

# Notes on quantum transport in mesoscopic systems

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## 0.1 Basics

### 0.1.1 Magnon

A magnon is a quasiparticle, a collective excitation of the electrons' spin structure in a crystal lattice. In the equivalent wave picture of quantum mechanics, a magnon can be viewed as a quantized spin wave. Magnons carry a fixed amount of energy and lattice momentum, and are spin-1, indicating they obey boson behavior.

### 0.1.2 Hall effect

#### Conventional Hall effect

#### Quantum Hall effect

#### Spin Hall effect

Occurs in paramagnetic systems as a result of spin-orbit interaction, refers to generation of pure spin current transverse to an applied electric field, even in the absence of magnetic field.

Similar to charge accumulation at sample edges in conventional Hall effect, spin accumulation is expected in spin Hall effect.

- extrinsic spin Hall effect: originates from asymmetric scattering for spin-up and spin-down.
- intrinsic spin Hall effect: originates from band structures without scattering.[1]

Fractional Hall effect

Anomalous Hall effect

## 0.2 Formulas in PRB. 88, 220406(R) (2013)

### 0.2.1 Formula 1

System Hamiltonian:

$$H = H_L + H_R + H_{sd}. \quad (1)$$

Left lead is metallic

$$H_L = \sum_{k\sigma} (\varepsilon_{k\sigma} - \mu_\sigma) c_{k\sigma}^\dagger c_{k\sigma}, \quad (2)$$

right lead is insulating magnetic

$$H_R \approx \sum_q \hbar w_q a_q^\dagger a_q + \text{constant}. \quad (3)$$

The interfacial electron-magnon interaction is described by

$$H_{sd} = - \sum_{k,q} J_q \left[ S_q^- c_{k\uparrow}^\dagger c_{k+q\downarrow} + S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right] \quad (4)$$

where  $S_q^- \approx \sqrt{2S_0} a_q^\dagger$ ,  $S_q^+ \approx \sqrt{2S_0} a_q$  are in the momentum space and  $J_q$  denotes the effective exchange coupling at the interface. The magnonic spin current operator can be obtained by

$$\hat{I}_S = \frac{d\hat{N}_R}{dt} = \frac{d}{dt} \sum_q a_q^\dagger a_q, \quad (5)$$

the magnonic spin current is obtained by taking average over the nonequilibrium ground state  $|\psi_0\rangle$  of the interacting system  $H$ :

$$I_S = \frac{dN_R}{dt} = \frac{d}{dt} \langle \sum_q a_q^\dagger a_q \rangle. \quad (6)$$

Using the Heisenberg equation, we get

$$I_S = \frac{i}{\hbar} \langle [H_{sd}, \sum_q a_q^\dagger a_q] \rangle. \quad (7)$$

$$[H_{sd}, \sum_q a_q^\dagger a_q] = \left[ - \sum_{k,q} J_q \left( S_q^- c_{k\uparrow}^\dagger c_{k+q\downarrow} + S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right), \sum_q a_q^\dagger a_q \right], \quad (8)$$

in which,

$$[a_q^\dagger, \sum_{q'} a_{q'}^\dagger a_{q'}] = \delta_{qq'} [a_q^\dagger, a_{q'}^\dagger a_{q'}] = [a_q^\dagger, a_q^\dagger a_q] = a_q^\dagger [a_q^\dagger, a_q] = -a_q^\dagger. \quad (9)$$

Similarly,

$$[a_q, \sum_{q'} a_{q'}^\dagger a_{q'}] = [a_q, a_q^\dagger a_q] = a_q. \quad (10)$$

So,

$$\begin{aligned} I_S &= \frac{i}{\hbar} \langle - \sum_{kq} J_q \left( -S_q^- c_{k\uparrow}^\dagger c_{k+q\downarrow} + S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right) \rangle \\ &= \frac{i}{\hbar} \sum_{kq} J_q \left( \langle S_q^- c_{k\uparrow}^\dagger c_{k+q\downarrow} \rangle - \langle S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \rangle \right). \end{aligned} \quad (11)$$

### 0.2.2 Formula 2

$$\frac{d}{dt} \left\langle S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right\rangle = \frac{i}{\hbar} \left\langle \left[ H_L + H_{sd} + H_R, S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right] \right\rangle. \quad (12)$$

The rhs. of eq. (12) is decomposed into 3 terms. The first term reads

$$\begin{aligned} \left\langle \left[ H_L, S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right] \right\rangle &= \left[ \sum_{k'\sigma} (\varepsilon_{k'\sigma} - \mu_\sigma) c_{k'\sigma}^\dagger c_{k'\sigma}, S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right] \\ &= S_q^+ \left[ \sum_{k'\sigma} (\varepsilon_{k'\sigma} - \mu_\sigma) c_{k'\sigma}^\dagger c_{k'\sigma}, c_{k+q\downarrow}^\dagger \right] c_{k\uparrow} \\ &\quad + S_q^+ c_{k+q\downarrow}^\dagger \left[ \sum_{k'\sigma} (\varepsilon_{k'\sigma} - \mu_\sigma) c_{k'\sigma}^\dagger c_{k'\sigma}, c_{k\uparrow} \right] \end{aligned} \quad (13)$$

Note that,

$$\left[ \sum_{k'\sigma} c_{k'\sigma}^\dagger c_{k'\sigma}, c_{k+q\downarrow}^\dagger \right] = \sum_{k'\sigma} c_{k'\sigma}^\dagger \delta_{k',k+q} \delta_{\sigma\downarrow} = c_{k+q\downarrow}^\dagger, \quad (14)$$

$$\left[ \sum_{k'\sigma} c_{k'\sigma}^\dagger c_{k'\sigma}, c_{k\uparrow} \right] = - \sum_{k'\sigma} \{ c_{k'\sigma}^\dagger, c_{k\uparrow} \} c_{k'\sigma} = -c_{k\uparrow}. \quad (15)$$

Eq. (14) (15) are derived using equity

$$\begin{aligned} [AB, C] &= A[B, C] + [A, C]B \\ &= A\{B, C\} - \{A, C\}B. \end{aligned} \quad (16)$$

So,

$$\left[ H_L, S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right] = (\varepsilon_{k+q\downarrow} - \varepsilon_{k\uparrow} + \mu_\uparrow - \mu_\downarrow) S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow}. \quad (17)$$

If  $\mu_\uparrow = \mu_\downarrow$ , then eq. (17) reduces to

$$\left[ H_L, S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right] = (\varepsilon_{k+q\downarrow} - \varepsilon_{k\uparrow}) S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow}. \quad (18)$$

The second term  $H_R = \sum_q \hbar \omega_q a_q^\dagger a_q$ , then using eq. (10), we get

$$\left[ H_R, S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right] = -\hbar \omega_q S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow}. \quad (19)$$

The third term in eq. (12) reads

$$\begin{aligned} \left[ H_{sd}, S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right] &= -J_q \left[ S_q^- c_{k\uparrow}^\dagger c_{k+q\downarrow}, S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right] \\ &= J_q \left[ S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow}, S_q^- c_{k\uparrow}^\dagger c_{k+q\downarrow} \right] \end{aligned} \quad (20)$$

Combine these three terms, we get

$$\begin{aligned} \frac{d}{dt} \left\langle S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right\rangle &= \frac{i}{\hbar} (\varepsilon_{k+q\downarrow} - \varepsilon_{k\uparrow} - \hbar \omega_q) \left\langle S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow} \right\rangle \\ &\quad + \frac{i}{\hbar} J_q \left\langle \left[ S_q^+ c_{k+q\downarrow}^\dagger c_{k\uparrow}, S_q^- c_{k\uparrow}^\dagger c_{k+q\downarrow} \right] \right\rangle, \end{aligned} \quad (21)$$

which is also eq. (2) in PRB. 88, 220406(R) (2013).

### 0.3 Spin current in NM-QD-MIL system

For system consists of quantum dot(QD) sandwiched by a left normal metal(NM) lead and a right magnetic insulating lead(MIL), the Hamiltonian is

$$H = H_L + H_{QD} + H_R + H_T. \quad (22)$$

$$H_L = \sum_{k\sigma} \varepsilon_{k\sigma} c_{k\sigma}^\dagger c_{k\sigma}, \quad (23)$$

$$H_{QD} = \sum_{\sigma} \varepsilon_{\sigma} d_{\sigma}^\dagger d_{\sigma}, \quad (24)$$

$$H_R \approx \sum_q \hbar \omega_q a_q^\dagger a_q, \quad (25)$$

$$H_T = V_L + V_R \quad (26)$$

$V_L$  is the coupling between left lead and QD, while  $V_R$  is the coupling between right lead and QD.

$$V_L = \sum_{k\sigma} (t_{k\sigma} c_{k\sigma}^\dagger d_{\sigma} + t_{k\sigma}^* d_{\sigma}^\dagger c_{k\sigma}) \quad (27)$$

$$V_R = - \sum_q J_q \left[ S_q^- d_{\uparrow}^\dagger d_{\downarrow} + S_q^+ d_{\downarrow}^\dagger d_{\uparrow} \right]. \quad (28)$$

where  $S_q^- \approx \sqrt{2S_0} a_q^\dagger$ ,  $S_q^+ \approx \sqrt{2S_0} a_q$  are in the momentum space and  $J_q$  denotes the effective exchange coupling between the QD and MIL.

#### 0.3.1 Spin-dependent current in left lead

The spin-dependent current flow out of left lead is  $I_{L\sigma}$ :

$$I_{L\sigma} = \frac{d}{dt} \langle N_{L\sigma} \rangle \quad (29)$$

in which,  $N_{L\sigma} = \sum_k c_{k\sigma}^\dagger c_{k\sigma}$  Heisenberg equation:

$$\frac{d}{dt} \langle N_{L\sigma} \rangle = \frac{i}{\hbar} \langle [H, N_{L\sigma}] \rangle \quad (30)$$

$$[H, N_{L\sigma}] = [H_T, N_{L\sigma}] = \sum_k \left( t_{k\sigma}^* d_{\sigma}^\dagger c_{k\sigma} - t_{k\sigma} c_{k\sigma}^\dagger d_{\sigma} \right) \quad (31)$$

so, the spin-dependent current

$$I_{L\sigma} = \frac{i}{\hbar} \sum_k \left( t_{k\sigma}^* \langle d_{\sigma}^\dagger c_{k\sigma} \rangle - t_{k\sigma} \langle c_{k\sigma}^\dagger d_{\sigma} \rangle \right). \quad (32)$$

Namely, the spin-up current is

$$I_{L\uparrow} = \frac{i}{\hbar} \sum_k \left( t_{k\uparrow}^* \langle d_{\uparrow}^\dagger c_{k\uparrow} \rangle - t_{k\uparrow} \langle c_{k\uparrow}^\dagger d_{\uparrow} \rangle \right), \quad (33)$$

the spin-down current is

$$I_{L\downarrow} = \frac{i}{\hbar} \sum_k \left( t_{k\downarrow}^* \langle d_{\downarrow}^\dagger c_{k\downarrow} \rangle - t_{k\downarrow} \langle c_{k\downarrow}^\dagger d_{\downarrow} \rangle \right), \quad (34)$$

The charge current in left lead is defined as

$$I_e = e(I_{L\uparrow} + I_{L\downarrow}). \quad (35)$$

The spin current in left lead is defined as

$$I_{LS} = \frac{1}{2}(I_{L\uparrow} - I_{L\downarrow}) \quad (36)$$

Substitute the spin-dependent current in, we get the spin current in left lead

$$I_{LS} = \frac{i}{2\hbar} \sum_k \left( t_{k\uparrow}^* \langle d_{\uparrow}^\dagger c_{k\uparrow} \rangle - t_{k\uparrow} \langle c_{k\uparrow}^\dagger d_{\uparrow} \rangle - t_{k\downarrow}^* \langle d_{\downarrow}^\dagger c_{k\downarrow} \rangle + t_{k\downarrow} \langle c_{k\downarrow}^\dagger d_{\downarrow} \rangle \right) \quad (37)$$

### 0.3.2 magnonic current in right lead

The magnonic current in right lead is

$$I_{RS} = \frac{d\langle N_R \rangle}{dt} = \frac{d}{dt} \langle \sum_q a_q^\dagger a_q \rangle, \quad (38)$$

From the Heisenberg equation, we have

$$\frac{d}{dt} \langle \sum_q a_q^\dagger a_q \rangle = \frac{i}{\hbar} \langle [H, \sum_q a_q^\dagger a_q] \rangle. \quad (39)$$

We have

$$\begin{aligned} & [H, \sum_q a_q^\dagger a_q] \\ &= [V_R, \sum_q a_q^\dagger a_q] \\ &= - \sum_q J_q \left( [S_q^- d_{\uparrow}^\dagger d_{\downarrow}, \sum_{q'} a_{q'}^\dagger a_{q'}] + [S_q^+ d_{\downarrow}^\dagger d_{\uparrow}, \sum_{q'} a_{q'}^\dagger a_{q'}] \right) \\ &= \sum_q J_q (S_q^- d_{\uparrow}^\dagger d_{\downarrow} - S_q^+ d_{\downarrow}^\dagger d_{\uparrow}) \end{aligned} \quad (40)$$

So, the magnon current reads

$$I_{RS} = \frac{i}{\hbar} \sum_q J_q (\langle S_q^- d_{\uparrow}^\dagger d_{\downarrow} \rangle - \langle S_q^+ d_{\downarrow}^\dagger d_{\uparrow} \rangle). \quad (41)$$

### 0.3.3 spin-dependent current in QD

Similarly, the spin-dependent current in the central QD is defined as

$$I_{C\sigma} = \langle \frac{dN_{C\sigma}}{dt} \rangle = \langle \frac{d}{dt} d_\sigma^\dagger d_\sigma \rangle, \quad (42)$$

Heisenberg equation:

$$\frac{d}{dt} d_\sigma^\dagger d_\sigma = \frac{i}{\hbar} [H, d_\sigma^\dagger d_\sigma]. \quad (43)$$

Specifically, we have

$$[H, d_\sigma^\dagger d_\sigma] = [V_L, d_\sigma^\dagger d_\sigma] + [V_R, d_\sigma^\dagger d_\sigma] \quad (44)$$

in which,

$$\begin{aligned} [V_L, d_\sigma^\dagger d_\sigma] &= \sum_{k'\sigma'} (t_{k'\sigma'} [c_{k'\sigma'}^\dagger d_{\sigma'}, d_\sigma^\dagger d_\sigma] + t_{k'\sigma'}^* [d_\sigma^\dagger c_{k'\sigma'}, d_\sigma^\dagger d_\sigma]) \\ &= \sum_{k'\sigma'} (t_{k'\sigma'} c_{k'\sigma'}^\dagger d_{\sigma'} \delta_{\sigma\sigma'} - t_{k'\sigma'}^* d_\sigma^\dagger c_{k'\sigma'} \delta_{\sigma\sigma'}) \\ &= \sum_k (t_{k\sigma} c_{k\sigma}^\dagger d_\sigma - t_{k\sigma}^* d_\sigma^\dagger c_{k\sigma}) \end{aligned} \quad (45)$$

We change the summation index from  $k'$  to  $k$  in the last line, which doesn't change the result.

$$[V_R, d_\sigma^\dagger d_\sigma] = - \sum_q J_q (S_q^- [d_\uparrow^\dagger d_\downarrow, d_\sigma^\dagger d_\sigma] + S_q^+ [d_\downarrow^\dagger d_\uparrow, d_\sigma^\dagger d_\sigma]) \quad (46)$$

in which,

$$\begin{aligned} [d_\uparrow^\dagger d_\downarrow, d_\sigma^\dagger d_\sigma] &= d_\uparrow^\dagger [d_\downarrow, d_\sigma^\dagger d_\sigma] + [d_\uparrow^\dagger, d_\sigma^\dagger d_\sigma] d_\downarrow \\ &= d_\uparrow^\dagger d_\downarrow \delta_{\sigma\downarrow} - d_\uparrow^\dagger d_\downarrow \delta_{\sigma\uparrow} \end{aligned} \quad (47)$$

So,

$$[V_R, d_\sigma^\dagger d_\sigma] = - \sum_q J_q [S_q^- (d_\uparrow^\dagger d_\downarrow \delta_{\sigma\downarrow} - d_\uparrow^\dagger d_\downarrow \delta_{\sigma\uparrow}) + S_q^+ (d_\downarrow^\dagger d_\uparrow \delta_{\sigma\uparrow} - d_\downarrow^\dagger d_\uparrow \delta_{\sigma\downarrow})] \quad (48)$$

The spin-dependent current is

$$I_{C\uparrow} = \frac{i}{\hbar} [H, d_\uparrow^\dagger d_\uparrow] \quad (49)$$

$$I_{C\downarrow} = \frac{i}{\hbar} [H, d_\downarrow^\dagger d_\downarrow] \quad (50)$$

which gives

$$I_{C\uparrow} = \frac{i}{\hbar} \left[ \sum_k (t_{k\uparrow} c_{k\uparrow}^\dagger d_\uparrow - t_{k\uparrow}^* d_\uparrow^\dagger c_{k\uparrow}) + \sum_q J_q (S_q^- d_\uparrow^\dagger d_\downarrow - S_q^+ d_\downarrow^\dagger d_\uparrow) \right] \quad (51)$$

and

$$I_{C\downarrow} = \frac{i}{\hbar} \left[ \sum_k (t_{k\downarrow} c_{k\downarrow}^\dagger d_\downarrow - t_{k\downarrow}^* d_\downarrow^\dagger c_{k\downarrow}) + \sum_q J_q (S_q^+ d_\downarrow^\dagger d_\uparrow - S_q^- d_\uparrow^\dagger d_\downarrow) \right]. \quad (52)$$

The spin current in central dot is

$$I_{CS} = \frac{1}{2} (I_{C\uparrow} - I_{C\downarrow}) \quad (53)$$

### 0.3.4 Verifying continuity condition

#### Charge current

Since the right lead is a insulating lead, there is no charge current flow through it, so the charge current is

$$I_{Re} = 0 \quad (54)$$

where the subscript R denotes the right lead, while the subscript e denotes the charge current.

Meanwhile, the charge current flows in left lead and QD is

$$I_e = e \left( \sum_\sigma I_{L\sigma} + \sum_\sigma I_{C\sigma} \right) = 0 \quad (55)$$



### Spin current

Spin current in the left lead and QD:

$$I_{LS} + I_{CS} = \frac{i}{\hbar} \sum_q J_q (\langle S_q^- d_{\uparrow}^\dagger d_{\downarrow} \rangle - \langle S_q^+ d_{\downarrow}^\dagger d_{\uparrow} \rangle). \quad (56)$$

The magnon current is

$$I_{RS} = \frac{i}{\hbar} \sum_q J_q (\langle S_q^- d_{\uparrow}^\dagger d_{\downarrow} \rangle - \langle S_q^+ d_{\downarrow}^\dagger d_{\uparrow} \rangle), \quad (57)$$

in which,  $I_{LS}, I_{CS}, I_{RS}$  is defined earlier. Thus, we have

$$\begin{aligned} I_{LS} + I_{CS} &= I_{RS} \\ &= \frac{i}{\hbar} \sum_q J_q (\langle S_q^- d_{\uparrow}^\dagger d_{\downarrow} \rangle - \langle S_q^+ d_{\downarrow}^\dagger d_{\uparrow} \rangle). \end{aligned} \quad (58)$$

### 0.3.5 Perturbation expansion of $G_d(\tau, \tau)$

When neglecting left lead, the hamiltonian is

$$H = H_{QD} + H_R + H_{sd} \quad (59)$$

Expand S-matrix up to the second order of  $J$ , we have

$$\begin{aligned} G_d(\tau, \tau) &= -i \langle T_C S s_q^+(\tau) s_q^-(\tau') \rangle \\ &= -i \sum_k g_{k\uparrow}(\tau', \tau) g_{k+q\downarrow}(\tau, \tau') \\ &\quad + \int_c d\tau_1 \int_c d\tau_2 \sum_{kq_1} J_{q_1}^2 g_{Rq_1}(\tau_2, \tau_1) g_{k\uparrow}(\tau', \tau_2) g_{k+q_1\downarrow}(\tau_2, \tau_1) g_{k\uparrow}(\tau_1, \tau) g_{k+q\downarrow}(\tau, \tau') \\ &\quad + \int_c d\tau_1 \int_c d\tau_2 \sum_{kq_1} J_{q_1}^2 g_{Rq_1}(\tau_2, \tau_1) g_{k\uparrow}(\tau', \tau) g_{k+q\downarrow}(\tau, \tau_1) g_{k+q-q_1\uparrow}(\tau_1, \tau_2) g_{k+q\downarrow}(\tau_2, \tau') \\ &\quad - \int_c d\tau_1 \int_c d\tau_2 \sum_{kk'} J_{q_1}^2 g_{Rq_1}(\tau_2, \tau_1) g_{k\uparrow}(\tau_1, \tau) g_{k+q\downarrow}(\tau, \tau_1) g_{k'\uparrow}(\tau', \tau_2) g_{k'+q\downarrow}(\tau_2, \tau') \end{aligned} \quad (60)$$

## 0.4 Checking formulas in notes

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### 0.4.1 Hamiltonian

$$H = H_L + H_R + H_d + H_T + H_{sd} \quad (61)$$

$$H_L = \sum_{k\sigma} \epsilon_{k\sigma,L} c_{k\sigma}^\dagger c_{k\sigma} \quad (62)$$

$$H_R = \sum_q \omega_q a_q^\dagger a_q \quad (63)$$

$$H_d = \sum_{n\sigma} \epsilon_{n\sigma} d_{n\sigma}^\dagger d_{n\sigma} \quad (64)$$

$$H_T = \sum_{k\sigma n} \left( t_{k\sigma n} c_{k\sigma}^\dagger d_{n\sigma} + t_{k\sigma n}^* d_{n\sigma}^\dagger c_{k\sigma} \right) \quad (65)$$

$$H_{sd} = - \sum_{qnm} J_q \left( d_{n\uparrow}^\dagger d_{m\downarrow} a_q^\dagger + a_q d_{m\downarrow}^\dagger d_{n\uparrow} \right) \delta(\epsilon_{n\uparrow} - \epsilon_{m\downarrow} - \omega_q) \quad (66)$$

$$s_q^+ = \sum_{nm} d_{n\uparrow}^\dagger d_{m\downarrow} \delta_{\uparrow\downarrow} \quad (67)$$

$$s_q^- = \sum_{nm} d_{m\downarrow}^\dagger d_{n\uparrow} \delta_{\uparrow\downarrow} \quad (68)$$

check operators

$$i\dot{a}_q = \omega_q a_q - J_q s_q^+ \quad (69)$$

$$i\dot{c}_{k\sigma} = \epsilon_{k\sigma,L} c_{k\sigma} + \sum_{k'} t_{k\sigma n} d_{n\sigma} \quad (70)$$

$$i\dot{d}_{n\uparrow} = \epsilon_{n\uparrow} d_{n\uparrow} + \sum_k t_{k\uparrow n}^* c_{k\uparrow} - \sum_{q,m} J_q a_q^\dagger d_{m\downarrow} \delta(\epsilon_{n\uparrow} - \epsilon_{m\downarrow} - \omega_q) \quad (71)$$

$$i\dot{d}_{n\downarrow} = \epsilon_{n\downarrow} d_{n\downarrow} + \sum_k t_{k\downarrow n}^* c_{k\downarrow} - \sum_{q,m} J_q a_q d_{m\uparrow} \delta(\epsilon_{m\uparrow} - \epsilon_{n\downarrow} - \omega_q) \quad (72)$$

### 0.4.2 spin current ???

$$-i\partial_{\tau'} G_{d,R}(\tau, \tau') = \omega_q G_{d,R}(\tau, \tau') - J_q G_d \quad (73)$$

or

$$G_{d,R} g_{Rq}^{-1} = -J_q G_d \quad (74)$$

or

$$G_{d,R}(\tau, \tau') = -J_q \int G_d(\tau, \tau_1) g_{Rq}(\tau_1, \tau') d\tau_1 \quad (75)$$

the minus before  $J_q$  originates from the minus in  $H_{sd}$ .

$$\begin{aligned}
I_s &= i \sum_q J_q \left( \langle s_q^+ a_q^\dagger \rangle - \langle a_q s_q^- \rangle \right) \\
&= \sum_q J_q (G_{d,R}^<(t, t') - G_{R,d}^<(t, t')) \\
&= -2\text{Re} \sum_q \int \text{Tr} [G_d^r(t, t_1) \Sigma_R^<(t_1, t') + G_d^<(t, t_1) \Sigma_R^a(t_1, t')] dt_1 \\
&= -2\text{Re} \sum_q \int \text{Tr} [(G_d^> - G_d^<) \Sigma_{Rq}^< + G_d^< (\Sigma_{Rq}^a - \Sigma_{Rq}^r)] dt_1
\end{aligned} \tag{76}$$

$$\Sigma_{Rq}(\tau, \tau') = J_q^2 g_{Rq}(\tau, \tau') \tag{77}$$

### 0.4.3 Calculation of $G_d$

Definition:

$$\begin{aligned}
G_d(\tau, \tau') &= -i \langle T_c S s_q^+(\tau) s_q^-(\tau') \rangle \\
&= -i \sum_{mnm'n'} \langle T_c S d_{n\uparrow}^\dagger d_{m\downarrow} d_{m'\downarrow}^\dagger d_{n'\uparrow} \rangle \delta(\epsilon_{n\uparrow} - \epsilon_{m\downarrow} - \omega_q) \delta(\epsilon_{n'\uparrow} - \epsilon_{m'\downarrow} - \omega_q)
\end{aligned} \tag{78}$$

When right lead is absent,

$$G_d(\tau, \tau') = -i \sum_{mnm'n'} G_{L,n'n\uparrow}(\tau', \tau) G_{L,mm'\downarrow}(\tau, \tau') \delta(\epsilon_{n\uparrow} - \epsilon_{m\downarrow} - \omega_q) \delta(\epsilon_{n'\uparrow} - \epsilon_{m'\downarrow} - \omega_q) \tag{79}$$

where

$$\begin{aligned}
G_{L,mn\sigma}(\tau, \tau') &= -i \langle T_c d_{m\sigma}(\tau) d_{n\sigma}^\dagger(\tau') \rangle \\
&= g_{n\sigma}(\tau, \tau') \delta_{mn} \\
&\quad + \iint d\tau_1 d\tau_2 g_{m\sigma}(\tau, \tau_2) \sum_k t_{k\sigma n} t_{k\sigma m}^* g_{k\sigma}(\tau_2, \tau_1) g_{n\sigma}(\tau_1, \tau') \\
&\quad + \dots \\
&= g_{n\sigma}(\tau, \tau') \delta_{mn} + \iint d\tau_1 d\tau_2 g_{m\sigma}(\tau, \tau_2) \Sigma_{L,mn\sigma}(\tau_2, \tau_1) g_{n\sigma}(\tau_1, \tau') \\
&\quad + \dots \\
&= ?
\end{aligned} \tag{80}$$

$$g_{n\sigma}(\tau, \tau') = -i \langle T_c d_n(\tau) d_{n\sigma}^\dagger(\tau') \rangle_0 \tag{81}$$

Self-energy of left lead

$$\Sigma_{L,mn\sigma}(\tau_2, \tau_1) = \sum_k t_{k\sigma n} t_{k\sigma m}^* g_{k\sigma}(\tau_2, \tau_1) \tag{82}$$

where

$$g_{k\sigma}(\tau_2, \tau_1) = -i \langle T_c c_{k\sigma}(\tau_2) c_{k\sigma}^\dagger(\tau_1) \rangle_0 \tag{83}$$

When left lead is absent,

$$\begin{aligned}
G_d(\tau, \tau') &= -i \sum_{mn} g_{n\uparrow}(\tau', \tau) g_{m\downarrow}(\tau, \tau') \delta(\varepsilon_{n\uparrow} - \varepsilon_{m\downarrow} - \omega_q) \\
&\quad - \int d\tau_1 \int d\tau_2 \sum_{mnm'n'} g_{n\uparrow}(\tau_1, \tau) g_{m\downarrow}(\tau, \tau_1) \Sigma_{R, mnm'n'}(\tau_1, \tau_2) g_{n'\uparrow}(\tau', \tau_2) g_{m'\downarrow}(\tau_2, \tau') \\
&\quad \times \delta(\varepsilon_{n\uparrow} - \varepsilon_{m\downarrow} - \omega_{q_1}) \delta(\varepsilon_{n'\uparrow} - \varepsilon_{m'\downarrow} - \omega_{q_1}) \\
&\quad + \dots \\
&= g_d(\tau, \tau') + \iint d\tau_1 d\tau_2 g_d(\tau, \tau_1) \Sigma_R(\tau_1, \tau_2) G_d(\tau_2, \tau')
\end{aligned} \tag{84}$$

in which,

$$g_d(\tau, \tau') = -i \sum_{mn} g_{n\uparrow}(\tau', \tau) g_{m\downarrow}(\tau, \tau') \delta(\varepsilon_{n\uparrow} - \varepsilon_{m\downarrow} - \omega_q), \tag{85}$$

the self-energy of right lead is

$$\Sigma_{R, mnm'n'}(\tau_1, \tau_2) = -i \sum_{q_1} J_{q_1}^2 g_{Rq_1}(\tau_1, \tau_2) \delta(\varepsilon_{n\uparrow} - \varepsilon_{m\downarrow} - \omega_{q_1}) \delta(\varepsilon_{n'\uparrow} - \varepsilon_{m'\downarrow} - \omega_{q_1}) \tag{86}$$

$$g_{Rq_1}(\tau_1, \tau_2) = -i \langle T_c a_{q_1}(\tau_1) a_{q_1}^\dagger(\tau_2) \rangle_0 \tag{87}$$

Hence, when both leads are present, we have

$$\begin{aligned}
? \quad G_d(\tau, \tau') &= -i \sum_{mnm'n'} G_{L, nn'\uparrow}(\tau', \tau) G_{L, mm'\downarrow}(\tau, \tau') \delta(\epsilon_{n\uparrow} - \epsilon_{m\downarrow} - \omega_q) \delta(\epsilon_{n'\uparrow} - \epsilon_{m'\downarrow} - \omega_q) \\
&\quad - i \sum_{mnm'n'} G_{L, nn'\uparrow}(\tau_1, \tau) G_{L, mm'\downarrow}(\tau, \tau_1) \Sigma_{R, mnm'n'}(\tau_1, \tau_2) G_d(\tau_2, \tau') \delta(\epsilon_{n\uparrow} - \epsilon_{m\downarrow} - \omega_q) \\
&\quad \times \delta(\epsilon_{n'\uparrow} - \epsilon_{m'\downarrow} - \omega_q)
\end{aligned} \tag{88}$$

For the sack of convenience, we rewrite the above formula as follows.

$$? \quad G_d(\tau, \tau') = -i G_{L\uparrow}(\tau', \tau) G_{L\downarrow}(\tau, \tau') - i G_{L\uparrow}(\tau_1, \tau) G_{L\downarrow}(\tau, \tau_1) \Sigma_R(\tau_1, \tau_2) G_d(\tau_2, \tau') \tag{89}$$

#### 0.4.4 continuation on Eq.(29)

$$A(\tau_1, \tau') \equiv \int d\tau_2 \Sigma_R(\tau_1, \tau_2) G_d(\tau_2, \tau') \tag{90}$$

$$B(\tau, \tau_1) \equiv G_{L\uparrow}(\tau_1, \tau) G_{L\downarrow}(\tau, \tau_1) \tag{91}$$

$$C(\tau, \tau') \equiv -i G_{L\uparrow}(\tau_1, \tau) G_{L\downarrow}(\tau, \tau_1) A(\tau_1, \tau') \rightarrow \tag{92}$$

$$C(\tau, \tau') = -i \int d\tau_1 B(\tau, \tau_1) A(\tau_1, \tau') \tag{93}$$

$$D(\tau, \tau') \equiv -i G_{L\uparrow}(\tau', \tau) G_{L\downarrow}(\tau, \tau') \tag{94}$$

So, we have

$$G_d(\tau, \tau') = D + C \tag{95}$$

Using the analytic continuation theorem, we have

$$D^< = -i G_{L\uparrow}^> G_{L\downarrow}^< \tag{96}$$

$$C^< = -i(B^r A^< + B^< A^a) \quad (97)$$

where

$$B^r = G_{L\uparrow}^a G_{L\downarrow}^< + G_{L\uparrow}^> G_{L\downarrow}^r + G_{L\uparrow}^a G_{L\downarrow}^r \quad (98)$$

$$A^< = \Sigma_R^r G_d^< + \Sigma_R^< G_d^a \quad (99)$$

$$B^< = G_{L\uparrow}^> G_{L\downarrow}^< \quad (100)$$

$$A^a = \Sigma_R^a G_d^a \quad (101)$$

Then, the analytic continuation theorem on Eq.(29) yields

$$G_d^< = -i G_{L\uparrow}^> G_{L\downarrow}^< - i \left[ (G_{L\uparrow}^a G_{L\downarrow}^< + G_{L\uparrow}^> G_{L\downarrow}^r + G_{L\uparrow}^a G_{L\downarrow}^r) (\Sigma_R^r G_d^< + \Sigma_R^< G_d^a) + (G_{L\uparrow}^> G_{L\downarrow}^<) (\Sigma_R^a G_d^a) \right] \quad (102)$$

Similarly,

$$\begin{aligned} C^r &= -i B^r A^r \\ &= -i (G_{L\uparrow}^a G_{L\downarrow}^< + G_{L\uparrow}^> G_{L\downarrow}^r + G_{L\uparrow}^a G_{L\downarrow}^r) (\Sigma_R^r G_d^r) \end{aligned} \quad (103)$$

$$D^r = -i (G_{L\uparrow}^a G_{L\downarrow}^< + G_{L\uparrow}^> G_{L\downarrow}^r + G_{L\uparrow}^a G_{L\downarrow}^r), \quad (104)$$

we have

$$\begin{aligned} G_d^r &= -i (G_{L\uparrow}^a G_{L\downarrow}^< + G_{L\uparrow}^> G_{L\downarrow}^r + G_{L\uparrow}^a G_{L\downarrow}^r) - i (G_{L\uparrow}^a G_{L\downarrow}^< + G_{L\uparrow}^> G_{L\downarrow}^r + G_{L\uparrow}^a G_{L\downarrow}^r) (\Sigma_R^r G_d^r) \\ &= \frac{-i (G_{L\uparrow} G_{L\downarrow})^r}{1 + i (G_{L\uparrow} G_{L\downarrow})^r \Sigma_R^r} \end{aligned} \quad (105)$$

$$(G_{L\uparrow} G_{L\downarrow})^r \equiv G_{L\uparrow}^a G_{L\downarrow}^< + G_{L\uparrow}^> G_{L\downarrow}^r + G_{L\uparrow}^a G_{L\downarrow}^r \quad (106)$$

Now we calculate  $G_d^a$ .

$$C^a = -i B^a A^a \quad (107)$$

$$B^a = G_{L\uparrow}^r G_{L\downarrow}^< + G_{L\uparrow}^> G_{L\downarrow}^a + G_{L\uparrow}^r G_{L\downarrow}^a \quad (108)$$

$$D^a = -i (G_{L\uparrow}^r G_{L\downarrow}^< + G_{L\uparrow}^> G_{L\downarrow}^a + G_{L\uparrow}^r G_{L\downarrow}^a) \quad (109)$$

So we have

$$G_d^a = -i (G_{L\uparrow}^r G_{L\downarrow}^< + G_{L\uparrow}^> G_{L\downarrow}^a + G_{L\uparrow}^r G_{L\downarrow}^a) - i (G_{L\uparrow}^r G_{L\downarrow}^< + G_{L\uparrow}^> G_{L\downarrow}^a + G_{L\uparrow}^r G_{L\downarrow}^a) (\Sigma_R^a G_d^a) \quad (110)$$

From Eq.(42) we have

$$\begin{aligned} G_d^< &= -i G_{L\uparrow}^> G_{L\downarrow}^< (1 + \Sigma_R^a G_d^a) - i (G_{L\uparrow} G_{L\downarrow})^r (\Sigma_q^< G_d^a + \Sigma_R^r G_d^<) \\ &= \frac{-i G_{L\uparrow}^> G_{L\downarrow}^< (1 + \Sigma_R^a G_d^a) - i (G_{L\uparrow} G_{L\downarrow})^r \Sigma_R^< G_d^a}{1 + i (G_{L\uparrow} G_{L\downarrow})^r \Sigma_R^r} \\ &= \frac{-i G_{L\uparrow}^> G_{L\downarrow}^< (1 + \Sigma_R^a G_d^a)}{1 + i (G_{L\uparrow} G_{L\downarrow})^r \Sigma_R^r} + G_d^r \Sigma_R^< G_d^a \\ &= -i (G_d^r \Sigma_R^r + 1) G_{L\uparrow}^> G_{L\downarrow}^< (1 + \Sigma_R^a G_d^a) + G_d^r \Sigma_R^< G_d^a \end{aligned} \quad (111)$$

Similarly,

$$G_d^> = -i (G_d^r \Sigma_R^r + 1) G_{L\uparrow}^< G_{L\downarrow}^> (1 + \Sigma_R^a G_d^a) + G_d^r \Sigma_R^> G_d^a \quad (112)$$

### 0.4.5 DC spin current

We have

$$G_d^>(E) - G_d^<(E) = -i (G_d^r \Sigma_R^r + 1) \left( G_{L\uparrow}^< G_{L\downarrow}^> - G_{L\uparrow}^> G_{L\downarrow}^< \right) (1 + \Sigma_R^a G_d^a) + G_d^r (\Sigma_R^> - \Sigma_R^<) G_d^a \quad (113)$$

$$(G_d^> - G_d^<) \Sigma_R^< = \left[ -i (G_d^r \Sigma_R^r + 1) \left( G_{L\uparrow}^< G_{L\downarrow}^> - G_{L\uparrow}^> G_{L\downarrow}^< \right) (1 + \Sigma_R^a G_d^a) + G_d^r (\Sigma_R^> - \Sigma_R^<) G_d^a \right] \Sigma_R^< \quad (114)$$

Fourier transformation

$$G_d^<(E) = \int_{-\infty}^{+\infty} dt G_d^<(t - t') e^{iE(t-t')} \quad (115)$$

and inverse Fourier transformation

$$G_d^<(t - t') = \frac{1}{2\pi} \int_{-\infty}^{+\infty} d\omega G_d^<(E) e^{-iE(t-t')} \quad (116)$$

Then,

$$G_{L,mn\uparrow}(E) = \quad (117)$$

$$G_{L\uparrow}^> = 1 - f_{L\uparrow} \quad (118)$$

$$G_{L\downarrow}^< = f_{L\downarrow} \quad (119)$$

$$\Sigma_R^<(t, t') = -i \sum_{q_1} J_{q_1}^2 g_{Rq_1}^<(t, t') \quad (120)$$

$$\Sigma_R^a - \Sigma_R^r = \quad (121)$$

$$G_d^< (\Sigma_{Rq}^a - \Sigma_{Rq}^r) = \quad (122)$$

$$? \quad G_{L\sigma}^< = i G_{L\sigma}^r \Gamma_{L\sigma} f_{L\sigma} G_{L\sigma}^a \equiv i D_{L\sigma} f_{L\sigma} \quad (123)$$

The following formula exists

$$(f_{L\uparrow} - 1) f_{L\downarrow} = - (f_{L\uparrow} - f_{L\downarrow}) f_L^B \quad (124)$$

where,

$$f_{L\sigma}(\epsilon) = \frac{1}{\exp(\beta_L(\epsilon - \mu_\sigma)) + 1} \quad (125)$$

$$f_L^B(\omega) = \frac{1}{\exp(\beta_L(\omega + \Delta\mu_s)) - 1} \quad (126)$$

and  $\omega = \varepsilon_\downarrow - \varepsilon_\uparrow, \Delta\mu_s = \mu_\uparrow - \mu_\downarrow$ .

### 0.4.6 Spin current from the left lead

Define spin density operator

$$N_{sk} = d_{k\uparrow}^\dagger d_{k\uparrow} - d_{k\downarrow}^\dagger d_{k\downarrow} \quad (127)$$

$$I_{sL} = (1/2) \partial_t N_s = (1/2) (I_\uparrow - I_\downarrow) \quad (128)$$

$$I_\sigma = \text{Tr} [(G_{d\sigma}^r - G_{d\sigma}^a) \Sigma_{L\sigma}^< + G_{d\sigma}^< (\Sigma_{L\sigma}^a - \Sigma_{L\sigma}^r)] \quad (129)$$

$$[G_{d\sigma}]_{nm} = -i \langle T_c S d_{n\sigma} d_{m\sigma}^\dagger \rangle \quad (130)$$

the factor of 1/2 comes from spin of electron while spin of magnon is 1.

# Bibliography

- [1] Y, K, Kato. Observation of the Spin Hall Effect in Semiconductors[J]. Science, 2004.