WdH

· Wz-Verteilung $W^{ij}(\tau) = \dfrac{Tr\{\overset{\text{2. Sprung}}{Z_i}\, e^{\mathcal{L}_0 \tau} \overset{\text{1. Sprung}}{Z_j} \bar\rho\}}{Tr\{Z_j \cdot \bar\rho\}}$

kondit. auf 1. Sprung

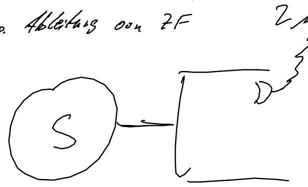
Langzeit-Wz-Verteilung

mittlere Wz zw. Sprüngen (j) und (i)

k-tes Moment $\langle\tau^k\rangle = \int_0^\infty W^{ij}(\tau)\cdot\tau^k\, d\tau$

· mikroskop. Ableitung von ZF

2 Messungen Bad: $t_0 = 0$, $t_1 = t$



Messe die Differenz einer Bad-Observable $\hat O$

Wert der 1. Messung

$$M_{tot}(\chi,t) = \sum_\ell Tr\{e^{+i\chi(\hat O - O_\ell)} U_{tot}(t)\, \rho_S \otimes \bar\rho_B^{(\ell)}\, U^\dagger_{tot}(t)\}$$

Mittelung über alt. Messergebnisse

$|\ell\rangle\langle\ell|\bar\rho_B|\ell\rangle\langle\ell| = \bar\rho_B^{(\ell)}$ kond. auf Mess. ℓ

z.B. $(-i\partial_\chi)^k M_{tot}(\chi,t)\big|_{\chi=0} = \sum_\ell Tr\{(\hat O - O_\ell)^k \rho_{tot}(t)\}$

→ verallg. Zeit-Ent.-Op. $U_{\chi/2}(t) = e^{+i\hat O\chi/2}\, U(t)\, e^{-i\hat O\chi/2}$ $\sum_\ell \bar\rho_B^{(\ell)}$

⇝ Abl. der Mastergl. z.B.: $[\mathcal{L}_0 + \ldots \mathcal{J}_+(\chi) + \ldots]\rho_S^0 \stackrel{!}{=} Tr_B\{U_{\chi/2}(t)\, \rho_S^0 \otimes \bar{\bar\rho}_B\, U^\dagger_{-\chi/2}(t)\}$

⇝ in der Mastergleichung bekommt der Sprungterm ein Zählfeld „$L_\alpha \rho L_\beta^\dagger \to L_\alpha \rho L_\beta^\dagger e^{+i\chi}$"

⇝ verallg. Korrelationsfunktion

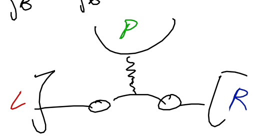
$$C_{\alpha\beta}(\tau) \to C^\chi_{\alpha\beta}(\tau) = Tr_B\{e^{-i\hat O\chi} e^{+iH_B\tau} B_\alpha e^{-iH_B\tau} e^{+i\hat O\chi} B_\beta \cdot \bar{\bar\rho}_B\}$$

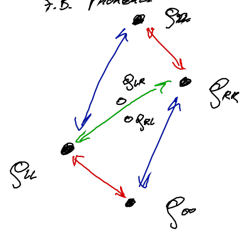
falls $\bar\rho_B = \sum_\ell P_\ell |\ell\rangle\langle\ell| \iff [\bar\rho_B, \hat O] = 0$

⇝ $\bar{\bar\rho}_B = \bar\rho_B$

Wann sinnvoll

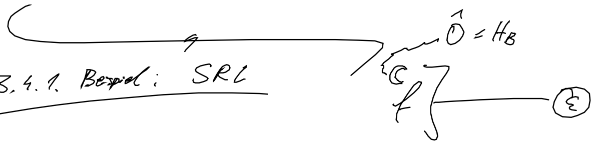
+ Kohärenzen
  z.B. Phononen-assist. Tunneln





Tracking mit mikroskop. ZF möglich

3.4.1. Beispiel: SRL



$$H = \underbrace{\varepsilon d^\dagger d}_{H_S} + \underbrace{d}_{A_1} \otimes \underbrace{\sum_k t_k c_k^\dagger}_{B_1} + \underbrace{d^\dagger}_{A_2} \otimes \underbrace{\sum_k t_k^* c_k}_{B_2} + \underbrace{\sum_k \varepsilon_k c_k^\dagger c_k}_{H_B}$$

$$\boxed{e^{+i\alpha c_k^\dagger c_k} c_k^\dagger e^{-i\alpha c_k^\dagger c_k} = c_k^\dagger \cdot e^{+i\alpha}}$$

$$\mathrm{Tr}_B\{c_k^\dagger c_q \bar{\rho}_B\} = \delta_{kq} f(\varepsilon_k)$$

$$C_{12}^\chi(\tau) = \sum_{kq} \mathrm{Tr}_B\left\{ t_k c_k^\dagger e^{+i\varepsilon_k \tau} e^{-i\varepsilon_k \chi} t_q^* c_q \bar{\rho}_B \right\}$$

$$= \sum_k |t_k|^2 \cdot f(\varepsilon_k) \cdot e^{+i\varepsilon_k(\tau-\chi)}$$

$$= \frac{1}{2\pi}\int \Gamma(\omega) f(\omega) e^{+i\omega\tau} e^{-i\omega\chi} d\omega$$

$$= \frac{1}{2\pi}\int \underbrace{\Gamma(-\omega)\cdot f(-\omega) e^{+i\omega\chi}}_{\gamma_{12}^\chi(\omega)} e^{-i\omega\tau} d\omega$$

analog: $$C_{21}^\chi(\tau) = \frac{1}{2\pi}\int \underbrace{\Gamma(+\omega)[1-f(+\omega)] e^{+i\omega\chi}}_{\gamma_{21}^\chi(\omega)} e^{-i\omega\tau} d\omega$$

$\rightsquigarrow$ BMS Ratengleichung (oder CG mit $\tau\to\infty$)

$$\gamma^\chi_{ab,ab} = \sum_{\alpha\beta} \gamma^\chi_{\alpha\beta}(E_b - E_a) \langle a|A_\alpha|b\rangle \langle a|A_\beta^\dagger|b\rangle^*$$

Rate $b \to a$

$E_0 = 0 \quad E_1 = \varepsilon$

$$\gamma^\chi_{01,01} = \gamma^\chi_{21}(+\varepsilon) = \Gamma(\varepsilon)[1-f(\varepsilon)] e^{+i\varepsilon\chi}$$

$$\gamma^\chi_{10,10} = \gamma^\chi_{12}(-\varepsilon) = \Gamma(\varepsilon) f(\varepsilon) \cdot e^{-i\varepsilon\cdot\chi}$$

Konvention: positiv, wenn in das Res. gezählt

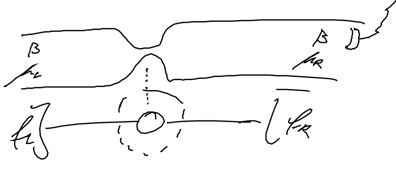
$$\hookrightarrow \mathcal{L}(\chi) = \Gamma(\varepsilon)\begin{pmatrix} -f(\varepsilon) & +[1-f(\varepsilon)]e^{+i\varepsilon\chi} \\ f(\varepsilon)\cdot e^{-i\varepsilon\chi} & -[1-f(\varepsilon)] \end{pmatrix}$$

$\rightsquigarrow$ konsistent

analog $\hat{O} = N_B$

3.4.2. Beispiel QPC

$\hat{O} = N^R_{B,QPC}$



$$H_{SET} = \varepsilon d^\dagger d + \sum_{\substack{k\nu \\ \nu\in\{L,R\}}} \left(t_{k\nu} d c_{k\nu}^\dagger + t_{k\nu}^* c_{k\nu}^\dagger d\right) + \sum_{k\nu} \varepsilon_{k\nu} c_{k\nu}^\dagger c_{k\nu}$$

$$H_{QPC} = \sum_k \sum_{\nu\in\{L,R\}} \epsilon_{k\nu} \gamma_{k\nu}^\dagger \gamma_{k\nu}$$

$$H_{SET-QPC} = \underbrace{\left(\mathbb{1} - \tau\, d^\dagger d\right)}_{A} \underbrace{\sum_{kk'} \Big(\underset{(L \to R)}{t_{kk'}\, \gamma_{kL} \gamma_{k'R}^\dagger} + \underset{(R \to L)}{t^*_{kk'}\, \gamma_{k'R} \gamma_{kL}^\dagger} \Big)}_{B}$$

Reduktion des Tunnelns bei besetztem SET-QD

$0 < \tau < 2$

betrachte nur die Kopplung an den QPC $\quad \hat{O} = \sum_k \gamma_{kR}^\dagger \gamma_{kR}$

$$\rho_{B,QPC} = \frac{e^{-\beta \sum_k (\epsilon_{kL} - \mu_L) \gamma_{kL}^\dagger \gamma_{kL}}}{Z_L} \; \frac{e^{-\beta \sum_k (\epsilon_{kR} - \mu_R) \gamma_{kR}^\dagger \gamma_{kR}}}{Z_R}$$

$$C^\chi(\tau) = \mathrm{Tr}\left\{ e^{-i\chi \hat{O}} e^{+iH_{QPC}\tau} B\, e^{-iH_{QPC}\tau} e^{+i\chi\hat{O}} B\, \bar{\rho}_B \right\} \qquad \left(\bar{\bar{\rho}}_B = \bar{\rho}_B\right)$$

$$= \sum_{\substack{kk' \\ qq'}} \mathrm{Tr}\Big\{ \Big[t_{kk'}\, \gamma_{kL} \gamma_{k'R}^\dagger\, e^{+i(\epsilon_{k'R} - \epsilon_{kL})\tau} e^{-i\chi} + t^*_{kk'}\, \gamma_{k'R} \gamma_{kL}^\dagger\, e^{-i(\epsilon_{k'R} - \epsilon_{kL})\tau} e^{+i\chi} \Big]$$
$$\times \Big[t_{qq'}\, \gamma_{qL} \gamma_{q'R}^\dagger + t^*_{qq'}\, \gamma_{q'R} \gamma_{qL}^\dagger \Big] \rho_{B,QPC} \Big\}$$

$$= \sum_{kk'} \Big\{ e^{-i\chi} |t_{kk'}|^2 e^{+i(\epsilon_{k'R} - \epsilon_{kL})\tau} \left[1 - f_L(\epsilon_{kL})\right] \cdot f_R(\epsilon_{k'R})$$
$$+ e^{+i\chi} |t_{kk'}|^2 e^{-i(\ldots)\tau} f_L(\epsilon_{kL}) \left[1 - f_R(\epsilon_{k'R})\right] \Big\}$$

$$T(\omega, \omega') = 2\pi \sum_{kk'} |t_{kk'}|^2 \delta(\omega - \epsilon_{kL}) \delta(\omega' - \epsilon_{k'R}) \qquad \text{Transmission}$$

$$\gamma(\Omega) = \int C(\tau) e^{+i\Omega\tau} d\tau$$

$$= e^{-i\chi} \frac{1}{2\pi} \int d\omega \int d\omega'\, T(\omega, \omega')\, e^{+i(\omega' - \omega)\tau} \left[1 - f_L(\omega)\right] f_R(\omega')$$
$$+ e^{+i\chi} \frac{1}{2\pi} \int d\omega \int d\omega'\, T(\omega, \omega')\, e^{-i(\omega' - \omega)\tau} f_L(\omega) \left[1 - f_R(\omega')\right] \qquad \frac{1}{2\pi} \int e^{i\bar{\omega}\tau} d\tau = \delta(\bar{\omega})$$

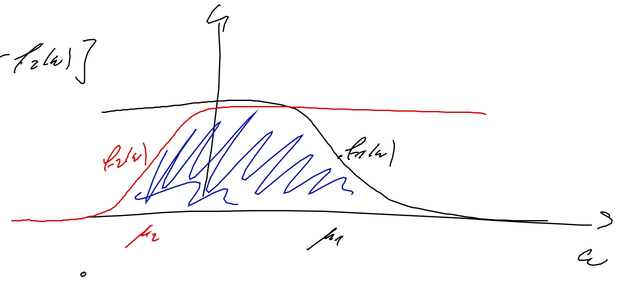
$$\gamma^\chi(\Omega) = e^{-i\chi} \int d\omega\, T(\omega, \omega - \Omega) \left[1 - f_L(\omega)\right] f_R(\omega - \Omega)$$

Transfer von $R \to L$ unter Absorption von Energie Ω aus dem System

$$+ e^{+i\chi} \int d\omega\, T(\omega, \omega + \Omega) f_L(\omega) \left[1 - f_R(\omega + \Omega)\right]$$

Transfer von $L \to R$

Integrale des Typs $\quad I = \int d\omega \quad f_1(\omega) \left[1 - f_2(\omega)\right]$



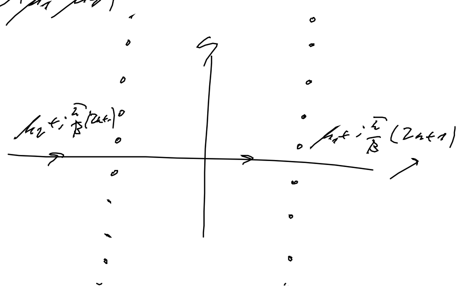
Vereinfachung $T(\omega, \omega') \approx T$

a) für $\beta \to \infty$ (Temp. $\to 0$)

$$I \longrightarrow (\mu_1 - \mu_2) \cdot \Theta(\mu_1 - \mu_2)$$

b.) für endl. Temp.

Funktionen-Theorie



$$\ldots \quad I = \frac{\mu_1-\mu_2}{1-e^{-\beta(\mu_1-\mu_2)}} \qquad \gamma_{ab,ab}^{\xi} = \gamma^{\xi}(E_a-E_b)\left|\langle a|[\xi-\tau\, d^\dagger d]|b\rangle\right|^2$$

$$\mathcal{L}_{QPC}(\xi) = \begin{pmatrix} 1 & 0 \\ 0 & |1-\tau|^2 \end{pmatrix} T\left[(e^{-i\xi}-1)\frac{V}{e^{\beta V}-1} + (e^{+i\xi}-1)\frac{V}{1-e^{-\beta V}}\right]$$

$$V = \mu_L^{QPC} - \mu_R^{QPC}$$

$$\mathcal{L}_{ges}(\xi) = \mathcal{L}_{SET} + \mathcal{L}_{QPC}(\xi)$$

a) z.B. $\Gamma_L = \Gamma_R \to 0$

$I_0 = T \cdot V$ $\qquad$ $I_1 = |1-\tau|^2 \cdot I_0$

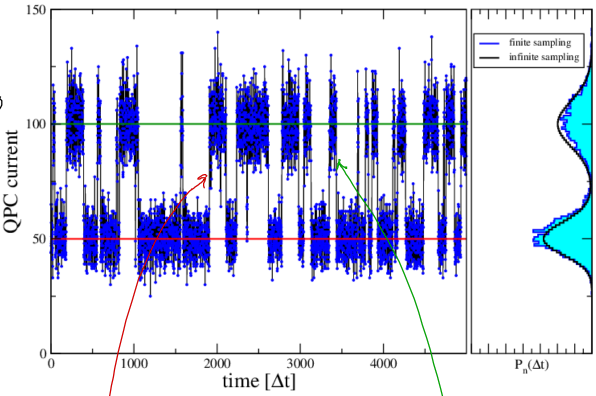
SET-QD leer $\qquad$ SET-QD besetzt

falls: $\{\Gamma_L, \Gamma_R\} \ll \{T\cdot V, |1-\tau|^2 \cdot T \cdot V\}$

b) $P_{\Delta n}(\Delta t) = \frac{1}{2\pi}\int \mathrm{Tr}\left\{e^{\mathcal{L}_{ges}(\xi)\cdot\Delta t - i\Delta n \xi}\rho(t)\right\} d\xi$

SET-QD leer

SET-QD besetzt



$I_{QPC} = \frac{\Delta n}{\Delta t}$

SET entleert sich (ins rechte Bad) $\qquad$ SET füllt sich (aus dem linken Bad)