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Inelastic Cotunneling Through an Interacting Quantum Dot with a Quantum Langevin Equation Approach

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In recent years, there has been great interest in investigation of electronic transport through semiconductor nanoscale devices. It is well known that tunneling through a quantum dot (QD) includes two distinct mechanisms: sequential (first-order) tunneling if the QD level is in resonance with the Fermi levels of the electrodes, and higher-order coherence tunneling (cotunneling)[1] when the QD level is far removed from resonance, with sequential tunneling exponentially suppressed. This kind of higher-order processes involves the simultaneous tunneling of two or more electrons through the device, which defines a primary limitation to the accuracy of quantum manipulation of single-electron devices. Therefore, it is desirable to develop a unified and effective theoretical approach for thorough examination nonequilibrium inelastic cotunneling through a single-level QD subject to a finite magnetic field in the strong Coulomb blockade regime, in the weak tunneling limit.

For this purpose, we have recently proposed a generic quantum Langevin equation approach[2] to establish a set of quantum Bloch-type dynamical equations describing inelastic cotunneling phenomenology modeled by the Kondo Hamiltonian[3] at arbitrary bias-voltage and temperature. In our formulation, the operators of the QD spin and the reservoirs were first expressed formally by integration of their Heisenberg equations of motion, exactly to all orders in the tunnel coupling constants. Next, under the assumption that the time scale of the decay processes is much slower than that of free evolution, we replaced the time-dependent operators involved in the integrands of these equations of motion approximately in terms of their free evolution. Thirdly, these equations of motion were expanded in powers of the tunnel-coupling constants to second order (linear response theory). On the basis of these consideration, jointly with normal ordering, we developed the Bloch-type equations describing the time evolution of the spin variables of the QD explicitly and compactly in terms of the response and the correlation functions of the free reservoir variables, which not only provides explicit analytic expressions for the relaxation and decoherence in the QD spin induced by cotunneling, but also facilitates the derivation of the nonequilibrium magnetization of the QD. Employing this resulting QD magnetization and performing linear response calculation, we can also derive closed-form expressions for the spin-resolved currents and their fluctuation, which facilitated our calculation of both the charge current [Fig. 1(a)] and the spin current (Fig. 2), as well as their frequency-independent auto- and cross-shot noises [Fig. 1(b) and Fig. 3].

Acknowledgment

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References

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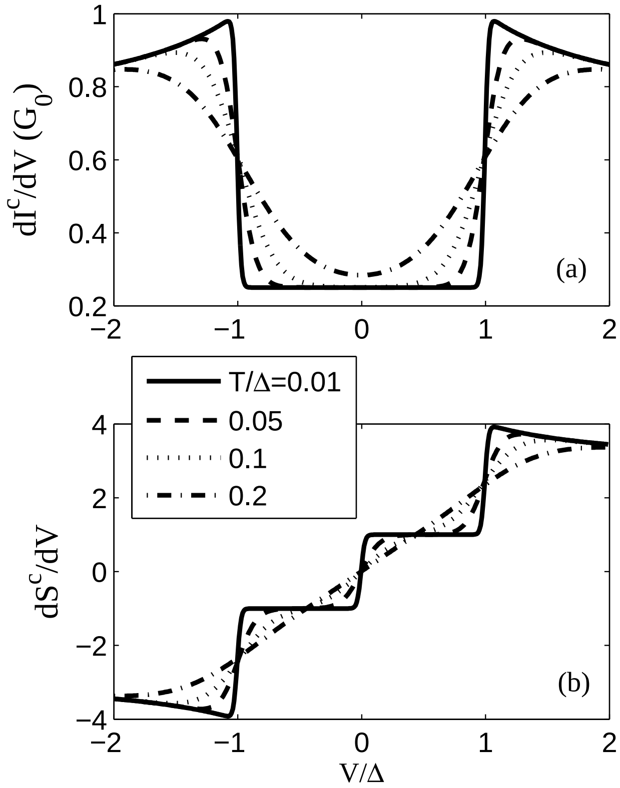

Fig. 1. (a) The calculated differential conductance dI^c/dV vs. bias-voltage V/Δ for several temperatures at nonzero magnetic field in units of $G_0 = 4\pi J_{LR}^2 \rho_L \rho_R$ (linear conductance at zero magnetic field); (b) The differential auto-shot noise dS_{LL}^c/dV vs. bias-voltage. The parameters we used in calculation are: $J_{LL}\rho_L = J_{RR}\rho_R = J_{LR}\sqrt{\rho_L \rho_R} = 0.02$.

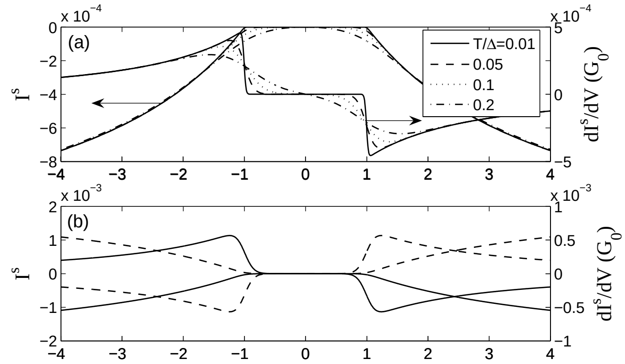

Fig. 2. The calculated spin current, I^s, and its differential conductance, dI^s/dV, as functions of bias-voltage V/Δ, at nonzero magnetic field. (a) exhibits results for several temperatures and $J_{RR}/J_{LL} = 4.0$, $J_{LL} = 0.02$. (b) plots the results for $J_{RR}/J_{LL} = 5.0$ ($J_{LL} = 0.02$) as solid lines, and for $J_{LL}/J_{RR} = 5.0$ ($J_{RR} = 0.02$) as dashed lines.

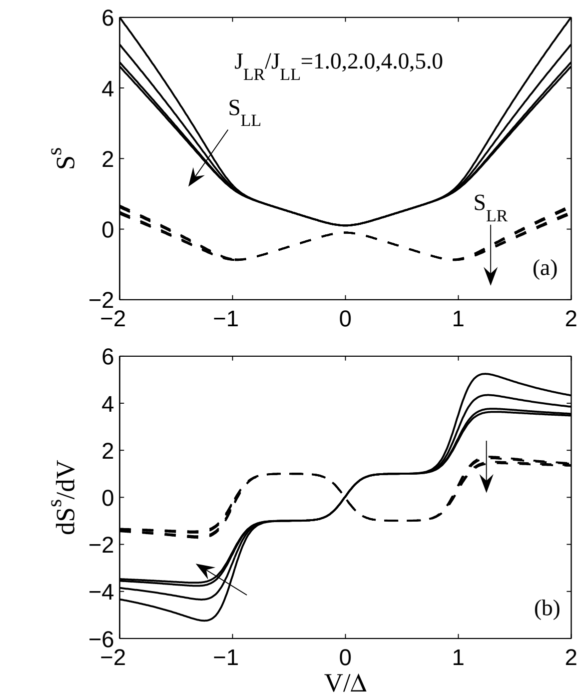

Fig. 3. (a) The calculated auto- (the solid lines) and cross-shot noises (the dashed lines) for spin current, S^s, and (b) the differential shot noise, dS^s/dV, as functions of bias-voltage V/Δ at the temperature $T = 0.05$ and various J_{RR}/J_{LL} ($J_{LL} = 0.02$).