Sequential tunneling and shot noise in ferromagnet/normal-metal/ferromagnet double tunnel junctions

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Abstract

The tunneling through a ferromagnet/normal metal/ferromagnet double junction in the Coulomb blockade regime is studied, assuming that the spin relaxation time of electron in the central metallic island is sufficiently large. Using the master equation, the current, the tunnel magnetoresistance (TMR), and the current noise spectrum have been calculated for devices of different parameters. It was shown that the interplay between spin and charge correlations strongly depends on the asymmetry of measured device. The charge correlation makes both the chemical potential shift, which describes the spin accumulation in the central island, and the TMR oscillated with the same period as the Coulomb staircase in current-voltage characteristics. This effect is smeared by the temperature. The spin correlation may cause an enhancement of noise at finite frequencies, while the zero frequency noise is still always sub-poissonian. The gate voltage causes an oscillation of not only conductance, but also TMR and noise.

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I. INTRODUCTION

Recently, transport in ferromagnetic single electron transistors (F-SETs) attracts much attention from both fundamental and application points of view \[1\]. In such a device a small metallic island (or quantum dot (QD) \[2\]) is coupled via tunneling junctions to two leads and capacitively to a gate. Depending on materials of QD and leads (normal (N) or ferromagnetic (F) metal) there are three kinds of F-SET: F/F/F-SET \[3, 5, 6\], F/F/N-SET \[3, 7\], and F/N/F-SET \[8, 9, 10, 11, 12, 13, 14, 15, 16\]. In these F-SETs the interplay between spin and charge correlations during the tunneling process leads to new phenomena such as an oscillation of the tunnel magnetoresistance (TMR) with increasing the bias voltage \[3\] or a non-equilibrium spin accumulation on the normal metallic QD \[9\], which in turn may produce a negative differential conductance (NDC) and an accompanied shot noise enhancement \[10, 11\].

The aim of this work is systematically to study the spin-dependent transport and the shot noise in Coulomb blockade F/N/F-SETs in the sequential tunneling regime \[17, 18\]. The equivalent circuit diagram of the device is drawn in the inset of Fig.1(b). We assume that two leads are made of the same ferromagnetic metal such as Ni, Fe or La_{0.7}Sr_{0.3}MnO_3, and the QD is made of a normal metal with a sufficiently long spin relaxation time such as Al. The key parameter in the problem is the polarization defined as \(P = (D_M - D_m)/(D_M + D_m)\), where \(D_M\) and \(D_m\) respectively are the density of states for the majority and minority spin bands at the Fermi level in leads. Depending on materials, \(P\) is often between \(\simeq 0.3(Ni)\) and \(\simeq 0.7(La_{0.7}Sr_{0.3}MnO_3)\) (see \[1\] p.149). Such an asymmetry between two spin bands causes TMR, defined as \(TMR = (R_{AP} - R_P)/R_P\), where \(R_P\) and \(R_{AP}\) respectively are device resistances in the cases, when magnetizations of two leads are parallel (P) and anti-parallel (AP). Neglecting the Coulomb charging effects it was shown that \(9\)

\[TMR = P^2/(1 - P^2). \tag{1}\]

In order to examine the interplay between spin and charge correlations, by solving the master equation, we calculate the current and the TMR for devices different in structure parameters, including the polarization \(P\) and the lead-magnetization alignment (parallel and anti-parallel), at a large range of bias voltage and temperature. The obtained results show that the charge effect not only makes TMR oscillated as the bias increases, but also considerably enhances it like that observed in F/F/F - and F/F/N-SETs \[3\]. We also
calculate the shot noise power as a function of the frequency as well as the bias voltage. Though the shot noise has been very extensively studied in metallic QD-structures \[19, 20, 21, 22, 23\], for Coulomb blockade F/N/F - single electron tunneling devices, when the magnetizations in ferromagnetic leads are collinear, we have found only two works by Bulka et al. \[10, 11\]. However, in contrast with our F/N/F-SETs of interest, where, as usually, the normal metallic QD is assumed to be large enough so that there is an electron thermalization, in these works the QD is assumed to have regularly separated discrete electron levels \[10\] or to have only a single electron level available for the tunneling process. Such a difference in model should be manifested in the noise behavior. Our study shows that though the spin correlation may cause a considerable enhancement of noise at finite frequencies, including a high peak, the zero-frequency noise is still always sub-poissonian even in the NDC region. The super-poissonian noise observed in \[10, 11\] is essentially related to particular structures of electron levels modelled. The gate voltage simply leads to an oscillation of the TMR and the noise with the same period as that for the conductance.

The paper is organized as follows. Sec.II is devoted to formulating the problem and presenting fundamental expressions. In Sec.III we present numerical results of current-voltage (I-V) characteristics, of TMR and of noise. In this section the effects of asymmetry, of polarization, of temperature, and of gate are in detail discussed. Lastly, a brief summary is given in Sec.IV.

II. GENERAL CONSIDERATION

Within the framework of the Orthodox theory \[18\] the state of the F-SET under study is entirely determined by the number of excess electrons in QD, \(n\). For a given \(|n\rangle\)-state, the free energy of the system has the form:

\[
F(n) = \frac{(C_2V/2 - C_1V/2 + C_gV_g - ne)^2}{2C_t} - \frac{(C_1V^2/4 + C_2V^2/4 + C_gV_g^2)/2 + e(n_1 - n_2)V/2}{2C_t},
\]

where \(e\) is the elementary charge, \(C_t = C_1 + C_2 + C_g\), and \(n_1(n_2)\) is the number of electrons that have entered the QD from the left (right). Any electron transfer across junctions results in a change in free energy \(F\). In the system of interest there are four possible sequential electron transfers across two junctions (\(\nu = 1\) and 2), to the right(+) or the left (-). The
change in free energy, $\Delta F^\pm_\nu$, associated with these electron transfers depends on the relative orientation of magnetizations in ferromagnetic leads. When the two lead-magnetizations are in parallel alignment (P-alignment), $\Delta F^\pm_\nu$ is independent of the orientation of electron spin [$\sigma = \uparrow$ (up) or $\downarrow$ (down)] and can be directly defined from (2) as

$$
\Delta F^\pm_1(n) = e^2 (1 \pm 2n) /2C_t \mp eC_gV_g/C_t \mp (C_2 + C_g/2) eV/C_t
$$

$$
\Delta F^\pm_2(n) = e^2 (1 \mp 2n) /2C_t \pm eC_gV_g/C_t \mp (C_1 + C_g/2) eV/C_t
$$

When lead-magnetizations are in anti-parallel alignment (AP-alignment), the up (down)-spin electron has a larger (smaller) tunneling rate for the source junction than for the drain junction. In this case, to ensure a balance between steady tunneling currents for each spin orientation, the chemical potential for up (down)-spin state, $\mu_{\uparrow(\downarrow)}$, in metallic QD should be shifted upwards (downwards) by (the same) amount, $\delta \mu_{\uparrow} = -\delta \mu_{\downarrow} \equiv \delta \mu$. Physically, such a chemical potential shift is equivalent to a non-equilibrium spin accumulation in QD. Taking into account this chemical potential shift, the change in free energy associated with the AP-alignment becomes depending on the orientation of electron spin $\sigma$ and the chemical potential shift $\delta \mu$ as :

$$
\Delta F^{\pm}_{\nu\sigma}(n) = \Delta F^{\pm}_{\nu}(n) \pm (-1)^{\nu-1}\delta \mu \sigma, \; \nu = 1, 2,
$$

where $\Delta F^{\pm}_{\nu}(n)$ is defined in (3) and for the Coulomb blockade device under study, when the spin-flip relaxation time is sufficiently large, the chemical potential shift $\delta \mu$ can be generally calculated from the balanced condition for spin currents.

Thus, though the free energy $F$ (2) of each charge state is spin independent, due to a non-equilibrium spin accumulation in QD and due to a difference between effective tunneling resistances associated with the majority and the minority spin, the tunneling rate, in general, depends on the spin orientation of tunneling electron. For the electron with spin $\sigma$, which tunnels across the $\nu$-junction, to the right (+) or the left (-), the rates are given by:

$$
\Gamma^{\pm}_{\nu\sigma} = (e^2 R_{\nu\sigma})^{-1} \Delta F^{\pm}_{\nu\sigma} /\left[\exp(\Delta F^{\pm}_{\nu\sigma}/k_BT) - 1\right]; \; \sigma = \uparrow, \downarrow,
$$

where $\Delta F^{\pm}_{\nu\sigma}$ are corresponding changes in free energy defined in eqs.(3) and (4), $R_{\nu\sigma}$ depends on the junction tunneling resistance $R_{\nu}$ and the spin polarization $P$ as:

$$
R_{\nu\uparrow(\downarrow)} = 2R_{\nu}/(1 \pm P_{\nu}), \; \nu = 1, 2,
$$

where $P_1 = P_2 \equiv P$ for the P-alignment and $P_1 = -P_2 = P$ for the AP-alignment device.
Using expressions (3)-(6), in principle, we can solve the master equation (ME) or perform Monte-Carlo simulations to calculate the current and further the TMR and the noise. In practice, for simple structures such as the F-SET under study the ME-method is much more efficient. Denoting \( p(n) \) as the probability of the state \(|n>\) of the system, the ME can be written in the matrix form:

\[
d\hat{p}(t)/dt = \hat{M}\hat{p}(t),
\]

where \( \hat{p}(t) \) is the column matrix of elements \( p(n, t) \) and \( \hat{M} \) is the evolution matrix with elements defined as follows: the diagonal elements,

\[
M(n, n) = -\left[ \sum_{\nu, \sigma} \Gamma_{\nu\sigma}^+(n) + \sum_{\nu, \sigma} \Gamma_{\nu\sigma}^-(n) \right]
\]

and non-diagonal ones,

\[
M(n, m) = \begin{cases} 
\sum_{\sigma} (\Gamma_{1\sigma}^+(m) + \Gamma_{2\sigma}^-(m)); & \text{if } m = n - 1 \\
\sum_{\sigma} (\Gamma_{1\sigma}^-(m) + \Gamma_{2\sigma}^+(m)); & \text{if } m = n + 1 \\
0; & \text{otherwise}.
\end{cases}
\]

Solving the ME (7) in the condition \( \sum_n p(n, t) = 1 \), one can calculate the stationary currents for each spin channel, \( I_\sigma, \sigma = \uparrow \text{ or } \downarrow \), which are time-independent and equal to the statistical average of corresponding currents through any of junctions, \( \nu = 1 \text{ or } 2 \): \( I_\sigma = \langle I_{\nu\sigma} \rangle = e \sum_n [\Gamma_{\nu\sigma}^+(n) - \Gamma_{\nu\sigma}^-(n)] p_{st}(n) \), where stationary probability \( p_{st}(n) \) is defined as \( p(n \leftarrow m | \tau \rightarrow \infty) = p_{st}(n)\delta_{nm} \) and \( p(n \leftarrow m | \tau) \) is the conditional probability for having state \(|n>\) at the time \( \tau \) under the condition that the state was \(|m>\) at an earlier time \( t = 0 \). This conditional probability obeys the same ME as for the probability \( p(n, t) \). Then, the total stationary net current is simply given by: \( I = I_\uparrow + I_\downarrow \). Further, from currents associated with the P-alignment and the AP-alignment of lead-magnetizations, we can calculate the TMR.

On the other hand, to study the noise we need to know the time-dependent net current \( I(t) \), which for F-SETs has the form:

\[
I(t) = \sum_\sigma I_\sigma(t) = \sum_\sigma \sum_\nu g_\nu I_{\nu\sigma}(t),
\]

where \( I_{\nu\sigma}(t) = e \sum_i [\Gamma_{\nu\sigma}^+(i) - \Gamma_{\nu\sigma}^-(i)] p(i, t) \), \( g_1 = C_2/C_t \) and \( g_2 = C_1/C_t \) [21].

In order to calculate the shot noise spectrum \( S(\omega) \) of this current \( I(t) \), we extended Korotkov’s expression of \( S(\omega) \) suggested for metallic SETs [20] to F/N/F-SETs of interest
and obtain

\[ S(\omega) = 2 \sum_{\nu} g_{\nu}^2 A_{\nu} + 4e^2 \sum_{\nu \mu \sigma \sigma'} g_{\nu} g_{\mu} \sum_{nm} [\Gamma_{\nu \sigma}(n) - \Gamma_{\nu \sigma}^{-}(n)] \]

\[ B_{nm} [\Gamma_{\mu \sigma'}^+(m|\mu^-)p_{st}(m|\mu^-) - \Gamma_{\mu \sigma'}^{-}(m|\mu^+)p_{st}(m|\mu^+)]. \]  

(10)

Here, \( A_{\nu} = e(I_{\nu}^+ + I_{\nu}^-) \) with \( I_{\nu}^\pm = e \sum_{n \sigma} p_{st}(n) \Gamma_{\nu \sigma}^\pm; \hat{B} = Re[(i\omega \hat{I} - \hat{M})^{-1}] \); and \( < m|\nu^\pm > \) is the state obtained from the state \( |m > \) by transferring an electron across the \( \nu \)-junction to the right (+)/ left (-).

Thus, once the ME has been solved, one can calculate the stationary current, the TMR and the noise. Except the case of zero temperature and at low bias of the first Coulomb staircase region, when the current expression can be analytically derived (see Appendix), in general, calculations have to be performed numerically. The results obtained for devices of different parameters (capacitances, tunneling resistances, polarizations and magnetization alignments) in a large range of bias voltage and temperature are presented in the next section, where the gate effect is also in detail analyzed.

III. NUMERICAL RESULTS

Numerical calculations have been systematically performed for a variety of devices with different parameters. The obtained results will be presented for only typical devices with (i) symmetric \( (R_1 = R_2 \equiv 16R_Q) \) and strongly asymmetric tunneling resistances \( (R_1 = 1000R_Q \) and \( R_2 = 5R_Q) \); (ii) two values of polarization, \( P = 0.3 \) and 0.9; and (iii) both P- and AP-alignments. Here \( R_Q = h/e^2 \) is the quantum resistance, and the value \( P = 0.9 \) is chosen to gain a more clear manifestation of spin effect. In all devices studied the capacitances are as follows: \( C_1 = 2C_2 \equiv 2C \). With chosen parameters these devices exhibit the most interesting behaviors in I-V curves such as a clear staircase structure and an NDC. Regarding the elementary charge \( e \), the quantum resistance \( R_Q \) and the capacitance \( C \) as basic units, in all figures presented below the voltage, the current, the energy (temperature, chemical potential) and the frequency are then measured in units of \( e/C, e/CR_Q, e^2/C, \) and \( (CR_Q)^{-1} \), respectively.

(a) Current and chemical potential shift. Fig.1 presents I-V characteristics for two typical devices mentioned above, symmetric (a) and asymmetric (b), in a large range of applied bias \( V \). In each figure two I-V curves corresponding to the case of P-alignment are certainly
coincident (solid lines), independent of $P$ (0.3 or 0.9). In the case of AP-alignment, on the contrary, the polarization effect becomes important: the dot-dashed curve of $P = 0.9$ is much lower than the correspondingly dashed curve of $P = 0.3$. In addition, for the symmetric device in Fig.1(a) the difference between two curves, corresponding to the same AP-alignment, but with different $P$ (or two curves corresponding to the same $P$ but with different alignments) seems to be much larger than that for the asymmetric device in Fig.1(b) and increases with increasing the bias. So, Fig.1 shows a relatively stronger spin effect in symmetric devices compared to asymmetric ones. This can be understood from the fact that the charge effect is more profoundly manifested in the asymmetric device (Fig.1(b)), where I-V curves show clear Coulomb staircases.

![I-V characteristics](image)

**FIG. 1:** I-V characteristics for (a) the symmetric device ($R_1 = R_2 = 16R_Q$) and (b) the asymmetric device ($R_1 = 1000R_Q$ and $R_2 = 5R_Q$). For both devices: $C_1 = 2C_2 = 2C$. The currents for P-alignment are independent of $P$ (solid lines). For the AP-alignment: dashed line - $P = 0.3$; dot-dashed line - $P = 0.9$. Insets (top and left in both figures): the chemical potential shift for the same device with the same $P$ as in the main figure. The equivalent circuit diagram of the device is drawn in the inset in bottom of Fig.1(b) [without gate and $T = 0$].

For the AP-alignment, when spin relaxation time is sufficiently longer than the time
between successive tunneling processes, as mentioned above, a non-equilibrium spin accu-
mulation in the QD may take place. Such a spin accumulation is equivalent to a difference
between two chemical potentials, corresponding to two spin states. With increasing the
bias, \( \mu_\uparrow \) rises to balance the spin incoming and outgoing rates, and \( \mu_\downarrow \) decreases by the same
amount of \( \delta \mu \). For systems without Coulomb blockade this chemical potential shift can be
simply evaluated as \( \delta \mu = PeV/2 \) \[14\], which seems to describe well even the data in the
inset of Fig.1(a) for the symmetric device, when the linearity of I-V curves are still weakly
affected by the charge correlation. For the asymmetric device, as can be seen in the inset of
Fig.1(b), though the average value of \( \delta \mu \) does increase with increasing \( P \) and \( V \) similar to
that observed in Fig.1(a), the charge correlation makes \( \delta \mu \) oscillated with the same period
of \( e/2C \) as the Coulomb staircase in I-V curves.

In Fig.1 the temperature is zero. Fig.2 describes the finite temperature effect in the most
interesting case of asymmetric devices with \( P = 0.3 \) (a) and 0.9 (b). As the temperature
increases, both the staircase in I-V curves and the oscillation of chemical potential shifts (see
insets) are steadily smeared. In principle, any finite temperature can destroys the Coulomb
gap, though in practice the current in the gap may be very small when the temperature is
still much smaller than the charging energy. Remarkably, for the asymmetric device with
\( P = 0.9 \), shown in Fig.2(b), an NDC region may be appeared at temperatures low enough.
The observed NDC gradually disappears when the temperature raises. In the particular
case of appropriate device parameters at zero temperature and low bias, when the current
expression can be analytically derived as shown in Appendix, actually, we can also derive
the condition for NDC to be observed.

(b) Tunnel magnetoresistance. As the typical measure of the spin effect in F-SETs, the
TMR attracts much attention from both experimental and theoretical sides. For F/N/F-
SETs under study, as can be seen in Fig.3, both the value and the bias-dependent behavior
of TMR are very sensitive to the asymmetry of SETs [(a) and (b) for symmetric, while (c)
and (d) for asymmetric SETs], to the polarization [(a) and (c) for \( P = 0.3 \), while (b) and
(d) for \( P = 0.9 \)], and to the temperature [\( k_B T = 0 \) (solid line), 0.01 (dashed line) and 0.02
(dot-dashed lines)]. Overall, in agreement with those reported for various F-SETs \[3, 8, 12\]
this figure generally shows that (i) the TMR oscillates with the same period of \( e/2C \) as that
for \( \delta \mu \) and with an oscillation amplitude decreasing as the bias \( V \) increases; (ii) the TMR
generally decreases with increasing \( V \) and becomes constant in the large bias limit; and
(iii) the temperature, smearing the oscillation of TMR at low biases, does not affect TMR at large biases, when the Coulomb blockade effect can be neglected. For the symmetric F-SETs, (a) and (b), the large-bias limiting values of TMR, defined quite well at $eV$ of several charging energy, seem to be in good agreement with the simple expression (1). For the asymmetric SETs, (c) and (d), the oscillation of TMR is much stronger and extends to a larger range of bias. By comparing four these figures to each other, one can learn much about the interplay between spin and charge effects in TMR. In particular, the symmetric device with $P = 0.9$ [Fig.3(b)] shows the most remarkable spin effect with high values of TMR, whereas the charge effect is so weak that TMR is almost bias-independent except a narrow region close to the Coulomb blockade threshold voltage.

Takahashi and Maekawa [4] and Kuo and Chen [14] have analyzed the gate effect in the tunneling current and the TMR in F-SETs. As well-known in the theory of SETs, the gate with voltage $V_g$ and capacitance $C_g$ leads to the effect similar to an offset charge of $C_g V_g$, which, in turn, can be related to the chemical potential shift in QD. Thus, one can expect to see an oscillation of TMR with increasing $V_g$ like that observed in the conductance of SETs.

In Fig.4 we show the TMR versus the gate parameter $C_g V_g$, calculated for the asymmetric device with $P = 0.3$ (a) and 0.9 (b) [the same devices as in Figs.3(c) and (d)] at two biases: $V = 0.7$ (solid line) and $V = 1.4$ (dashed lines). It is clear from both figures that all the curves, though strongly different in value and form, exhibit a well-defined oscillation with
FIG. 3: TMR is plotted as a function of $V$ [$V \geq V_c$, where $V_c$ is the Coulomb blockade threshold voltage] at various temperatures ($k_B T$): 0 (solid line); 0.01 (dashed line); and 0.02 (dot-dashed line). Figures: (a) and (b) - symmetric device with $P = 0.3$ and 0.9, respectively; (c) and (d) - asymmetric device with $P = 0.3$ and 0.9, respectively [without gate].

The same period of $e/C_g$ as that well-known for the conductance. Note that for the device of $P = 0.3$ (a) the TMR though smaller in value is relatively more sensitive to the change of gate, compared to the device of higher polarization in figure (b). Moreover, comparing two curves in each figure, we see that the amplitude of TMR-oscillation is larger at lower bias, when the Coulomb blockade effect is more important.

(c) Shot noise. The shot noise in F-SETs, as mentioned above, has been studied by Bulka et al. [10, 11], but for QD-models different from ours. Fig.5 shows the frequency dependence of the normalized noise $S(\omega)/2eI$ calculated from eq.(10) for the asymmetric devices with AP-alignment. In each figure [(a) for $P = 0.3$ and (b) for $P = 0.9$] the results taken at different biases, $V = 0.47$, 0.53, and 0.74, are compared. These biases are specially chosen from the typical regions of I-V curve (NDC region, local minimum, and PDC region). It is clear in both figures that the normalized noise generally tends to a constant value greater than 0.5 in the limit of high frequency. This limiting value depends on device parameters and on bias. It may be even greater than 1 as can be seen in Fig.5(b). In the opposite region of low frequency, the picture is more complicated, very sensitive to device parameters. Even for a given device the noise may experience a very high hill or a deep valley, depending only on
FIG. 4: TMR is plotted versus the gate parameter $C_g V_g$ for asymmetric devices with $P = 0.3$ (a) and 0.9 (b) at two biases: $V = 0.7$ (solid line) and 1.4 (dashes line) [$T = 0$].

the bias. In fact, from the noise expression (10) we can at least show there really exists such a maximum (or minimum) of noise at some frequency. The calculation, though elementary, is too lengthy to be presented here. We like only to emphasize that the noise enhancement observed is due to the spin correlation. This explains why the noise for the device of $P = 0.9$ in Fig.5(b) is generally larger than that in Fig.5(a). As one more demonstration, we show in Fig.5(b) the data for the same asymmetric device of $P = 0.9$, but with P-alignment, and at the same bias $V = 0.74$ (dashed line). It is clear that in this case like in normal metallic SETs [20] there is no noise-enhancement in the whole range of frequency. Here, note that for normal metallic SETs the high-frequency limiting value of normalized noise is $g_1^2 + g_2^2$, which is equal to 0.5 for the SET with equal junction capacitances [$C_1 = C_2$].

In Fig.6 the Fano factor, $F_n = S(0)/2eI$, is plotted as a function of bias $V$ [two upper curves, see the left axis] for the same devices as in Fig.5. Interestingly, in both cases under study, $P = 0.3$ (solid line) and $P = 0.9$ (dashed line), $F_n$ oscillates with the same period of $e/2C$ as that for $\delta \mu(V)$ [two lower curves, borrowed from Fig.2; see the right axis]. An accurate comparison of two corresponding curves, $F_n$ (upper) and $\delta \mu$ (lower), for the same $P$ reveals that in each period the highest value of $F_n$ exactly corresponds to the minimum
FIG. 5: The frequency dependence of normalized noise calculated for asymmetric devices with AP-alignment and with $P = 0.3$ (a) and $0.9$ (b) at biases (from bottom): $V = 0.49$, $0.53$, and $0.74$. In (b) the data for the same device of $P = 0.9$ at $V = 0.74$, but with P-alignment, is also shown by the dashed line, which should be compared with the first solid line in the top [without gate].

In the δµ(V). Thus, Fig.6 demonstrates that the $F_n$- and the δµ-oscillations have the same root as the Coulomb staircase in I-V curves. Experimentally, an exact correspondence between the noise oscillation and the current staircase has been observed in the system of a single InAs-QD embedded between resonant tunneling barriers [24]. Another important noise feature deduced from Fig.6 is that for F/N/F-SETs under study the zero frequency noise seems to be always sub-poissionian [$F_n < 1$] in spite of the noise enhancement realized at finite frequencies [Fig.5] and an NDC region observed in I-V curves [Fig.2]. Deviations of the shot noise $S(0)$ from the full (poissonian) value $2eI$, i.e. $F_n \neq 1$, are the subject of a great number of works [see references in [23]]. It is widely accepted that the charge correlation may suppress or enhance the noise, depending on the conduction regime. And, two phenomena, NDC and super-poissionian noise [$F_n > 1$] are not necessarily accompanied by each other [22, 23].

Finally, we demonstrate in Fig.7 how the gate affects the Fano factor $F_n$ for the same
FIG. 6: The zero-frequency normalized noises (two upper curves) and the corresponding chemical potential shifts (two lower curves) are plotted versus the bias for asymmetric devices with $P = 0.3$ (solid line) and 0.9 (dashed line) [without gate].

device as in Fig.6(b) [with $P = 0.9$] and at the same biases [$V = 0.49$ (solid line), 0.53 (dashed line), and 0.74 (dot-dashed line)] as in Fig.5. At any bias, as expected, the gate makes the factor $F_n$ oscillated with the period of $e/C_g$ as the gate voltage $V_g$ increases. The amplitude of oscillation, however, decreases as the bias increases, showing a gradual weakness of charge correlation effect. Besides, it is important that, despite the gate-induced oscillation, the zero-frequency noise $S(0)$ is still always sub-poissonian.

FIG. 7: The zero frequency normalized noise is plotted versus the gate parameter $C_gV_g$ for the asymmetric device with $P = 0.9$ at several biases: $V = 0.49$ (solid line); 0.53 (dashed line), and 0.74 (dot-dashed line).
IV. CONCLUSION

We have studied the tunneling through F/N/F-SETs in the Coulomb blockade regime, assuming that the spin relaxation time in the normal metallic QD is much larger than other characterizing times in the problem. Using the master equation, we have calculated the I-V characteristics, the TMR and the current noise spectrum in devices different in structure parameters, in polarization, and in lead-magnetization alignment.

It was shown that the interplay between spin and charge correlations strongly depends on the asymmetry of measured device. While in symmetric devices of equal tunneling resistances the spin correlation considerably reduces the current, in asymmetric devices the charge correlation becomes more important, leading to I-V curves with Coulomb staircases and even with NDC regions. The charge correlation also makes both the chemical potential shift, which describes the spin accumulation in QD, and the TMR oscillated as the bias increases with the same period as the Coulomb staircase. All these effects are gradually smeared by increasing the temperature. In the limit of large bias, when the charge correlation can be neglected, the TMR becomes independent of bias. Typical manifestations of the interplay between two correlations can be also found in the frequency dependence as well as the bias-dependence of the noise spectrum. While the charge correlation always suppresses the noise in F-SETs, the spin correlation may cause a noise enhancement at finite-frequencies, including a very high peak. The zero-frequency noise is however always sub-poissonian, regardless of I-V curve behaviors. The gate voltage causes an oscillation of not only conductance, but also TMR and noise. While some of current and TMR results obtained in this work are generally in agreement with those reported in literature for different kinds of F-SETs, the noise results are new and useful to better understand the physics of the tunnel process in F/N/F-SETs.

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Appendix

Following the way suggested in ref. [25], we can derive an analytical expression for the stationary net current \( I \) at zero temperature within the first Coulomb staircase region, \( e/2C_1 \leq V \leq e/C_1 \) (assuming \( C_1 > C_2 \) and \( C_g = 0 \)). Actually, under these conditions, the rate expression (5) becomes simple as \( \Gamma_{\nu\sigma}^\pm = \Theta(\Delta F_{\nu\sigma}^\pm|\Delta F_{\nu\sigma}^\pm|/e^2R_{\nu\sigma}) \) and all the probabilities \( p(n) \) are equal to zero except those for two states \(|-1> \) and \(|0>\). The master equation can be then exactly solved that gives

\[
I = \frac{[\Gamma_{1t}^+(1) + \Gamma_{1i}^-(1)]\Gamma_{2t}^+(0) + \Gamma_{2i}^+(0)}{\Gamma_{1t}^+(1) + \Gamma_{1i}^-(1) + \Gamma_{2t}^+(0) + \Gamma_{2i}^+(0)}
\]

Correspondingly, the quantities \( \Delta F_{\nu\sigma}^\pm(n) \) in the rate expression are now defined as

\[
\Delta F_{1t(\nu)}^+(1) = -e^2/2C_t - eC_2V/C_t + \mu ; \quad \Delta F_{2t(\nu)}^+(0) = e^2/2C_t - eC_1V/C_t + \mu ,
\]

where

\[
\mu = \left[cV(1 + \gamma) - \sqrt{(1 + \gamma)^2e^2V^2 - 4(1 - \gamma)^2\alpha\beta}\right]/2(1 - \gamma),
\]

\[
\gamma = (1 - P)^2/(1 + P)^2; \quad \alpha = eC_1V/C_t - e^2/2C_t; \quad \beta = eC_2V/C_t + e^2/2C_t ; \quad \text{and} \ C_t = C_1 + C_2.
\]

From the current expression obtained the condition for observing an NDC could be also derived.

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