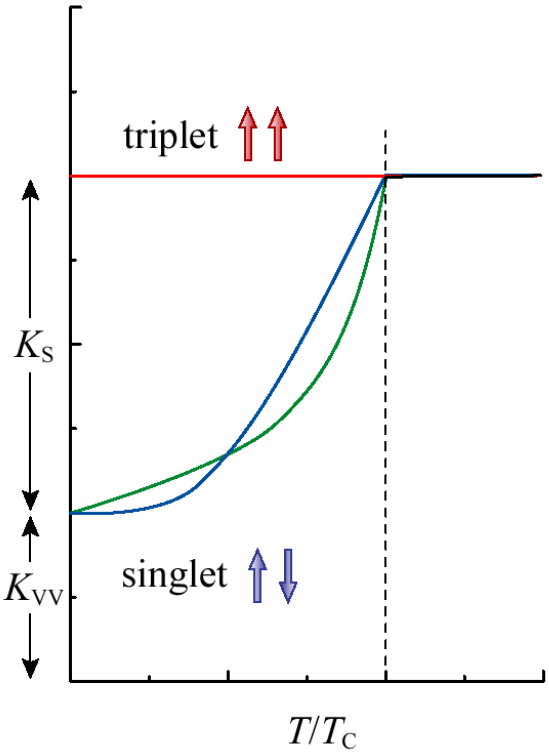
***d*-wave**

$1/T_1 \propto T^3$!!

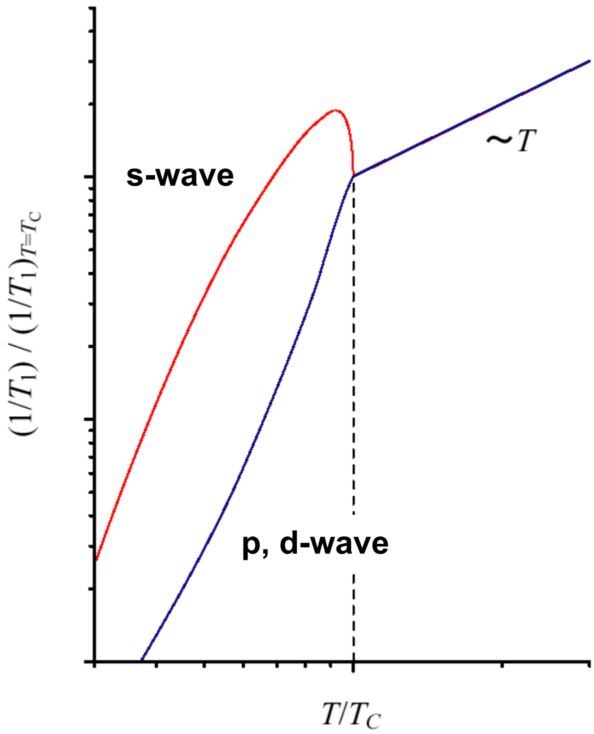
AFM-SC UPd_2Al_3

Summary: NMR probe for SC characteristics

Knight shift



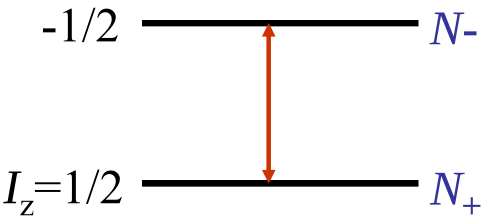
$1/T_1$



NMRからみた「スピンのゆらぎ」と「d波超伝導」

NMR Probe for「Spin Fluctuations」and「d-wave superconductivity」

The formula of $1/T_1$



Time-dependent perturbation, $H' = -\gamma_N \hbar \vec{I} \cdot \vec{H}_{loc}(t)$ allows us to calculate

Relaxation rate $1/T_1$ due to fluctuations of local magnetic field $\boldsymbol{H}_{loc}$

$$-\frac{\gamma_N \hbar}{2}\left(I^+ H^-_{loc}(t) + I^- H^+_{loc}(t)\right)$$

$$I^\pm = I_x \pm i I_y, \quad H^\pm_{loc} = H^x_{loc} \pm i H^y_{loc}$$

$$\frac{1}{T_1} = \frac{2\pi}{\hbar}\left(\frac{\gamma_N \hbar}{2}\right)^2 \sum_{n,m} \exp(-\beta\varepsilon_n)\left(\left|\langle m|H^+_{loc}|n\rangle\right|^2 \delta(\varepsilon_m - \varepsilon_n + \hbar\omega_N) + \left|\langle m|H^-_{loc}|n\rangle\right|^2 \delta(\varepsilon_m - \varepsilon_n - \hbar\omega_N)\right)$$

$$= \frac{\gamma_N^2}{4}\sum_{n,m}\exp(-\beta\varepsilon_n)\int_{-\infty}^{\infty}\left[\left|\langle m|H^+_{loc}|n\rangle\right|^2 \exp\left(\frac{i(\varepsilon_m - \varepsilon_n)t}{\hbar}\right) + \left|\langle m|H^-_{loc}|n\rangle\right|^2 \exp\left(\frac{i(\varepsilon_n - \varepsilon_m)t}{\hbar}\right)\right]\exp(i\omega_N t)dt$$

$$= \frac{\gamma_N^2}{4}\sum_{n,m}\exp(-\beta\varepsilon_n)\int_{-\infty}^{\infty}\left(\langle n|H^-_{loc}|m\rangle\langle m|e^{\frac{iHt}{\hbar}} H^+_{loc} e^{-\frac{iHt}{\hbar}}|n\rangle + \langle n|e^{\frac{iHt}{\hbar}} H^+_{loc} e^{-\frac{iHt}{\hbar}}|m\rangle\langle m|H^-_{loc}|n\rangle\right)\exp(i\omega_N t)dt$$

$$= \frac{\gamma_N^2}{2}\int_{-\infty}^{\infty}\left\langle\left\{H^-_{loc}, H^+_{loc}(t)\right\}\right\rangle \exp(i\omega_N t)dt \qquad \left(\{A, B\} = \frac{1}{2}(AB + BA) \quad H^+_{loc}(t) = e^{\frac{iHt}{\hbar}} H^+_{loc} e^{-\frac{iHt}{\hbar}}\right)$$

Transition probability ↔ Correlation function
(General principle , Neutron scattering)

In general, for magnetic fluctuations of correlated electrons

$$\frac{1}{T_1} = \frac{\gamma_n{}^2}{2}\sum_q A_q A_{-q}\int_{-\infty}^{\infty} dt \cos\omega_0 t\, \langle[S^+_q(t),\ S^-_{-q}(0)]\rangle$$

Using the fluctuations-dissipation theorem :

$$\frac{2\hbar\chi''_\perp(\boldsymbol{q},\ \omega_0)}{(\gamma_e\hbar)^2(1 - e^{-\hbar\omega_0/k_B T})} = \frac{1}{2}\int_{-\infty}^{\infty} dt \cos\omega_0 t\, \langle[S^+_q(t),\ S^-_{-q}(0)]\rangle$$

$$\hbar\omega_0 \ll k_B T$$

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

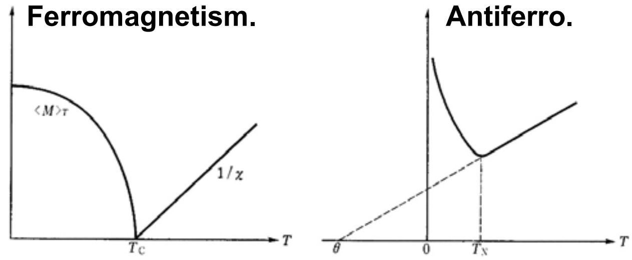
Itinerant Magnetism & Spin-fluctuations

Metal — **Insulator**

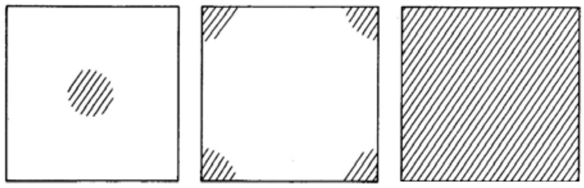
Metal-Insulator transition

Stoner model for itinerant electrons

Increase of electron correlation → Heisenberg model for itinerant electrons



Localized magnetism



Weak itinerant Ferro. | Weak itinerant Antiferro. | Localized electrons mag.

$$\mathscr{H}=\sum_{i\,j\,\sigma} t_{ij}\, a^{+}_{i\sigma} a_{j\sigma}+U\sum_{i} n_{i\uparrow} n_{i\downarrow}$$

$$S_{iz}=\frac{1}{2}\left(n_{i\uparrow}-n_{i\downarrow}\right)$$

This relationship replaces the abvoe second term in Hamiltonian to the follows;

$$-2I\sum_{i} S_{iz}^{\,2}+\text{const}$$

taking $\langle S_{iz}\rangle$=const.

$$\chi=\frac{\chi_0}{(1-\alpha_0)}$$

$\alpha_0 = I\chi_0$

Wave-number dependent susceptibility follows a Currie Weiss law in a different origin from the localized model

Self-consistent renormalization (SCR) theory:

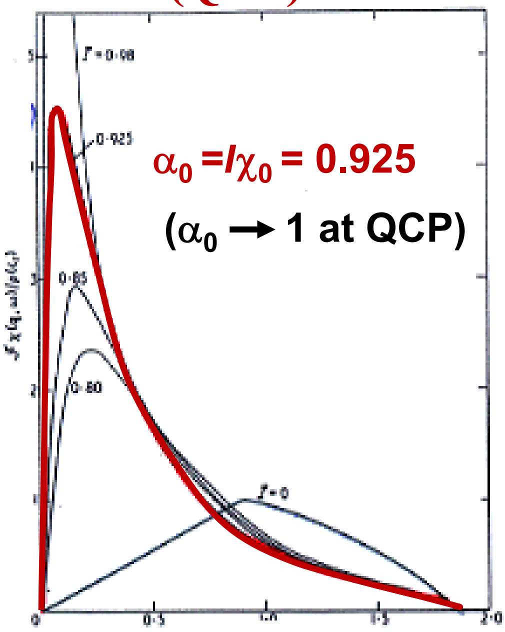
$$\langle S_{iz}(t)S_{iz}(t')\rangle \sim \langle S_{iz}(t)\rangle\langle S_{iz}(t')\rangle$$

$$\chi(q,\omega)=\frac{\chi_0(q,\omega)}{1-I\chi_0(q,\omega)+\lambda(q,\omega)}$$

Dynamical susceptibility and NMR-$1/T_1$

Near ferromagnetic critical point (QCP)

$\chi''(q,\omega)$



ω

E_F

$$\chi''(q,\omega)/\omega \propto \chi_0/(\alpha_0-1+Aq^2)$$

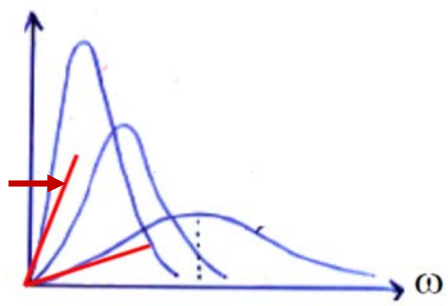
$$1/T_1T \sim \chi''(Q,\omega_0)/\omega_0$$

$$1/T_1T \propto \Sigma_q\, \chi''(q,\omega_0)/\omega_0$$

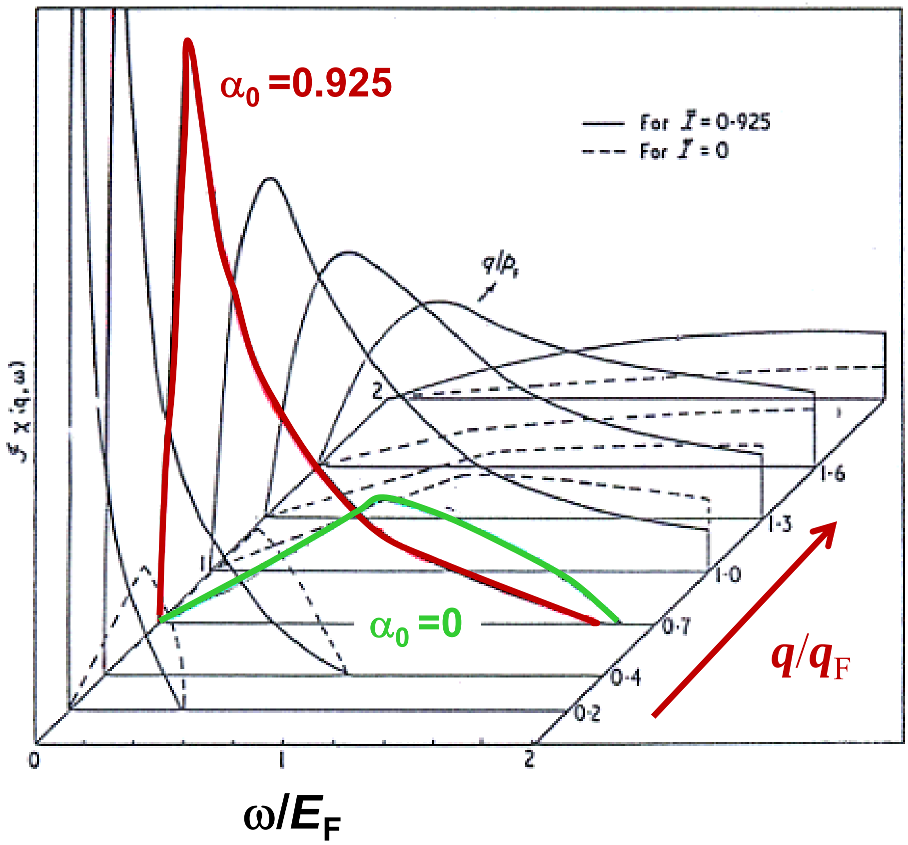
Neutron scattering

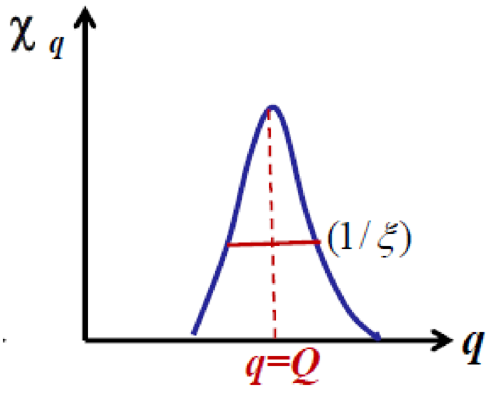
$$\frac{d^2\sigma}{d\Omega\, d\omega} \propto \frac{\chi''(q,\omega)}{1-\exp(-\omega/T)}$$

AFM-*QCP* near *q=Q*



Near ferromagnetic critical point





$Q = (\pi/a, \pi/a)$

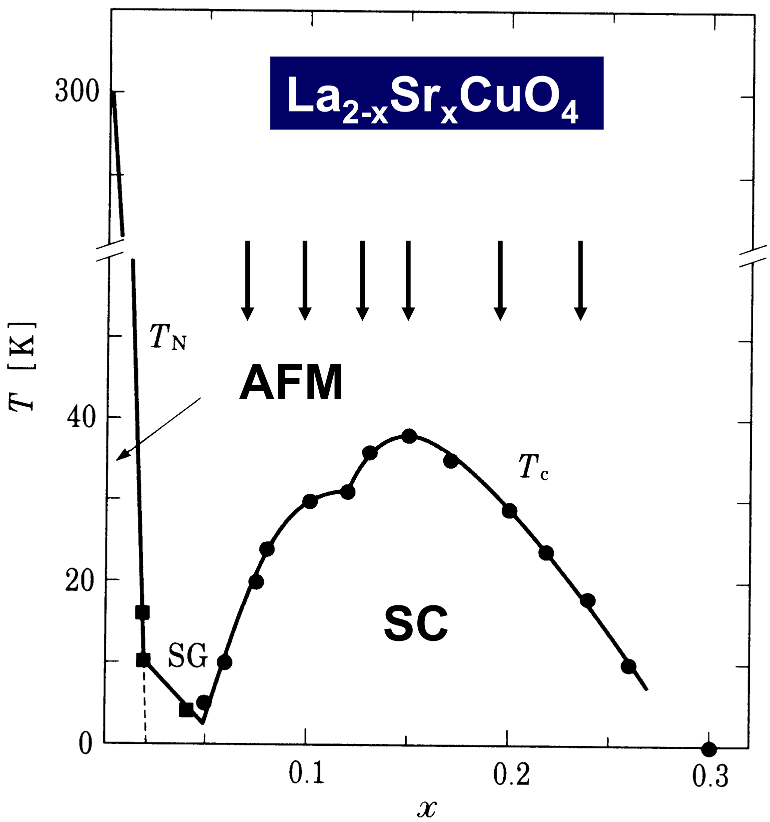
Near AFM critical point

$$\alpha_0 = I\chi_q \sim 1$$

$$1/T_1T \sim \chi''(Q, \omega_0)/\omega_0$$

$$\sim \chi_Q(T)$$

Spin Fluctuations of High-Temperature Superconductivity



Phase diagram of AFM and SC

1/T_1T of ^{63}Cu-NMR in $La_{2-x}Sr_xCuO_4$ and $YBa_2Cu_3O_7$

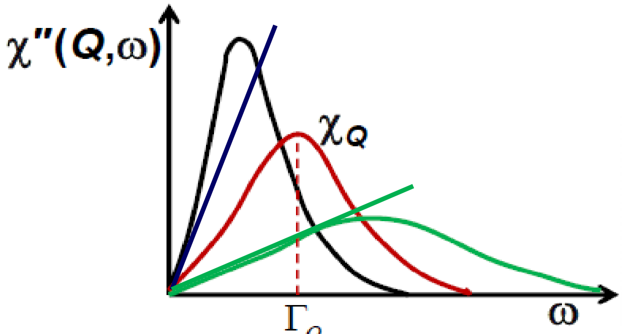
$1/T_1T \propto \chi''(Q,\omega_0)/\omega_0$

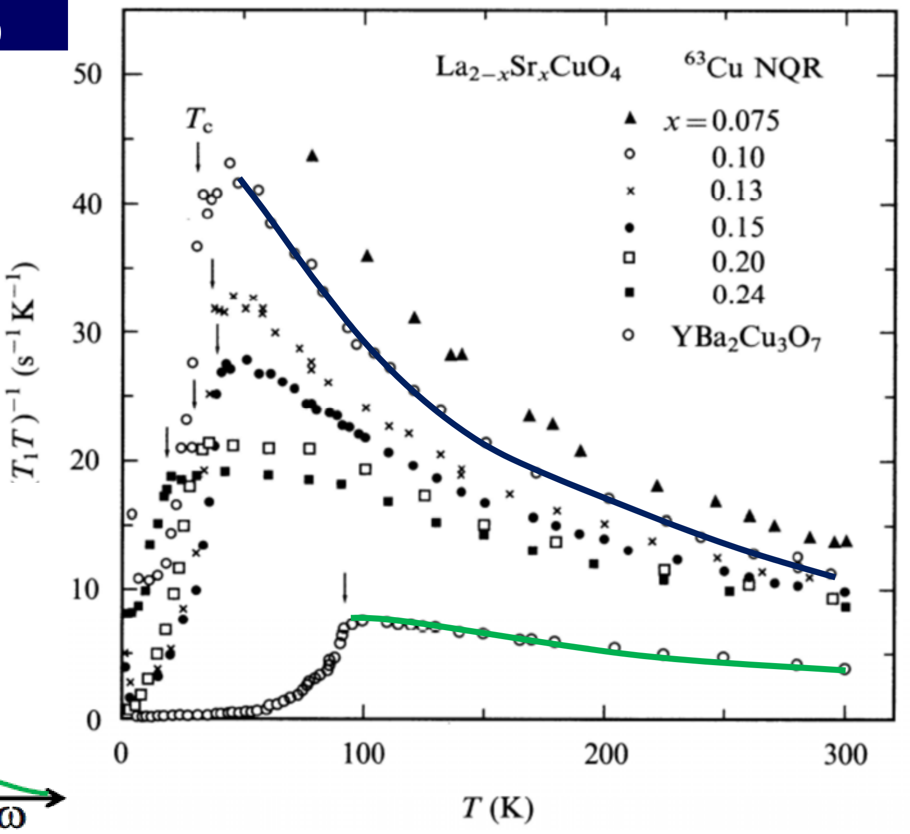
ω_0 : NQR frequency

Q : $(\pi/a \pm \delta, \pi/a \pm \delta)$

$\chi'(Q,\omega=0) \sim \int[\chi''(Q,\omega)/\omega]d\omega$

$\rightarrow \infty$ (AFM order)





$1/T_1T$ (x, T) probes AFM spin fluctuations

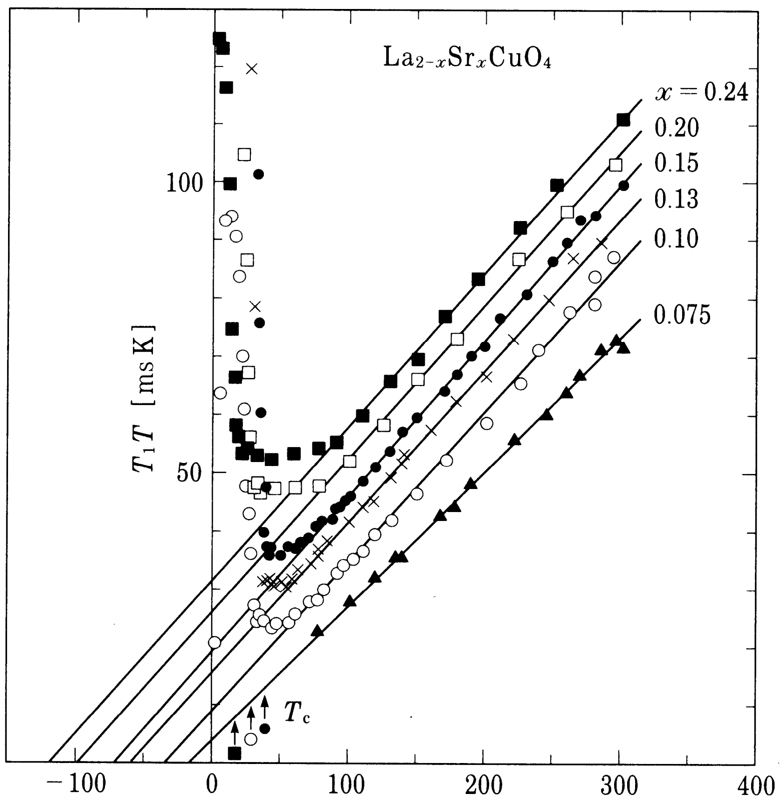
Antiferromagnetic Spin Fluctuations in LSCO

2D-AFM spin fluctuations :

$$1/T_1T \propto \chi_Q(T) \propto C/(T+\theta)$$

↓

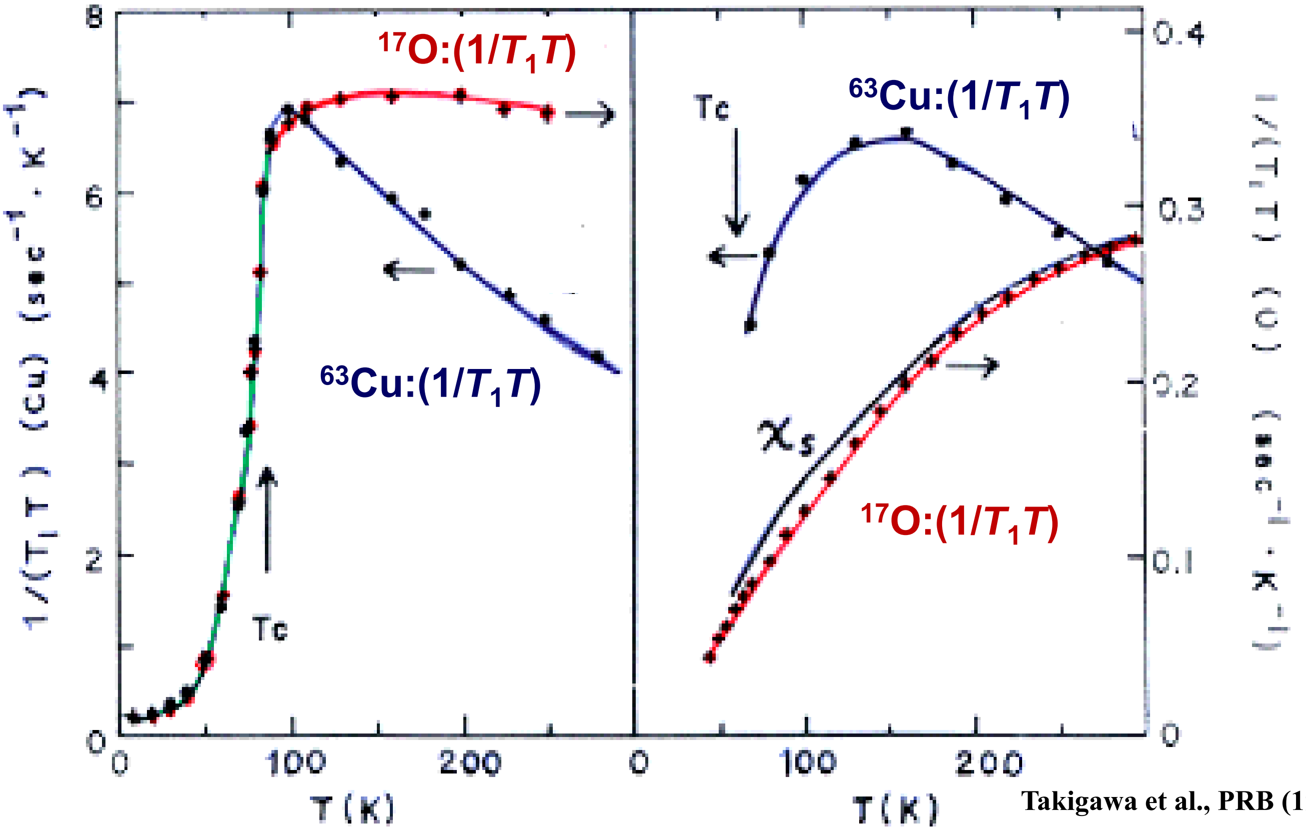
$$T_1T \propto 1/\chi_Q(T) \propto (T+\theta)$$



θ → 0 (QCP) at $x \sim 0.05$

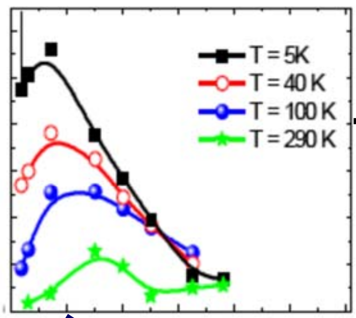
Characteristics of Antiferromagnetic Spin Fluctuations in HTSC

$1/T_1T$: $YBa_2Cu_3O_7$ (T_c=93 K) $YBa_2Cu_3O_{6.63}$ (T_c=60 K)



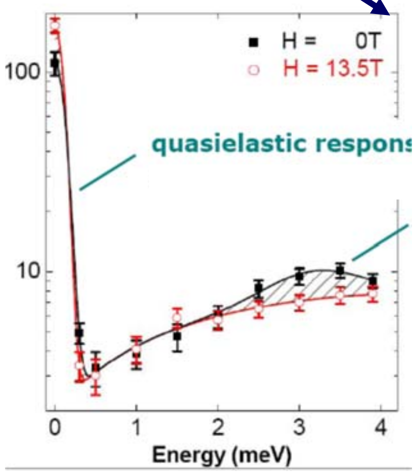
Takigawa et al., PRB (1991)

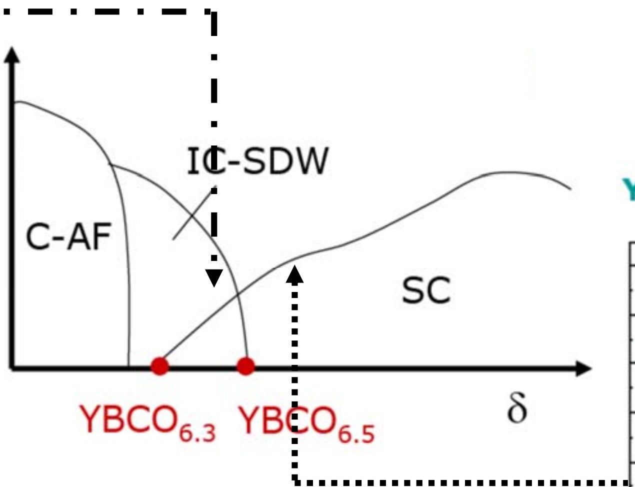
Spin Fluctuations in $YBa_2Cu_3O_x$ probed by neutron



$YBa_2Cu_3O_{6.45}$ (T_c = 35 K)

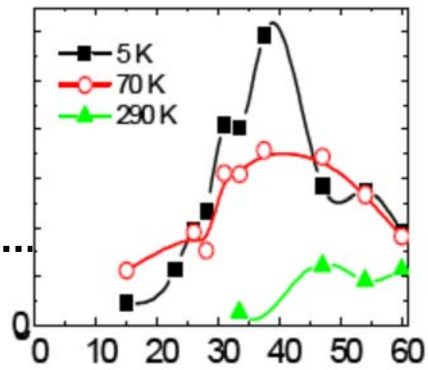
- quasielastic intensity
- gapless excitations





Keimer's group (MPI, Stuttgart)

$YBa_2Cu_3O_{6.6}$ (T_c = 61 K)



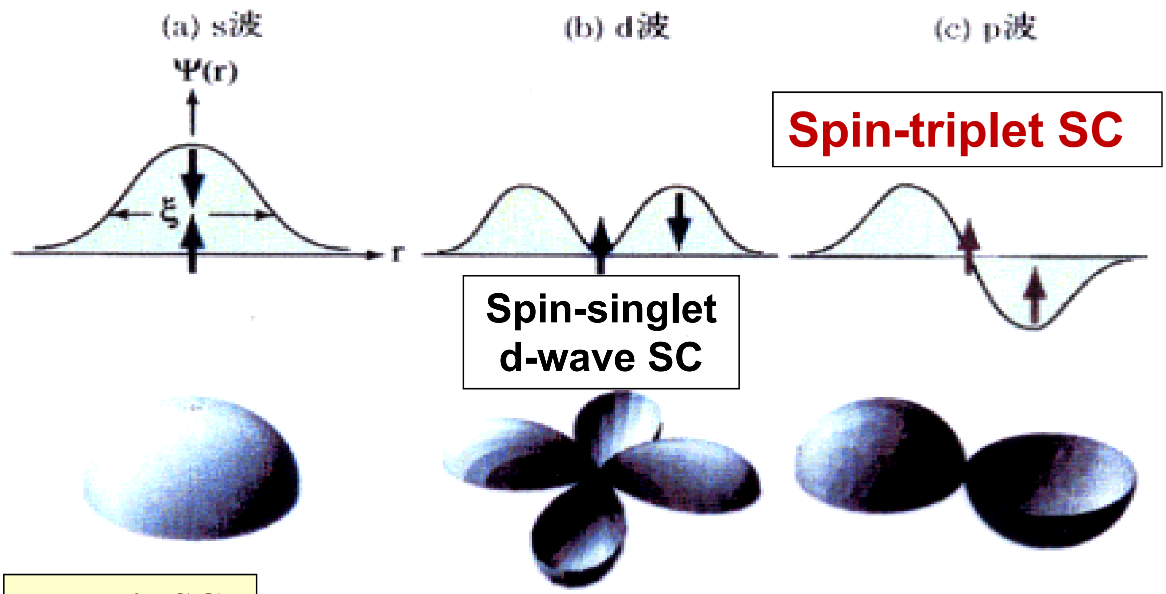
No quasielastic intensity

Large spin gap below T_c

スピンゆらぎによって媒介されるd波超伝導

Spin-fluctuations mediated d-wave superconductivity

Various types of SC pairing states



Metallic SC

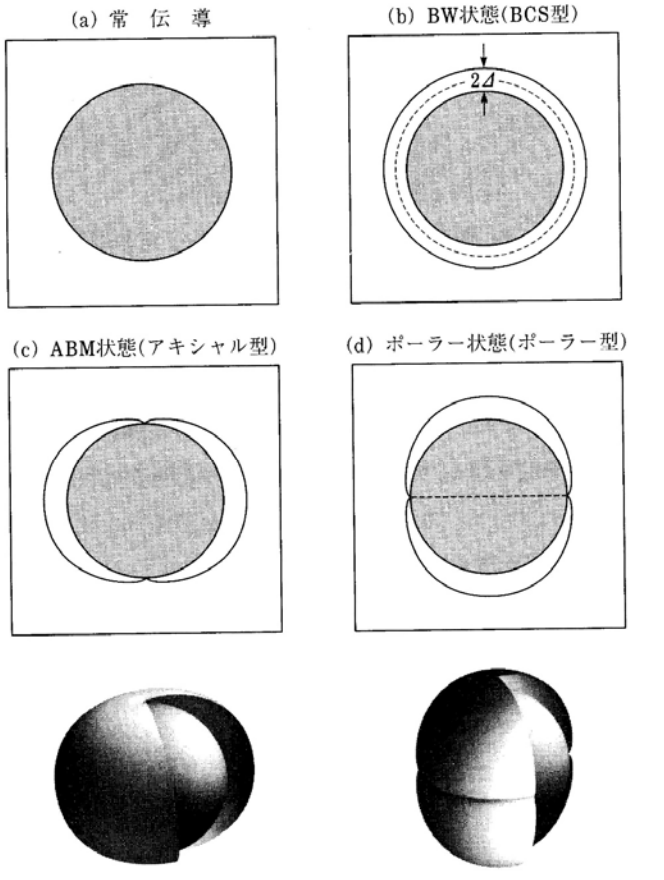
Copper oxides high-T_c SC

Heavy- electrons SC

UPt_3, Sr_2RuO_4

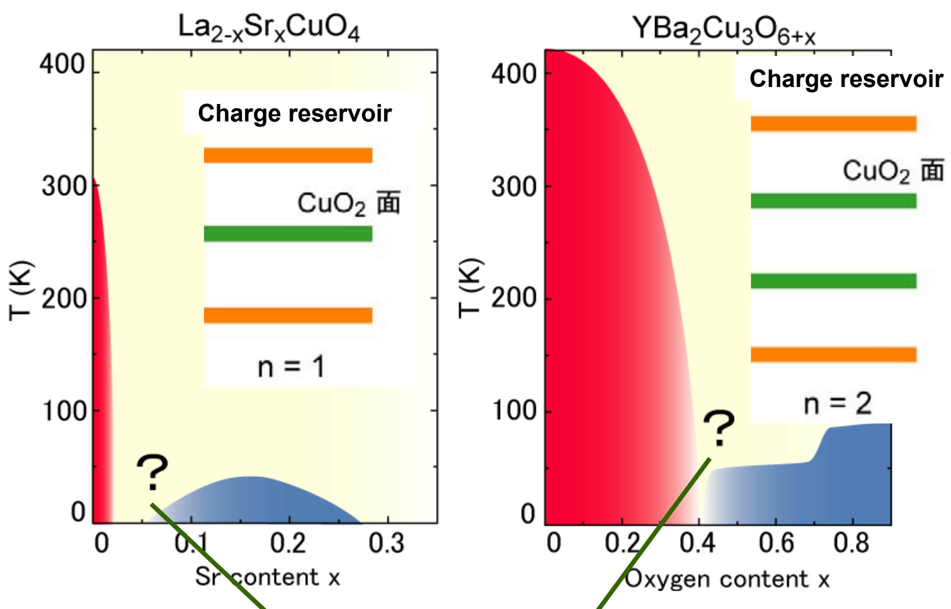
UNi_2Al_3

Energy gap structure of unconventional SC



7-3図　BW，ABM，ポーラー状態に対するエネルギーギャップの様子

Phase Diagram of high-T_c copper oxides



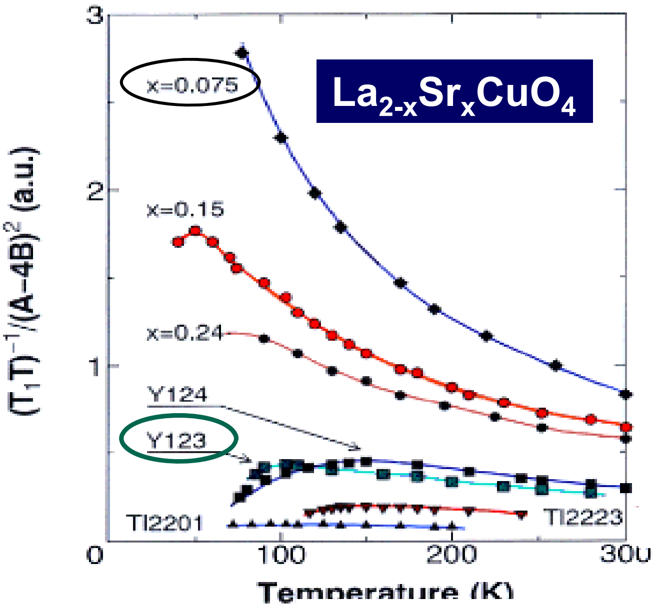
Anomalous phases, Pseudo gap phase, AFM phase inside the vortex core･･･

i) Intrinsic phase in a underdoped region ?

ii) Effect of a number of CuO_2 planes ?

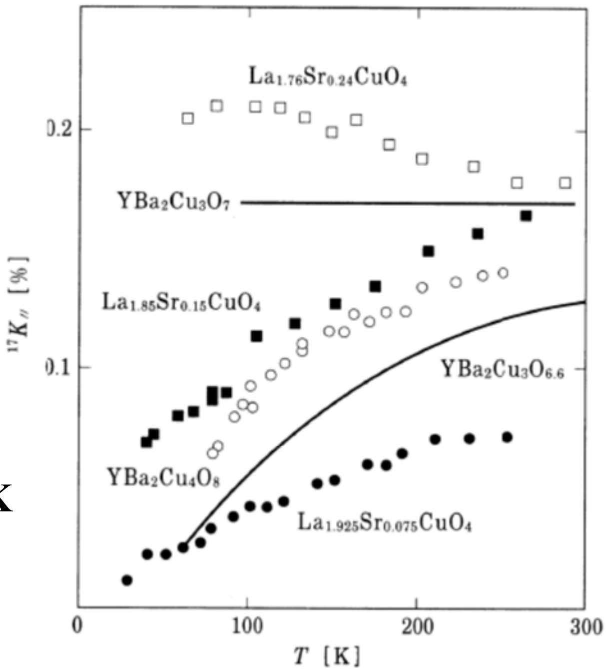
Summary: Carrier-density Dependence of Spin Fluctuations

$(T_1T)^{-1}$

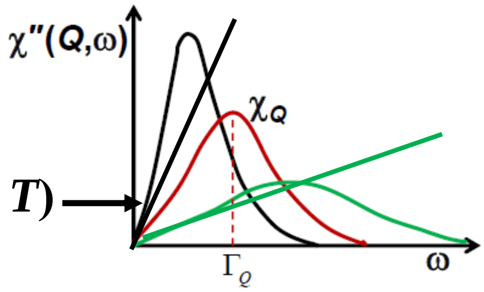


T_c=130 K

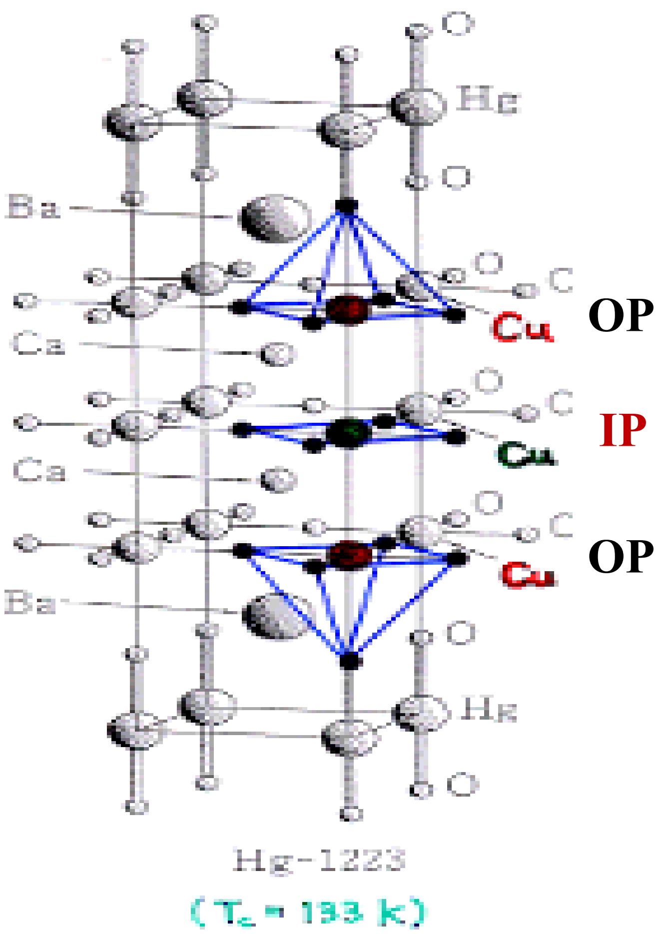
uniform spin $\chi(q=0)$



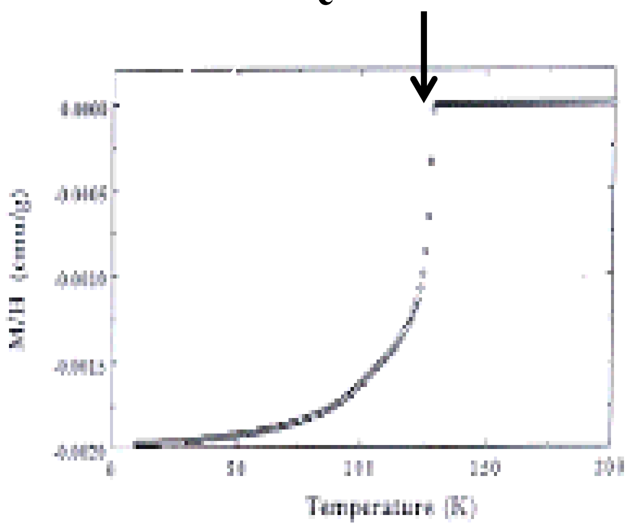
$1/T_1T$ (x, T)



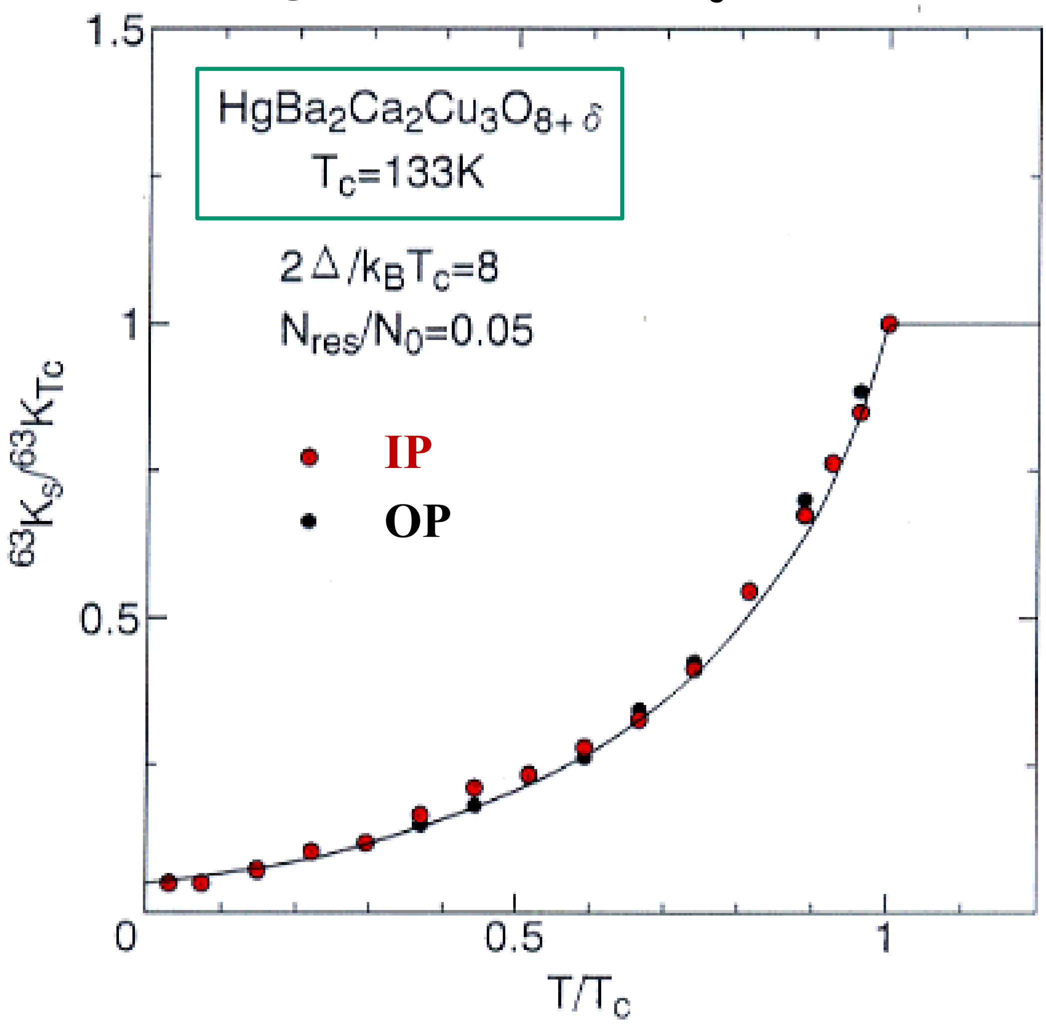
$HgBa_2Ca_2Cu_3O_{8+\delta}$



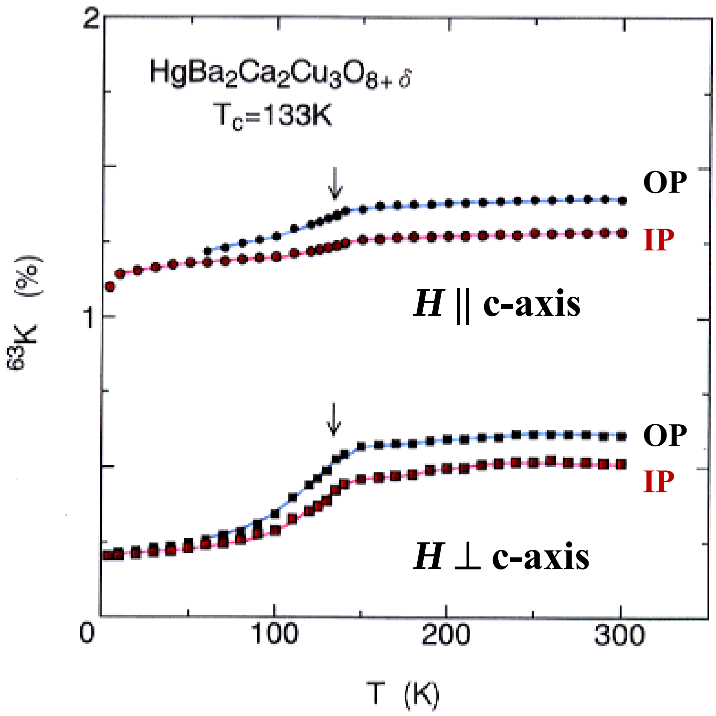
T_c = 133 K



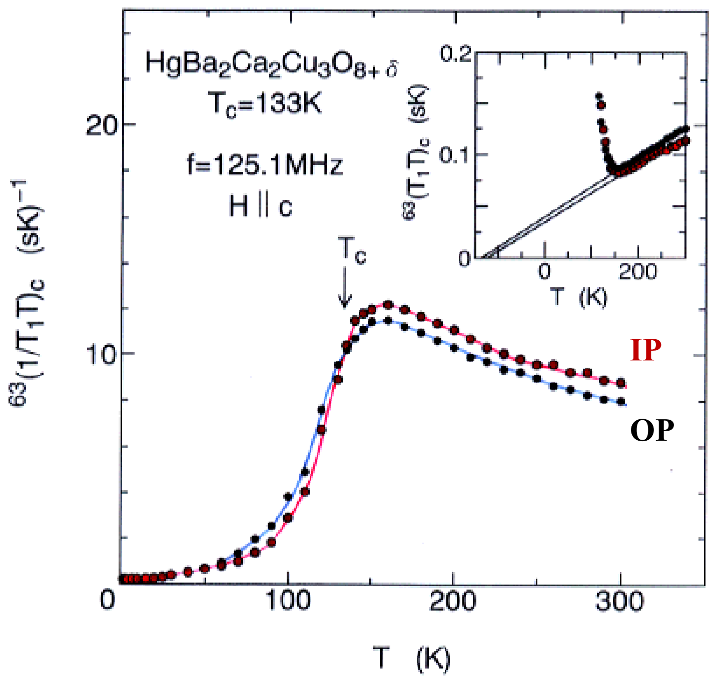
Knight Shift below T_c



Knight Shift

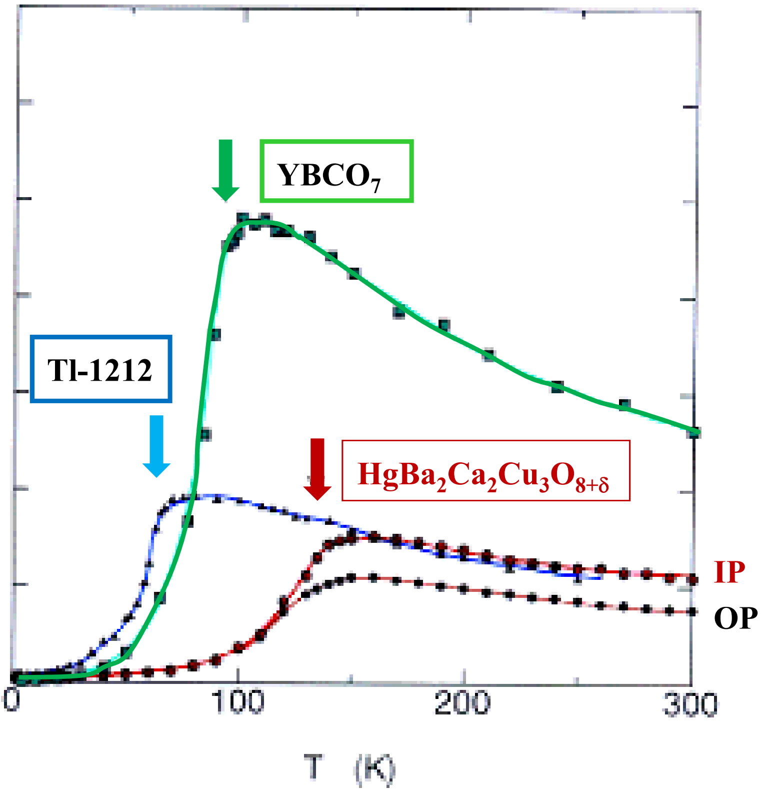


$1/T_1T$



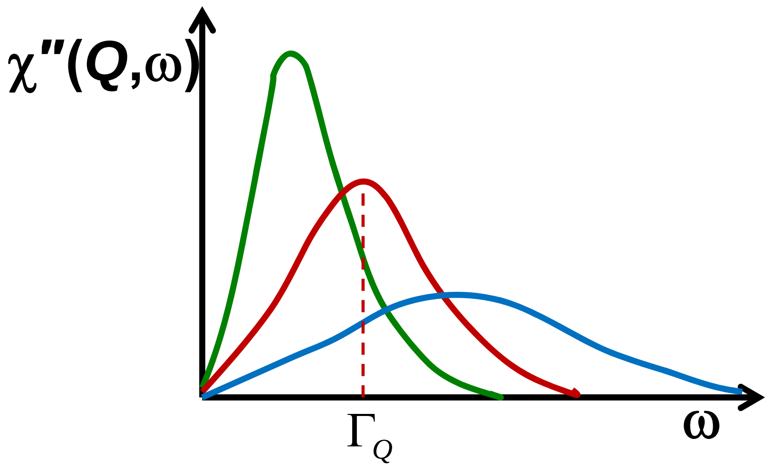
$$\boxed{\frac{1}{T_1T}} \propto \frac{\chi''(Q,\omega_{NMR})}{\omega_{NMR}} = \frac{\chi_Q}{\Gamma_Q}$$

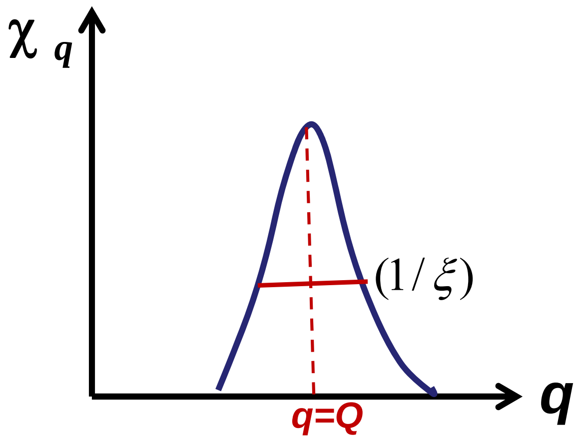
$$\frac{\chi''(q,\omega)}{\omega} = \frac{\chi_Q}{1+(q-Q)^2\xi^2}\frac{\Gamma_q}{\omega^2+\Gamma_q^{\ 2}}$$



When Γ_Q increases, T_c is enhanced.

The Spin-fluctuations theory: $T_c \propto \xi^2\Gamma_Q \propto \frac{T_1T}{T_{2G}^{\ 2}}$



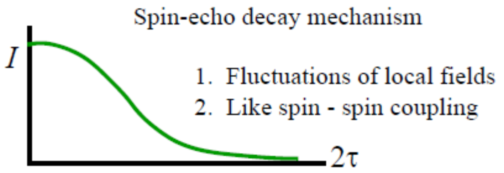


AFM spin fluctuations are described by

$$\frac{\chi''(q,\omega)}{\omega} = \frac{\chi_Q}{1+(q-Q)^2\xi^2}\frac{\Gamma_q}{\omega^2+\Gamma_q^{\ 2}} \qquad \Gamma_q = \Gamma_Q[1+(q-Q)^2\xi^2]$$

Temperature dependence of spin-echo decay rate $1/T_{2G}$

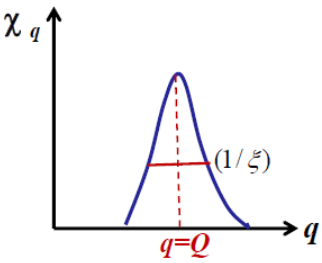
Magnetic Correlation Length: ξ

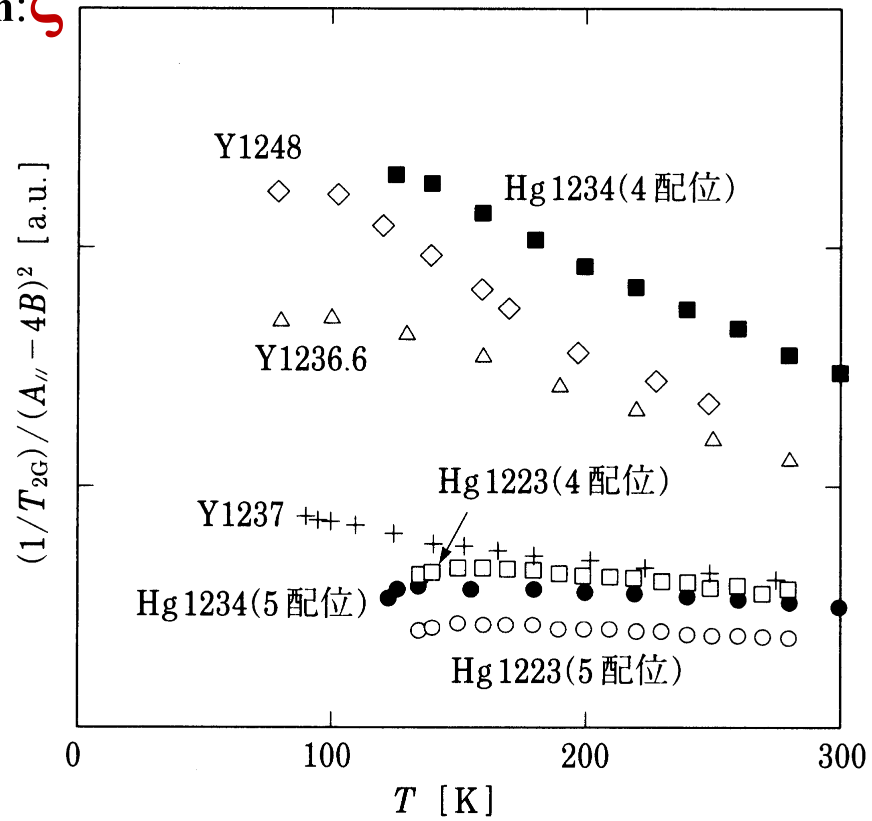


$$H_{\text{spin-spin}} = \sum_{j,k} \vec{I}_j \cdot \tilde{a}_{jk} \cdot \vec{I}_k = \sum_j \hbar\gamma_N \vec{I}_j \cdot \vec{H}_j^{\text{loc}}$$

$$\vec{H}_j^{\text{loc}} = \frac{1}{\hbar\gamma_N} \sum_k \tilde{a}_{jk} \cdot \vec{I}_k \sim A_{hf}^2 \xi$$

indirect nuclear spin-spin coupling via spin fluctuations





6－26 図 種々の系の CuO_2 面内の ^{63}Cu の $1/(A_{/\!/}-4B)^2T_{2G}$²

Spin Fluctuations mediated d-wave superconductivity

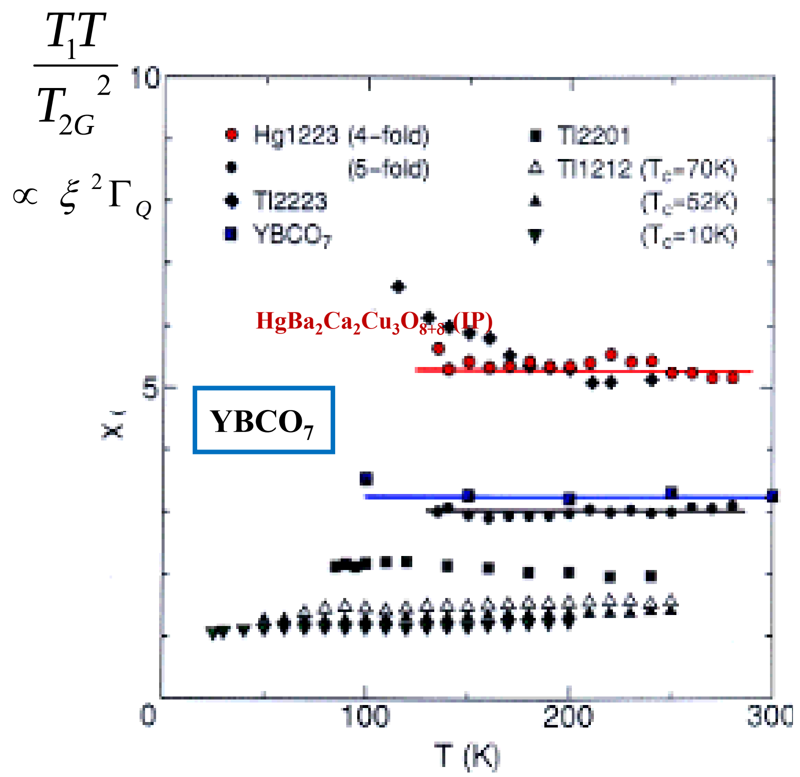
Spin-fluctuations parameters derived from T_1 and T_{2G}

$$\left(\frac{1}{T_{2G}}\right)^2 = \frac{0.69(\gamma_N\hbar)^4(A_c-4B)^4}{32\pi\hbar^2}\frac{\chi_Q^2}{\xi^2} \sim \frac{\chi_Q^2}{\xi^2} \qquad \sim\xi^2$$

$$\left(\frac{1}{T_1T}\right)_c = \frac{k_B(\gamma_N\hbar)^2(A_c-4B)^2}{2\hbar^2(2R-1)}\frac{\chi_Q}{\Gamma_Q\xi^2} \sim \frac{\chi_Q}{\Gamma_Q\xi^2} \qquad \sim 1/\Gamma_Q$$

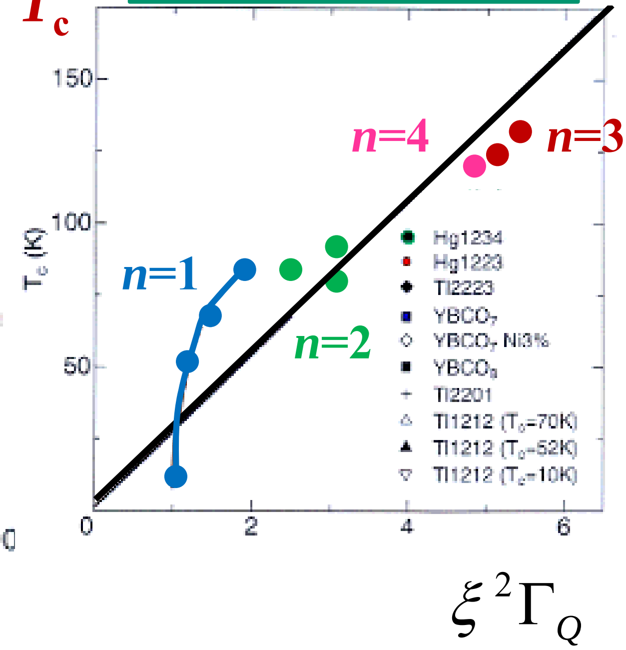
$$\frac{(T_1T)_c}{(T_{2G})^2} = \frac{0.69(\gamma_N\hbar)^2(A_c-4B)^2(2R-1)}{16\pi\hbar k_B}\chi_Q\hbar\Gamma_Q$$

Relationship between spin-fluctuation parameters and T_C



The Spin-fluctuations theory:

$$T_c \propto \xi^2\Gamma_Q \propto \frac{T_1T}{T_{2G}^2}$$



BCS theory predicts the many-body ground state for the superconducting state described by the following wave function as

$$\psi_{BCS} = \prod_k (u_k + v_k c_{k\uparrow}^{\dagger} c_{-k\downarrow}^{\dagger})|0\rangle \qquad (1)$$

The BCS Hamiltonian is given by

$$\mathcal{H} = \sum_{k,\sigma}\left(\frac{\hbar^2 k^2}{2m} - \mu\right) c_{k\sigma}^{\dagger} c_{k\sigma} - \sum_{k,k'} V_{kk'} c_{k\uparrow}^{\dagger} c_{-k\downarrow}^{\dagger} c_{-k'\downarrow} c_{k'\uparrow}$$

Using (1), by minimizing the expectation value of the above BCS Hamiltonian, the parameters u_k and v_k are expressed as follows;

$$u_k^2 = \frac{1}{2}\left(1 + \frac{\xi_k}{E_k}\right), \qquad v_k^2 = \frac{1}{2}\left(1 - \frac{\xi_k}{E_k}\right) \quad \text{with} \quad E_k = (\xi_k^2 + |\Delta_k|^2)^{1/2}$$

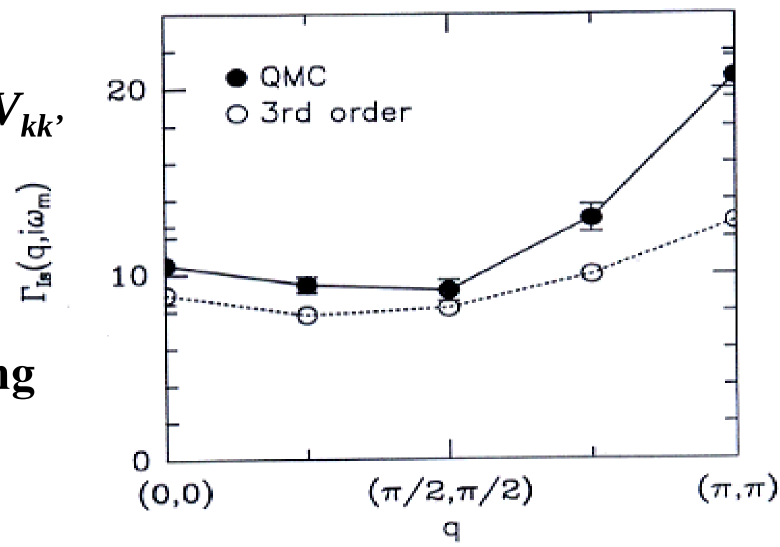
Here note that $\Delta_k = \langle c_{-k\downarrow} c_{k\uparrow}\rangle$ based ion the mean field approximation and when it is assumed as k-independent, we get the following relations using the density of state at the Fermi Level , N(0) and the Deby frequency, ω_D .

$$1 = \frac{1}{2} N(0)\, V \int_{-\hbar\omega_D}^{\hbar\omega_D} \frac{1}{\sqrt{\xi^2 + \Delta^2}}\, d\xi \qquad \Delta = \frac{\hbar\omega_D}{\sinh\left(\frac{1}{N(0)V}\right)} \approx 2\hbar\omega_D \exp\left(-\frac{1}{N(0)V}\right)$$

$$\Delta_k = -\Sigma_{k'} V_{k,k'} \frac{\Delta_{k'}}{2E_{k'}} \tanh\left(\frac{E_k(T)}{2k_B T}\right)$$

d-wave superconductivity due to the on-site Coulomb repulsive interaction

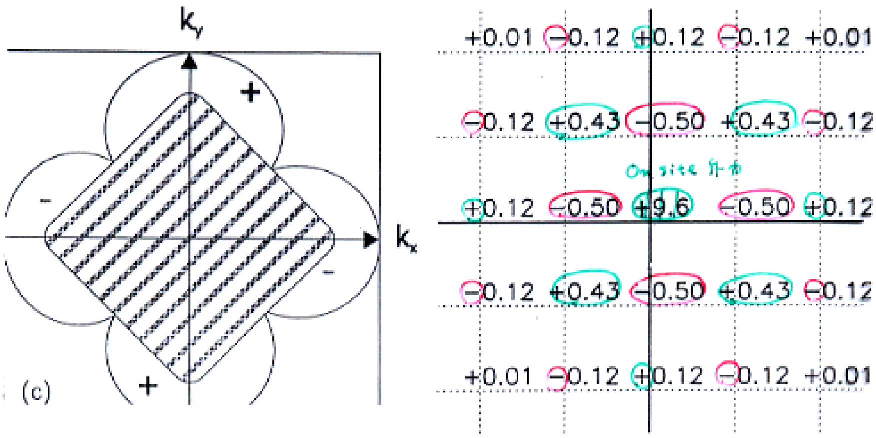
$V_{kk'}$



Gap equation for d_{x2-y2} pairing

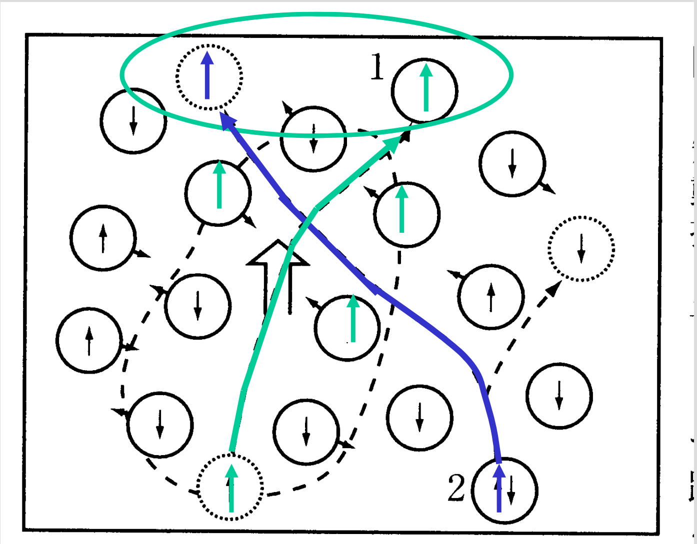
$$\Delta_k = -\Sigma_{k'} V_{k,k'} (\Delta_{k'}/E_{k'})$$

d_{x2-y2} pairing

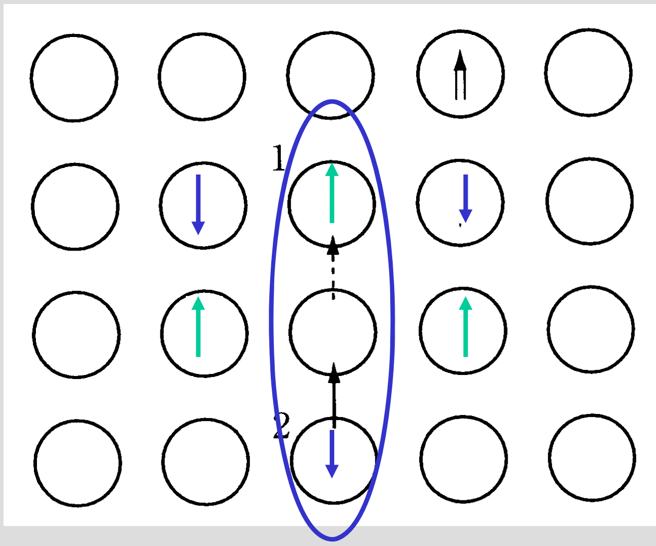


Magnetic fluctuations mediated SC mechanism

Ferromagnetic case



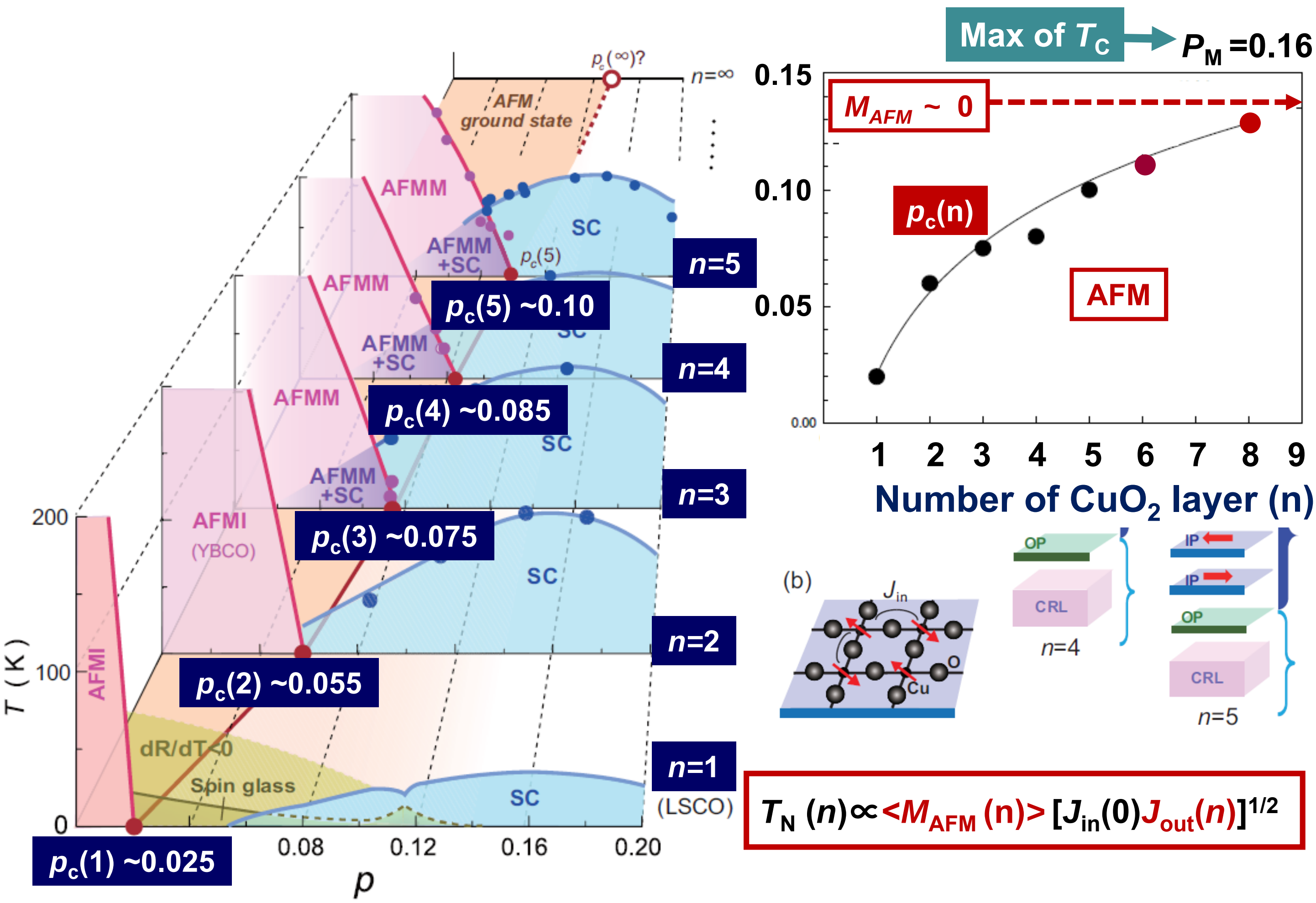
Antiferromagnetic case



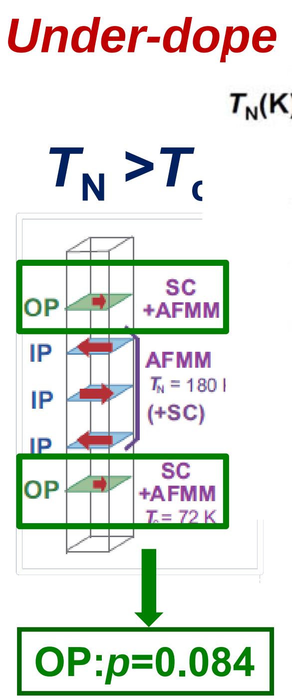
Recent Topics in Multilayer High-T_c Cuprates

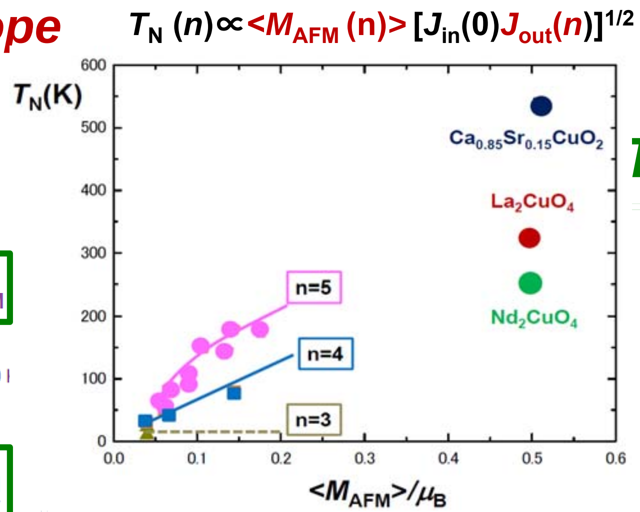
- **Novel phase diagram for single CuO_2 plane deduced from n = 3, 4, 5 and *6 compounds (new)***

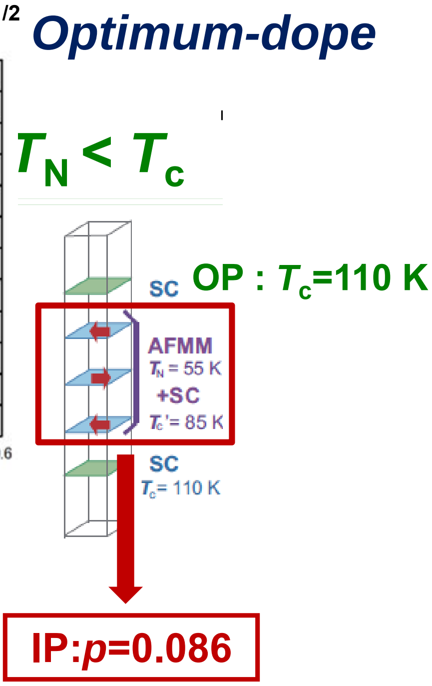
CuO_2-layer number dependence of phase diagram



AFM and SC characteristics inherent to a single CuO_2 plane







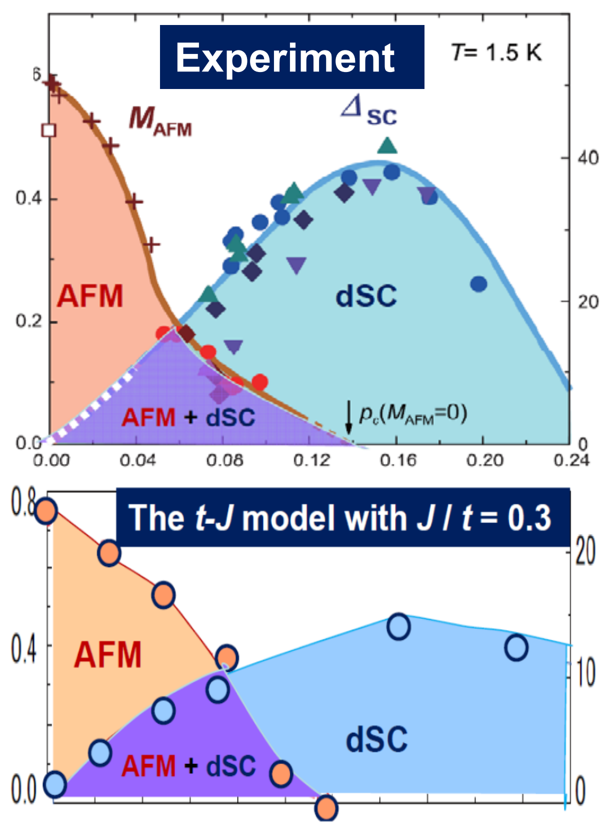
	T_c (Δ_{SC})	
72 K	⟷	85 K
	M_{AFM}	
$0.09\mu_B$	⟷	$0.1\mu_B$

T_c (Δ_{SC}) and M_{AFM} depend only on a hole density

Summary (II)

	Copper Oxides
Mother compound	AFM-Mott Insulators (T_N ~ 500 K)
Phase diagram	Carrier doping
Electronic state	Single band
SC symmetry	d wave (T_c = 135 K at P = 0)
Pairing interaction	AFM superexchange Interaction J

$$H = \sum_{\langle i,j \rangle} t_{ij} a^{\dagger}_{i\sigma} a_{j\sigma} + \sum_{i} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$



In strong coupling regime of electron correlation (U > 8t):

Doped Mott Insulator is the superconductor, leading to the high T_c superconductivity mediated by the AFM superexchage interaction!

第5回おわり