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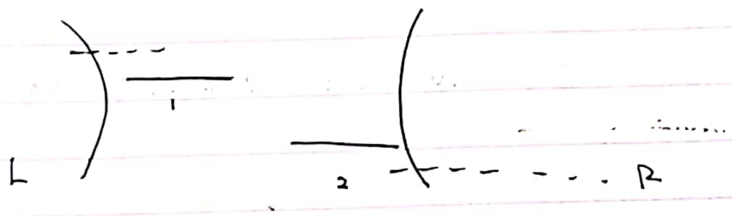

1. We consider a simple two-level model as one example of e-bath. The Hamiltonian of the e-bath is:

$$H_e = \sum_{i=1,2} \varepsilon_i d_i^\dagger d_i + t_{12}(d_1^\dagger d_2 + h.c.)$$

The level 1 couples to the left electrode, characterized by broadening parameter γ_L. Similarly, level 2 couples to R electrode, through γ_R.

We let $t_{12} = 0$. in the following.

2. Green's functions. (GF)

The retarded GF of electrons:

$$G^{r/a}(\varepsilon) = \frac{1}{(\varepsilon \pm i\delta) - H_e \pm i(\gamma_L + \gamma_R)}$$

r — retarded ; a — advanced.

We have: $G^r = (G^a)^\dagger$ in general.

Here, since $G^r = (G^r)^T$. we also have

$$G^r = (G^a)^*.$$

Next, we write it out explicitly

$$G^r = \begin{bmatrix} (\varepsilon - \varepsilon_1 + i\gamma_L)^{-1} & 0 \\ 0 & (\varepsilon - \varepsilon_2 + i\gamma_R)^{-1} \end{bmatrix}.$$

Since we have ignored the explicit coupling between 1, 2. there's no current flow in any case.

And, 1 is in thermal equilibrium with L,

2 - - - - - - - - - - R.

* The self-energy due to coupling to L. is

$$\Sigma_L^{r/a}(\varepsilon) = \mp i \cdot \frac{\gamma_L}{\hbar}$$

$$\Sigma^{<}_{L(\varepsilon)} = (-f_{L(\varepsilon)}) \cdot (-2i\gamma_L) = 2i f_L \cdot \gamma_L$$

similarly, $\Sigma^{>}_L(\varepsilon) = -2i(1-f_L)\gamma_L.$

$$\Sigma_R^{r/a} = \mp i \frac{\gamma_R}{\hbar}$$

$$\Sigma^{<}_R(\varepsilon) = 2i f_R \gamma_R, \quad \Sigma^{>}_{R(\varepsilon)} = -2i(1-f_R)\gamma_R$$

* The less, greater GF

$$G^< = G^r \Sigma^< G^a = \begin{pmatrix} (\varepsilon-\varepsilon_1+i\gamma_L)^{-1} & \\ & (\varepsilon-\varepsilon_2+i\gamma_R)^{-1} \end{pmatrix}$$

$$\begin{pmatrix} 2i\gamma_L f_L & \\ & 2i\gamma_R f_R \end{pmatrix} \begin{pmatrix} (\varepsilon-\varepsilon_1-i\gamma_L)^{-1} & \\ & (\varepsilon-\varepsilon_2-i\gamma_R)^{-1} \end{pmatrix}$$

$$= \begin{pmatrix} \dfrac{2i\gamma_L f_L}{(\varepsilon-\varepsilon_1)^2+\gamma_L^2} & \\ & \dfrac{2i\gamma_R f_R}{(\varepsilon-\varepsilon_2)^2+\gamma_R^2} \end{pmatrix}$$

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* The spectral function.

$$A_L = G^r \Gamma_L G^a = \begin{pmatrix} \frac{2\gamma_L}{(\varepsilon-\varepsilon_1)^2+\gamma_L^2} & 0 \\ 0 & 0 \end{pmatrix}$$

$$A_R = \begin{pmatrix} 0 & 0 \\ 0 & \frac{2\gamma_R}{(\varepsilon-\varepsilon_2)^2+\gamma_R^2} \end{pmatrix}.$$

Check:

$$A = A_L + A_R = i\,(G^r - G^a)$$

3. To generate energy / charge transport, we introduce one bosonic mode.

$$\mathcal{H}_{ph} = \left(\tfrac{1}{2} + a^\dagger a\right)\hbar\Omega = \frac{p^2}{2} + \frac{1}{2}\Omega^2 \cancel{x}\, u^2$$

It couples to the electrons through

$$\mathcal{H}_{int} = m\left(d_1^\dagger d_2\, \cancel{x}\, u + h.c.\right)$$

m – e-ph coupling constant.

* ~~Phonon~~ Boson GF:

$$D^r(\omega) = \frac{1}{(\omega+i\delta)^2 - \Omega^2}. \quad \leftarrow \text{isolated boson mode.}$$

Coupling to ph-bath through γ_{ph}:

$$D^r(\omega) = \frac{1}{(\omega + i\gamma_{ph})^2 - \Omega^2}.$$

* EHP DOS :

Since we have only one mode in the system. we drop the indices.

$$\Gamma^{\alpha\beta}(\omega) = -\frac{1}{\hbar\omega}\int d\varepsilon \; m^2 A_\alpha(\varepsilon) A_\beta(\varepsilon-\hbar\omega)$$

$$\times \left(f_\alpha(\varepsilon) - f_\beta(\varepsilon-\hbar\Omega)\right)$$

$$= -\frac{m^2}{\hbar\omega}\int d\varepsilon \cdot \frac{2\gamma_\alpha}{(\varepsilon-\varepsilon_\alpha)^2+\gamma_\alpha^2} \cdot \frac{2\gamma_\beta}{(\varepsilon-\varepsilon_\beta)^2+\gamma_\beta^2}$$

$$\times \left(f_\alpha(\varepsilon) - f_\beta(\varepsilon-\hbar\Omega)\right).$$

$$= -\frac{m^2}{\hbar\omega}\int d\varepsilon \cdot \frac{2\gamma_\alpha}{(\varepsilon-\varepsilon_\alpha)^2+\gamma_\alpha^2} \cdot \frac{2\gamma_\beta}{(\varepsilon-\varepsilon_\beta)^2+\gamma_\beta^2} \; \times$$

$$\left[\frac{1}{[e^{\beta(\varepsilon-\mu_\alpha)}+1]} - \frac{1}{e^{\beta(\varepsilon-\hbar\Omega-\mu_\beta)}+1}\right]$$

$$\frac{e^{\beta(\varepsilon-\hbar\Omega-\mu_\beta)} - e^{\beta(\varepsilon-\mu_\alpha)}}{\left(e^{\beta(\varepsilon-\mu_\alpha)}+1\right)\left(e^{\beta(\varepsilon-\hbar\Omega-\mu_\beta)}+1\right)}$$