Wdh

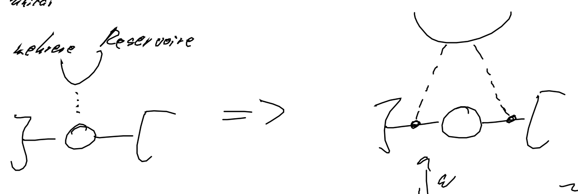
- Polaron-Mastergleichung

$$H = H_S + \underbrace{S}_{\text{Kopplung}} \underbrace{\sum_k (h_k b_k + h_k^* b_k^+)}_{\mathcal{A}} + \underbrace{\sum_k \omega_k b_k^+ b_k}_{\text{Bad}} + \sum_k \frac{|h_k|^2}{\omega_k} S^2$$

$$U_p = \exp\left[ S \sum_k \frac{h_k^*}{\omega_k}(b_k^+ - b_k) \right] \quad \text{vermischt System- \& Bad-Observablen}$$

$$H' = \underbrace{U_p}_{\text{unitär}} H U_p^+ = \underbrace{U_p H_S U_p^+}_{\text{beinhaltet Kopplung}} + \sum_k \omega_k b_k^+ b_k \quad \rightsquigarrow \text{Ableitung einer Standard-Mastergl.}$$

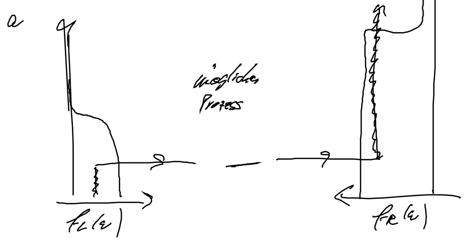
- mehrere Reservoire




Dissipatoren sind nicht additiv in den Bädern

$$C_{ij}(\tau) = C_{ij,el}(\tau) \cdot C_{ph}(\tau)$$

$\rightsquigarrow \gamma_{ij}(\omega)$ ist i. A. eine Faltung



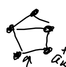

- Bogoliubov-Trafo — keine bosonische Erz./Vern. ("Quasiteilchen")

$$a_k = \sum_q \left( u_{kq} b_q + v_{kq} b_q^+ \right) \qquad u = (u_{kq})$$

$$a_k^+ = \sum_q \left( u_{kq}^* b_q^+ + v_{kq}^* b_q \right) \qquad V = (v_{kq})$$

$$\boxed{\begin{aligned} u u^+ - V V^+ &= \mathbb{1} \\ u V^T - V \cdot u^T &= \mathbb{0} \end{aligned}}$$

Wahlfreiheit $\rightsquigarrow$ vereinfache Hamiltonian



$a_k^+ a_k, \; a_k^2, \; (a_k^+)^2 \quad \Rightarrow \quad \begin{matrix} \Omega_1 b_1^+ b_1 \\ \vdots \\ \Omega_S b_S^+ b_S \end{matrix}$

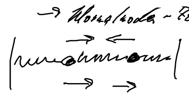
$a_k^+ a_q, \; a_k a_q$

nur quadratische Terme

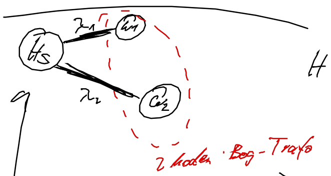
entkoppelte Moden

Analogon Mechanik: gek. Oszillatoren

$\rightarrow$ Normalmoden-Zerlegung



### 4.3.2. 2 Moden Beispiel



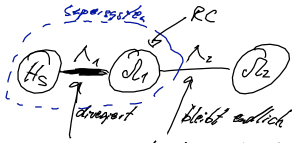

kann WW enthalten

$$H = H_S + \omega_1\left(a_1^+ + \frac{\lambda_1}{\omega_1} \cdot S\right)\left(a_1 + \frac{\lambda_1}{\omega_1} \cdot S\right) + \omega_2\left(a_2^+ + \frac{\lambda_2}{\omega_2} S\right)\left(a_2 + \frac{\lambda_2}{\omega_2} S\right)$$

$$= H_S + \Omega_1\left(b_1^+ + \frac{\Lambda_1}{\Omega_1} \cdot S\right)\left(b_1 + \frac{\Lambda_1}{\Omega_1} \cdot S\right) + \Omega_2\left(b_2^+ + \frac{\Lambda_2}{\Omega_2}(b_1 + b_1^+)\right)\left(b_2 + \frac{\Lambda_2}{\Omega_2}(b_1 + b_1^+)\right)$$

finde Bog.-Trafo so, dass

$$a_k = \sum_{q=1}^{2} \left( u_{kq} b_q + v_{kq} b_q^+ \right)$$




$\lambda_i \to \infty$ (starke Kopplung)

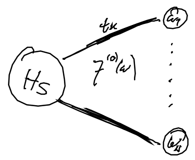
$$\mathrm{Tr}_{RC}\{\rho_{S+RC}(t)\} = \rho_S(t)$$

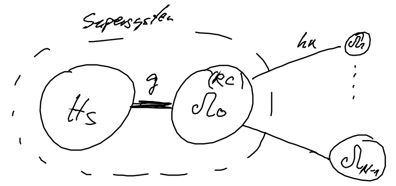
## 4.3.3. Ableitung der RC-Abbildung

$$H = H_S + \sum_k \omega_k \left(a_k^\dagger + \frac{t_k}{\omega_k} S\right)\left(a_k + \frac{t_k}{\omega_k} S\right) = H_S + \Omega_0 \left(b^\dagger + \frac{g}{\Omega_0} S\right)\left(b + \frac{g}{\Omega_0} S\right) + \sum_k \Omega_k \left(b_k^\dagger + \frac{h_k}{\Omega_k}(b+b^\dagger)\right) \times \left(b_k + \frac{h_k}{\Omega_k}(b+b^\dagger)\right)$$

Kopplung: $J^{(0)}(\omega) = 2\pi \sum_k |t_k|^2 \delta(\omega - \omega_k)$

ursprüngliche SD




$J^{(1)}(\omega) = 2\pi \sum_k |h_k|^2 \delta(\omega - \Omega_k)$

residuale SD

Res.-Kopplung

Wo liegen die Residual-Bad-Energ.

$$J^{(0)}(\omega) \quad \Rightarrow \quad g, \Omega_0, J^{(1)}(\omega) \ ?$$

Trafo: $a_k = u_{k0} \cdot b + \sum_{q \geq 1} u_{kq} \cdot b_q + v_{k0} b^\dagger + \sum_{q\geq 1} v_{kq} b_q^\dagger$

Koeffizientenvergleich
- Terme linear in $S$: $\sum_k t_k (a_k + a_k^\dagger) \stackrel{!}{=} g(b + b^\dagger)$
- Terme quadratisch in $S$: $\sum_k \frac{t_k^2}{\omega_k} = \frac{g^2}{\Omega_0}$

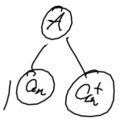
$$\boxed{\Omega_0^2 = \frac{\int_0^\infty \omega \cdot J^{(0)}(\omega)\, d\omega}{\int_0^\infty \frac{J^{(0)}(\omega)}{\omega}\, d\omega} \qquad g^2 = \frac{1}{2\pi \Omega_0} \int_0^\infty \omega \cdot J^{(0)}(\omega)\, d\omega}$$

Abb. der spektralen Dichte: finde BWGL für Operator $A$ im System

Heisenberg-BWGL $\tilde{A} = e^{+iHt} A e^{-iHt}$

① $\dot{\tilde{A}} = e^{+iHt} i[H, A] e^{-iHt}$

$= i \tilde{S}_1 + i \tilde{S}_2 \sum_k t_k (\tilde{a}_k + \tilde{a}_k^\dagger)$




$\tilde{S}_1 = e^{+iHt} [H_S + \sum_k \frac{t_k^2}{\omega_k} S^2, A] e^{-iHt}$

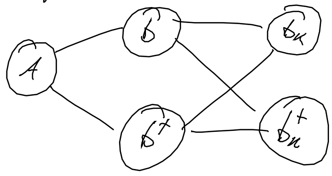
$\tilde{S}_2 = e^{+iHt} [S, A] e^{-iHt}$

$\dot{\tilde{a}}_k = -i\omega_k \tilde{a}_k - i t_k \tilde{S}$

$\dot{\tilde{a}}_k^\dagger = +i\omega_k \tilde{a}_k^\dagger + i t_k \tilde{S}$

⇝ eliminiere $\tilde{a}_k$ & $\tilde{a}_k^\dagger$ ⇝ Gleichung für $\dot{\tilde{A}}$ → Vergleich

② analog im 2. Bild mit $\tilde{A}, \tilde{b}, \tilde{b}^\dagger, \tilde{b}_k, \tilde{b}_k^\dagger$




eliminiere (nach FT) $b_k, b_k^\dagger$, dann $b, b^\dagger$ ⇝ Gleichung für $\dot{\tilde{A}}$

Cauchy-Trafo von $J(\omega)$ $\quad J(-\omega) = -J(\omega)$

$$W(z) = \frac{2}{\pi} \int_0^\infty \frac{\omega J(\omega)}{\omega^2 - z^2} d\omega = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{J(\omega)}{\omega - z} d\omega$$

$$\lim_{\varepsilon\to 0} W(\omega + i\varepsilon) = \lim_{\varepsilon\to 0} \frac{1}{\pi} \int \frac{J(\omega')}{\omega' - \omega - i\varepsilon} d\omega' = \lim_{\varepsilon \to 0} \frac{1}{\pi} \int \frac{J(\omega')[\omega' - \omega + i\varepsilon]}{(\omega'-\omega)^2 + \varepsilon^2} d\omega'$$

$$= \frac{1}{\pi} \mathcal{P} \int \frac{J(\omega')}{\omega' - \omega} d\omega' + i J(\omega)$$

Trick

: [Skript]

$$\Rightarrow \boxed{J^{(1)}(\omega) = \frac{4g^2 \cdot J^{(0)}(\omega)}{\left[\frac{1}{\pi}\mathcal{P}\int \frac{J^{(0)}(\omega')}{\omega-\omega'}d\omega'\right]^2 + \left[J^{(0)}(\omega)\right]^2}}$$

- $J^{(0)}(\omega) \to \alpha \cdot J^{(0)}(\omega)$
  $g^2 \to \alpha \cdot g^2$
  $J^{(1)}(\omega) \to J^{(1)}(\omega)$ bleibt gleich
  $\rightsquigarrow$ Starke Kopplung $J^{(0)}(\omega)$ kann mit Supersystem behandelt werden
- rekursive Anw. möglich
- für SDs mit komp. Support $J^{(0)}(\omega)=0$ $\forall\, \omega \notin [0, \omega_{max}]$

$$J(\omega) = \omega \cdot \sqrt{1-\frac{\omega^2}{\omega_{max}^2}}\;\Theta(\omega_{max}^2-\omega^2)$$

Rubin-SD

4.3.4 Anw. Spin-Boson-Modell

$$H = \frac{\omega}{2}\sigma^z + \sigma^z \sum_k t_k (a_k + a_k^\dagger) + \sum_k \omega_k a_k^\dagger a_k + \sum_k \frac{t_k^2}{\omega_k}\cdot \mathbf{1}$$

$$= \underbrace{\underbrace{\frac{\omega}{2}\sigma^z}_{H_S} + \Omega_0\left(b^\dagger + \frac{g}{\Omega_0}\sigma^z\right)\left(b + \frac{g}{\Omega_0}\sigma^z\right)}_{H_S' \;\rightsquigarrow\; ME} + \sum_k \Omega_k\left(b_k^\dagger + \frac{h_k}{\Omega_k}(b+b^\dagger)\right)\left(b_k + \frac{h_k}{\Omega_k}(b+b^\dagger)\right)$$

hier: Born-Markov-Näherungen

$$\dot\rho = -i[H_S', \rho] - \left\{\int_0^\infty C(\tau)\left[(b+b^\dagger), e^{-iH_S'\tau}(b+b^\dagger)e^{+iH_S'\tau}\rho\right]d\tau + h.c.\right\}$$

$$\int_0^\infty C(\tau) e^{-iH_S'\tau}(b+b^\dagger)e^{+iH_S'\tau}d\tau = \sum_{ab}\langle a|(b+b^\dagger)|b\rangle \underbrace{\int_0^\infty C(\tau)\, e^{-i(E_a-E_b)\tau}d\tau}\, |a\rangle\langle b| \qquad H_S'|a\rangle = E_a|a\rangle$$

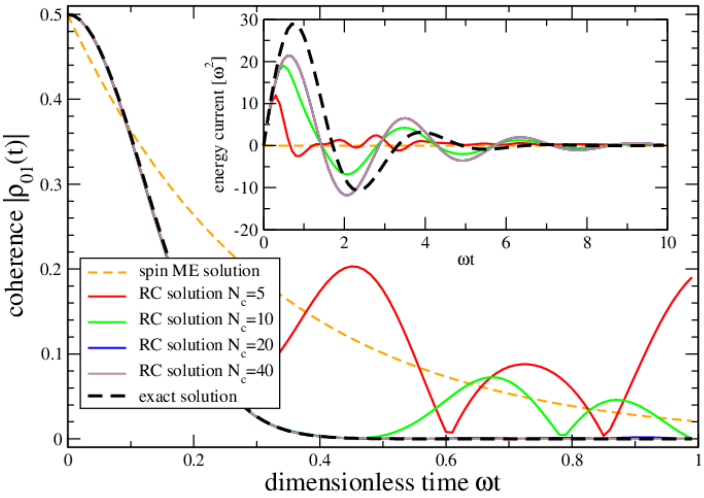
$$\rightarrow \frac{\gamma(E_b-E_a)}{2} + \underbrace{\frac{i}{\pi}\mathcal{P}\int\frac{\gamma(\omega)}{E_b-E_a-\omega}d\omega}_{\text{Lamb-shift} \approx 0}$$

$J^{(1)}(\omega)[1+n_B(\omega)]$

berechne • $|\rho_{01}| = \left|\frac{1}{2}\mathrm{Tr}\{(\sigma_x + i\sigma_y)\underbrace{\rho(t)}_{\text{Super-System}}\}\right|$ Kohärenz

- $\frac{d}{dt}\langle \sum_k \omega_k a_k^\dagger a_k\rangle = -\frac{d}{dt}\langle \sigma^z \sum_k t_k(a_k + a_k^\dagger)\rangle = -\frac{d}{dt}\, g\,\langle\sigma^z (b+b^\dagger)\rangle$

für $\rho_0 \approx \rho_S^0 \otimes \frac{e^{-\beta\Omega_0[b^\dagger b + \Delta (b+b^\dagger)^2]}}{Z_{RC}}$


coherence $|\rho_{01}(t)|$
dimensionless time ωt
spin ME solution
RC solution $N_c$=5
RC solution $N_c$=10
RC solution $N_c$=20
RC solution $N_c$=40
exact solution
energy current [$\omega^2$]
ωt