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Kondo-type transport through an interacting quantum dot coupled to ferromagnetic leads

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Abstract

We investigate the equilibrium and out-of-equilibrium Kondo effects in a single-level interacting quantum dot connected to two ferromagnetic leads. Within the noncrossing approximation, we calculate the total density of states (DOS), the linear conductance and the nonlinear differential conductance for both the parallel and the antiparallel alignments of the spin polarization orientation in the leads, followed by a brief discussion regarding the validity of this approach. Numerical calculations show that, for the antiparallel alignment, a single Kondo peak always appears in the equilibrium DOS, resulting in conventional temperature behaviour in the linear conductance and the zero-bias maximum in the differential conductance. The strength of the DOS peak is gradually suppressed with increasing polarization, due to the fact that formation of the Kondo-correlated state is more difficult in the presence of higher polarization. In contrast, for the parallel configuration the Kondo peak in the DOS descends precipitately and splits into two peaks to form a very steep valley between them. This splitting contributes to the appearance of a 'hump' in the temperature-dependent linear conductance and a nonzero-bias maximum in the differential conductance. Moreover, application of a bias voltage can split each Kondo peak into two in the nonequilibrium DOS for both configurations. Finally we point out that the tunnel magnetoresistance could be an effective tool to demonstrate the different Kondo effects in the different spin configurations found here.

1. Introduction

The discovery of the Kondo effect in a quantum dot (QD) connected to two normal reservoirs has stimulated much experimental and theoretical interest in this many-body phenomenon [1],

resulting in several novel findings, such as the splitting of the Kondo peak under nonequilibrium conditions [2], an unusual enhancement of conductance in the cases when an even number of electrons resides in a QD [3, 4] and double peaks of the differential conductance in coupled double QDs [5, 6]. Recently, increasing attention has been paid, because of its potential application in magnetoelectronics and quantum computing [7], to the spin-polarized electron tunnelling through systems consisting of two ferromagnetic (FM) leads sandwiched by a QD, which features a significant Kondo effect at low temperatures when it connects to normal leads. Generally speaking, the Kondo resonance in the density of states (DOS) at the Fermi energy originates from screening of the dot spin due to exchange coupling with the conduction electrons. Therefore it is interesting to observe whether the Kondo-correlated state can form when the conduction band is of spin polarization and, if so, what is the difference from the conventional patterns.

In a recent paper, Sergueev *et al* [8] and Zhang *et al* [9] presented a theoretical analysis of the transport characteristics of such a FM/QD/FM system, using the ansatz proposed by Ng [10] and the standard equation-of-motion (EOM) technique for the retarded Green function. They found that there is always a sharp single Kondo resonant peak in nonlinear differential conductivity at zero bias, regardless of the polarization orientation of the two leads, parallel (P) or antiparallel (AP) configurations. In contrast, Martinek *et al* [11] reported a markedly different result for similar systems, based also on an EOM technique and an additional assumption to replace the bare level of QD in the resultant self-energy expression with the one self-consistently determined. They found that, for P alignment of the lead magnetizations, the Kondo resonances in the DOS split for spin-up and -down electrons. Thus the differential conductance exhibits a nonzero-bias maximum and the linear conductance drops to a low value even with the polarization being as small as 0.2. Later on, Lü and Liu [12] also reported a similar splitting by applying Ng's ansatz. López and Sánchez [13] and Ma *et al* [14] employed, respectively, the infinite- U slave-boson mean-field (SBMF) approach and the finite- U SBFM approach [15, 16] to investigate the spin-polarized transport of this system and found drastically different behaviours depending on the polarization alignment of the two leads. By using the numerical renormalization group method, Choi *et al* [17] addressed the fact that the expected splitting appears in the regime of charge fluctuations but disappears in the presence of sole spin fluctuations. In view of the ongoing controversy, further analysis of the influence of spin polarization on the Kondo-correlated state in a QD is desirable, preferably based on more advanced schemes.

In this paper, we employ the noncrossing approximation (NCA) based on the auxiliary boson technique to carry out a detailed analysis of the FM/QD/FM Kondo problem. The NCA is a diagrammatic technique to sum all the noncrossing diagrams in the leading order $|V|^2/N$ (where V is the hopping matrix element between the local electron and conduction electrons and N is the number of the spin degeneracy of the local level) [18]. It is proved to be an accurate approach for the case of $N = 2$ (of interest for a QD), even under out-of-equilibrium conditions [19–21]. For a symmetric FM/QD/FM system considered in the present paper, although the individual QD is exactly spin-degenerate, the spin-polarized leads can lift this degeneracy in the case of P alignment through the tunnelling-induced spin-related self-energies. However, if the spin polarization strength p of the two leads is small enough, the self-energies are of weak spin dependence and, as a consequence, the NCA should be adequate to treat this system. Actually, we calculate the equilibrium and nonequilibrium transmissions for the FM/QD/FM system with a polarization strength as low as $p = 0.2$ for the P configuration. Numerical results show a complete splitting for the equilibrium transmission (DOS) and a nonzero-bias maximum for the voltage-dependent differential conductance, which are in qualitative agreement with those of Martinek [11] and Lü [12].

The rest of the paper is organized as follows. In section 2 we describe the model Hamiltonian and give a brief description of applications of the infinite- U NCA to the spin-dependent transport in FM/QD/FM systems, as well as a qualitative discussion about its validity. In section 3 numerical computations and discussions are presented, including the equilibrium and out-of-equilibrium DOS, the linear conductance and the nonlinear differential conductance, for both the P and the AP polarization configurations. Finally, all the results are summarized in section 4.

2. Model and formulation

The system Hamiltonian for a QD with a single spin-degenerate energy level ϵ_d ($N = 2$) connected to two ferromagnetic leads is written as

$$H = \sum_{\eta,k,\sigma} \epsilon_{\eta k\sigma} c_{\eta k\sigma}^\dagger c_{\eta k\sigma} + \epsilon_d \sum_{\sigma} c_{d\sigma}^\dagger c_{d\sigma} + U n_{d\uparrow} n_{d\downarrow} + \sum_{\eta,k,\sigma} (V_{\eta\sigma} c_{\eta k\sigma}^\dagger c_{d\sigma} + \text{h.c.}), \quad (1)$$

where $c_{\eta k\sigma}^\dagger$ ($c_{\eta k\sigma}$) and $c_{d\sigma}^\dagger$ ($c_{d\sigma}$) are the creation (annihilation) operators for electrons with momentum k and spin σ in the lead η ($=L, R$) and for a spin- σ electron on the QD, respectively. The third term describes the Coulomb interaction among electrons on the QD, which is assumed to be infinite ($U \rightarrow \infty$) in the present paper, forbidding double occupancy. The fourth term represents the tunnelling coupling between the QD and the reservoirs via

$$\Gamma_{\sigma}^{\eta}(\omega) = 2\pi \sum_k |V_{\eta\sigma}|^2 \delta(\omega - \epsilon_{\eta k\sigma}), \quad (\eta = L, R). \quad (2)$$

In the wide band limit, Γ_{σ}^{η} is assumed to be constant. For identical leads and symmetric barriers, of interest in the present investigation, the ferromagnetism of the leads can be accounted for by the polarization-dependent couplings $\Gamma_{\uparrow}^L = \Gamma_{\uparrow}^R = (1+p)\Gamma_0$ and $\Gamma_{\downarrow}^L = \Gamma_{\downarrow}^R = (1-p)\Gamma_0$ for the P alignment, with $\Gamma_{\uparrow}^L = \Gamma_{\downarrow}^R = (1+p)\Gamma_0$ and $\Gamma_{\downarrow}^L = \Gamma_{\uparrow}^R = (1-p)\Gamma_0$ for the AP alignment. Γ_0 and p ($0 \leq p < 1$) describe the tunnelling coupling between the QD and the nonmagnetic leads and the polarization strength of the leads. Under this approximation, the current I through the QD can be expressed in terms of the total transmission $\mathcal{T}(\omega)$ as [22]

$$I = \frac{e}{\hbar} \int d\omega [f_L(\omega) - f_R(\omega)] \mathcal{T}(\omega), \quad (3)$$

where

$$\mathcal{T}(\omega) = \sum_{\sigma} \frac{\Gamma_{\sigma}^L \Gamma_{\sigma}^R}{\Gamma_{\sigma}^L + \Gamma_{\sigma}^R} \rho_{\sigma}(\omega), \quad (4)$$

with $\rho_{\sigma}(\omega) = -(1/\pi) \text{Im} G_{\sigma}^r(\omega)$ being the DOS for spin- σ electrons. $G_{\sigma}^r(\omega)$ is the Fourier transform of the retarded Green function:

$$G_{\sigma}^r(t) = -i\theta(t) \langle c_{\sigma}(t), c_{\sigma}^{\dagger}(0) \rangle. \quad (5)$$

The main purpose of this work is to calculate the DOS $\rho_{\sigma}(\omega)$ as a function of temperature T , bare-level energy ϵ_d and bias voltage V for different polarization configurations and strengths p and the associated linear and nonlinear conductance.

According to the infinite- U slave-boson approach, the ordinary electron operators on the QD can be decomposed into a boson operator b and a pseudo-fermion operator f_{σ} :

$$\begin{aligned} c_{d\sigma}(t) &= b^{\dagger}(t) f_{\sigma}(t), \\ c_{d\sigma}^{\dagger}(t) &= f_{\sigma}^{\dagger}(t) b(t), \end{aligned} \quad (6)$$

with a constraint for the auxiliary operators $b^\dagger b + \sum_\sigma f_\sigma^\dagger f_\sigma = 1$. In the slave-boson representation, the Hamiltonian (1) for the FM/QD/FM systems becomes

$$H = \sum_{\eta,k,\sigma} \epsilon_{\eta k\sigma} c_{\eta k\sigma}^\dagger c_{\eta k\sigma} + \epsilon_d \sum_\sigma f_\sigma^\dagger f_\sigma + \sum_{\eta,k,\sigma} (V_{\eta\sigma} c_{\eta k\sigma}^\dagger b^\dagger f_\sigma + \text{h.c.}). \quad (7)$$

In order to evaluate the DOS $\rho_\sigma(\omega)$, Wingreen and Meier [20] generalized the NCA to study the nonequilibrium properties of the Anderson model connected with two normal conduction bands, using the Keldysh nonequilibrium Green function formalism. It is well known that the NCA is a self-consistent conserving perturbation expansion for the pseudo-fermion and slave-boson self-energies to first order in the effective coupling $J = |V|^2$. At the lowest order in perturbation diagrams the boson self-energy involves the bare fermion propagator while the fermion self-energy involves the bare boson propagator. By replacing these bare propagators with the dressed auxiliary particle propagators in the Feynman diagram, one can obtain a set of coupled integral equations, which self-consistently determine the self-energies of these auxiliary particles. Solving these coupled equations is equivalent to summing up a subset of diagrams to all orders in J . Furthermore, it can be proved that the NCA includes all diagrams of leading orders in $1/N$ [18]. Therefore, the NCA is expected to be a quantitative approach in the limit of large N . For a QD connected with normal leads, $N = 2$, it is already proved to be satisfactory in qualitatively describing the linear and nonlinear Kondo-type transport [20, 21].

Unfortunately, when the level degeneracy is broken, the NCA could produce spurious peaks in the DOS and thus is unreliable for transport investigation. For example, as mentioned by Wingreen [20], the NCA without vertex corrections produces an additional Kondo peak at the chemical potential in a finite magnetic field due to a false self-interaction of each level, whereas other methods find that the Kondo peak splits into two peaks. Similarly, the NCA without vertex corrections seems also to be inappropriate for the FM/QD/FM systems, because spin-related tunnelling lifts the level degeneracy in the QD. However, the present situation is somewhat different from magnetotransport. The degeneracy lifting is evident in the presence of a magnetic field, while it is dependent on the relative polarization orientation of the two leads and, of course, the strength of polarization for the FM/QD/FM systems.

When the polarization orientations of the two FM leads is antiparallel, the self-energies are actually independent of spin and the degeneracy remains as 2 for the case of the identical leads and symmetric barriers. On the other hand, for the P configuration spin-related tunnelling results in the self-energies to be different for spin-up and -down electrons. However, it is natural that the deviation depends on the polarization strength p . Namely, the NCA could still be reliable for the FM/QD/FM systems with small enough p . Numerical calculations in the next section show that the conventional Kondo peak in DOS indeed splits completely into two peaks at the polarization $p = 0.2$ for the P configuration. Even though one can observe an additional peak located at the chemical potential but an order of magnitude smaller than the two real Kondo peaks, these results are in agreement with previous predictions [11]. Consequently, this convinces us that the NCA provides an appropriate description for the symmetric FM/QD/FM systems in either the AP alignment with arbitrary polarizations or the P configuration with weak polarizations. Of course, this scheme's validity being dependent on the polarization p should be carefully checked, for example, by the modified NCA including vertex corrections. This, however, entails numerically a much heavier task than the original NCA and is beyond the scope of the present paper. We leave this examination to a future publication.

We outline the formulation employed in this paper as follows. The interested reader can refer to [20] and [21] for details. In the slave-boson representation, the retarded Green functions for the boson and pseudo-fermions are defined as

$$D^r(\omega) = \frac{1}{\omega - \Pi^r(\omega)}, \quad (8)$$

$$G_{f\sigma}^r(\omega) = \frac{1}{\omega - \epsilon_d - \Sigma_{f\sigma}^r(\omega)}, \quad (9)$$

with the corresponding retarded self-energies $\Pi^r(\omega)$ and $\Sigma_{f\sigma}^r(\omega)$. Furthermore, the ‘lesser’ Green functions for the boson and fermions are related to the ‘lesser’ self-energies $\Pi^<(\omega)$ and $\Sigma_{f\sigma}^<(\omega)$ as

$$D^<(\omega) = D^r(\omega)\Pi^<(\omega)D^a(\omega), \quad (10)$$

$$G_{f\sigma}^r(\omega) = G_{f\sigma}^<(\omega)\Sigma_{f\sigma}^<(\omega)G_{f\sigma}^a(\omega). \quad (11)$$

The self-consistent NCA equations for out-of-equilibrium are

$$\Pi^r(\omega) = \sum_{\eta=L,R,\sigma} \frac{\Gamma_\sigma^\eta}{2\pi} \int d\varepsilon f(\varepsilon - \omega - \mu_\eta) G_{f\sigma}^r(\varepsilon), \quad (12)$$

$$\Sigma_{f\sigma}^r(\omega) = \sum_{\eta=L,R} \frac{\Gamma_\sigma^\eta}{2\pi} \int d\varepsilon f(\varepsilon - \omega + \mu_\eta) D^r(\varepsilon), \quad (13)$$

$$\Pi^<(\omega) = \sum_{\eta=L,R,\sigma} \frac{\Gamma_\sigma^\eta}{2\pi} \int d\varepsilon f(\varepsilon - \omega + \mu_\eta) G_{f\sigma}^<(\varepsilon), \quad (14)$$

$$\Sigma_{f\sigma}^<(\omega) = \sum_{\eta=L,R} \frac{\Gamma_\sigma^\eta}{2\pi} \int d\varepsilon f(\varepsilon - \omega - \mu_\eta) D^<(\varepsilon), \quad (15)$$

where $f(x) = [\exp(\beta x) + 1]^{-1}$ (with $\beta = 1/k_B T$) is the Fermi distribution function and μ_η is the chemical potential of the η lead. After solving this set of self-consistent equations, the imaginary part of the retarded local Green function, the DOS $\rho_\sigma(\omega)$, can be calculated within the NCA as

$$\rho_\sigma(\omega) = \frac{1}{Z} \int \frac{d\varepsilon}{2\pi} [D^<(\varepsilon) \text{Im} G_{f\sigma}^r(\varepsilon + \omega) + G_{f\sigma}^<(\varepsilon) \text{Im} D^r(\varepsilon - \omega)], \quad (16)$$

where

$$Z = \int d\varepsilon \left[D^<(\varepsilon) + \sum_\sigma G_{f\sigma}^<(\varepsilon) \right]. \quad (17)$$

Finally we can use equations (3) and (4) to calculate the current through the QD.

3. Numerical results and discussions

3.1. Density of state

In this section we present numerical calculations and discussions. First, we deal with the total equilibrium and out-of-equilibrium DOS (transmission) equation (4) for the FM/QD/FM systems with a fixed bare-level energy $\epsilon_d = -4.0$ (Γ_0 is used as the energy unit throughout the rest of the paper). It is worth noting that the systems considered here belong to the deep Kondo regime and are appropriate to demonstrate the strong correlated effects.

Figure 1(a) shows the total DOS in the AP configuration for several different polarizations $p = 0, 0.2$ and 0.4 as well as various temperatures $T = 0.01, 0.02$ and 0.04 . Clearly, a significant Kondo peak remains at the Fermi energy (which is chosen to be the energy zero) under the addition of the spin-polarized leads. The contribution of spin-polarized leads is to suppress both the Kondo peak and the single-particle excitation peak (see the overall shapes of the DOS in the inset of figure 1). This suppression is more pronounced with increasing

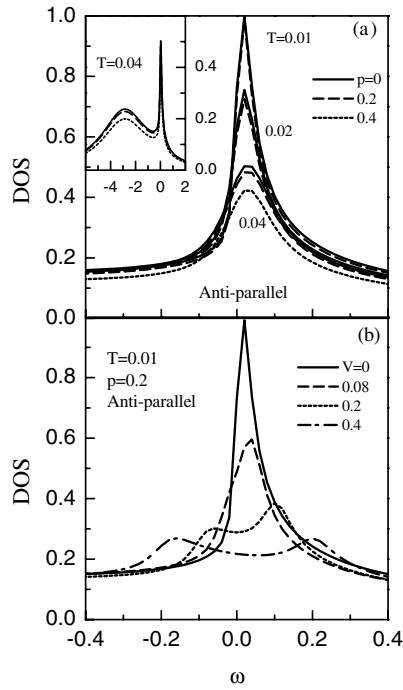


Figure 1. (a) The total equilibrium DOS $T(\omega)$ in the AP configuration for different temperatures $T/\Gamma_0 = 0.01, 0.02$ and 0.04 and different polarizations $p = 0, 0.2$ and 0.4 ; and (b) the nonequilibrium DOS for $T = 0.01$ and $p = 0.2$. The QD in the FM/QD/FM system has a single bare-level energy $\epsilon_d = -4.0$ and an infinite on-site Coulomb interaction $U \rightarrow \infty$.

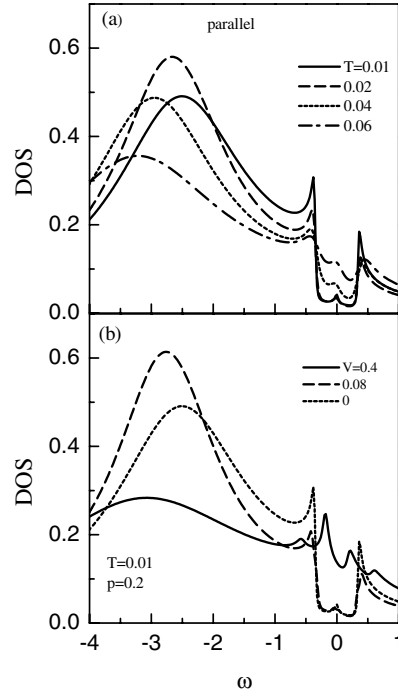


Figure 2. (a) The total equilibrium DOS in the P configuration for different temperatures $T/\Gamma_0 = 0.01, 0.02, 0.04$ and 0.06 ; and (b) the nonequilibrium DOS for $T = 0.01$ and $p = 0.2$. The system is the same as described in figure 1.

polarization p . These results are understandable with the aid of the following considerations. Suppose that in the extreme case of two completely spin-polarized leads $p = 1$, spin-down electrons are completely absent in the left lead, but electrons in the right lead are all spin-up and could provide compensation to screen the dot spin and to guarantee the formation of the Kondo-correlated singlet state. Thus the Kondo peak still exists with a reduced amplitude. Naturally, the cases of weak polarizations $p < 1$ are more likely to form the Kondo state. Note that increasing the temperature can broaden the peak and suppress the Kondo resonance as usual. In addition, effects of the external bias voltage on the out-of-equilibrium DOS are plotted in figure 1(b). For convenience, we choose a symmetric voltage drop such that the chemical potential $\mu_L = -\mu_R = eV/2$ for the left and right leads. As expected, we find a splitting of the Kondo peak with a width nearly equal to the bias voltage applied between the source and drain leads.

In short, the QD connected with two AP magnetized leads develops the same Kondo resonance as the QD with two normal leads, whereas the former is suppressed to some extent, depending on the polarization p . In contrast, the situation is drastically different for the P configuration as shown in figure 2, where we plot the total DOS for the polarization $p = 0.2$ with various temperatures (a) and bias voltages (b). It is clear that the P polarization significantly changes the DOS of the QD in comparison with the case $p = 0$. The Kondo resonance splits into two distinct peaks with different amplitudes. One moves from the original

location $\omega = 0$, the Fermi energies of the two leads, to a lower energy position, while the other shifts in the opposite direction at the expense of its height. Moreover the magnitudes of both Kondo resonances are largely suppressed by the introduction of spin polarization. We observe that there appears to be a remnant peak located at the Fermi energy, which is produced by the NCA calculation without vertex corrections as mentioned above. But its amplitude is one order smaller than the two shifted Kondo peaks and can be neglected. As a result, a very steep valley is found between the two peaks with a nearly vanished bottom. Finally we find that increasing the temperature can not only smooth and broaden the peaks as usual, but also raise the bottom of the deep valley gradually, which can result in a peculiar temperature dependence of the linear conductance, as shown in figure 3 (in the next subsection).

Figure 2(b) depicts the effects of changing bias voltage on the total DOS (transmission probability) for the same system as in figure 2(a). If we keep the temperature low, $T = 0.01$, and increase the bias voltage, the two resonances first experience suppression and then each of them splits into two distinct peaks. Each pair of peaks has a width about equal to the bias voltage. Increasing the temperature would eventually wash out the peak splitting and recover a single but much less pronounced peak in both equilibrium and out-of-equilibrium cases.

3.2. Linear and nonlinear conductance

In figure 3 we plot the calculated linear response conductance G versus $\log T$ for various polarizations $p = 0, 0.1, 0.15$ and 0.2 . In the AP configuration (thin curve in figure 3) the linear conductance G_{AP} exhibits the similar overall temperature dependence to those of nonmagnetic leads $p = 0$, though smaller in magnitude, resulting from the suppression of the Kondo resonance as addressed in figure 1(a). For the opposite orientation, the conductance G_P depends strongly on the polarization strength p and exhibits no universal T behaviour at low temperatures. Increasing p , G_P is largely suppressed first and develops a ‘hump’ as a function of temperature. This peak is due to the fact that the Kondo resonance is shifted away from the Fermi energy as shown in figure 2(a). To demonstrate the dramatic change of conductance under different polarization orientations, we plot the tunnel magnetoresistance (TMR) defined as $TMR = (G_P - G_{AP})/G_{AP}$ in the inset of figure 3. We find the TMR begins at a value as large as 100% at the lowest temperature calculated in this work and falls rapidly with increasing T , which can be attributed to the peculiar Kondo resonance in the P configuration. At high temperatures G_P approaches the value of nonpolarization $p = 0$, leading to a saturated and small positive linear TMR.

Figure 4 shows the linear conductance as a function of bare-level energy ϵ_d , which can be tuned via the external gate voltage, for nonpolarization $p = 0$, as well as the P and the AP configurations with $p = 0.2$. As expected, G_{AP} shows the same trend as that of nonpolarization though a smaller amplitude. The peak of G_P , however, shifts towards the Fermi energy. This means that the linear TMR changes its sign at a certain level energy and has approximately a symmetric shape around this point. Near the empty orbital regime $\epsilon_d \simeq 0$ and near the deep Kondo regime $\epsilon_d \simeq -4$, the linear TMR reaches its maximum value as large as 30% at the temperature $T = 0.1$.

Nonlinear differential conductance dI/dV is believed to be a very useful and sensitive tool in experiments to detect the formation of the Kondo-correlated state due to its proportionality to $T(eV)$ derived from the current formula equation (3), assuming that the total transmission $T(\omega)$ (nonequilibrium DOS) is unchanged under the external bias voltage V . So we illustrate in figure 5 the calculated dI/dV under the P (a) and the AP (b) configurations, as well as the nonlinear TMR (c) at various temperatures. As pointed out above, because electrons with spin-up and spin-down are equally available in the AP configuration, the formation of the

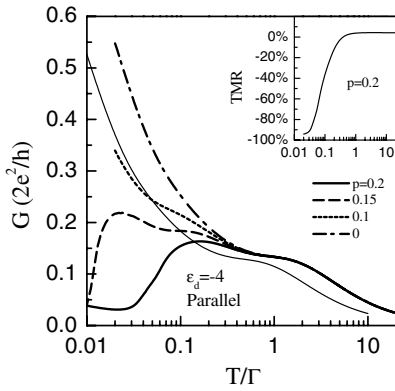


Figure 3. The linear conductance G versus temperature at different polarizations p for the same system as described in figure 1. The thick curves correspond to the results for the P alignment, while the thin curve is for the AP alignment at $p = 0.2$. Inset: the calculated TMR versus temperature for $p = 0.2$.

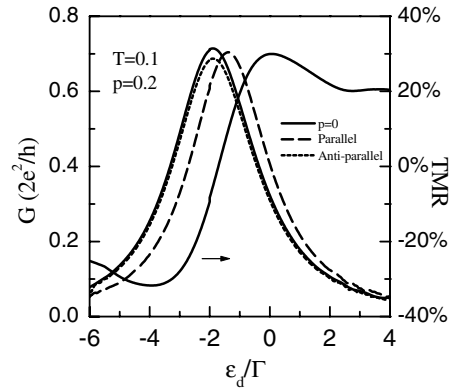


Figure 4. The linear conductance G and the TMR versus the bare-level energy of the QD at $T = 0.1$.

Kondo-correlated state should not be affected. As a result, all the curves in figure 5(b) exhibit a single zero-bias peak and rapid decrease in peak height with increasing temperature. When the magnetization is rotated to the P alignment, adding bias voltage can greatly enhance dI/dV at low temperatures. This is apparently due to the complete splitting of the Kondo peak in the DOS shown in figure 2. The nonzero-bias maximum in dI/dV is in good agreement with previous EOM calculations [11], except for the reduced width of splitting and the fine shape in the differential conductance. These inconsistencies can be attributed to the significant change of the nonequilibrium DOS with increasing bias voltage (see figure 2(b)). Furthermore, the nonlinear TMR displays a large dip in the linear regime and changes its sign at a certain bias voltage. This large change in the TMR versus bias voltage reflects the different behaviours of the Kondo resonance in the P and the AP configurations.

4. Summary

We have investigated the low-temperature, nonequilibrium properties of a spin-valve system consisting of a QD connected to two FM leads in the Kondo regime. Based on the NCA approach we find markedly different behaviours in the equilibrium DOS when changing the relative orientation of spin polarization. In the AP configuration, we find that a single Kondo peak always appears through the whole range of polarization $0 \leq p \leq 1$, just as in a QD connected to two normal leads. Increasing polarization p can slightly suppress the amplitude of the peak. In the P configuration, the Kondo peak decreases greatly and splits completely into two peaks even for a weak polarization as low as $p = 0.2$, leading to a steep valley with nearly a zero bottom. In both configurations the chemical-potential difference (the bias voltage) appears in the DOS via the splitting of the Kondo peak into two peaks. Thus four peaks can be found at a moderate bias voltage for the P alignment. Of course the amplitudes of these peaks are suppressed by increasing temperature.

Experimentally, we predict, based on the NCA investigation, that the different Kondo effects can be observed in transport through a QD by either linear or nonlinear measurements. For the AP configuration, the calculations exhibit the usual temperature dependence of the linear conductance and a zero-bias maximum in the nonlinear conductance, which are the

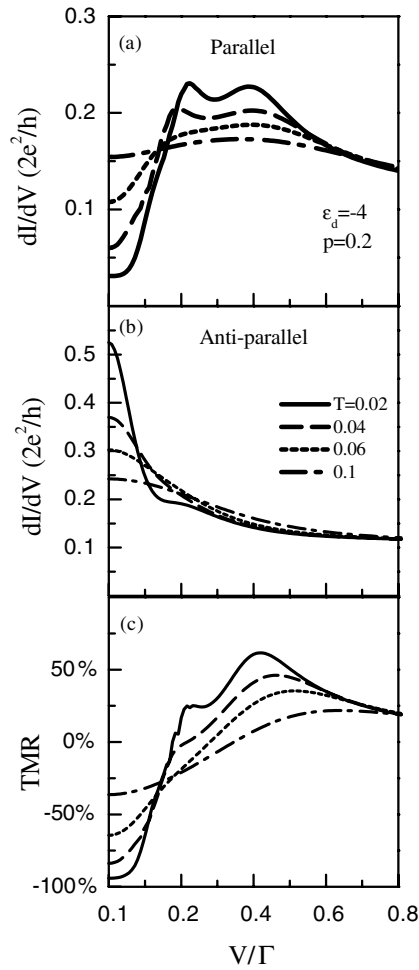


Figure 5. The differential conductance dI/dV versus the bias voltage eV at different temperatures $T = 0.02, 0.04, 0.06$ and 0.1 in the P (a) and the AP (b) configurations. (c) The nonlinear TMR versus the bias voltage.

conventional properties of Kondo-dominated transport through a QD. For the P configuration, however, we find a ‘hump’ in the temperature-dependent linear conductance and a nonzero-bias maximum in the differential conductance. These peculiar behaviours are associated with the fact that the Kondo peak of the QD is split and shifted away from the Fermi level in the case of the P alignment. Furthermore, we suggest that the TMR is a more effective tool to explore the different features of the Kondo resonance in different configurations.

Finally, we point out again the applicability of the NCA approach to the FM/QD/FM systems. No spin splitting in the case of the AP alignment guarantees that the NCA is a reliable approximation for quantities involving the DOS. For the P configuration our numerical results for the DOS show satisfactory agreement with previous EOM predictions in the case of weak polarization $p = 0.2$. Thus we believe that the self-consistent second-order perturbation approach provides some qualitative features of the Kondo effect in the DOS, as long as the polarizations of the leads are weak enough, which can serve to furnish a deeper understanding

of transport properties in FM/QD/FM systems. Advanced NCA studies containing vertex corrections are required to examine the validity of this approach. Work along this line is in progress.

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