Spin-polarized transport in ferromagnet–marginal Fermi liquid systems

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Spin-polarized transport through a marginal Fermi liquid (MFL) which is connected to two noncollinear ferromagnets via tunnel junctions is discussed in terms of the nonequilibrium Green function approach. It is found that the current-voltage characteristics deviate obviously from the ohmic behavior, and the tunnel current increases slightly with temperature, in contrast to those of the system with a Fermi liquid. The tunnel magnetoresistance (TMR) is observed to decay exponentially with increasing bias voltage, and to decrease slowly with increasing temperature. With increasing coupling constant of the MFL, the current is shown to increase linearly, while the TMR is found to decay slowly. The spin-valve effect is observed.

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Spin-polarized transport in magnetic hybrid nanostructures has been an active subject under investigation in the last decades, which is mainly motivated by potential applications in information technology. A new field coined as spintronics is thus emerging (for review, see, e.g., Refs. 1–5). The well-known character in spintronics is that the current flowing through the structures depends sensitively on the relative orientation of the magnetization directions due to the spin-dependent scattering of conduction electrons. Among others, the magnetic tunnel junction (MTJ) is an important family of spintronic devices.[6,7] For these structures, Jullière[8] was the first to observe the tunnel magnetoresistance (TMR) of 14% in Fe-Ge-Co junctions at 4.2 K. In 1995, Moodera *et al.*[9] made a breakthrough by observing reproductively a large TMR as high as 24% at 4.2 K and 11% at 295 K. Recently, clear spin-valve signals at 4.2 K as well as at room temperature have been observed in ferromagnet–normal metal–ferromagnet (FM-N-FM) all-metal structures.[10] Earlier theories on the spin-dependent transport in FM-N-FM junctions[11] are based on the Fermi liquid theory, where interactions between electrons in the normal metal are treated on a mean-field level. There has been recent studies on the spin transport in FM–Luttinger liquid–FM tunnel junctions where the interactions between electrons are taken into account and applied directly to carbon nanotubes,[12,13] but they are primarily aimed at one-dimensional interacting quantum wires. Besides, spin-polarized transport through an interacting quantum dot that is described by the Anderson model has also gained much attention.[14] On the other hand, there appear intriguing experimental and theoretical works on the spin-polarized transport in FM–high Tc superconductor tunnel junctions recently (e.g., Ref. 15). It is thought that the anomalous normal state properties of high Tc cuprates in the optimally doped regime can be well described by the marginal Fermi liquid (MFL),[16] where the interactions between electrons in the cuprates are phenomenologically included in a one-particle self-energy due to exchange of charge and spin fluctuations. Therefore, the study on the spin-dependent transport in FM-MFL-FM tunnel junctions would be interesting, as it would be useful for understanding the transport properties of FM–high Tc cuprate junctions in the normal state.

In this paper, by using Keldysh's nonequilibrium Green function formalism, the spin-dependent transport in FM-MFL-FM tunnel junctions is investigated. It is observed that the current-voltage characteristics in this spintronic structure show non-ohmic behaviors, and the tunnel current increases slowly with temperature, which are in contrast to those of the structure with a Fermi liquid, showing that the interactions between electrons in the normal metal have remarkable effects on the transport properties. The TMR is found to decay exponentially with increasing magnitude of bias voltage and to decrease slowly with increasing temperature. With increasing coupling constant λ of the MFL, the current is shown to increase linearly, while the TMR is seen to decay slowly, implying that the interactions of electrons tend to suppress the TMR. In addition, the spin-valve effect is observed.

Let us consider a MTJ in which the two FM electrodes, connected with the bias voltage $V/2$ and $-V/2$, respectively, are separated by a normal metal which is described by the MFL, as schematically depicted in Fig. 1. The molecular field $\mathbf{h}_L$ in the left (L) FM is assumed to be parallel to the z axis, while the molecular field $\mathbf{h}_R$ in the right (R) FM is parallel to the z' axis which deviates the z axis by a relative angle θ. $T_{k\alpha q}$ $(\alpha=L,R)$ stand for the elements of the tunneling matrix between the α electrode and the central region. The tunnel current flows along the x axis and perpendicular to the junction plane. In the central region, the interactions between conduction electrons are supposed to be described phenomenologically by a retarded one-particle self-energy due to the exchange of charge and spin fluctuations:[16]

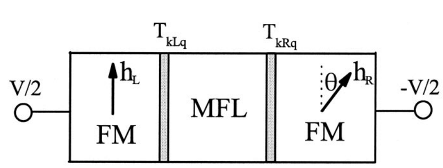

FIG. 1. (Color online) Schematic illustration of the double tunnel junction consisting of two ferromagnets (FM) and a marginal Fermi liquid (MFL) separated by insulating films, where $T_{k\alpha q}$ $(\alpha=L,R)$ stand for the elements of coupling matrix between the α electrode and the central region, and both magnetizations are aligned by a relative angle θ.

$$\Sigma(\varepsilon)=\lambda\left[\varepsilon\ln\frac{x}{E_c}-i\frac{\pi}{2}x\right], \qquad (1)$$

where $x=\max(|\varepsilon|,k_BT)$, E_c is a cut-off energy, and λ is a coupling constant. When $\lambda=0$, the MFL junction recovers the conventional Fermi liquid. For simplicity, the spin-orbital coupling in the MFL will be ignored. It is worthy of note that the exact Hamiltonian of the MFL is not yet available. However, since the single-particle Green function is explicitly written down, the concrete form of the microscopic Hamiltonian is irrelevant. In the calculations, we just need to adopt a formal Hamiltonian such as a Fermi liquid with the electron operators understood as those of quasiparticles. Because the final results are all expressed by Green functions, we only need to use the MFL Green functions to replace the quasiparticle Green functions.

By means of the nonequilibrium Green function, the tunnel current through the left electrode can be obtained by

$$I_L(V)=e\langle\dot{N}_L\rangle=-\frac{2e}{\hbar}\Re e\sum_{\mathbf{kq}\sigma}T_{\mathbf{k}L\mathbf{q}}G^{<}_{\mathbf{q}\sigma L\mathbf{k}\sigma}(t,t), \qquad (2)$$

where N_L is the occupation number of electrons in the left electrode, $G^{<}_{\mathbf{q}\sigma' L\mathbf{k}\sigma}(t,t')=i\langle a^{\dagger}_{\mathbf{k}\sigma}(t')c_{\mathbf{q}\sigma'}(t)\rangle$ is the lesser Green function, $a_{\mathbf{k}\sigma}$ and $c_{\mathbf{k}\sigma}$ are annihilation operators of electrons with momentum $\mathbf{k}$ and spin σ $(=\pm 1)$ in the left and central region, respectively. In order to get the lesser Green function, we define a time-ordered Green function $G^{t}_{\mathbf{q}\sigma' L\mathbf{k}\sigma}(t,t')=-i\langle T\{a^{\dagger}_{\mathbf{k}\sigma}(t')c_{\mathbf{q}\sigma'}(t)\}\rangle$. In terms of the equation of motion, we have

$$G^{t}_{\mathbf{q}\sigma' L\mathbf{k}\sigma}(t-t')=\sum_{\mathbf{q}'}\int G^{t}_{\mathbf{q}\sigma'\mathbf{q}'\sigma}(t-t_1)T_{\mathbf{k}L\mathbf{q}}g^{t}_{\mathbf{k}L\sigma}(t_1-t')dt_1,$$

where $g^{t}_{\mathbf{k}L\sigma}(t)=(i\hbar(\partial/\partial t)-\varepsilon_{\mathbf{k}L\sigma})^{-1}$ with $\varepsilon_{\mathbf{k}L\sigma}=\varepsilon_L(\mathbf{k})-(eV/2)-\sigma M_L$, $\varepsilon_L(\mathbf{k})$ is the single-particle dispersion in the left electrode and $M_L=g\mu_B h_L/2$ (g, Landé factor; μ_B, Bohr magneton), and $G^{t}_{\mathbf{q}\sigma'\mathbf{q}'\sigma}(t-t')$ is the time-ordered Green function in the central region. By applying Langrenth theorem[17] and Fourier transform, one may obtain formally

$$G^{<}_{\mathbf{q}\sigma' L\mathbf{k}\sigma}(\varepsilon)=\sum_{\mathbf{q}'}T_{kLq'}[G^{r}_{\mathbf{q}\sigma'\mathbf{q}'\sigma}(\varepsilon)g^{<}_{\mathbf{k}L\sigma}(\varepsilon)+G^{<}_{\mathbf{q}\sigma'\mathbf{q}'\sigma}(\varepsilon)g^{a}_{\mathbf{k}L\sigma}(\varepsilon)], \qquad (3)$$

where $G^{r}_{\mathbf{q}\sigma'\mathbf{q}'\sigma}(\varepsilon)$ is the Fourier transform of the retarded Green function of electrons in the MFL of the central region and $G^{<}_{\mathbf{q}\sigma'\mathbf{q}'\sigma}(\varepsilon)$ is the corresponding lesser Green function, and $g^{<}_{\mathbf{k}L\sigma}(\varepsilon)$ and $g^{a}_{\mathbf{k}L\sigma}(\varepsilon)$ are the lesser and advanced Green functions for the uncoupled electrons in the left electrode. By defining $\Gamma_\alpha(\varepsilon)_{\mathbf{q}'\sigma\mathbf{q}\sigma'}=2\pi D(\varepsilon)T_{\mathbf{k}\alpha\mathbf{q}}T_{\mathbf{k}\alpha\mathbf{q}'}\delta_{\sigma\sigma'}$ with $D(\varepsilon)$ the density of states (DOS) in the α electrode and using the Fourier transform, after a tedious but direct derivation, Eq. (2) can be rewritten as

$$I_L(V)=-\frac{ie}{\hbar}\int\frac{d\varepsilon}{2\pi}\mathrm{Tr}\left\{\Gamma_L\left(\varepsilon+\frac{eV}{2}+\sigma M_L\right)\times\{f_L(\varepsilon)[G^r(\varepsilon)-G^a(\varepsilon)]+G^{<}(\varepsilon)\}\right\}, \qquad (4)$$

where $f_\alpha(\varepsilon)$ is the Fermi function of the α electrode and Tr is the trace over the momentum and spin space. Note that in Eq. (4) all Green functions $G^{r,a,<}(\varepsilon)$ are for electrons in the MFL of the central region, where $G^{r,a}(\varepsilon)$ are known with the presumed self-energy $\Sigma(\varepsilon)$ in the MFL [Eq. (1)], say, $G^r(\varepsilon)=[\varepsilon-\varepsilon_k-\Sigma_0^r-\Sigma(\varepsilon)+i\eta]^{-1}$, where Σ_0^r, $\Sigma(\varepsilon)$ denote the coupling of MFL to the two ferromagnets and the retarded self-energy of the MFL, respectively, while $G^{<}(\varepsilon)$ is unknown and needs to be obtained.

To get the lesser Green function $G^{<}(\varepsilon)$ of the central region, we invoke Ng's ansatz:[18] $\Sigma^{<}=\Sigma_0^{<}B$, where $\Sigma_0^{<}(\varepsilon)=i[f_L(\varepsilon)\Gamma_L(\varepsilon+(eV/2)+\sigma M_L)+f_R(\varepsilon)R\Gamma_R(\varepsilon-(eV/2)+\sigma M_R)R^{\dagger}]$, $B=(\Sigma_0^r-\Sigma_0^a)^{-1}(\Sigma^r-\Sigma^a)$, $\Sigma_0^r(\varepsilon)-\Sigma_0^a(\varepsilon)=-i[\Gamma_L(\varepsilon+(eV/2)+\sigma M_L)+R\Gamma_R(\varepsilon-(eV/2)+\sigma M_R)R^{\dagger}]$, $\Sigma^r(\varepsilon)-\Sigma^a(\varepsilon)=\Sigma_0^r(\varepsilon)-\Sigma_0^a(\varepsilon)-i\lambda\pi x$, with $R=\begin{pmatrix}\cos\theta/2 & -\sin\theta/2\\ \sin\theta/2 & \cos\theta/2\end{pmatrix}$ the rotation matrix, and $M_R=g\mu_B h_R/2$. Under this presumption, one may find eventually that Eq. (4) becomes

$$I_L(V)=\frac{e}{\hbar}\int\frac{d\varepsilon}{2\pi}\mathrm{Tr}\left\{(f_R-f_L)\Gamma_L\left(\varepsilon+\frac{eV}{2}+\sigma M_L\right)\times G^r(\varepsilon)R\Gamma_R\left(\varepsilon-\frac{eV}{2}+\sigma M_R\right)R^{\dagger}BG^a(\varepsilon)\right\}. \qquad (5)$$

The TMR ratio can be defined according to the current as usual:[19]

$$\mathrm{TMR}=\frac{I(\theta=0)-I(\theta=\pi)}{I(\theta=0)}. \qquad (6)$$

When the magnetizations of the two FMs are noncollinearly arranged, the TMR ratio can be described by

$$\mathrm{TMR}(\theta)=\frac{I(0)-I(\theta)}{I(0)}. \qquad (7)$$

Obviously, $\mathrm{TMR}(\pi)=\mathrm{TMR}$, and $\mathrm{TMR}(0)=0$.

In the following, for the sake of simplicity for numerical calculations, and considering that the electrons near the Fermi level in metals are dominant in the tunneling process, we may suppose $\Gamma_\alpha(\varepsilon)_{q'\uparrow q\uparrow}=\Gamma_{\alpha\uparrow}$, $\Gamma_\alpha(\varepsilon)_{q'\downarrow q\downarrow}=\Gamma_{\alpha\downarrow}$, and the polarization $P_\alpha=(\Gamma_{\alpha\uparrow}-\Gamma_{\alpha\downarrow})/(\Gamma_{\alpha\uparrow}+\Gamma_{\alpha\downarrow})$. If the two ferromagnets are made of the same materials, then $P_L=P_R=P$, $\Gamma_{L\uparrow}=\Gamma_{R\uparrow}\equiv\Gamma$, $\Gamma_{L\downarrow}=\Gamma_{R\downarrow}=(1-P/1+P)\Gamma$. We will take $I_0=e\Gamma/\hbar$ and $G_0=e^2/\hbar$ as scales, respectively, for the tunnel current and the differential conductance, and hereafter take Γ as an energy scale.[20]

The bias and temperature dependence of the tunnel current in the parallel and antiparallel configurations of magnetizations are presented for different coupling constant λ of the MFL, as shown in Fig. 2. It is seen that when $\lambda=0$, namely, the MFL recovers to the normal Fermi liquid in this case, the tunnel current is proportional to the bias voltage at small bias, suggesting that the system behaves as an ohmic

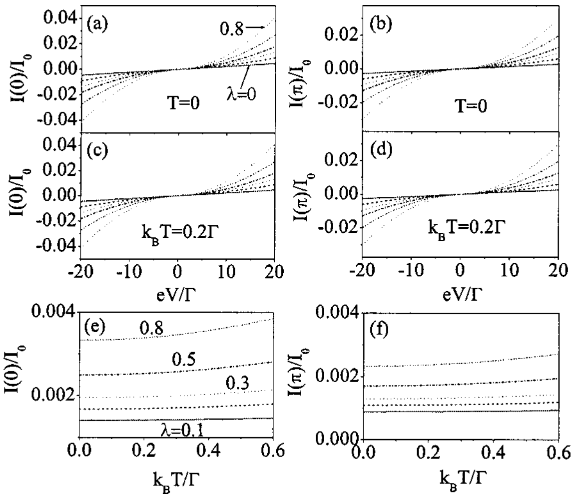

FIG. 2. (Color online) Tunnel current as a function of the bias voltage (a)–(d) and of temperature (e) and (f) in parallel $I(0)$ and antiparallel $I(\pi)$ configurations of magnetizations for different coupling parameter $\lambda=0,0.1,0.2,0.3,0.5,0.8$, where the polarization $P=0.5$.

law in this case, in agreement with the conventional result in the Fermi liquid. With increasing coupling constant λ, $I-V$ curves deviate obviously from linear relation, and non-ohmic behaviors appear, i.e., the current increases quadratically with the bias voltage. The larger the coupling λ, the more obvious the distinction from the ohmic behavior, as illustrated in Figs. 2(a)–2(d). This observation shows that the interactions between electrons in the normal metal would have a remarkable effect on the current-voltage characteristics where the Ohm's law no longer holds. An alternative reason for the nonlinearity of $I-V$ characteristics may be that the energy dependent self-energy of the MFL in the central region leads to a renormalization of the density of states which becomes energy dependent, thereby resulting in a nonlinear voltage dependence of the current. When λ is small, the tunnel current almost does not change with temperature; while λ becomes larger, the current increases slowly with temperature, as shown in Figs. 2(e) and 2(f). This behavior also differs from that in the usual Fermi liquid where the current decreases slowly with increasing temperature, as thermal fluctuations enhance scatterings of conduction electrons and thereby contribute to the resistance of the system. It is interesting to note that the typical $I-V$ characteristics of $Ni_{80}Fe_{20}$/Co/Al-oxide junction (Figure 3.10 in Ref. 21) are very similar to the shapes of the curves shown in our Figs. 2(a)–2(d).

The differential conductance can be obtained by $G=dI(V)/dV$. The results are shown in Figs. 3(a)–3(d). As $\lambda=0$, the conductance is independent of the bias voltage, which is nothing but the Ohm's law. When λ is nonzero, the differential conductance behaves as $G=G_0+G_1V$ with G_0 and G_1 being nonzero constants at low biases. The non-ohmic behavior of G comes from the interactions between conduction electrons via the exchange of charge and spin fluctuations in the central region. The differential conductance is observed to increase slowly with increasing temperature at larger λ and almost does not change when λ

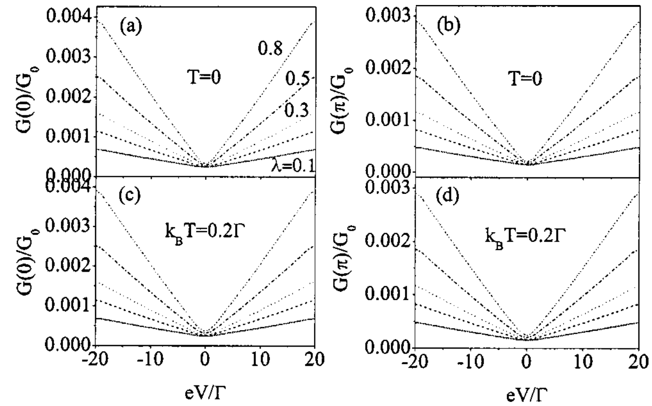

FIG. 3. (Color online) Differential conductance as a function of bias voltage in parallel $G(0)$ and antiparallel $G(\pi)$ configurations for different coupling constant $\lambda=0.1,0.2,0.3,0.5,0.8$ at temperature $T=0$ (a) and (b) and $T=0.2\Gamma/k_B$ (c) and (d), where the parameters are taken the same as in Fig. 1.

is smaller (e.g., $\lambda=0.1$). This observation is manifested in Figs. 2(e) and 2(f). We notice that the linear bias dependence of the differential conductance in various junctions with $La_{1.85}Sr_{0.15}CuO_4$-In (Ref. 22) and even YBCO films[23] have also been observed. It is worthy of note that the differential conductance of a contact between an ordinary metal and a MFL is shown to depend linearly on the applied voltage,[24] where due to the asymmetry of electrodes, the conductance for positive and negative biases is asymmetric. This result is compatible with our observation. The origin of the linearity between the conductance and the bias voltage could be explained by assuming charging effects,[25] the voltage-dependent tunneling penetration probabilities,[26] DOS effects,[16,27] inelastic scattering,[22] and so on. Our present study might offer a different possibility, namely, such a linearity between G and V could result from strong interactions between conduction electrons via exchanging the charge and spin fluctuations. The real part of the self-energy gives the correction of the single-particle energy, describing the elastic scattering of quasiparticles, whereas the imaginary part determines the lifetime of the quasiparticles, reflecting the inelastic scatterings. Therefore, the linearity between G and V could also be dominated by the inelastic scatterings between conduction electrons.

The TMR ratio as a function of the bias and temperature for different coupling constant λ is shown in Figs. 4(a)–4(c). It is seen that the TMR decreases with increasing absolute magnitude of the bias and is symmetric to the zero-bias axis. The larger the coupling constant λ, the more rapidly the TMR decreases, as presented in Figs. 4(a) and 4(b). It suggests that the strong interactions between conduction electrons tend to suppress the TMR ratio, which is a disadvantage for the application of the FM-MFL-FM tunnel junction as a possible magnetic random access memory (MRAM). This property of the TMR has also been observed in various junctions (see Figure 3.7 in Ref. 21). One may observe that the TMR decreases slowly with increasing temperature, as shown in Fig. 4(c).

The current and the TMR ratio as functions of the cou-

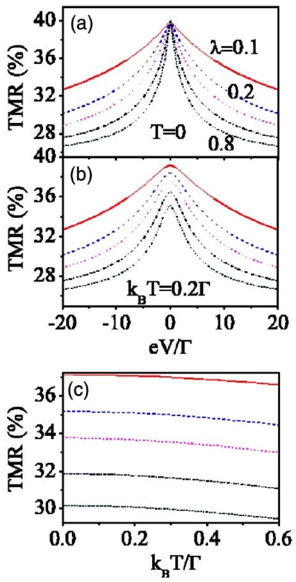

FIG. 4. (Color online) Tunnel magnetoresistance as a function of the bias voltage as a function of bias voltage at $T=0$ (a) and $T=0.2\Gamma/k_B$ (b) and as a function of temperature (c) for different coupling constant $\lambda=0.1,0.2,0.3,0.5,0.8$ at $V=5\Gamma/e$, where the parameters are taken the same as in Fig. 1.

pling constant λ in the MFL for different temperatures are presented in Figs. 5(a)–5(d). It is found that the current depends linearly on the coupling constant λ in the parallel or antiparallel alignment of magnetizations. This behavior is also manifested in Figs. 2(a)–2(d). It can be understood that, with the increase of the coupling constant, the single-particle scattering rate which is proportional to λ increases, leading to the quantum well levels in the MFL that could be broadened. Such a level broadening could make more electrons tunnel through the barrier, thereby resulting in an increase of the current with λ, as observed in Figs. 5(a) and 5(b). In either case, $T=0$ or $T>0$, $I(0)$ is greater than $I(\pi)$, implying a spin valve effect (see below). The TMR ratio is found to decay with increasing coupling constant λ, as shown in Figs. 5(c) and 5(d), suggesting that the interactions of electrons are

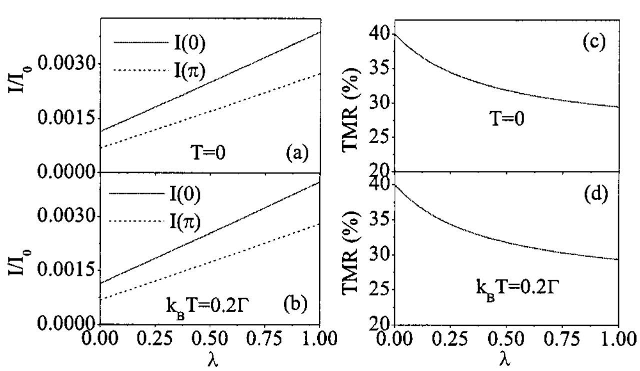

FIG. 5. (Color online) Tunnel current as a function of the coupling constant λ at $T=0$ (a) and $T=0.2\Gamma/k_B$ (b); tunnel magnetoresistance as a function of the coupling constant λ at $T=0$ (c) and $T=0.2\Gamma/k_B$ (d), where $V=5\Gamma/e$ and the other parameters are taken the same as in Fig. 1.

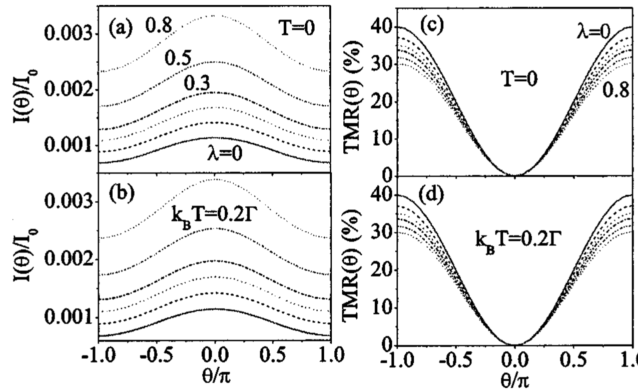

FIG. 6. (Color online) Tunnel current as a function of the relative orientation angle θ at $T=0$ (a) and $T=0.2\Gamma/k_B$ (b); tunnel magnetoresistance as a function of the relative orientation angle θ at $T=0$ (c) and $T=0.2\Gamma/k_B$ (d), where the coupling constant $\lambda=0,0.1,0.2,0.3,0.5,0.8$, $V=5\Gamma/e$, and the other parameters are taken the same as in Fig. 1.

detrimental to the TMR effect. This may be because the inelastic scatterings of electrons via exchanging the charge and spin fluctuations weaken the spin-dependent scattering of electrons, leading to the TMR ratio that decreases with increasing λ.

The relative angle θ dependences of the current as well as the TMR ratio for different coupling constant are presented in Figs. 6(a)–6(d). The current as a function of θ shows a cosine-like shape, $G(\theta)\sim\tilde{G}_0+\tilde{G}_1\cos\theta$ with $\tilde{G}_0$, $\tilde{G}_1$ constants, i.e., it decreases with increasing θ from zero to π, as illustrated in Figs. 6(a) and 6(b) for $T=0$ and $0.2\Gamma/k_B$, respectively. The TMR ratio as a function of θ shows a shape similar to $(1-\cos\theta)$. These results display nothing but the spin-valve effect. However, as discussed above, the coupling constant λ tends to suppress the TMR effect.

In summary, we have discussed the spin-dependent transport in FM-MFL-FM tunnel junctions. It is found that the current-voltage characteristics in this system deviate obviously from the ohmic behavior, and the tunnel current increases slightly with temperature, which are in contrast to those of the system with a Fermi liquid where the Ohm's law is satisfied. The TMR is observed to decay exponentially with increasing bias voltage, but to decay slowly with increasing temperature. These results are qualitatively consistent with the experimental observations found in various junctions, suggesting that the present study might offer a possible different route to understand the unusual experimental results of the $I-V$ and $G-V$ characteristics. With increasing coupling constant of the MFL, the current is shown to increase linearly, while the TMR is seen to decay slowly. It appears that the interactions between electrons in the central normal metal via exchanging the charge and spin fluctuations tend to suppress the TMR effect. In addition, the spin-valve effect is also observed.

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