Spin-dependent transport through an interacting quantum dot system*

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Using an equation of motion technique, we report on a theoretical analysis of transport characteristics of a spin-valve system formed by a quantum dot coupled to ferromagnetic leads, whose magnetic moments are oriented at an angle θ with respect to each other, and a mesoscopic ring by the Anderson Hamiltonian. We analyse the density of states of this system, and our results reveal that the density of states show some noticeable characteristics depending on the relative angle θ of magnetic moment M, and the spin-polarised strength P in ferromagnetic leads, and also the magnetic flux Φ and the number of lattice sites $N_{\rm R}$ in the mesoscopic ring. These effects might have some potential applications in spintronics.

Keywords: Kondo effect, spin-polarised transport, density of states

PACC: 7335, 7335C, 7225

1. Introduction

Since the giant magnetoresistance (GMR) effect was discovered,[1] there has been aroused a lot of interest in the spin-dependent electron transport through systems consisting of two ferromagnetic (FM) layers coupled to a nonmagnetic structure of different types, including insulator,[2] semiconductor quantum well,[3] carbon nanotube,[4] and composite structure.[5,6] Recently, FM/QD/FM system has attracted much extensive theoretical and experimental attention. Different from the previously studied nonmagnetic structure, a quantum dot (QD) features the characteristics induced by the strong electronic correlation which are sensitive to the relative orientation of magnetisation between the two electrodes in it, for example, not only the Coulomb blockade can dominate its electronic transport, but also, particularly, a significant Kondo effect may arise when it connects to normal leads, exhibiting zero-bias maximum in the differential conductance in the case where odd number of electrons occurs. So it is interesting to see what happens when the normal metal leads are replaced by ferromagnetic leads.

2. Model and solution

In this paper, we use the equation of motion (EOM) technique to study the spin-polarised transport through a QD coupled to ferromagnetic leads and a mesoscopic ring as shown in Fig. 1. The magnetic moment M of the left FM leads is pointing to the z direction, the electric current flows in the x direction, while the moment of the right FM leads is at an angle θ to the z axis in the y-z plane. Our results show that the Kondo resonance at the Fermi level of the dot is modulated, not only by the relative angle θ and the spin polarised strength P of the two magnetic moments, but also by the magnetic flux Φ and the number of lattice sites $N_{\rm R}$ in the mesoscopic ring.

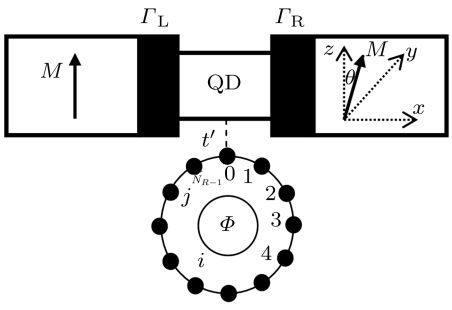


Fig. 1. Schematic of QD system considered in our work where QD is coupled by a mesoscopic ring and two magnetic leads through the tunneling barriers. The magnetic moments of the leads are oriented at an angle θ with respect to each other, and the QD-leads couplings are denoted as $\Gamma_{\rm L}$ and $\Gamma_{\rm R}$.

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Here the Hamiltonian of our coupled system is decomposed into the three parts, i.e.

$$H = H_0 + \sum_{\alpha=\mathrm{L,R}} H_\alpha + H_\mathrm{T}, \tag{1}$$

where H_0 is the Hamiltonian term for the dot-ring system, H_α describes the left (L) and the right (R) leads respectively, and H_T accounts for the tunneling between the QD and the two leads. H_0 is decomposed into

$$H_0 = H_\mathrm{QD} + H_\mathrm{ring} + H_{\mathrm{t}'} \tag{2}$$

where H_QD, H_ring, and $H_{\mathrm{t}'}$ represent Hamiltonians of the QD, the mesoscopic ring, and the tunneling interaction between the ring and the dot, respectively. The ring is described by an ideal one-dimensional tight-binding model with N_R lattice sites. Those Hamiltonians are expressed as

$$H_\mathrm{QD} = \sum_\sigma \varepsilon_{d\sigma} d_\sigma^+ d_\sigma + U n_{d,\sigma} n_{d,\sigma-}, \tag{3a}$$

$$H_\mathrm{ring} = -t \sum_{j=0}^{N_\mathrm{R}-1} \sum_\sigma (\,\mathrm{e}^{\,\mathrm{i}2\pi\phi/N_\mathrm{R}} c_{j+1,\sigma}^+ c_{j,\sigma} + \mathrm{H.c}), \tag{3b}$$

$$H_{\mathrm{t}'} = -t' \sum_\sigma (d_\sigma^+ c_{0\sigma} + c_{0\sigma}^+ d_\sigma), \tag{3c}$$

where t denotes the hopping integral between the neighbouring sites; QD, which has a much small size compared with the ring, can be described by a spin-degenerate single level with a strong on-site Coulomb repulsion U; $\varepsilon_{d\sigma}$ is the single-particle energy; H_ring can be diagonalised with the eigenvalues $\varepsilon_m = -2t\cos[(1/N_\mathrm{R})(2\pi m + \varphi)]$, with m being an integer within the interval $[0,\, N_\mathrm{R}-1]]$ and $\varphi = 2\pi\Phi/\Phi_0$, and Φ and $\Phi_0 (= hc/e)$ being the magnetic flux and the flux quantum, respectively. At the site '0' of the ring, electrons are allowed to hop to the dot or vice versa. These processes are characterised by a tunnel-matrix element t'. The two leads are described by the corresponding reservoirs, consisting of noninteracting electrons with the single particle energies $\varepsilon_{k\alpha} (\alpha = \mathrm{L,R})$,

$$\sum_{\alpha=\mathrm{L,R}} H_\alpha = \sum_{k\sigma\alpha} \varepsilon_{k\sigma\alpha} a_{k\sigma\alpha}^+ a_{k\sigma\alpha}, \tag{4}$$

and the difference between the chemical potentials is proportional to the applied voltage V, i.e. $\mu_\mathrm{L} - \mu_\mathrm{R} = \mathrm{eV}$. Finally, the tunneling between the QD and the reservoirs is written as

$$H_\mathrm{T} = \sum_{k\sigma} \Big[V_{\mathrm{L}k\sigma} a_{\mathrm{L}k\sigma}^+ d_\sigma + V_{\mathrm{R}k\sigma} \Big(\cos\frac{\theta}{2} a_{\mathrm{R}k\sigma}^+ - \sigma \cdot \sin\Big(\frac{\theta}{2} a_{\mathrm{R}k\sigma-}^+\Big)\Big) d_\sigma + \mathrm{H.c.}\Big], \tag{5}$$

where the tunneling matrix elements $V_{\mathrm{L(R)}k\sigma}$ transfer electrons out of the dot through an insulating barrier. The total Hamiltonian is transformed to the following form by using the diagonalized basis of H_ring as

$$\begin{aligned} H \;=\; & \sum_\sigma \varepsilon_{d\sigma} d_\sigma^+ d_\sigma + U n_{d,\sigma} n_{d,\sigma-} + \sum_{m\sigma} \varepsilon_m c_{m\sigma}^+ c_{m\sigma} \\ & + \sum_{m\sigma} (t_m d_\sigma^+ c_{m\sigma} + \mathrm{H.c.}) + \sum_{k\sigma\alpha} \varepsilon_{k\sigma\alpha} a_{k\sigma\alpha}^+ a_{k\sigma\alpha} \\ & + \sum_{k\sigma} \Big[V_{\mathrm{L}k\sigma} a_{\mathrm{L}k\sigma}^+ d_\sigma + V_{\mathrm{R}k\sigma} \Big(\cos\Big(\frac{\theta}{2} a_{\mathrm{R}k\sigma}^+\Big) \\ & - \sigma \cdot \sin\Big(\frac{\theta}{2} a_{\mathrm{R}k\sigma-}^+\Big)\Big) d_\sigma + \mathrm{H.c.}\Big], \end{aligned} \tag{6}$$

where $t_m = -t'/\sqrt{N_\mathrm{R}}$. In the model above, the operator $a_{k\sigma\alpha}^+ (a_{k\sigma\alpha})$ creates (annihilates) a conduction electron with spin index σ inside the α electrode. Similarly, $d_\sigma^+ (d_\sigma)$ is the creation (annihilation) operator of electrons with spin σ for the QD region. In our notations, for simplicity in the following we will consider that the values of molecular field M are the same for the two electrodes and the spin-valve effect can be obtained[7–9] by varying the angle θ. In reality, M refers to the difference in density of states (DOS) between spin-up ($\sigma = 1$) and spin-down ($\sigma- = -\sigma = -1$) electrons in the electrodes, and their DOSs are therefore different for different FM materials. Within the Keldysh formalism, the transport current $I = \sum_\sigma I_\sigma$ through a QD for $\Gamma_{\mathrm{R}\sigma}(\omega) = \lambda_\sigma \Gamma_{\mathrm{L}\sigma}(\omega)$ is[10]

$$\begin{aligned} I_\sigma \;=\; & \frac{e}{\hbar} \int \mathrm{d}\omega \frac{\Gamma_{\mathrm{L}\sigma}(\omega)\Gamma_{\mathrm{R}\sigma}(\omega)}{\Gamma_{\mathrm{L}\sigma}(\omega) + \Gamma_{\mathrm{R}\sigma}(\omega)} \\ & \times [f_\mathrm{L}(\omega) - f_\mathrm{R}(\omega)] \rho_\sigma(\omega), \end{aligned} \tag{7}$$

where $\Gamma_{\alpha\sigma}(\omega) = 2\pi \sum_k |V_{\alpha k\sigma}|^2 \, \delta(\omega - \varepsilon_{k\sigma\alpha})$ is the coupling strength between the QD level and the lead α; $f_\alpha(\omega) = 1/(\,\mathrm{e}^{\beta(\omega-\mu_\alpha)} + 1)$ is the Fermi function of lead α; μ_α the chemical potential of the αth lead, which is assumed to be in an equilibrium state at temperature $1/\beta$; $\rho_\sigma(\omega) = -(1/\pi)\,\mathrm{Im} G_\sigma^\mathrm{ret}(\omega)$ is the spectral DOS in the QD. The calculation of the current in Eq. (7) needs only the DOS in the QD, which can be obtained by using the EOM approach. We obtain the retarded dot Green function in the infinite-U limit as

$$G^r(\omega) = \frac{1- < n_{d\sigma-} >}{\omega - \varepsilon_d - \Sigma^r_{0\mathrm{L}} - \Sigma^r_{0\mathrm{R}} - \Sigma^r_{1\mathrm{L}} - \Sigma^r_{1\mathrm{R}} - \eta^r_0 - \eta^r_1 + \mathrm{i}0^+}. \tag{8}$$

Here

$$\Sigma^r_{0\mathrm{L}}(\omega) = \sum_k \frac{|V_{\mathrm{L}k\sigma}\,|^2}{\omega - \varepsilon_{k\mathrm{L}\sigma} + \mathrm{i}0^+}, \tag{9}$$

$$\Sigma^r_{0\mathrm{R}}(\omega) = \sum_k \left(\frac{\cos^2\frac{\theta}{2}}{\omega - \varepsilon_{k\mathrm{R}\sigma} + \mathrm{i}0^+} + \frac{\sin^2\frac{\theta}{2}}{\omega - \varepsilon_{k\mathrm{R}\sigma-} + \mathrm{i}0^+} \right) |V_{\mathrm{R}k\sigma}|^2, \tag{10}$$

$$\Sigma^r_{1\mathrm{L}}(\omega) = \sum_k \frac{\left|V_{\mathrm{L}k\sigma-}\right|^2 f_{\mathrm{L}}(\varepsilon_{k\mathrm{L}\sigma-})}{\omega - \varepsilon_{d\sigma} + \varepsilon_{d\sigma-} - \varepsilon_{k\mathrm{L}\sigma-} + \mathrm{i}/2\tau_{\sigma-}}, \tag{11}$$

$$\Sigma^r_{1\mathrm{R}}(\omega) = \sum_k \left(\frac{f_{\mathrm{R}}(\varepsilon_{k\mathrm{R}\sigma-})\cos^2\frac{\theta}{2}}{\omega - \varepsilon_{d\sigma} + \varepsilon_{d\sigma-} - \varepsilon_{kR\sigma-} + \mathrm{i}/2\tau_{\sigma-}} + \frac{f_{\mathrm{R}}(\varepsilon_{k\mathrm{R}\sigma})\sin^2\frac{\theta}{2}}{\omega - \varepsilon_{d\sigma} + \varepsilon_{d\sigma-} - \varepsilon_{k\mathrm{R}\sigma} + \mathrm{i}/2\tau_{\sigma-}} \right) |V_{\mathrm{R}k\sigma-}|^2, \tag{12}$$

$$\eta^r_{0\sigma}(\omega) = \frac{1}{N_{\mathrm{R}}} \sum_m \frac{t'^2}{\omega - \varepsilon_m + \mathrm{i}0^+}\,, \tag{13}$$

$$\eta^r_{1\sigma}(\omega) = \frac{1}{N_{\mathrm{R}}} \sum_m \frac{t'^2 f(\varepsilon_m)}{\omega - \varepsilon_{d\sigma} + \varepsilon_{d\sigma-} - \varepsilon_m + \mathrm{i}0^+}\,, \tag{14}$$

where the occupation number is subject to the self-consistency condition $\langle n_{d\sigma}\rangle = -\mathrm{i}\int (G^<_\sigma(\omega)/(2\pi))\mathrm{d}\omega$. And the finite life-time in Eq. (11) for finite bias voltage and magnetic field can be obtained by using the second-order perturbation theory.[11]

3. Results and discussion

In the following we focus on a small energy range around the Kondo peak. For our QD system, we calculate the DOSs at different polarisation angles θ (units set by $\hbar = e = 2m = 1$). As usual the spin dependence of the coherent transport can be conveniently considered by introducing magnetic polarisation factors P_{L} and P_{R} for the left and the right leads, respectively. $\Gamma^{\mathrm{L}}_{\uparrow(\downarrow)} = \Gamma_0(1 \pm P_{\mathrm{L}})$, and $\Gamma^{\mathrm{R}}_{\uparrow(\downarrow)} = \alpha\Gamma_0(1 \pm P_{\mathrm{R}})$. Γ_0 describes the coupling between the QD and the left electrode without internal magnetisation and α denotes the tunnel asymmetry between the left and the right leads. In this work we assume the leads to be symmetric, i.e. $\alpha = 1, P_{\mathrm{L}} = P_{\mathrm{R}} = P$.[12,13]

Figures 2(a)–2(e) show the spin-dependent DOSs for spin-up (solid line) and spin-down(dot line) for equilibrium case, calculated for different values of orientation angle θ versus energy ω. We can see that the Kondo resonance for each spin is clearly observed by a sharp peak around Fermi energy which is caused by the Kondo effect in DOS. From Fig. 2(a), when $\theta = 0$, namely, the magnetic moments of the two FM leads are parallel, the Kondo resonance for down-spin is enhanced, while the up-spin resonance is suppressed. Secondly, the broad single-particle resonances shift away from the Fermi level, but in the opposite directions for different spins. The down-spin shifts towards higher energy, while the up-spin shifts to lower energy, which is due to the splitting of the dot levels renormalized by the spin-dependent interacting self-energy $\tilde{\varepsilon}_{d\sigma}$ satisfying the self-consistent equation $\tilde{\varepsilon}_{d\sigma} = \varepsilon_d + \mathrm{Re}[\Sigma^r_{1\mathrm{L}}(\tilde{\varepsilon}_{d\sigma}, \tilde{\varepsilon}_{d\sigma-}) + \Sigma^r_{1\mathrm{R}}(\tilde{\varepsilon}_{d\sigma}, \tilde{\varepsilon}_{d\sigma-}) + \eta^r_{1\sigma}(\tilde{\varepsilon}_{d\sigma}, \tilde{\varepsilon}_{d\sigma-})]$.[14] And the inset in Fig. 2(a) shows the spin-dependent DOSs in the nonequilibrium case for spin up (solid line) and spin down(dot line). We set the chemical potentials $\mu_{\mathrm{L}} = 0, \mu_{\mathrm{R}} = 0.3\Gamma$. So a finite bias voltage, $\mu_{\mathrm{R}} - \mu_{\mathrm{L}} = eV > 0$ again leads to a splitting for each spin, and the peak heights are suppressed since the electrons dissipatively jump from the lead with high chemical potential to that with low potential through the QD. However, with the increase of θ, we find that the splittings of up- and down-spins moves towards the Fermi level respectively, i.e. the splitting of up-spin moves towards the right side, while that of down-spin electrons moves towards the left side. Furthermore, the amplitude of the DOS for up-spin electrons is enhanced as θ increases. In contrast, with the increase of θ, the peak of the DOS

for down-spin electrons are suppressed. When θ increases to π for which the moments are antiparallel (AP) (Fig. 2(e)), the behaviours of the DOS for up- and down-spins in leads are similar, which also has one sharp peak at the Fermi energy. In this situation, the DOSs for up-and down-spins in leads are the same, $\rho_{\rm L}\uparrow+\rho_{\rm R}\uparrow=\rho_{\rm L}\downarrow+\rho_{\rm R}\downarrow$, and the spin current of electrons cannot be polarised. In other word, under the condition of AP configuration, electrode effects on electrons in QD are fully counteracted. In Fig. 2(f), we plot the total DOSs at different polarisation angles θ as a function of ω. With the increase of θ from 0 to π, we can see that the Kondo resonance is degenerated from two peaks to only one peak since the splitting for each spin.

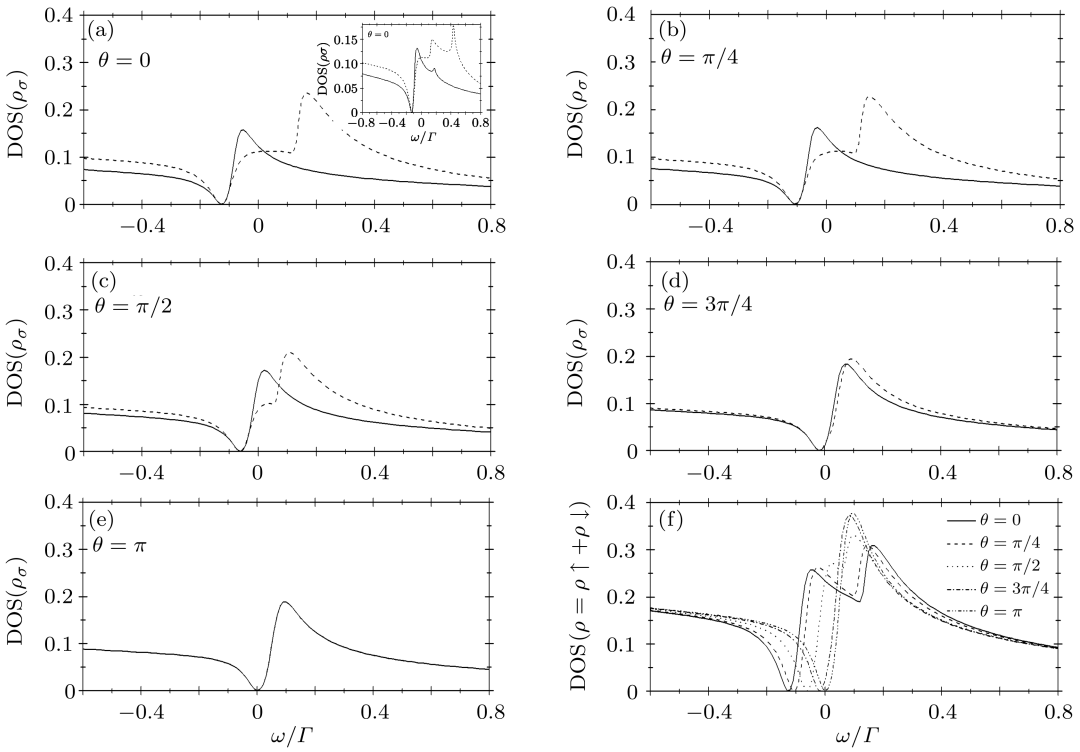


Fig. 2. (a)–(e): Spin-dependent DOS for spin-up(solid line) and spin-down(dot line) for equilibrium case ($\mu_{\rm L} = \mu_{\rm R} = 0$), calculated for orientation angles θ. (a) inset: DOS for nonequilibrium case ($\mu_{\rm L} = 0$, $\mu_{\rm R} = 0.3$), $\theta = 0$. (f) Total DOS for equilibrium case ($\mu_{\rm L} = \mu_{\rm R} = 0$) for different values of orientation angle θ. The other parameters are $P = 0.3$, $T/\Gamma = 0.005$, $\varepsilon/\Gamma = -4, N_{\rm R} = 52$, and $\varphi = 0$.

Figure 3 shows the total DOSs as a function of ω at different polarisations $P = 0$, 0.3, 0.5, 0.7 and 0.9 on two leads in parallel ($\theta = 0$) and in antiparallel ($\theta = \pi$) configurations. From Fig. 3(a) for parallel configuration, when $P = 0$ there is only one Kondo peak around the Fermi energy, and it splits into two Kondo resonances, which are away from the Fermi level respectively, as P increases. This result suggests that when $P \neq 0$ the up and down spin splittings of the dot levels in the interacting regime due to the magnetic properties of the electrodes lead to essential changes in transport property. In addition, as P increases, the spectral weight of $\rho_\downarrow$ goes up, while the spectral weight of $\rho_\uparrow$ comes down, namely, there is an overall asymmetry for up- and down-spins. Thus a net magnetic moment is induced by the magnetic coupling. So when $P \neq 0$ there are two peaks for total DOS. Compared with the behaviours shown in Fig. 3(a), in the case of antiparallel configuration ($\theta = \pi$) (Fig. 3(b)), the behaviours of the total DOS in leads are similar, in which also one sharp peak appears at the Fermi energy for each value of P. Because of the symmetry of two leads, in addition to the influence of the spin-polarisation strength, the rates of up-spin and down-spin in the QD are the same, resulting in zero net magnetic moment of the QD. This moment (i.e. the Kondo resonance) forms, which is the same as those for non-magnetic electrodes, and up-spin electrons make the same contributions to the transmission probability as down-spin electrons behave.

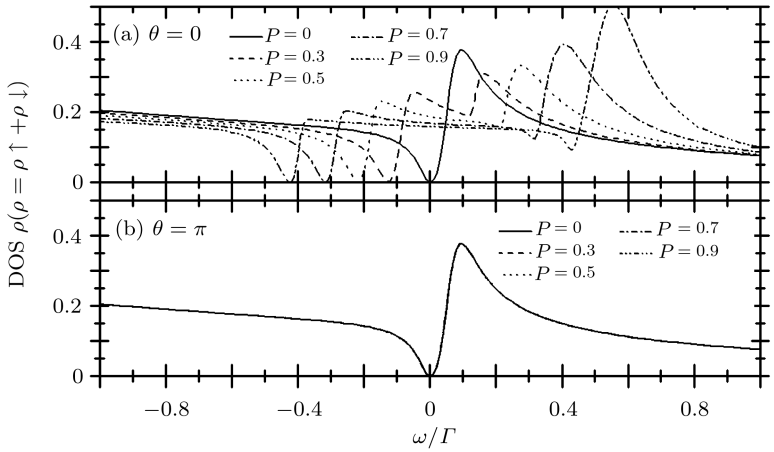


Fig. 3. Total DOSs versus ω for different values of spin polarisation P of the leads for equilibrium case ($\mu_{\rm L} = \mu_{\rm R} = 0$) and $\theta = 0$ (a), π (b). The other parameters are same as those used in Fig. 2.

In Fig. 4, we plot spin-dependent DOSs of the QD for up- and down- spins in the parallel configuration ($\theta = 0$), calculated for different values of phase φ and the number of lattice sites $N_{\rm R}$ in the mesoscopic ring. From Fig. 4, the Kondo resonance at the Fermi level is strongly dependent on magnetic flux and this resonance depends on $N_{\rm R}$ (for small sized rings $N_{\rm R} < 1000$) as well. Namely, the $\rho_\sigma(\omega)$ for a given $N_{\rm R}$ and φ satisfies the relation $\rho_{N_{\rm R}\uparrow(\downarrow)}(\omega, \varphi) \approx \rho_{N_{\rm R}+2\uparrow(\downarrow)}(\omega, \varphi + \pi)$. This result follows from the expression of the single particle energies of the ring: $\varepsilon_m = -2t\cos[(1/N)(2\pi m + \varphi)]$, because for large $N_{\rm R}(\gg 1)$, the configuration of the energy levels and its occupation near the Fermi level are invariant under the transformation $N_{\rm R} \to N_{\rm R}+2$ along with $\varphi \to \varphi + \pi$. Besides, It is worth mentioning that $\rho_\sigma(\omega)$ depends on $N_{\rm R4} \equiv N_{\rm R}$ modulo 4 for small sized rings ($N_{\rm R} < 1000$). The N_4 dependence of $\rho_\sigma(\omega)$ can be regarded as a generic feature of the system containing a mesoscopic ring with spin degree of freedom, as in the case of the persistent current.[15]

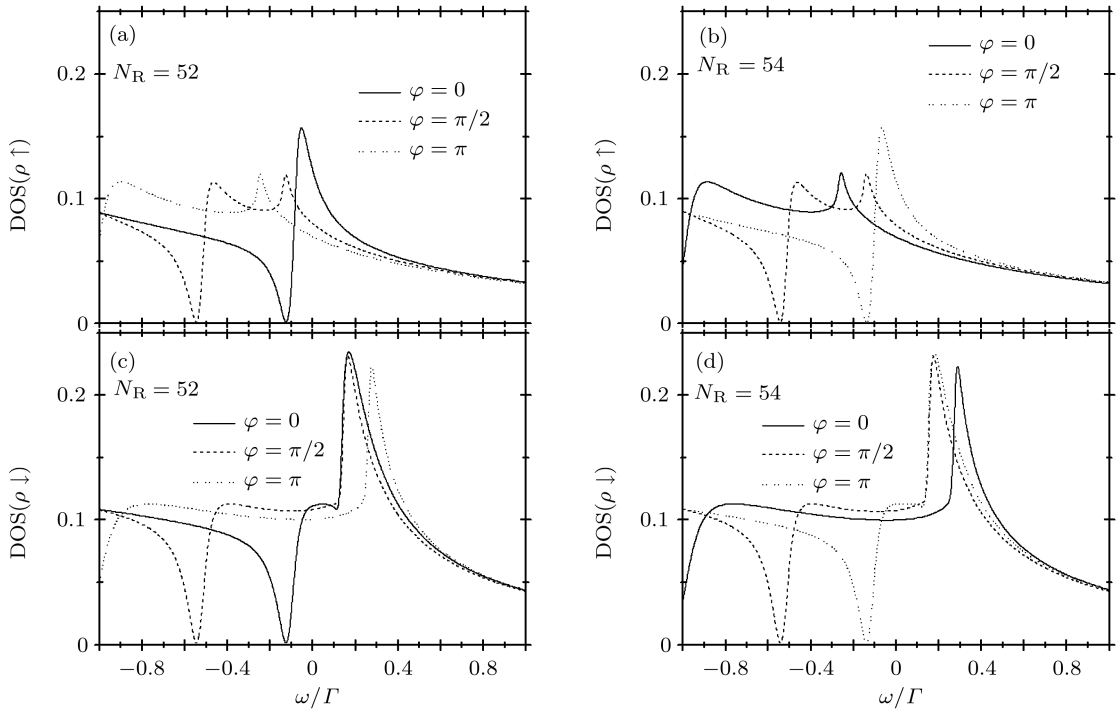


Fig. 4. Spin-dependent DOSs of QD for spin-up((a) and (b)) and spin-down((c) and (d)) in the parallel configuration ($\theta = 0$), calculated for different values of phase φ and number of lattice sites $N_{\rm R}$ in the mesoscopic ring. The other parameters are the same as those used in Fig. 2.

Figure 5 shows the $N_{\rm R}$ dependence of the DOS for the QD level in the absence of the AB flux. We can see that by reducing $N_{\rm R}$, the Kondo resonance is suppressed or split into two peaks with a pseudo-gap, depending on the value of N_4. Such effects are signatures of the destruction of the Kondo cloud, caused by the finite size of the ring.[15] And for large $N_{\rm R}$, the DOS is shown to be independent of $N_{\rm R}$ and φ as shown in the inset of Fig. 5(d), which implies that all the mesoscopic effects in transport disappear for large size rings. A similar feature was found in the study of a 'Kondo box',[16] which also shows a parity-dependent Kondo resonance.

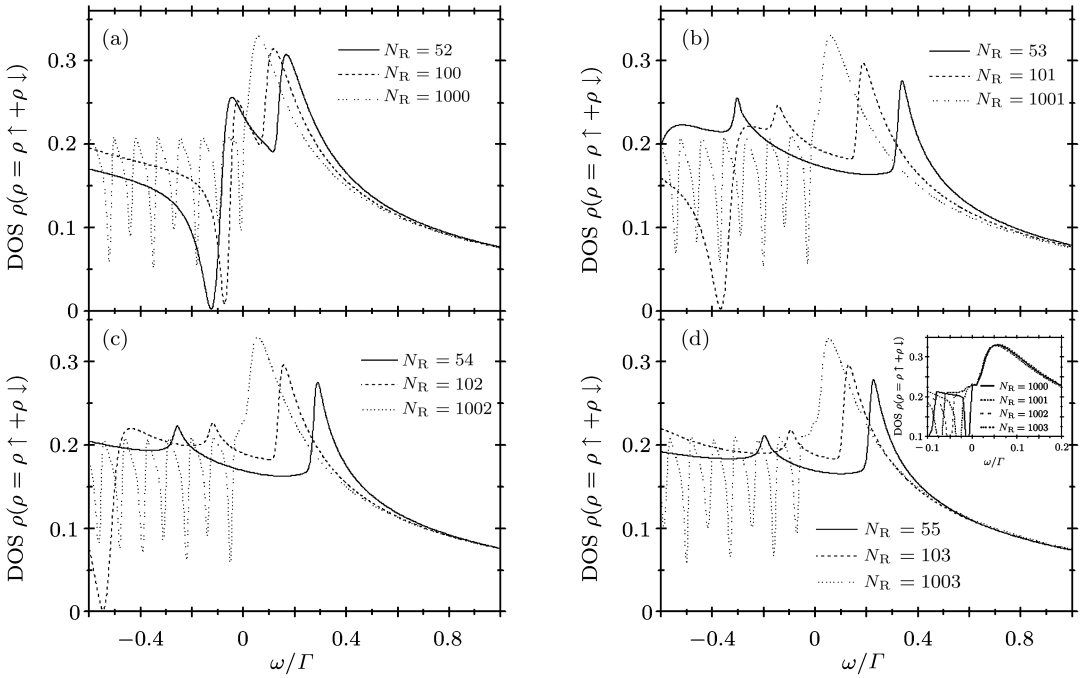


Fig. 5. Total DOSs of the QD level for $\varphi=0$, $\theta=0$ and the different values of $N_{\rm R}$ (modulo 4). The other parameters are the same as those used in Fig. 2.

4. Conclusion

Using the EOM technique we present a qualitative study of the spin-polarised transport in a QD coupled to ferromagnetic leads and a mesoscopic ring. Our results suggest that the Kondo peaks in the DOS can be modulated not only by the relative angle θ of magnetic moment M, the spin-polarised strength P in ferromagnetic leads, but also by the magnetic flux Φ and the number of lattice sites $N_{\rm R}$ in the mesoscopic ring. In a parallel configuration ($\theta=0$), the Kondo peaks for up- and down-spins are observed at the different levels. But by increasing the value of θ, the peaks turn close to each other. And when the value of θ increases to π, i.e. in an antiparallel configuration, the peaks are superposed completely. Secondly, the total DOSs at different values of polarisation P on two leads in parallel ($\theta=0$) and in antiparallel ($\theta=\pi$) configurations also have the dissimilar behaviours. Finally, our results show that the Kondo resonance at the Fermi level of the dot presents a periodic change along with the aggrandizement of the magnetic flux and the number of lattice sites $N_{\rm R}$ in the mesoscopic ring for small sized rings, which clearly demonstrates the mesoscopic nature of the Kondo scattering. But it implies that all the mesoscopic effects in transport disappear for large size rings. Based on the results above we believe that the system in our study is a good system for the experimental investigation of Kondo effect since it carries low spin-polarised current which can be controlled by polarisation, magnetic moment of the ferromagnetic leads, magnetic flux Φ and number of lattice sites $N_{\rm R}$ in the mesoscopic ring as well. It is expected that these effects might have some potential applications in spintronics.

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