Asymmetry-induced effects in Kondo quantum dots coupled to ferromagnetic leads

K P Wójcik, I Weymann and J Barnaś

1 Faculty of Physics, Adam Mickiewicz University, 61-614 Poznań, Poland
2 Institute of Molecular Physics, Polish Academy of Sciences, 60-179 Poznań, Poland

E-mail: weymann@amu.edu.pl

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Abstract
We study the spin-resolved transport through single-level quantum dots strongly coupled to ferromagnetic leads in the Kondo regime, with a focus on contact and material asymmetry-related effects. By using the numerical renormalization group method, we analyze the dependence of relevant spectral functions, the linear conductance and the tunnel magnetoresistance on the system asymmetry parameters. In the parallel magnetic configuration of the device the Kondo effect is generally suppressed due to the presence of an exchange field, irrespective of the system's asymmetry. In the antiparallel configuration, on the other hand, the Kondo effect can develop if the system is symmetric. We show that even relatively weak asymmetry may lead to suppression of the Kondo resonance in the antiparallel configuration and thus give rise to nontrivial behavior of the tunnel magnetoresistance. In addition, by using the second-order perturbation theory we derive general formulas for the exchange field in both magnetic configurations of the system.

1. Introduction

The transport properties of nanoscopic objects, such as quantum dots or molecules, tunnel coupled to external leads have attracted a lot of attention from both the theoretical and the experimental side [1–6]. This is mainly due to possible applications in nanoelectronics and spintronics, and due to the unique possibility to study various many-body correlation effects between single charges and spins. When the coupling between the quantum dot and the external leads is relatively strong, the electronic correlations may lead to the Kondo effect if the dot’s occupation number is odd [7–10]. For quantum dots coupled to ferromagnetic leads, on the other hand, it has been shown that the Kondo resonance can be suppressed due to the presence of an effective exchange field, $\Delta \varepsilon_{\text{exch}}$, that leads to the spin splitting of the quantum dot level [11–19]. This suppression occurs if the magnetic moments of the external leads form a parallel (P) magnetic configuration and when $|\Delta \varepsilon_{\text{exch}}| \gtrsim T_K$, where $T_K$ is the Kondo temperature and $\Delta \varepsilon_{\text{exch}}^{P}$ denotes the level splitting due to the exchange field in the parallel configuration [15].

For an antiparallel magnetic configuration of the device, the exchange field was found to vanish, $\Delta \varepsilon_{\text{exch}}^{AP} \rightarrow 0$, since the effective coupling to external leads then becomes spin independent [12, 13, 15, 20]. This is, however, true only for fully symmetric systems, while, as we show in this paper, for systems exhibiting some asymmetry, either left–right contact asymmetry or the material’s asymmetry, the exchange field may also develop in the antiparallel configuration. Since experimentally it is very difficult to build a truly symmetric device, it seems desirable to analyze the effects of contact and material asymmetry on the spin-resolved transport properties of quantum dots.

In this paper we thus thoroughly study the transport through quantum dots coupled to ferromagnetic leads in the Kondo regime, focusing especially on asymmetry-induced effects. To obtain the correct picture, we employ Wilson’s numerical renormalization group (NRG) method [21–23] with
Figure 1. A schematic of a single-level quantum dot coupled to left and right ferromagnetic electrodes. The magnetizations of the electrodes are assumed to be collinear and they can form either a parallel (P) or an antiparallel (AP) magnetic configuration, as indicated in the figure. The dot is coupled to the left and right leads with the coupling strengths $\Gamma_{r,\sigma}$ ($r = L, R$). The dot level has energy $\varepsilon_d$ and $U$ denotes the Coulomb correlation on the dot.

the idea of a full density matrix (fDM) [24]. By using
NRG, we calculate the dependence of relevant spin-resolved
spectral functions, the linear conductance in the parallel and
antiparallel configurations, and the tunnel magnetoresistance
(TMР) on the asymmetry between the couplings to the
left and right leads and for different spin polarizations
of the electrodes. We show that even relatively small
asymmetry may fully suppress the Kondo resonance in the
antiparallel configuration, leading to nontrivial dependence
of the TMР effect on the asymmetry parameters. We also
show that although asymmetry generally destroys the Kondo
effect in the antiparallel configuration, there is a range of
asymmetry parameters where the Kondo resonance can be
restored. In addition, by using the second-order perturbation
theory, we derive general formulas for the exchange field in
both magnetic configurations depending on the asymmetry
parameters.

2. Theoretical description

The system consists of two ferromagnetic leads coupled to
a single-level quantum dot, see figure 1. The magnetizations
of the leads are assumed to be collinear and they can form two
different magnetic configurations: the parallel (P) and antiparallel (AP)
oneS. Switching between different magnetic configurations of
the device can be obtained by sweeping the hysteresis
loop, provided the left and right ferromagnets have different
coercive fields. The system considered can be described by the
single-impurity Anderson Hamiltonian

$$
H = \sum_{r=L,R} \sum_{k,\sigma} \epsilon_{r,k,\sigma} a_{r,k,\sigma}^\dagger a_{r,k,\sigma} + \varepsilon_d \sum_{\sigma} n_{\sigma} + U n_{\uparrow} n_{\downarrow} \\
+ \sum_{r=L,R} \sum_{k,\sigma} \left( V_{r,k,\sigma} a_{r,k,\sigma}^\dagger d_{\sigma} + \text{h.c.} \right),
$$

(1)

where $a_{r,k,\sigma}^\dagger$ creates an electron with spin $\sigma$, momentum $k$
and energy $\epsilon_{r,k,\sigma}$ in the left ($r = L$) or right ($r = R$) lead.
The energy of the dot level is denoted by $\varepsilon_d$. $U$ describes
the Coulomb interaction of two electrons residing on the dot and

$$
n_{\sigma} = d_{\sigma}^\dagger d_{\sigma} \quad \text{is the particle number operator, with } d_{\sigma}^\dagger \text{ creating a}
$$

spin-$\sigma$ electron on the dot. The last term of the Hamiltonian
(1) describes the tunneling processes between the dot and
the ferromagnetic electrodes, with the $V_{r,k,\sigma}$ being the relevant
hopping matrix elements. Due to the coupling to the external
leads, the dot level acquires a certain width, which is described
by the spin-dependent hybridization function, $\Gamma_{r,\sigma} = \pi \rho V_{r,\sigma}^2$
for lead $r$ and spin $\sigma$. Here, $\rho$ is the density of states at the
Fermi level and we assume that $V_{r,k,\sigma}$ is independent of the
momentum $k$ [12, 13]. The conduction bands of the leads
are assumed to be energy and spin independent, $\rho = 1/(2W)$,
where $W \equiv 1$ is used as the energy unit. These assumptions
are justifiable since we are interested in the Kondo regime which
is mainly related with the conduction electron states around
the Fermi level. Next, by introducing the spin polarization
of lead $r$, $p_r = (\Gamma_{r,\uparrow} - \Gamma_{r,\downarrow})/(\Gamma_{r,\uparrow} + \Gamma_{r,\downarrow})$, the couplings can be
expressed as $\Gamma_{r,\sigma} = (1 + \sigma p_r) \Gamma_r$, with $\Gamma_r = (\Gamma_{r,\uparrow} + \Gamma_{r,\downarrow})/2$.
Here, $\Gamma_{r,\sigma}$ denotes the coupling to the spin-majority ($\sigma = \uparrow$) or
spin-minority ($\sigma = \downarrow$) conduction band of the ferromagnetic
lead $r$. For convenience, we have incorporated the effect
of the leads’ ferromagnetism in the spin-dependent tunnel
matrix elements. This assumption is commonly used in NRG
calculations [12, 20].

The asymmetry-induced effects to be studied in this paper
will include the left–right contact asymmetry, $\Gamma_L \neq \Gamma_R$,
and the material asymmetry, i.e. different spin polarizations
of the leads, $p_L \neq p_R$. In particular, we will study how the
linear-response transport properties depend on the parameters
of the system, especially on the coupling ratio $\Gamma_R/\Gamma_L$
and spin polarization ratio $p_R/p_L$. The linear-response spin-dependent
conductance of the system can be found from the
Meir–Wingreen formula [25],

$$
G_\sigma = \frac{e^2}{4} \frac{4 \Gamma_L \sigma \Gamma_{R,\sigma}}{\Gamma_L + \Gamma_{R,\sigma}} \int d\omega \left( -\frac{\partial f(\omega)}{\partial \omega} \right) \pi A_\sigma(\omega),
$$

(2)

where $f(\omega)$ denotes the Fermi function and $A_\sigma(\omega)$ is the
spectral function of the dot level. The spectral function is
given by $A_\sigma(\omega) = -\frac{1}{\pi} \text{Im} G^R_\sigma(\omega)$, where $G^R_\sigma(\omega)$ is the Fourier
The spin dependence of the effective couplings gives rise to the exchange field $\Delta \epsilon_{\text{exch}}$, which can be found analytically by calculating second-order corrections $\delta \delta_{\text{exch}}$ to the energy of the quantum dot levels. $\Delta \epsilon_{\text{exch}} \equiv \delta \delta_{\downarrow \uparrow} - \delta \delta_{\uparrow \downarrow}$. At low temperature, one then gets for the parallel and antiparallel magnetic configurations

$$\Delta \epsilon_{\text{exch}}^{\parallel \uparrow} = \frac{2}{\pi} \beta^{\parallel \uparrow} \rho \Gamma \ln \frac{\epsilon_d}{\epsilon_d + U}.$$  

There are actually two factors that determine the strength of the exchange field. The first one, $\sim \ln |\epsilon_d/(\epsilon_d + U)|$, is related to the gate voltage, which can be used to change the position of the dot level. This factor leads to the cancelation of $\Delta \epsilon_{\text{exch}}^{\parallel \uparrow}$ at the particle–hole symmetry point of the model, i.e., $\epsilon_d = -U/2$, irrespective of the magnetic configuration and asymmetry. The second factor, $\sim \beta^{\parallel \uparrow}$, on the other hand, is associated with the asymmetry in the system and depends on the magnetic configuration, see equations (6) and (7). It may either increase or suppress the exchange field, depending on the magnetic configuration and parameters of the model.

As can be seen from equation (2), the main quantity to be calculated is the spin-resolved spectral function of the dot level. This is performed with the aid of the numerical renormalization group method with full density matrix (fDM–NRG). This method, known as the most powerful and versatile method to study various quantum impurity problems, allows us to determine the dependence of the spectral function on the parameters of the system in the most accurate and reliable way. The starting point for the NRG is logarithmic discretization of the conduction band of the leads and mapping of the initial Hamiltonian to the Hamiltonian of a tight-binding chain with exponentially decaying hoppings, the so-called Wilson chain [21]. The chain Hamiltonian is then solved in an iterative manner and its discarded eigenstates are used for the construction of a full density matrix [24], which enables the calculation of relevant static and dynamic quantities at arbitrary temperature. In our calculations we have, in particular, employed the flexible density matrix numerical renormalization group code [27]. In our calculations we kept 1024 states at each iteration and used the Abelian symmetries for the total spin $\mathbf{t}$th component and the total charge.

### 3. Results and discussion

In the following we present and discuss the numerical results for the linear conductance and spin polarization of the current in both magnetic configurations as well as the resulting TMR effect. First, we analyze the effects related to the contact asymmetry, $\Gamma_L \neq \Gamma_R$, and then the effects due to different spin polarizations of the left and right leads, $p_L \neq p_R$, are discussed. Finally, we present the general case when both asymmetries are present.

#### 3.1. The effects of left–right contact asymmetry, $\Gamma_L \neq \Gamma_R$

By changing the ratio $\Gamma_R/\Gamma_L$ one changes both the magnitude of the exchange field and the Kondo temperature. However,
the dependences of the two quantities on the strength of the coupling $G = G_L + G_R$ are different: While $|\Delta \varepsilon_{\text{exch}}| \sim \Gamma$, the Kondo temperature $T_K$ depends on $\Gamma$ in an exponential way \cite{28, 29}. $T_K = \sqrt{\Upsilon/2} \exp[\pi \varepsilon_d/(2U)]$ (for $p_L = p_R = 0$). Tuning the contact asymmetry ratio will thus change the ratio $|\Delta \varepsilon_{\text{exch}}|/T_K$, which conditions the occurrence of the Kondo effect, as discussed and presented in the following.

Figure 2 shows the linear conductance in the parallel and antiparallel configurations, as well as the resulting TMR effect as a function of the coupling ratio $\Gamma_R/\Gamma_L$ and the level position $\varepsilon_d/U$. Experimentally, the position of the dot level can be changed by tuning the gate voltage. When $\Gamma_R/\Gamma_L = 0$, the dot is coupled only to a single (left) lead and the conductance through the system is obviously equal to zero. On increasing the coupling to the right lead, the linear conductance becomes finite and exhibits a strong dependence on the level position. In the elastic cotunneling regime, i.e. for $|\varepsilon_d/\Gamma| \gg 1$ or $(\varepsilon_d + U)/\Gamma \ll 0$, the conductance in the parallel configuration is $G_P \sim (1 + p_L p_R) \Gamma_L \Gamma_R$, while for the antiparallel configuration one obtains $G_{AP} \sim (1 - p_L p_R) \Gamma_L \Gamma_R$, yielding $\text{TMR} = 2 p_L p_R / (1 - p_L p_R)$ \cite{20, 30}, which for the parameters assumed in figure 2 gives TMR $\approx 0.38$. Note that this value is independent of the coupling asymmetry, provided the current is mediated by elastic cotunneling events.

In the Coulomb blockade regime, on the other hand, the situation is more complex, since the dot is singly occupied and the electronic correlations may lead to the Kondo effect. Moreover, the occurrence of the Kondo effect is conditioned by the ratio of the Kondo temperature and the exchange field-induced splitting. In the parallel configuration, the exchange field is always present, irrespective of $\Gamma_R/\Gamma_L$, and the Kondo resonance is suppressed, except at the particle–hole symmetry point, $\varepsilon_d = -U/2$. By moving away from this point, the conductance drops once $|\Delta \varepsilon_{\text{exch}}| \gtrsim T_K$. Since $T_K$ depends on the coupling strength $\Gamma$, increasing $\Gamma_R/\Gamma_L$ raises the Kondo temperature, which leads to a larger width of the Kondo peak in the middle of the Coulomb blockade regime, see figure 2(a). In the antiparallel configuration, the exchange field vanishes if the system is symmetric, and there is a broad Kondo resonance in the whole local moment regime, see figure 2(b) for $\Gamma_R/\Gamma_L \approx 1$. Nevertheless, if $\Gamma_R/\Gamma_L \neq 1$, the Kondo effect becomes suppressed when $|\Delta \varepsilon_{\text{exch}}| \gtrsim T_K$. This happens faster for $\Gamma_R/\Gamma_L < 1$ than for $\Gamma_R/\Gamma_L > 1$, since for smaller coupling $\Gamma$ the Kondo temperature is lower and the above condition can be fulfilled for relatively small asymmetries of the couplings. As already mentioned, for the particle–hole symmetry point the exchange field vanishes in both magnetic configurations, see equation (9); the zero-temperature conductance is then just given by $G^{P/\text{AP}} = e^2/h \sum_n (\Gamma_L \Gamma_R) / (\Gamma_L + \Gamma_R)^2$, with the couplings correspondingly dependent on the magnetic configuration of the device. For symmetric couplings, $\Gamma_R/\Gamma_L = 1$, both $G^P$ and $G^{AP}$ reach the maximum, with $G^P = 2e^2/h$ and $G^{AP} = (1 - p_L p_R) 2e^2/h$. The respective behavior of the conductance in both magnetic configurations leads to the corresponding dependence of the TMR, which is shown in figure 2(c). Generally, the TMR is negative in the whole blockade regime, except at the particle–hole symmetry point, which is associated with the fact that $|\Delta \varepsilon_{\text{exch}}| > |\Delta \varepsilon_{\text{exch}}|$, and consequently $G^P < G^{AP}$. Only for $\varepsilon_d = -U/2$, when the exchange field is suppressed, does one find a typical spin-valve effect with positive tunnel magnetoresistance. Thus, by tuning the position of the dot level and the asymmetry factors, one can obtain a device with desired magnetoresistive properties.

Another quantity describing the spin-resolved transport properties of the system, interesting from an application point of view, is the spin polarization $p^P/\text{AP}$ of the current flowing through the device, which is shown in figures 3(c) and (f) for both magnetic configurations. The behavior of the spin polarization can be understood from the spin-resolved conductance. In the parallel magnetic configuration the coupling of the spin-up level is much stronger than the coupling of the spin-down level, since the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{The zero-temperature linear conductance in the parallel (a) and antiparallel (b) magnetic configurations and the resulting TMR (c) as a function of the level position $\varepsilon_d/U$ and the left–right coupling ratio $\Gamma_R/\Gamma_L$. The parameters are $U = 0.12W$, $\Gamma_L = 0.005W$ and $p_L = p_R = 0.4$, with $W \equiv 1$ the band’s halfwidth.}
\end{figure}
Figure 3. The spin-resolved linear conductance in the parallel ((a), (b)) and antiparallel ((d), (e)) magnetic configurations for the spin-up ((a), (d)) and spin-down ((b), (e)) channels, and the spin polarization of the current in the parallel (c) and antiparallel (f) configurations as a function of $\varepsilon_d/U$ and $0_R/0_L$. The parameters are the same as in figure 2.

spin-up electrons belong to the spin-majority band. As a consequence, the spin-up channel gives the main contribution to the conductance, see figures 3(a) and (b). The difference between $G^P\uparrow$ and $G^P\downarrow$ is most visible around the resonances, $\varepsilon_d \approx 0$ and $\varepsilon_d \approx -U$, where the spin polarization $P^P$ takes large positive values, approaching unity for $0_R/0_L \ll 1$. This is in contrast to the region around the particle–hole symmetry point where $G^P\uparrow \approx G^P\downarrow$ and the spin polarization is suppressed, $P^P \rightarrow 0$. In the antiparallel configuration the situation is slightly more complex, since the spin-resolved couplings depend greatly on the system’s asymmetry, see equation (5). For equal spin polarizations of the leads, $p_L = p_R$, as assumed in figure 3, one finds the effective couplings $\Gamma_{\sigma}^{\text{AP}} = \Gamma + \sigma p (0_L - 0_R)$. In consequence, the spin-resolved couplings fulfill the following relations: $\Gamma_{\sigma}^{\text{AP}} > \Gamma_{\sigma}^{\text{AP}}$ for $\Gamma_R/\Gamma_L < 1$, and $\Gamma_{\sigma}^{\text{AP}} < \Gamma_{\sigma}^{\text{AP}}$ for $\Gamma_R/\Gamma_L > 1$, with $\Gamma_{\sigma}^{\text{AP}} = \Gamma_{\sigma}^{\text{AP}}$ for the symmetric case, $\Gamma_L = \Gamma_R$. This gives rise to the corresponding behavior of the spin polarization: $P^{\text{AP}} \leq 0$ for $\Gamma_R/\Gamma_L \leq 1$, and $P^{\text{AP}} \approx 0$ for $\Gamma_R/\Gamma_L \approx 1$. In the region around $\varepsilon_d \approx -U/2$, where the effective field vanishes, the behavior of $P^{\text{AP}}$ is, however, different. The spin-dependent conductances are then given by $G_{\sigma}^{\text{AP}} = 4e^2/h (1 + p^2) (\Gamma_R/\Gamma + \sigma p (\Gamma_L - \Gamma_R))^2$, which yields negative spin polarization, $P^{\text{AP}} \leq 0$, for $\Gamma_R/\Gamma_L < 1$, and positive spin polarization, $P^{\text{AP}} > 0$, for $\Gamma_R/\Gamma_L > 1$. Note that this is exactly opposite to the case when the exchange field is present, i.e. $\varepsilon_d \neq -U/2$. The above analysis clearly demonstrates that by properly engineering the couplings between the dot end electrodes, and by tuning the occupancy of the dot with the gate voltage, one can obtain desired spin polarizations of the flowing current, spanning almost the whole range from $-1$ to $1$.

From an experimental point of view, it may be important to know how large the asymmetry should be to suppress the Kondo resonance in the antiparallel configuration. To address this question, in figure 4 we plot the linear conductance as a function of $\Gamma_R/\Gamma_L$ for different values of the coupling $\Gamma_L$. Since $T_K$ depends exponentially on $\Gamma$, changing $\Gamma_L$ corresponds to a huge change in the Kondo temperature (note that $T_K$ also depends on $\Gamma_R/\Gamma_L$). On the other hand, the dependence of the exchange field on $\Gamma_L$ and the ratio $\Gamma_R/\Gamma_L$ is only algebraic. It can be seen that with decreasing $\Gamma_L$, the suppression of the Kondo effect occurs for smaller asymmetries, e.g. for very weak coupling even relatively small asymmetry between the left and right contacts can fully suppress the linear conductance in the antiparallel configuration. Proper and very careful implementation of a quantum dot/molecular device is therefore necessary in order to observe desired effects, such as, e.g., restoration of the Kondo effect when switching the magnetic configuration from the parallel to the antiparallel one [15].
Figure 4. The linear conductance in the antiparallel configuration as a function of the left–right contact asymmetry $\Gamma_R/\Gamma_L$ for different values of the coupling to the left lead $\Gamma_L$ for $p_L = p_R = 0.4$. Each line corresponds to a different value of $\Gamma_L$, increasing in the direction indicated by the arrow from $\Gamma_L = 0.0025W$ to $\Gamma_L = 0.0075W$ in steps of 0.0005W. The thick black line corresponds to $\Gamma_L = 0.005W$, the value used in previous figures. The parameters are the same as in figure 2, with $\epsilon_d = -U/3$.

3.2. The effects of different spin polarizations of the leads, $p_L \neq p_R$

Up to now we have focused on the asymmetry related to the left–right contacts; however, asymmetry can be also present if the electrodes have different spin polarizations, $p_L \neq p_R$. The corresponding transport characteristics are shown in figure 5 for equal couplings $\Gamma_L = \Gamma_R$ and different spin polarization ratios $p_R/p_L$, with $p_L = 0.4$. The maximum value, $p_R/p_L = 2.5$, corresponds to a fully spin-polarized right lead, while $p_R/p_L = 0$ corresponds to a nonmagnetic right electrode. Now, by changing $p_R/p_L$, one can tune the magnitude of the exchange field, while the relevant Kondo temperature is constant. Generally, with increase of the ratio $p_R/p_L$, the average spin polarization increases, and so does the exchange field. This intuitive behavior is, however, only valid for the parallel magnetic configuration and is nicely visible in figure 5(a). It can be seen that $G^P$ displays a Kondo resonance at the particle–hole symmetry point, whose width decreases with increasing strength of the exchange field, i.e. with increase of the ratio $p_R/p_L$. In the antiparallel configuration, on the other hand, the exchange field is a nonmonotonic function of $p_R/p_L$: it is maximum for $p_R = 0$, vanishes for $p_R = p_L$, and again reaches a local maximum for $p_R = 1$. Consequently, $G^{AP}$ displays the Kondo effect in the whole Coulomb blockade regime when $p_L \approx p_R$, which becomes then suppressed with change of the material asymmetry ratio from the point $p_R/p_L = 1$, see figure 5(b). Moreover, it can be seen that the Kondo resonance around $\epsilon_d = -U/2$ is now broader than in the case of the parallel configuration since, generally, $|\Delta \epsilon^{AP}_{\text{exch}}| > |\Delta \epsilon^{P}_{\text{exch}}|$. The different dependences of $G^P$ and $G^{AP}$ on the spin polarization ratio $p_R/p_L$ are reflected in nontrivial behavior of the TMR effect, see figure 5(c). The TMR is positive in the whole elastic cotunneling regime and is given by the Julliere value, while it takes large negative values in the local moment regime for $p_R/p_L \approx 1$ when $\text{TMR} \rightarrow -1$, and becomes again positive in the middle of the Coulomb blockade regime.

The spin polarization of the conductance in both magnetic configurations as a function of the level position and the leads’ spin polarization ratio $p_R/p_L$ is shown in figure 6. In the parallel configuration, the dependence of $G^P$ is quite intuitive: the spin polarization increases with increase of the average spin polarization $p$, i.e. increase of $p_R/p_L$, and reaches unity for $p_R \rightarrow 1$, since then the right electrode supports only spin-up electrons. Finite spin polarization is mainly due to the presence of an exchange field. Consequently, in the middle of the Coulomb blockade regime the spin polarization is suppressed, because $\Delta \epsilon^{P}_{\text{exch}} \rightarrow 0$. In the antiparallel configuration, the spin polarization changes sign with increase of the ratio $p_R/p_L$. When $p_L > p_R$, there are more spin-up tunneling processes than spin-down ones and
the spin polarization is positive, while for $p_L < p_R$, the sign of $\mathcal{P}_{\text{exch}}^{\text{AP}}$ is determined by the majority band of the right lead (spin-down electrons), therefore $\mathcal{P}_{\text{exch}}^{\text{AP}} < 0$, reaching $-1$ for $p_R \to 1$. On the other hand, once $p_R \approx p_L$, the spin polarization vanishes since the resultant couplings to spin subbands are comparable.

3.3. The effects of both contact and material asymmetry, $\Gamma_L \neq \Gamma_R$ and $p_L \neq p_R$

From our discussion it follows that asymmetry can destroy the Kondo resonance in the antiparallel configuration if $|\Delta \epsilon_{\text{exch}}^{\text{AP}}| \gtrsim T_K$. However, it turns out that even if there is an asymmetry in the system, either related to the contacts or to the material, there is a parameter range where the exchange field can still vanish in the antiparallel configuration. This happens precisely when the condition (8) is met, so that $\Gamma_L^{\text{AP}} = \Gamma_R^{\text{AP}}$. Figure 7 shows the dependence of the linear conductance in the antiparallel magnetic configuration as a function of the relevant asymmetry parameters, i.e. $p_R/p_L$ and $\Gamma_R/\Gamma_L$, for $\epsilon_d = -U/3$. Away from the particle–hole symmetry point, $\epsilon_d \neq -U/2$, the presence and the strength of the exchange field are conditioned by the system's asymmetry parameters, see equation (9). For $p_R/p_L \to 0$, the conductance $G^{\text{AP}}$ behaves similarly to that for the parallel configuration, since then trivially there is only one magnetic electrode.

The conductance is then generally suppressed and starts to increase only for $\Gamma_R/\Gamma_L > 1$, when the Kondo temperature increases, so that the condition $|\Delta \epsilon_{\text{exch}}^{\text{AP}}| \gtrsim T_K$ is only weakly met or even not met. For $p_R/p_L > 0$, the case becomes much more interesting, since for certain asymmetry parameters one finds an increased conductance due to the Kondo effect. This happens when the condition (8) is satisfied, as presented by a dashed line in figure 7. The exchange field increases as one moves away from this line. The width of the restored Kondo resonance increases with increasing $\Gamma_R/\Gamma_L$, since a larger asymmetry is then needed to suppress the Kondo effect, which occurs for $|\Delta \epsilon_{\text{exch}}^{\text{AP}}| \gtrsim T_K$.

4. Conclusions

In this paper we have studied the Kondo effect in quantum dots asymmetrically coupled to ferromagnetic leads. The calculations were performed with the aid of the numerical renormalization group method. In particular, we have determined the dependence of the linear conductance in different magnetic configurations of the device, the TMR and the current spin polarization on the contact and material asymmetry parameters. For a quantum dot symmetrically coupled to external leads, the conductance in the parallel configuration is suppressed due to the presence of an exchange field, while in the antiparallel configuration the exchange field is absent. On the other hand, when the dot is coupled asymmetrically to the leads, we have shown that an exchange field can also develop in the antiparallel configuration. If the magnitude of the exchange field-induced level splitting is larger than the Kondo temperature, the Kondo effect becomes suppressed, which may occur even for a relatively small asymmetry between the couplings to the left and right leads. This leads to a nontrivial dependence of the tunnel magnetoresistance on the asymmetry parameters. In addition, we have demonstrated that even if the system is asymmetric, there is a range of parameters in the antiparallel configuration where the exchange field can still vanish. We have also derived
approximate analytical formulas for the exchange field in both magnetic configurations depending on the asymmetry parameters.

In conclusion, the presented analysis shows that by properly tuning the parameters of the system, one can, in principle, construct a magnetoresistive device with desired properties, including a source of spin-polarized electrons with basically any designed spin polarization. Moreover, very careful fabrication of the sample seems inevitable if one wants to observe suppression and restoration of the Kondo effect by changing the magnetic configuration of the device.

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