

Wdh. \rightarrow Übergang in TD-Lines $N \rightarrow \infty$ $V \rightarrow \infty$ $\left. \vphantom{\begin{matrix} N \\ V \end{matrix}} \right\} \frac{N}{V} = \text{const}$

+ im 3D + gebundene Zust. $\left. \vphantom{\begin{matrix} 1 \\ k \end{matrix}} \right\} \frac{1}{V} \sum \frac{1}{k e^{\beta(\epsilon_k - \mu)} \pm 1} \xrightarrow{\text{TD-Lines}} \frac{N_{\text{stat}}}{z^2} \int_0^{\infty} \frac{\epsilon^2 d\epsilon}{e^{\beta(\epsilon - \mu)} \pm 1}$

o. Fermiideal $z = e^{\beta \mu}$



\Rightarrow Fermi $(T=0)$ bleibt endlich

- + Kollaps von Spinnen
- + hat Einfluss auf versch. Eigenschaften von FK
- + resultiert nicht aus Gitter-Modell von e- in FK, sondern aus Fermi-Statistik

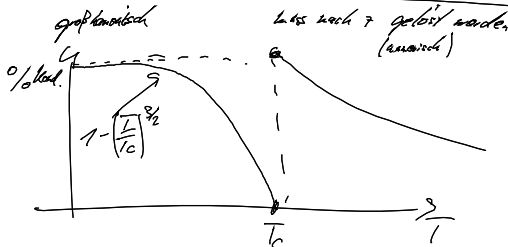
b.) Positiv: GZ ableiten

$$\frac{N}{V} = \frac{z}{V(1-z)} + \left(\frac{4}{2\pi\hbar^2 \beta} \right)^{3/2} g_{3/2}(z)$$

Kontinuum-Limit Integral in angeregten ZS

$$g_{\lambda}^{\pm}(z) = \frac{1}{\Gamma(\lambda)} \int_0^{\infty} \frac{x^{\lambda-1}}{z^{-1} e^x \pm 1} dx$$

$$g_{\lambda}(z=1) = \zeta(\lambda)$$



3.2.6. Planck'sches Strahlungsgesetz

Strahlung: $\epsilon(\nu) = \frac{h^2 \nu^2}{2\pi^2}$ $p = \frac{1}{3} \epsilon$ ϵ ist additiv

also: $\epsilon^2 = p^2 c^2 + h_0^2 c^4$

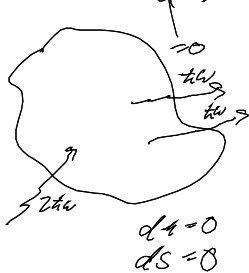
Planckengesetz: $h_0 = 0$ $\epsilon(\epsilon) = h\nu = \epsilon c^2$

$\epsilon \propto V^{-1/3} \rightarrow \frac{\partial \epsilon}{\partial V} = -\frac{1}{3} \frac{\epsilon}{V}$

$\Rightarrow P_{\text{ir}} = \frac{2}{3} \frac{u}{V}$

$P_{\text{ref}} = \frac{1}{3} \frac{u}{V}$

$dH = TdS - pdV + \mu dN$



$\rightarrow 0 = \mu \cdot dN$
 $dH \neq 0$

$\mu_{\text{stat}} = 0$

$$h_0 = \frac{1}{e^{\beta \hbar \omega} - 1}$$

$$u = \frac{N}{V} = \frac{1}{V} \sum_{\vec{k}} \frac{1}{e^{\beta \hbar c k} - 1} \rightarrow \frac{2 \cdot V}{(2\pi)^3} \int \frac{k^2}{e^{\beta \hbar c k} - 1} dk \quad N_{ph} = 2$$

$$\frac{N}{V} = \frac{2}{\pi^2} \int \frac{\xi(\beta)}{(k c)^3} dk \quad \text{Teilzahndichte}$$

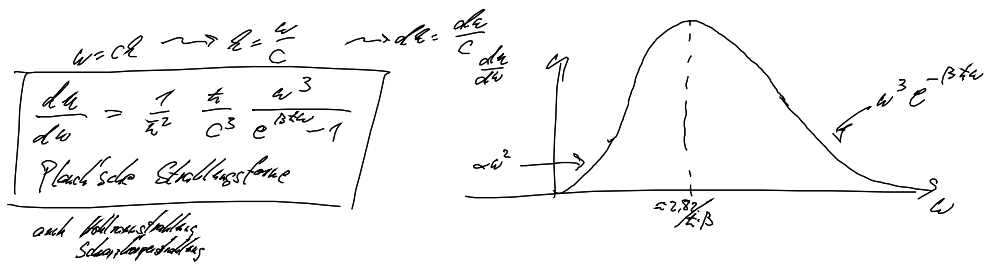
$$\frac{u}{V} = \frac{1}{V} \sum_{\vec{k}} \frac{\hbar c k}{e^{\beta \hbar c k} - 1} \rightarrow \frac{2}{\pi^2} \int \frac{\hbar c k^3}{e^{\beta \hbar c k} - 1} dk = \frac{\pi^2}{15} \frac{1}{(\hbar c)^3 \beta^4} = u = \frac{u}{V} \quad \text{Energiedichte}$$

$$p_{rel} = \frac{1}{3} \frac{u}{V} = 0$$

aus Komp.-relation

$$\frac{S}{V} = \frac{1}{T} \left(\frac{u}{V} + p - \frac{N}{V} \right) = \frac{1}{T} \frac{4}{3} \frac{u}{V} \quad S(T \rightarrow 0) \rightarrow 0 \quad \text{Nernst'sches WT}$$

$$\frac{1}{3} \frac{u}{V}$$



3.3 Quanten-Spin-Modelle

Spin (Klassik): $S_i \in \{-1, +1\}$
 quant.: Operatoren: versch. Anzahle z. kommut. Operatoren korrektion nicht
 falls $[H_i, H_j] = 0 \rightarrow$ klassische Spin-Systeme $H = H_0 + H_1 \quad [H_0, H_1] = 0$

3.3.1. Quanten-Ising-Modell

$$\hat{H} = -J \sum_{\langle ij \rangle} \hat{S}_i^x \hat{S}_j^x - \gamma \sum_i \hat{S}_i^z \quad \hat{S}_{x,y,z} = \hat{S}_i^x, \hat{S}_i^y, \hat{S}_i^z$$

externes Feld $\gamma > 0$: ferromagnet. NN-Modell

Klassische Limit $\hat{S}_i^x \rightarrow \hat{S}_i^z$

$$\hat{S}_i^z |0\rangle = +1 |0\rangle \quad \hat{S}_i^z |z\rangle = (-1)^z |z\rangle$$

$$\hat{S}_i^z |1\rangle = -1 |1\rangle \quad z \in \{0,1\}$$

für 2 Spins

$$\begin{aligned} |0,0\rangle &= |0\rangle \otimes |0\rangle \\ |0,1\rangle &= |0\rangle \otimes |1\rangle \\ |1,0\rangle &= |1\rangle \otimes |0\rangle \\ |1,1\rangle &= |1\rangle \otimes |1\rangle \end{aligned}$$

$$\hat{S}_i^x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \hat{S}_i^y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \hat{S}_i^z = \begin{pmatrix} +1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$[\hat{S}_i^x, \hat{S}_j^y] = 2i \hat{S}_i^z \cdot \delta_{ij}$$

$$\hat{S}_i^x \rightarrow \hat{S}_i^y \quad i \pm j = N$$

- exaktes Modell welches für $N \rightarrow \infty$ gelöst werden kann
 - links: nur klassische PT's: weicht analyt. Verhalten bei $T = T_c$
 - Ising-Modell hat QPT: auch bei $T=0$ bei $g = g_{crit}$
- $$\hat{S}_i^z |z_1 \dots z_N\rangle = (-1)^{z_i} |z_1 \dots z_N\rangle \quad \hat{S}_i^x |z_1 \dots z_i \dots z_N\rangle = |z_1 \dots (1-z_i) \dots z_N\rangle$$

a) nur ext. Feld

$$\hat{b}^x | \rightarrow \rangle = \frac{1}{\sqrt{2}} (| \rightarrow \rangle + | \leftarrow \rangle) \rightarrow | \rightarrow \rangle = \frac{1}{\sqrt{2}} [| 0 \rangle + | 1 \rangle]$$

$$| \leftarrow \rangle = \frac{1}{\sqrt{2}} [| 0 \rangle - | 1 \rangle]$$

$| \psi_0(z=0) \rangle = | \rightarrow \rangle \otimes \dots \otimes | \rightarrow \rangle$ "paragonische Phase"
 ist gerade: $\sum^x | \psi_0(z=0) \rangle = +1 \cdot | \psi_0(z=0) \rangle$

b) nur HH-WW

für $z \gg \xi$ "ferromagnetische Phase"
 $| \psi_0^+(z=0) \rangle = | 0 \dots 0 \rangle$
 $| \psi_0^-(z=0) \rangle = | 1 \dots 1 \rangle$

$$\sum^x = \frac{1}{N} \sum_{e=1}^N \hat{b}_e^x$$

Bohring-Parität

$$[\sum^x, H] = [\sum^x, \sum_{i,j} \hat{b}_i^x \hat{b}_j^x] (f(z)) = 0$$

$$| \psi_0^\pm \rangle = \frac{1}{\sqrt{2}} [| 0 \dots 0 \rangle \pm | 1 \dots 1 \rangle]$$

o Schritte zum Group

$$\begin{cases} \hat{D}_n^x = 1 - 2\hat{c}_n^x \hat{c}_{n+1}^x \\ \hat{D}_n^z = -(\hat{c}_n + \hat{c}_n^x) \hat{H} (1 - 2\hat{c}_n^x \hat{c}_n) \end{cases}$$

Fordan-Lessner-Trick

$$\hat{c}_n = \sum_k \hat{C}_k e^{ikn} \quad ; \quad \text{FT für Latticop.}$$

↑
neue Latticop.

$$\hat{C}_k = \hat{a}_k \hat{r}_k + \hat{a}_k^x \hat{r}_k^x$$

keine Fermionen

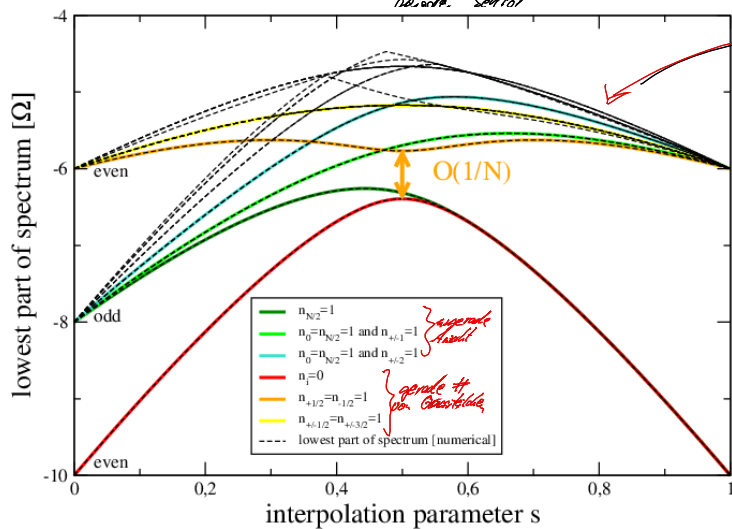
$$\epsilon_k = 2\sqrt{g^2 + \gamma^2} - 2g \cdot \gamma \cos\left(\frac{2kx}{\pi}\right)$$

$\cos(2kx/\pi)$

→ am Ende: $H = \hat{P}^- H \hat{P}^+ + \hat{P}^+ H \hat{P}^-$

↑
normale Selbst

$$H^+ = \sum_{k \in \text{BZ}} \epsilon_k (\hat{r}_k^x \hat{r}_k - \frac{1}{2})$$

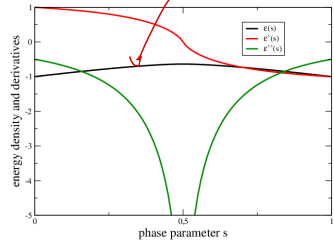


$z^{10} = 10^{20}$ Basiswert

$$E_0 = \sum_k \epsilon_k (-1/2)$$

$$\frac{E_0}{N} = \int_{-1/2}^{+1/2} \epsilon(k) dk$$

$\epsilon(k) =$ Erwartungswert des GZ



$$\begin{aligned} \partial \mathcal{L} / \partial s &= 9 & \text{Seite } 1/2 \rightarrow \text{für } 7 \\ \partial \mathcal{L} / \partial (1-s) &= 7 \end{aligned}$$