Many-body Effects in Nanospintronics Devices

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The physics of nanostructures have extended the frontier of quantum mechanics and have realized several important quantum effects, such as the Kondo effect in quantum dot (QD), the Aharonov–Bohm (AB) effect, etc. Recent fabrication technique of magnetic nanostructures evolved the active research field "spintronics". The nanospintronics devices possess basic interests since they provide a way to control the spin degrees of freedom and realize novel many-body states.

We analyze the possibility of the Kondo effect in a QD coupled to two ferromagnetic leads. We show that for parallel alignment of magnetizations, the zero-bias anomaly is split. For antiparallel alignment and symmetric coupling, the Kondo resonance recovers and splitting is suppressed. We show that such anomalous behavior induces a negative large dip in the bias voltage dependence of the tunnel magnetoresistance.

We also theoretically investigate the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction between two semiconducting QDs embedded in an AB ring. In such a system, the RKKY interaction can be controlled by the flux and the flux-dependent RKKY interaction dominates the conductance. For the ferromagnetic coupling, the amplitude of AB oscillations is enhanced by the Kondo correlations. For the antiferromagnetic coupling, the phase of AB oscillations is shifted by π.

Discussed many-body effects, which were very recently demonstrated experimentally, can be utilized for future nanospintronics devices.

Key words: nanospintronics devices, Kondo effect, RKKY interaction, Aharonov–Bohm effect, nonequilibrium spin-dependent transport

I. Introduction

Recent fabrication technique for magnetic nanostructures has evolved the active research field, "spintronics", where the application and the basic physics interest are closely related with each other.[1] In such nanostructures, the magnetic structure affects significantly transport properties. For example, several 10% of the tunnel magnetoresistance (TMR) has been observed at room temperature for the spin-polarized tunneling between two ferromagnets throught an insulating barrier[2] or a vacuum barrier.[3] The TMR is associated with the change of configuration for two magnetizations between parallel (P) and antiparallel (AP) alignments. For certain metal and magnet multilayers, the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction between magnetic layers[4] dominates the magnetic structure of multilayers and consequently transport properties.[5] The interplay between the exchange coupling and the spin dependent transport is remarkable feature of the nanospintronics device physics.

The Kondo effect,[6] which is one of the most basic concepts in the field of magnetism similarly as the RKKY interaction, is also realized in a nanostructure so called quantum dot (QD).[7] The Kondo effect in QD possesses two remarkable features being impossible to realize in bulk systems. First, we can observe the Kondo effect for only one local spin. Second, it is easy to generate the nonequilibrium Kondo state by applying the source-drain bias voltage. Though semiconductor QDs are mainly adopted for the Kondo effect, recently, the Kondo effect was observed in novel kinds of QDs, single-atom[8] and single-molecule[9)–12] transistors. Especially, the Kondo effect is realized in a carbon nanotube coupled with superconducting leads.[12] They open a new direction for the exploration of the many-body effect in nanostructures. A problem of a local spin coupled with two ferromagnetic leads was originally discussed in ref. 13 to explain the anomalous decrease of TMR with increasing temperature or bias voltage observed universally in early experiments on ferromagnetic tunnel junctions. The problem was revived recently in the context of the Kondo effect mediated by spin-polarized itinerant electrons and a flood of related publications[14)–17] based on various approaches appeared in the last couple of years. In the section II, we will review our theoretical prediction for an experiment[12] and our recent developments on this topic.

As for the RKKY interaction, though it is well established for spintronics, surprisingly, the RKKY interaction acting between *two local spins* has been observed very recently in a semiconductor nanostructure.[18] Almost at the same time, we theoretically examined the possibility of the RKKY interaction between two semiconducting QDs embedded in an Aharonov–Bohm (AB) ring. In Section III, we will review our discussion.

II. Kondo Effect in Quantum Dot Coupled to Ferromagnetic Leads

A. Spin splitting of Kondo resonance

Because for a semiconductor QD or a single molecule QD, the strong Coulomb interaction suppresses *real* charge fluctuations, the QD with odd numbers of electrons behaves as a local spin 1/2. Such a local spin could couple antiferromagnetically with itinerant lead electron spins and thus induce the Kondo effect at low temperature, which reveals itself as the *zero bias anomaly* in the nonlinear differential conductance.

If two lead electrodes are spin-polarized and their magnetizations are parallel, we can show that the local spin inside the QD tends to align to the direction of magnetizations because of spin dependent virtual (*quantum*) charge fluctuations. We will explain the physics following ref. 15. In order to make the discussion simple, let us consider the case where a single level ε_0 inside QD is below the left (right) electrode Fermi energy, $\mu_{L(R)}$ but above the bottom of the band for lead electrons as shown in Fig. 1(a). Such a situation is typical for QDs. Furthermore, we assume that the Coulomb interaction U is infinity to forbid the double occupancy and thus only a single spin 1/2 is inside QD. In such a case, an electron with majority spin inside QD can gain the kinetic energy, because it can fluctuate between leads and the QD more than an electron with minority spin. Thus the majority spin is stabilized just in the same way in the case of the kinetic exchange interaction[19] and the spin degeneracy of QD level is lifted by the energy $\Delta\varepsilon$. The perturbative scaling analysis indicates

$$\Delta\varepsilon \sim P\frac{\Gamma}{\pi}\ln\frac{D}{|\varepsilon_0|}\,,\quad \Gamma=(\Gamma_\uparrow+\Gamma_\downarrow)/2\,, \tag{1}$$

where the coupling strength with left and right leads $\Gamma_\sigma=\Gamma_{L\sigma}+\Gamma_{R\sigma}$ is spin dependent, and D denotes the itinerant electron band width. The total spin polarization factor of ferromagnetic leads P is

$$P\equiv(\Gamma_\uparrow-\Gamma_\downarrow)/(\Gamma_\uparrow+\Gamma_\downarrow)\,. \tag{2}$$

The spin splitting suppresses the Kondo effect in a similar way as Zeeman splitting due to magnetic field. It quenches low energy spin flip scattering processes and thus effectively splits the Kondo resonance. Consequently, the zero bias anomaly is also split as schematically shown in Fig. 1(b).

However, the Kondo effect can be recovered by the compensation of the splitting by applying external magnetic filed. In this situation the Kondo temperature depends on the spin polarization factor as

$$k_B T_K \approx |\varepsilon_0|\exp\left\{-\frac{\pi|\varepsilon_0|}{\Gamma}\frac{\operatorname{arctanh}(P)}{P}\right\}. \tag{3}$$

It is maximal for nonmagnetic leads, $P=0$, and vanishes for $P\to 1$, which is reasonable, since for normal metal leads, we can expect the ordinary Kondo effect, and for half-metallic leads, the Kondo effect is obviously suppressed.

B. Nonlinear transport *via* Keldysh formalism and equation-of-motion technique

In this section, we review the nonlinear transport following ref. 15. We adopted the Keldysh non-equilibrium Green functions formalism using equation-of-motion (EOM) technique for calculation of Green functions. We assumed that the spin splitting can be taken into account by the self-consistent determination of the level self-energy accounting spin-dependent quantum charge fluctuations.

In Figs. 2 and 3 we plot the DOS of the QD for both spin components in the antiparallel (AP) and parallel (P) alignments, respectively, with spin polarization $P=0.2$ in the leads. In the AP alignment there is one Kondo resonance [Fig. 2(a)] and the DOS is the same as

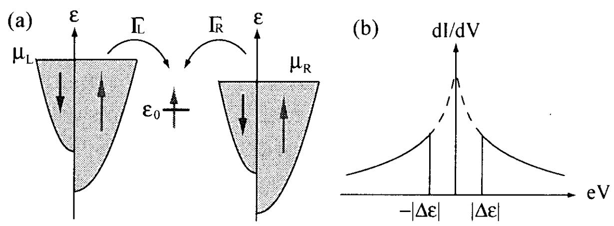

Fig. 1 (a) Energy diagram of a quantum dot (single site) coupled to two ferromagnetic leads. For parallel alignment, the up spin inside the dot is stabilized by the kinetic energy gain caused by spin-dependent quantum change fluctuations. (b) A schematic plot of the zero bias anomaly (dashed line). When the dot is coupled to ferromagnetic leads, because of the spin splitting, the zero bias anomaly effectively splits (solid line).

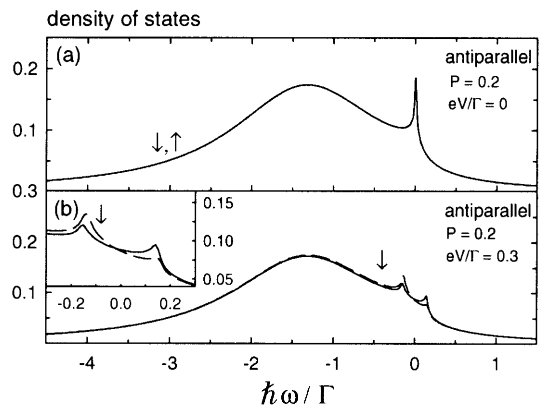

Fig. 2 Spin dependent DOS for spin up (solid line) and spin down (dashed), calculated for AP alignment, for the spin polarization of the leads $P=0.2$. The part (b) is the effect of an applied bias voltage V and the inset shows its magnification. The other parameters are: $k_BT/\Gamma=0.005$, $\varepsilon_0/\Gamma=-2$ and $D/\Gamma=50$.

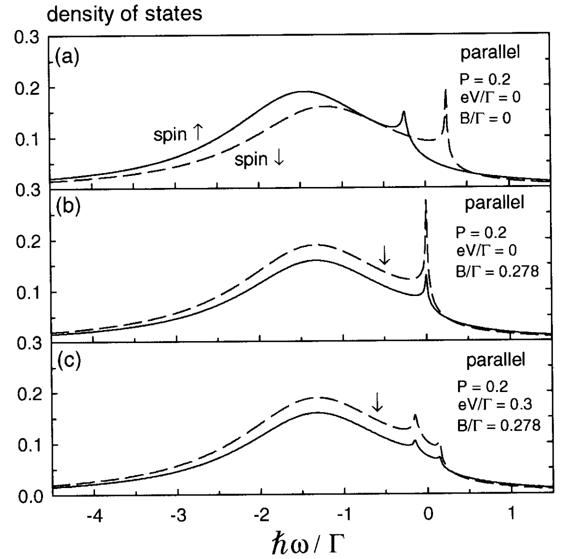

Fig. 3 Corresponding plot of Fig. 2 for P alignment. The parts (b) include the effect of an applied magnetic field B and (c) of an applied bias voltage V. Other parameters are the same as in Fig. 2.

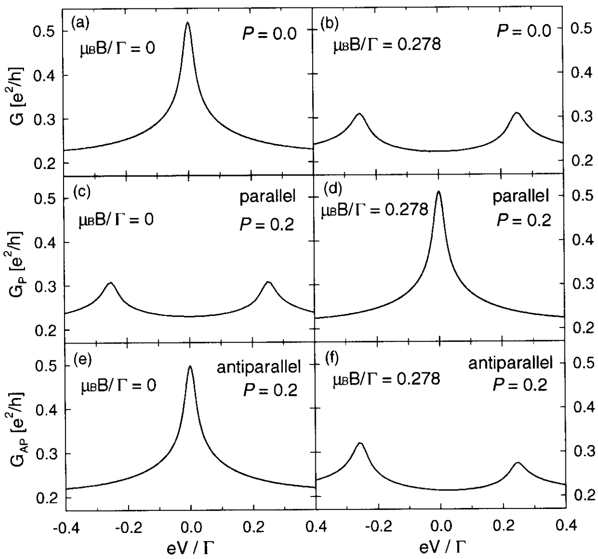

Fig. 4 Total differential conductance *vs.* the applied bias voltage V at zero magnetic field $B=0$ (a, c, e) and at finite magnetic field (b, d, f) for normal (a, b) and ferromagnetic leads with parallel (c, d) and antiparallel (e, f) alignment of the lead magnetizations. Other parameters are the same as in Fig. 2.

for the case of nonmagnetic leads. For the P alignment, however, the Kondo resonance splits [Fig. 3(a)], which can be compensated by an external magnetic field B [Fig. 3(b)]. In the latter case, the amplitude of the Kondo resonance for spin down significantly exceeds that for spin up. A finite bias voltage, $\mu_R-\mu_L=eV>0$, again leads to a splitting for both the AP and the P alignment, [Figs. 2(b) and 3(c)]. In the AP alignment, the amplitude of the upper and the lower Kondo peak appears asymmetric [inset of Fig. 2(b)].

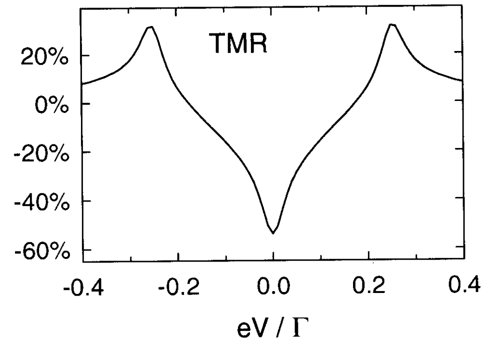

Fig. 5 Tunnel magnetoresistance, $TMR=(G_P-G_{AP})/G_{AP}$, for the cases Figs. 4(c) and (e).

In Fig. 4 we show the differential conductance as a function of the transport voltage. For nonmagnetic leads, there is a pronounced zero-bias maximum [Fig. 4(a)], which splits in the presence of a magnetic field [Fig. 4(b)]. For magnetic leads and P alignment, we find a splitting of the peak in the absence of a magnetic field [Fig. 4(c)], which can be tuned away by an appropriate external magnetic field B [Fig. 4(d)]. In AP alignment, the opposite happens, no splitting at $B=0$ [Fig. 4(e)] but finite splitting at $B>0$ [Fig. 4(f)] with an additional asymmetry in the peak amplitudes as a function of the bias voltage.

In Fig. 5, we show the TMR. Because for AP alignment, the conductance is enhanced by the Kondo effect and for P alignment the conductance is suppressed, we can find a *negative* large TMR around zero bias voltage. Though the sign is opposite, -60% is much larger than the TMR without the Kondo effect.

C. Nonlinear transport *via* real-time diagrammatic technique

In the EOM approach, we accounted for the effect of spin dependent quantum charge fluctuations in the self-consistent but intuitive manner. The real-time diagrammatic technique enables one to construct the systematic approach, where the ferromagnetic electrodes effect can be analyzed without any additional assumptions. This technique gives more reasonable results and allows for further systematic insight into physics. This technique is related to the Keldysh formalism adopted for the ferromagnetic tunnel junction before.[20]

Using this technique, we analyzed how the effect of asymmetric coupling $\Gamma_L \neq \Gamma_R$ modifies our effect.[21] Figures 6(a) and (b) show the nonlinear differential conductance and the local magnetization for the P alignment. In each panel, we plot curves for various ratio of the left and right coupling strengths Γ_R/Γ_L ($\Gamma=\Gamma_R+\Gamma_L$). The splitting is not sensitive for this asymmetry because, as Eq. (1) indicates, $\Delta\varepsilon$ depends only on the total spin polarization factor, which is independent of

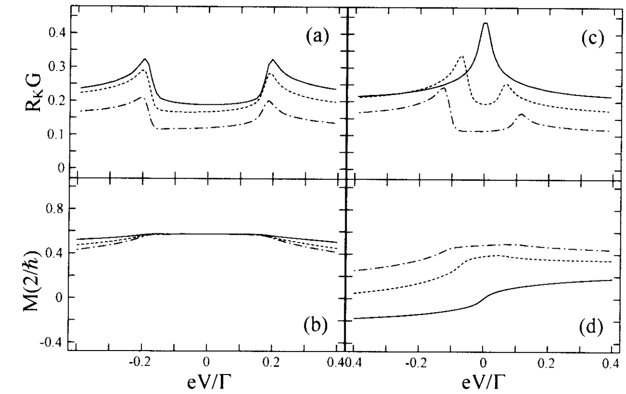

Fig. 6 Differential conductance (a) and local magnetization (b) for P alignment ($P=0.2$). Solid lines, dashed lines and dot-dashed lines are results for $\Gamma_R/\Gamma_L=1$, 0.5 and 0.25. Panels (c) and (d) are the corresponding plot of the panels (a) and (b) with AP alignment. Parameters are the same as for Fig. 2.

the ratio of coupling strength for the P alignment. The local magnetization of QD is not affected by the asymmetric coupling so much either.

For the AP alignment, there is a splitting of the zero bias anomaly for asymmetric coupling [Fig. 6(c)] accompanying by the spin accumulation [Fig. 6(d)]. The splitting is due to the fact that for the asymmetric coupling, the exchange interactions from both leads do not cancel each other. The strong asymmetry in amplitudes of two peaks is related with the fact that the intensities of split Kondo resonance out of equilibrium are different for AP alignment.

D. Numerical renormalization group theory

Though our scaling theory and nonequilibrium approaches could capture the relevant physics, they have their own drawbacks or limitations. Especially, for nonequilibrium situations there are no exact approaches. In the following, we shortly describe our attempts for a more advanced method in equilibrium.

The scaling analysis provides an instructive insight in physical mechanisms. However it breaks down at $k_B T_K$ energy scale due to divergencies. The numerical renormalization-group (NRG) technique[6] is one of powerful methods free of above mentioned problems, which allows to study the Kondo effect in the full range of parameters. Recently, this method was adapted to the case of a quantum dot attached to ferromagnetic leads.[16), 17)]

The NRG study generally confirms the predictions of the scaling analysis, and in addition provides answers to many other questions. It shows that the Kondo resonance is split, as a consequence of the exchange field. By appropriately tuning an external magnetic field, this splitting can be fully compensated and the Kondo effect can be restored.[16] Precisely at this field, the occupancy of the local level is the same for spin up and down, $\langle n_\uparrow \rangle = \langle n_\downarrow \rangle$, the fact that follows also from the Friedel sum rule. Moreover, the Kondo effect has then unusual properties such as a strong spin polarization of the Kondo resonance amplitude. Nevertheless, the quantum dot conductance is found to be the same for each spin channel, $G_\uparrow = G_\downarrow$. Furthermore, by analyzing the spin spectral function, the Kondo temperature can be determined, and the functional dependence on P as given by Eq. (3) has been confirmed.

More recently, the NRG scheme has been adapted to account for structured densities of states,[22] also with strong particle-hole asymmetry as well. Using this extension the possibility of gate-controlled spin splitting was demonstrated, allowing for controlling of magnetic properties of the system by external electric field.

E. Experimental results

In this section, we mention very recent experiments[12), 23)] indicating confirmation of our theoretical predictions. Pasupathy *et al.*[12] measure Kondo-assisted tunneling *via* a single C_{60} molecule attached to ferromagnetic nickel electrodes. It was demonstrated that Kondo correlations exist in the presence of ferromagnetism, but the zero bias anomaly is split, by an amount that decreases (even to zero) as the magnetizations in the two electrodes are turned from P to AP alignment. The splitting is too large to be explained by a local magnetic field. Moreover, the voltage and magnetic-field dependence of the signals agree with predictions for an exchange splitting of the Kondo resonance. The Kondo effect leads to very large negative values of TMR as we predicted. In ref. 23 a similar splitting was observed in a carbon nanotube system in the presence of small magnetic particles.

III. RKKY Interaction between Two Quantum Dots

The RKKY interaction was first discussed in the 1950s.[24] When two magnetic moments are embedded in a metal, they induce spin polarization in a conduction electron sea and couple to each other even if they are spatially separated. Today, the rapid and continuous progress in semiconducting nonofabrication technique has realized complex nanostructures containing QDs. They are powerful tools for explorations of the wide range of topics such as qubits,[25] the quantum phase transition,[26] the coherent transport through an interacting region[27), 28)] and the Fano effect.[29]

Motivated by those experiments, we theoretically analyzed the possibility of the RKKY interaction in semiconducting nanostructures.[30] Our discussion was performed for an AB ring embedded with a QD (in the Coulomb blockade regime with odd numbers of electrons) in each arm (Fig. 7). Because the Fermi wave length $\lambda_F \equiv 2\pi/k_F$ (k_F is the Fermi wave number) of a 2-dimensional (2D) electron gas at GaAs/AlGaAs inter-

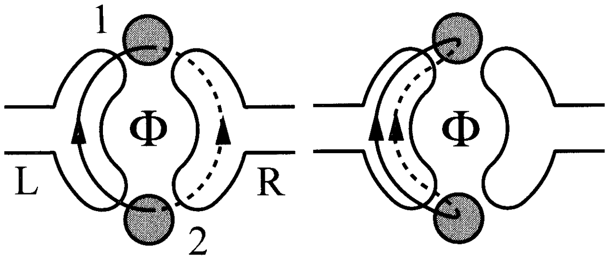

Fig. 7 Aharonov–Bohm ring embedded with one QD (denoted by 1 or 2) in each arm. The magnetic flux Φ dependent (left panel) and independent (right panel) particle-hole excitation. The directed solid and dashed lines show the particle propagation and the hole propagation.

face is typically of the order 100 nm and the RKKY interaction decays weakly as $1/(k_F l)$ for 1D channel, where l is the distance between two QDs, it could be possible to fabricate a sample with the long range RKKY interaction. Actually, very recently, the RKKY interaction has been demonstrated for two QDs coupled indirectly thorough an open QD,[18] which has stimulated intensive discussions.[31] We show that the RKKY interaction in AB ring depends on the flux and dominates AB oscillations in a characteristic manner, which could be a good evidence of the RKKY interaction.

A. Flux dependent RKKY interaction

In the following, we will review ref. 30. Our model consists of two local spins coupled antiferromagnetically with electron spins in two leads. Because of the quantum mechanics, an electron wave function splits into two ways and acquires the "orbital phase" factor, $e^{ik_F l}$, during the propagation for each path, and then interferes with itself. When the magnetic field is applied, an additional phase factor, $e^{\pm i\phi/2}$ ($\phi=2\pi\Phi/\Phi_0$, where $\Phi_0=hc/e$ is the flux quantum), is also counted for an electron traveling between two QDs in the clockwise/anticlockwise direction. This phase factor modifies the interference effect and induces the conductance oscillation as a function of flux (AB effect). Here, the flux is written with the vector potential $\boldsymbol{A}$ as, $\Phi=\oint \boldsymbol{A}\cdot d\boldsymbol{l}$ where the line integral is performed along the ring in the clockwise direction.

The RKKY coupling constant is obtained by the second order perturbation theory in terms of the antiferromagnetic coupling constant J (>0):

$$J_{\mathrm{RKKY}}(\phi)=(J^2/2)\chi(2+2\cos\phi)\,. \tag{4}$$

A phase dependent $2\cos\phi$ is related to two configurations of particle-hole excitations, which enclose the flux (the left panel of Fig. 7), and pick up a phase factor $e^{i\phi}$ or $e^{-i\phi}$. The other two configurations (the right panel) are independent of the flux and give term 2. The physical meaning is the following: At integer values of flux, an electron wave function constructively interfere and thus the maximum coupling is induced. At half-integer values of flux, because of the destructive interference, the interaction is switched off. Thus one can control the amplitude of the RKKY interaction by means of the flux.

The susceptibility function χ counts details of electron states in leads and is related with the orbital phase. It shows the RKKY oscillations as

$$J_{\mathrm{RKKY}}(\phi)\simeq -\pi(J\rho)^2 D\cos(2k_F l)(1+\cos\phi)/(2k_F l)\,, \tag{5}$$

where ρ and D are DOS and the band width of lead electrons, respectively.

B. Linear conductance

Due to the RKKY interaction, the two QD spins are entangled and probabilities of the singlet and triplet states depend on the flux through the flux dependent RKKY interaction. Thus the spin state, consequently the RKKY interaction would leave footprints on the flux dependence of the linear conductance. We calculate the conductance perturbatively in terms of J by using the real-time diagrammatic technique.[32]

First, we will discuss three cases classified by the value of the RKKY coupling constant J_{RKKY} and temperature: (i) the uncorrelated local spins [$|J_{\mathrm{RKKY}}(\phi)|\ll k_B T$], (ii) the ferromagnetic (F) coupling [$-J_{\mathrm{RKKY}}(\phi)\gg k_B T$], and (iii) the antiferromagnetic (AF) coupling [$J_{\mathrm{RKKY}}(\phi)\gg k_B T$] cases. For the case (i), the local-spin state is equally distributed among one singlet state and three triplet states. The conductance is the sum of the component showing AB oscillations, which is related with the cotunneling process preserving the spin, and the background of AB oscillations related with spin-flip processes enhanced by Kondo correlations by ln T:

$$\frac{G}{G_K}\simeq(\pi J\rho)^2\left[1+\cos\phi\cos^2(k_F l)+3\left(1+4J\rho\ln\frac{D}{k_B T}\right)\right], \tag{6}$$

where $G_K=h/e^2$ is the conductance quantum. For the case (ii), two local spins form a triplet state and the conductance is that of the spin-1 Kondo model:

$$\frac{G}{G_K}\simeq(\pi J\rho)^2\left[8J\rho\cos^2(k_F l)\cos^2\frac{\phi}{2}\ln\frac{2T^*}{\pi T} +\left(3+4J\rho\ln\frac{D}{k_B T}\right)\left\{1+\cos\phi\cos^2(k_F l)\right\}\right]. \tag{7}$$

The striking feature is that as opposed to the case (i), Kondo correlations enhance the oscillatory component as shown in the second term. This is because two spins are no longer independent phase-breaking scatterer, and become correlated. The first term appears because the spin-1 moment stretches over l and temperature T^* is related with the time for an electron traveling between two QDs. For the case (iii), two local moments form a singlet state. As the singlet state is decoupled from lead electrons, *i.e.*, electrons flowing through QDs cannot excite the system from the singlet state to a triplet state, only the cotunneling process preserving spin contributes to the conductance:

$$G/G_K\simeq(\pi J\rho)^2\{1+\cos\phi\cos^2(k_F l)\}\,. \tag{8}$$

Next, we will discuss the conductance in the full

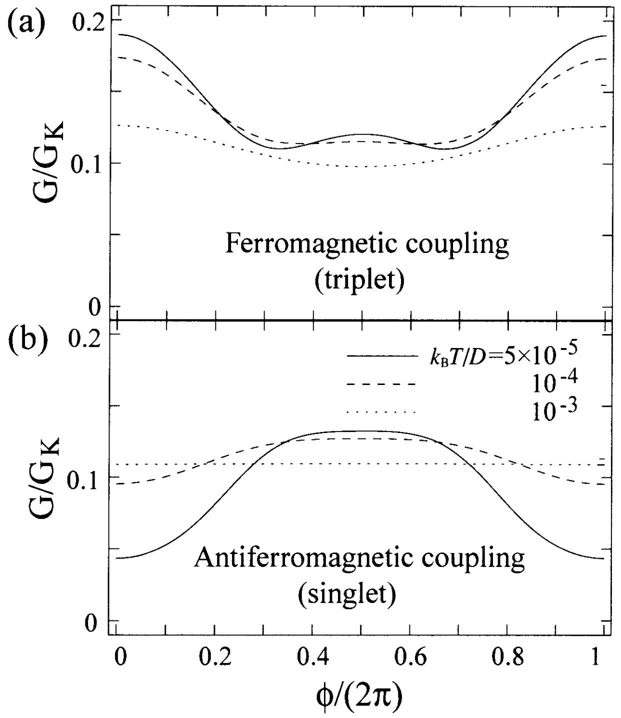

Fig. 8 Flux dependent conductance for (a) $k_F l/(\pi) = 50$ (ferromagnetic coupling where spins form the triplet state) and (b) 50.25 (antiferromagnetic coupling where spins form the singlet state). Parameters: $k_B T/D = 5\times10^{-5}$ (solid line), 10^{-4} (dashed line) and 10^{-3} (dotted line). $J\rho = 0.04$.

range of the flux ϕ for various temperatures (Fig. 8). The panels (a) and (b) are for F coupling case [$k_F l/\pi$ is an integer for Eq. (5)] and for AF coupling case [$k_F l/\pi$ is a half-integer for Eq. (5)], respectively. In the vicinity of zero or one flux, the maximum ferromagnetic RKKY interaction is induced [Eq. (4)]. For F coupling case, the triplet state is formed at low temperature and the conductance is enhanced [case (ii)]. For AF coupling case, at low temperature, the singlet is formed and the conductance is suppressed [case (iii)]. At half flux, the RKKY interaction is switched off [Eq. (4)]. Surprisingly we can observe the maximum in the conductance for both panels where, usually, we expect the suppression of the conductance because of the destructive interference. According to the discussion in (i), this maximum corresponds to the incoherent transport thought the two independent spin-1/2 local moments enhanced by Kondo correlations.

By combining above behaviors, for AF coupling case, the phase of AB oscillations is shifted by π, and for F coupling case, the amplitude of AB oscillations is enhanced by Kondo correlations and an additional maximum appears at half-integer values of the flux. Such characteristic behavior will be a clear evidence of the RKKY interaction in our system.

IV. Summary

In summary, we theoretically investigated many-body effects realized in nanospintronics devices.

We showed that the Kondo resonance in a QD is split when QD is coupled to ferromagnetic leads. The spin dependent quantum charge fluctuations are responsible for this mechanism. The Kondo resonance recovers for AP alignment with symmetric coupling, because two ferromagnetic leads compensates the spin polarization factor with each other. We showed that such anomalous behavior induces *negative* TMR as much as −60%.

We also showed that the RKKY interaction between two QDs embedded in an AB ring can be controlled by the flux: Around integer (half-integer) values of flux, the RKKY interaction is maximum (switched off). The RKKY interaction can be observed by the conductance measurement. For the ferromagnetic coupling, the amplitude of AB oscillations is enhanced by the Kondo correlations and an additional maximum appears at half-integer value of flux. For the antiferromagnetic coupling, the phase of AB oscillations is shifted by π, which is attributed to the formation of a singlet state around an integer value of flux.

We hope our attempts encourage efforts for explorations of novel many-body effects in nanospintronics and for explorations of future nanospintronics devices.

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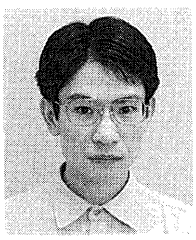

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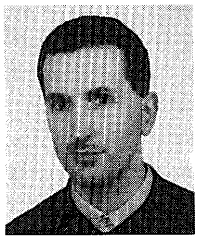

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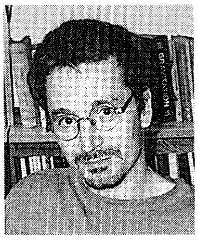

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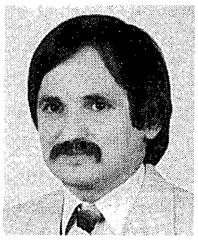

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