Noise of quantum dots in the ac Kondo regime: Slave-boson mean-field method and Floquet theorem

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The noise of quantum dots in the ac Kondo regime is investigated by means of slave-boson mean-field method and Floquet theorem. A nonadiabatical formula for the noise power is obtained in the Floquet-Green formalism to take into account interaction effects. We show that, as a manifestation of many-particle correlations, the singularities of photon-assisted noise for noninteracting dots cannot survive in the ac Kondo regime. These peculiar features of the photon-assisted noise thus provide us an alternative probe to distinguish the noninteracting resonant tunneling and the many-particle Kondo resonance.

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The noise of phase-coherent conductors has recently drawn much attention[1] in making a full description of the charge transport. As a time varying field provides us a direct access to modulate the phase of wave functions,[2,3] considerable recent interest is focused on the photon-assisted noise to reveal coherent effects that are absent in conductance measurements.[4–7] In particular, Lesovik and Levitov (LL) (Ref. 4) demonstrated the sensitivity of the photon-assisted noise to the phase of transport electrons subjected to both an ac field and a dc bias. It is found that the commensurability of the two energy scales, which are defined by the external voltage bias V and the ac frequency Ω, can lead to singular dependence of the noise power S as a function of V. This phase-coherent phenomenon is also expected to remain distinct at weak ac field for mesoscopic conductors in the nonadiabatic regimes.[5] A more recent example of the photon-assisted noise is the possibility to manipulate the relative noise level via ac fields as shown by Camalet *et al.*[6] However, these previous studies were based on the assumption that the coherent conductors are free from the Coulomb interaction.[4–6]

For realistic quantum dots, Coulomb interaction plays an important role and the transport behavior is genuinely many particle. Particularly, when the temperature is lower than the characteristic Kondo temperature T_K, the transport with strong Coulomb interaction is dominated by the well-known Kondo effect, i.e., the transport via many-particle Kondo resonance.[8–10] One can readily verify that the singular behavior of the noise power which was predicted for noninteracting dot by LL is most pronounced when the dot is in the resonant tunneling. Because the Kondo resonance has a close analogy to the noninteracting resonance in many aspects such as the unitary limit in conductance measurements,[11] it is thus interesting to ask whether such a behavior can be expected in the many-particle Kondo resonance. As we will show in the following, the two resonances, namely, the noninteracting resonance and the Kondo resonance, show diverse behaviors in the photon-assisted noise, in contrast to the conductance measurement.

In the ac Kondo regime, the coherence is influenced by the interplay between the time-dependent field and the Coulomb interactions. Comparing with the noninteracting cases, a general formula of the photon-assisted noise in the ac Kondo regime has been lacking. There have been some attempts to study the conductance and local density of states (LDOS) of quantum dots in the ac Kondo regime.[12–20] It is noteworthy that several studies[14–16] have implied that the Kondo resonance is actually not influenced by an ac gate voltage when the energy scale of the ac parameters is much lower than the Kondo temperature. However, a clear picture on the robustness of the Kondo resonance against the weak ac field is less illuminated.

In this Brief Report, a generic formula [Eq. (7)] for the time-averaged zero-frequency noise power of an interacting dot in ac field is developed. Remarkably, it is found that singularities of the photon-assisted noise cannot survive in the strongly correlated Kondo regime. This is in great contrast to the predictions of LL for noninteracting resonant dots.[4,5] Moreover, we show that the robustness of the Kondo resonance discussed above is a direct manifestation of the genuine many-particle correlations. As both the noninteracting resonance and the Kondo resonance can reach the unitary conductance, our results show that the photon-assisted noise provides an alternative probe to distinguish the noninteracing and Kondo resonances, which cannot be achieved by traditional conductance measurements.

Our results are based on the slave-boson technique[21,22] in the mean-field (SBMF) approximation.[23,24] The strong-coupling SBMF theory has been well known to be a reliable and powerful method in describing the Kondo physics at low temperatures.[9] Here we will generalize this method with the help of Floquet theorem[2,3] to include a weak monochroic ac field nonadiabatically. We believe that it can still yield reliable results since the energy scales of interest defined by the ac and dc parameters are lower than the Kondo temperature.

The system of interest is a single level quantum dot attached to the left (L) and right (R) leads, which is depicted in the inset of Fig. 1. The energy level is modulated by an oscillating gate voltage. For a large Coulomb interaction on the dot, the system can be represented by the infinite-U (U is the Coulomb strength) Anderson model by introducing the slave-boson field b and a pseudofermion operator f_σ (Refs. 21 and 23) as

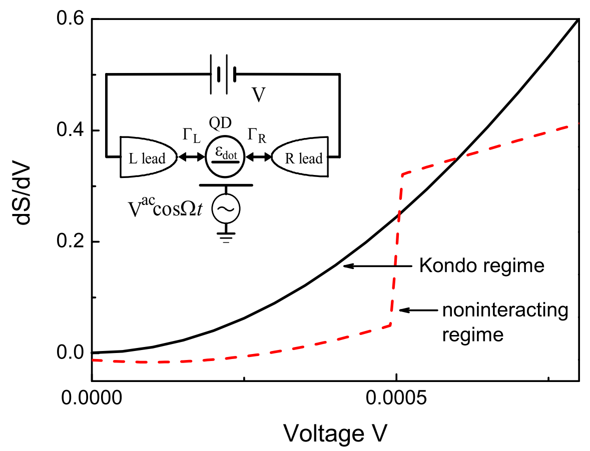

FIG. 1. (Color online) The derivative of noise with respect to bias dS/dV for quantum dots in the ac Kondo regime (solid line) and noninteracting situations (dashed line). The inset shows the schematic plot of the quantum dot driven by an oscillating gate voltage.

$$H = \sum_{\alpha,q,\sigma} (\epsilon_q + eV_\alpha^{\rm dc}) c^\dagger_{q\alpha\sigma} c_{q\alpha\sigma} + \sum_{\alpha,q,\sigma} (V_\alpha b^\dagger c^\dagger_{q\alpha\sigma} f_\sigma + \text{H.c.}) + \sum_\sigma (\epsilon_{\rm dot} + eV^{\rm ac}\cos\Omega t) f^\dagger_\sigma f_\sigma + \lambda(t)\left(\sum_\sigma f^\dagger_\sigma f_\sigma + b^\dagger b - 1\right), \quad (1)$$

where the last term with the Lagrange multiplier λ represents the constraint to prevent double occupancy in the limit of $U\to\infty$ at any time throughout the evolution of the system, i.e., $\Sigma_\sigma f^\dagger_\sigma(t) f_\sigma(t) + b^\dagger(t)b(t) = 1$. $c^\dagger_{q\alpha\sigma}$ ($c_{q\alpha\sigma}$) is the creation (annihilation) operator for electrons in the α (α=L,R) lead with the quantum number q and spin index σ. V_α is the hopping matrix element between the dot and α lead. In the following, we treat the dot-lead coupling in the wide-band limit; i.e., the coupling strength $\Gamma_\alpha(\epsilon) = 2\pi\Sigma_q |V_\alpha|^2 \delta(\epsilon - \epsilon_q)$ is energy independent for $|\epsilon| < D$, where D represents the bandwidth. $\epsilon_{\rm dot}$ is the energy level of the dot. $V^{\rm ac}$ is the ac amplitude with the frequency Ω. $V^{\rm dc}_{\rm L,R} = \pm\frac{1}{2}V$ for symmetric coupling, where V is the dc bias across the quantum dot.

In the lowest order of mean-field approximation, we replace the slave-boson operator by its expectation value, i.e., $\langle b(t)\rangle = b(t)$,[23] and neglect the fluctuations of the slave operator around its expectation value. From the constraint condition and the equation of motion of the slave-boson operator, we have a set of self-consistent equations for the mean values of $b(t)$ and $\lambda(t)$ as

$$b^*(t)b(t) + \sum_\sigma \langle f^\dagger_\sigma(t) f_\sigma(t)\rangle = 1,$$

$$-i\hbar\frac{\partial}{\partial t} b(t) = \lambda(t) b(t) + \sum_{q\alpha\sigma} V_\sigma \langle c^\dagger_{q\alpha\sigma}(t) f_\sigma(t)\rangle. \quad (2)$$

In order to solve the above equations self-consistently, one needs information on the *double-time* Green's functions $G^<_{\sigma;q\alpha\sigma}(t,t') = i\langle c^\dagger_{q\alpha\sigma}(t') f_\sigma(t)\rangle$ and $G^<_{\sigma;\sigma}(t,t') = i\langle f^\dagger_\sigma(t') f_\sigma(t)\rangle$. For the sake of convenience, we take $\hbar = e = k_B = 1$ and drop the spin index σ from Green's function $G_{\sigma;\sigma}$ of the quantum dot since the spin degeneracy is conserved.

As Hamiltonian (1) is invariant under the discrete time translation by one period of the driving, i.e., $H(t) = H(t+2\pi/\Omega)$, it is more convenient to work within an enlarged Hilbert space to include the Floquet basis of time periodic functions $|k\rangle = \exp(-ik\Omega t)$.[2] The periodicity of the driving field allows us to write $b(t) = \Sigma_k b_k e^{-ik\Omega t}$ and $\lambda(t) = \Sigma_k \lambda_k e^{-ik\Omega t}$. With the help of Floquet theorem, the set of equations in Eq. (2) can be closed as nonlinear integral equations by eliminating the degrees of freedom of the lead and Fourier transform the double-time functions in the Floquet space,

$$\mathcal{B}\cdot\mathcal{B}^\dagger - 2i\int \frac{d\epsilon}{2\pi}\mathcal{G}^<(\epsilon) = 1,$$

$$\mathcal{B}^\kappa\cdot\mathcal{B}^\dagger + \mathbf{\Lambda}\cdot\mathcal{B}\cdot\mathcal{B}^\dagger - 2i\int\frac{d\epsilon}{2\pi}\mathcal{G}^<(\epsilon)(\epsilon - \mathcal{H}^F_{\rm dot}) = 0, \quad (3)$$

where the elements of the matrices in Eq. (3) are given by $\mathcal{B}_{k,k'} = b_{k-k'}$, $\mathcal{B}^\kappa_{k,k'} = (k-k')\Omega b_{k-k'}$, and $\mathbf{\Lambda}_{k,k'} = \lambda_{k-k'}$, with k and k' as the indices for the Floquet basis. The matrix element of the Floquet-Green function is $[\mathcal{G}^<(\epsilon)]_{k,k'} = \langle\langle k|G^<(t,\epsilon)|k'\rangle\rangle$. Here $G^<(t,\epsilon)$ is the Fourier transform of the double-time Green's function $G^<(t,t')$ and the inner product is defined as $\langle\langle k|k'\rangle\rangle := \frac{\Omega}{2\pi}\int_0^{2\pi/\Omega} e^{ik\Omega t} e^{-ik'\Omega t}$. $\mathcal{H}^F_{\rm dot}$ is the Floquet Hamiltonian of the quantum dot, which is defined as $\mathcal{H}^F_{\rm dot} = \epsilon_{\rm dot} + eV^{\rm ac}\cos(\Omega t) + \lambda(t) - i\hbar\frac{\partial}{\partial t}$. One can see that the Lagrange multiplier $\lambda(t)$ acts as a dynamical field which contributes to the time evolution of the system. As we will show later, this time-dependent Lagrange field which arises from the zero or single occupancy constraint plays an important role in the ac Kondo regime.

From the Keldysh formalism for the double-time Green's function, the lesser Floquet-Green function $\mathcal{G}^<$ that appears in Eq. (3) can be written in matrix form as

$$\mathcal{G}^<(\epsilon) = \mathcal{G}^r(\epsilon)\mathcal{E}^<(\epsilon)\mathcal{G}^a(\epsilon), \quad (4)$$

where the retarded (r) and advanced (a) Floquet-Green's functions $\mathcal{G}^{r/a}$ in Eq. (4) can be found from the resolvent $\mathcal{G}^r(\epsilon) = [\mathcal{G}^a(\epsilon)]^\dagger = 1/(\epsilon - \mathcal{H}^F_{\rm dot} - \mathcal{E}^r(\epsilon))$. The Floquet self-energy due to the coupling to the leads is $\mathcal{E}^r(\epsilon) = \Sigma_\alpha \mathcal{E}^r_\alpha(\epsilon) = -\frac{i}{2}\Sigma_\alpha \mathcal{B}\cdot\mathbf{\Gamma}_\alpha\cdot\mathcal{B}^\dagger$, where $[\mathbf{\Gamma}_\alpha(\epsilon)]_{k,k'} = \Gamma_\alpha(\epsilon + k\Omega)\delta_{k,k'}$. The lesser Floquet self-energy can be proved as $\mathcal{E}^<(\epsilon) = \Sigma_\alpha \mathcal{E}^<_\alpha = i\Sigma_\alpha \mathcal{B}\cdot\mathbf{\Gamma}_\alpha(\epsilon)\cdot\mathcal{F}^<_\alpha(\epsilon)\cdot\mathcal{B}^\dagger$, where $[\mathcal{F}^<_\alpha]_{k,k'}(\epsilon) = f_\alpha(\epsilon + k\Omega)\delta_{k,k'}$ and f_α is the Fermi distribution function in the α lead. In the absence of ac field, the matrices in Eq. (3) are trivially diagonal in the Floquet space. Equation (3) can then recover the self-consistent equations for stationary cases.[25,26]

We are interested in the photon-assisted noise in the ac Kondo regime. The noise can be characterized by the current fluctuation as

$$S_{\rm L}(t,t') = \frac{1}{2}\langle\{\Delta\hat{J}_{\rm L}(t), \Delta\hat{J}_{\rm L}(t')\}\rangle, \quad (5)$$

with the operator $\Delta\hat{J}_{\rm L}(t) = \hat{J}_{\rm L}(t) - \langle\hat{J}_{\rm L}(t)\rangle$ representing the fluctuations of the current from the left lead, $\hat{J}_{\rm L}(t)$, from its expectation value $\langle \hat{J}_{\rm L}(t)\rangle$. The current operator $\hat{J}_{\rm L}(t)$ can be found from the evolution of the charge numbers of the left lead as

$$\hat{J}_{\rm L}(t) = \frac{ie}{\hbar}\sum_{q\sigma}[V_{\rm L}c^{\dagger}_{k{\rm L}\sigma}(t)f_{\sigma}(t)b^{\dagger}(t) - \text{H.c.}]. \tag{6}$$

By inserting Eq. (6) into Eq. (5) and replacing the slave-boson operator with its mean-field value, one can arrive at the time-averaged zero-frequency noise spectrum power as

$$\begin{aligned} S(0) &= \frac{\Omega}{2\pi}\int_0^{2\pi/\Omega} dt 2\int dt' S_{\rm L}(t,t') \\ &= \frac{2e^2}{h}\int d\epsilon[\mathcal{E}^{>}_{\rm L}\mathcal{G}^{<} + \mathcal{G}^{>}\mathcal{E}^{<}_{\rm L} - (\mathcal{G}^{r}\mathcal{E}^{>}_{\rm L} + \mathcal{G}^{>}\mathcal{E}^{a}_{\rm L})\cdot(\mathcal{G}^{r}\mathcal{E}^{<}_{\rm L} \\ &\quad + \mathcal{G}^{<}\mathcal{E}^{a}_{\rm L}) + \mathcal{G}^{>}\cdot(\mathcal{E}^{r}_{\rm L}\mathcal{G}^{r}\mathcal{E}^{<}_{\rm L} + \mathcal{E}^{r}_{\rm L}\mathcal{G}^{<}\mathcal{E}^{a}_{\rm L} + \mathcal{E}^{<}_{\rm L}\mathcal{G}^{a}\mathcal{E}^{a}_{\rm L}) \\ &\quad + (\mathcal{E}^{r}_{\rm L}\mathcal{G}^{r}\mathcal{E}^{>}_{\rm L} + \mathcal{E}^{r}_{\rm L}\mathcal{G}^{>}\mathcal{E}^{a}_{\rm L} + \mathcal{E}^{>}_{\rm L}\mathcal{G}^{a}\mathcal{E}^{a}_{\rm L})\cdot\mathcal{G}^{<} - (\mathcal{E}^{r}_{\rm L}\mathcal{G}^{>} \\ &\quad + \mathcal{E}^{>}_{\rm L}\mathcal{G}^{a})\cdot(\mathcal{E}^{r}_{\rm L}\mathcal{G}^{<} + \mathcal{E}^{<}_{\rm L}\mathcal{G}^{a}) + \text{H.c.}]_{0,0}, \end{aligned} \tag{7}$$

where $\mathcal{G}^{>}$ and $\mathcal{E}^{>}_{\rm L}$ are the greater Floquet-Green function of the dot and the corresponding greater self-energy due to the coupling to the L lead. The Keldysh formalism for $\mathcal{G}^{>}$ has the same structure as Eq. (4) with the replacement of $< \to >$ and the greater Floquet self-energy $\mathcal{E}^{>}(\epsilon)=\Sigma_{\alpha}\mathcal{E}^{>}_{\alpha}(\epsilon)$, with $\mathcal{E}^{>}_{\alpha}(\epsilon)=-i\mathcal{B}\cdot\mathbf{\Gamma}_{\alpha}(\epsilon)\cdot\mathcal{F}^{>}_{\alpha}(\epsilon)\cdot\mathcal{B}^{\dagger}$, where $\mathcal{F}^{>}_{\alpha}=1-\mathcal{F}^{<}_{\alpha}$.

Equation (7) expresses the time-averaged zero-frequency noise within the compact Floquet-Green formalism. It goes beyond the adiabatic limit and is valid for arbitrary ac parameters. Different from the formula presented in Ref. 6, which is valid for a noninteracting conductor and only the retarded Floquet-Green function is needed, Eq. (7) can be applied to the situations with interaction effects provided that the Hamiltonian can be written in the quadratic form and the Wick theorem is applicable.[26] As a matter of fact, not only the retarded and advanced Floquet-Green functions but also the lesser and greater Floquet-Green functions which can describe the nonequilibrium distribution in the conductor appear in the formula presented above.

Limited by the validation of SBMF theory, the parameters of the ac and dc fields are restricted to be lower than the relevant energy scale defined by the Kondo temperature T_K. For the sake of convenience, we have set $\Gamma=\Gamma_{\rm L}+\Gamma_{\rm R}=1$ as the energy unit. The device parameters are given by $\epsilon_{\rm dot}=-3.5$ and $D=60$ at zero temperature, so that the Kondo temperature T_K is $T_K\approx 10^{-3}$. The ac frequency and amplitude of the time oscillating gate are chosen as $V^{\rm ac}=\Omega=0.5T_K$. For equilibrium Kondo dot, the LDOS displays a narrow peak, i.e., the Kondo resonance, with the width of T_K at the Fermi level of the leads. If the quantum dot is driven out of equilibrium, the peak and width of the LDOS will be renormalized due to the many-particle correlation.

For the parameters given above, the Kondo dot at stationary operates in the unitary limit and the transport behavior resembles greatly that of the noninteracting dot with the level shifted to resonance. For better understanding of the role of the many-particle correlation, both results of dS/dV for noninteracting dot and Kondo dot are obtained from Eq. (7) and presented in Fig. 1 for comparison. The parameters of the noninteracting dot are chosen to make its LDOS identical to the Kondo resonance at equilibrium. The behavior of dS/dV of a noninteracting dot is displayed as the dashed line in Fig. 1. A steep rise is observed at $\Omega=V$, consistent with the predictions by LL.[4] The distinct step in dS/dV shows the extreme sensitivity of noise properties to the modification of phase by the weak ac field. The behavior of dS/dV in ac Kondo regime is displayed as the solid line in Fig. 1. No steps are found in dS/dV, in great contrast to the noninteracting dot. Moreover, our numerical results show that the difference in the noise between Kondo dots with or without the weak ac field can be neglected. The disappearance of the noise singular behavior in Kondo resonance has also been observed when different ac parameters which are within the validity of the SBMF method in the numerical calculation are chosen. The disappearance of singularities of noise in the ac Kondo regime indicates that the phase-coherent transport is merely slightly modified by the ac field. In other words, the ac field is effectively screened to influence the phase of Kondo resonance. This differs drastically to that of noninteracting resonance situations.

The physical origin of this screen effect can be best understood by looking at the mean-field Hamiltonian in Eq. (1) and comparing it with that of the ac-driven non-interacting dot. One can see that besides the external ac gate voltage with frequency Ω which modulates the electron level, the slave boson $b(t)$, and Lagrange multiplier $\lambda(t)$ fields which arise due to the many-particle effect act as dynamic potentials and influence the dynamics of the quantum dot in the ac Kondo regime. Both $b(t)$ and $\lambda(t)$ must be determined self-consistently by the constraint equations defined in Eq. (3). For the weak ac fields, our numerical results show that the oscillating part of the slave-boson mean field $b(t)$ is not strong enough to modulate the dynamics of the dot. The dominant contribution of $b(t)$ to the renormalization is the dc part b_0. However, in order to fulfill the constraint of zero or single occupancy, the oscillating part of $\lambda(t)$ follows the evolution of the external ac gate voltage with a phase shift of π, i.e., $\lambda_{\pm 1}=-V^{\rm ac}/2$, while λ_n for $|n|>1$ can be neglected. The interplay between the ac gate voltage and the dynamical Lagrange field cancels each other and guarantees the constraint of zero or single occupancy at each instance of time. In this way, the external ac field is effective screened by the Lagrange field. The Kondo resonance then feels effectively no ac field and resembles much the stationary situation. Therefore both the robustness of LDOS against ac fields discussed previously[14–16] and noise properties obtained here are distinct manifestations of the many-particle correlations.

Our results have shown that the distinct singular behavior of noise depends on the origin of the resonance tunneling is the noninteracting or many-particle Kondo effect. The two resonances can be experimentally realized by tuning the energy level and the shape of semiconductor quantum dots by the gate voltages at low temperature. Therefore, the photon-assisted noise measurements provide an alternative probe to reveal the electron interactions. We wish this can be experimentally verified since the typical Kondo temperature ranges from 1 mK to 1 K and corresponds to frequency varying between 20 MHz and 20 GHz.[19] Both the ac Kondo effect and the time-averaged noise power measurements in this energy scale are in the reach of present technologies.[7,27,28] Very recently, a measurement of the noise of a tunnel junction under ac field was reported.[29]

Of course, we do not conclude that the noise properties in the ac Kondo regime will show the screen effect in the whole ac parameter space. The phenomena discussed above are believed to hold when the Kondo temperature T_K defines the largest energy scale. For cases where the parameters such as T, V, V^{ac}, or Ω are much larger than T_K, the SBMF method is not reliable and one has to rely on other techniques such as the renormalization-group techniques. Actually, if the ac intensities or frequencies are large enough, the decoherence or ionization effects will destroy the coherent many-particle Kondo resonance.[14,28]

In conclusion, we have investigated the noise properties of quantum dots in the ac Kondo regime by means of SBMF method and Floquet theorem. A compact expression for the noise is obtained in the Floquet-Green formalism. This expression is general to include the arbitrary ac field nonadiabatically and the Coulomb effects in the Kondo regime. Our results show that contrary to the noninteracting dot, the singular behavior of photon-assisted noise cannot survive in the many-particle Kondo regime. These remarkable diverse noise behaviors provide us an alternative means to distinguish the noninteracting resonance and the Kondo resonance through quantum dots.

In this Brief Report, the Coulomb effect on photon-assisted noise is considered in two extremes, i.e., the noninteracting ($U=0$) and the strongly correlated ($U=\infty$) limits, which are within the validity of our techniques. Our results have shown that the step behavior of the photon-assisted noise in noninteracting regime cannot survive in the strong Coulomb interaction limit. These results may indicate that the photon-assisted noise crosses over from singular to smooth curve upon increasing the Coulomb strength from zero to the large limit. This conclusion is qualitatively in agreement with a recent study[30] where the step structure of the ac noise of Luttinger liquid in carbon nanotube is found to be smoothed out by the Coulomb interaction. However, a quantitative description of the evolution of photon-assisted noise with increasing Coulomb interaction is still far from adequate due to the complexity of Coulomb effect. For full understanding of the Coulomb effects on the photon-assisted noise behavior, more effects are needed in the future to investigate the role of Coulomb interaction on photon-assisted noise behavior in various transport regimes, such as the Coulomb blockade regime, which are beyond the validity of the approximations used above.

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