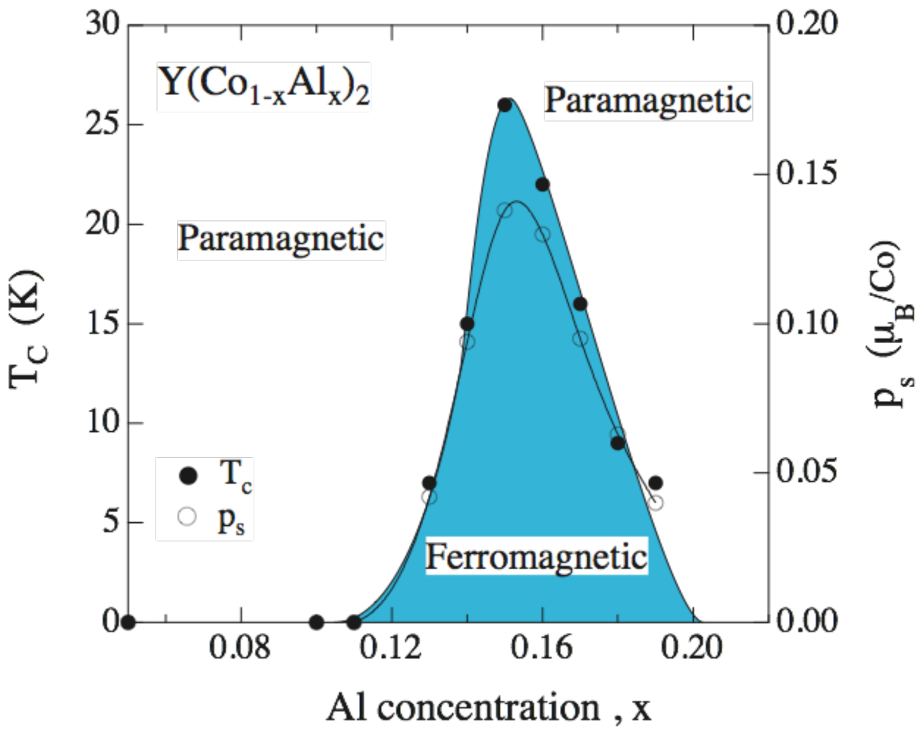
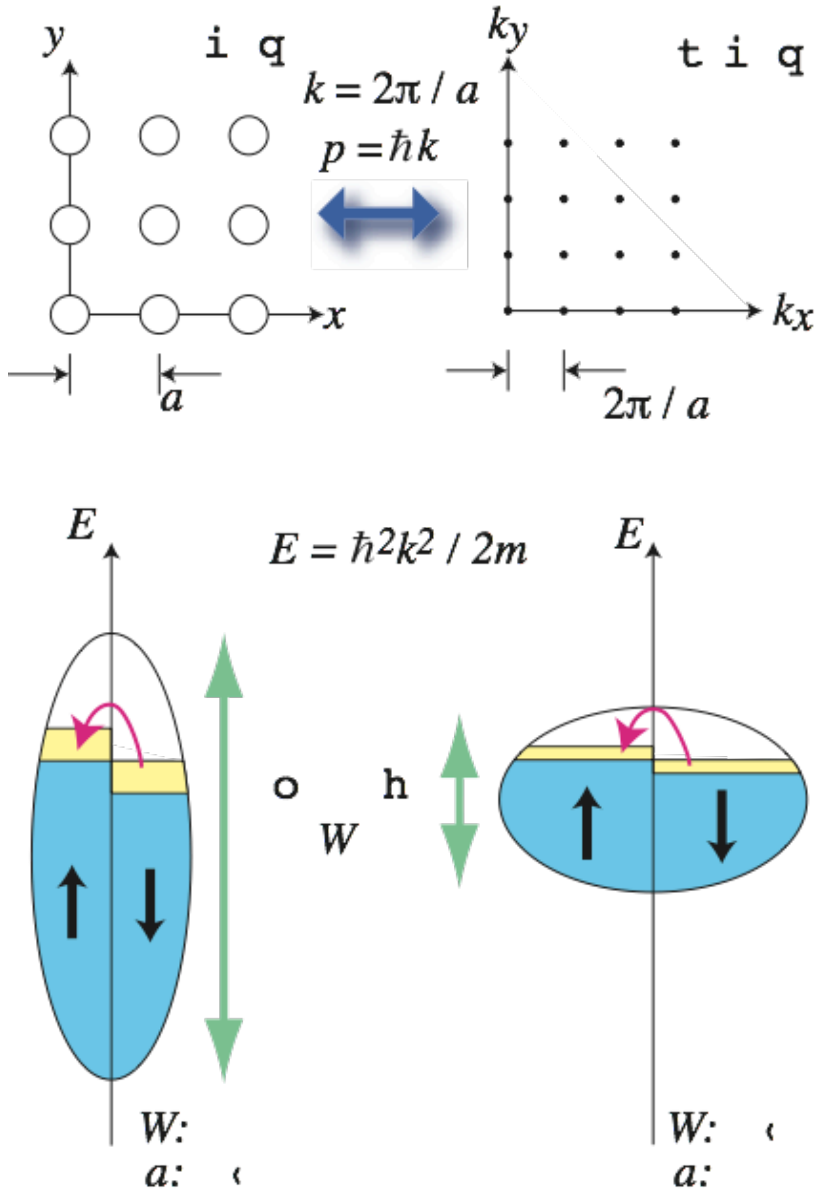
Y(Co-Al)$_2$の遍歴電子強磁性



(Solid State Commun., 56 (1985) 767
Phys. Rev. B 37 (1988) 3593.)



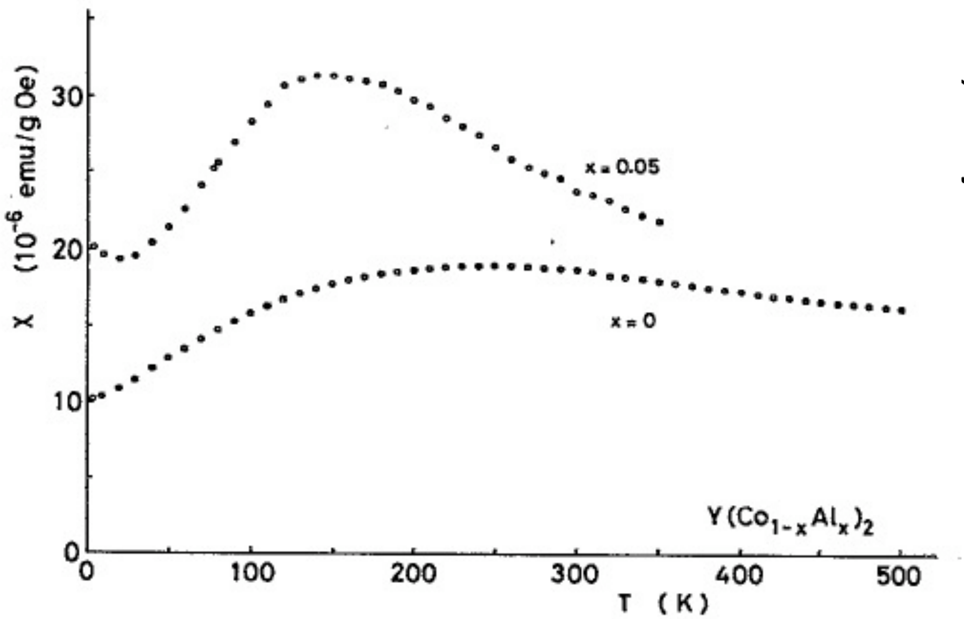
磁気体積効果を利用して
フェルミ液体から弱い強磁性体創製

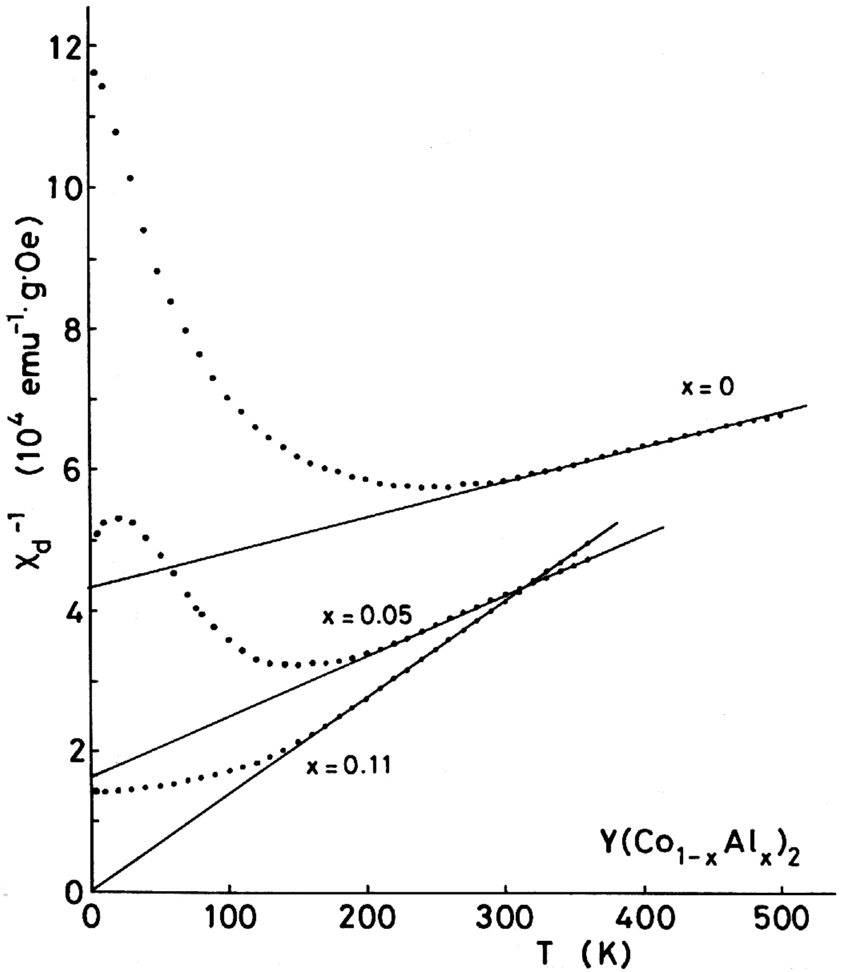
Y(Co-Al)$_2$の磁化率

χ vs T → Max!

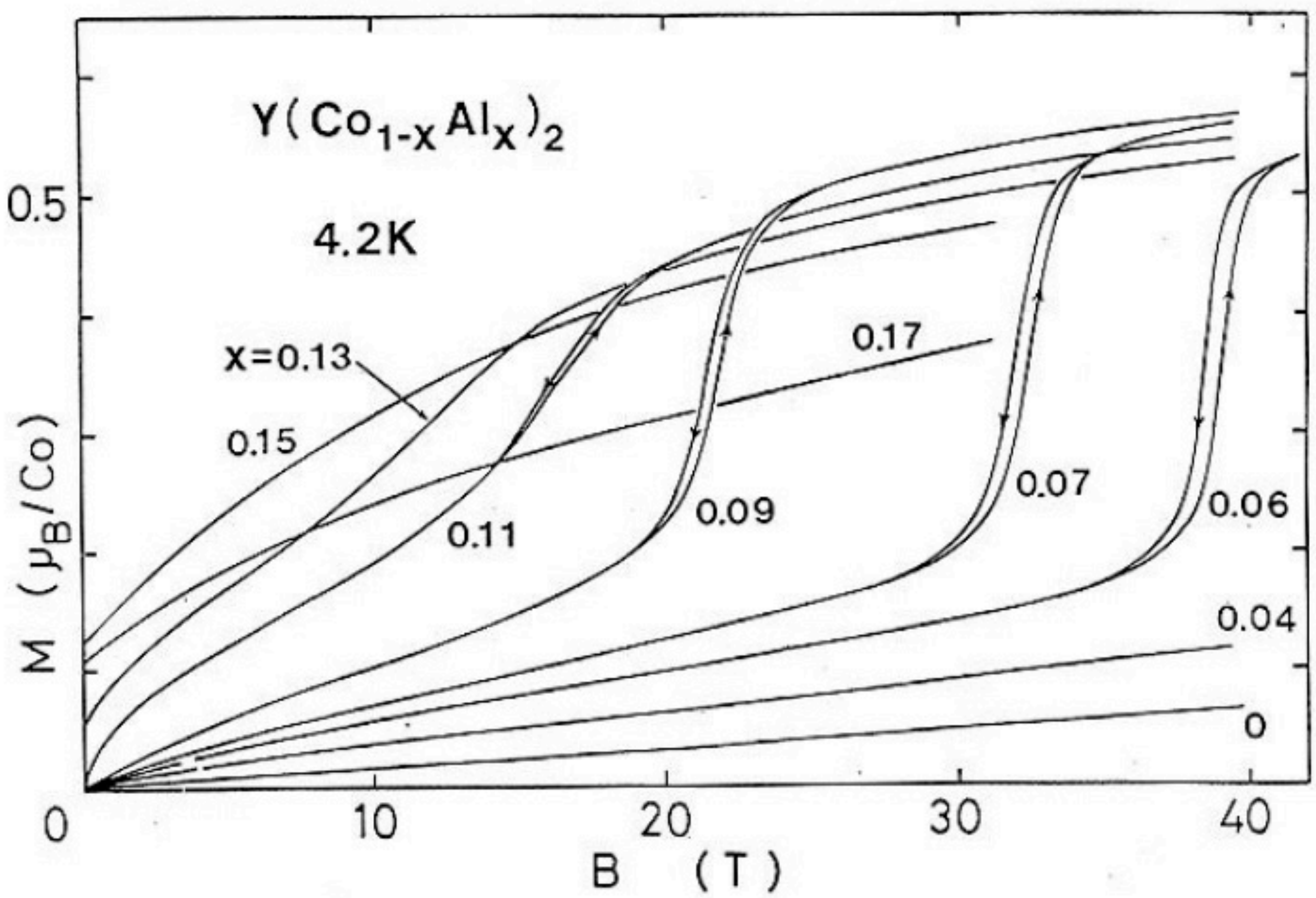
↓

遍歴電子メタ磁性転移





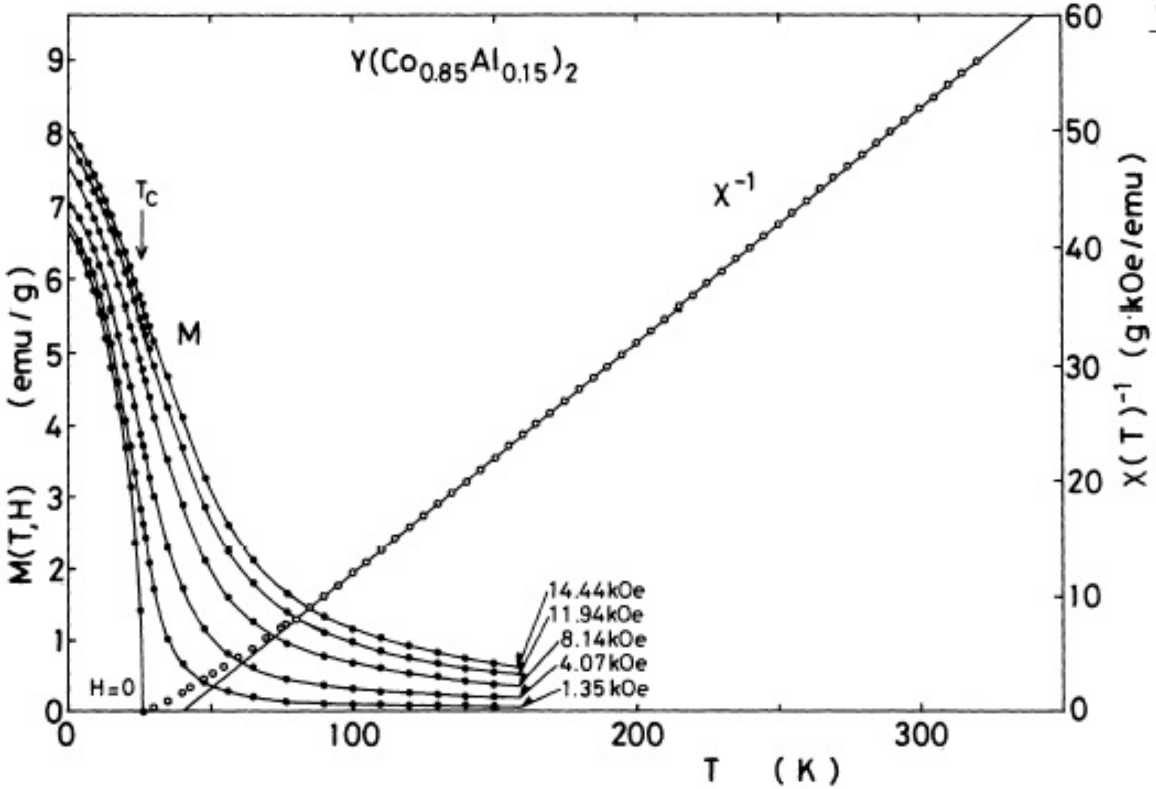
遍歴電子メタ磁性転移→Band磁性の証拠



$Y(Co_{1-x}Al_x)_2$ の弱い遍歴電子強磁性

Table I. Magnetic parameters of the $Y(Co_{1-x}Al_x)_2$ system.

x	T_C(K)	θ (K)	p_s (μ_B/Co)	p_{eff} (μ_B/Co)	p_{eff}/p_s	$\bar{F}_1(10^4$ K)
0.11	—	—	0	2.54	—	4.82
0.13	7	9	0.042	2.50	59.5	2.10
0.14	15	30	0.094	2.24	23.8	1.10
0.15	26	40	0.138	2.15	15.6	1.00
0.16	22	33	0.130	2.14	16.5	0.95
0.17	16	25	0.095	2.13	22.4	1.56
0.18	9	13	0.063	2.08	33.0	2.77
0.19	7	8	0.040	2.04	51.0	4.11



SCR理論 The Self-Consistent Renormalization (SCR) Theory of Spin Fluctuations

The dynamical susceptibility:

$$\chi^{-+}(q,\omega) = \frac{\chi_0^{-+}(q,\omega)}{1 - I\chi_0^{-+}(q,\omega) + \lambda(q,\omega)}, \quad (T > T_C)$$

The long wave approximation:

$$\frac{\chi_0^{-+}(q,\omega)}{\chi_0^{-+}(0,0)} = 1 - Aq^2 - B\left(\frac{\omega}{q}\right)^2 + iC\omega q + \cdots$$

$$\lambda(q,\omega) = \left(\frac{5\alpha}{2\pi\rho}\right)(1+\delta)F_1\sum_q\int_0^\infty d\omega \frac{1}{e^{\omega/T}-1}\cdot\frac{C\omega/q}{(\delta + Aq^2)^2 + (C\omega q)^2}$$

$$\delta = \frac{\chi_0}{\alpha\chi} = \frac{1-\alpha+\lambda}{\alpha}$$

$$\lambda(q,\omega) \approx \lambda(0,0) = \frac{5}{3}\chi_0 g N_0^2 S_L(T)^2 = \frac{5}{3}\frac{\chi_0}{N_0}\overline{F}_1 S(T)_L^2$$

$$\frac{1}{\chi} = \frac{(1-\alpha)}{\chi_0} + \frac{5}{3}gN_0^2 S_L(T)^2 = \left[4N_0 I^2 S_L(T_C)^2/3T_C T_0\right](T - T_C)$$

Stoner Enhancement Factor: $\dfrac{1}{1-\alpha}$ $\quad \alpha = I\rho$

I: the intra-atomic exchange interaction,
ρ : the density of states at the Fermi level.

Landau Expansion of Free Energy:

$$F(M) = \frac{1-\alpha}{2\chi_0}M^2 + \frac{1}{4}\overline{F}_1 M^4 + \cdots - 2\mu_B H\cdot M$$

$$\overline{F}_1 M^2 = \frac{2\mu_B H}{M} + \frac{2(\alpha-1)}{\rho}$$

Arrott Plots:

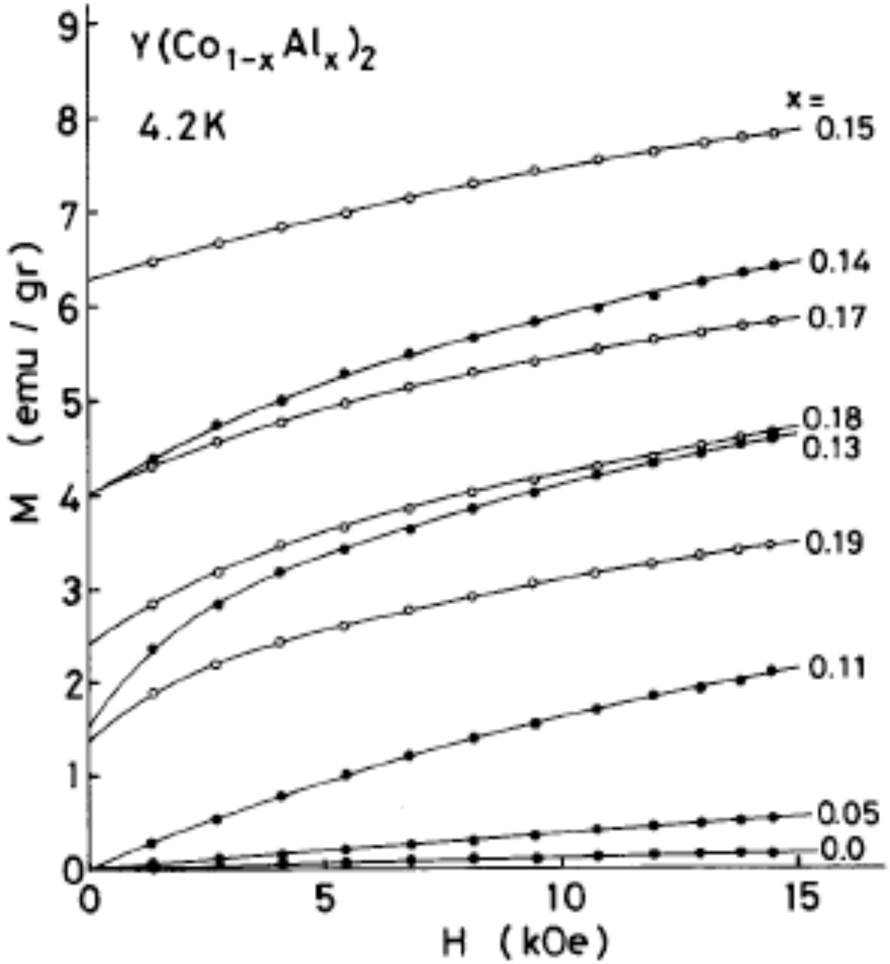
$$\overline{F}_1\left[M(T,H)^2 - M(T,0)^2\right] = 2\mu_B\frac{H}{M(T,H)}, \quad p_s = 2M(0,0)$$

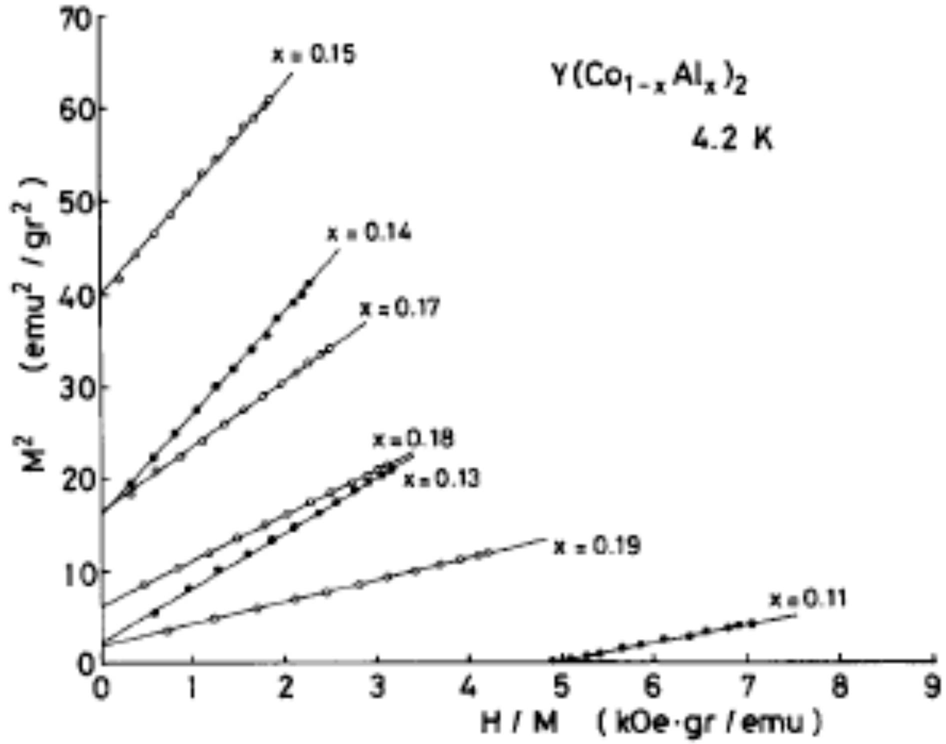
$$\left[-\frac{(\alpha-1)}{\chi_0} + \frac{5}{3}gN_0^2\overline{m}^2\right]M + gM^3 = h$$

$$m^2 = m_{//}{}^2 + m_\perp{}^2 = S_L^2 - (M/N_0)^2$$

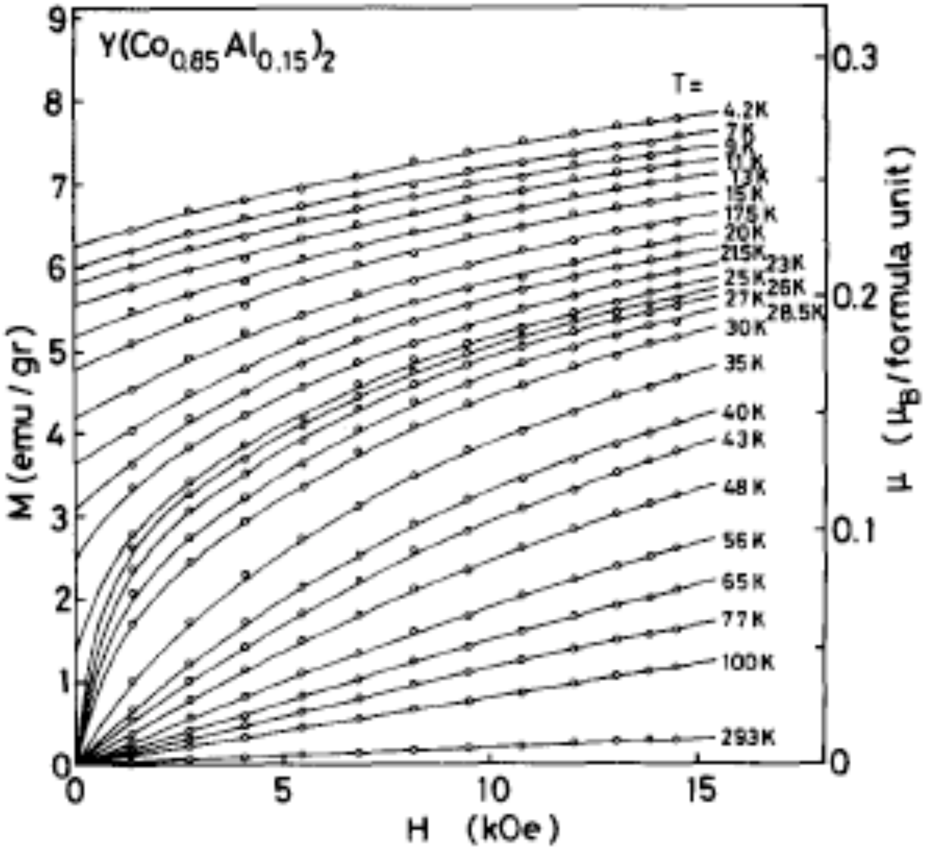
$$\overline{m}^2 = \frac{3}{5}\left(3m_{//}{}^2 + 2m_\perp{}^2\right)$$

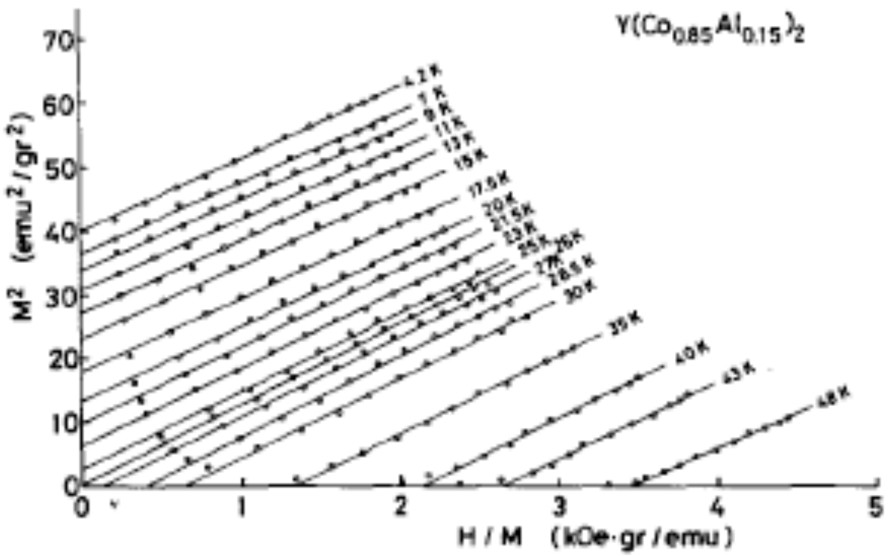
磁化曲線, アロット・プロット





磁化曲線, アロット・プロット

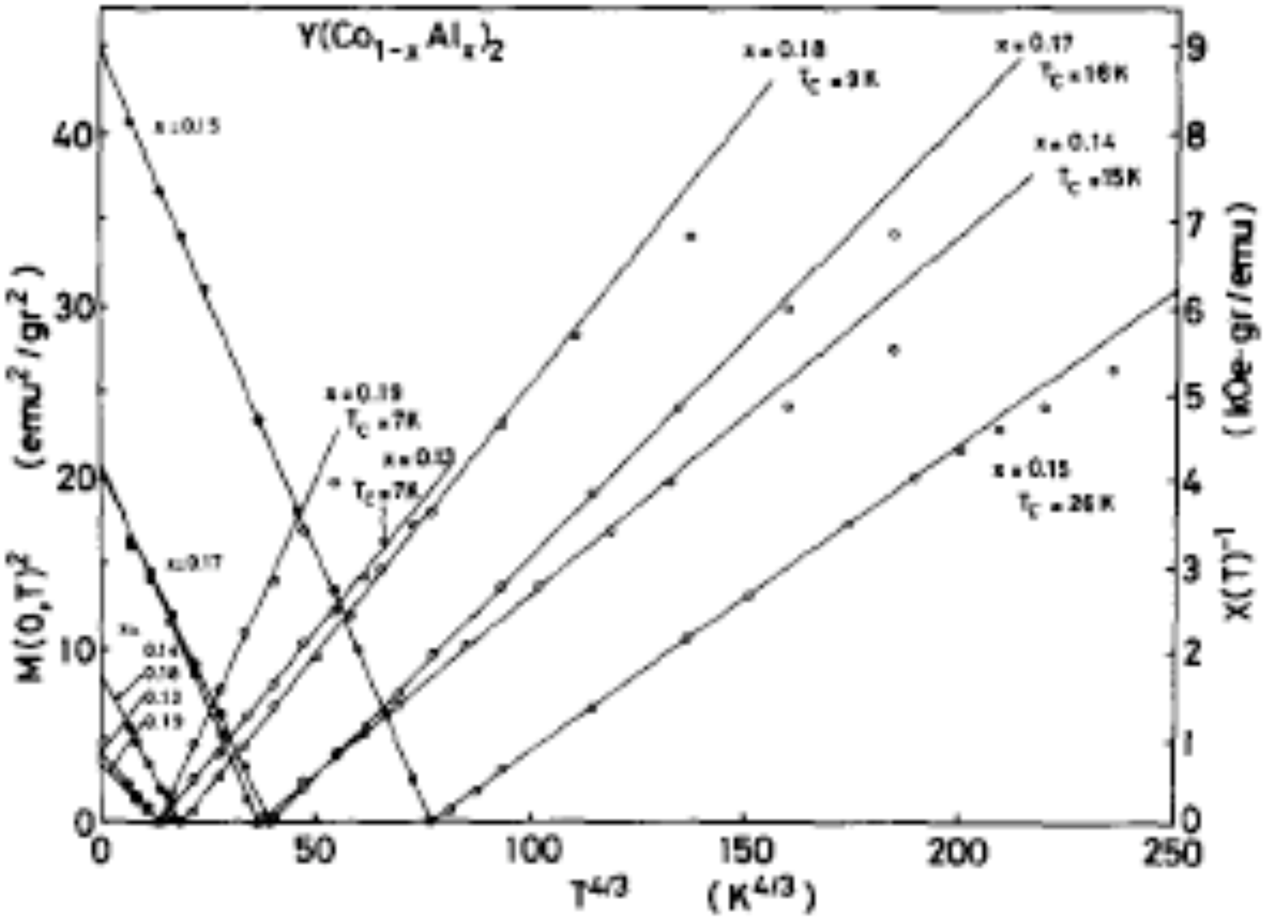




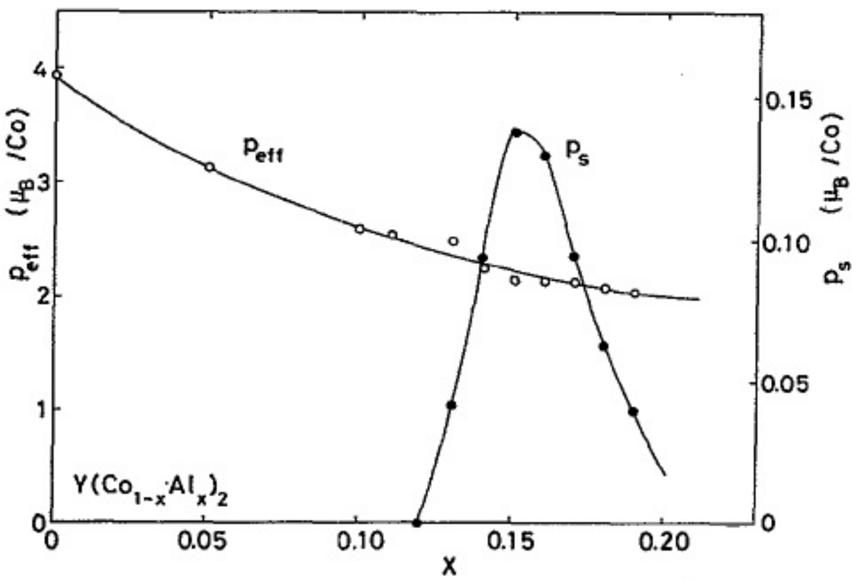
SCR理論：磁化曲線，逆帯磁率

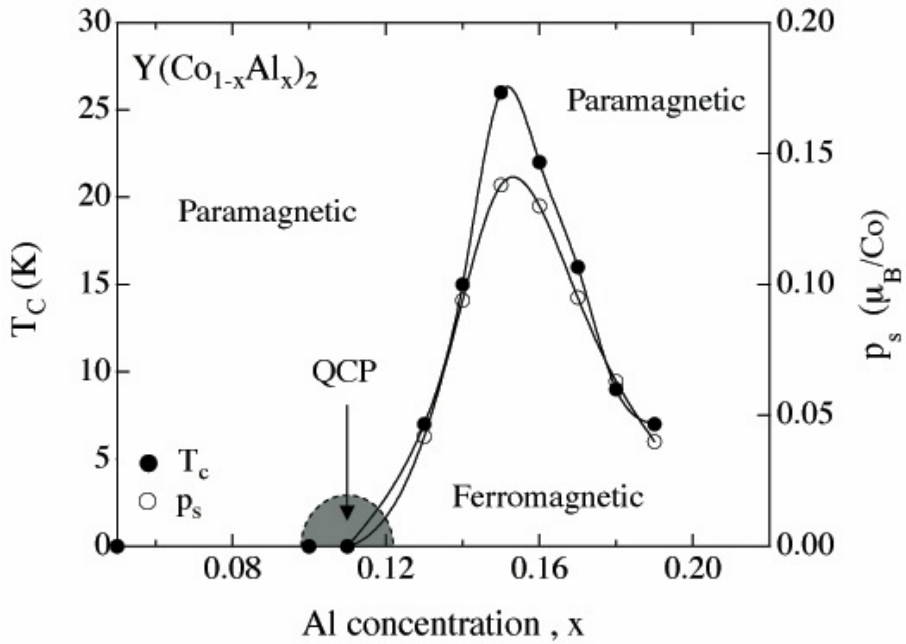
$Y(Co_{1-x}Al_x)_2$

$T^{4/3}$-law



$Y(Co\text{-}Al)_2$の弱い遍歴電子強磁性





金属中のNMRシフト（ナイトシフト）の測定例　（Pt）

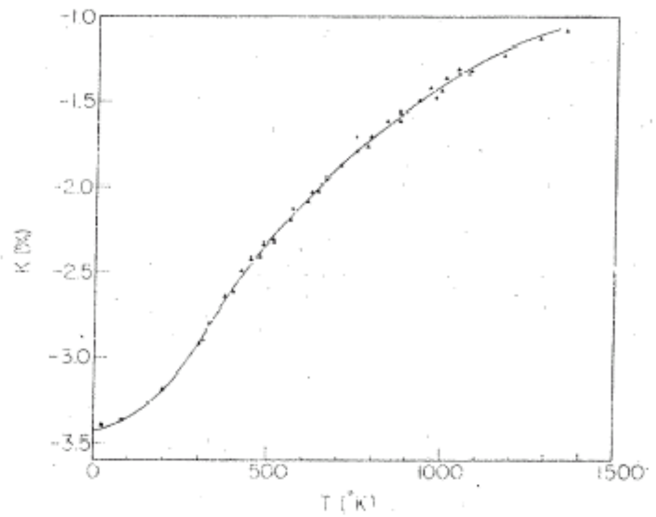


FIG. 1. Knight shift as a function of temperature. Solid squares, low-temperature NBS measurements; solid triangles, our experimental results.

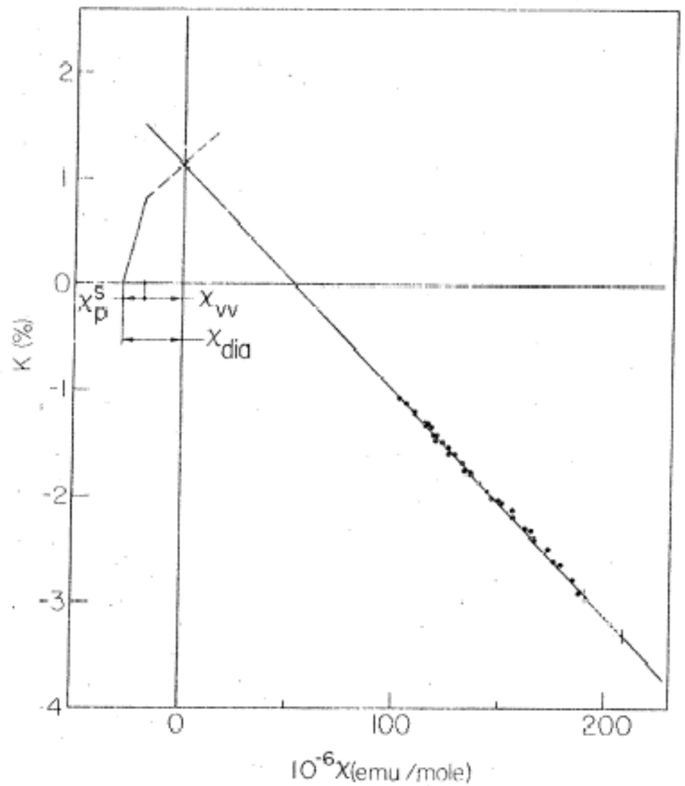


FIG. 3. Plot of *K* vs χ. Dashed line, least-squares fit of Clogston *et al*. (Ref. 1).

K-χ analysis

$$\chi(T) = \chi_{\mathrm{dia}} + \chi_{\mathrm{s}} + \chi_{\mathrm{orb}} + \chi_{\mathrm{d,spin}}(T)$$

$$K(T) = (K_{\mathrm{dia}}) + K_{\mathrm{s}} + K_{\mathrm{orb}} + K_{\mathrm{d,spin}}(T)$$

$$K_{\mathrm{d,spin}}(T) = H_{\mathrm{cp}} \frac{\chi_{\mathrm{d,spin}}(T)}{\mu_{\mathrm{B}}}$$

Pd: M. Takigawa and Yasuoka, JPSJ 51 (1982)787.

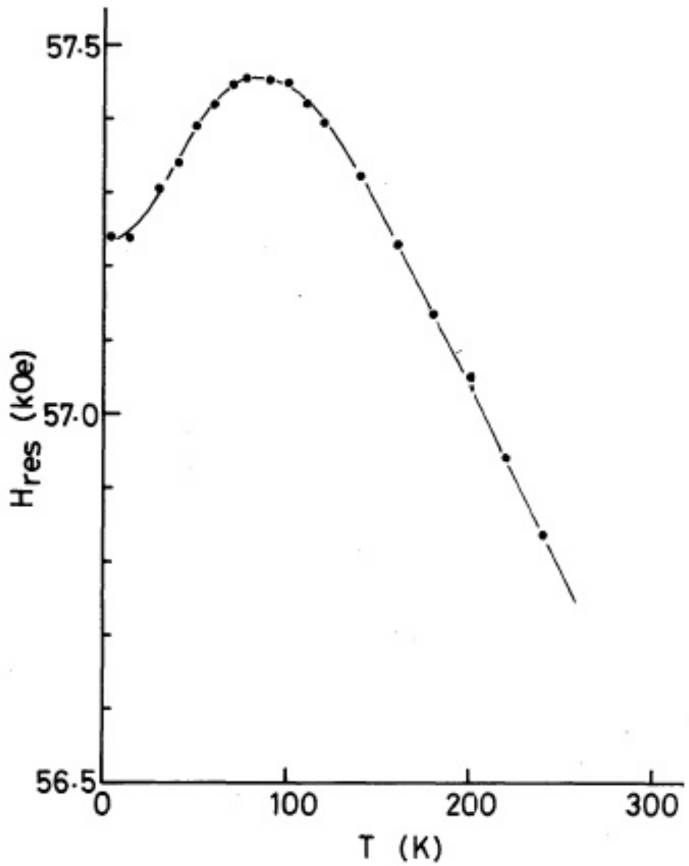
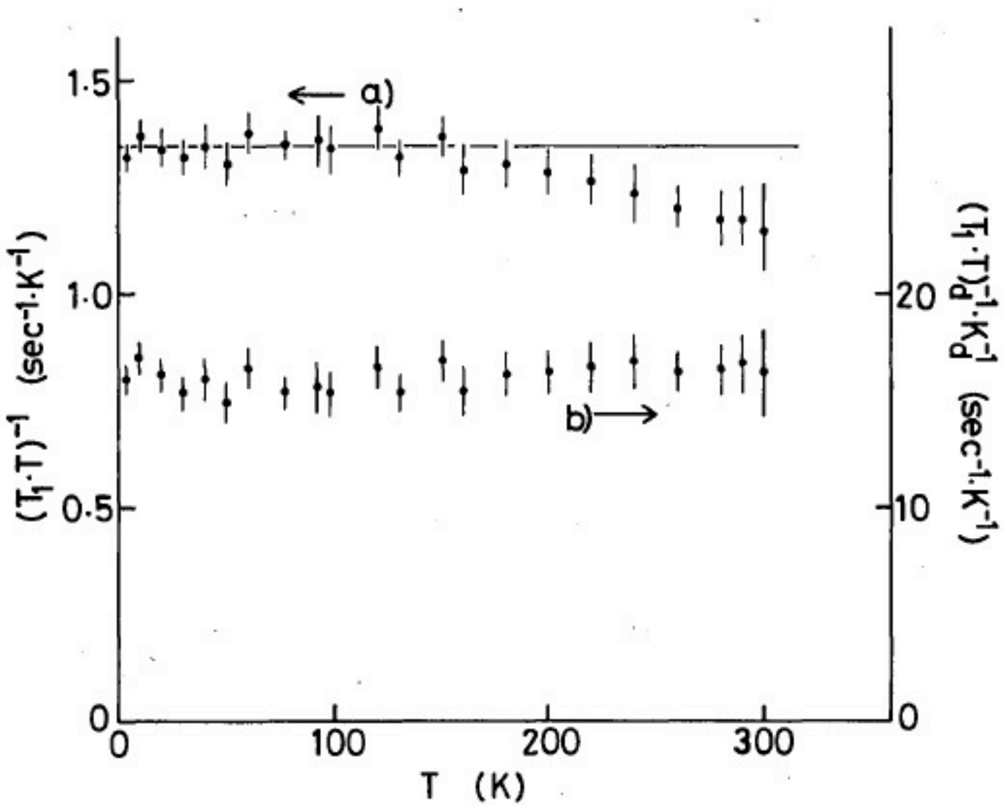
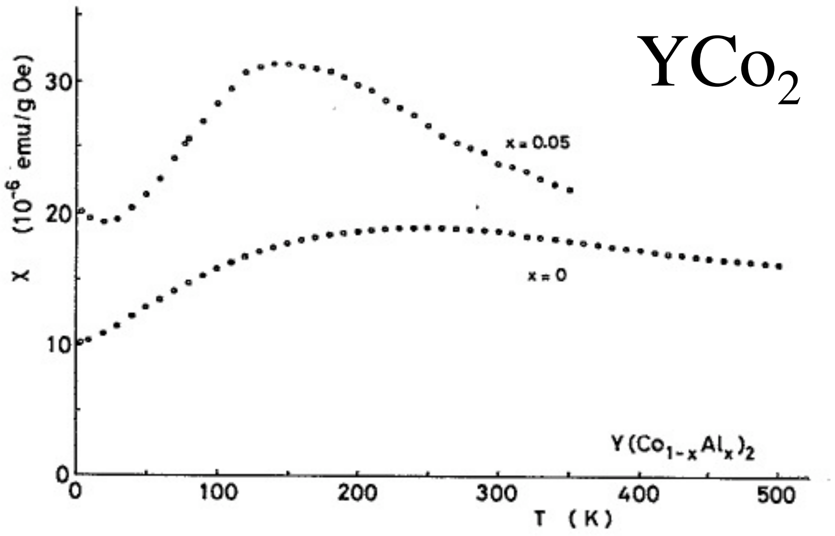
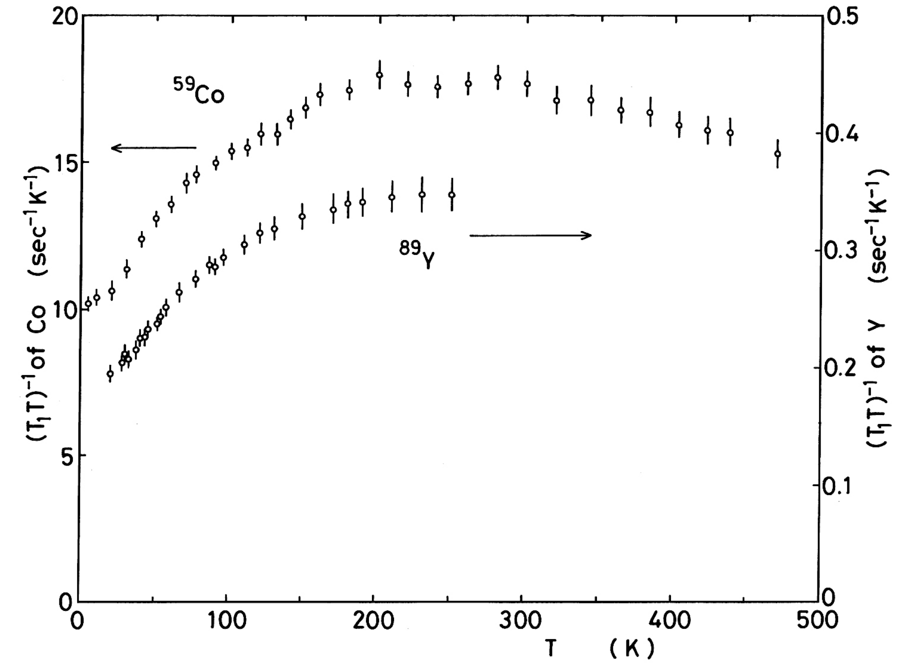


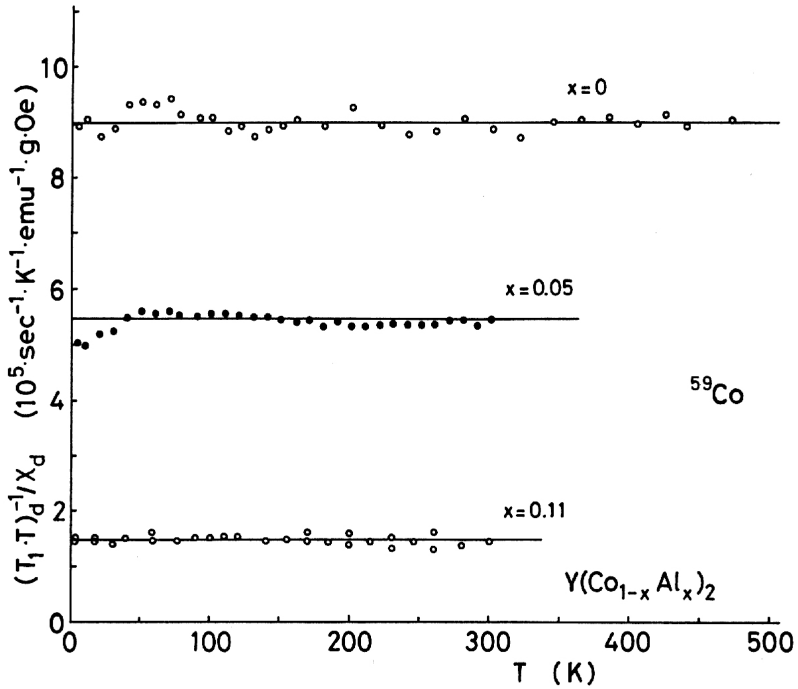
Fig. 3. Temperature dependence of the field for resonance of ^{105}Pd nuclei (H_{res}) in Pd metal at a fixed frequency of 10.7000 MHz.



核磁気緩和率$1/T_1$：磁化率χ：　YCo_2

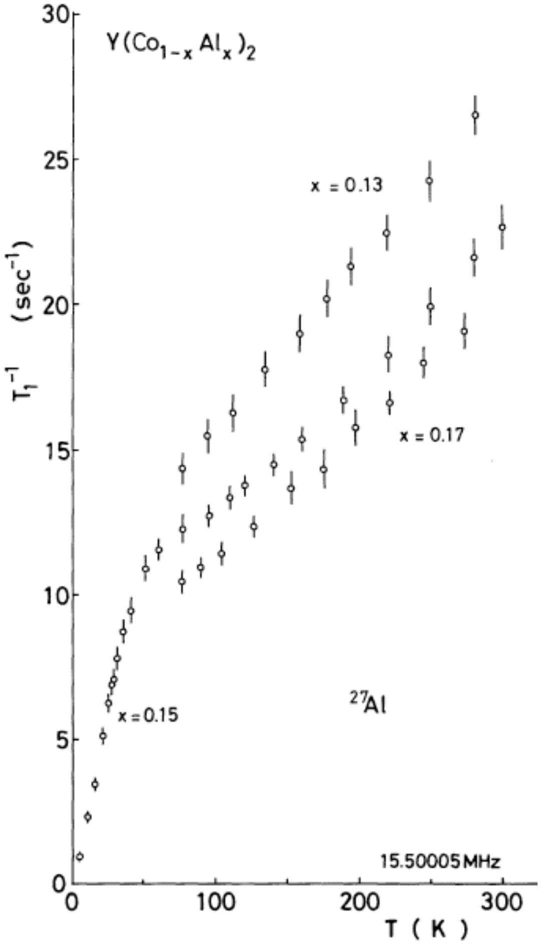


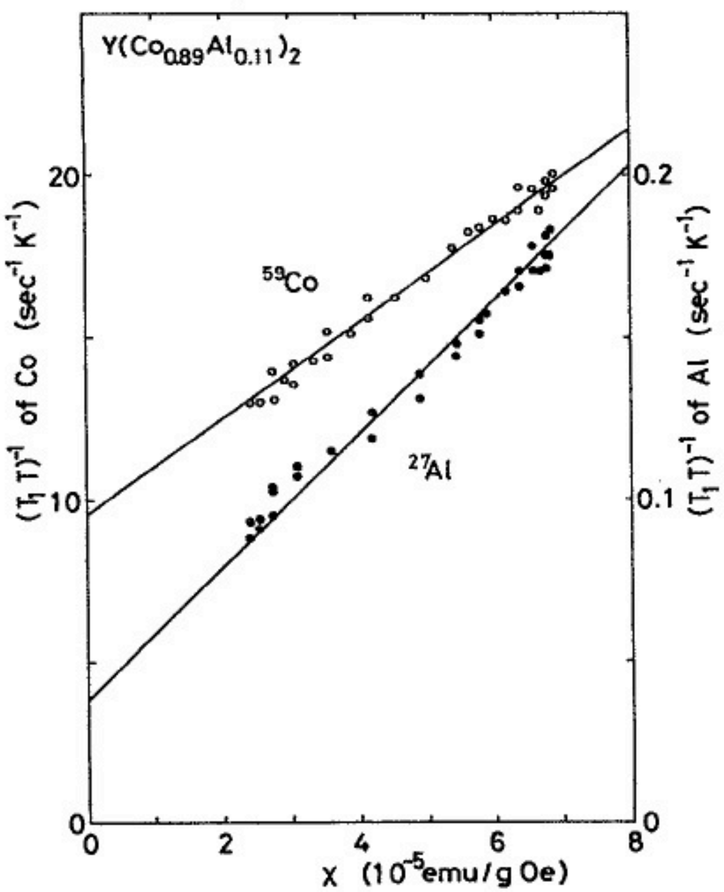


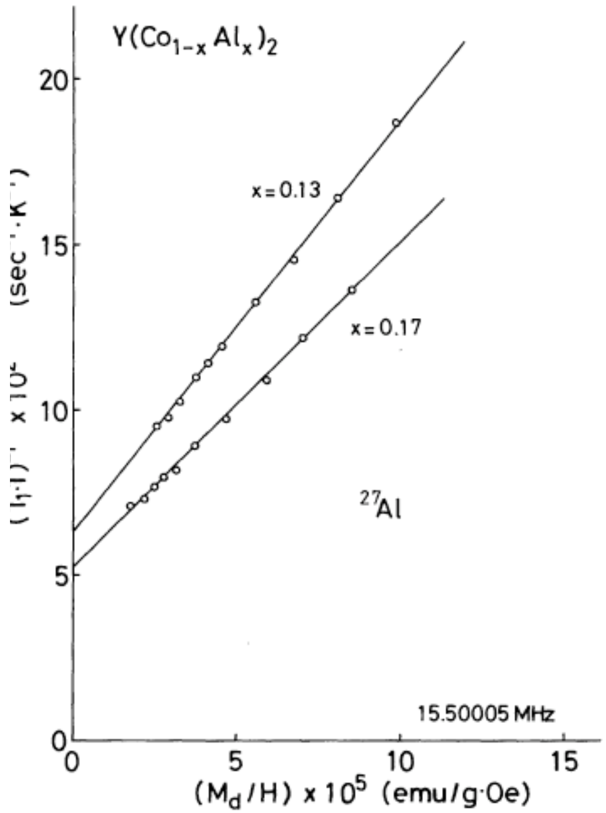


$Y(Co_{1-x}Al_x)_2$ の $1/T_1T$

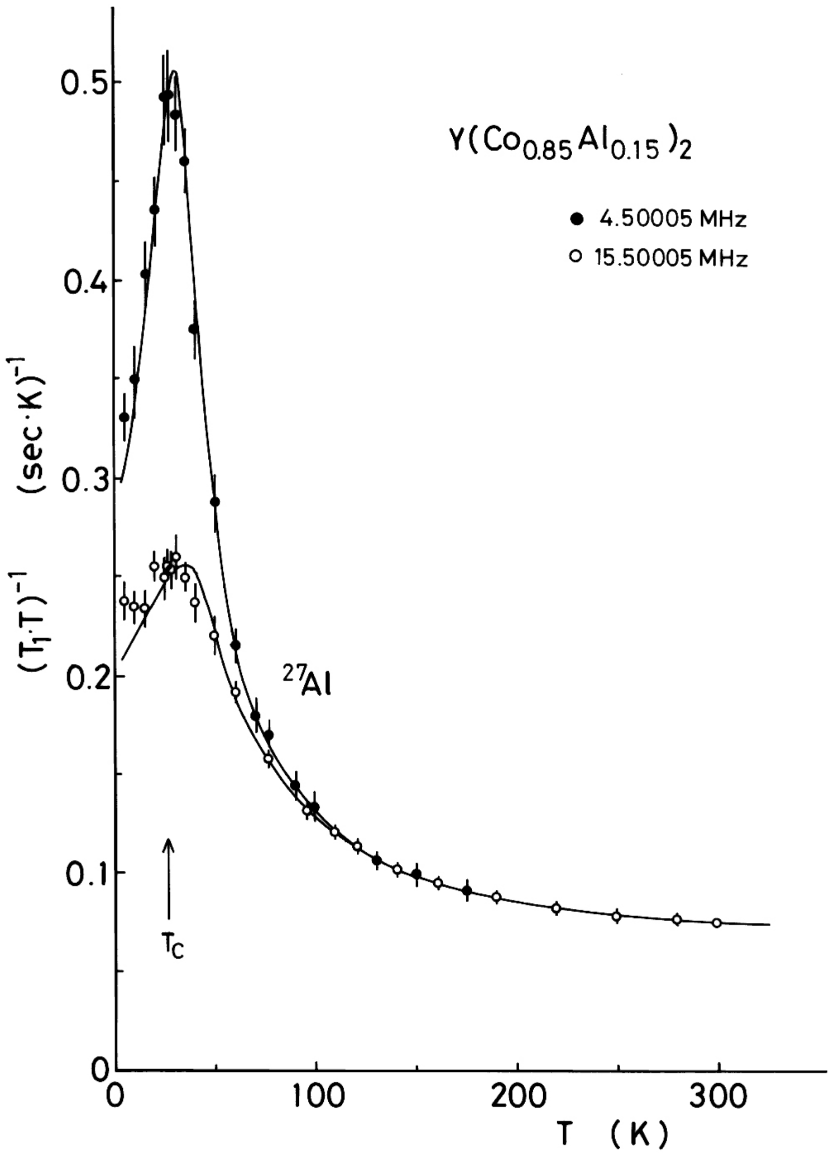
$$\frac{1}{T_1} = \gamma_N^2 A_{hf}^2 T \frac{\chi}{4\pi^2 \mu_B \Gamma_0}, \quad T_0 = \frac{\Gamma_0 q_B^3}{2\pi}$$







弱い遍歴電子強磁性体 (SCR)



スピン-格子緩和率, $1/T_1$

$$\left(\frac{1}{T_1}\right)^{F}_{SCR} \propto \frac{T}{M_0^2} \propto \frac{T}{T_c - T} \quad (T < T_c)$$

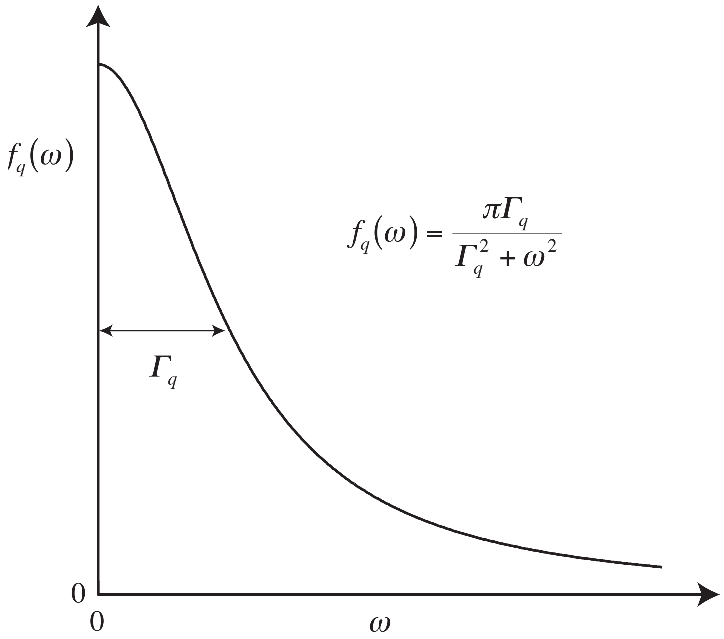
$$\left(\frac{1}{T_1}\right)^{F}_{SCR} \propto T\chi_0 \propto \frac{T}{T - T_c} \quad (T > T_c)$$

$$\frac{1}{T_1} = \gamma_N^2 A_{hf}^2 T \frac{\chi}{4\pi^2 \mu_B \Gamma_0}, \quad T_0 = \frac{\Gamma_0 q_B^3}{2\pi}$$

$$\left(\frac{1}{T_1}\right)_{SCR} \propto \frac{T\left(\dfrac{M}{H}\right)}{1 + \dfrac{AM^3}{H}}$$

$$\overline{A} = AN_0/\rho, \quad T_A = \overline{A} q_B^2$$

スピン-格子緩和率, 1/ T_1



$$\frac{1}{T_1} = 2(\gamma_n A)^2 kT \sum_q \frac{\operatorname{Im}\chi_\perp(q,\omega_0)}{\omega_0}$$

$$\frac{\operatorname{Im}\chi(q,\omega)}{\omega} = \chi(q,0) f_q(\omega)$$

$$f_q(\omega) = \frac{\pi\Gamma_q}{\Gamma_q^2 + \omega^2}$$

$$\frac{\operatorname{Im}\chi(q,\omega_0)}{\omega_0} = \frac{\pi\chi(q,0)}{\Gamma_q}$$

$$\frac{1}{T_1} = 2(\gamma_n A_{hf})^2 k_B T \sum_q \frac{\pi\chi(q,0)}{\Gamma_q} \approx 2(\gamma_n A)^2 k_B T \frac{\pi\chi(0,0)}{\Gamma}$$

$$\xrightarrow[T>>1]{} \propto (\gamma_n A_{hf})^2 \frac{1}{\Gamma} = (\gamma_n A_{hf})^2 \tau$$

局在モーメント系

$$\langle S_L^2 \rangle = \frac{3k_BT}{N_0}\sum_q \chi_q = \frac{3k_BT}{N_0}\sum_{q,\omega}\frac{\mathrm{Im}\,\chi(q,\omega)}{\omega}$$

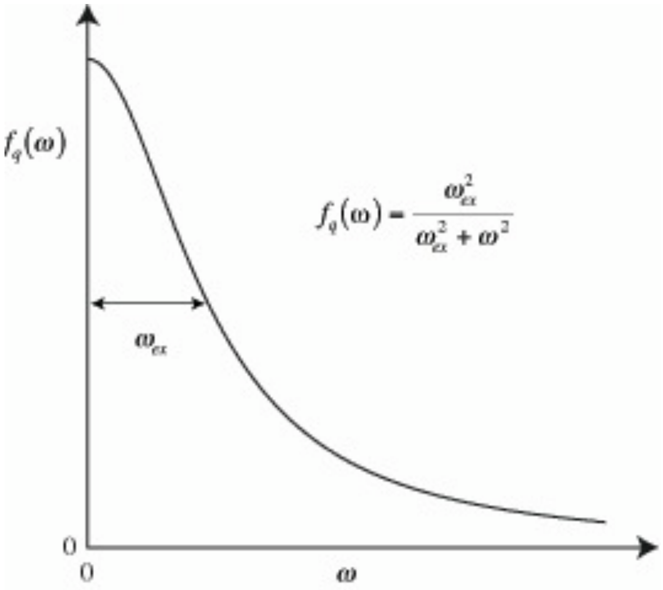
$$\frac{1}{T_1} = 2\gamma_N^2 k_BT\sum_q A_q^2\frac{\mathrm{Im}\,\chi(q,\omega_0)}{\omega_0}$$

$$\frac{\mathrm{Im}\,\chi(q,\omega)}{\omega} = \frac{\mathrm{Im}\,\chi(q,\omega_0)}{\omega_0}f_q(\omega),\quad f_q(\omega) = \frac{1}{1+(\omega/\omega_{ex})^2}$$

$$\chi_q(\approx\chi_0) \propto \int_0^\infty d\omega\frac{\mathrm{Im}\,\chi(q,\omega)}{\omega} = \pi\frac{\mathrm{Im}\,\chi(q,\omega_0)}{\omega_0}\cdot\omega_{ex}$$

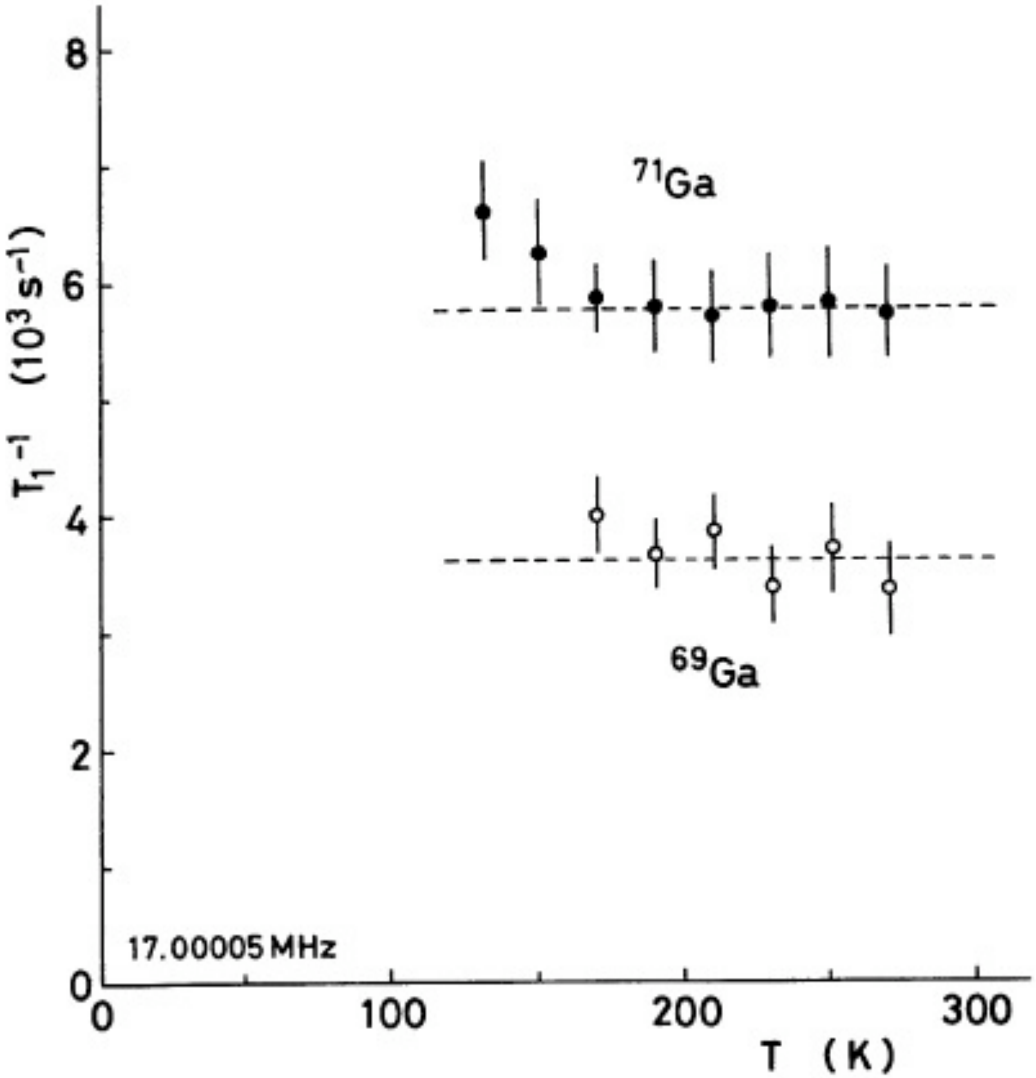
$$\langle\{S_+(t),S_-(0)\}\rangle = \frac{3}{2}S(S+1)\exp\left(-\frac{1}{2}\omega_{ex}^2t^2\right)$$

$$\omega_{ex}^2(=1/\tau_{ex}^2) = \frac{8zJ^2S(S+1)}{3\hbar^2}\qquad S(\omega_0) = \frac{4\pi S(S+1)}{3}$$



$$\frac{1}{T_1} = \frac{1}{T_2} = (2\pi)^{1/2}\left(\frac{A}{\hbar}\right)^2\frac{S(S+1)}{3}\frac{1}{\omega_{ex}} = (2\pi)^{1/2}\left(\frac{A}{\hbar}\right)^2\frac{S(S+1)}{3}\tau_{ex}$$

局在スピン系：Mn Heusler Alloy



スピン-格子緩和率，**1/ T_1**

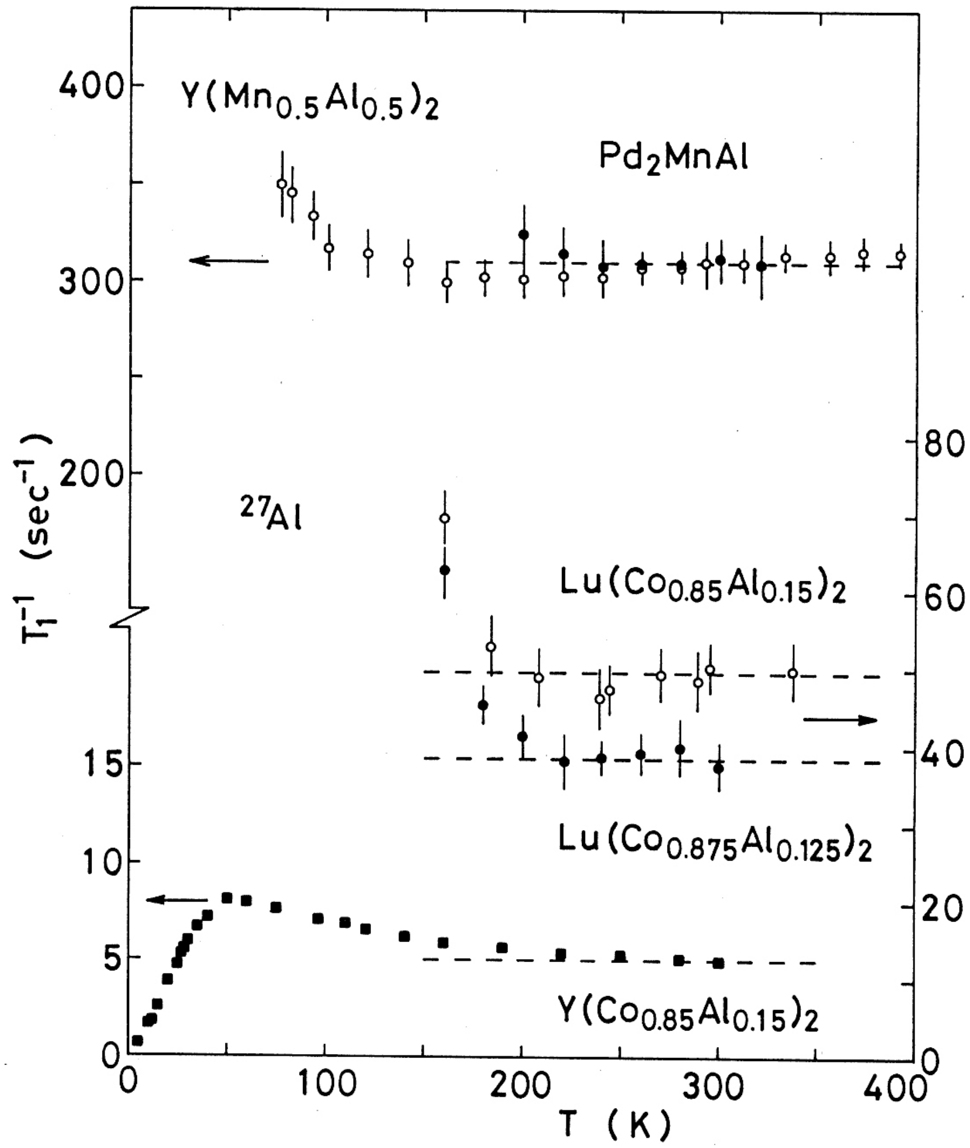
$$\frac{1}{T_1} = 2\left(\gamma_n A_{hf}\right)^2 kT \sum_q \frac{\operatorname{Im}\chi(q\omega_0)}{\omega_0}$$

$$\frac{\operatorname{Im}\chi(q\omega)}{\omega} = \chi(q,0)\, f_q(\omega)$$

$$f_q(\omega) = \frac{\pi\Gamma_q}{\Gamma_q^2 + \omega^2} \qquad \frac{\operatorname{Im}\chi(q\omega_0)}{\omega_0} = \frac{\pi\chi(q,0)}{\Gamma_q}$$

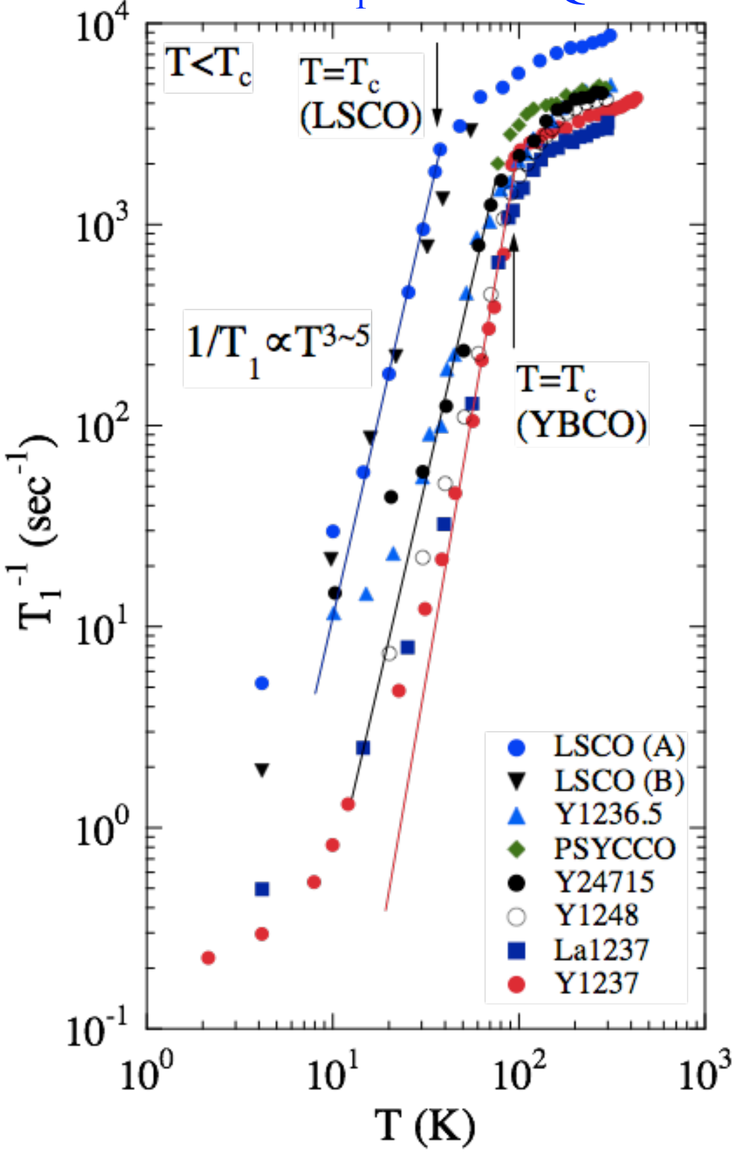
$$\frac{1}{T_1} = 2\left(\gamma_n A_{hf}\right)^2 k_B T \sum_q \frac{\pi\chi(q,0)}{\Gamma_q} \approx 2\left(\gamma_n A\right)^2 k_B T \frac{\pi\chi(0,0)}{\Gamma}$$

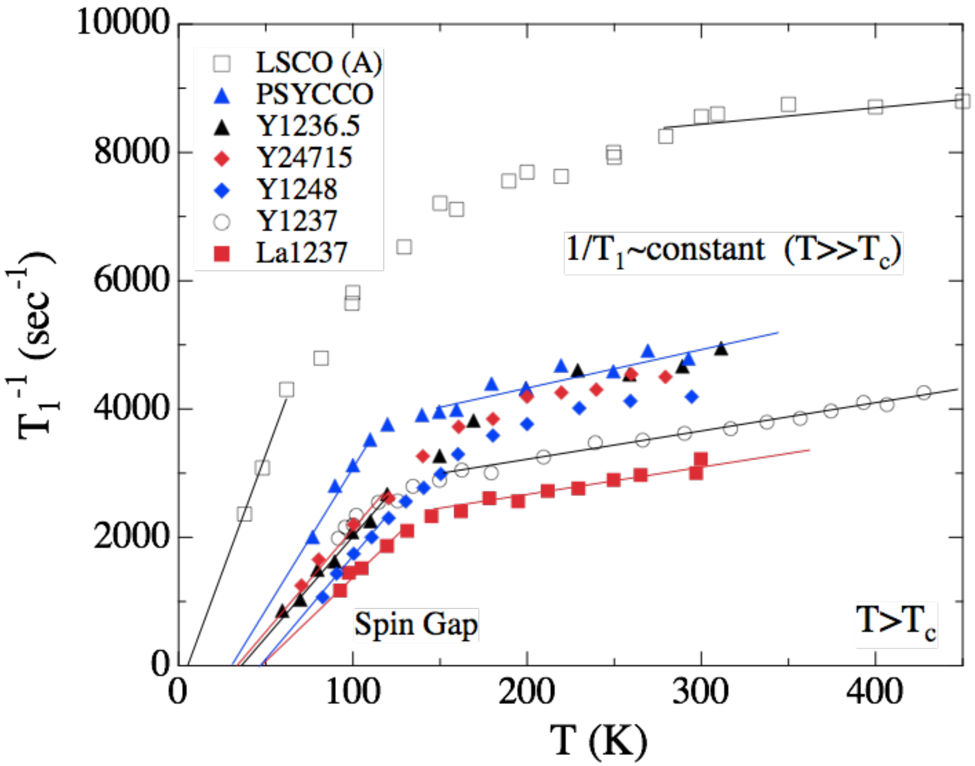
$$\xrightarrow[T>>1]{} \propto \left(\gamma_n A_{hf}\right)^2 \frac{1}{\Gamma} = \left(\gamma_n A_{hf}\right)^2 \tau$$

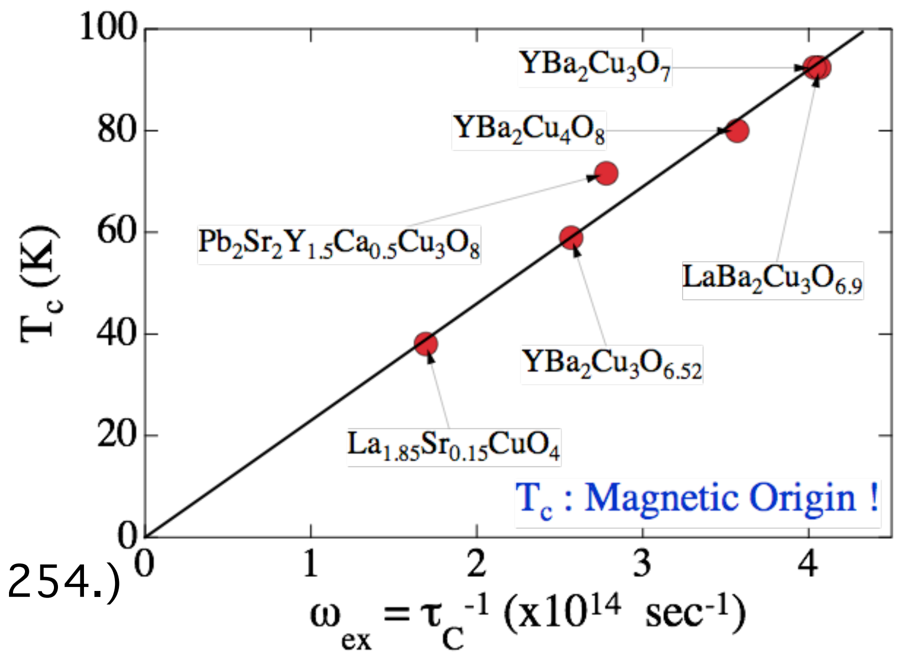


銅酸化物高温超伝導体の核磁気緩和

$1/T_1$: ^{63}Cu NQR

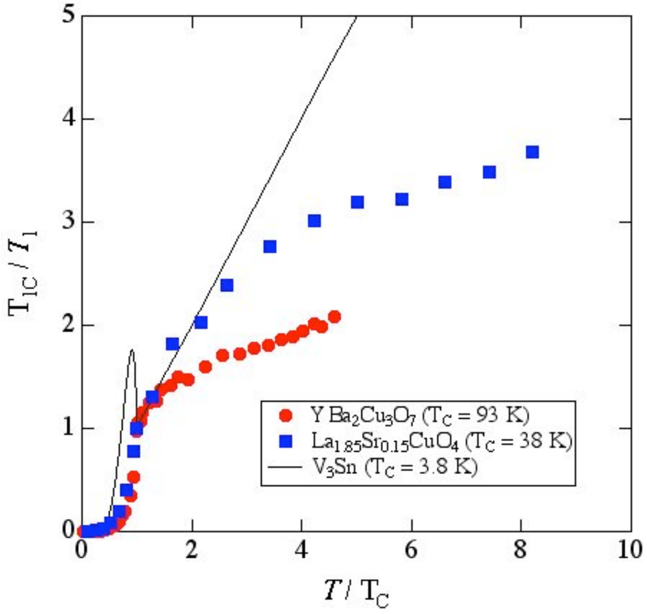


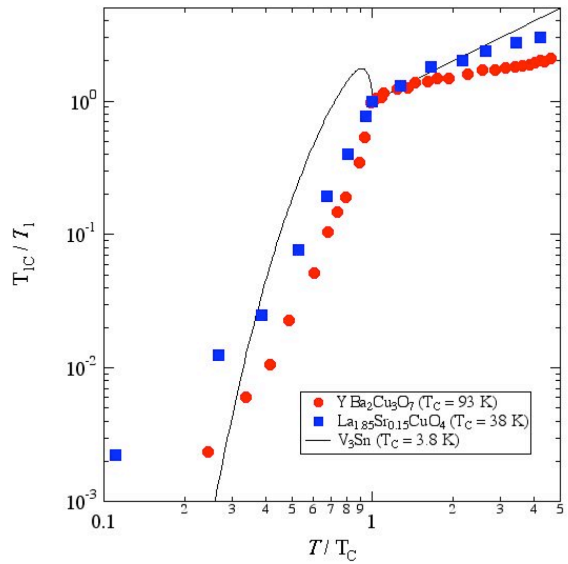


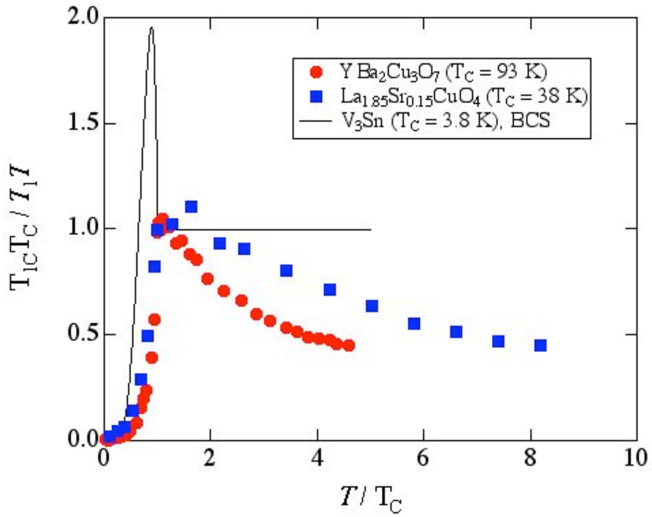


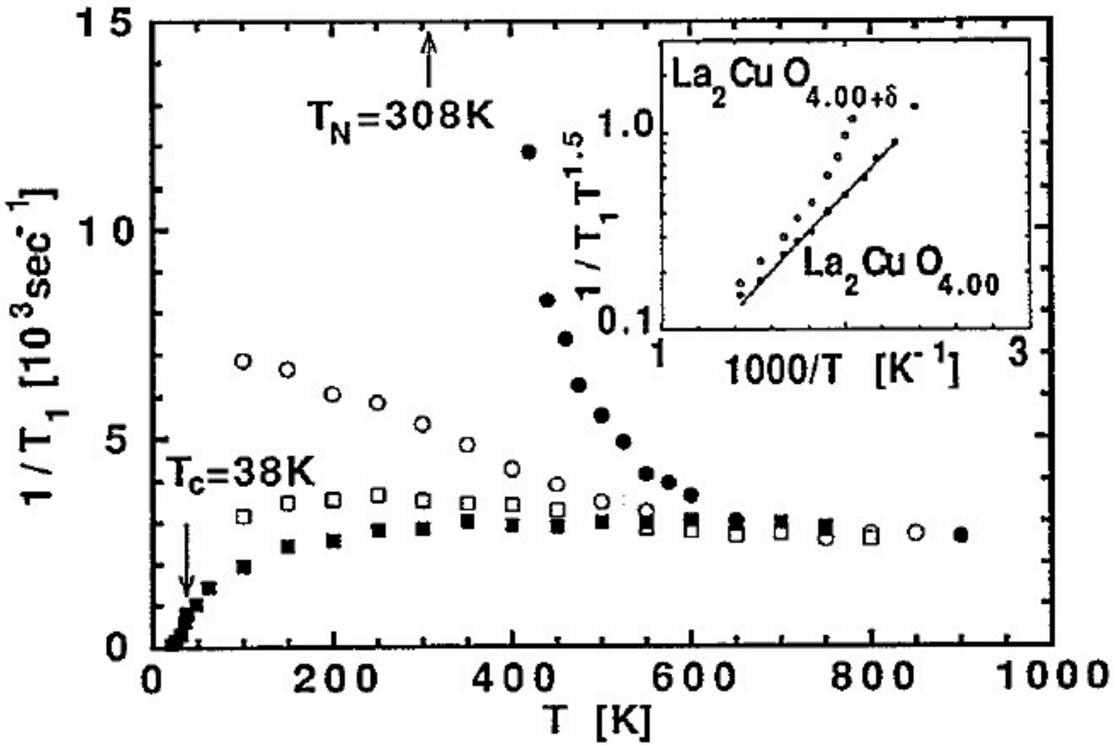
(Phys. Rev. Lett. 70 (1993) 1002; 71 (1993) 1254.)

高温超伝導体の$1/T_1$と$1/T_1T$









Phys. Rev. Lett. 70 (1993) 1002; 71 (1993) 1254.

- **The Self-Consistent Renormalization (SCR) Theory of Spin Fluctuations**

$$\mathrm{Im}\,\chi(q,\omega) = \frac{\chi(0,0)}{1+q^2/\kappa^2}\cdot\frac{\omega\Gamma_q}{\omega^2+\Gamma_q^2}$$

$$\Gamma_q = \Gamma_0 q\left(\kappa^2+q^2\right), \quad \Gamma_0 = A/C$$

$$\kappa^2 = \frac{1}{2\bar{A}}\cdot\frac{N_0}{\chi}, \quad \bar{A} = AN_0/\rho$$

- **Quantitative aspects** (The spin fluctuation parameters)
: Takahashi& Moriya (1985)

$$p_s, \quad \bar{F}_1, \quad T_0 = \Gamma_0 q_B^3/2\pi, \quad T_A = \bar{A}q_B^2$$

($q_B = \left(\frac{6\pi^2}{v_0}\right)^{1/3}$, v_0 the volume per magnetic atom)

The SCR theory ⇔ Experiments

<The Curie temperature, T_C>

$$p_s^2/4 \cong \frac{15cT_0}{T_A}\eta^4 = \frac{15cT_0}{T_A}\left(\frac{T_C}{T_0}\right)^{4/3}$$

$$c = \frac{1}{3^{3/2}}(2\pi)^{-1/3}\Gamma(4/3)\zeta(4/3) = 0.3353\cdots\cdots$$

<Reduced Susceptibility, y>

$$y = \frac{N_0}{2T_A\eta^2}\chi^{-1} \cong \frac{\bar{F}_1 p_s^2}{8T_A\eta^2}\left\{-1 + \frac{1}{c}\int_0^{1/\eta} dz z^3\left[\ln u - \frac{1}{2u} - \psi(u)\right]\right\}$$

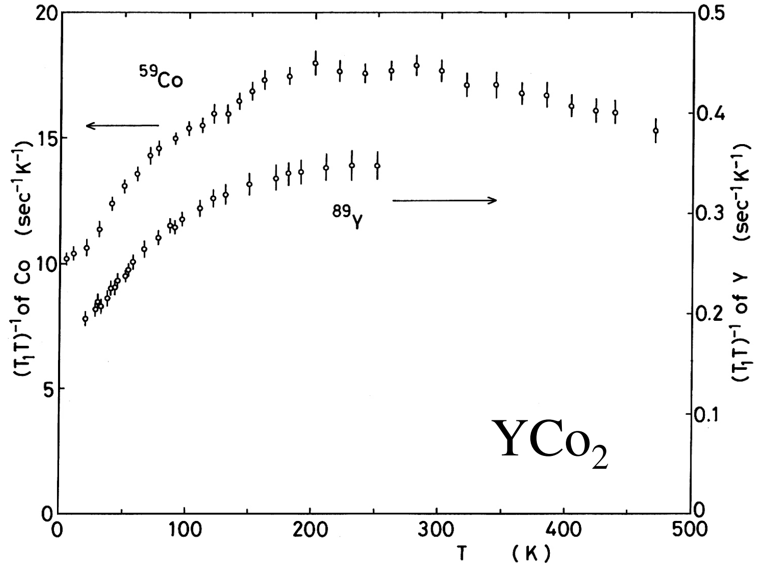
$u = z\left(y + z^2\right)/t$, $\quad t = T/T_C$, $\quad \eta = \left(T_C/T_0\right)^{1/3}$, $\quad \psi$: digamma function

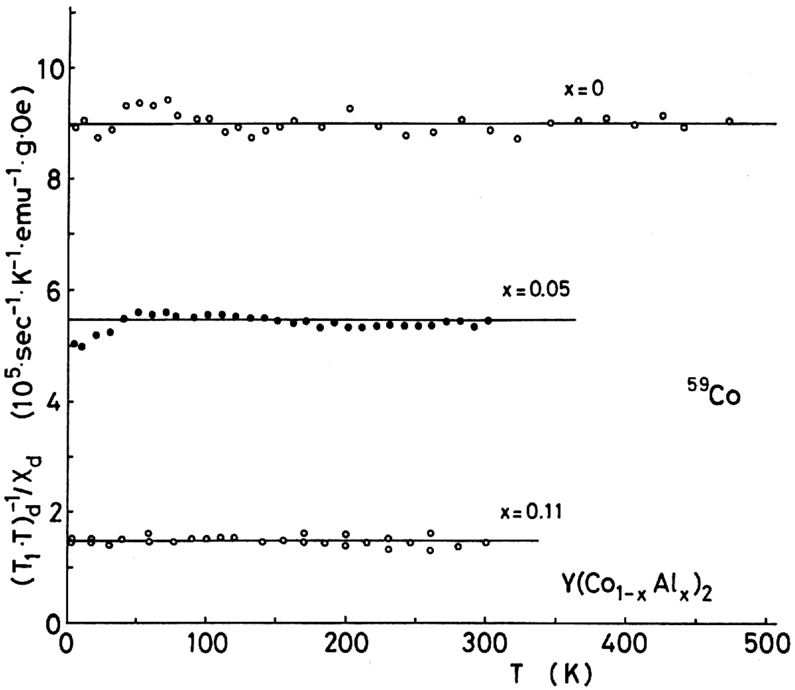
$$\chi = \frac{N_0 p_{eff}^2}{3k_B T_C\left(t^{4/3} - 1\right)}$$

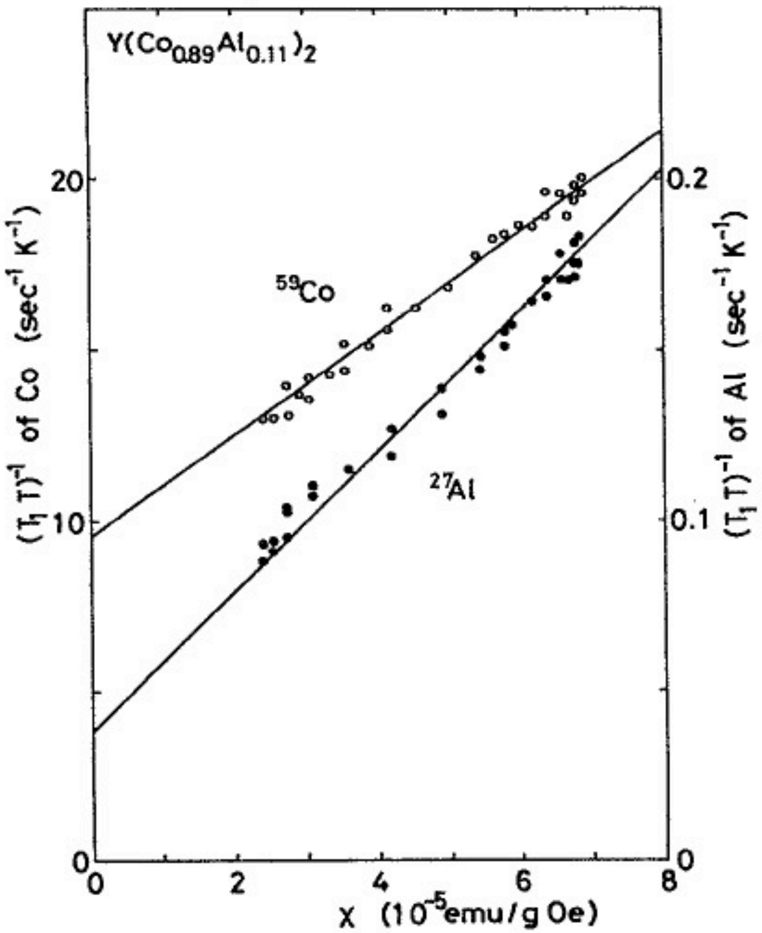
<NMR, T_1>

$$\frac{1}{T_1} = \gamma_N^2 A_{hf}^2 T \frac{\chi}{4\pi^2\mu_B\Gamma_0}, \quad T_0 = \frac{\Gamma_0 q_B^3}{2\pi}$$

核磁気緩和率$1/T_1$：磁化率χ







スピンゆらぎのパラメータ（SCR理論）

Table III. Spin-fluctuation parameters and comparisons between observed and calculated magnetic parameters.

x	$K_0\left(\frac{\mathrm{g\cdot Oe}}{\mathrm{sec\cdot K\cdot emu}}\right)$	$\beta\left(\frac{1}{\mathrm{sec\cdot K}}\right)$	$v_0(\text{Å}^3)$	$\Gamma_0(k_B\,\text{Å}^3)$	$T_0(\mathrm{K})$	$\bar{A}(10^3\,k_B\,\text{Å}^2)$	$T_A(10^4\,\mathrm{K})$	η	η^*
0.13	1244	0.0636	21.14	5135	2290	5.79	1.16	0.145	0.145
0.15	891	0.0590	20.79	4675	2119	3.17	0.634	0.231	0.230
0.17	985	0.0530	20.37	4524	2093	3.45	0.703	0.197	0.197

x	$\bar{f}_1$	$p_{\mathrm{eff}}^{\mathrm{cal}}(\mu_B/\mathrm{Co})$	$p_{\mathrm{eff}}^{\mathrm{obs}}(\mu_B/\mathrm{Co})$	$\theta^{\mathrm{cal}}(\mathrm{K})$	$\theta^{\mathrm{obs}}(\mathrm{K})$	$p_{\mathrm{eff}}^{\prime\mathrm{cal}}(\mu_B/\mathrm{Co})$	$p_{\mathrm{eff}}^{\prime\mathrm{obs}}(\mu_B/\mathrm{Co})$
0.13	0.0190	2.48	2.50	10	9	3.71	3.05
0.15	0.0706	2.60	2.15	41	40	3.68	3.15
0.17	0.0646	2.33	2.13	26	25	3.33	2.84

TABLE I. The temperature T_M at which χ shows maximum, the magnetic susceptibility χ_0 and χ_M at $T=0$ K and T_M, the linear electronic specific-heat coefficient γ, the Stoner enhancement factor $1/(1-\alpha_0)$, and the ratio $\mathcal{K}(\alpha_0)$ in the $Y(Co_{1-x}Al_x)_2$ system.

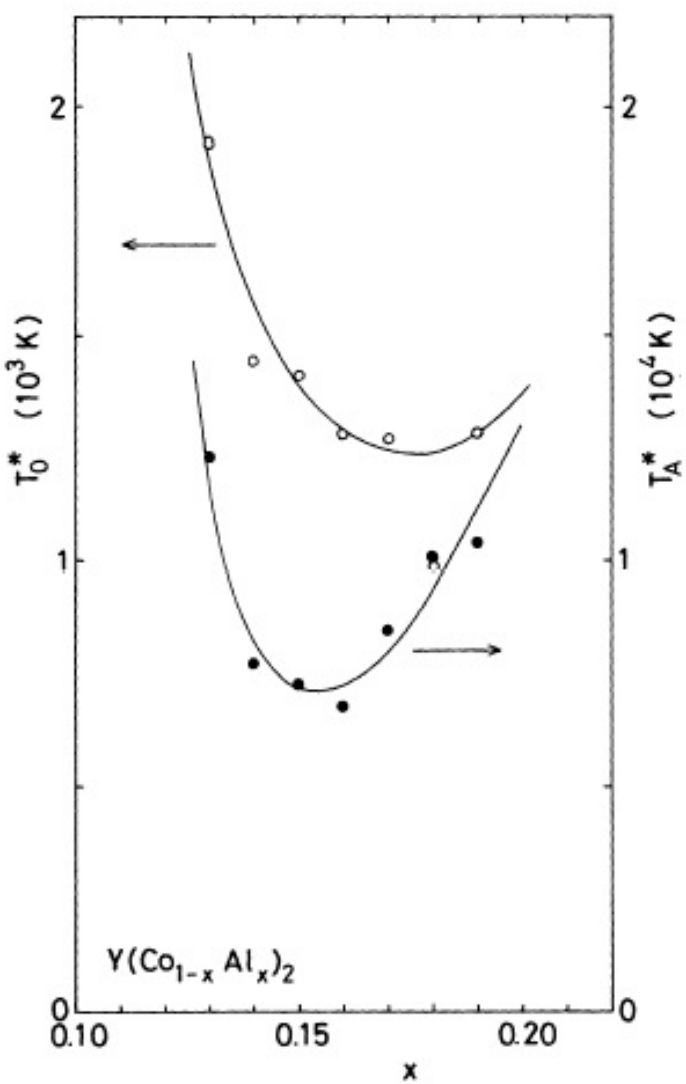
x	T_M (K)	χ_0 (10^{-3} emu/mol Oe)	χ_M (10^{-3} emu/mol Oe)	γ (mJ/mol K^2)	$1/(1-\alpha_0)$	$\mathcal{K}(\alpha_0)$
0.00	250	2.17	3.93	24–36	8–13	0.19–0.28
0.05	145	4.21	6.39	31	19	0.14
0.11	~10	13.9	14.0	45	44	0.04

TABLE II. Hyperfine coupling constant due to the d-electron spins; $A_{hf}(d)$ the coefficient $\mathcal{K}_0=(1/T_1T)_d/\chi_d$ and the Korringa relation term in $1/T_1T$; β the d-spin contribution to $1/T_1T$ at $T=0$ K; $(1/T_1T)_d^0$ and the ratio $\mathcal{K}(\alpha)$ in the $Y(Co_{1-x}Al_x)_2$ system.

x	Nucleus	$A_{hf}(d)$ (10^5 Oe/spin)	$\mathcal{K}_0$ ($sec^{-1}K^{-1}emu^{-1}$ mol)	β ($sec^{-1}K^{-1}$)	$(1/T_1T)_d^0$ ($sec^{-1}K^{-1}$)	$\mathcal{K}(\alpha)$
0.00	^{59}Co	−1.798	4300	2.5	7.5	0.29–0.31
0.05	^{59}Co	−1.199	2690	2.1	10.4	0.18
0.11	^{59}Co	−1.062	700.9	9.5	10.5	0.018
0.11	^{27}Al	−0.1543	10.29	0.038	0.137	0.010

TABLE III. Estimated values of Γ_0 and T_0 together with v_0 (see text).

x	Nucleus	v_0 (Å^3)	Γ_0 (Å^3k_B)	T_0 (K)
0.00	^{59}Co	23.50	909	365
0.05	^{59}Co	25.00	724	273
0.11	^{59}Co	27.17	2687	932
0.11	^{27}Al	27.17	4423	1534



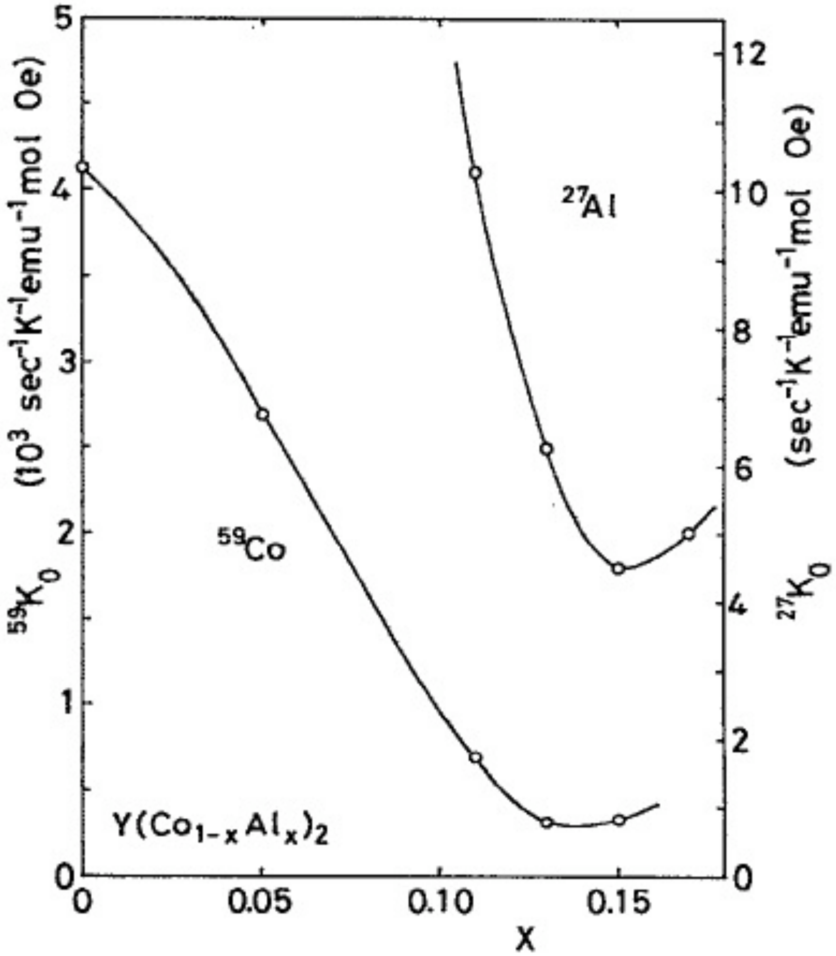
SCR Theory

$$p_s^2/4 \cong \frac{15cT_0}{T_A}\eta^4 = \frac{15cT_0}{T_A}\left(\frac{T_C}{T_0}\right)^{4/3}$$

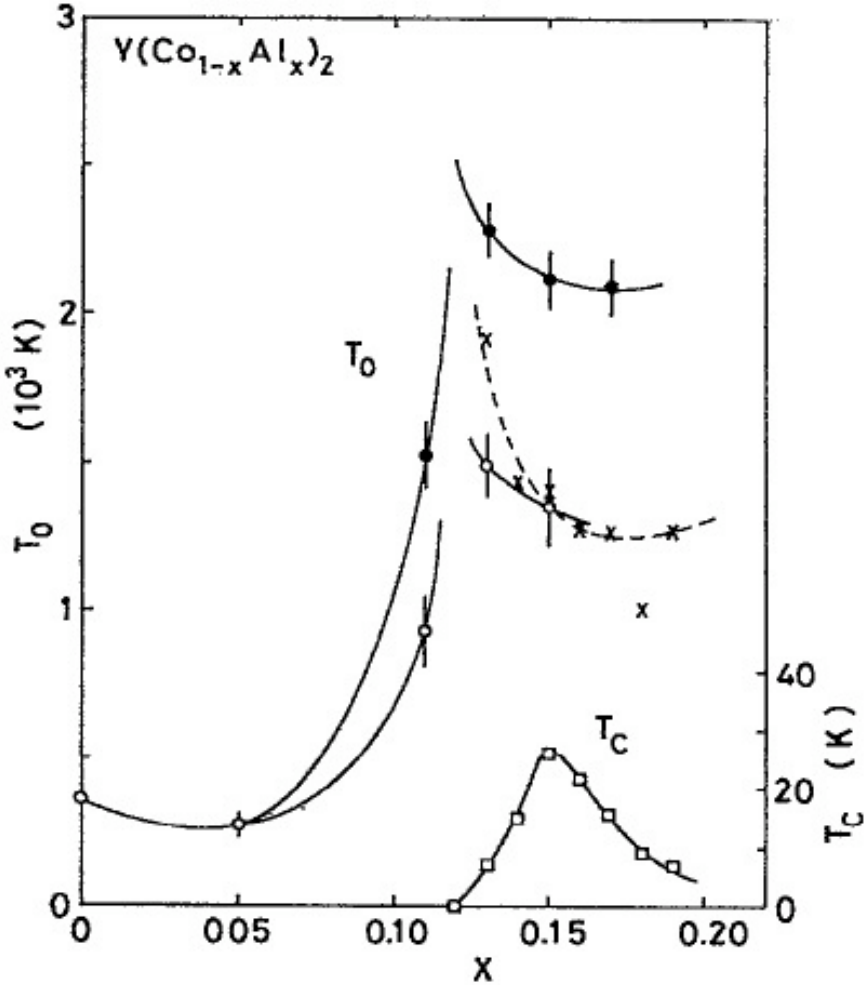
Takahashi Theory

$$\bar{F}_1 = \frac{4\,k_B T_A^2}{15\,T_0}$$

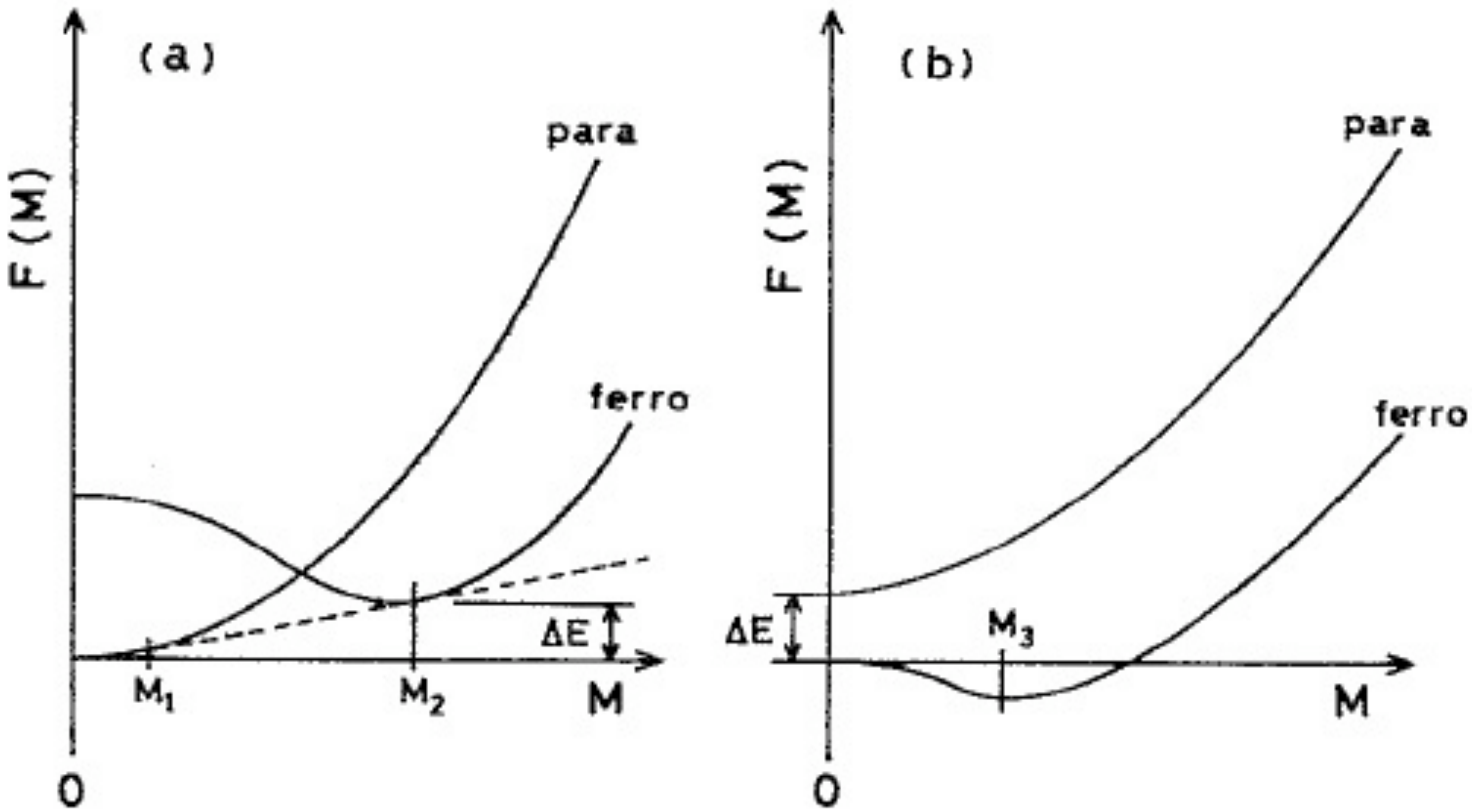
核磁気緩和とT_0



$(10^3\ sec^{-1}K^{-1}emu^{-1}mol\ Oe)$
$^{59}K_0$
$(sec^{-1}K^{-1}emu^{-1}mol\ Oe)$
$^{27}K_0$
^{27}Al
^{59}Co
$Y(Co_{1-x}Al_x)_2$
X



$Y(Co_{1-x}Al_x)_2$
T_0
$(10^3\ K)$
T_0
T_C
$T_C\ (K)$
X

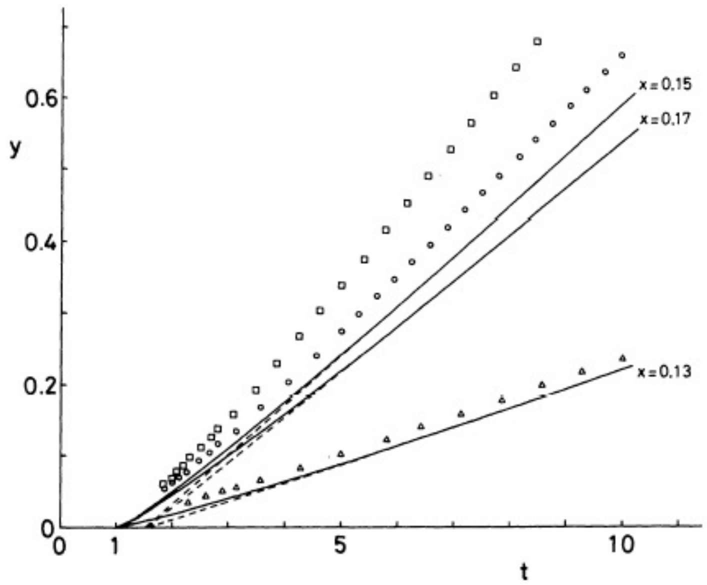

(a)
F (M)
para
ferro
ΔE
M1
M2
M
0
(b)
F (M)
para
ferro
ΔE
M3
M
0

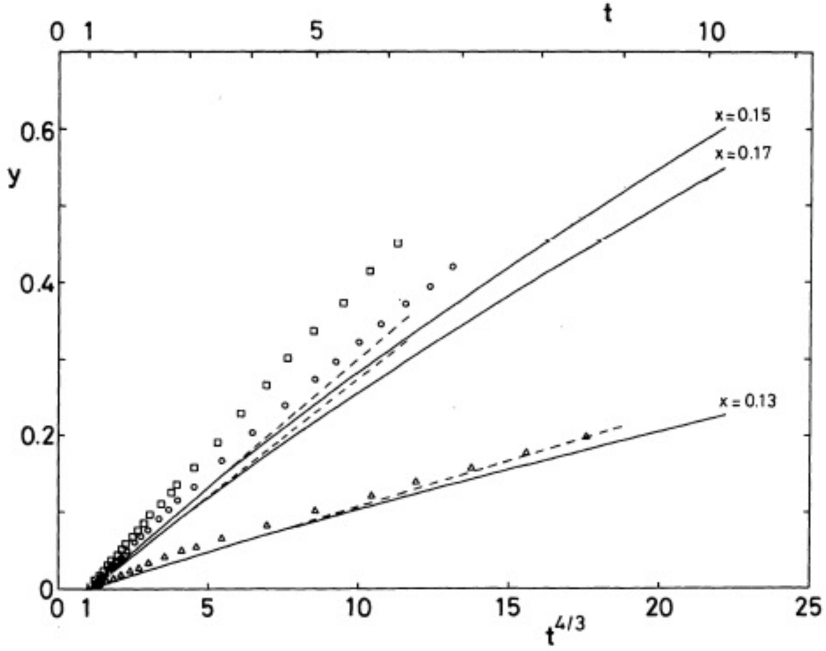
SCR理論による定量的解析

$$p_s,\quad \overline{F}_1,\quad T_0 = \Gamma_0 q_B^3/2\pi,\quad T_A = \overline{A}q_B^2$$

$$y = \frac{N_0}{2T_A\eta^2}\chi^{-1} \cong \frac{\overline{F}_1 p_s^2}{8T_A\eta^2}\left\{-1+\frac{1}{c}\int_0^{1/\eta} dz z^3\left[\ln u - \frac{1}{2u} - \psi(u)\right]\right\}$$

$$u = z\left(y + z^2\right)/t,\quad t = T/T_C,\quad \eta = \left(T_C/T_0\right)^{1/3},\quad \psi\text{: digamma function}$$





SCR理論,Takahashi理論による定量的解析

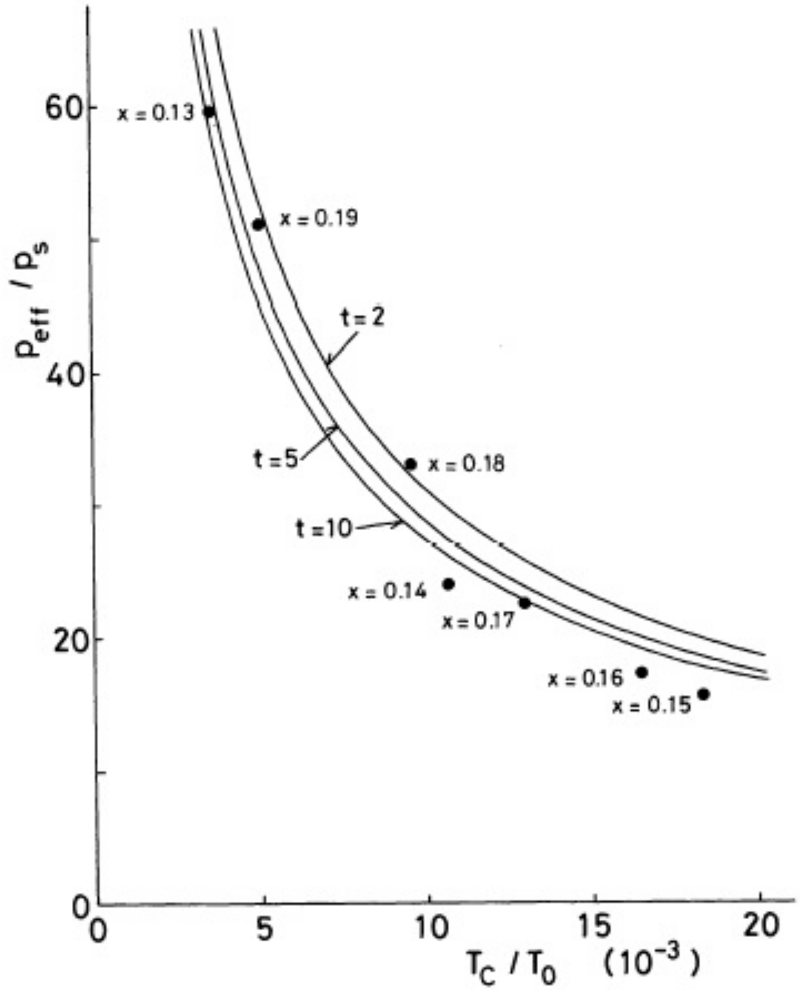
Table IV. Parameters, T_0^*, T_A^*, $p_{\rm eff}^*$ and $p_{\rm eff}'^*$ for x=0.13, 0.15 and 0.17.

x	$T_0^*(10^3\ \mathrm{K})$	$T_A^*(10^4\ \mathrm{K})$	$p_{\rm eff}^{*\rm cal}(\mu_{\rm B}/\mathrm{Co})$	$p_{\rm eff}'^{*\rm cal}(\mu_{\rm B}/\mathrm{Co})$
0.13	1.92	1.23	2.77	4.20
0.15	1.41	0.726	3.24	4.78
0.17	1.27	0.846	3.16	4.70

Table V. Spin-fluctuation parameters, T_0^*, T_A^*, $T_{\rm C}/T_0^*$ and the observed values of $p_{\rm eff}'^{\rm obs}$ and $p_{\rm eff}'^{\rm obs}/p_s$ for $0.13 \leqq x \leqq 0.19$.

x	0.13	0.14	0.15	0.16	0.17	0.18	0.19
$T_0^*(10^3\ \mathrm{K})$	1.92	1.44	1.41	1.28	1.27	0.984	1.28
$T_A^*(10^4\ \mathrm{K})$	1.23	0.772	0.726	0.676	0.846	1.01	1.40
$T_{\rm C}/T_0^*(10^{-3})$	3.6	10.7	18.4	17.2	13.0	9.6	5.1
$p_{\rm eff}'^{\rm obs}(\mu_{\rm B}/\mathrm{Co})$	3.05	3.10	3.15	2.98	2.84	2.67	2.38
$p_{\rm eff}'^{\rm obs}/p_s$	72.6	33.0	22.8	22.9	29.9	42.4	59.5

SCR, Takahashiによる
一般的な
p_{eff}/p_s vs T_C/T_0プロット



SCR

$$p_s^2/4 \cong \frac{15cT_0}{T_A}\eta^4 = \frac{15cT_0}{T_A}\left(\frac{T_C}{T_0}\right)^{4/3}$$

Takahashi

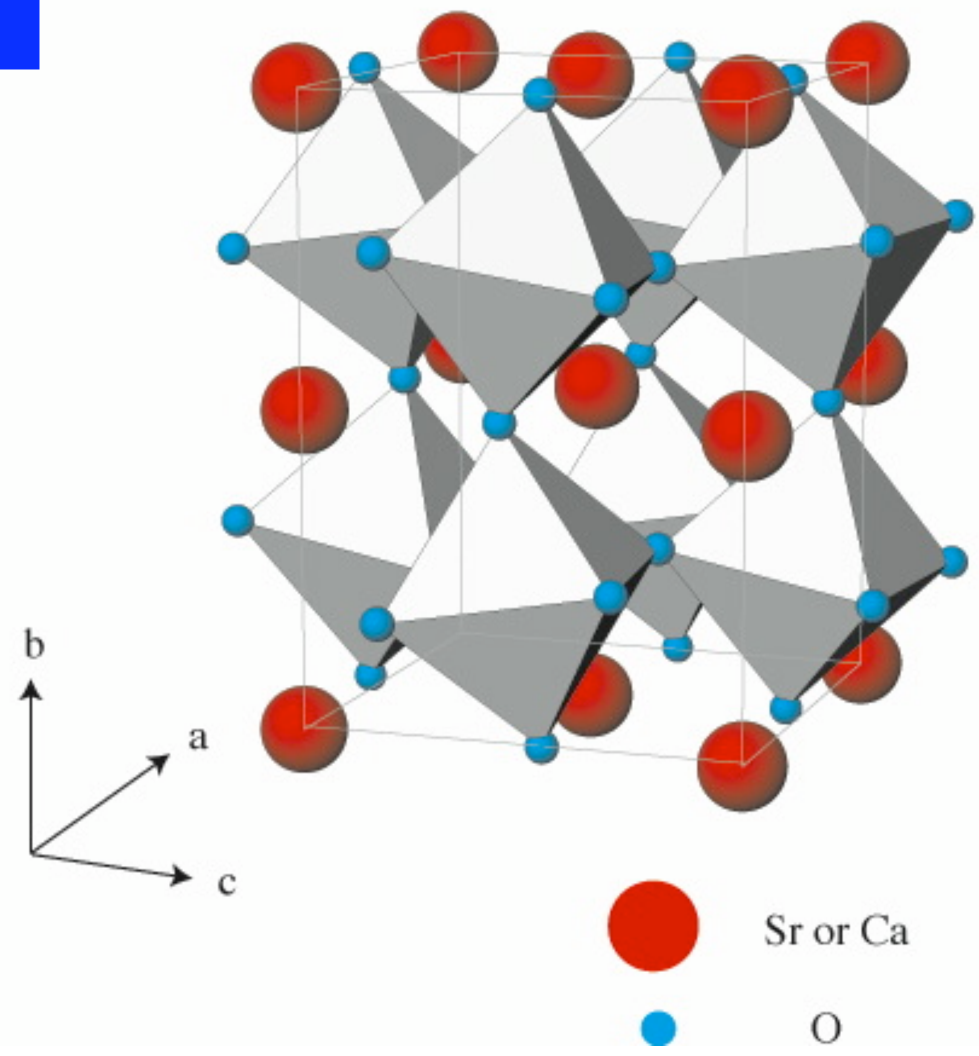
$$\bar{F}_1 = \frac{4\,k_B T_A^2}{15\,T_0}$$

磁化率

$$y = \frac{N_0}{2T_A\eta^2}\chi^{-1} \cong \frac{\bar{F}_1 p_s^2}{8T_A\eta^2}\left\{-1 + \frac{1}{c}\int_0^{1/\eta} dz z^3\left[\ln u - \frac{1}{2u} - \psi(u)\right]\right\}$$

$Sr_{1-x}Ca_xRuO_3$

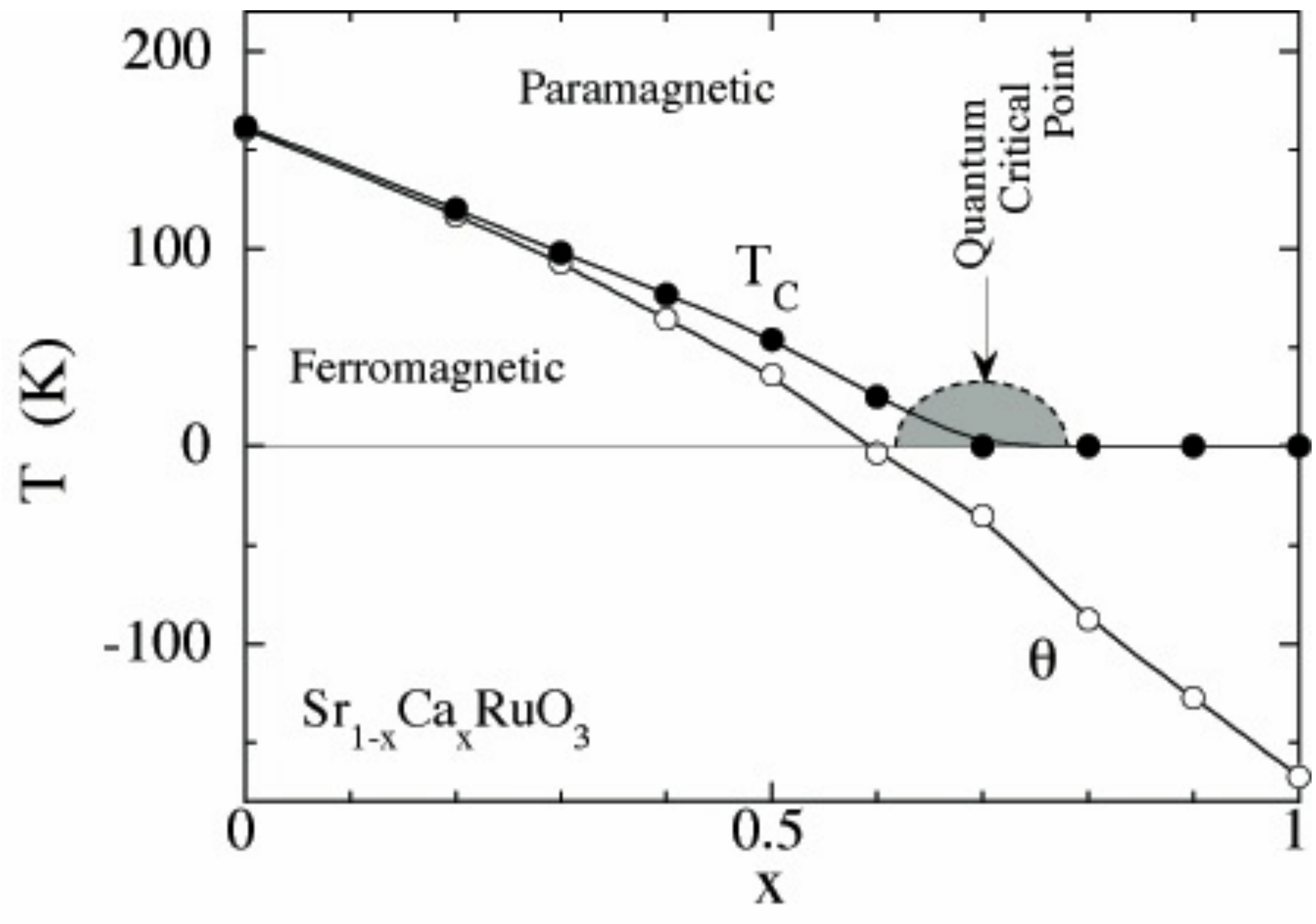
遍歴電子強磁性系



歪んだペロブスカイト構造

$GdFeO_3$ type

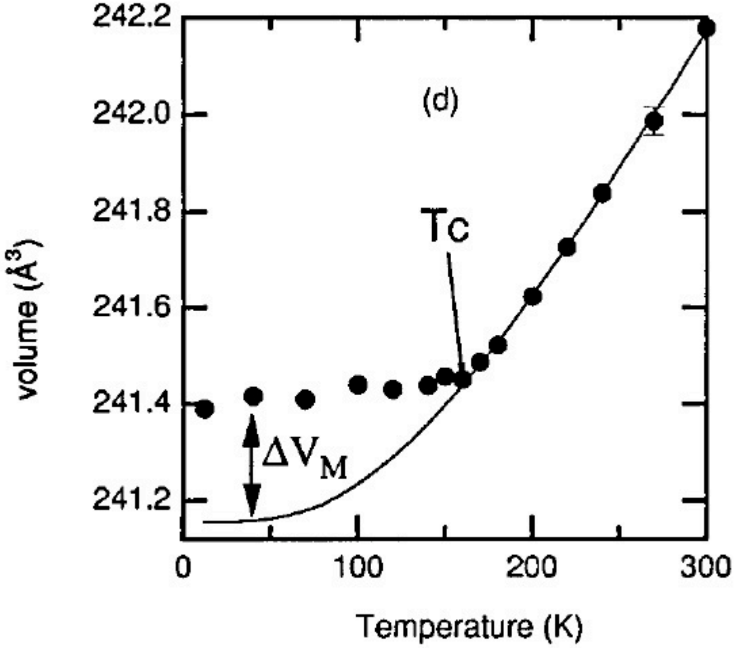
$Sr_{1-x}Ca_xRuO_3$の磁性



強磁性
↓
反強磁性

Goodenough et al.

↑
???

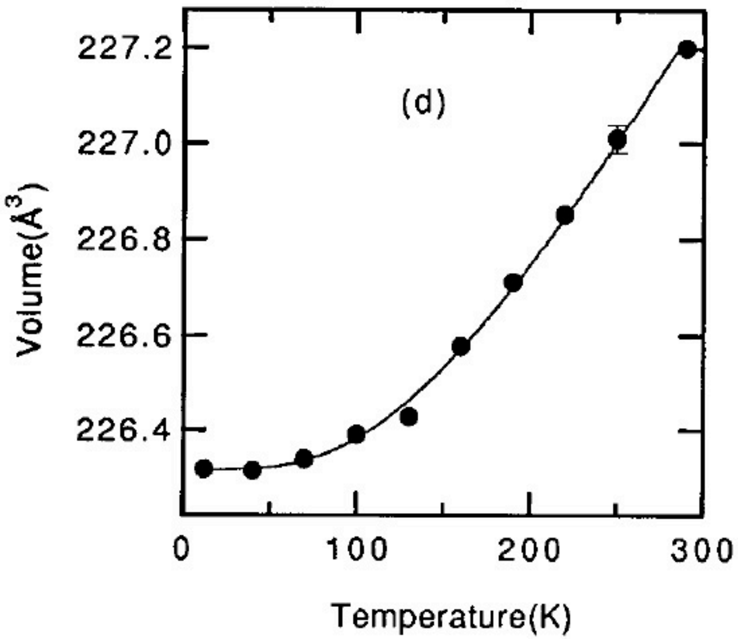


SrRuO$_3$

インバー効果の観測

↓

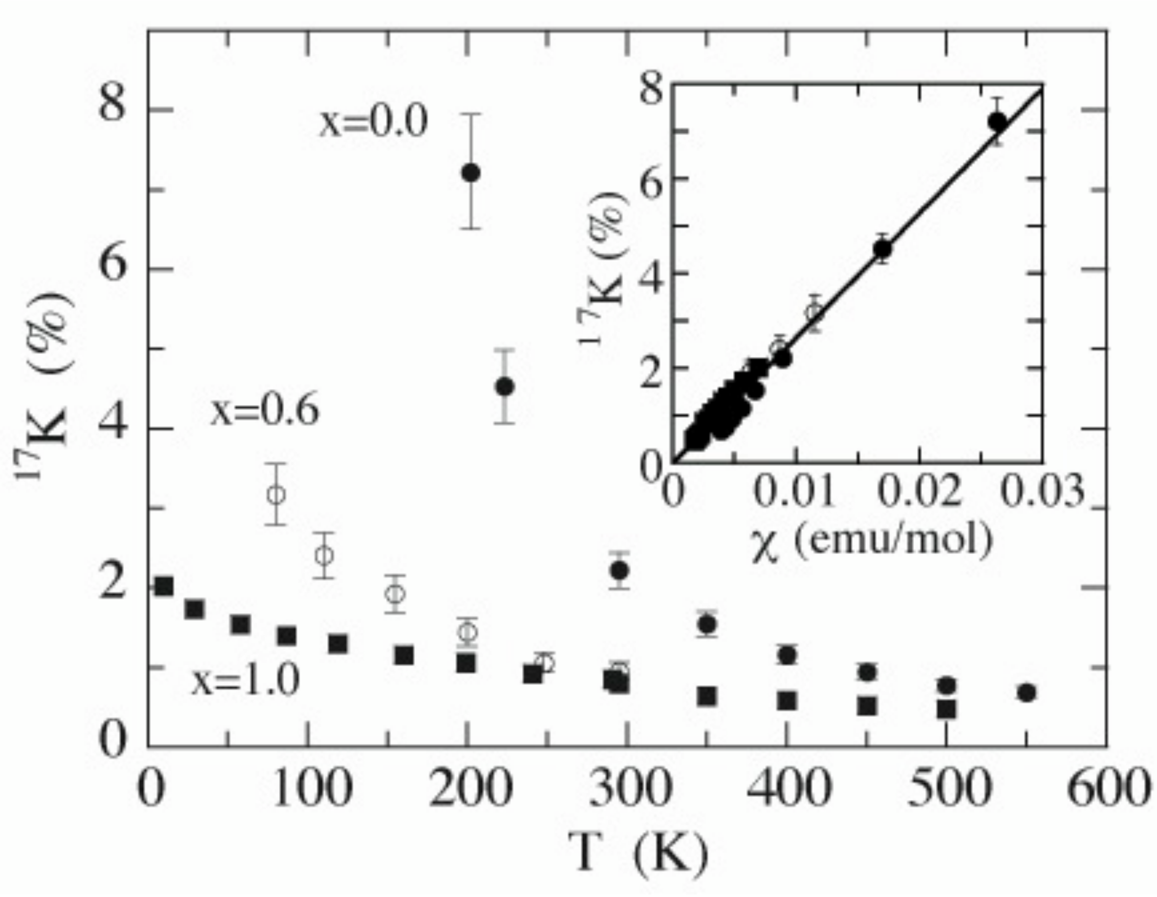
遍歴電子強磁性



CaRuO$_3$

Pauli常磁性

$Sr_{1-x}Ca_xRuO_3$における^{17}O NMRナイトシフト

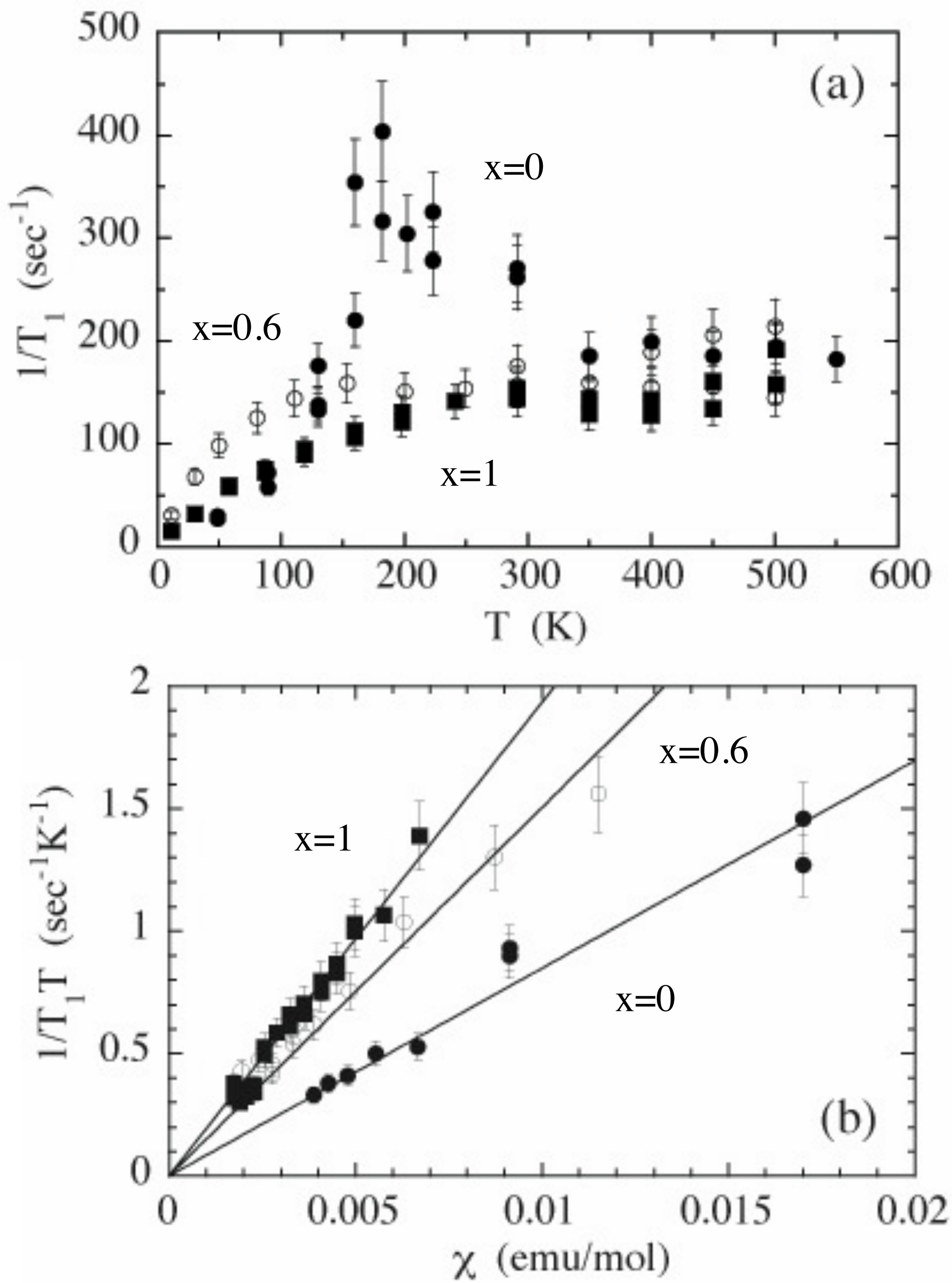


$Sr_{1-x}Ca_xRuO_3$ における ^{17}O 核磁気緩和 $1/T_1$

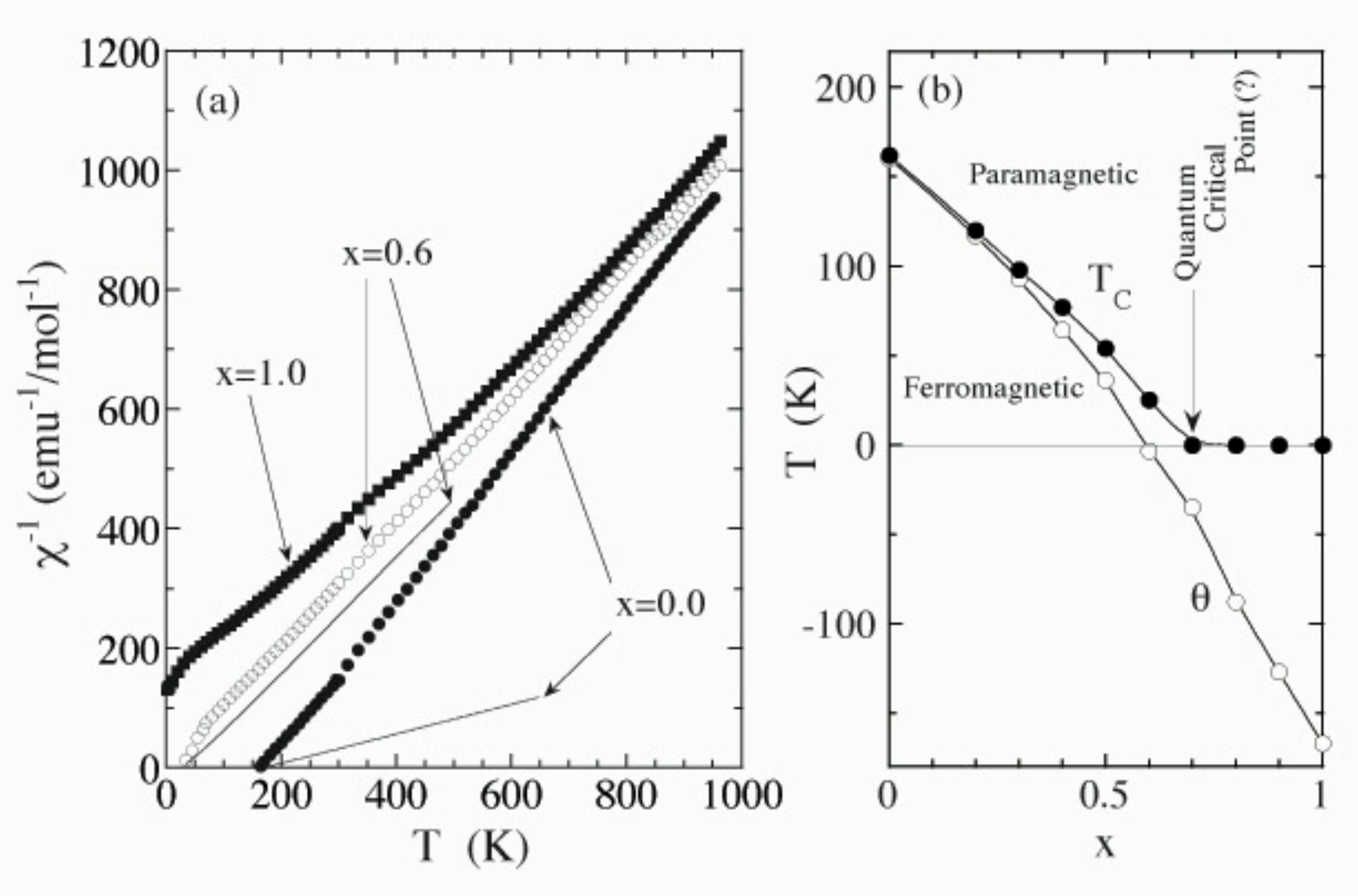
$$\left(\frac{1}{T_1}\right)_{SCR}^{F} \propto \frac{T}{M_0^2} \propto \frac{T}{T_c - T} \quad (T < T_c)$$

$$\left(\frac{1}{T_1}\right)_{SCR}^{F} \propto T\chi_0 \propto \frac{T}{T - T_c} \quad (T > T_c)$$

$$\frac{1}{T_1} = \gamma_N^2 A_{hf}^2 T \frac{\chi}{4\pi^2 \mu_B \Gamma_0}, \quad T_0 = \frac{\Gamma_0 q_B^3}{2\pi}$$



SCR理論による定量的解析：磁化率



$$y = \frac{N_0}{2T_A\eta^2}\chi^{-1} \cong \frac{\overline{F}_1 p_s^2}{8T_A\eta^2}\left\{-1+\frac{1}{c}\int_0^{1/\eta} dz z^3\left[\ln u - \frac{1}{2u} - \psi(u)\right]\right\}$$ ：SCR theory