Spin-Polarized Transport in Ferromagnet-Marginal Fermi Liquid Systems

Hai-Feng Mu, Gang Su*, Qing-Rong Zheng and Biao Jin

College of Physical Sciences, Graduate School of the Chinese Academy of Sciences, P.O. Box 3908, Beijing 100039, China

Spin-polarized transport through a marginal Fermi liquid (MFL) which is connected to two non-collinear 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 the bias voltage, and to decrease slowly with increasing temperature. With increasing the 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 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, 2, 3, 4, 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].

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 the magnitude of bias voltage, and to decrease slowly with increasing temperature. With increasing the 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 h_L in the left (L) FM is assumed to be parallel to the z axis, while the molecular field 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_B} (α = 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.

\[ \Sigma(\varepsilon) = \lambda[\varepsilon \ln \frac{x}{E_c} - \frac{\pi}{2}], \]  

(1)

where \( x = \max(|\varepsilon|, k_B T) \), \( E_c \) is a cut-off energy and \( \lambda \) is a coupling constant. When \( \lambda = 0 \), the MFL junction re-
Green function in the central region. By applying Langrenth theorem and Fourier transform, one may obtain formally

$$
G_{\mathbf{q}^0 t^0 L k \sigma}^<(\varepsilon) = \sum_{\mathbf{q}^0} T_{\mathbf{k} L \mathbf{q}^0} [G_{\mathbf{q}^0 t^0 \mathbf{q}^0}^r(\varepsilon) g_{\mathbf{k} L \sigma}^<(\varepsilon) + G_{\mathbf{q}^0 t^0 \mathbf{q}^0}^< (\varepsilon) g_{\mathbf{k} L \sigma}^r(\varepsilon)],
$$

where $G_{\mathbf{q}^0 t^0 \mathbf{q}^0}^r(\varepsilon)$ is the Fourier transform of the retarded Green function of electrons in the MFL of the central region, and $G_{\mathbf{q}^0 t^0 \mathbf{q}^0}^<(\varepsilon)$ is the corresponding lesser Green function. $g_{\mathbf{k} L \sigma}^<(\varepsilon)$ and $g_{\mathbf{k} L \sigma}^r(\varepsilon)$ are the lesser and advanced Green functions for the uncoupled electrons in the left electrode. By defining $\Gamma(\varepsilon) = 2\pi D(\varepsilon) T_{\mathbf{k} \mathbf{q}^0} T_{\mathbf{q}^0} \delta_{\mathbf{q}^0}^r$ with $D(\varepsilon)$ the density of states (DOS) in the $\alpha$ electrode and using the Fourier transform, after a tedious but direct derivation, Eq. (2) can be rewritten as

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

where $f_\alpha(\varepsilon)$ is the Fermi function of the $\alpha$ electrode, and $Tr$ is the trace over the momentum and spin space. Note that in Eq. (3) all Green functions, $G^r, a,<(\varepsilon)$, are for electrons in the MFL of the central region, where $G^\alpha(\varepsilon)$ are known with the presumed self-energy $\Sigma(\varepsilon)$ in the MFL [Eq. (1)], say, $G^\alpha(\varepsilon) = [\varepsilon - \epsilon_k - \Sigma_0^\alpha - \Sigma(\varepsilon) + i\eta]^{-1}$, where $\Sigma_0^\alpha, \Sigma(\varepsilon)$ 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[15]: $\Sigma^\lessgtr = \Sigma^\lessgtr_0 B$, where $\Sigma^\lessgtr_0(\varepsilon) = i[f_L(\varepsilon)\Gamma_L(\varepsilon + eV/2 + \sigma M_L) + f_R(\varepsilon)\Gamma_R(\varepsilon - eV/2 + \sigma M_R)R^\dagger]$, $B = (\Sigma^\lessgtr_0 - \Sigma_0^\lessgtr)^{-1}(\Sigma^\lessgtr - \Sigma^\lessgtr_0)$, $\Sigma^\lessgtr_0(\varepsilon) = -i\Gamma_L(\varepsilon + eV/2 + \sigma M_L) + \Gamma_R(\varepsilon - eV/2 + \sigma M_R)R^\dagger$, $\Sigma^\lessgtr(\varepsilon) = -\Sigma^\lessgtr_0(\varepsilon) - i\lambda\pi x$, with $R = \left( \begin{array}{cc} \cos \theta/2 - i \sin \theta/2 & \sin \theta/2 \\ \sin \theta/2 & \cos \theta/2 \end{array} \right)$ the rotation matrix, and $M_R = g\mu_B h R/2$. Under this presumption, one may find eventually that Eq. (4) becomes

$$
I_L(V) = e\hbar \int \frac{d\varepsilon}{2\pi} Tr \{ (f_R - f_L)\Gamma_L(\varepsilon + eV/2 + \sigma M_L) \times G^r(\varepsilon) R^\dagger R(\varepsilon - eV/2 + \sigma M_R)R^1BG^a(\varepsilon) \}.
$$

The TMR ratio can be defined according to the current as usual[16]:

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

When the magnetizations of the two FMs are non-collinearly arranged, the TMR ratio can be described by...
If the two ferromagnets are made of the same materials, deviate obviously the linear relation, and non-ohmic magnetizations are presented for different coupling parameter $\lambda = 0, 0.1, 0.2, 0.3, 0.5, 0.8$, where the polarization $P = 0.5$.

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

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

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 $\Gamma_{\alpha}(\epsilon)_{q'q} = \Gamma_{\alpha\uparrow\downarrow} = \Gamma_{\alpha\downarrow\uparrow} = \Gamma_{\alpha\uparrow\downarrow} = \Gamma_{\alpha\downarrow\uparrow} = \Gamma_{\alpha\downarrow\uparrow}$, and the polarization $P_{\alpha} = (\Gamma_{\alpha\uparrow\downarrow} - \Gamma_{\alpha\downarrow\uparrow})/(\Gamma_{\alpha\uparrow\downarrow} + \Gamma_{\alpha\downarrow\uparrow})$. If the two ferromagnets are made of the same materials, then $P_L = P_R = P$, $\Gamma_{L\uparrow\downarrow} = \Gamma_{R\uparrow\downarrow} = \Gamma_{L\downarrow\uparrow} = \Gamma_{R\downarrow\uparrow} = \Gamma$. We will take $I_0 = eV/d$ and $G_0 = e^2/d$ as scales, respectively, for the tunnel current and the differential conductance, and hereafter take $\Gamma$ as an energy scale.

The bias- and temperature-dependence of the tunnel current in the parallel and antiparallel configurations of magnetizations are presented for different coupling constant $\lambda$ 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 an ohmic law in this case, in agreement with the conventional result in the Fermi liquid. With increasing the coupling constant $\lambda$, $I - V$ curves deviate obviously the linear relation, and non-ohmic behaviors appear, i.e. the current increases quadratically with the bias voltage. The larger the coupling $\lambda$, the more obvious the distinction from the ohmic behavior, as illustrated in Figs. 2(a)-(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 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 $\lambda$ is small, the tunnel current almost does not change with temperature; while $\lambda$ becomes larger, the current increases slowly with temperature, as shown in Figs. 2(e)-(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$_8$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)-(d).

The differential conductance can be obtained by $G = dI(V)/dV$. The results are shown in Figs. 3(a)-(d). As $\lambda = 0$, the conductance is independent of the bias voltage, which is nothing but the Ohm law. When $\lambda$ is nonzero, the differential conductance behaves as $G = G_0 + G_1V$ with $G_0$ and $G_1$ 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 $\lambda$, and almost does not change when $\lambda$ is smaller (e.g. $\lambda = 0.1$). This observation is manifested itself in Figs. 2(e)-(f). We notice that the linear bias-dependence of the differential conductance in various of junctions with La$_{1.85}$Sr$_{0.15}$CuO$_{4+\delta}$ [22] and even YBCO films [23] have also been observed. It is worthy of noting 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 com-

FIG. 2: (Color online) Tunnel current as a function of the bias voltage (a)-(d) and of temperature (e)-(f) in parallel $I(0)$ and antiparallel $I(\pi)$ configurations of magnetizations for different coupling parameter $\lambda = 0, 0.1, 0.2, 0.3, 0.5, 0.8$ at temperature $T = 0$ (a)-(b) and $T = 0.2\Gamma/k_B$ (c)-(d), where the parameters are taken the same as in Fig. 1.

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 $\lambda = 0.1, 0.2, 0.3, 0.5, 0.8$.
FIG. 4: (Color online) Tunnel magnetoresistance as a function of temperature for different coupling constant λ. The TMR decreases with increasing temperature, as shown in Fig. 4(c). It is seen that the TMR decreases with increasing the absolute magnitude of the bias, and is symmetric to the zero-bias axis. The larger the coupling constant, the more rapidly decreasing the TMR, as presented in Figs. 4(a) and (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 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 coupling constant λ in the MFL for different temperatures are presented in Figs. 5(a)-(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)-(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 that the quantum well levels in the MFL 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 (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 the coupling constant λ, as shown in Figs. 5(c) and (d), suggesting that the interactions of electrons are detrimental to the TMR effect. This may be that the inelastic scatterings of electrons via exchanging the charge and spin fluctuations weaken the spin-dependent scattering of electrons, leading to that the TMR ratio decreases with increasing λ.

The relative angle \( \theta \) dependences of the current as well as the TMR ratio for different coupling constant are presented in Figs. 6(a)-(d). The current as a function of \( \theta \) shows a cosine-like shape, \( G(\theta) \sim \hat{G}_0 + \hat{G}_1 \cos \theta \) with \( \hat{G}_0, \hat{G}_1 \) constants, i.e., it decreases with increasing \( \theta \) from zero to \( \pi \), as illustrated in Figs. 6(a) and (b) for \( T = 0 \) and \( 0.2\Gamma/k_B \), respectively. The TMR ratio as a function...
of $\theta$ shows a shape similar to $(1 - \cos \theta)$. These results display nothing but the spin-valve effect. However, as discussed above, the coupling constant $\lambda$ 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 law is satisfied. The TMR is observed to decay exponentially with increasing the 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 the 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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*Corresponding author. E-mail: gsu@gscas.ac.cn.