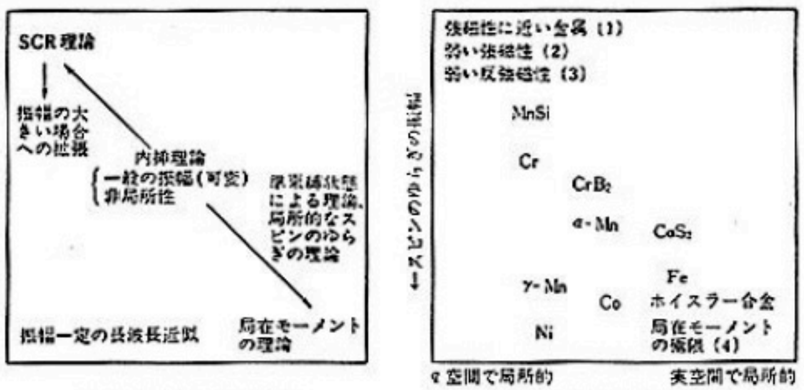


(a) スピンのゆらぎに対する近似理論　(b) 振幅と空間分布からながめた物質の位置

図 2.2 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がめた物質の位置（守谷の作ったもの[1]を補強）
(1) Pd, Sc, $TiBe_2$, YCo_2　(3) β-Mn, Cr, V_2Se_4, V_3Se_4, ……
(2) Sc_3In, $ZrZn_2$, Ni_3Al, Ni-Pt, ……　(4) 絶縁体磁性化合物，4f 金属，……

局在モーメントモデル

乱雑位相近似（RPA）

自己無撞着（SCR）
スピン揺らぎ理論

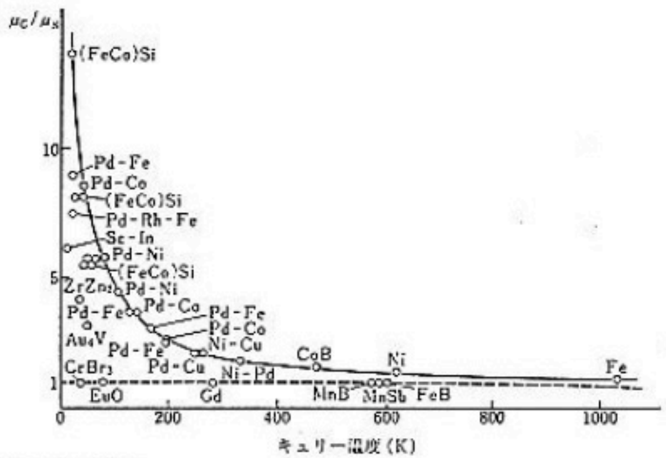
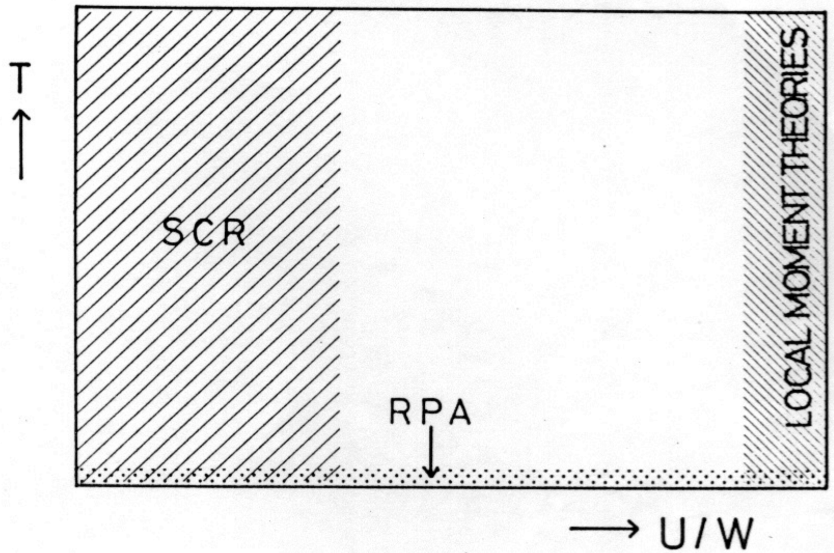
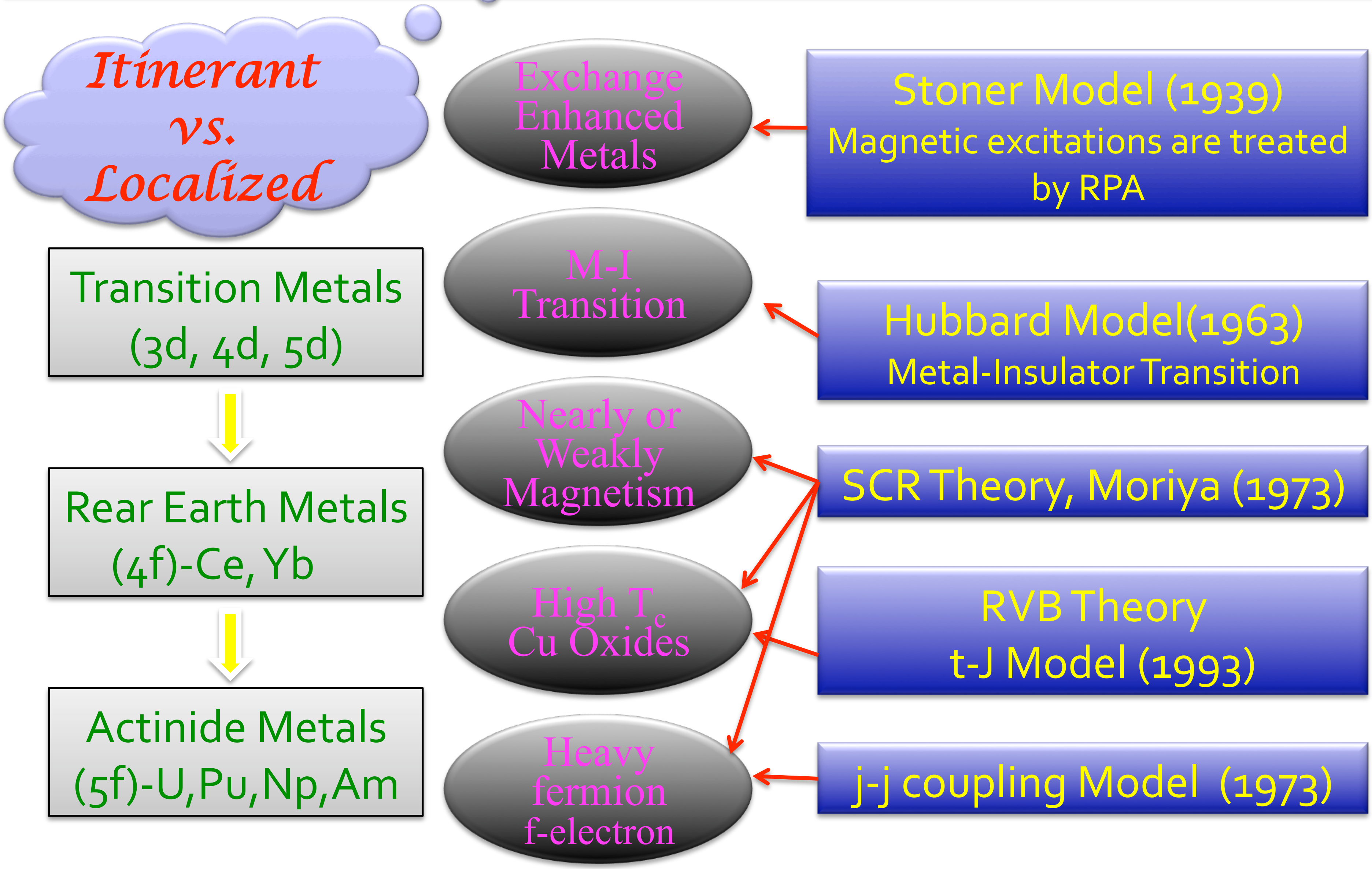


図 2.3 常磁性モーメント μ_c と強磁性飽和磁気モーメント μ_s の比 μ_c/μ_s とキュリー温度 T_C との関係．$\mu_s = M/N_0(\mu_B)$，μ_c はキュリー定数 $C = N_0\mu_B \times \mu_c(\mu_c+1)/3k$ より求めてある（文献 16）を補強した）



Conceptional Research Stream of the Magnetism in Metals



遍歴電子磁性理論：Stonerモデル→RPA近似→SCR理論

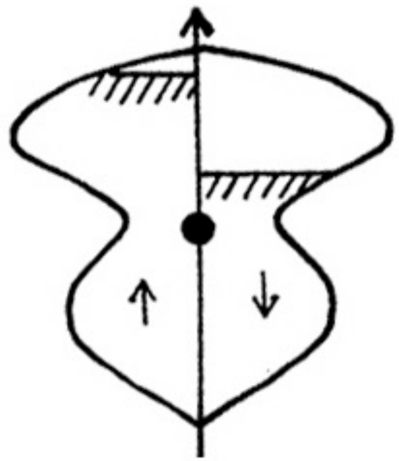
$$S^{+}=c_{\uparrow}^{\dagger}c_{\downarrow},\quad S^{-}=c_{\downarrow}^{\dagger}c_{\uparrow},\quad S^{z}=\frac{1}{2}(c_{\uparrow}^{\dagger}c_{\uparrow}-c_{\downarrow}^{\dagger}c_{\downarrow}).$$

$$\langle S^2\rangle=\frac{3}{2}n-\frac{3}{4}n^2-\frac{3}{4}\langle\delta n^2\rangle$$

Landau展開

$$F(M)=\left(\frac{1}{2\chi_0}-I\right)M^2+\frac{1}{4}gM^4-Mh$$

$$\chi(q,\omega)=\frac{2\chi_0(q,\omega)}{1+I\chi_0(q,\omega)}$$



$$\langle S^2\rangle=\mathrm{const}-O((k_BT/W)^2)$$

$$S^{+}=\sum_{\mu=1,2}c_{\mu\uparrow}^{\dagger}c_{\mu\downarrow},\quad S^{-}=\sum_{\mu=1,2}c_{\mu\downarrow}^{\dagger}c_{\mu\uparrow}$$

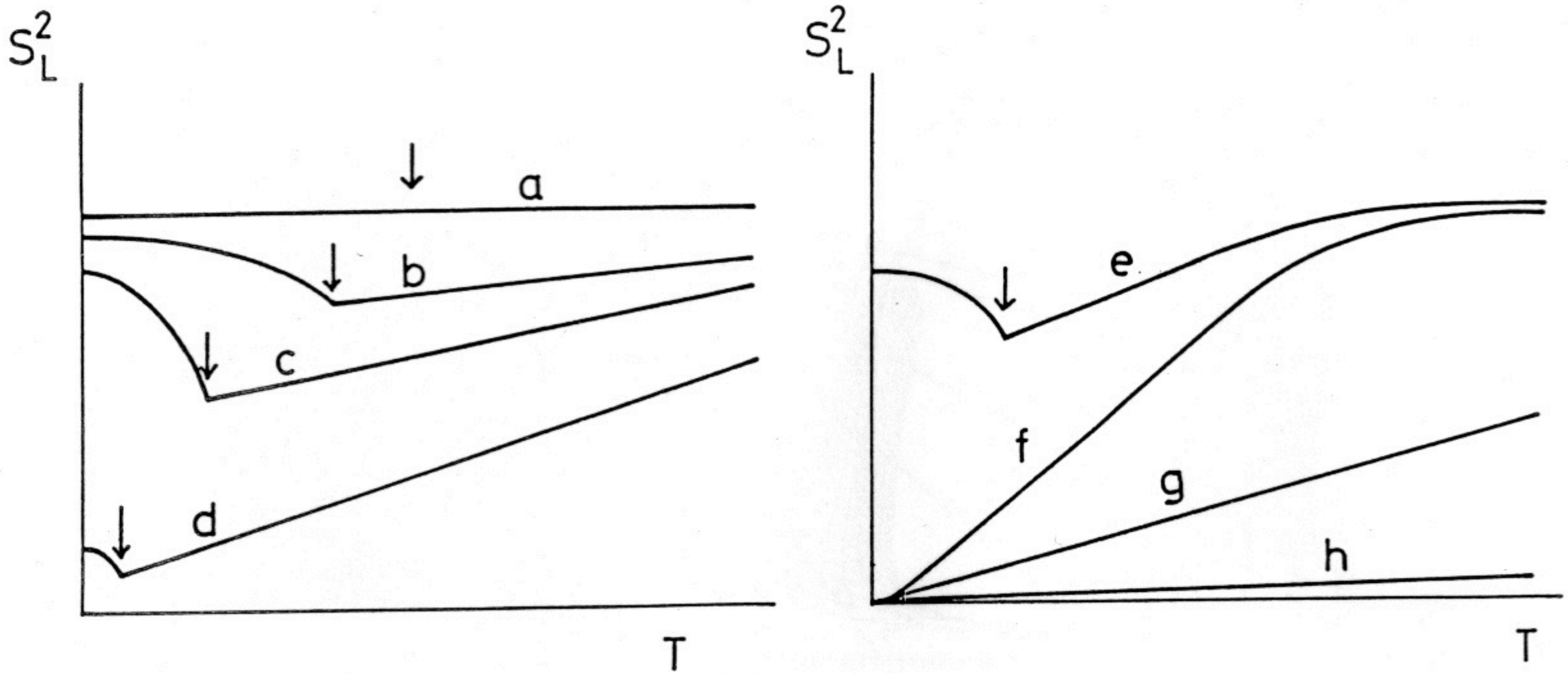
$$S^{z}=\sum_{\mu=1,2}\frac{1}{2}(c_{\mu\uparrow}^{\dagger}c_{\mu\uparrow}-c_{\mu\downarrow}^{\dagger}c_{\mu\downarrow})$$

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

Spin Fluctuations

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

$$= \left[4 N_0 I^2 S_L(T_C)^2 / 3 T_C T_0\right](T - T_C)$$



スピンの揺らぎ

$$\langle S^2 \rangle = \frac{3}{N_0^2} \sum_q \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \coth\left(\frac{\beta\omega}{2}\right) \times \mathrm{Im}\,\chi(q,\omega).$$

$$\langle S^2 \rangle = \langle S^2 \rangle_{\mathrm{T}} + \langle S^2 \rangle_{\mathrm{Z.P.}}$$

$$\langle S^2 \rangle_{\mathrm{T}} = \frac{6}{N_0^2} \sum_q \int_0^{\infty} \frac{d\omega}{\pi} n(\omega)\, \mathrm{Im}\,\chi(q,\omega),$$

$$\langle S^2 \rangle_{\mathrm{Z.P.}} = \frac{3}{N_0^2} \sum_q \int_0^{\infty} \frac{d\omega}{\pi} \mathrm{Im}\,\chi(q,\omega),$$

$$\coth\frac{\beta\omega}{2} = \mathrm{sgn}\,(\omega)(1+2n(|\omega|)),$$

$$(n(\omega) = (e^{\beta\omega}-1)^{-1}). \qquad n(\omega) = \frac{1}{e^{\beta\omega}-1}, \quad \beta = \frac{1}{k_B T}$$

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

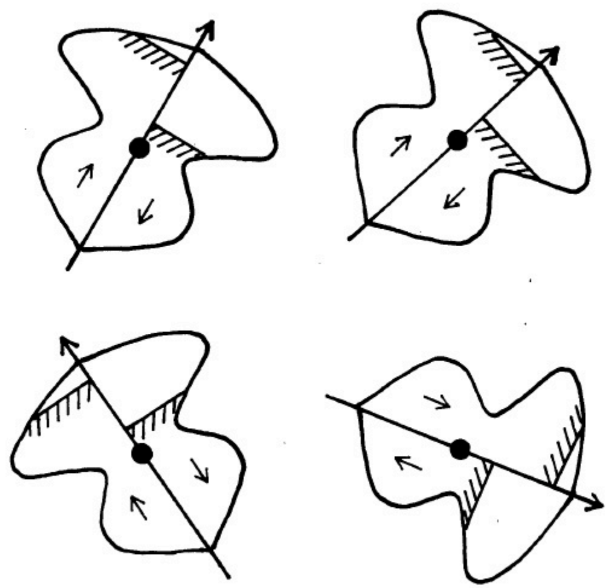
$$m^2 = m_{//}^2 + m_{\perp}^2 = S_L^2 - (M/N_0)^2$$

$$\frac{3k_B T}{N_0} \sum_q \mathrm{Re}\,\chi(q,0) = \langle S^2 \rangle = S(S+1)$$

$$\mathrm{Re}\,\chi(q,0) = \frac{1}{\pi} \int_{-\infty}^{\infty} d\omega \frac{\mathrm{Im}\,\chi(q,\omega)}{\omega}$$

$$\left[-\frac{(\alpha-1)}{\chi_0} + \frac{5}{3} g N_0^2 \overline{\overline{m}}^2\right] M + gM^3 = h$$

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



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: $\frac{1}{1-\alpha}$ $\quad \alpha = I\rho$

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:

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

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

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

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

SCR理論

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

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

$$\lambda(q,\omega) \to \lambda(0,0) = \frac{5}{3}\chi_0 g N_0 S_L(T)^2 = \frac{5}{3}\frac{\chi_0}{N_0}\overline{F_1} S_L(T)^2$$

$$\Gamma_q = \Gamma_0 q(\kappa^2 + q^2) \qquad \chi(0)\kappa^2 = \frac{N_0}{2\bar{A}}$$

$$\left[-\frac{(\alpha - 1)}{\chi_0} + \frac{5}{3} g N_0^2 \overline{m}^2\right] M + gM^3 = h$$

$$\langle S^2 \rangle_{\mathrm{Z.P.}} = \frac{3}{\pi}\frac{v_0}{(2\pi)^3}\frac{1}{2\bar{A}}\int d^3q \frac{1}{\kappa^2 + q^2}\int_0^{\omega_c(q)} d\omega \frac{\omega\Gamma_q}{\omega^2 + \Gamma_q^2},$$

$$= \frac{3}{\pi}\frac{v_0}{(2\pi)^3}\frac{\Gamma_0}{2\bar{A}}\int d^3q \frac{q}{2}[\log\{\omega_c(q)^2 + \Gamma_q^2\} - 2\log\Gamma_q],$$

$$x = q/q_B, \quad (q_B = (6\pi^2/v_0)^{1/3}),$$

$$f(x) = \omega_c(q)/\Gamma_0 q q_B^2,$$

$$T_0 = \Gamma_0 q_B^3/2\pi,$$

$$T_A = \bar{A} q_B^2,$$

$$y = \kappa^2/q_B^2.$$

$$\langle S^2 \rangle_{\mathrm{Z.P.}} = \frac{9T_0}{2T_A}\int_0^1 dx\, x^3\{\log(f(x)^2 + (x^2 + y)^2) - 2\log(x^2 + y)\}$$

$$\langle S^2 \rangle_{\mathrm{T}} = \frac{9T_0}{T_A}\eta^4 \int_0^{1/\eta} dz\, z^3 \left\{\log u - \frac{1}{2u} - \psi(u)\right\}$$

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

$$u = z(y/\eta^2 + z^2)/t,$$

$$\eta^3 = T_C/T_0,$$

$$\log u - \frac{1}{2u} - \psi(u) = 2\int_0^\infty \frac{t\,dt}{\exp 2\pi t - 1}\cdot\frac{1}{t^2 + u^2}$$

スピンの揺らぎの高橋理論

$$\frac{1}{2}Z(y) = -c_{4/3}(\eta^*)^4 + \eta^4 \int_0^{1/\eta} dz z^3 \times \left\{\log u - \frac{1}{2u} - \psi(u)\right\}.$$

$$c_{4/3}(\eta^*)^4 = \frac{T_A}{9T_0}\{\langle S^2\rangle - \langle S^2\rangle_{Z.P.}(T_C)\}$$

$$(\eta^*)^4 = \frac{\eta^4}{c_{4/3}} \int_0^{1/\eta} dz z^3 \left\{\log z^3 - \frac{1}{2z^3} - \psi(z^3)\right\},$$

$$c_{4/3} = \int_0^{\infty} dz z^3 \left\{\log z^3 - \frac{1}{2z^3} - \psi(z^3)\right\},$$

$$= \frac{1}{3^{3/2}} \frac{1}{(2\pi)^{1/3}} \Gamma(4/3)\zeta(4/3) = 0.3353\ldots.$$

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

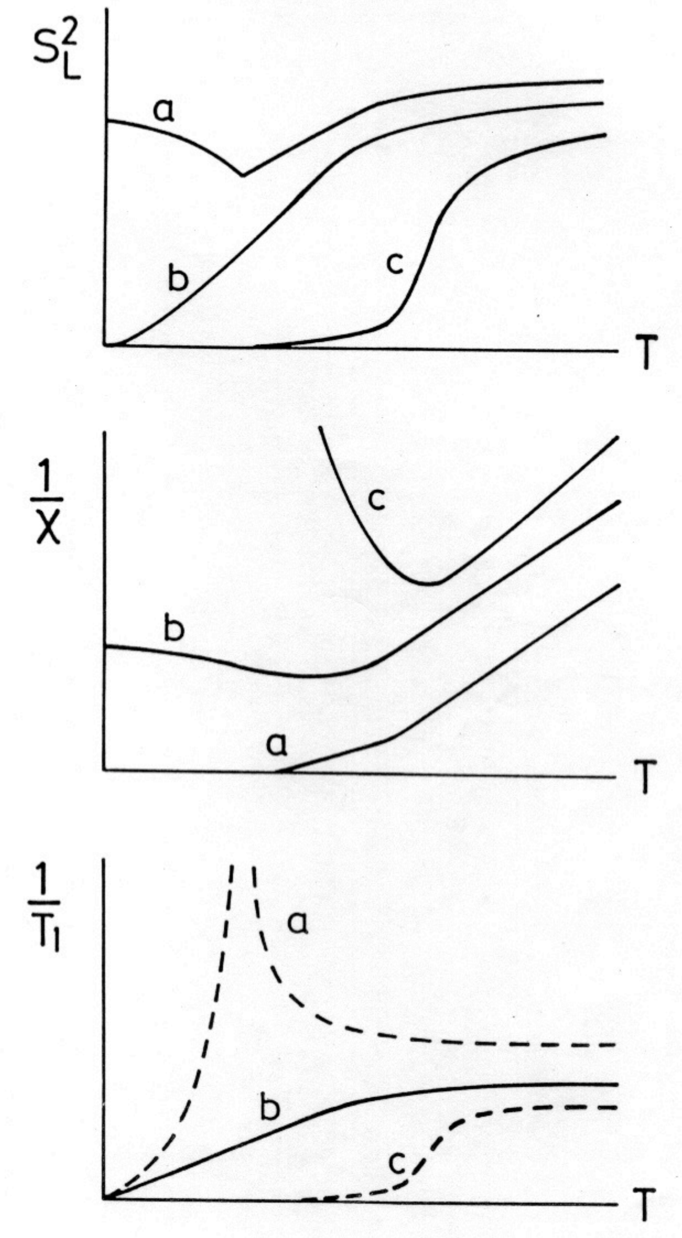
$$\langle S^2\rangle - \langle S^2\rangle_{Z.P.} = \langle S^2\rangle_T$$

$$\langle S^2\rangle_{Z.P.}(T_C) - \langle S^2\rangle_{Z.P.}(T) = -\{\langle S^2\rangle - \langle S^2\rangle_{Z.P.}(T_C)\} + \langle S^2\rangle_T(T)$$

$$\langle S^2\rangle = \langle S^2\rangle_T + \langle S^2\rangle_{Z.P.} = 一定$$

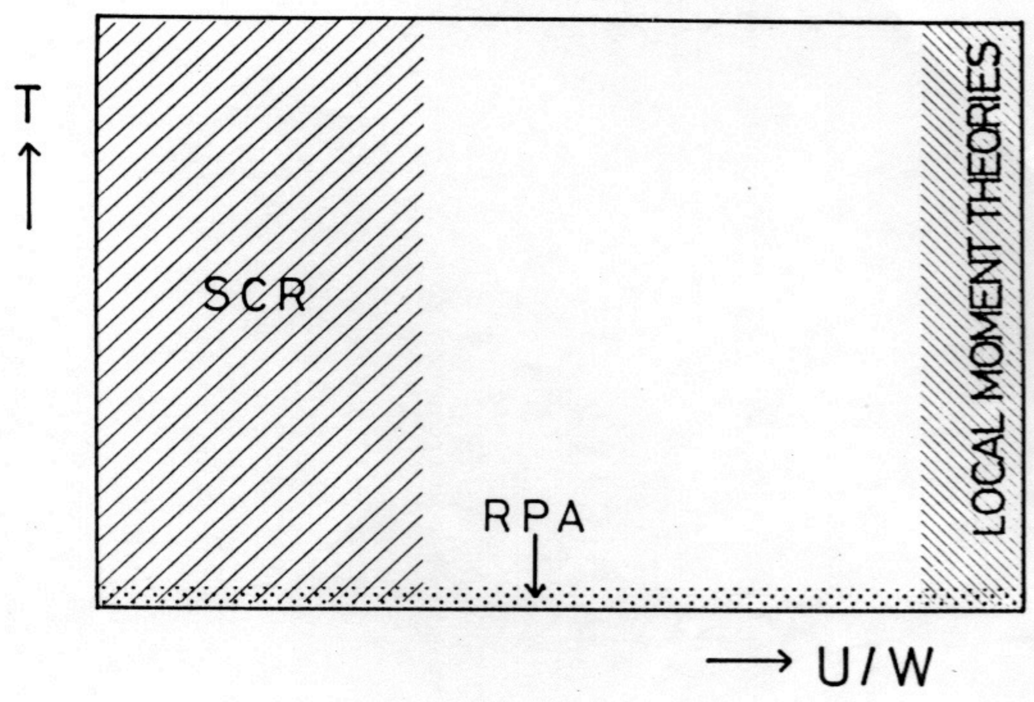
Y.Takahashi,
JPSJ 55 (1986) 3553

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



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

$$= \left[4 N_0 I^2 S_L(T_C)^2 / 3 T_C T_0\right](T - T_C)$$

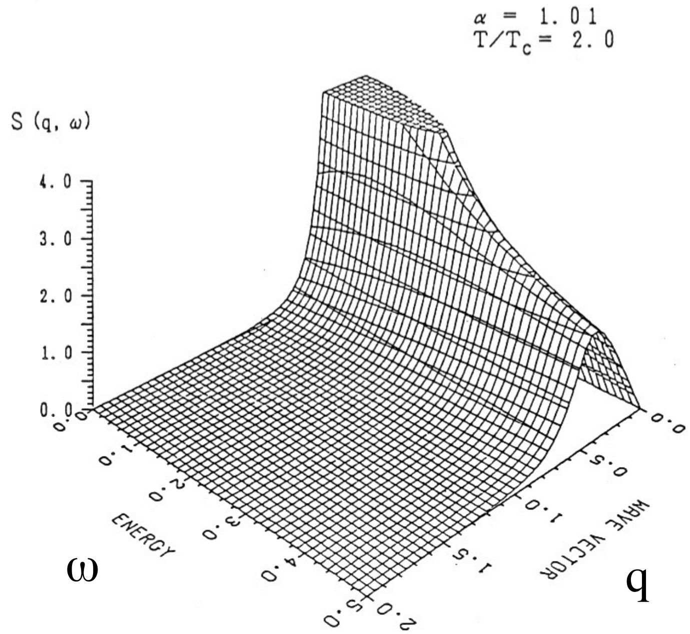


- **The Self-Consistent Renormalization (SCR) Theory of Spin Fluctuations**

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

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

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

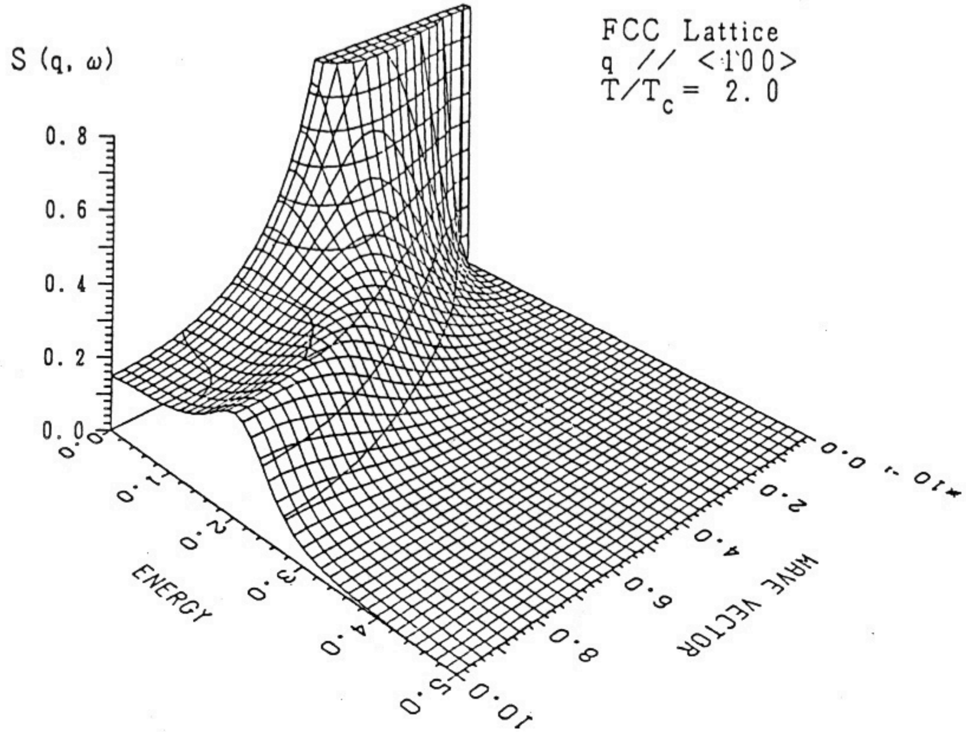


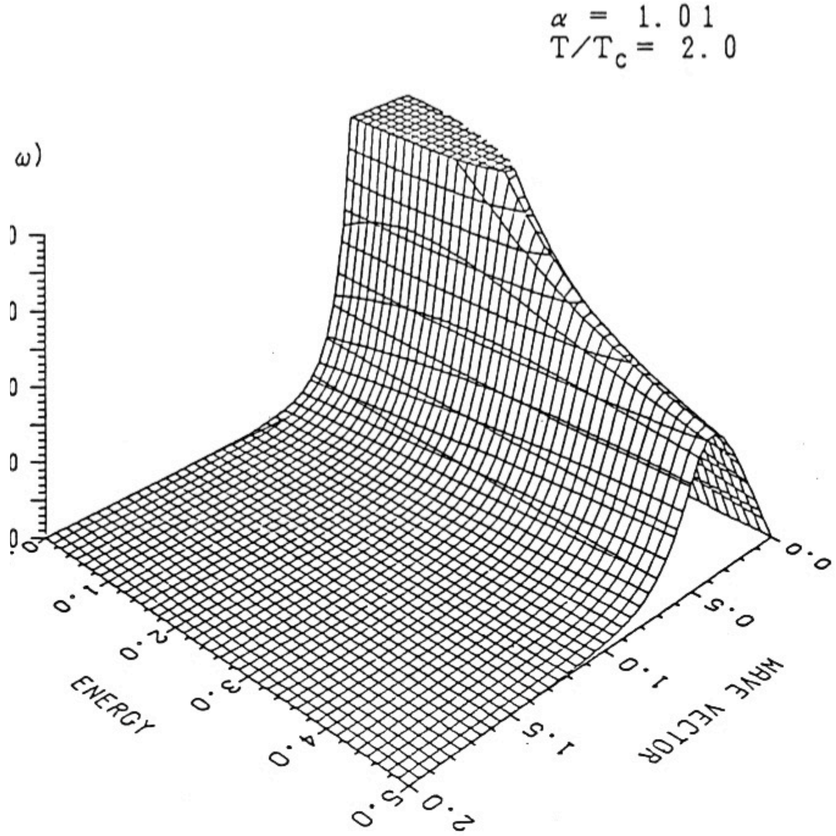
- **Quantitative aspects** (The spin fluctuation parameters)

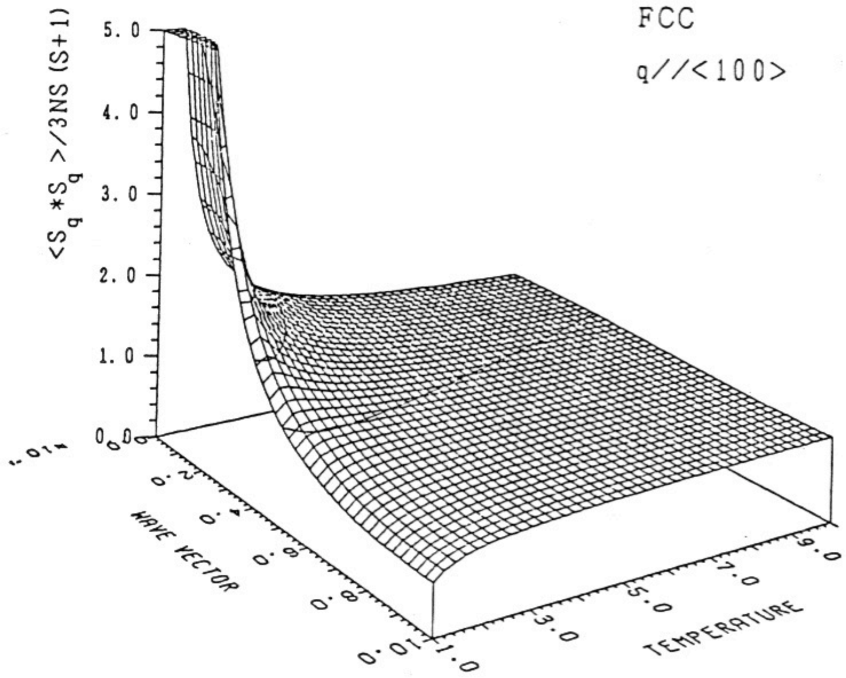
: Takahashi& Moriya (1985)

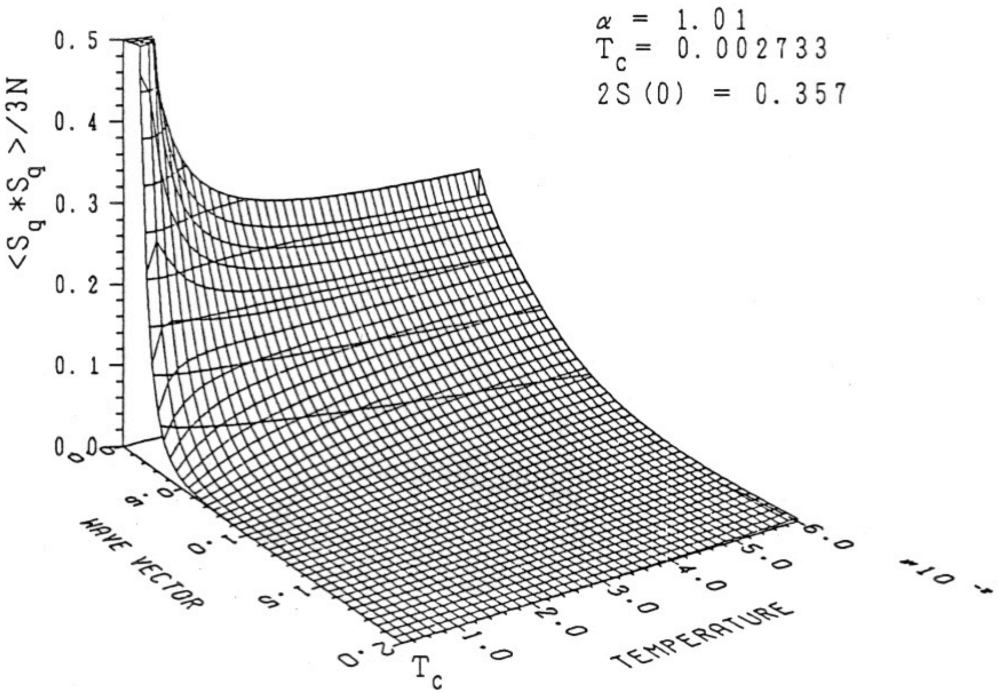
$$p_s,\quad \bar{F}_1,\quad T_0 = \Gamma_0 q_B^3/2\pi,\quad T_A = \bar{A}q_B^2$$

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


S (q, ω)
0. 8
0. 6
0. 4
0. 2
0. 0
FCC Lattice
q // <100>
T/T_c = 2. 0
ENERGY
WAVE VECTOR


α = 1. 01
T/T_c = 2. 0
ω)
ENERGY
WAVE VECTOR


FCC
q//<100>
<S_q*S_q>/3NS(S+1)
5.0
4.0
3.0
2.0
1.0
0.0
WAVE VECTOR
TEMPERATURE
1.0
3.0
5.0
7.0
9.0


α = 1.01
T_c = 0.002733
2S(0) = 0.357
<S_q*S_q>/3N
0.5
0.4
0.3
0.2
0.1
0.0
WAVE VECTOR
TEMPERATURE
T_c
1.0
2.0
3.0
4.0
5.0
6.0

The SCR theory⇔Experiments

<The Curie temperature, T_C>

$$p_s^2/4 \cong \frac{15cT_0}{T_A}\eta^4 = \frac{15cT_0}{T_A}\left(\frac{T_C}{T_0}\right)^{4/3} \qquad c = \frac{1}{3^{3/2}}(2\pi)^{-1/3}\Gamma(4/3)\zeta(4/3) = 0.3353\cdots\cdots$$

<Reduced Susceptibility, y>

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

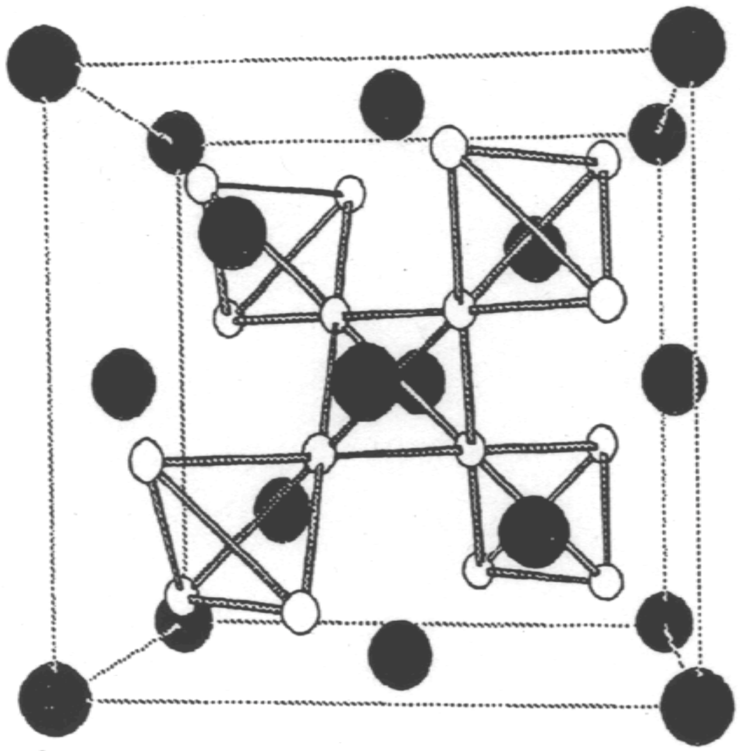
$u = z(y+z^2)/t$, $t = T/T_C$, $\eta = (T_C/T_0)^{1/3}$, ψ: digamma function

$$\frac{1}{\chi} = \frac{(1-\alpha)}{\chi_0} + \frac{5}{3}gN_0^2 S_L(T)^2 = \frac{4N_0 I^2 S_L(T_C)^2/T_0}{3T_C^2(t-1)} \qquad \chi = \frac{N_0 p_{eff}^2}{3k_B T_C\left(t^{4/3}-1\right)} \quad (T_C近傍)$$

<NMR, T_1>

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

YCo_2 の結晶構造



立方晶C15ラーベス構造

● Y　8a　　　　ダイヤモンド格子
○ Co　16d　　　パイロクロア格子
（正四面体が3次元的に頂点を共有）

RCo_2の遍歴電子磁性

RCo_2 (R=Rare Earth)はRの種類によって様々なCoの遍歴電子磁性

- Rが非磁性　：　交換増強されたパウリ常磁性
- Rが軽希土類金属　：　遍歴電子強磁性
- Rが重希土類金属　：　フェリ磁性

- これらのCoの遍歴電子磁性はCo間の強い交換相互作用に起因
- Rに磁性があるときはRがつくる分子場が寄与！
- Yは非磁性なのでYCo_2は交換増強されたパウリ常磁性

$Y(Co\text{-}Fe)_2$→強磁性→非磁性元素の置換で強磁性出現を！