Spin current manipulation through a Rashba dot by tunable nonequilibrium Fano-Kondo effect

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Abstract. Though the Rashba-type spin-orbit interaction offers a possibility of manipulating electron’s spin totally by electric field, it has been argued that the mere existence of spin-orbit interaction is insufficient to produce such spin-dependent transport. In the present work, we investigate how spin transport through a single-level dot is possible: Finite spin current appears as a result of spin-orbit interaction, strong electronic correlation and finite bias voltage. We show, by applying finite interaction slave-boson mean field theory, that Kondo physics is responsible for generating such spin-dependent transport.

1. Introduction
In semiconducting devices, the Rashba-type spin-orbit interaction is generated by the potential asymmetry in the direction perpendicular to the semiconductor plane. Utilizing the effect opens up a possibility of controlling electron’s spin totally by electric field alone. It has been argued, however, that the Rashba-type spin-orbit interaction alone is insufficient to realize finite spin transport or spin filtering effect. Because of it, there have been various suggestions how to attain spin transport by combining with other effect such as magnetic field, finite bias effect [1, 2, 3, 4]. So far nonetheless, electrically generated spin-dependent transport due to many-body effect remains largely unexplored.

In the present work, we investigate the electric generation of spin current and transport through an interacting Rashba dot (a dot with the Rashba spin-orbit interaction and the Coulomb interaction) embedded in a ring geometry. We will show that spin transport can manifest itself electrically once the following three conditions are met: (1) strong Coulomb interaction is present on the dot (2) under finite bias voltage \( V_{\text{bias}} \) (3) at very low temperature \( T \). Having the characteristic temperature of the system (= the Kondo temperature) seriously affected by the presence of the Rashba interaction and the Coulomb interaction, we need to treat both effects in a unified way. We argue that many-body effect responsible for generating spin current originates from Kondo physic, so that either too large bias voltage or temperature destroys the effect.

2. Model and analysis

Model Our theoretical model is a ring system attached with two leads and embedded with a Rashba dot in one arm, as shown in Fig. 1. The Hamiltonian takes a form of nonequilibrium
Figure 1. Schematic illustration of the model. On the quantum dot (QD), Coulomb interaction is present and the Rashba spin-orbit interaction is incorporated as a spin-dependent flux $\phi_\sigma$ (see the text).

The single impurity Anderson model accommodating the direct hopping between left and right leads:

$$H = H_{\text{leads}} + H_{\text{dot}} + H_{\text{dot-lead}} + H_{\text{arm}},$$  

(1)

$$H_{\text{leads}} + H_{\text{arm}} = \sum_{n,\sigma} \varepsilon_n c_{n\sigma}^\dagger c_{n\sigma} + \sum_{m,n,\sigma} V_{mn} c_{m\sigma}^\dagger c_{n\sigma},$$  

(2)

$$H_{\text{dot}} = \sum_{\sigma} \varepsilon_d n_{\sigma} + U n_{\uparrow} n_{\downarrow},$$  

(3)

$$H_{\text{dot-lead}} = \sum_{n,\sigma} \left( V_{dn\sigma} c_{n\sigma}^\dagger + h.c \right).$$  

(4)

where $n_{\sigma}$ is the dot number operator with spin $\sigma$ and finite bias voltage is introduced as a difference of two chemical potentials $\mu_{R,L} = \pm eV_{\text{bias}}/2$. The Rashba-type spin-orbit interaction is incorporated as a spin-dependent flux $\phi_{\sigma} = \sigma \phi_{\text{so}}$ (with $\sigma = \pm 1$) through the ring [1]:

$$\exp(i\phi_{\sigma}) = V_{Rd\sigma} V_{d\sigma L}/|V_{Rd\sigma} V_{d\sigma L}|.$$  

(5)

Approach and analysis The above model is very similar to the standard Aharonov-Bohm interferometer with the dot except for spin-dependent flux $\phi_{\sigma}$. In fact, it is possible to show that the system in the linear response regime becomes identical, where there is no spin transport. To cope with a nonequilibrium situation with finite bias voltage, we resort to nonequilibrium Green function approach, adopting finite $U$ slave-boson mean field approximation [5, 6]. The approach is known to reproduce correctly various low-temperature behavior observed in experiments, such as conductance enhancement due to the Kondo effect including the gate-voltage dependence (See, for instance, [7, 8] for recent applications of the method to conductance through a carbon nanotube dot.)

By the help of the nonequilibrium Green function formalism, we can write down spin current $I_{\sigma}$ and spin-dependent conductance $G_{\sigma} = I_{\sigma}/V_{\text{bias}}$ by

$$I_{\sigma} = \frac{-2e}{h} \int d\varepsilon \left[ T_b + T_{1\sigma}(\varepsilon) \right] [f_L(\varepsilon) - f_R(\varepsilon)].$$  

(6)

Spin current $I_{\sigma}$ is composed of the two contributions: the one comes from the background transmission through the arm $T_b = 4\xi/(1 + \xi)^2$, and the other, from the exact retarded Green function of the dot $G_{dd}^R$,

$$T_{1\sigma}(\varepsilon) = T_b \Gamma \text{Im} \left[ (1 + i q_{\sigma})(1 + i q_{\sigma}^*) G_{dd\sigma}^R(\varepsilon) \right].$$  

(7)

Here we have introduced the spin-dependent Fano parameter $q_{\sigma} = \sqrt{\xi}(e^{i\phi_{\sigma}} - \xi e^{-i\phi_{\sigma}})/2\sqrt{\xi}$ with $\xi = 4\pi^2 \rho_L \rho_R |V_{RL}|^2$. Finite $U$ slave-boson mean field theory enables us to evaluate the exact Green function $G_{dd}^R$ approximately, whose renormalized counterpart $\tilde{G}_{dd}^R$ takes a Fermi-liquid form.
3. Results and discussion

Characteristics of energy scale renormalized by the Rashba interaction
We first identify the characteristic energy scale of the system by the inverse of the renormalized Green function, 

\[ T^*(\phi_{so}) = \left| G^{R,0}_{dd}(0) \right|^{-1} \]

which we use as a criteria for how the Kondo physics is relevant. Like in the AB interferometer, it is shown that the Rashba interaction renormalizes substantially \( T^* \), providing noticeable \( \phi_{so} \) dependence.

Generating spin transport by finite bias voltage
In Fig. 2, we present how finite bias voltage induces spin-dependence of conductance (right), while such spin-dependence is absent in the linear response regime (left). We set \( \phi_{so} = \pi/4 \) to have a relatively large spin filtering effect. One observes that finite bias voltage \( V_{bias} \) causes conductance to get spin-dependent only for singly-occupied region \( (\varepsilon_d = 0 \sim U) \). Unlike previous studies [3], however, we see that further large \( V_{bias} \) does not necessarily produce larger spin dependence. There is an optimal value of \( V_{bias} \), which corresponds roughly to \( eV_{bias} \sim 0.6T^*(\phi_{so}) \). These features strongly suggest that the phenomena is due to the Kondo physics.

Temperature dependence of spin conductance
Further To examine the nature of this spin-dependent transport, we examine its temperature evolution (see Fig. 3). One sees the spin dependence of conductance \( \Delta G = G_\uparrow - G_\downarrow \) get reduced with increasing \( T \). We interpret it as another evidence that spin transport is controlled by the Kondo effect, which higher temperature reduces such effect. The result indicates that electrical spin filtering by the present mechanism is possible at temperature lower than the Kondo temperature.

4. Conclusion
We have shown that, even for a single-level dot, spin dependent transport can occur as a result of an intertwining effect of the Rashba-type spin-orbit interaction, Coulomb interaction, and finite bias voltage. The phenomena can be regarded as a truly “nonequilibrium strong correlation effect” because either non-interacting dot or linear conductance does not exhibit such behavior. We have also argued that the phenomena is closely connected with the Kondo physics, and either too large bias voltage or temperature suppresses such spin-dependent transport. This clearly contrasts with previous studies that exhibit larger spin dependence by applying larger bias voltage.
Figure 3. $\Delta G = G_1 - G_1$ as a function of the gate voltage $\varepsilon_d$ by varying $T$. Other parameters are the same as in Fig. 2.

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