

2006年07月26日 (Dゼミ)

K.NAKADA

バンド模型による強磁性

On the conditions of ferromagnetism by the band model, M.SHIMIZU, Proc. Phys. Soc., 84 (1964) 397.
On the conditions of ferromagnetism by the band model:II, M.SHIMIZU, Proc. Phys. Soc., 86(1965) 147.

磁性の模型

- 局在電子模型(稀土類金属、酸化物、化合物)

1928 Heisenberg
$$H = -2J \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$

磁気モーメント
$$\vec{M} = 2\mu_B \sum_i \langle \vec{S}_i \rangle$$

- 遍歴電子模型(3d遷移金属、合金、化合物)

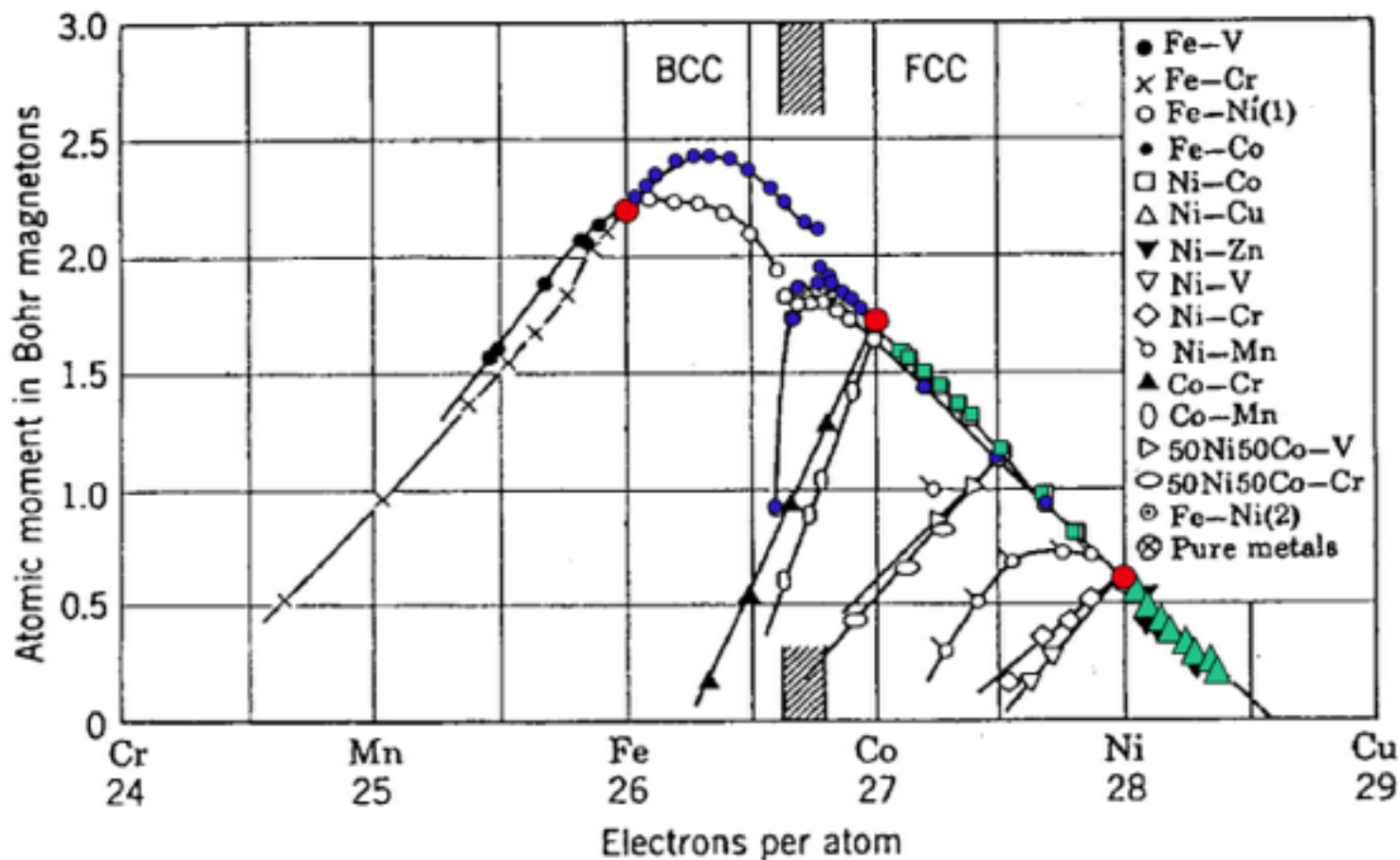
1933 Slater, Stoner

電子構造に基づく磁性理論

磁気モーメント
$$M = \mu_B (n_{\uparrow} - n_{\downarrow})$$

電子構造のより正確な計算方法の開発
電子相関の研究

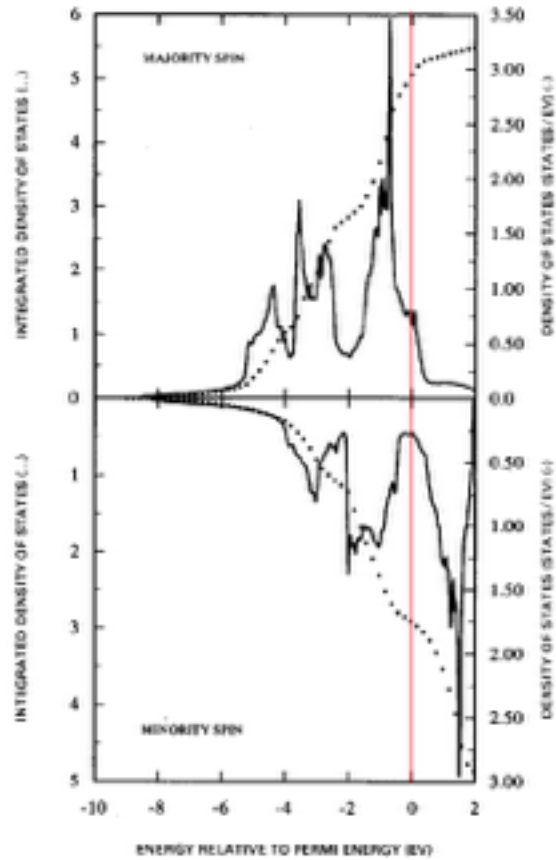
Slater-Pauling 曲線 (S.Chikazumi, "Physics and Applications of Inver Alloys (1978)"



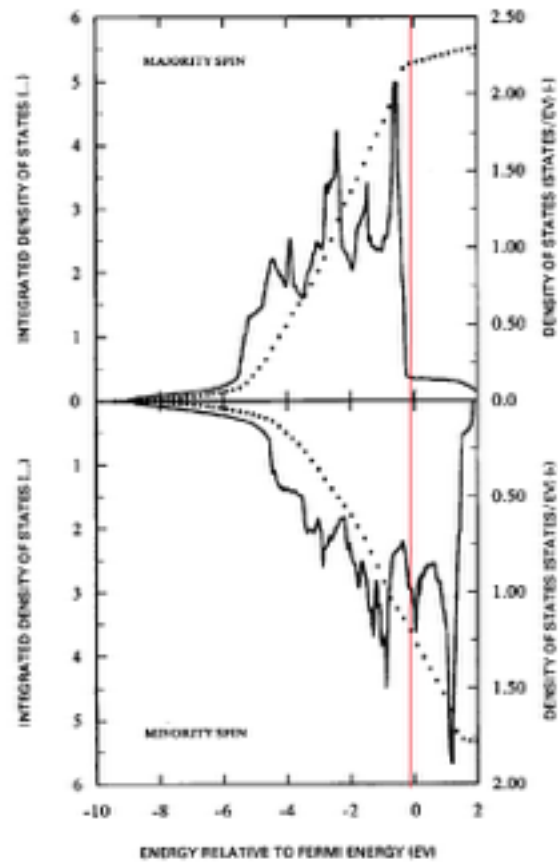
- 単体のFe,Co,Niはそれぞれ2.2,1.7,0.6 M_B の磁気モーメントで局在電子模型では説明できない
- Fe,Co,Ni同士の合金の磁気モーメントは、単体のFe,Co,Niの磁気モーメントの組成平均ではない
- CrやMnとの合金の磁気モーメントは減少する

Moruzzi *et al.* 1978

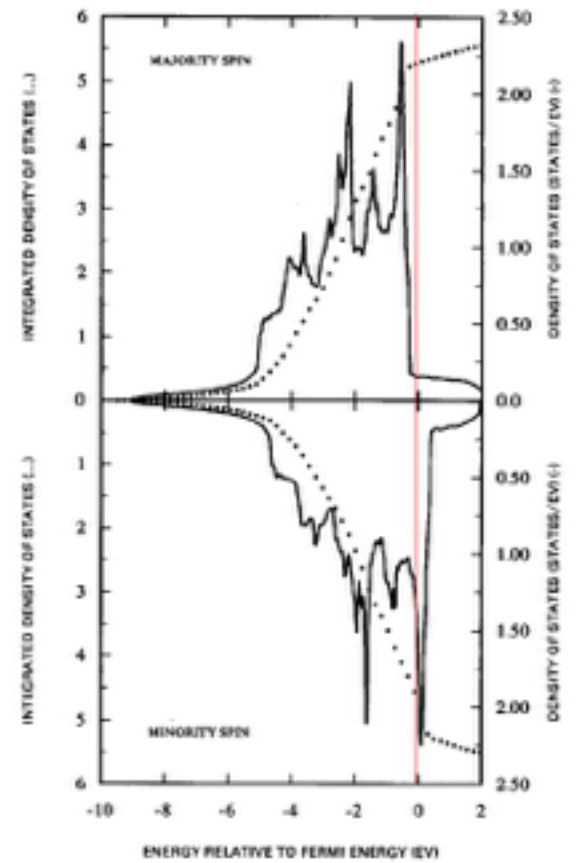
bcc Fe



fcc Co



fcc Ni



金属磁性研究

1895: Currie

1907: Weiss 分子場理論

1928: Heisenberg Model

1933: Stoner Model

1962: Wohlfarth and Rhodes

1965: Shimizu

1991: Hathaway and Cullen

1993: Yamada 理論

バンド計算

1937: Slater

1940~50年代 手法開発期

1964: DFT

1974: K.A

1980: Weinert

1984: Schwarz
(fix-spin moment)

Stoner model (1933)

自由電子モデルに分子場を導入して議論した

分子場(IM) I: 分子場係数, exchange parameter

$$H_{eff} = H + IM$$

$$M = \chi_0 H_{eff} = \chi_0 (H + IM)$$

$$M = \frac{\chi_0(T)}{1 - I\chi_0(T)} H$$

$$\chi(T) = \frac{\chi_0(T)}{1 - I\chi_0(T)} \quad \frac{1}{1 - I\chi_0(T)} : \text{exchange enhancement factor}$$

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

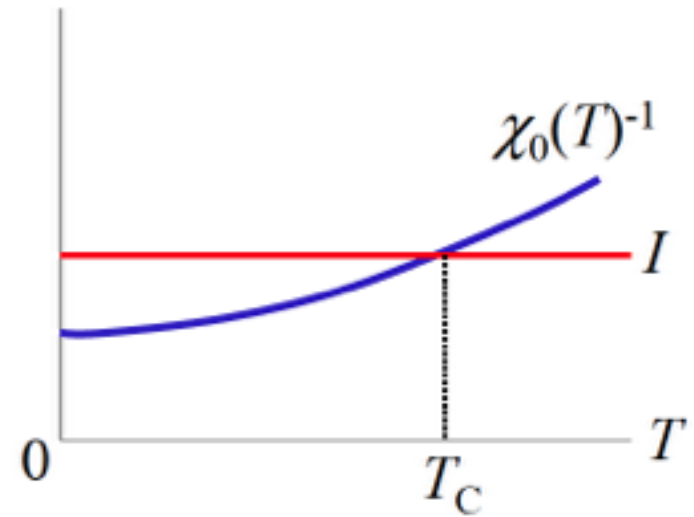
Instability

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

$$\frac{1}{\chi_0(T)} - I < 0$$

$1 - I\chi_0 = 0$ のとき、強磁性が出現

$$D(\varepsilon_F^0) = 1/2\mu_B^2 I \quad \text{Stoner 条件}(T=0)$$



$$T_C^2 = \frac{1}{2C_2 k_B^2} \frac{2ID_0 - 1}{\left(D_0' / D_0\right)^2 - D_0'' / D_0}$$

$$C_2 = \frac{\pi^2}{12}$$

$$T=0[K]$$

$$v(\varepsilon) \equiv v_1(\varepsilon)$$

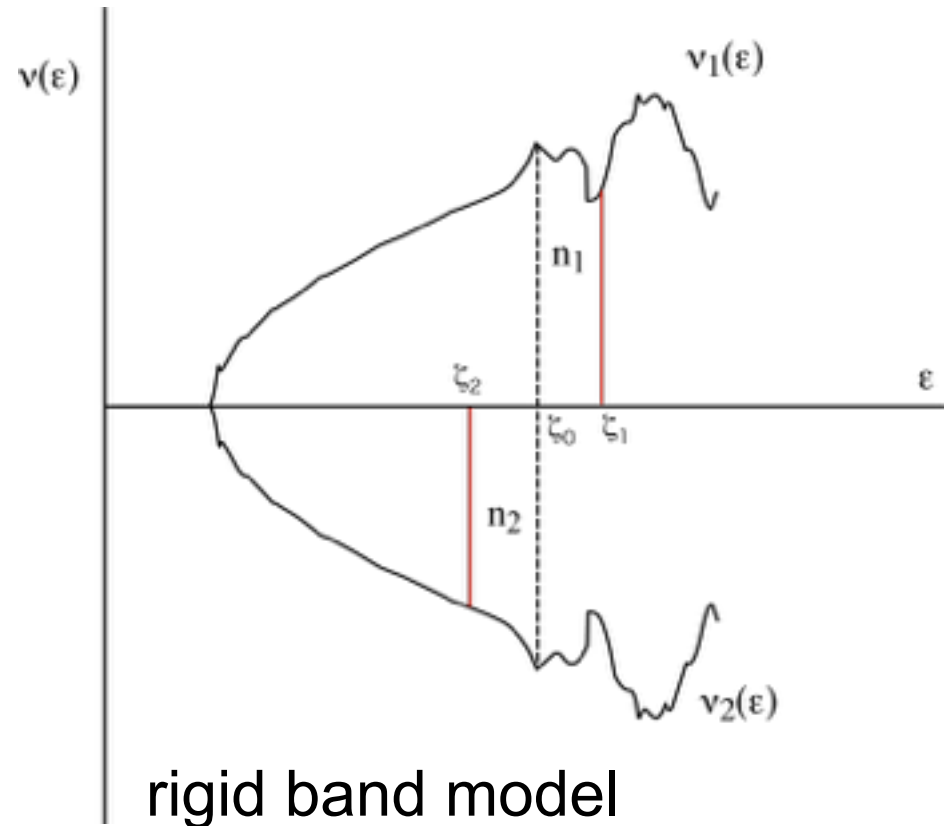
$$v(\varepsilon) \equiv v_2(\varepsilon)$$

$$n_1(\zeta_1) = \int_{\zeta_0}^{\zeta_1} v_1(\varepsilon) d\varepsilon$$

$$n_2(\zeta_2) = \int_{\zeta_2}^{\zeta_0} v_2(\varepsilon) d\varepsilon$$

$$n_1(\zeta_1) = n_2(\zeta_2) = n$$

$$M = 2\mu_B n$$



磁化した電子のエネルギーの全変化

$$E = \int_{\zeta_0}^{\zeta_1} \varepsilon v_1(\varepsilon) d\varepsilon - \int_{\zeta_2}^{\zeta_0} \varepsilon v_2(\varepsilon) d\varepsilon + E_{\text{ex}}$$

Mの変化に対してEが極値を取る条件

$$\frac{\partial E}{\partial M} = 0$$

$$\frac{\partial E}{\partial M} = \frac{\zeta_1 - \zeta_2}{2\mu_B} + \frac{\partial E_{\text{ex}}}{\partial M} = 0$$

$$\frac{\partial^2 E}{\partial M^2} > 0$$

$$\frac{\partial^2 E}{\partial M^2} = \frac{v_1(\zeta_1)^{-1} + v_2(\zeta_2)^{-1}}{4\mu_B^2} + \frac{\partial^2 E_{\text{ex}}}{\partial M^2} > 0$$

エネルギー極小の条件

M=0 において E=0

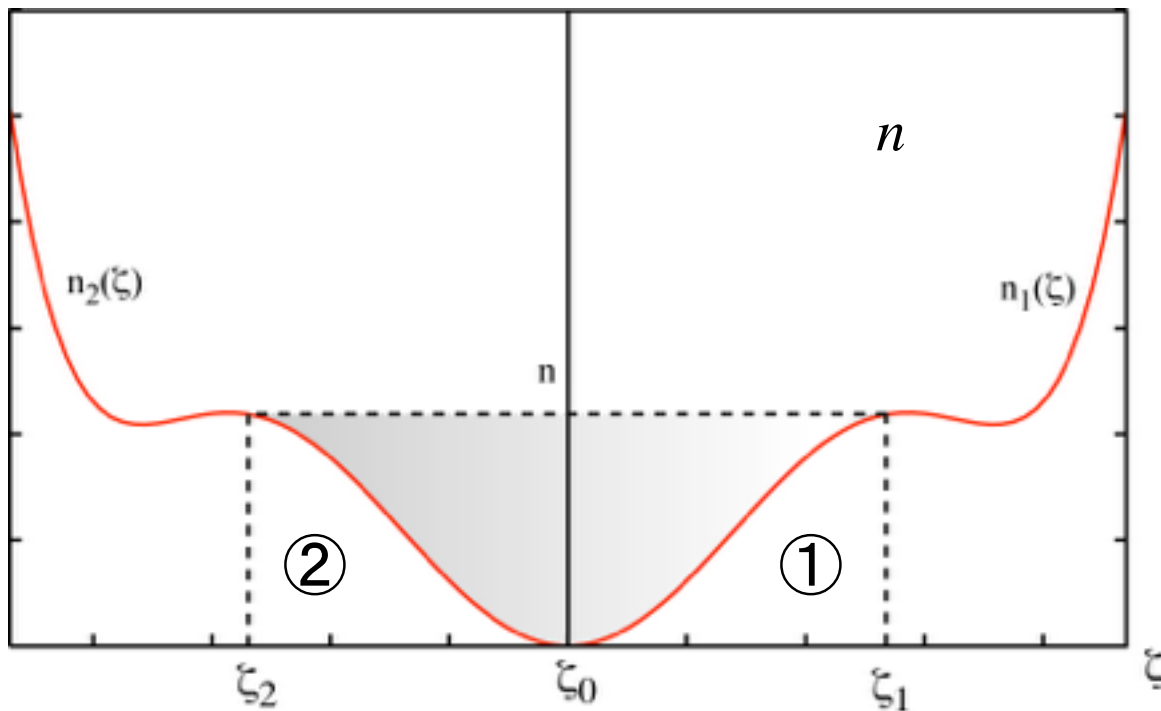
M≠0 において E<0

ならば、バンドモデルにおいて強磁性が期待できる

全エネルギーの符号の変化

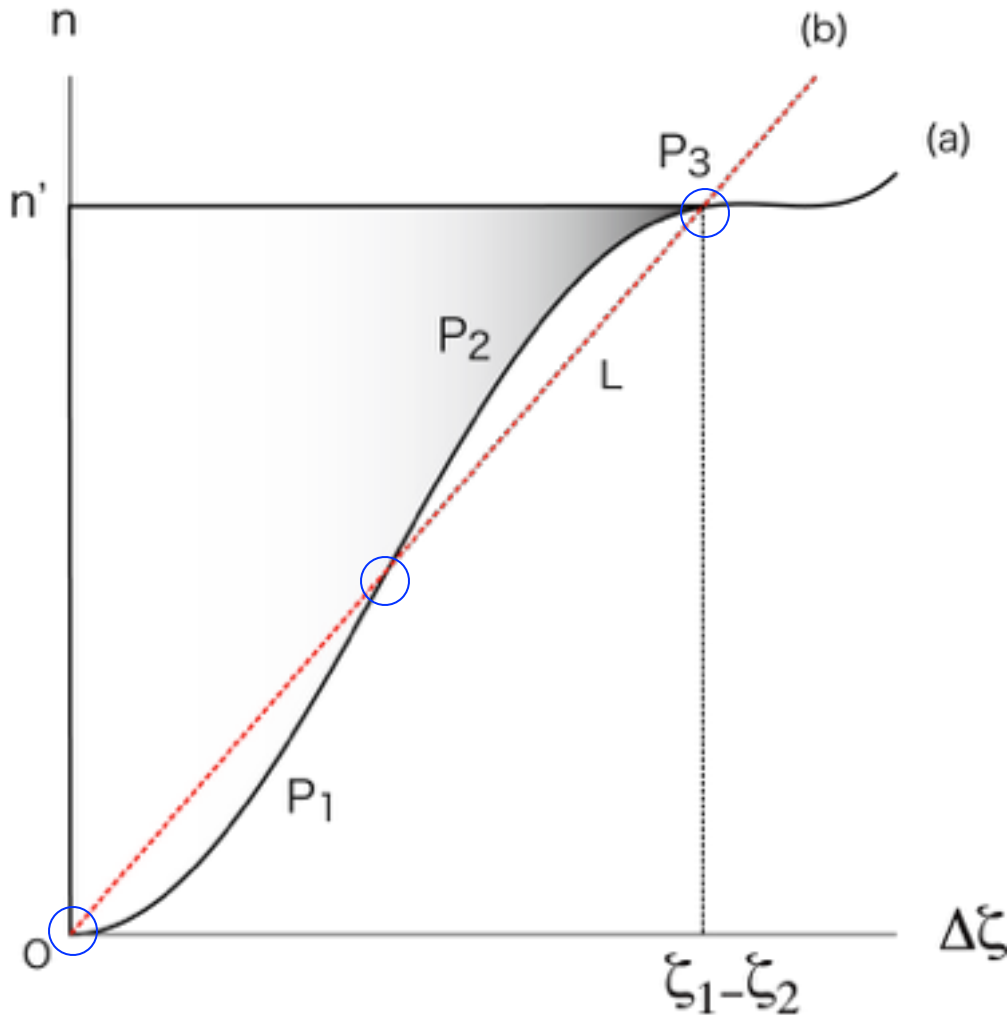
$$E = \int_{\zeta_0}^{\zeta_1} \varepsilon v_1(\varepsilon) d\varepsilon - \int_{\zeta_2}^{\zeta_0} \varepsilon v_2(\varepsilon) d\varepsilon$$

$$= \underbrace{(\zeta_1 - \zeta_2)n}_{\text{①}} - \underbrace{\int_{\zeta_0}^{\zeta_1} n_1(\varepsilon) d\varepsilon}_{\text{②}} - \underbrace{\int_{\zeta_2}^{\zeta_0} n_2(\varepsilon) d\varepsilon}_{\text{②}}$$



極値条件の書き直し①

$$E = (\zeta_1 - \zeta_2)n - \int_{\zeta_0}^{\zeta_1} n_1(\varepsilon)d\varepsilon - \int_{\zeta_2}^{\zeta_0} n_2(\varepsilon)d\varepsilon$$



$$\frac{\partial E}{\partial M} = \frac{\zeta_1 - \zeta_2}{2\mu_B} + \frac{\partial E_{\text{ex}}}{\partial M} = 0$$

$$\Delta\zeta = -\frac{\partial E_{\text{ex}}}{\partial n}$$

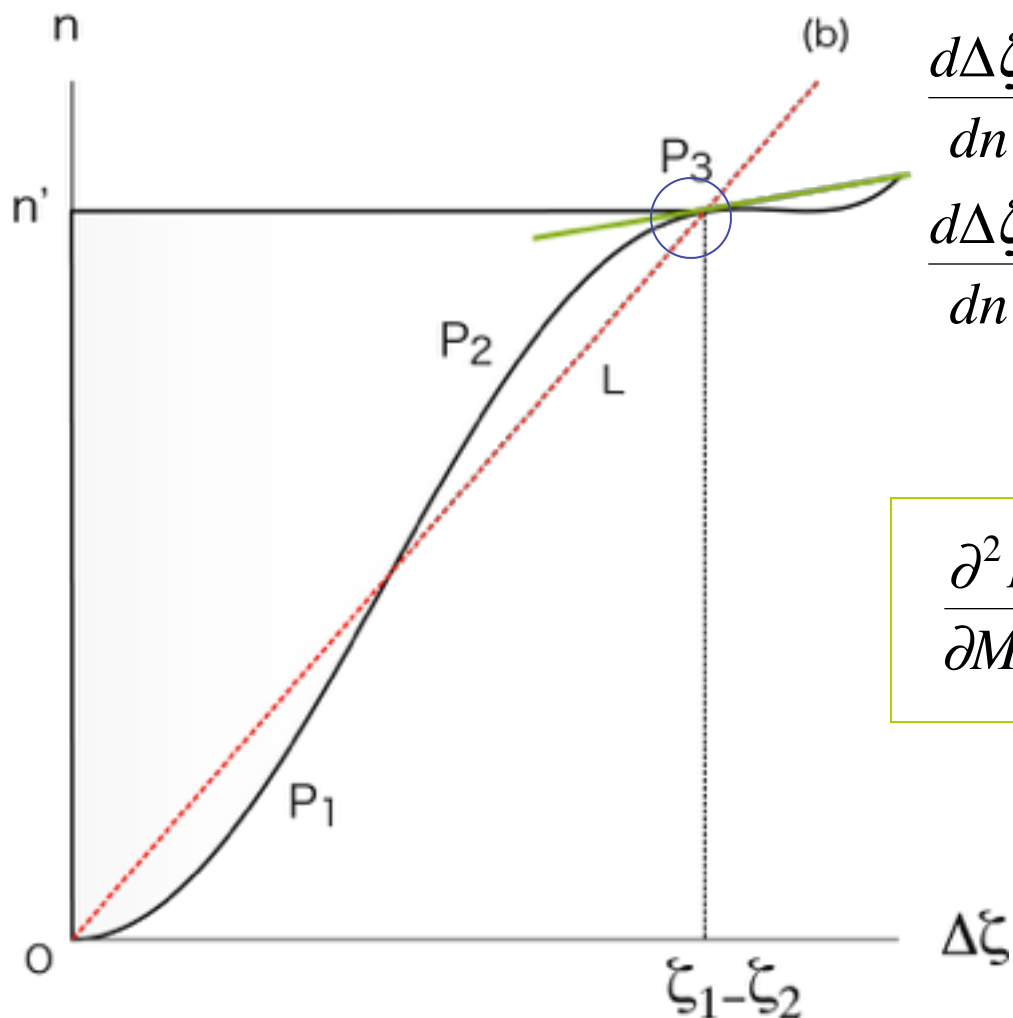
$$\text{もし、 } E_{\text{ex}} = -\frac{1}{2}\alpha M^2$$

$$\Delta\zeta = 2\mu_B\alpha M \quad (\text{b})$$

$$(\quad = 4\mu_B^2\alpha n)$$

極値条件の書き直し

$$\frac{\partial^2 E}{\partial^2 M^2} = \frac{v_1(\zeta_1)^{-1} + v_2(\zeta_2)^{-1}}{4\mu_B^2} + \frac{\partial^2 E_{\text{ex}}}{\partial M^2} > 0$$

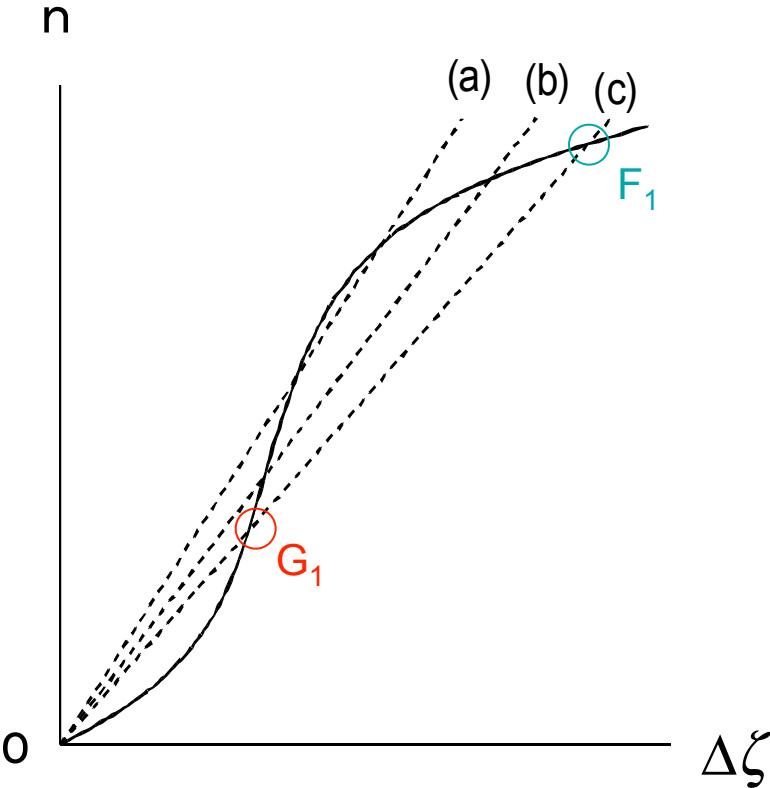
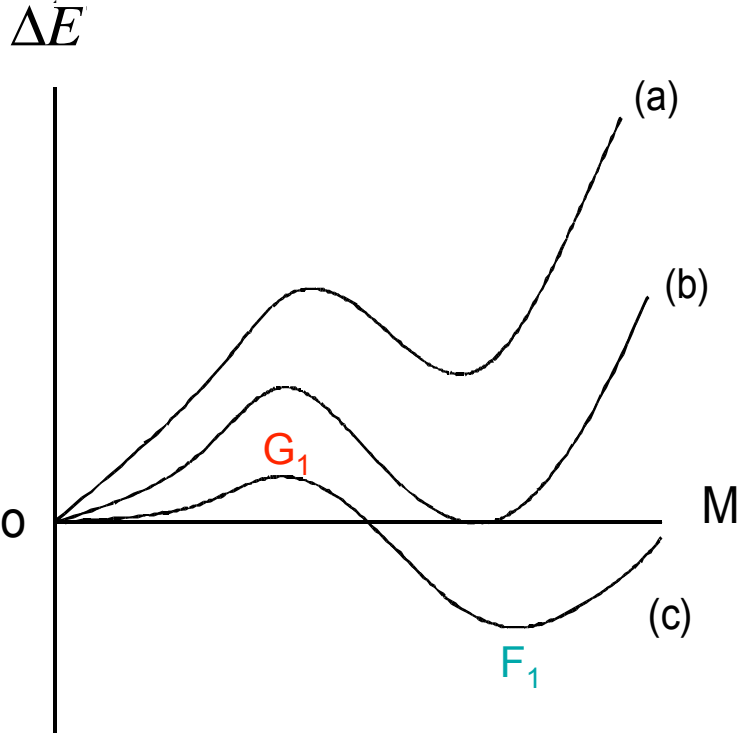


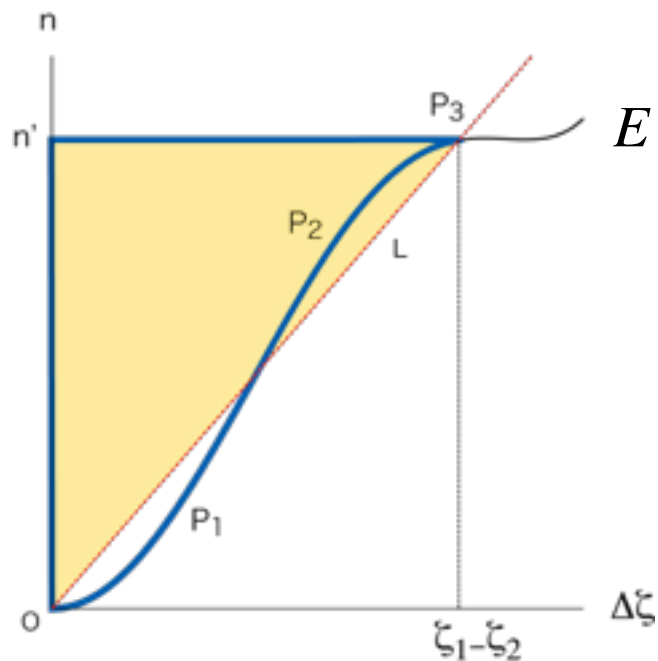
$$\frac{d\Delta\zeta}{dn} = -\frac{\partial^2 E_{\text{ex}}}{\partial n^2} = 4\mu_B^2 \alpha$$

$$\frac{d\Delta\zeta}{dn} = \frac{\partial^2 E(\Delta\zeta)}{\partial n^2} = \{v_1^{-1}(\zeta_1) + v_2^{-1}(\zeta_2)\}$$

$$\frac{\partial^2 E}{\partial M^2} = \frac{\partial^2 n}{\partial E_{\text{ex}}^2} - \{v_1^{-1} + v_2^{-1}\}^{-1} > 0$$

強磁性の出現条件

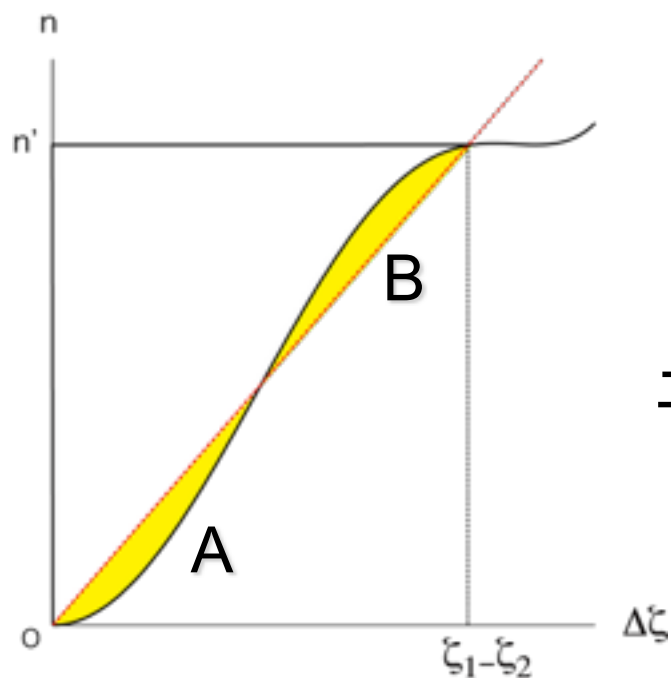




$$E = (\zeta_1 - \zeta_2)n - \int_{\zeta_0}^{\zeta_1} n_1(\varepsilon)d\varepsilon - \int_{\zeta_2}^{\zeta_0} n_2(\varepsilon)d\varepsilon - (-E_{\text{ex}})$$

領域 OP_3n'

領域 $OP_1P_2P_3$



AとBの面積差によって
エネルギーと磁化の関係が議論できる

常磁性

$$\Delta\zeta = \zeta_1 - \zeta_2 = 0$$

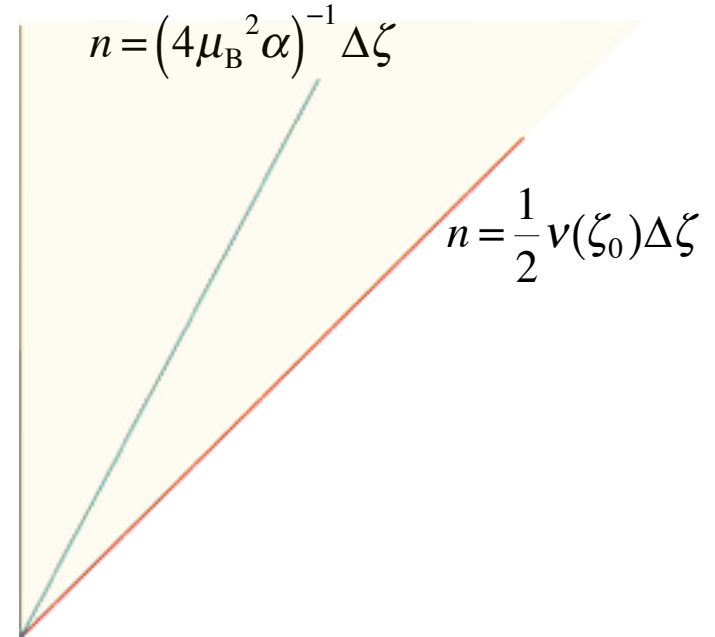
$$\frac{dn}{d\Delta\zeta} = \{v_1(\zeta_1)^{-1} + v_2(\zeta_2)^{-1}\} = \frac{1}{2}v(\zeta_0)$$

$$n = \frac{1}{2}v(\zeta_0)\Delta\zeta$$

強磁性

$$\frac{dn}{d\Delta\zeta} = -\frac{\partial n^2}{\partial^2 E_{\text{ex}}} = (4\mu_B^2\alpha)^{-1}$$

$$n = (4\mu_B^2\alpha)^{-1}\Delta\zeta$$



$$\frac{1}{2}v(\zeta_0) < (4\mu_B^2\alpha)^{-1}$$

$$\alpha^{-1} > \alpha_S^{-1} (= 2\mu_B^2 v(\zeta_0))$$

On the conditions of ferromagnetism by the band model,
M.SHIMIZU, Proc. Phys. Soc., 84 (1964) 397.

- 一般の形状の状態密度(リジッドバンド)から強磁性を議論できる
- Stoner条件を満たさない時でも、強磁性の出現が可能である

→ 有限温度への拡張
強磁性出現条件の詳細な議論(landau展開)

On the conditions of ferromagnetism by the band model:II, M.SHIMIZU, Proc. Phys. Soc., 86(1965) 147.

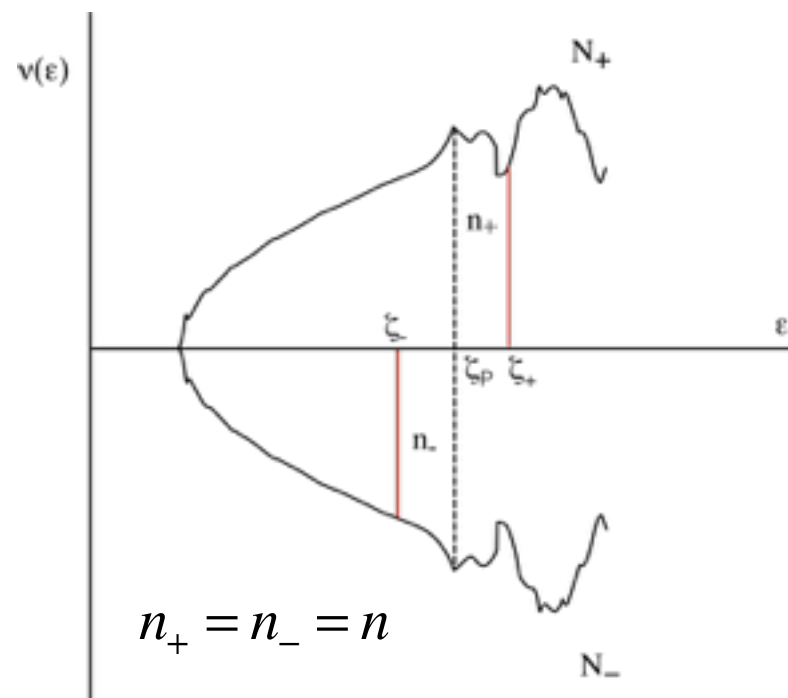
フェルミ分布関数の温度変化 (有限温度)

$$N = N_+ + N_-$$

$$M = \mu_B (N_+ - N_-) = 2\mu_B n$$

$$N_+ = \frac{1}{2}N + n = \int_{-\infty}^{\infty} f_+ v(\epsilon) d\epsilon$$

$$N_- = \frac{1}{2}N - n = \int_{-\infty}^{\infty} f_- v(\epsilon) d\epsilon$$



$$E = \int_{-\infty}^{\infty} (f_+ + f_-) \epsilon v(\epsilon) d\epsilon + E_{\text{ex}}(M)$$

$$S = -k_B \int \{f_+ \ln f_+ + (1 - f_+) \ln(1 - f_+) + f_- \ln f_- + (1 - f_-) \ln(1 - f_-)\} v(\epsilon) d\epsilon$$

$$f_{\pm}(\epsilon - \zeta_{\pm}) = \left\{ 1 + \exp\left(\frac{\epsilon - \zeta_{\pm}}{kT}\right) \right\}^{-1} \quad \text{フェルミ分布関数}$$

自由エネルギー

$$F = E - TS$$

$$\begin{aligned} &= -kT \int_{-\infty}^{\infty} \left[\ln \left\{ 1 + \exp \left(\frac{\zeta_+ - \varepsilon}{kT} \right) \right\} + \ln \left\{ 1 + \exp \left(\frac{\zeta_- - \varepsilon}{kT} \right) \right\} \right] \nu(\varepsilon) d\varepsilon \\ &\quad + N_+ \zeta_+ + N_- \zeta_- + E_{\text{ex}}(M) \end{aligned}$$

常磁性状態

$$F_P = -kT \int 2 \ln \left\{ 1 + \exp \left(\frac{\zeta_P - \varepsilon}{kT} \right) \right\} \nu(\varepsilon) d\varepsilon + N \zeta_P$$

強磁性と常磁性とのエネルギー差

$$\begin{aligned} \Delta F &= F - F_P \\ &= - \int_{\zeta_P}^{\zeta_+} n_+(\zeta) d\zeta - \int_{\zeta_-}^{\zeta_P} n_-(\zeta) d\zeta + (\zeta_+ - \zeta_-) n + E_{\text{ex}}(M) \end{aligned}$$

強磁性の出現条件

$$\frac{\partial \Delta F}{\partial M} = 0 \quad \longrightarrow \quad \zeta_+ - \zeta_- = -2\mu_B \frac{\partial E_{\text{ex}}}{\partial M}$$

$$\frac{\partial^2 \Delta F}{\partial M^2} > 0 \quad \longrightarrow \quad \frac{(\partial n_+ / \partial \zeta_+)^{-1} - (\partial n_- / \partial \zeta_-)^{-1}}{4\mu_B^2} + \frac{\partial^2 E_{\text{ex}}}{\partial M^2} > 0$$

$$\frac{dn}{d\Delta\zeta} = -\frac{\partial n^2}{\partial^2 E_{\text{ex}}} = \left\{ -4\mu_B^2 \left(\frac{\partial^2 E_{\text{ex}}}{\partial M^2} \right) \right\}^{-1} \quad \textcircled{1}$$

$$\frac{dn}{d\Delta\zeta} = \frac{\partial n^2}{\partial^2 \Delta F(\Delta\zeta)} = \left\{ \left(\frac{\partial n}{\partial \zeta_+} \right)^{-1} - \left(\frac{\partial n}{\partial \zeta_-} \right)^{-1} \right\}^{-1} \quad \textcircled{2}$$

① > ② ならば極小値を持つ

$$\frac{\partial^2 \Delta F}{\partial M^2} = \frac{1}{4} \{ N_+(\zeta_+)^{-1} + N_-(\zeta_-)^{-1} \} + \frac{\partial^2 E_{\text{ex}}}{\partial M^2} > 0$$

$$N_1(\zeta_\sigma) = - \int_0^\infty D(\varepsilon) \frac{df(\varepsilon - \zeta_\sigma)}{d\varepsilon} d\varepsilon$$

$$T=0 : N_1(\zeta_\sigma) = D(\zeta_\sigma)$$

$$E_{\text{ex}} = -\frac{1}{2} \alpha M^2$$

$$D(\zeta_+)^{-1} + D(\zeta_-)^{-1} > 4\alpha$$

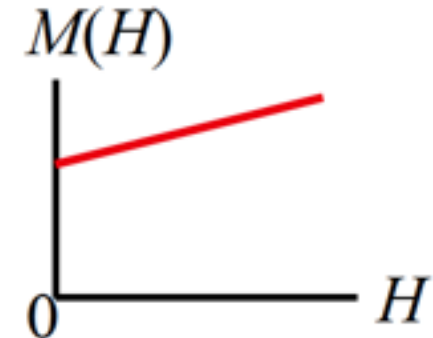
強磁性安定条件

高磁場帯磁率 (high field susceptibility)

Wohlfarth, Phys. Lett. 3 (1962) 17.

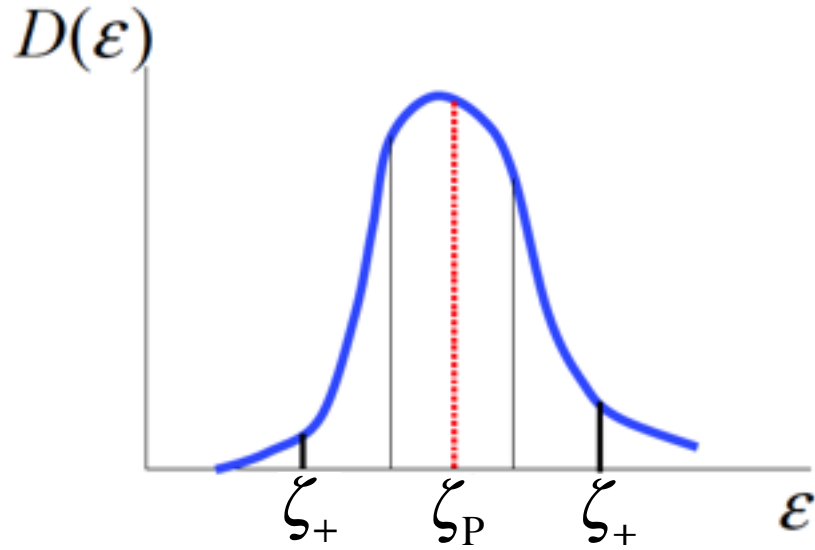
$$M(H) = M(0) + \chi_{\text{HF}} H$$

$$\chi_{\text{HF}} = 4\mu_B^2 / [D(\zeta_+)^{-1} + D(\zeta_-)^{-1} - 4I] > 0$$



弱い磁性体の高磁場帯磁率は大きい (遍歴性が強い)

高磁場帯磁率



$$\chi_{\text{HF}} = 4\mu_{\text{B}}^2 / [D(\zeta_+)^{-1} + D(\zeta_-)^{-1} - 4I]$$

$D(\zeta_+), D(\zeta_-)$ が共に大きいときは χ_{HF} は大きく、遍歴性が強い

$D(\zeta_+), D(\zeta_-)$ のどちらかが小さいとき χ_{HF} は小さくなる

Landau 展

$$\begin{aligned}\frac{\partial \Delta F}{\partial M} &= \frac{1}{2\mu_B}(\zeta_+ - \zeta_-) + \frac{\partial E_{\text{ex}}}{\partial M} \\ &= \frac{1}{2\mu_B}(\zeta_+ - \zeta_-) - \alpha M\end{aligned} \quad \left. \begin{array}{l} \\ \end{array} \right\} E_{\text{ex}} = -\frac{1}{2}\alpha M^2$$

$$\begin{aligned}\Delta F(M) &= F(M) - F(0) = \int_0^M \frac{1}{2\mu_B}(\zeta_+ - \zeta_-)dM - \frac{1}{2}\alpha M^2 \\ &= \int \frac{1}{2\mu_B} 2\mu_B(a_0' M + b_0 M^3 + \dots) dM - \frac{1}{2}\alpha M^2 \\ &= \frac{1}{2}a_0 M^2 + \frac{1}{4}b_0 M^4 + \dots \quad \left(a_0 = a_0' - \alpha\right)\end{aligned}$$

Landau 展開と同形式

Landau の理論では係数はただの係数だが、WRS理論で物理的意味を与える

Landau 係数

a

$$H = \frac{\partial \Delta F(M)}{\partial M} = a_0 M + b_0 M^3 + \dots$$

$$\chi = \frac{M}{H} = \frac{M}{M(a_0 + b_0 M^2 + \dots)} = \frac{1}{a_0 + b_0 M^2 + \dots}$$

$M \ll 1$ のとき

$$\chi^{-1} = a_0$$

$$a_0 = \frac{1}{2\mu_B^2 D(\zeta_P)} - I$$

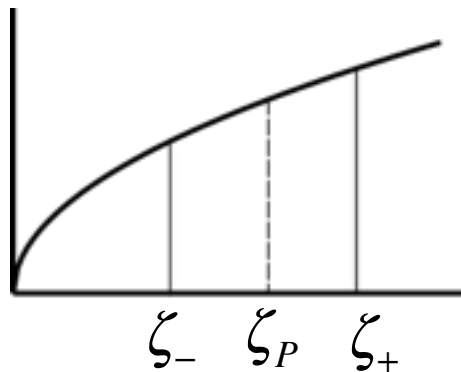
$$\chi = \frac{\chi_0}{1 - I\chi_0}$$

$$\chi_0(T) = \frac{M}{H} = -2\mu_B^2 \int_{-\infty}^{\infty} D(\varepsilon) \frac{\partial f(\varepsilon - \zeta_P)}{\partial E} dE$$

$$T = 0$$

$$\chi_0(T) = 2\mu_B^2 D(\zeta_P)$$

Landau 係数の導出



$$n(\zeta_+) \equiv N(\zeta_+) - N(\zeta_P)$$

$$n(\zeta_-) \equiv N(\zeta_-) - N(\zeta_P)$$

$$n(\zeta_+) + n(\zeta_-) = 0$$

$$n(\zeta_+) - n(\zeta_-) = m$$

$n(\zeta_+), n(\zeta_-)$ をそれぞれ $\zeta_+ - \zeta_P, \zeta_- - \zeta_P$ で展開する

$$n(\zeta_+) = \sum_{n=1}^{\infty} \frac{1}{n!} \left\{ \frac{d^n N}{d\varepsilon^n} \right\}_{\zeta_P} \delta\zeta_+^n, \quad \delta\zeta_+ = \zeta_+ - \zeta_P$$

$$n(\zeta_-) = \sum_{n=1}^{\infty} \frac{1}{n!} \left\{ \frac{d^n N}{d\varepsilon^n} \right\}_{\zeta_P} \delta\zeta_-^n, \quad \delta\zeta_- = \zeta_- - \zeta_P$$

$$N_1 \equiv \left(\frac{dN(\varepsilon)}{d\varepsilon} \right)_{\zeta_P}, \quad N_n \equiv \frac{1}{N_1} \left(\frac{d^n N(\varepsilon)}{d\varepsilon^n} \right)_{\zeta_P}$$

Landau 係数

$$n(\zeta_+) = N_1 \left\{ \delta\zeta_+ + \frac{1}{2} N_2 \delta\zeta_+^2 + \frac{1}{3!} N_3 \delta\zeta_+^3 + \cdots \right\} = \frac{1}{2} m$$

$$n(\zeta_-) = N_1 \left\{ \delta\zeta_- + \frac{1}{2} N_2 \delta\zeta_-^2 + \frac{1}{3!} N_3 \delta\zeta_-^3 + \cdots \right\} = -\frac{1}{2} m$$

$\delta\zeta_+$, $\delta\zeta_-$ を逐次近似で解く

$$\delta\zeta_+ = \frac{m}{2N_1} - \frac{1}{8} \frac{N_2}{N_1^2} m^2 - \frac{1}{48} \frac{N_3 - 3N_2^2}{N_1^3} m^3 + \cdots$$

$$\delta\zeta_- = -\frac{m}{2N_1} - \frac{1}{8} \frac{N_2}{N_1^2} m^2 + \frac{1}{48} \frac{N_3 - 3N_2^2}{N_1^3} m^3 + \cdots$$

$$\zeta_+ - \zeta_- = 2(a'_0 m + b_0 m^3 + c_0 m^5 + \cdots)$$

$$= \frac{m}{N_1} - \frac{N_3 - 3N_2^2}{24N_1^3} m^3 + \cdots$$

Landau 係数

$$\zeta_+ - \zeta_- = 2(a_0 M + b_0 M^3 + \dots)$$

$$a_0 = \frac{1}{2N_1} - I$$

$$b_0 = -\frac{N_3 - 3N_2^2}{48N_1^3}$$

$$N_1 \equiv \left(\frac{dN(\varepsilon)}{d\varepsilon} \right)_{\zeta_P}, \quad N_n \equiv \frac{1}{N_1} \left(\frac{d^n N(\varepsilon)}{d\varepsilon^n} \right)_{\zeta_P}$$

N_1 を低温展開すると

$$N_1 = D_0 \left\{ 1 - 2C_2 (k_B T)^2 \left(\frac{D_0'^2}{D_0^2} - \frac{D_0''}{D_0} \right) \right\} \quad C_2 = \frac{\pi^2}{12}$$

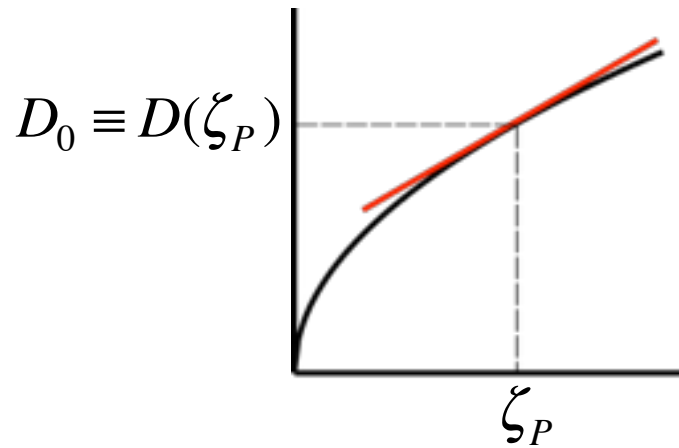
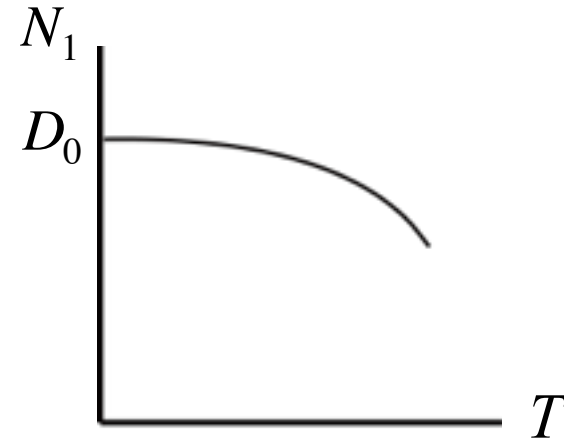
$$a_0 = \frac{1}{\chi} = \frac{1}{2N_1} - I$$

帯磁率 χ の型に D_0'' は重要な役割を果たす

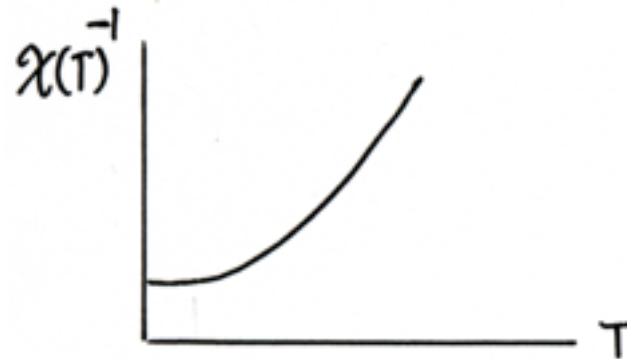
帯磁率と状態密度(Landau 係数 a の議

$$D_0'' < 0$$

$$N_1 = D_0 \left\{ 1 - 2C_2(k_B T)^2 \left(\frac{D_0'^2}{D_0^2} - \frac{D_0''}{D_0} \right) \right\}$$

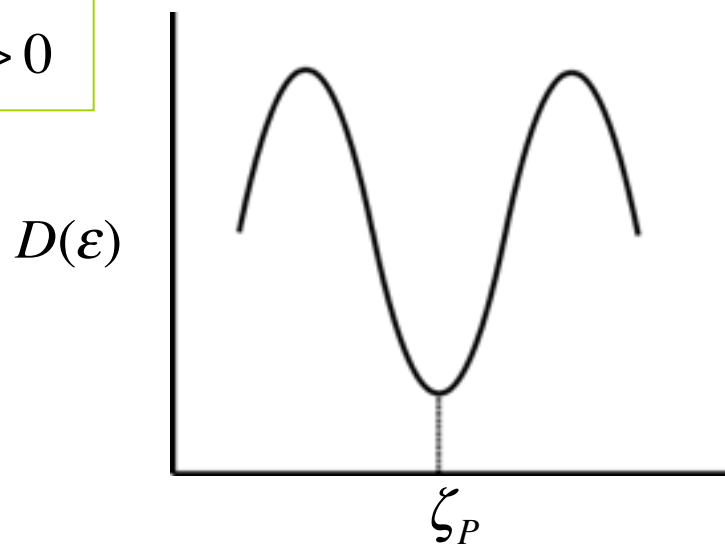


$$a_0 = \frac{1}{\chi} = \frac{1}{2N_1} - I$$

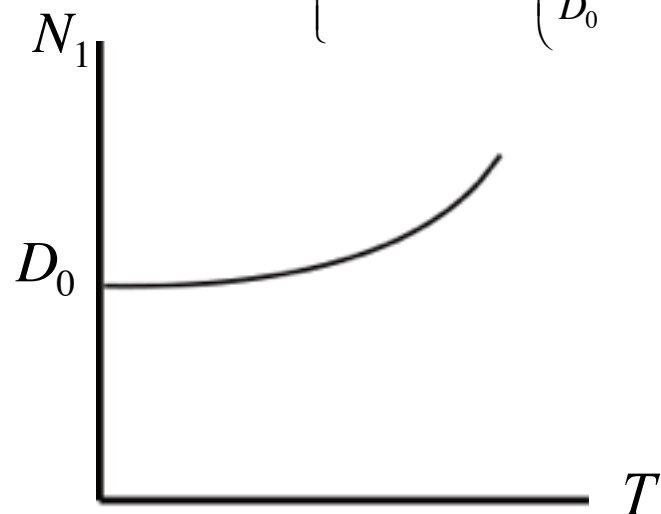


帯磁率と状態密度(Landau 係数 a の議

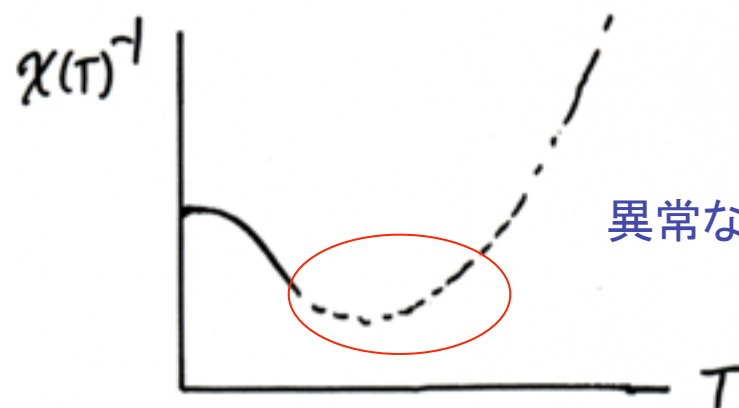
$$D_0'' > 0$$



$$N_1 = D_0 \left\{ 1 - 2C_2 (k_B T)^2 \left(\frac{D_0'^2}{D_0^2} - \frac{D_0''}{D_0} \right) \right\}$$



$$a_0 = \frac{1}{\chi} = \frac{1}{2N_1} - I$$



異常な帯磁率の温度変化

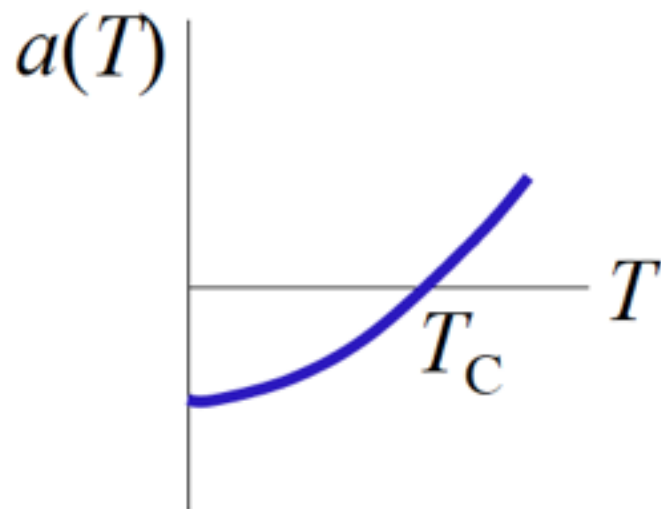
Fermi 分布関数の温度変化を通して得られた Curie 温度

$a_0 < 0$ (T_C で $a=0$ のとき)

$$a = \frac{1}{2N_1} - I = 0$$

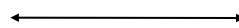
$$N_1 = \frac{1}{2I} = D_0 \left\{ 1 - 2C_2 (k_B T_C)^2 \left(\frac{D_0'^2}{D_0^2} - \frac{D_0''}{D_0} \right) \right\}$$

$$\frac{D_0'^2}{D_0^2} - \frac{D_0''}{D_0} > 0$$



$$T_C^2 = \frac{1}{2C_2 k_B^2} \frac{2ID_0 - 1}{\left(D_0' / D_0 \right)^2 - D_0'' / D_0}$$

Stoner 模型におけるCurie温度

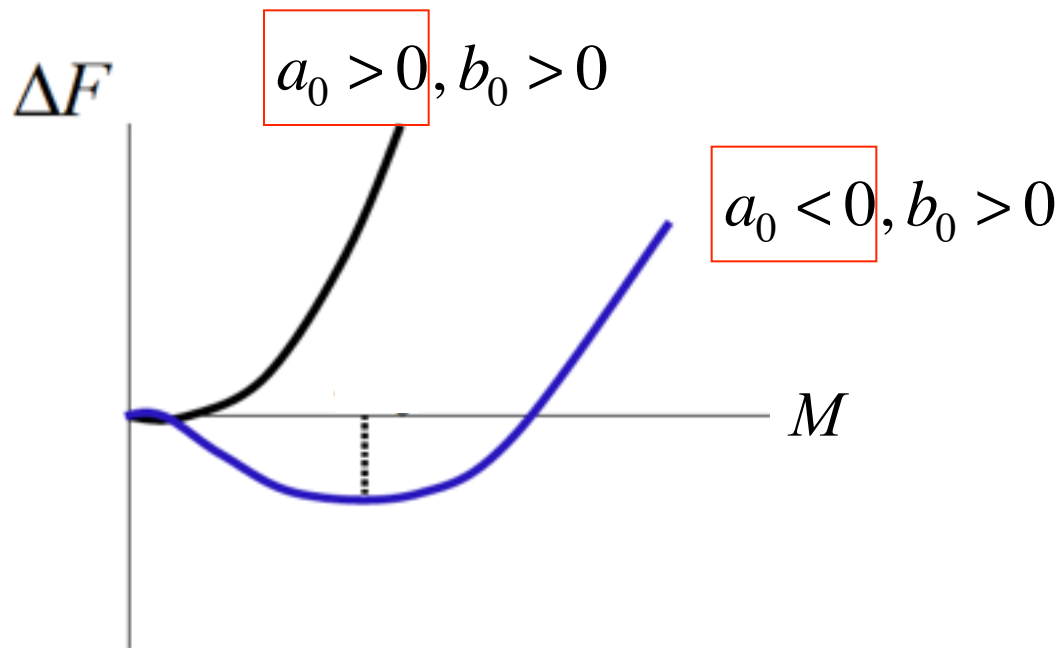


Moriya $T_C \propto (2ID_0 - 1)^{\frac{3}{4}}$

強磁性の出現

1

$$\Delta F = \frac{1}{2}a_0M^2 + \frac{1}{4}b_0M^4 + \dots$$



強磁性

$$T < T_C : a_0 < 0 \quad (\text{ferro})$$

$$T > T_C : a_0 > 0 \quad (\text{para})$$



T_C の前後で符号が入れ替わる

$$a_0 = \beta(T - T_C)$$

β はパラメータ

$$T < T_C$$

$$\Delta F(M) = \frac{\beta}{2}(T - T_C)M^2 + \frac{1}{4}b_0M^4$$

$$\frac{\partial \Delta F(M)}{\partial M} = \beta(T - T_C)M + b_0M^3 = 0$$

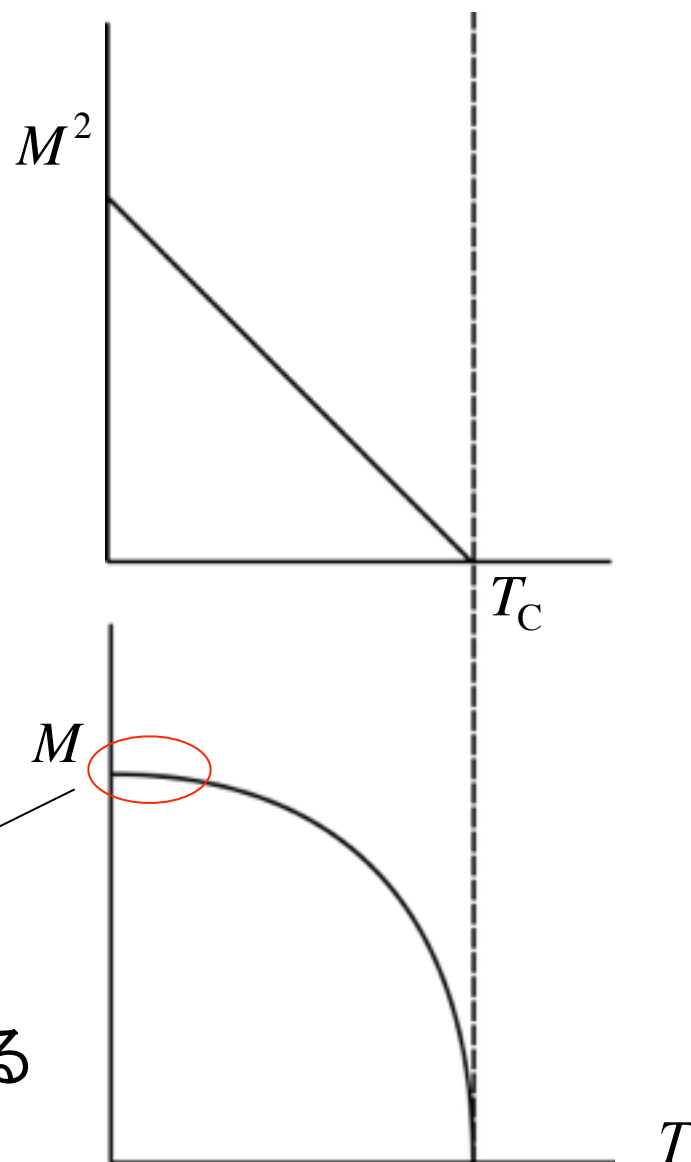
$$M^2 = \frac{\beta}{b_0}(T_C - T)$$

①

T_C 近傍しか成り立たない
(高次の展開項を入れていない)

実験値は
 $T=0$ 近傍で
フラットになる

Curie-Weiss



Curie-Weiss の帯磁率

$$T > T_C$$

$$\begin{aligned} H &= \frac{\partial \Delta F(M)}{\partial M} \\ &= \beta(T - T_C)M + b_0 M^3 \end{aligned}$$

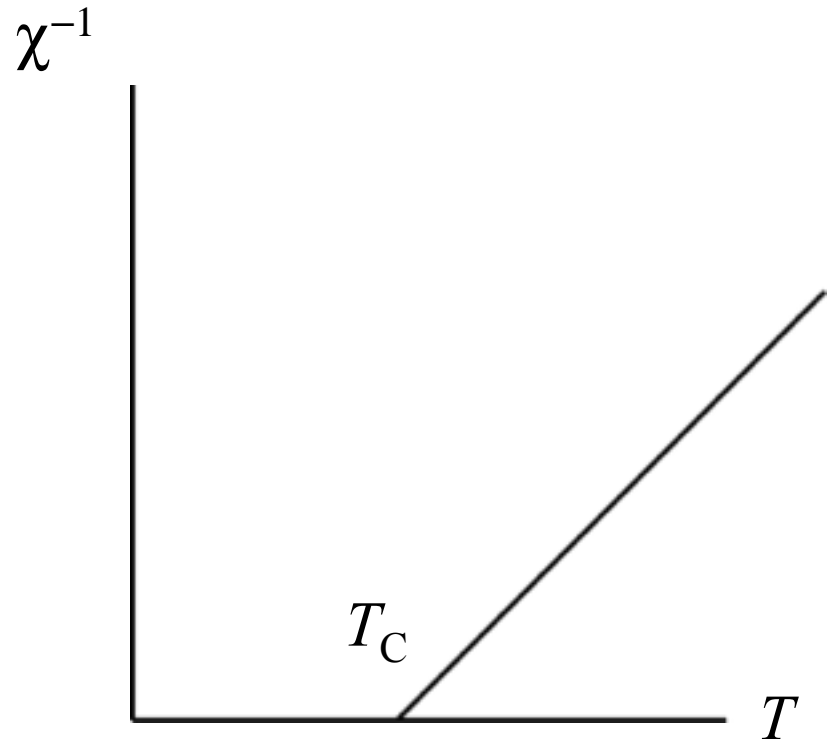
$$M \ll 1$$

$$\frac{M}{H} = \frac{1}{\beta(T - T_C)}$$

$$\chi^{-1} = \beta(T - T_C)$$

②

Curie-Weiss の帯磁率

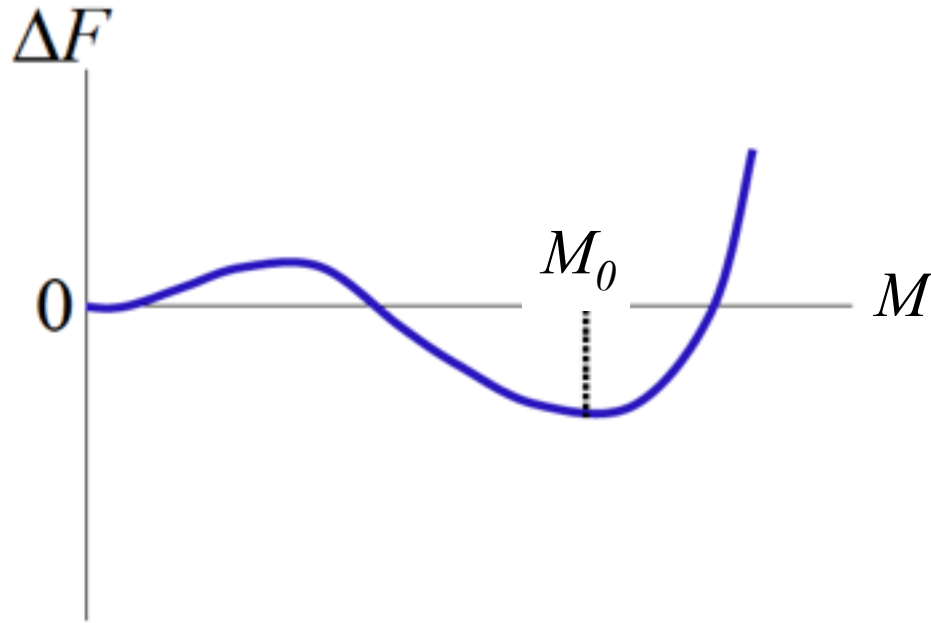


Landau 理論は①と②を同時に説明できる
(ただし、 β はパラメータ)

強磁性の出現

2

$a_0 > 0$ でも $b < 0, c > 0$ なら強磁性が安定する場合がある



$$\Delta F(M) = \frac{1}{2}a_0M^2 + \frac{1}{4}b_0M^4 + \frac{1}{6}cM^6$$

$$\frac{d}{dM}\Delta F = a_0M_0 + b_0M_0^3 + c_0M_0^5 = 0$$

$$M_0^2 = \frac{1}{2c_0} \left[-b_0 + \sqrt{b_0^2 - 4a_0c_0} \right]$$

$a_0c_0/b_0^2 > 3/16$ のとき $\Delta F(M_0) < 0$ となる

ま

め

- 有限温度(フェルミ分布関数の温度変化)
- 一般の状態密度の形状から議論

強磁性出現を議論



Landau 展開と同形式

Landau 係数の物理的考察

これまでの磁性理論を現象論的に説明

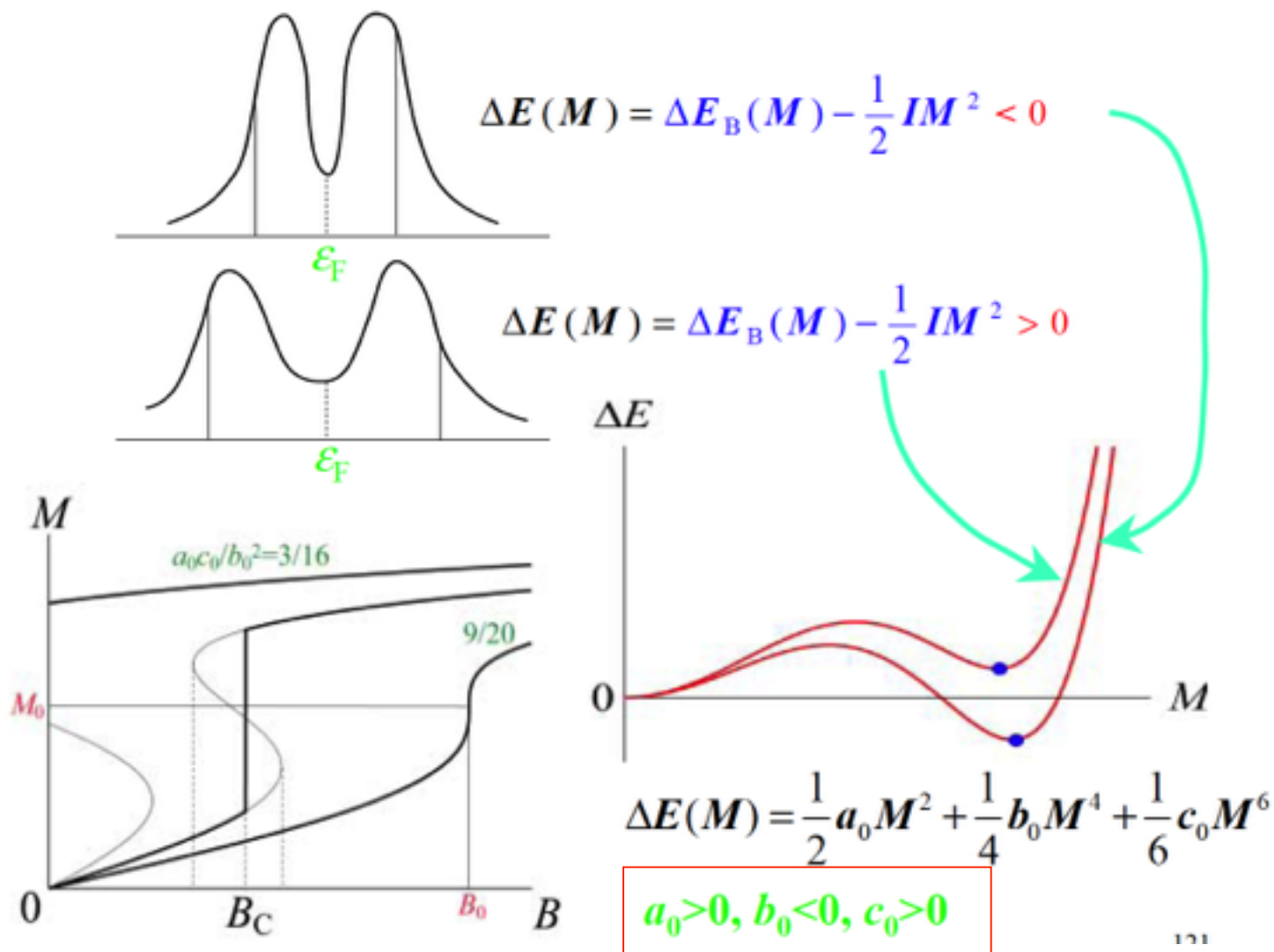
スピンの揺らぎを取り入れた Landau 展開の理論

————→ Yamada 理論

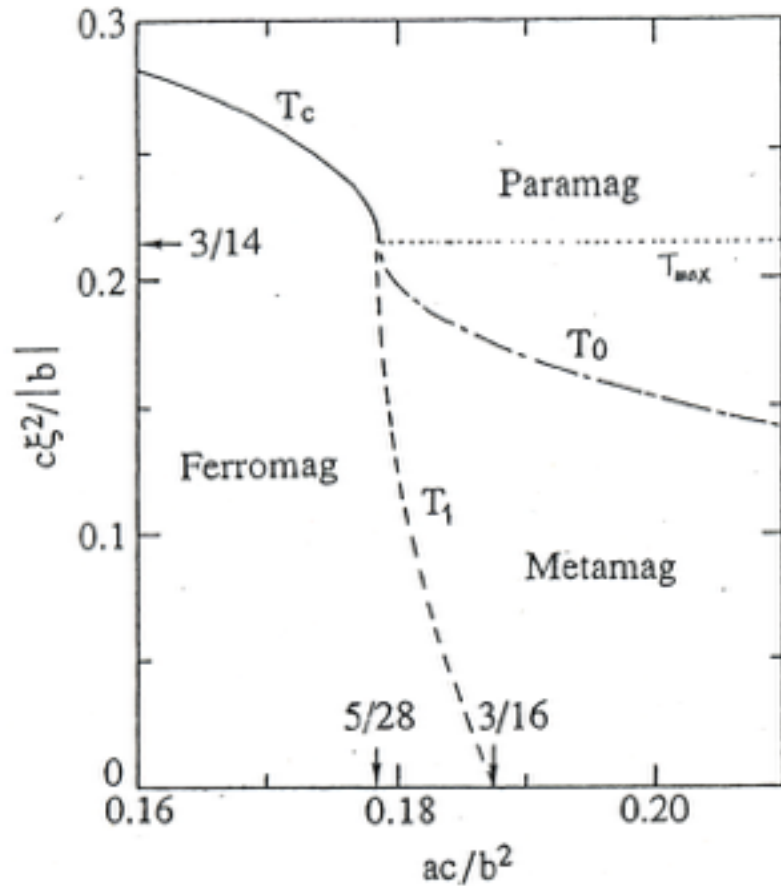
磁気体積効果/メタ磁性転移/磁気熱量効果

バンド計算から Landau 係数を議論することにより議論できる

メタ磁性転

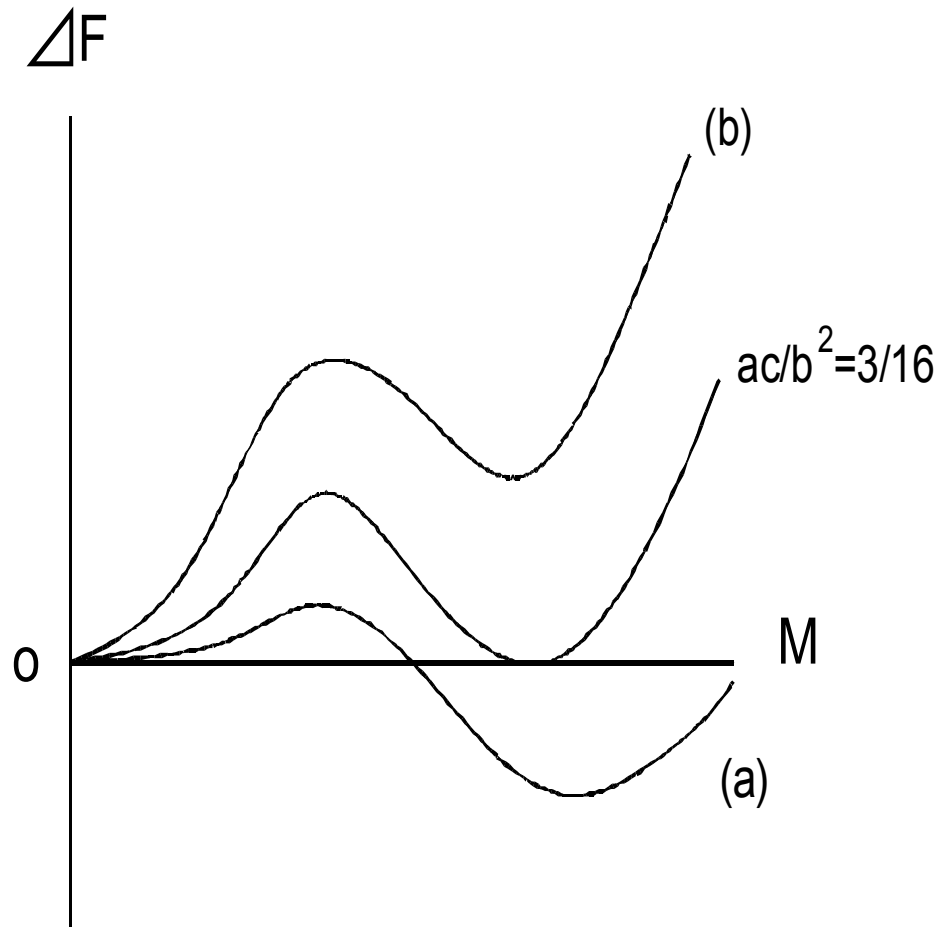


Moriya and Yamada



Landau-Ginzburg 模型に基づき
スピンの揺らぎを取り入れる
(Yamada理論)

メタ磁性出現条件



× 磁性出現条

