



## Franceの磁性物理学の巨人

Pierre Curie, Paul Langevin  
 Pierre Weiss, Leon Brillouin, Louis Neel

Curieの法則:  $\chi=C/T, \chi=C/(T-\theta)$  (1895年頃)  
 強磁性転移点: キュリー温度の発見(Fe, Co, Ni)

Langevin の理論 (1905年) 原子磁気モーメント  $M$

$$-M \cdot H = -MH \cos \theta$$

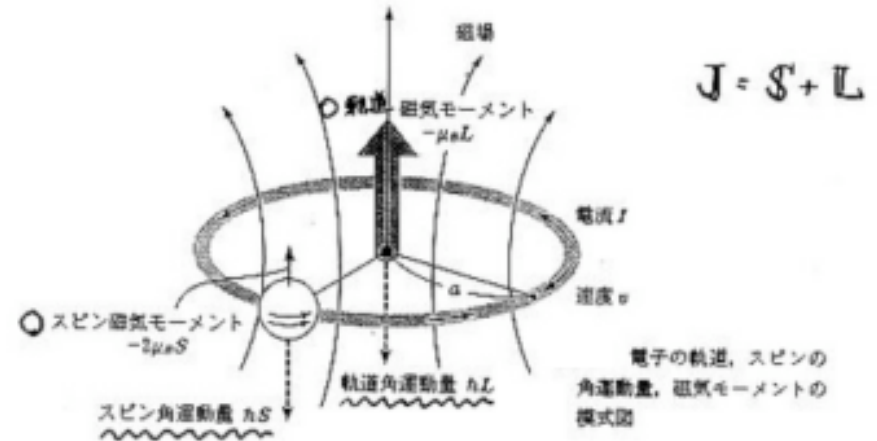
$$M = N \frac{\int MH \cos \theta \exp(MH \cos \theta / k_B T) d\omega}{\int \exp(MH \cos \theta / k_B T) d\omega}$$

$$= NM \left[ \coth\left(\frac{MH}{k_B T}\right) - \frac{1}{\left(\frac{MH}{k_B T}\right)} \right] = NM L\left(\frac{MH}{k_B T}\right)$$

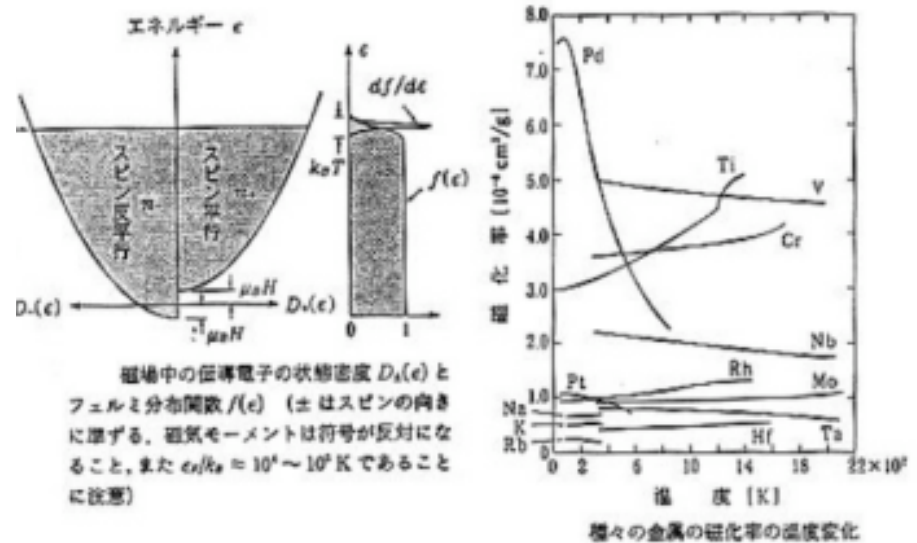
$$\left\{ \begin{array}{l} x \rightarrow \infty \rightarrow NM \\ x \ll 1 \rightarrow NM \frac{1}{3} \left(\frac{MH}{k_B T}\right) = \frac{NM^2 H}{3k_B T} \rightarrow \chi = \frac{C}{T}, C = \frac{NM^2}{3k_B} \text{ キュリー則} \end{array} \right.$$

Weiss Langevin 理論を強磁性に導入 (1907年)  
 分子磁場  $AM$   $M = NM L\left(\frac{\mu(H+AM)}{k_B T}\right) \rightarrow NM L\left(\frac{\mu AM}{k_B T}\right)$   
 $\chi = \frac{\mu AM}{k_B T}, M = NM L(x), M = \frac{k_B T}{\mu A} x$   
 $k_B T_c = \frac{1}{3} NM^2 A, T > T_c: \chi = C/(T-T_c) \text{ キュリー-ワイス則}$

原子の磁気モーメント ... 電子



金属の磁性 ... Pauli 常磁性





# International Conference on Magnetism

**August 20-25, 2006  
Kyoto, Japan**

**Kyoto International  
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<http://icm2006.com/>

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## Calendar

Call for papers November 1 (Tue.), 2005  
 Abstract deadline January 18 (Wed.), 2006  
 Deadline for contributed papers May 24 (Wed.), 2006  
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## Satellites

19th International Colloquium on Magnetic Films and Surfaces (ICMFS2006)  
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 4th International Conference on Physics and Application of Spin-related Phenomena in Semiconductors (PASPS-IV)  
 August 15-18, 2006, Sendai  
[http://www.isl.titech.ac.jp/~munelab/PASPS4/Flyer\\_PASPS.pdf](http://www.isl.titech.ac.jp/~munelab/PASPS4/Flyer_PASPS.pdf)  
 Yamada Conference LX on Research in High Magnetic Fields  
 August 16-19, 2006, Sendai  
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 Advances in Neutron, SR,  $\mu$ SR and NMR Researches -complementary probes for magnetism-  
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**日本:磁性大国!**

**ICM-1965  
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**日本、京都で!**

# 超伝導のGinzburg-Landau理論

$$F_s - F_n = \int d\mathbf{r} \left[ -a|\psi|^2 + \frac{1}{2}b|\psi|^4 + \frac{1}{8\pi}(\text{rot}\mathbf{A})^2 + \frac{1}{4m} \left| -i\hbar \frac{\partial\psi}{\partial\mathbf{r}} - \frac{2e}{c}\mathbf{A}\psi \right|^2 \right]$$

自由エネルギーのLandau展開

$$p \Rightarrow p + \frac{e}{c}\mathbf{A} \quad \nabla \Rightarrow \nabla + \frac{e}{i\hbar c}\mathbf{A} \quad B = \text{rot}\mathbf{A}$$

<ゲージ変換, ゲージ不変性>

$$H = \int d\mathbf{r} \sum_{\sigma} \psi_{\sigma}^+(r) \left( -\frac{\hbar^2}{2m} \right) \left\{ \nabla - \frac{ie}{\hbar c}\mathbf{A}(r) \right\}^2 \psi_{\sigma}(r) + H_{\text{int}}$$

$$\mathbf{A}' = \mathbf{A} + \frac{\partial\chi}{\partial\mathbf{r}} \quad : \text{ベクトルポテンシャルのゲージ変換}$$

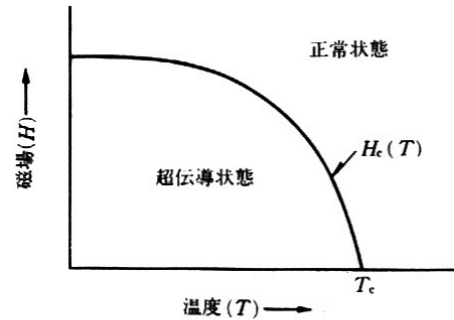
$$-\frac{\hbar^2}{4m} \left( \frac{\partial}{\partial\mathbf{r}} - \frac{2ie}{\hbar c}\mathbf{A} \right)^2 \psi = a\psi - b|\psi|^2\psi \quad : \text{GL方程式}$$

$$2\pi\sqrt{2}H_c\xi\lambda = \phi_0 = \frac{\pi\hbar c}{|e|}$$

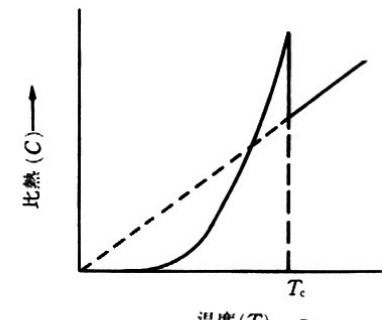
$$\sqrt{2}\kappa > 1 \Rightarrow H_{c2} > H_c \quad : \text{第2種超伝導体}$$

$$\sqrt{2}\kappa < 1 \Rightarrow H_{c2} < H_c \quad : \text{第1種超伝導体}$$

$$\kappa = \lambda/\xi = \sqrt{\frac{m^2c^2b}{2\pi\hbar^2e^2}} \quad H_c = \sqrt{\frac{4\pi a^2}{b}} \quad H_{c2} = \frac{2mca}{\hbar|e|} = \frac{\phi_0}{2\pi\xi^2} = \sqrt{2}\kappa H_c$$



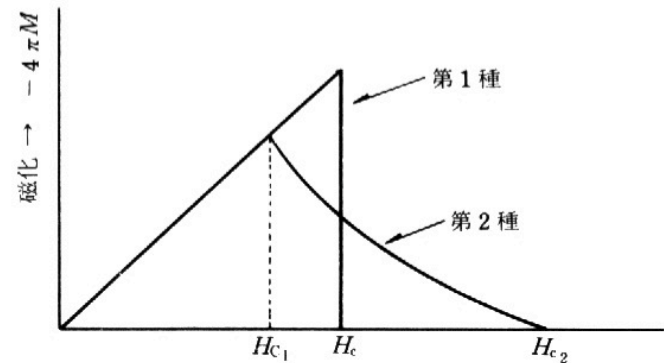
超伝導体の磁場と温度の関係 (相図)



超伝導体の比熱の温度変化

$$\psi \Rightarrow \psi_{\sigma}'(r) = \psi_{\sigma}(r) \exp\left\{ \frac{2ie}{\hbar c}\chi(r) \right\}$$

$$\theta = \frac{2e}{\hbar c}\chi(r) \quad \psi'(r) = \psi(r) \exp(i\theta)$$



超伝導体の磁化 (M) と磁場 (第1種, 第2種超伝導体)

# 超伝導のBCS (Bardeen, Cooper, Schrieffer) 理論

電子対 (クーパー対) 凝縮 : 電子のもつ波動性がマクロなスケールで出現することが本質

$$\langle \text{Bose粒子系の量子力学} \rangle \quad \left. \begin{aligned} [b_k, b_{k'}^+] &= \delta_{kk'} \\ [b_k, b_{k'}] &= [b_k^+, b_{k'}^+] = 0 \end{aligned} \right\} \quad H_B = \sum_k \hbar\omega_k b_k^+ b_k$$

$$\mathfrak{S} = H - \mu N \quad (N: \text{粒子数を表す演算子}, \mu: \text{化学ポテンシャル})$$

<位相表示>  $N^*$  : 平均,  $n$  : ゆらぎ

$$\phi_\theta = \sqrt{\frac{1}{\Delta N}} \sum_{-\Delta N/2 < n < \Delta N/2} e^{in\theta} \phi(N^* + n) \quad \theta = \left(\frac{2\pi}{\Delta N}\right)l, \quad l = 0, \pm 1, \pm 2, \pm 3, \dots, \pm \frac{1}{2}\Delta N$$

$$\langle \phi_\theta | b_0 | \phi_\theta \rangle = (\Delta N)^{-1} \sum_n \langle \phi(N^* + n - 1) | b_0 | \phi(N^* + n) \rangle \approx N_0^{1/2} e^{i\theta}$$

電子と同じようにBose粒子を量子化された波と見なし, 空間の各点 $r$ で定義された演算子で記述する

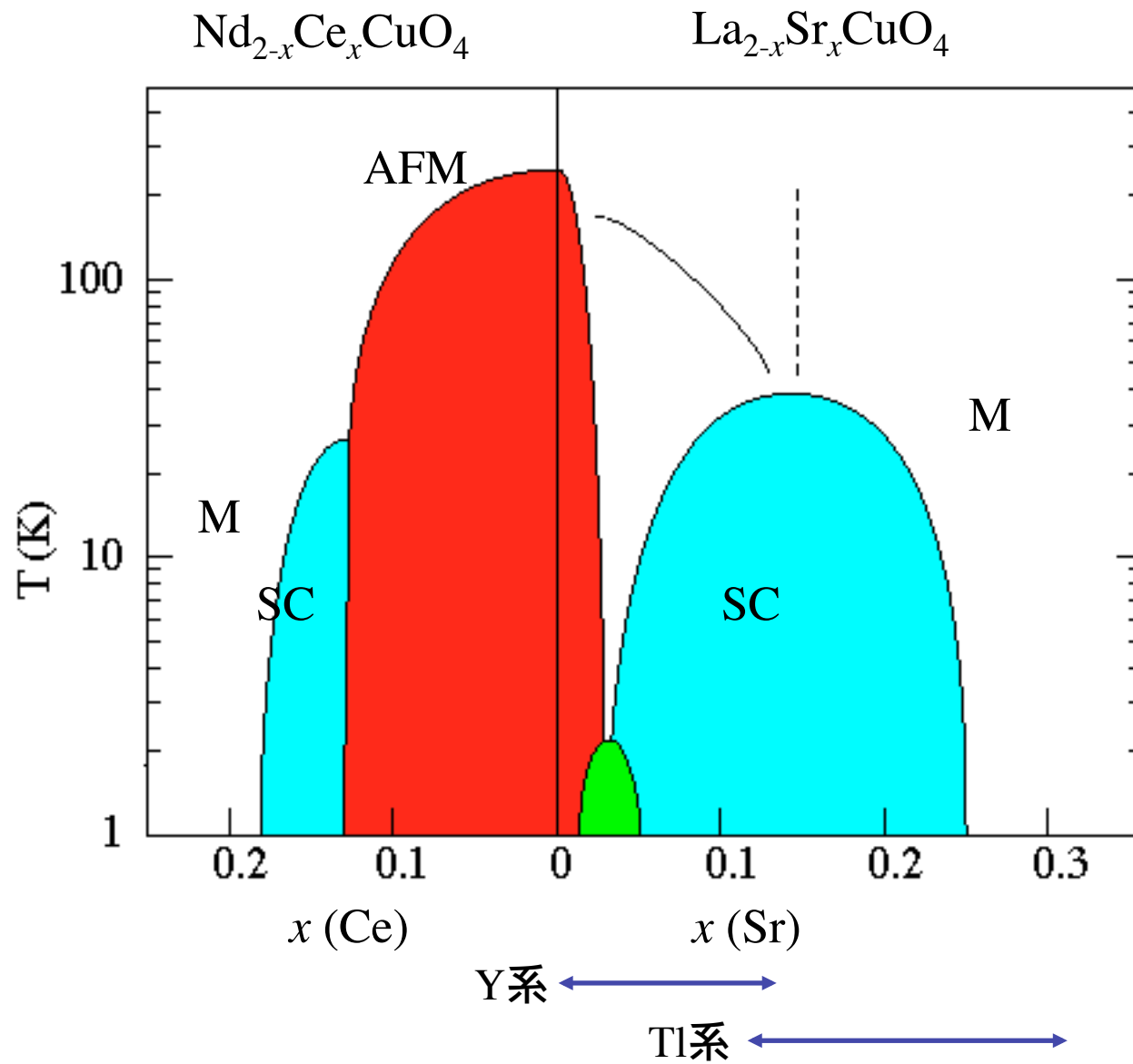
$$\psi(r) = \frac{1}{\sqrt{V}} \sum_k e^{ik \cdot r} b_k \quad \langle \psi(r) \rangle = \langle \phi_\theta | \psi(r) | \phi_\theta \rangle \approx \left(\frac{N_0}{V}\right)^{1/2} e^{i\theta} = \rho^{1/2} e^{i\theta}$$

<電子対>             $\uparrow \uparrow$  triplet     $\uparrow \downarrow$  singlet

重心が静止し逆向きのスピンをもった電子対の消滅・生成  $B_k = a_{k\uparrow} a_{-k\downarrow}$ ,  $B_k^+ = a_{-k\downarrow}^+ a_{k\uparrow}^+$

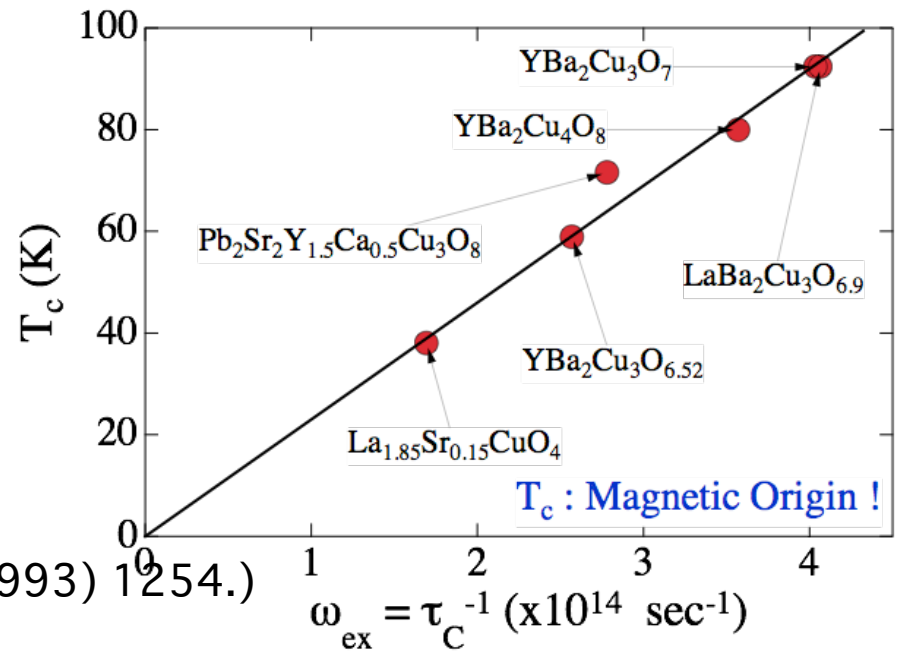
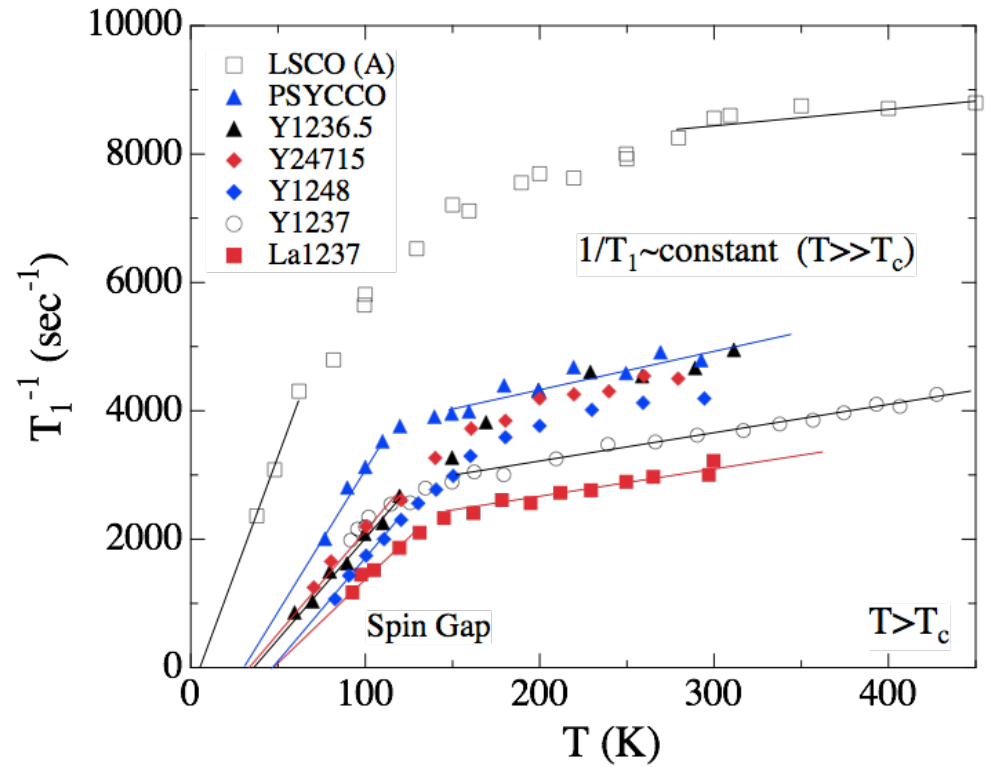
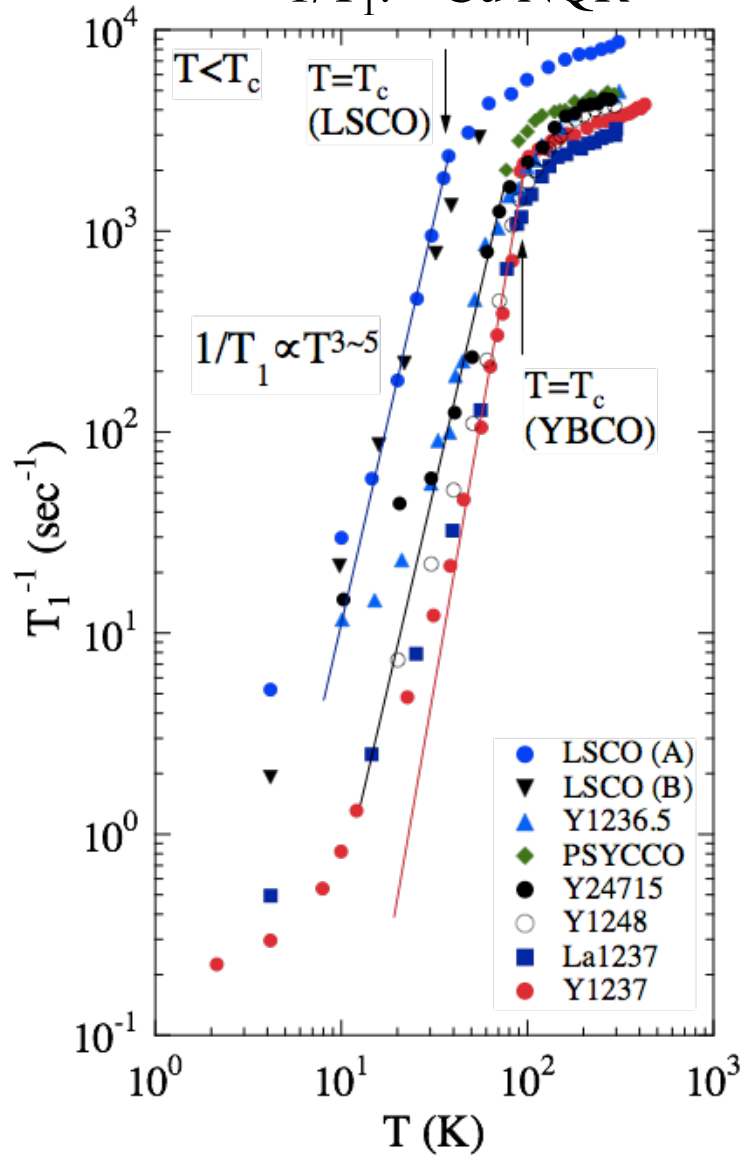
$$\text{フェルミガス状態: } \phi_F = \prod_{k < k_F} B_k^+ \phi_V \quad (\phi_V \text{は真空状態を表す})$$

# 高温超伝導体の電子状態の相図



# 銅酸化物高温超伝導体の核磁気緩和

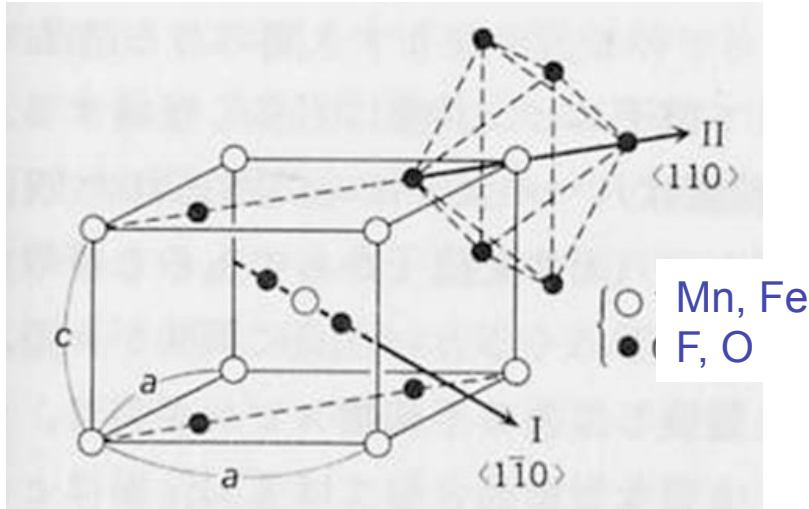
$1/T_1$ :  $^{63}\text{Cu}$  NQR



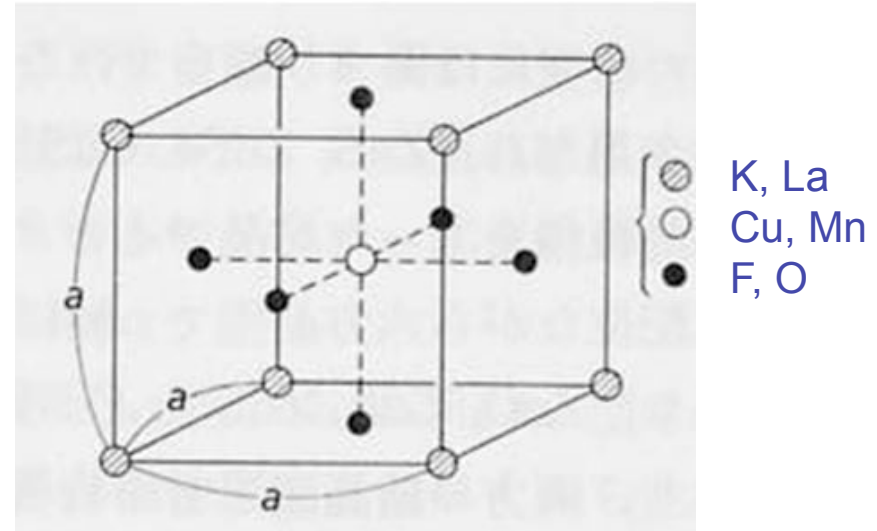
(Phys. Rev. Lett. 70 (1993) 1002; 71 (1993) 1254.)

# 結晶場によるエネルギー準位の分裂

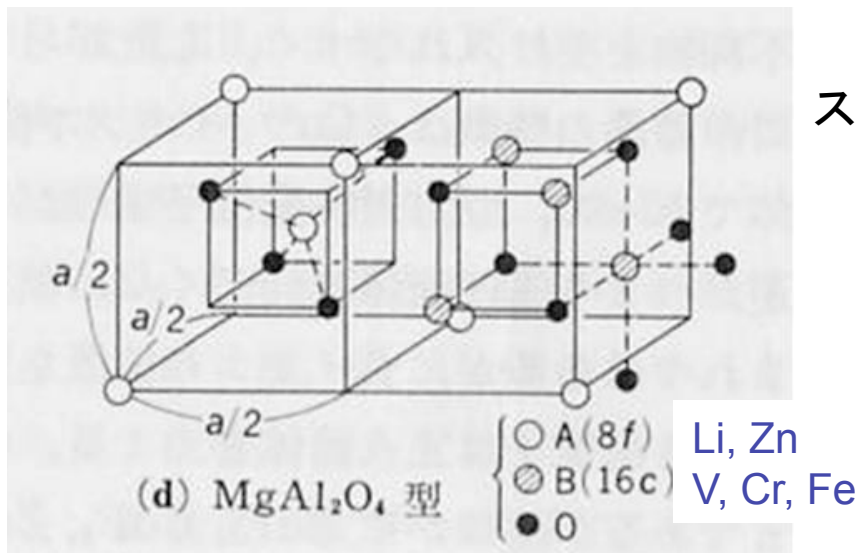
## 色々なイオン結晶磁性体の構造



ルチル (tetragonal),  $\text{MnF}_2$ ,  $\text{VO}_2$



ペロブスカイト (cubic),  $\text{KCuF}_3$ ,  $\text{LaMnO}_3$



スピネル (cubic),  $\text{Fe}_3\text{O}_4$ ,  $\text{ZnCr}_2\text{O}_4$ ,  $\text{LiV}_2\text{O}_4$

周囲の陰イオンが作る電場は球対称性を破る。



d状態のエネルギー準位が分裂

## 結晶場の原因

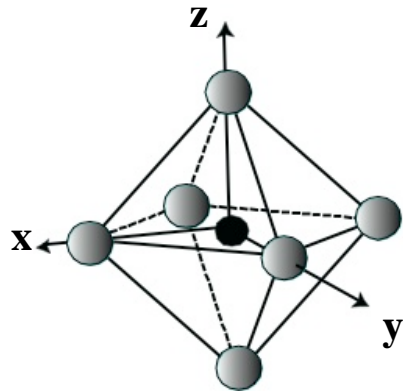
1. 周囲の陰イオンが作る静電ポテンシャル
2. 陰イオンのp状態との混成(d-p 混成)

3d遷移金属イオンでは結晶場のエネルギーがスピン軌道相互作用より大きい。

大きさを正確に計算するのは困難

結晶場の固有状態は対称性によって決まる。(群論)

例: 正八面体の結晶場 ( $O_h: 4C_3, 3C_4, 6C_2$  など)



3d波動関数  
(線形変換)

$$Y_{2,0} = \frac{\sqrt{10}}{4} (3\cos^2\theta - 1) \frac{1}{\sqrt{2\pi}}$$

$$Y_{2,\pm 1} = \frac{\sqrt{15}}{2} \sin\theta \cos\theta \frac{1}{\sqrt{2\pi}} \exp(\pm i\varphi)$$

$$Y_{2,\pm 2} = \frac{\sqrt{15}}{4} \sin^2\theta \frac{1}{\sqrt{2\pi}} \exp(\pm i2\varphi)$$

$$\left. \begin{aligned} \Psi_1 &= \frac{1}{\sqrt{2}} (Y_{2,1} + Y_{2,-1}) = \frac{\sqrt{15}}{2\sqrt{\pi}} \frac{xz}{r^2} \\ \Psi_2 &= \frac{1}{\sqrt{2}i} (Y_{2,1} - Y_{2,-1}) = \frac{\sqrt{15}}{2\sqrt{\pi}} \frac{yz}{r^2} \\ \Psi_3 &= \frac{1}{\sqrt{2}i} (Y_{2,2} - Y_{2,-2}) = \frac{\sqrt{15}}{2\sqrt{\pi}} \frac{xy}{r^2} \end{aligned} \right\} d\varepsilon (t_{2g})$$

$$\left. \begin{aligned} \Psi_4 &= \frac{1}{\sqrt{2}} (Y_{2,2} + Y_{2,-2}) = \frac{\sqrt{15}}{4\sqrt{\pi}} \frac{(x^2 - y^2)}{r^2} \\ \Psi_5 &= Y_{2,0} = \frac{\sqrt{15}}{4\sqrt{\pi}} \frac{(3z^2 - r^2)}{r^2} \end{aligned} \right\} d\gamma (e_g)$$

# 正八面体結晶場の固有状態とエネルギー準位

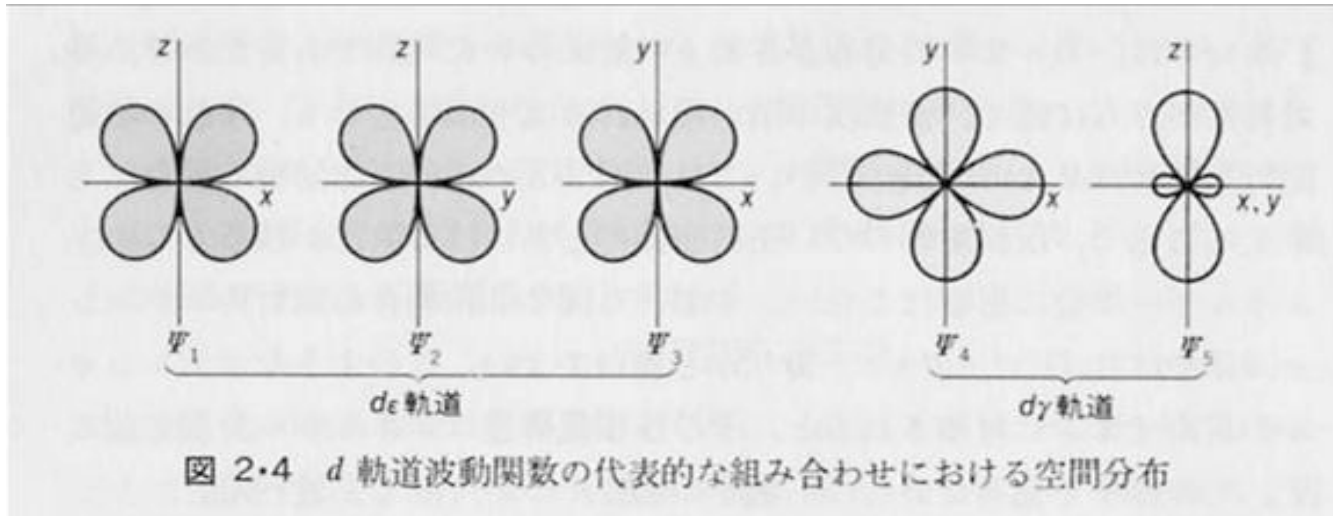


図 2.4 d 軌道波動関数の代表的な組み合わせにおける空間分布

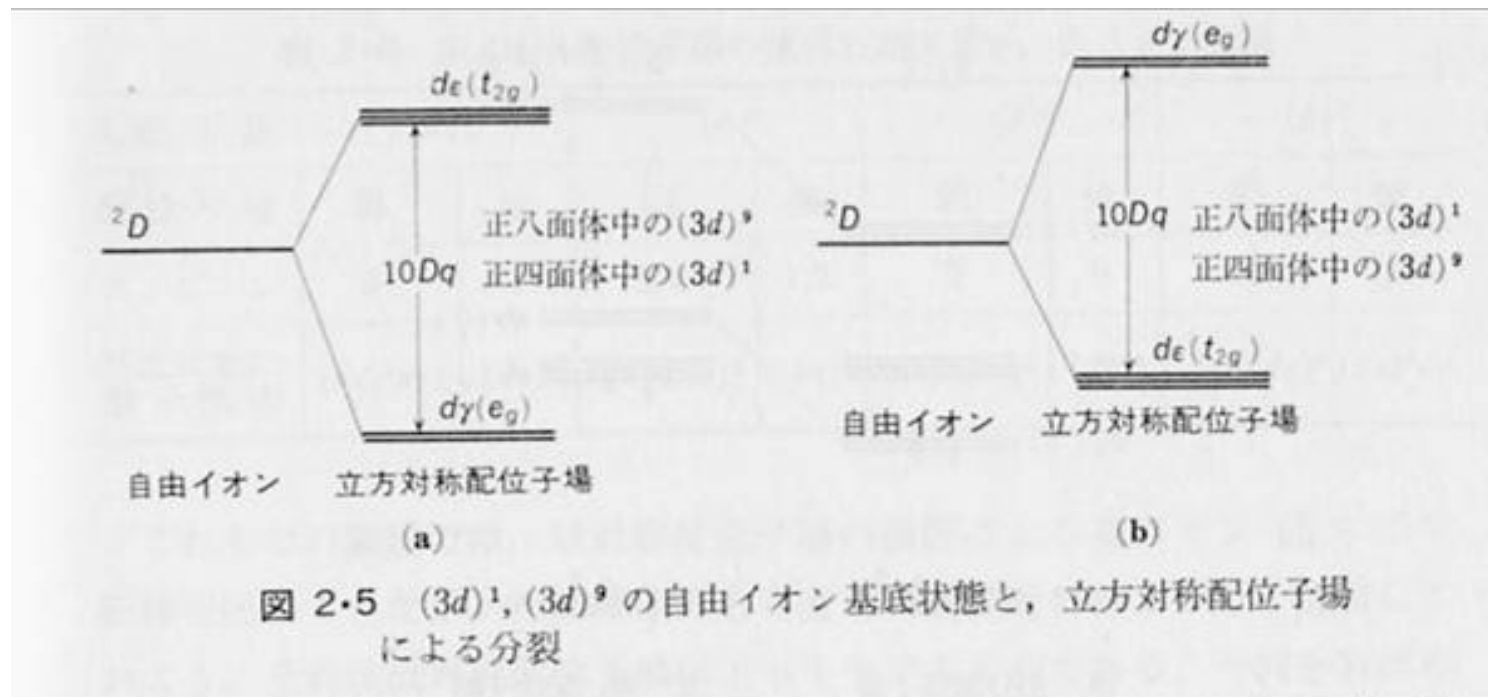
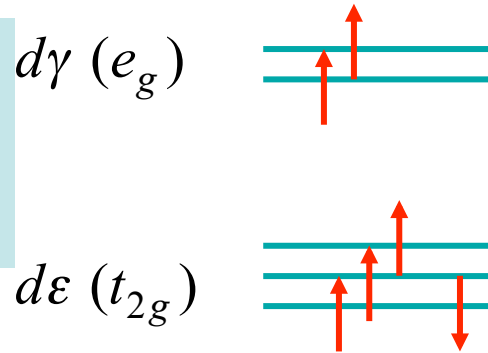


図 2.5  $(3d)^1, (3d)^9$  の自由イオン基底状態と、立方対称配位子場による分裂

# 多電子状態

## 1. 結晶場 < Hund結合 (弱い結晶場、High Spin State)

例:  $3d^6$   
( $Fe^{2+}$ )



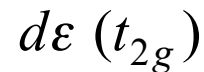
$S=2$

基底L多重項の  
( $2L+1$ )の状態が結晶場で  
分裂する。

## 2. 結晶場 > Hund結合 (強い結晶場、Low Spin State)



$S=0$



## スピン・ハミルトニアン

### 軌道角運動量の消失

基底状態に軌道の縮退がないとき、軌道角運動量の期待値はゼロ！

ハミルトニアンは実関数  $\longrightarrow$  波動関数  $\varphi_g(\mathbf{r})$  は実関数に選ぶことができる。

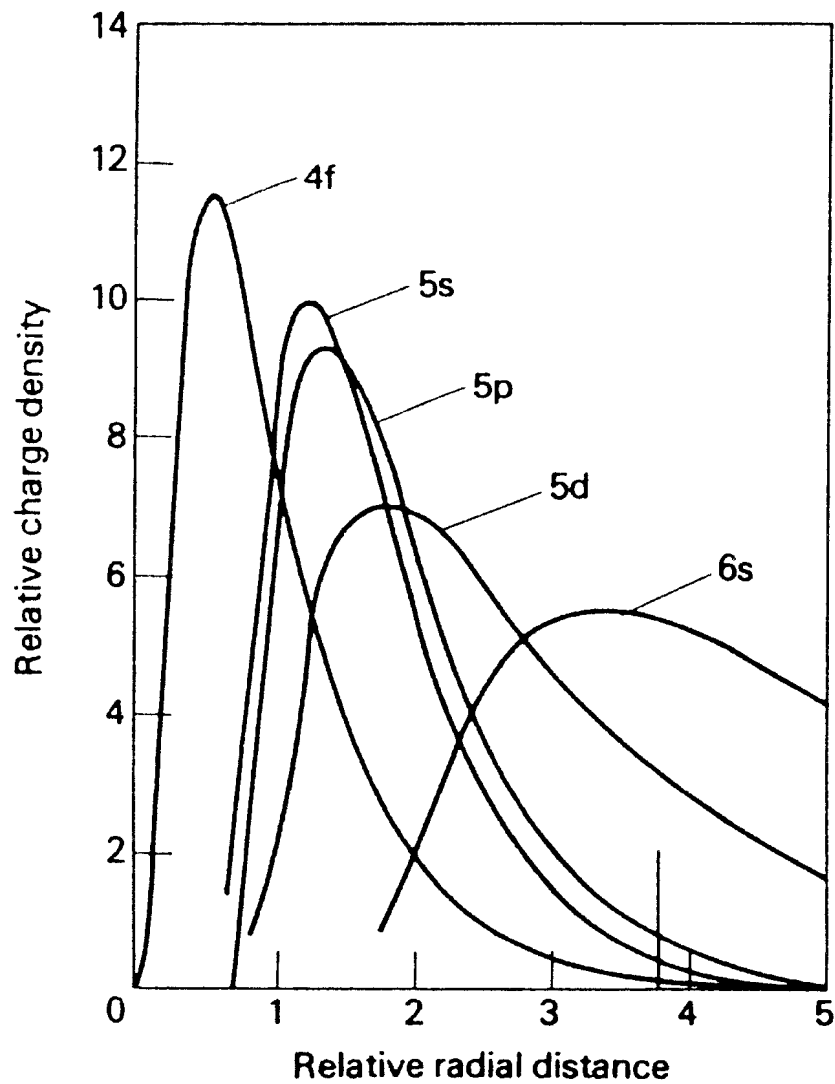
$$\vec{L} = \frac{\hbar}{i} \vec{r} \times \vec{\nabla} \quad \langle \varphi_g | \vec{L} | \varphi_g \rangle = \int \varphi_g \vec{L} \varphi_g d\mathbf{r} = - \left( \int \varphi_g \vec{L} \varphi_g d\mathbf{r} \right)^* = - \langle \varphi_g | \vec{L} | \varphi_g \rangle^*$$

$$\langle \varphi_g | \vec{L} | \varphi_g \rangle \text{ は実だから } \langle \varphi_g | \vec{L} | \varphi_g \rangle = 0$$

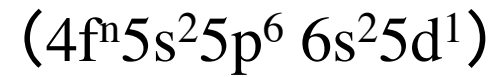
軌道ゼーマンエネルギーの1次の項は消えるが、高次の項が残る。



軌道常磁性 (van Vleck paramagnetism) と有効スピン・ハミルトニアン

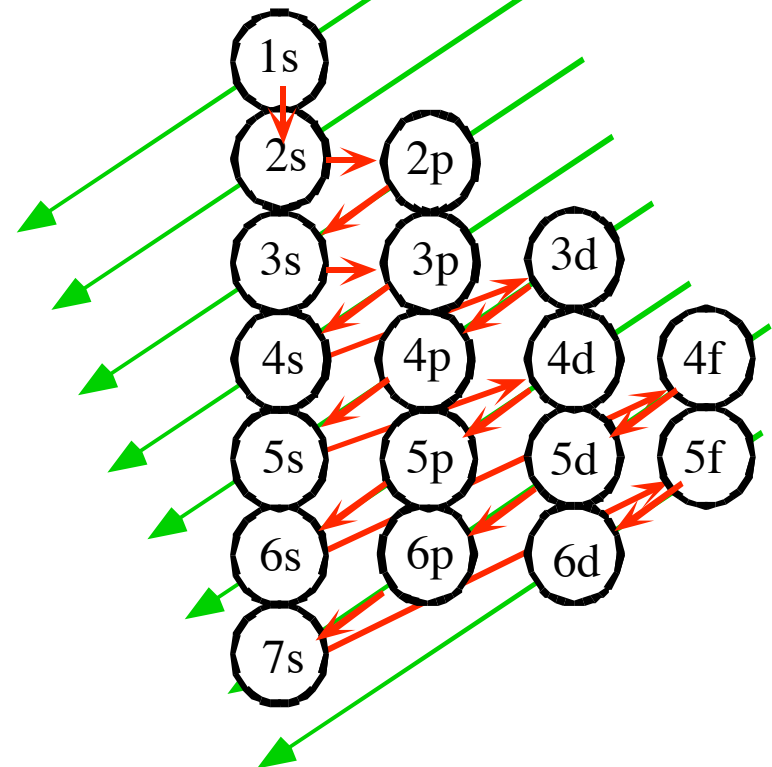


## 希土類元素(4f電子系)



$4f^n$ の外側に $5s^2, 5p^6$ の閉殻電子軌道がある!

電気的に遮蔽



Debye  
Brillouin の理論 (1928~1932) 量子論を導入

$$M = N \sum_{J_z=-J}^J -g\mu_B J_z \exp(-g\mu_B J_z H / k_B T) / \sum_{J_z=-J}^J \exp(-g\mu_B J_z H / k_B T)$$

$$g\mu_B J H / k_B T = x$$

$$\left\{ \begin{array}{l} \sum_{J_z=-J}^J -J_z \exp(-x J_z / J) = J \frac{d}{dx} \sum_{J_z=-J}^J \exp(-x J_z / J) \\ \sum_{J_z=-J}^J \exp(-x J_z / J) = \sinh\left(\frac{2J+1}{2J} x\right) / \sinh\left(\frac{x}{2J}\right) \end{array} \right\}$$

$$M = \underbrace{Ng\mu_B J}_{M_0} \left[ \frac{2J+1}{2J} \coth\left(\frac{2J+1}{2J} x\right) - \frac{1}{2J} \coth\left(\frac{x}{2J}\right) \right]$$

$M_0 : \mu_0 = g\mu_B J$   $B_J(x) : \text{Brillouin function}$   
 $x \ll 1$

$$\chi = \frac{M}{H} = \frac{N(g\mu_B)^2 J(J+1)}{3k_B T} = \frac{N M_{\text{eff}}^2}{3k_B T} \quad M_{\text{eff}} \neq M_0$$

Heisenberg の強磁性理論 (1928年)

$$E_{\text{ex}} = -2J \sum_{\langle i,j \rangle} S_i \cdot S_j \quad A = N^{-1} (g\mu_B)^{-2} 2zJ \quad \begin{array}{l} \text{分子場} \\ \text{交換場} \end{array}$$

$$M = Ng\mu_B S B_S(x), \quad x = g\mu_B S A M / k_B T \quad J \sim 10^{-2} \text{eV}$$

$$k_B T_C = \frac{1}{3} N (g\mu_B)^2 S(S+1) A = \frac{2}{3} z J S(S+1) \quad (r_{12} \sim 3\text{\AA})$$

$$T > T_C : \chi = C / (T - T_C), \quad C = N (g\mu_B)^2 S(S+1) / 3k_B$$

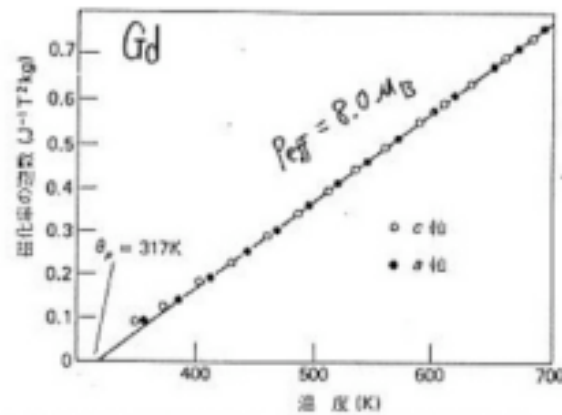
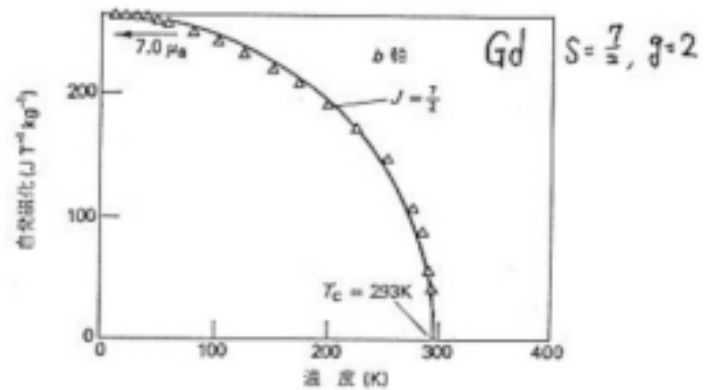
Néel 理論

Heisenberg Model に反強磁性, 正負強磁性 等の一般の場合へ拡張 (1936年)

ネーエル温度

局在モーメント理論 確立 (P. W. Anderson) (1950~1960)

$Gd^{3+} 4f^7$



$$\mu_{\text{eff}} = g \sqrt{J(J+1)}$$

$$\rightarrow 2 \cdot \sqrt{\frac{7}{2} \times \left(\frac{7}{2} + 1\right)}$$

$$\approx 7.94 \mu_B$$

# ワイスの分子場理論

## ハイゼンベルグ・モデルの分子場理論

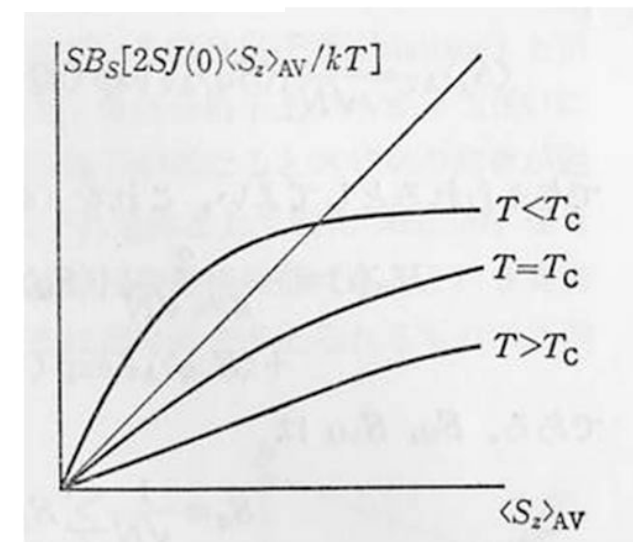
$$H = \sum_j J_{ij} \langle \vec{S}_j \rangle \cdot \vec{S}_i$$

$$\frac{\sigma}{S} = B_S \left( \frac{Sg\mu_B H_{\text{eff}}}{kT} \right) = B_S \left( -\frac{S\sigma J(Q)}{kT} \right)$$

$$B_S(x) \approx \frac{S+1}{3S} x - \alpha x^3$$

$$SB_S \left( -\frac{S\sigma J(Q)}{k_B T} \right) \approx -\frac{S(S+1)J(Q)}{3k_B T} \sigma - \beta \sigma^3$$

$$SB_S(S\sigma J(Q)/k_B T)$$



$\sigma$

磁気秩序  
転移温度

$$T < T_c = -\frac{J(Q)S(S+1)}{3k_B}$$

で解をもつ!

## $T > T_c$ : 常磁性磁化率

外部磁場  $H_0$   $\langle \vec{S}_i \rangle \parallel H_0$  一様磁化

$$\text{分子場 } H_{\text{eff}} = H_0 - \frac{J(0)\sigma}{g\mu_B}$$

$$g\mu_B\sigma = \tilde{\chi}H_{\text{eff}}, \quad \tilde{\chi} = \frac{C}{T}, \quad C = \frac{(g\mu_B)^2 S(S+1)}{3k_B}, \quad \tilde{\chi}: \text{相互作用がないときの磁化率}$$

(一様)磁化率

$$\chi \equiv \frac{g\mu_B\sigma}{H_0} = \tilde{\chi} \frac{H_{\text{eff}}}{H_0} = \tilde{\chi} \left( 1 - \frac{J(0)\sigma}{g\mu_B H_0} \right) = \tilde{\chi} \left( 1 - \frac{J(0)\chi}{(g\mu_B)^2} \right)$$

自己無撞着 (self-consistent) に  $\chi$  を決める。... 分子場近似

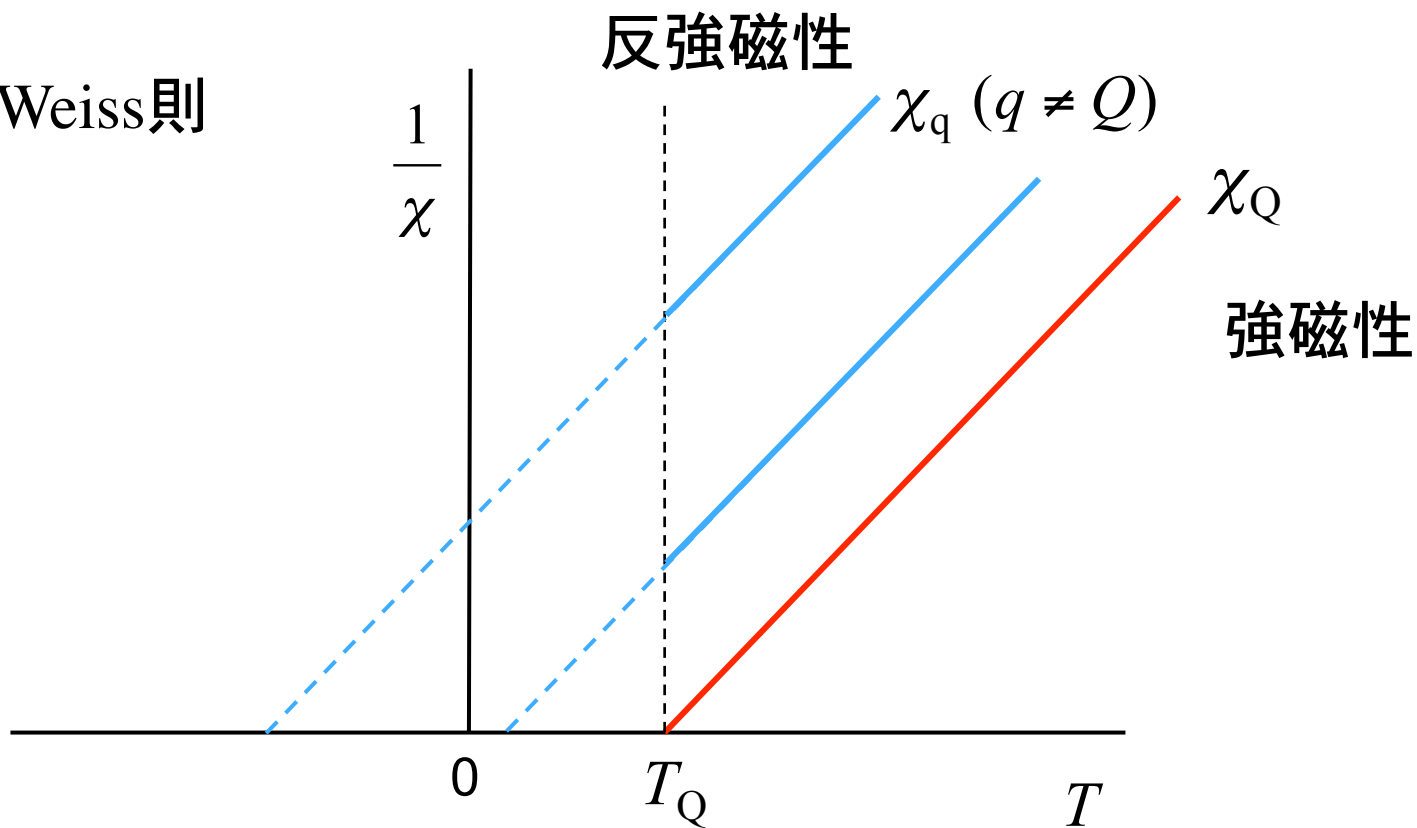
$$\frac{1}{\tilde{\chi}} = \frac{1}{\chi} - \frac{J(0)}{(g\mu_B)^2}$$

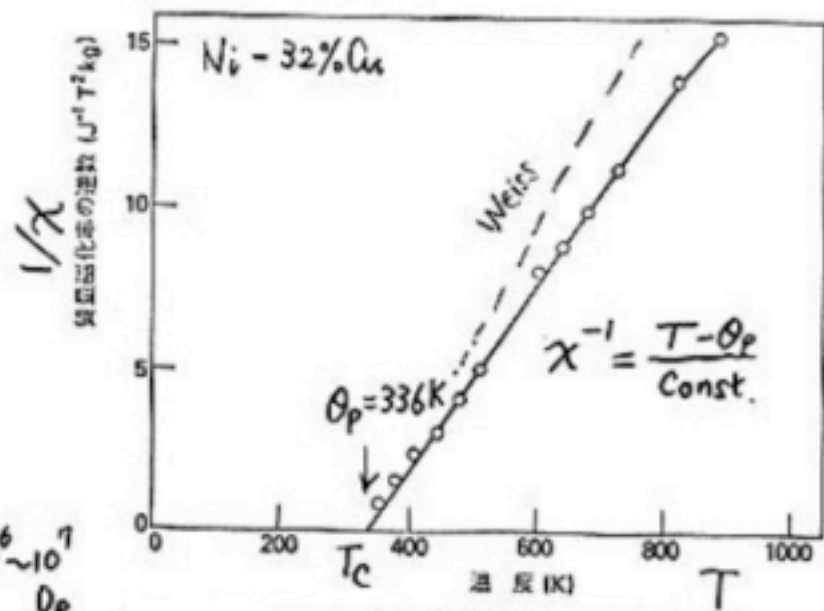
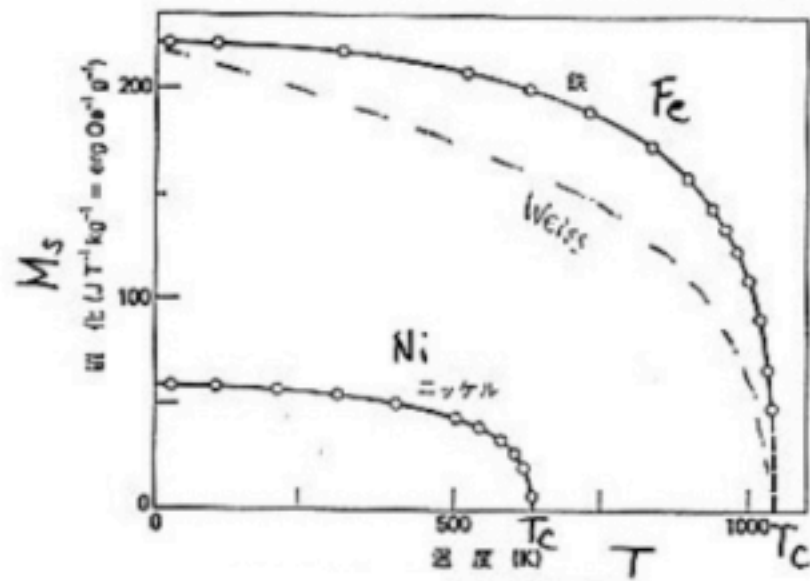
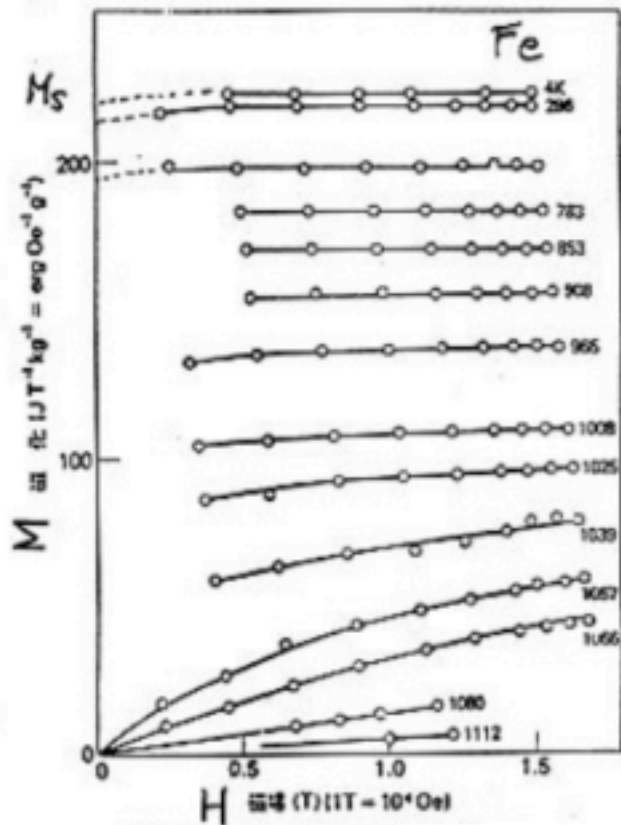
$$\chi = \frac{C}{T - T_0}, \quad T_0 = -\frac{J(0)S(S+1)}{3k_B}$$

Curie Weiss則

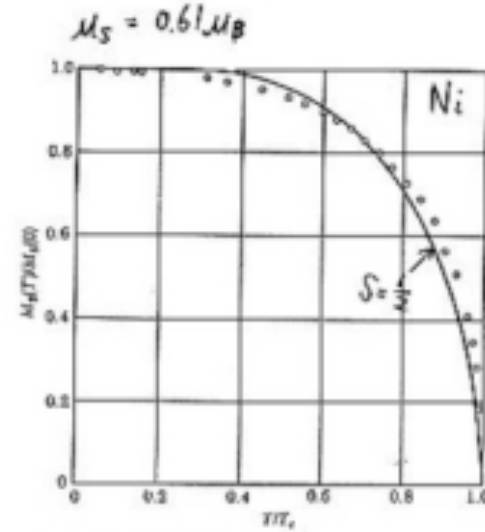
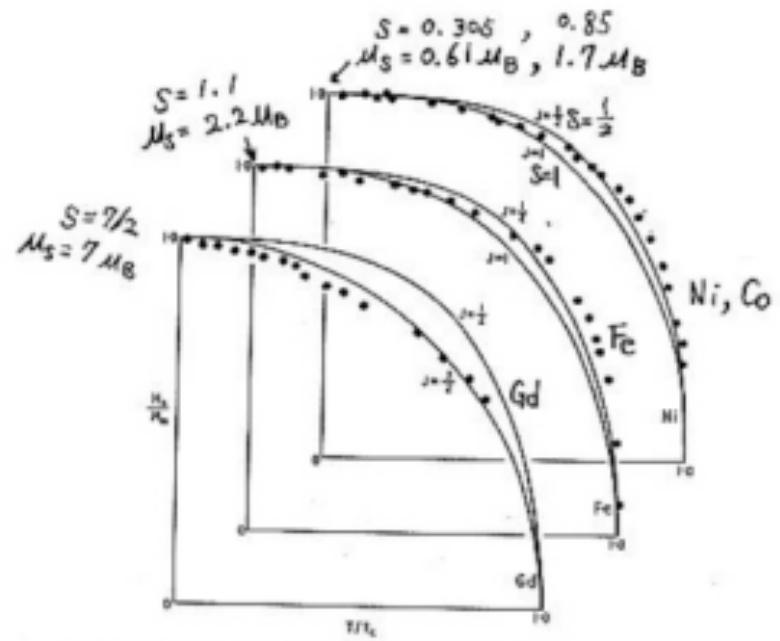
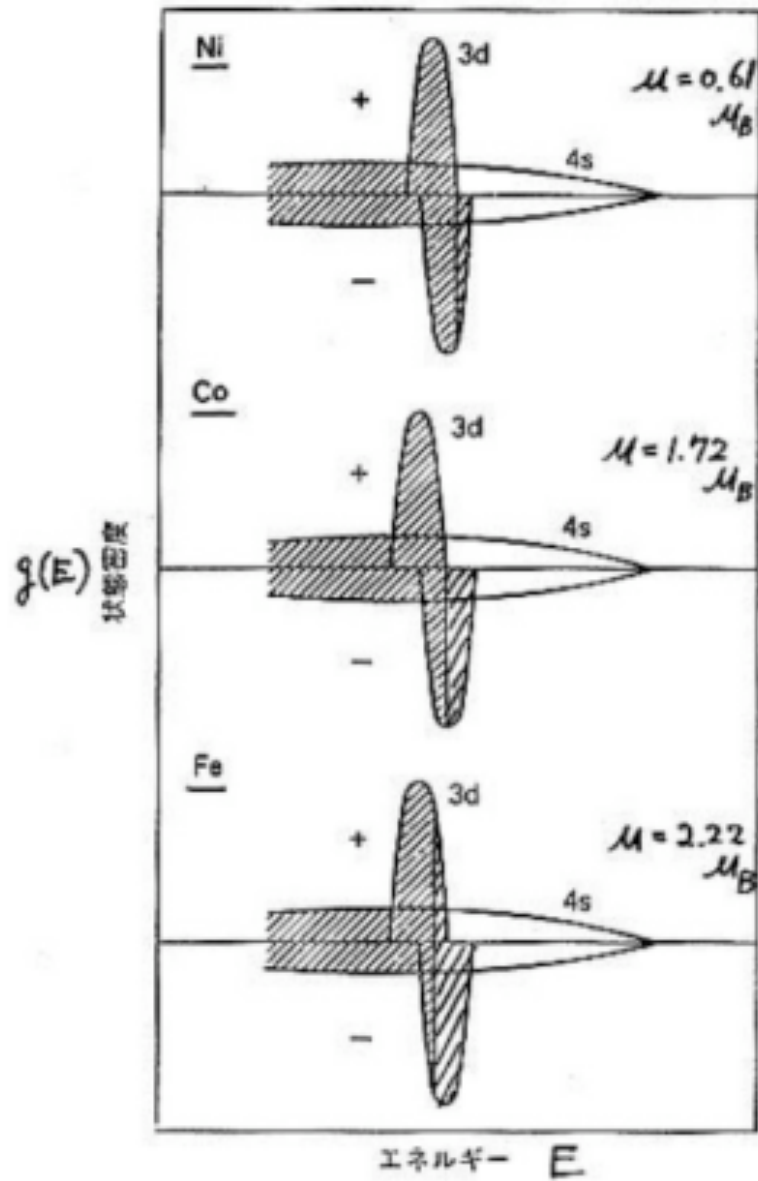
$$\chi_q = \frac{C}{T - T_q}, \quad T_q = -\frac{J(q) S(S+1)}{3k_B}$$

Curie-Weiss則





$$MA = 10^6 \sim 10^7 \text{ Oe}$$



自発磁化の  
温度依存性  
Fe, Co, Ni, Gd

The Schrödinger wave equation

$$\left[ -\frac{\hbar^2}{2m} \nabla^2 + V(r) \right] \psi = E\psi \quad \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \quad \hbar = h/2\pi$$

$$-\frac{\hbar^2}{2m} \nabla^2 \psi = E\psi$$

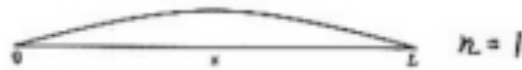
Free Electron Model

$$E = \frac{\hbar^2 k^2}{2m}$$

$$\begin{cases} V=0, 0 \leq x \leq L \\ V=\infty, x(0, x) > L \end{cases}$$

$$\nabla^2 \psi = -k^2 \psi$$

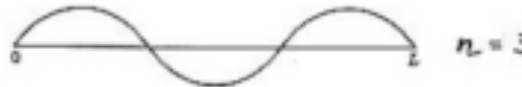
$$\begin{cases} k = |\mathbf{k}| = 2\pi/\lambda \\ \lambda = h/p \\ p = (2mE)^{1/2} \end{cases}$$



$n=1$



$n=2$



$n=3$

$$\psi_n = (2/L)^{1/2} \sin(n\pi x/L)$$

$$E_n = \frac{\hbar^2}{2m} \left(\frac{\pi}{L}\right)^2 n^2, \quad (n=1, 2, 3, \dots)$$

3次元

$$E_n = \frac{\hbar^2}{2m} \left(\frac{2\pi}{L}\right)^2 (n_x^2 + n_y^2 + n_z^2) = \frac{\hbar^2 n^2}{2mV^{2/3}}$$

$$k = (2\pi/L)n$$

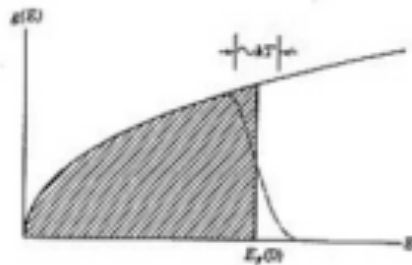
here the volume  $V = L^3$  and  $n^2 = n_x^2 + n_y^2 + n_z^2$ .

$$\int g(E) dE = N = \frac{1}{3\pi^2} (2mE/\hbar^2)^{3/2}$$

$$g(E) = \frac{1}{2\pi^2} (2m/\hbar^2)^{3/2} E^{1/2}$$

$$G(E) \propto \sqrt{E}$$

A plot is given in Fig. 10.3.



Pauli 常磁性 (金属の弱磁性)

$$M = \mu_B \int_0^\infty [D(E - \mu_B H) - D(E + \mu_B H)] f(E) dE$$

$$\approx \mu_B \int_0^\infty f(E) \frac{dD(E)}{dE} \cdot 2\mu_B H dE$$

Fermi 分布関数

$$\chi_p = 2\mu_B^2 D(E_F) \left[ 1 - \frac{\pi^2}{6} (kT)^2 \left( \frac{d^2 \ln D(E)}{dE^2} \right)_{E=E_F} \dots \right]$$

自由電子の  $\chi_p(T) = \chi_p(0) \left[ 1 - \frac{\pi^2}{12} \left( \frac{T}{T_F} \right)^2 \right]$

Stoner の遍歴電子強磁性理論 (1938~1951)

平均場近似 (H.F):  $\theta'$  分子場傾数

$$D(E) = \frac{3}{4} \frac{N}{E_F^{3/2}} E^{1/2} \quad (\text{自由電子}), \quad \zeta = \frac{M}{N\mu_B}, \quad \eta = E_F/k_B T$$

$$N = \frac{3}{4} \left( \frac{N}{E_F^{3/2}} \right) \int_0^\infty dE \left[ \frac{E^{1/2}}{\exp\left(\frac{E - k_B \zeta - \mu_B H}{kT} - \eta\right) + 1} + \frac{E^{1/2}}{\exp\left(\frac{E + k_B \zeta + \mu_B H}{kT} - \eta\right) + 1} \right]$$

$$M = \frac{3}{4} \mu_B \left( \frac{N}{E_F^{3/2}} \right) \int_0^\infty dE \left[ \dots - \dots \right]$$

$\zeta$  は  $\zeta$  ( $\sim M$ ),  $\eta \in T, H$  の関数としてとく.

$$T=0: \frac{k\theta'}{E_F} = \frac{1}{2\zeta_0} \left[ (1+\zeta_0)^{3/2} - (1-\zeta_0)^{3/2} \right]$$

$$T=T_c: \frac{k\theta'}{E_F} = \frac{2}{3} \left[ 1 + \frac{\pi^2}{12} \left( \frac{kT_c}{E_F} \right)^2 + \dots \right]$$

$$T < T_c: \zeta^2 = \frac{9\pi^2}{8} \left( \frac{kT_c}{E_F} \right)^2 \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right]$$

X, Y, Z の3方向があるので、各々

$$p_X = \frac{h}{L} n_X \quad , \quad n_X = 0, \pm 1, \pm 2, \dots$$

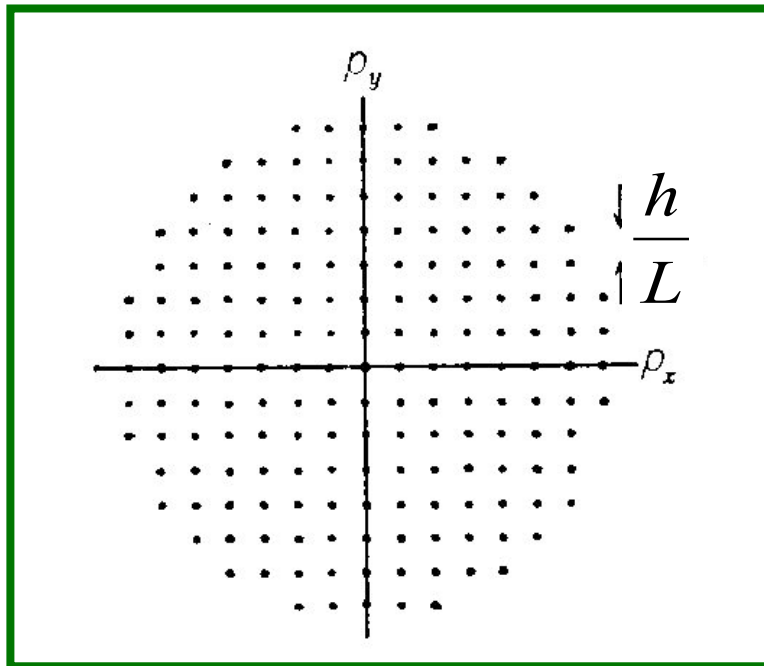
$$p_Y = \frac{h}{L} n_Y \quad , \quad n_Y = 0, \pm 1, \pm 2, \dots$$

$$p_Z = \frac{h}{L} n_Z \quad , \quad n_Z = 0, \pm 1, \pm 2, \dots$$

運動量がとびとびの値しかとれない

$$\begin{aligned} E(n_X, n_Y, n_Z) &= \frac{1}{2m} (p_X^2 + p_Y^2 + p_Z^2) \\ &= \frac{h^2}{2mL^2} (n_X^2 + n_Y^2 + n_Z^2) \end{aligned}$$

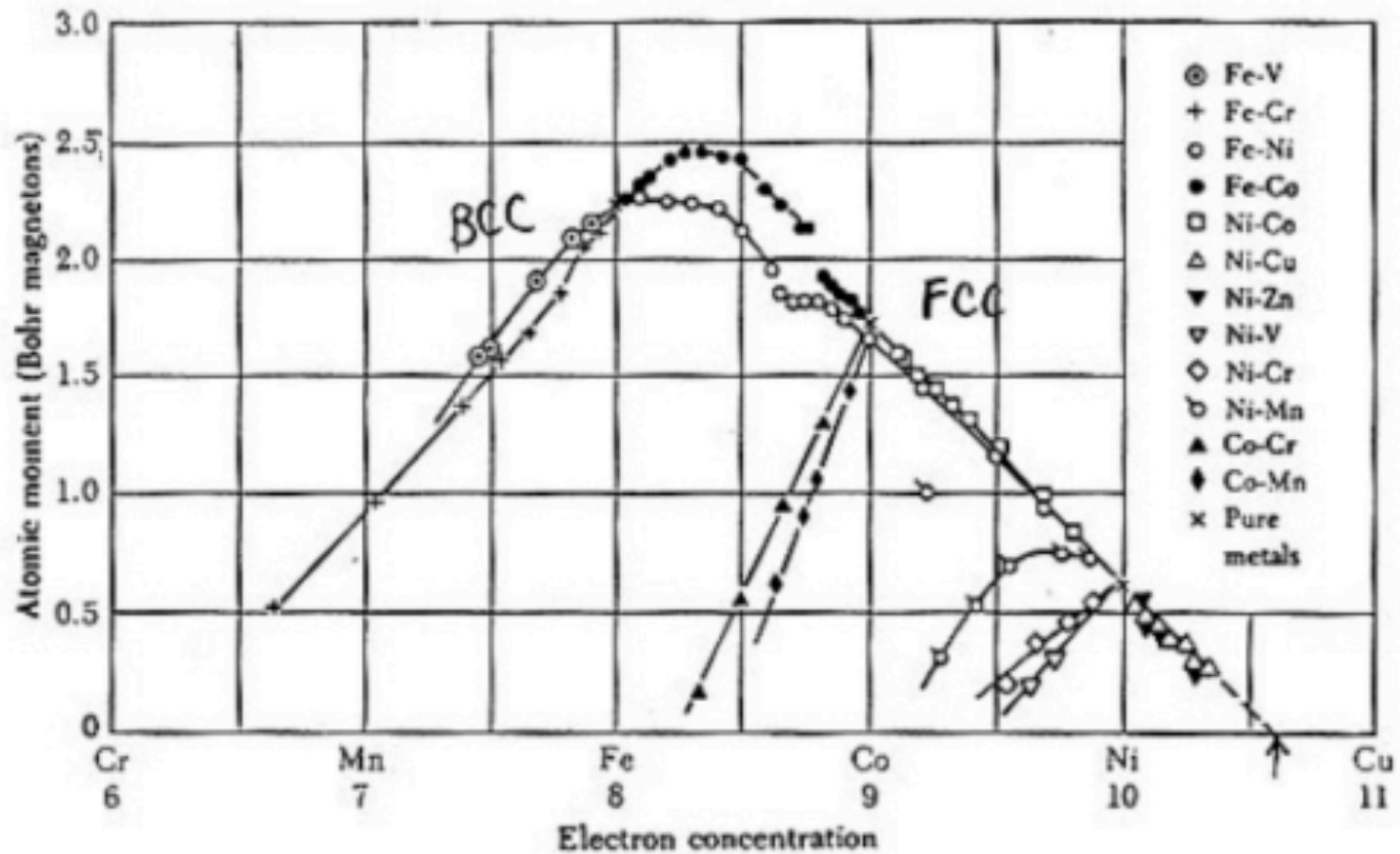
エネルギーもとびとびの値しかとれない



(L x L x L の箱の中の粒子)

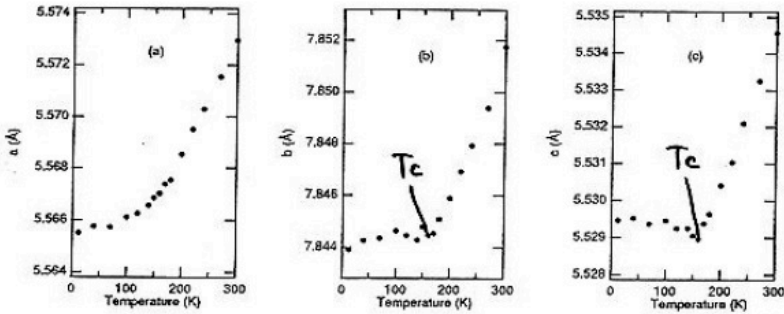
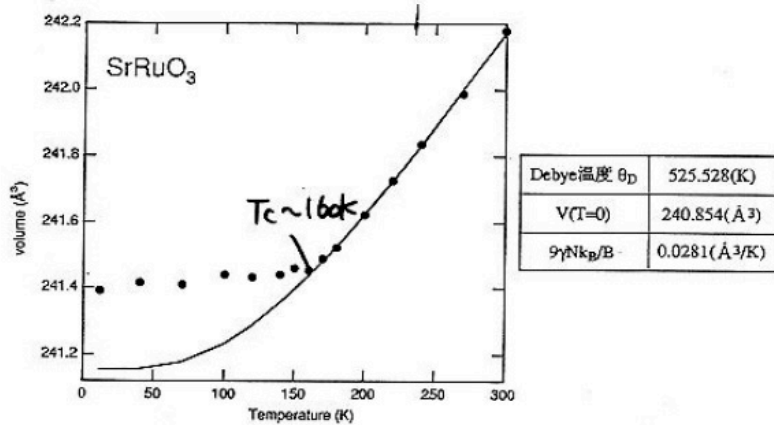


# Slater-Pauling 曲線



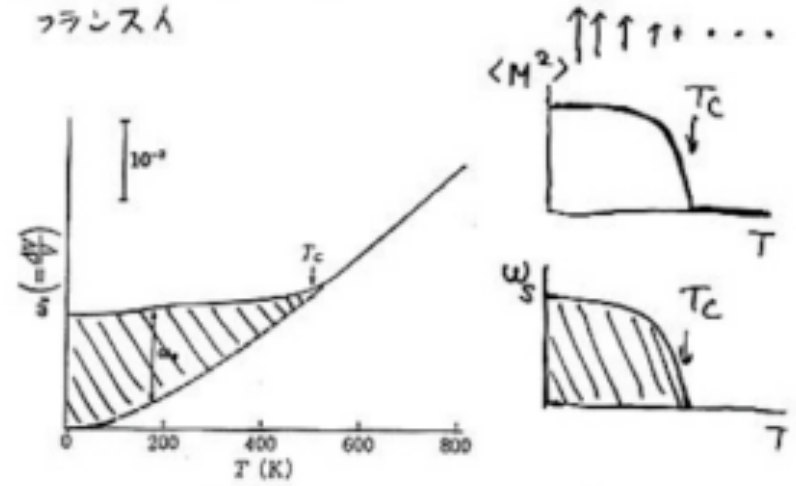
# 自発磁気体積効果

$$V = V(T=0) + \int_0^T \frac{\gamma C_v}{B} dT = V(T=0) + \frac{9\gamma Nk_B}{B} T \left( \frac{T}{\theta_D} \right)^3 \int_0^{\frac{\theta_D}{T}} \frac{x^3}{e^x - 1} dx$$



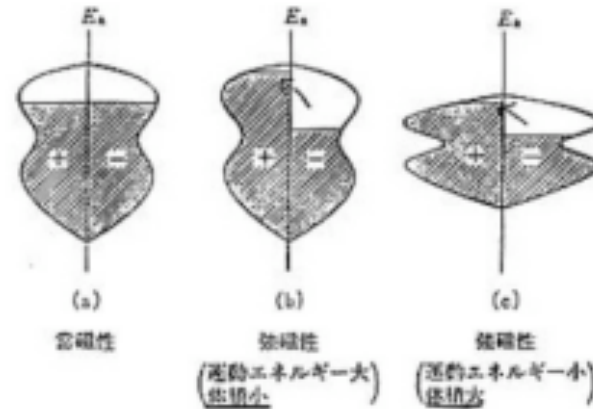
SrRuO<sub>3</sub>の格子定数および体積の温度変化  
体積の温度変化はDebye関数でフィッティングした結果を実線で示してある。

ギヨーム  
Guillaume (1897年 invar 発見)  
フランス人

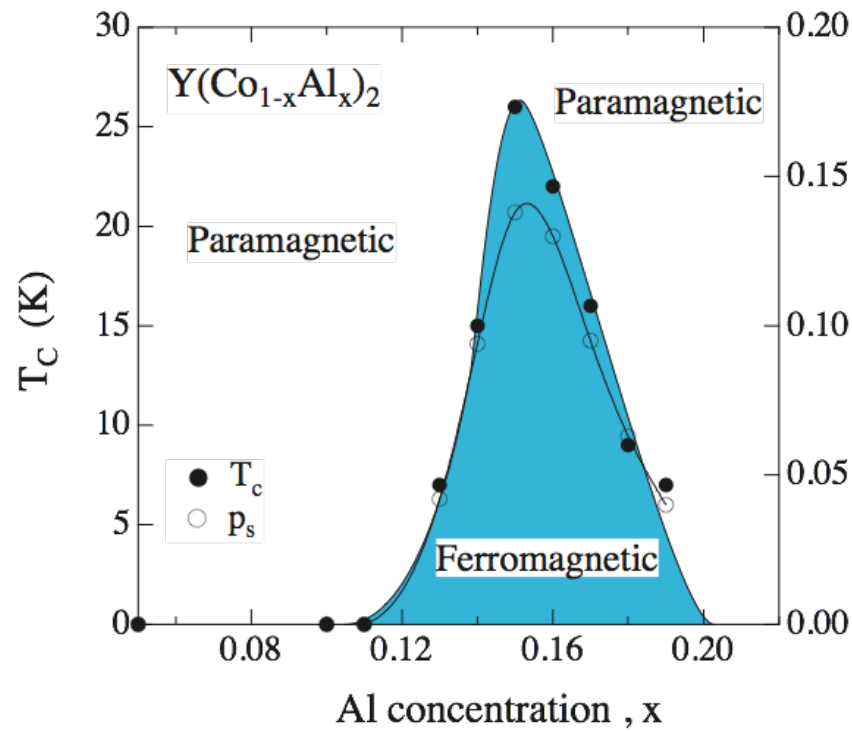


$$\omega_s \propto M_s^2$$

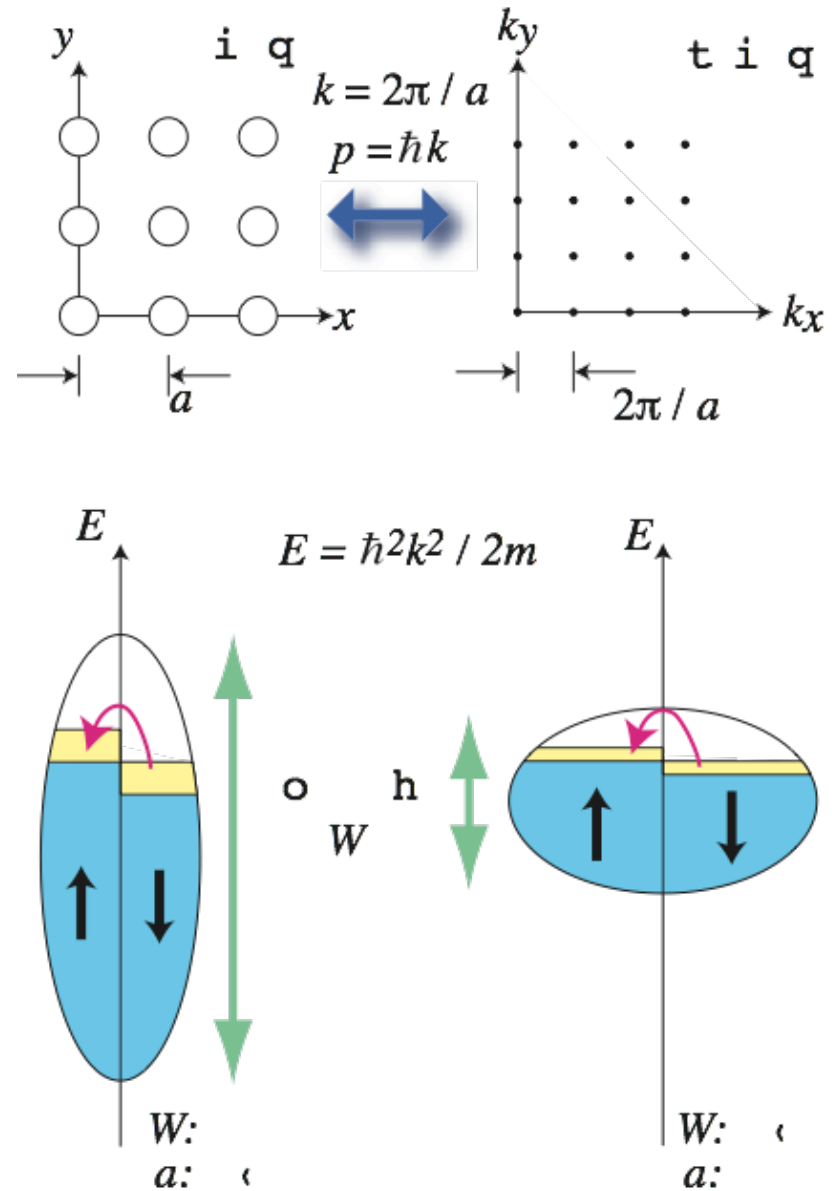
# FeNi合金のインバー効果



# Y(Co-Al)<sub>2</sub>の遍歴電子強磁性

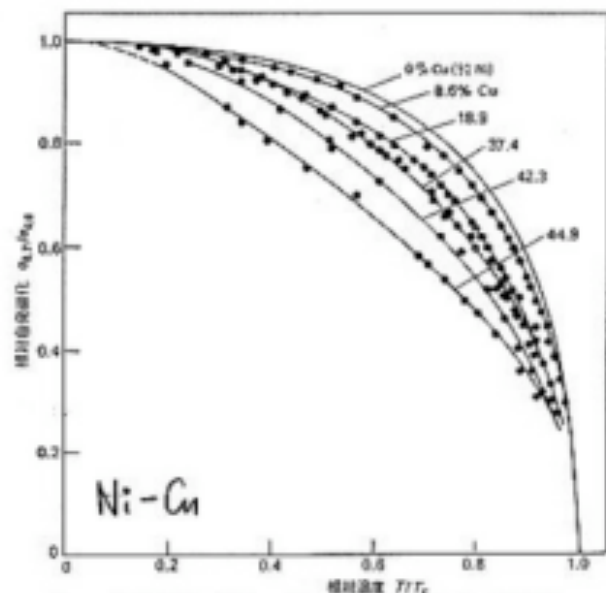
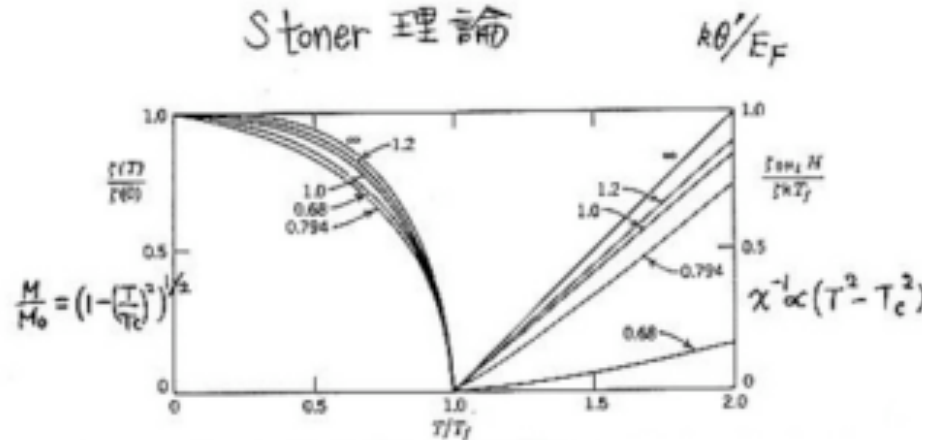


K.Yoshimura *et al.*, *Solid State Commun.*, 56 (1985) 767, *Phys. Rev. B* 37 (1988) 3593.

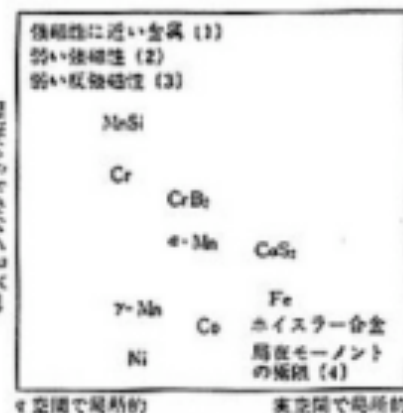


磁気体積効果を利用して  
フェルミ液体から弱い強磁性体創製

# Stoner 理論



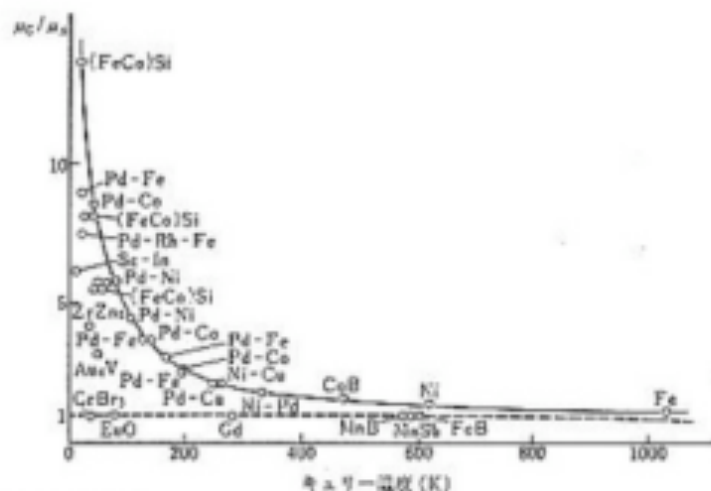
(a) スピンのゆらぎに対する近似理論



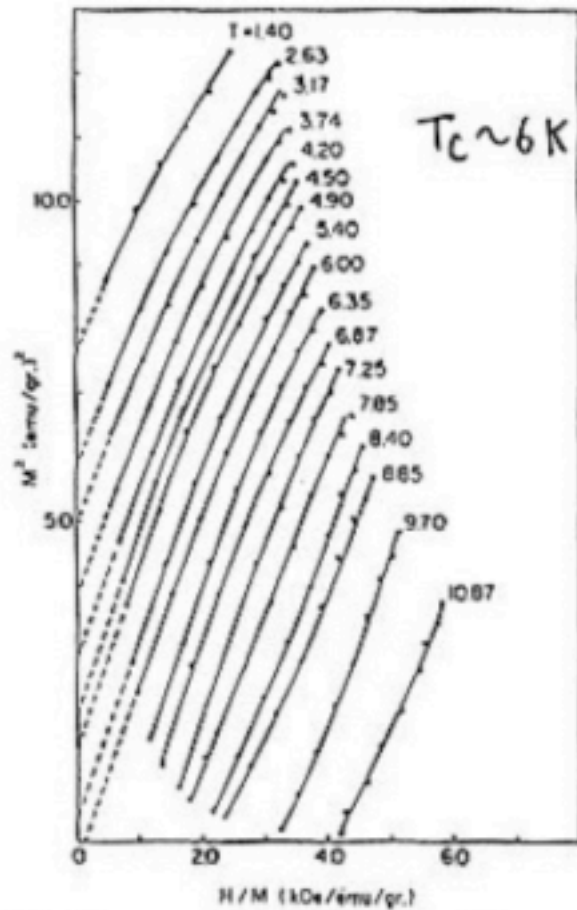
(b) 振幅と空間分布からなめた物質の位置

強磁性、反強磁性のスピンのゆらぎに対する近似理論 (a) と、スピンのゆらぎの振幅と空間分布からなめた物質の位置 (守谷の作ったもの<sup>1)</sup> を特例)

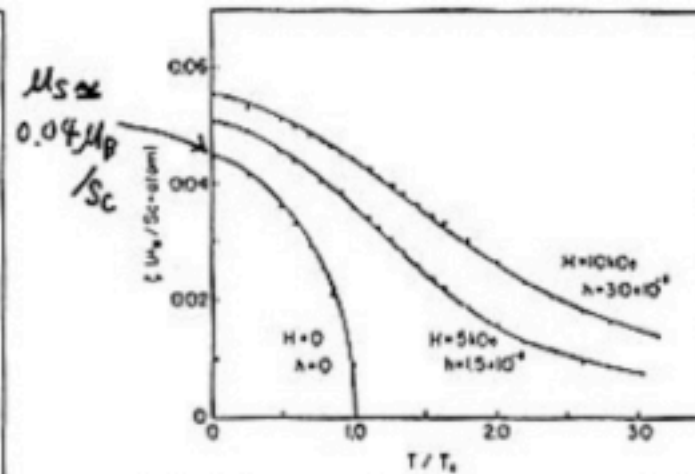
(1) Pd, Sc, TiBe<sub>2</sub>, YCo<sub>5</sub> (2) Sc<sub>2</sub>In, ZrZn<sub>2</sub>, Ni<sub>3</sub>Al, Ni-Pt, ..... (3) β-Mn, Cr, V, Se<sub>2</sub>, V, Se<sub>2</sub>, ..... (4) 絶縁体磁性化合物, f 金属, .....



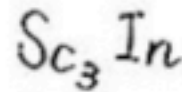
強磁性モーメント  $\mu_C$  と強磁性軌道磁気モーメント  $\mu_B$  の比  $\mu_C / \mu_B$  とキュリー温度  $T_c$  との関係  $\mu_C = M / N_A (\mu_B)$ ,  $\mu_C$  はキュリー定数  $C = N_A \mu_B \times \mu_C (\mu_C + 1) / 3k$  より求めてある (文献 16) を踏襲した)



The magnetization for  $\text{Sc}_{0.7572}\text{In}_{0.2428}$  in magnetic fields from 1.50 to 11.3 kOe in terms of the Arrott plot. The dashed line represents the extrapolation of the experimental data to zero field.



The reduced magnetization  $\zeta = M/N$  in magnetic fields of 0, 5 and 10 kOe obtained from Fig. 3 as a function of  $T/T_c$ . The solid line represents the results of the numerical calculation of the magnetization given in eqs. (11) and (12) in cases of  $h=0$ ,  $1.5 \times 10^{-6}$  and  $3.0 \times 10^{-6}$ .



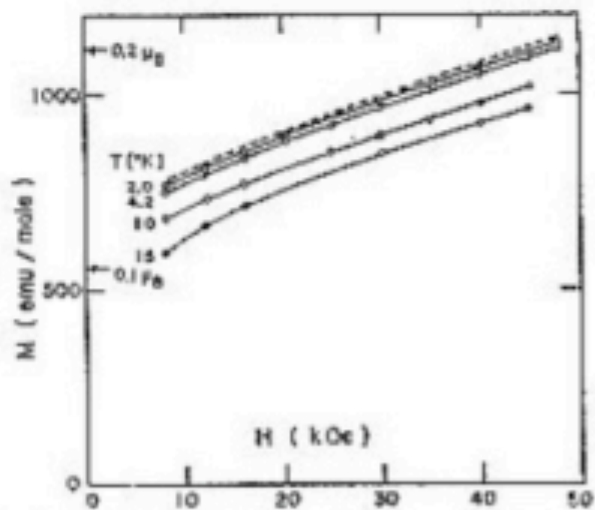
Landau 展開

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

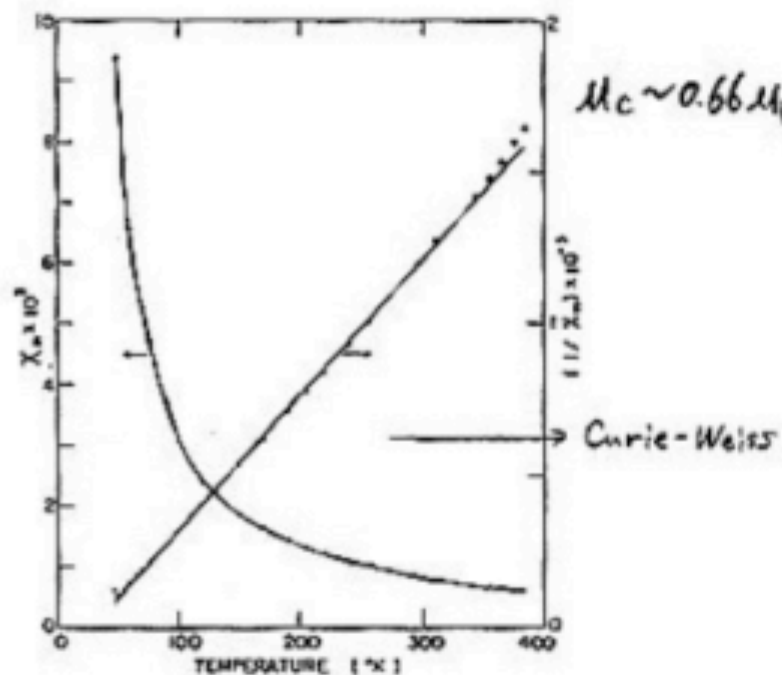
$$M(H, T)^2 = \frac{2\mu_B H}{\bar{F}_1} \frac{H}{M} + M(0, T)^2$$

Takeuchi & Masuda

$\mu_B \sim 0.12 \mu_B$

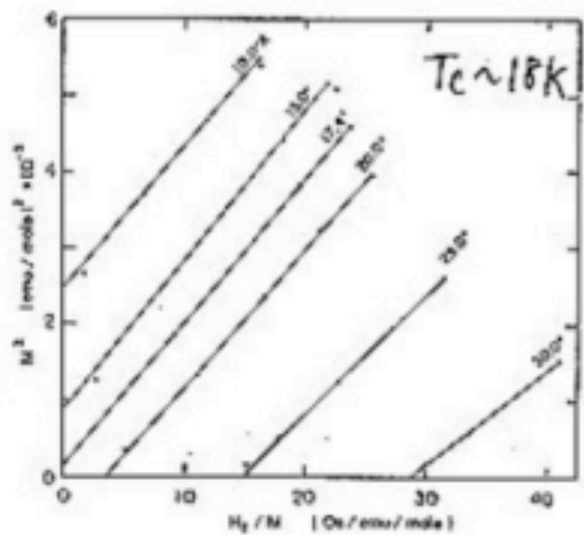


ZrZn<sub>2</sub>



$\mu_C \sim 0.66 \mu_B$

Curie-Weiss

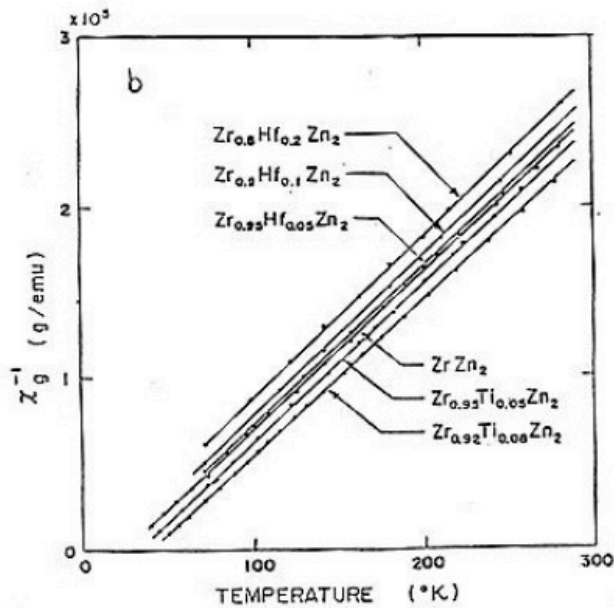
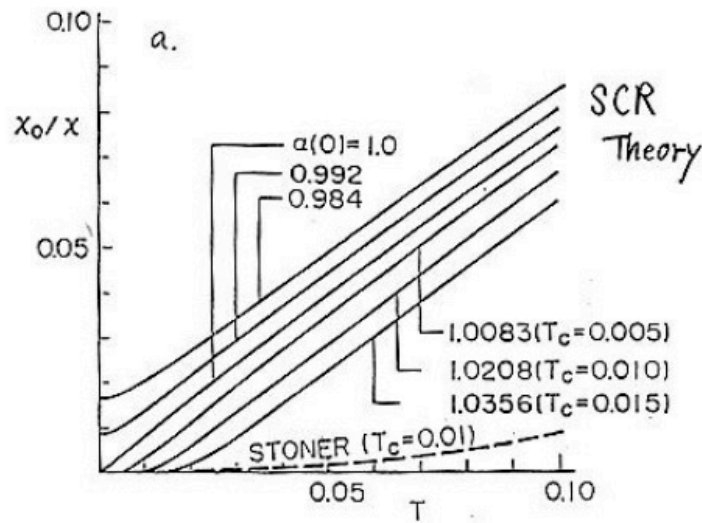


$T_c \sim 18K$

Landau 展開

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

$$\underline{M(H, T)^2} = \frac{2\mu_B}{\bar{F}_1} \frac{H}{M} + M(0, T)^2$$



Stoner Theory

$$\begin{cases} F_0(M, T) = F_0(0, T) + \frac{M^2}{2\chi_0(T)} + \dots - H \cdot M \\ \chi_0(T) = 2\rho \left[ 1 - \left(\frac{\pi^2}{6}\right) R T^2 + \dots \right] \end{cases}$$

$$\left( \frac{\partial F}{\partial M} = H, \quad \frac{\partial^2 F}{\partial M^2} = \frac{1}{\chi} \right)$$

$$F_{\text{Stoner}}(M, I) = \frac{1}{4\rho} (1 - I\rho) M^2 + \frac{\rho}{4} M^4 + \dots - H \cdot M$$

$$F_{\text{Stoner}}^{(M, T)} = F_0(M, T) - \frac{1}{4} I M^2$$

$$\frac{1}{\chi} = \frac{\partial^2}{\partial M^2} F_{\text{Stoner}} = \frac{\partial^2}{\partial M^2} F_0 - \frac{1}{2} I = \frac{1}{\chi_0(T)} - \frac{1}{\chi_0(T_c)}$$

$$\simeq \frac{1}{2\rho} \cdot \frac{\pi^2}{6} R (T^2 - T_c^2)$$

T. Moriya Self-consistent Renormalization Theory  
of Spin Fluctuations. (1973)

$$F_{\text{SCR}} = \left[ -\frac{1-\alpha}{\chi_0} + \frac{5}{3} g N_0^2 \tilde{m}^2 \right] M^2 + \frac{\rho}{4} M^4 + \dots - H M$$

$$\tilde{m}^2 = \frac{3}{5} (3m_{\parallel}^2 + 2m_{\perp}^2)$$

$$\frac{1}{\chi_{\parallel}} = -\frac{\alpha-1}{\chi_0} + \frac{5}{3} g N_0^2 (\tilde{m}^2 + M \frac{\partial}{\partial M} \tilde{m}^2) + 3\rho M^2$$

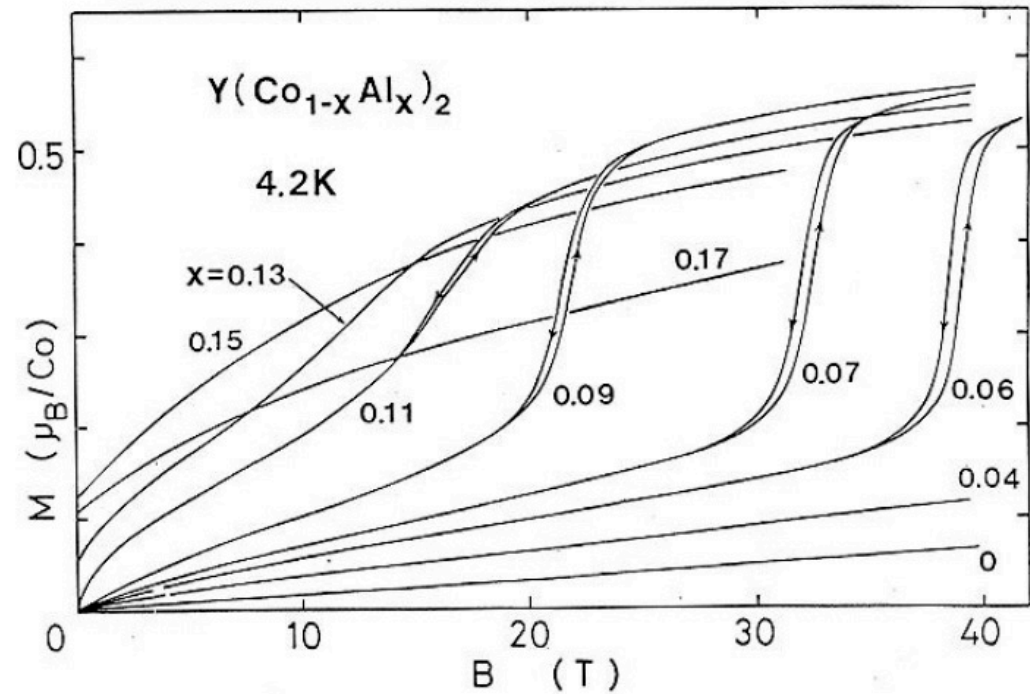
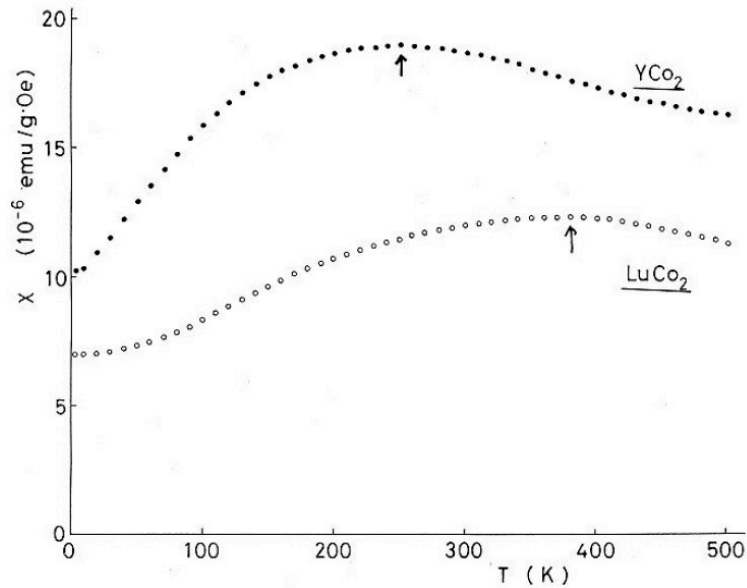
$T > T_c$

$$\frac{1}{\chi} = \frac{1-\alpha}{\chi_0} + \frac{5}{3} g N_0^2 S_L^2(T)$$

$$S_L^2(T) = \frac{3}{\pi} \int_0^{\infty} d\omega \frac{1}{e^{\beta\omega} - 1} N_0^{-2} \sum_{\mathbf{k}} \chi^{-+}(\mathbf{k}, \omega)$$

$$S_L^2(T) \propto T - T_c \Rightarrow \text{キズリ・ワイス則}$$

# $Y(\text{Co-Al})_2$ の遍歴電子磁性：遍歴電子メタ磁性転移

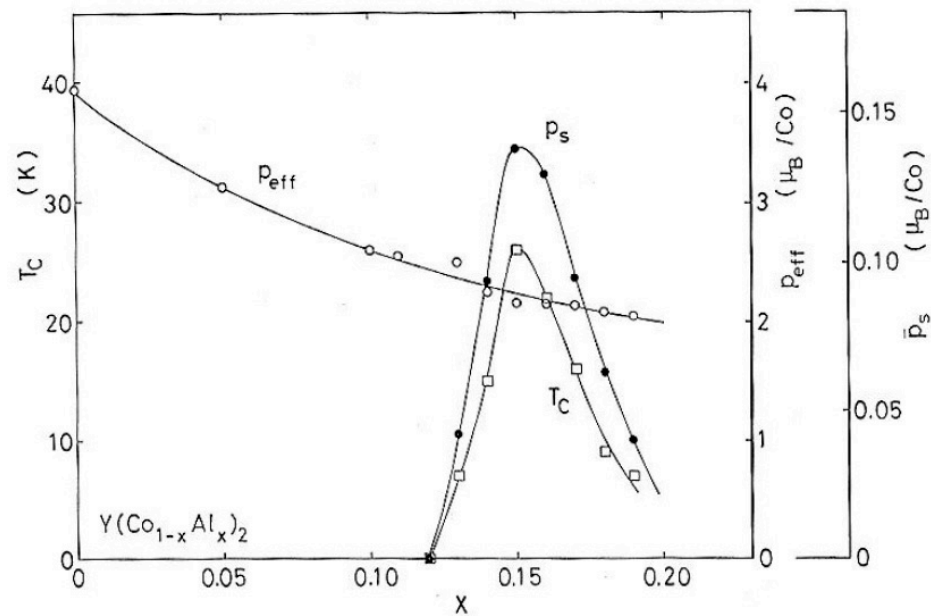
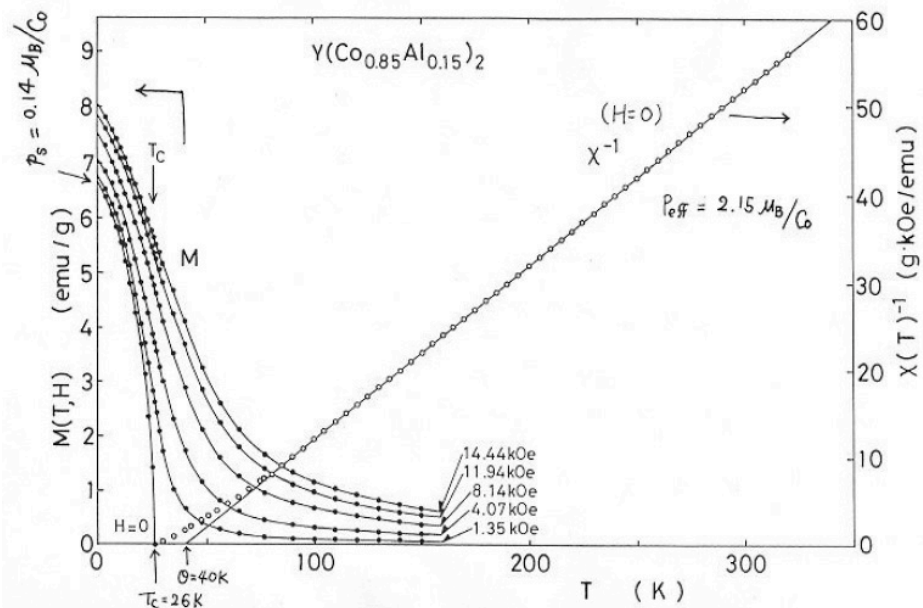


Nearly Ferromagnetic Metal  
(Exchange-Enhanced Pauli Paramagnet)

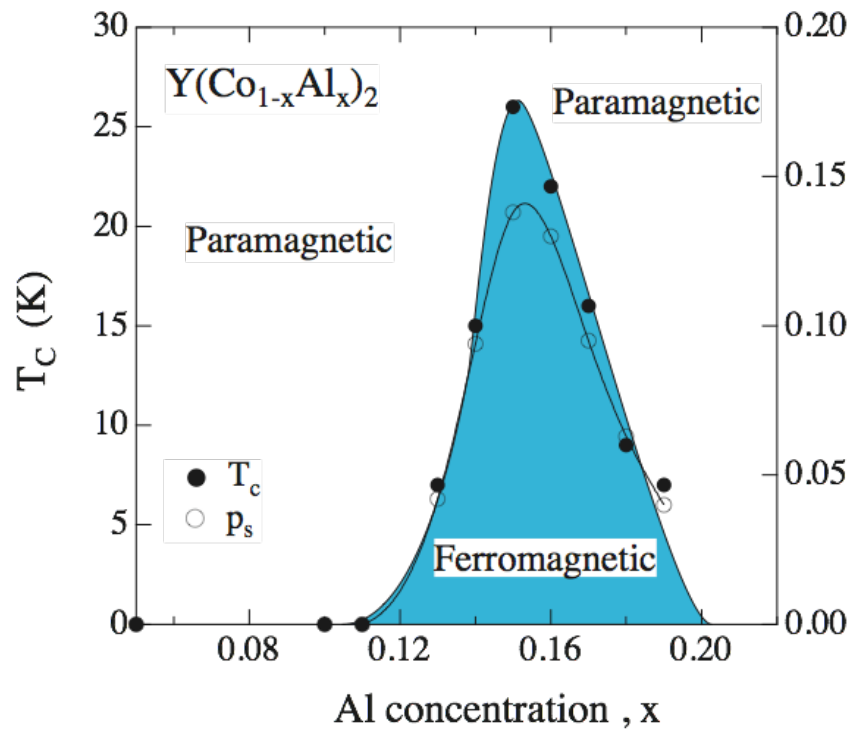
遍歴電子メタ磁性転移

# 弱い遍歴電子強磁性体

## Weakly Itinerant Ferromagnet

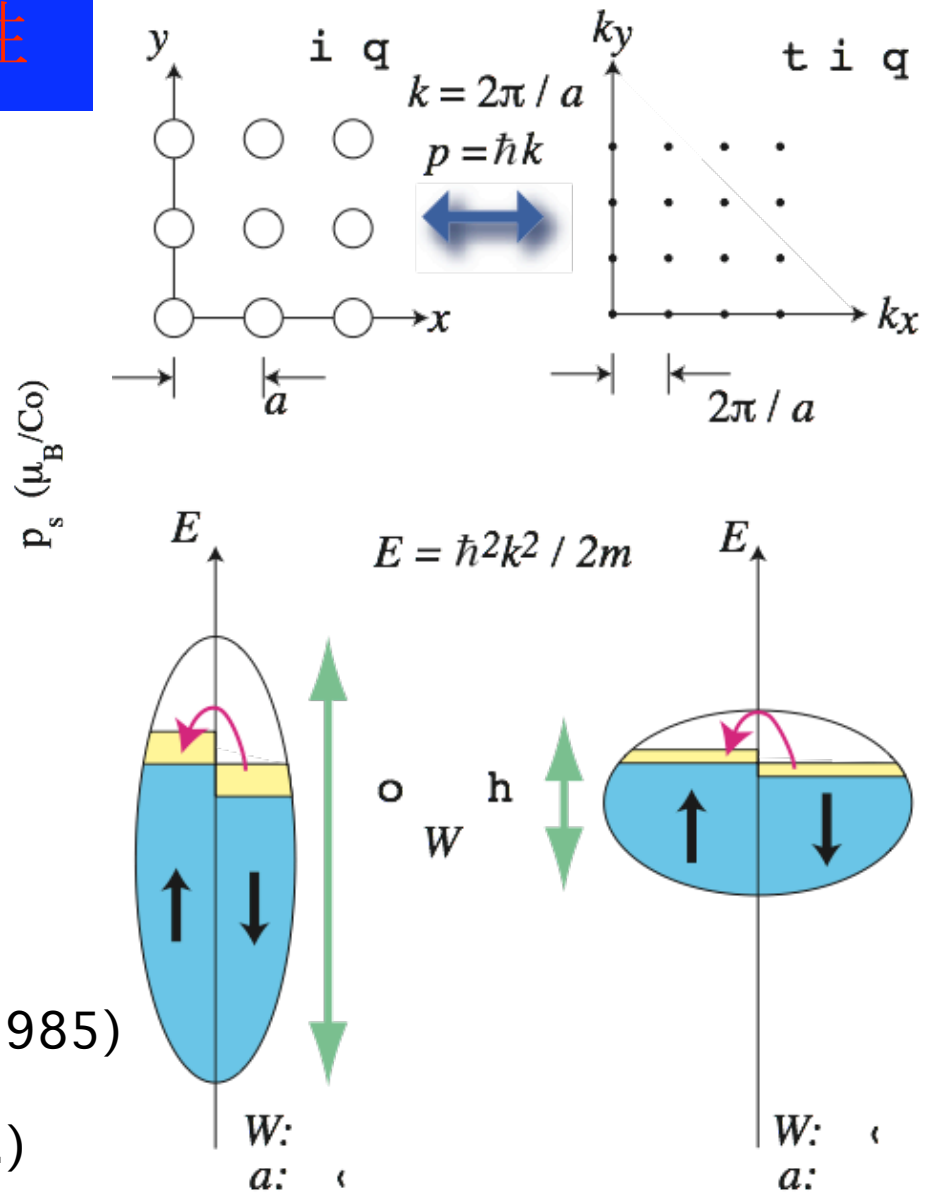


# Y(Co-Al)<sub>2</sub>の遍歴電子強磁性

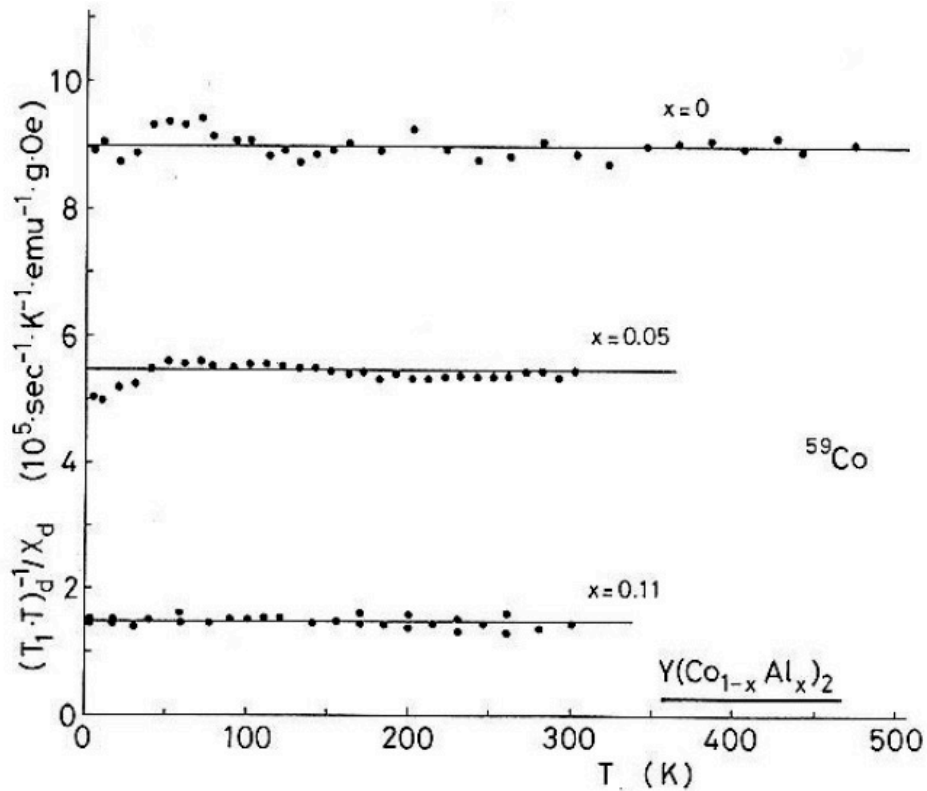


(Solid State Commun., 56 (1985) 767  
 Phys. Rev. B 37 (1988) 3593.)

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



# 遍歴電子強磁性体およびそれに近い金属での 核スピン・格子緩和率 $1/T_1$



$$\frac{1}{T_1 T} = 2k_B \cdot \gamma_N^2 \sum_q A_{hf}(q)^2 \frac{\text{Im} \chi(q, \omega)}{\omega}$$

局在モーメントモデル

$$\frac{1}{T_1} = \sqrt{2\pi} \cdot (2\mu_B \cdot \gamma_N \cdot A_{hf}(q))^2 \cdot \frac{S(S+1)}{3z\omega_x}$$

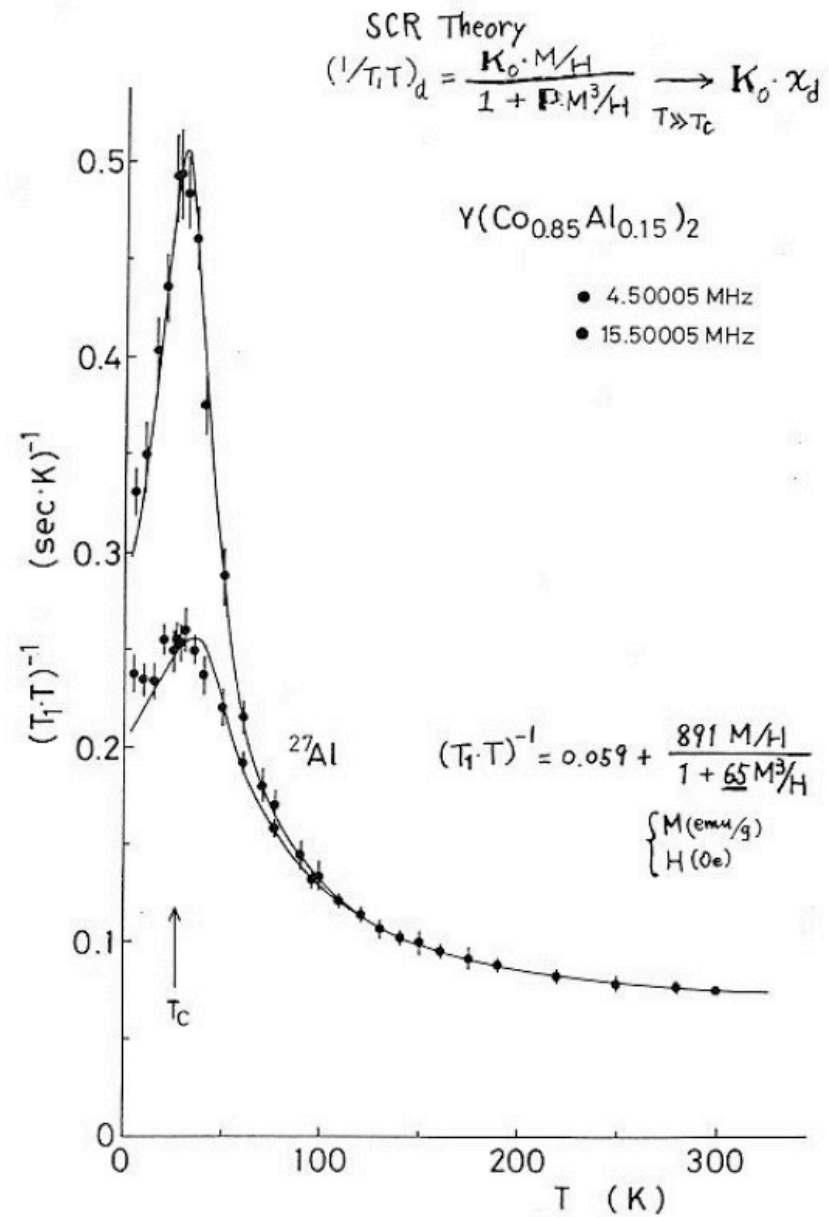
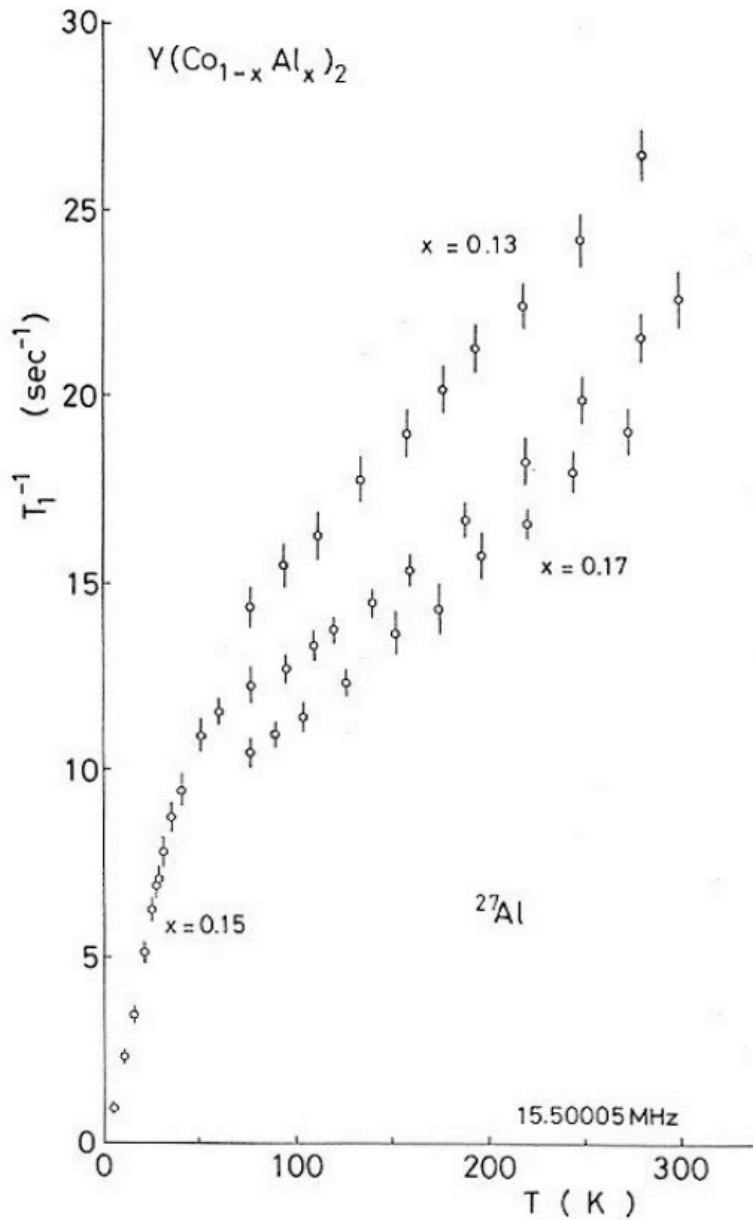
$$(\hbar\omega_x)^2 = \frac{2}{3} \cdot (2J)^2 \cdot z \cdot S(S+1) = (k_B\theta)^2 \cdot \left[ \frac{6}{z \cdot S(S+1)} \right]$$

SCR理論

$$\frac{1}{T_1 T} = K_0 \cdot \chi(\text{spin}) = \left[ \frac{(\gamma_N \cdot A_{hf}(q))^2 \cdot k_B \nu_0}{2\pi^2 \Gamma_0} \right] \cdot \chi(\text{spin})$$

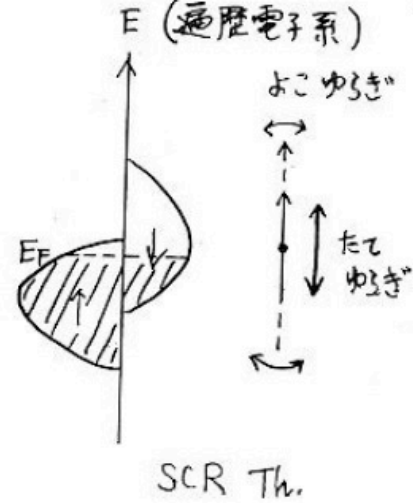
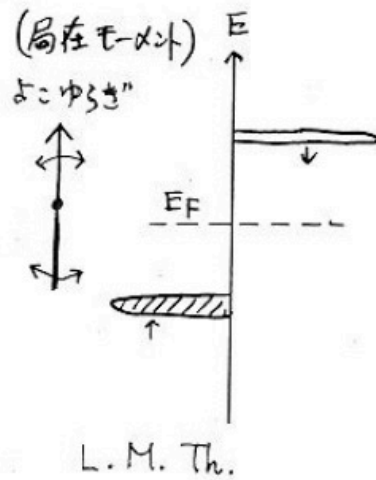
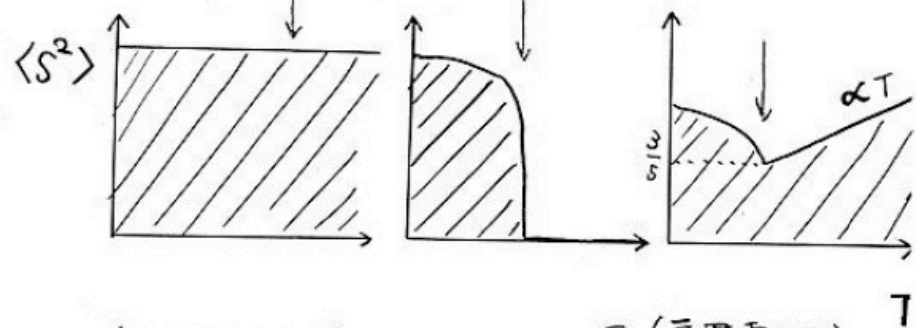
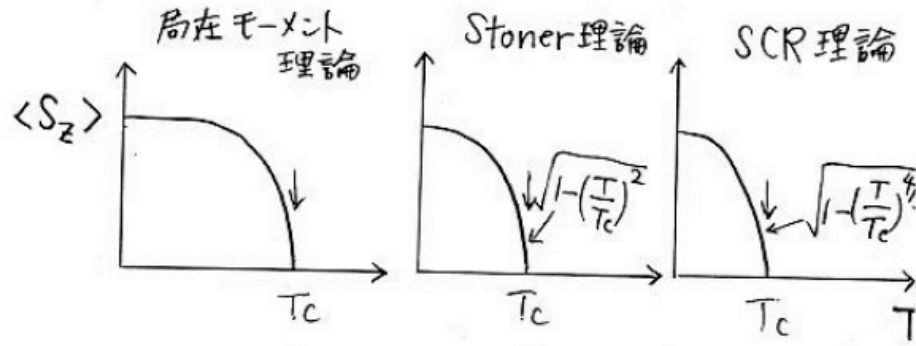
$$T_0 = \frac{3\pi\Gamma_0}{\nu_0}$$

# 弱い遍歴電子強磁性体での核スピン・格子緩和



# スピンの揺らぎの自己無撞着 繰り込み理論 (SCR理論)

↓  
現象論的統一理論



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