Noise in an ac biased junction. 
Non-stationary Aharonov-Bohm effect.

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Abstract

We study excess noise in a quantum conductor in the presence of constant voltage and alternating external field. Due to a two particle interference effect caused by Fermi correlations the noise is sensitive to the phase of the time dependent transmission amplitude. We compute spectral density and show that at $T = 0$ the noise has singular dependence on the dc voltage $V$ and the ac frequency $\Omega$ with cusplike singularities at integer $eV/\hbar\Omega$. For a metallic loop with an alternating flux the phase sensitivity leads to an oscillating dependence of the strengths of the cusps on the flux amplitude.

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There is a variety of phenomena related with the quantum coherence of transport in small conductors [1]: weak localization, Aharonov-Bohm effect with the flux quantum $\hbar c/2e$, universal conductance fluctuations, etc. Each of these effects can also be seen in the spectrum of noise, equilibrium or non-equilibrium. The equilibrium noise is simply proportional to conductance according to the fluctuation-dissipation theorem. The non-equilibrium noise in coherent conductors is expressed through eigenvalues of the scattering matrix [2,3,4], and, therefore, is also related with the conductance, though in a less trivial way. For that reason all the coherence phenomena are present in the non-equilibrium noise as well. However, for a better understanding of transport in small conductors it is interesting to analyze the converse line of thinking and to look for coherence effects that are present in the noise but are absent in the conductance. Such effects, if they exist, are genuinely many-particle [5], otherwise they would show up in the conductance. As long as we are talking about non-interacting fermions it is only statistics that can produce such coherence. A purpose of this letter is to describe an effect caused by two-particle statistical correlations that leads to phase sensitivity of a two-particle observable, i.e., of electric noise, but does not affect one-particle observables, e.g., conductance. The phase sensitivity manifests itself in an oscillating dependence on the amplitude of an ac flux, in many aspects similar to the A-B effect. However, it will occur in a single-connected conducting loop, i.e., in the geometry where the normal A-B effect is absent.

Let us specify which coherence effects we are going to study. In simple words, when an electron is scattered inside a conductor its wavepacket splits into two portions, forward and backward, presenting a choice to the electron to be either transmitted or reflected with the probabilities $D$ and $1 - D$. Part of this picture of the wavepacket splitting, involving the relation of $D$ with the conductance [6,7] and of $D(1 - D)$ with the noise [8] is well understood. However, there is another part, quite unusual, related with the behavior of current fluctuations in the time domain. Recently, we studied the distribution of the charge transmitted through a resistor during fixed interval of time [9]. We found that the distribution is very close to the binomial, which means that the attempts to have electron transmitted are highly correlated in time. (Were the sequence of the attempts perfectly periodic the distribution would be exactly binomial.) The origin of the correlation is the Pauli principle that forbids passing of electrons through the resistor simultaneously. The attempts follow almost periodically, spaced by the interval $\hbar/eV$. Because the periodicity is not perfect it does not affect the average current, but shows up in its second moment, i.e., noise, leading at zero temperature to a sharp edge of the spectral density of excess noise $S_\omega$ near $\omega_0 = eV/\hbar$: $S_\omega = 2\pi D(1 - D)\hbar(|\omega_0 - |\omega||)$ for $|\omega| < \omega_0^2$, 0 otherwise. (Excess noise is the difference of the actual noise and the equilibrium $S_\omega = 2\pi D\hbar\omega \coth(\hbar\omega/2T)$.) The corresponding current-current correlation in time is $\langle\langle j(t)j(t + \tau)\rangle\rangle = \frac{2\pi^2}{\tau} D(1 - D)\sin^2(\omega_0\tau/2)/\tau^2$, oscillating with the period $2\pi/\omega_0$ and decaying.

Having realized that the frequency $eV/\hbar$ is characteristic for the time correlation of the attempts one has to think of a simple experimental situation were the presence of this frequency could be studied. It is natural to consider a system driven both dc and ac, and to look for the effects of commensurability of $\Omega$ and $eV/\hbar$, where $\Omega$ is the frequency of the ac bias and $V$ is the dc voltage. In this letter we study such a system and demonstrate that due to the ac bias the singularity at $\omega = \omega_0$ can be shifted down to zero frequency thus making it easier to observe. Below, we compute the noise in a model resistor in the presence
of combined dc-ac bias and find that the low frequency noise power \( S_0 \) has singularities at \( eV = nh\Omega \), when the "internal" frequency of the problem \( eV/h \) is a multiple of the external frequency \( \Omega \). We find that \( \partial S_0/\partial V \) is a stepwise function of \( V \) that rises in positive steps at \( V_n = nh\Omega/e \). Another interesting observation is that the heights of the steps of \( \partial S_0/\partial V \) are phase sensitive, i.e., they depend on the phase of the transmission amplitude in an oscillating way resembling A-B effect. The phase sensitivity of the noise should be opposed to the pure dc situation where only the probabilities of transmission and reflection enter the expression for the noise, which makes the noise power insensitive to the phase picked by the wavefunction across the system. In the simplest situation when the ac bias is supplied by alternating flux threading the current loop, \( \Phi(t) = \Phi_0 \sin(\Omega t) \), the heights of the steps in \( \partial S_0/\partial V \) are proportional to the squares of the Bessel functions \( J_n^2(2\pi \Phi_a/\Phi_0) \), where \( \Phi_0 = hc/e \). Let us note that we are not talking about the trivial effect of the e.m.f. \(-\partial \Phi/c \partial t\) induced in the circuit by the alternating flux. The effect in the noise will persist in the quasistatic limit \( |\partial \Phi/c \partial t| \ll V \) when the ac component of the current vanishes.

Let us start with recalling general facts about scattering off an oscillating potential. We consider a model one dimensional system where electrons are scattered by alternating scalar and vector potentials \( U(x, t) \), \( A(x, t) \) localized in the interval \([-d, d] \), \( U(x, t) = A(x, t) = 0 \) for \(|x| > d \). As a function of time they are periodic: \( U(x, t) = \sum_{n=-\infty}^{\infty} U_n(x) \exp(-i m \Omega t) \), where \( U_0(x) \) is the static part of the potential, and the other harmonics \( U_m(x) \), \( m \neq 0 \) describe ac bias. (Expression for \( A(x, t) \) is similar.) The dc bias is expressed in the framework of the Landauer model as the difference of the population of the right and the left scattering states. An important difference is that in our case the states describe inelastic scattering because an electron can gain several quanta \( \hbar \Omega \) while passing through the region \([-d, d] \). It will be useful to have the states expressed through the amplitudes of transmission and reflection:

\[
\psi_{L,k}(x, t) = \begin{cases} 
 e^{-iEt+ikx} + \sum_n B_{L,n} e^{-iE_n t - ik_n x} & x < -d \\
 \sum_n A_{L,n} e^{-iE_n t + ik_n x} & x > d
\end{cases},
\]

\[
\psi_{R,k}(x, t) = \begin{cases} 
 \sum_n A_{R,n} e^{-iE_n t - ik_n x} & x < -d \\
 e^{-iEt - ikx} + \sum_n B_{R,n} e^{-iE_n t + ik_n x} & x > d
\end{cases},
\]

(1)

where the amplitudes \( A_{L(R),n}, B_{L(R),n} \) are time independent. Here \( E = \hbar^2 k^2/2m \), \( E_n = E + n\hbar\Omega \), and \( k_n \) are defined by \( \hbar^2 k_n^2 = 2mE_n \). The states (1) are solutions of the Schrödinger equation

\[
E \psi(x, t) = \frac{1}{2} (-i \frac{\partial}{\partial x} - \frac{e}{c} A(x, t))^2 + U(x, t) |\psi(x, t)|.
\]

They can be used as a basis to study transport through the system the same way it is done for the static barrier. The amplitudes \( A_{L(R),n}, B_{L(R),n} \) satisfy unitarity relation,

\[
\sum_{n,n',\alpha,\alpha'} \delta(E_n - E'_{n'}) (\bar{A}_{\alpha,n}(E) A_{\alpha',n'}(E') + \bar{B}_{\alpha,n}(E) B_{\alpha',n'}(E')) = \delta(E - E') \delta_{\alpha\alpha'}
\]
that one obtains by the standard reasoning about conservation of current.

The operator of electric current, \( \hat{j}(x,t) = -ie\hat{\psi}^+(x,t)\nabla\hat{\psi}(x,t) \) is written in terms of second-quantized electrons, \( \hat{\psi}(x,t) = \psi_L(x,t) + \hat{\psi}_R(x,t) \), \( \hat{\psi}_L(x,t) = \sum_k \psi_{L,k}(x,t)\hat{a}_k \), \( \hat{\psi}_R(x,t) = \sum_k \psi_{R,k}(x,t)\hat{b}_k \), where \( a_k \) and \( b_k \) are canonical Fermi operators corresponding to the states (1) coming out of the reservoirs, the left and the right respectively. It is straightforward to write the coefficients \( I_m \) in terms of the scattering amplitudes, so the condition \( \sum_k |A_{L,R,k}|^2 \leq 1 \) enables one to neglect the energy dependence of the scattering amplitudes, so the condition \( t_f\Omega \ll 1 \) enables one to neglect the energy dependence of \( A_{L(R),n} \). In the usual dc situation \( S(t_1,t_2) = S(t_1 - t_2) \) and its Fourier transform gives spectral density \( S_\omega = \langle \hat{j}\omega\hat{j}_{-\omega} \rangle \) of the noise. In our ac case the situation is somewhat more complex because the spectral density \( S_\omega \) does not provide a complete description of the noise. Indeed, \( S(t_1,t_2) \) will depend now separately on \( t_1 \) and \( t_2 \), not only on the difference \( t_1 - t_2 \). However, it satisfies \( S(t_1,t_2) = S(t_1 + 2\pi/\Omega, t_2 + 2\pi/\Omega) \) resulting from the periodicity of the ac bias. For the Fourier components \( \hat{a}_\omega \) it means that the average \( \langle \hat{a}_\omega\hat{a}_{\omega'} \rangle \) does not vanish whenever \( \omega + \omega' = m\Omega \), where \( m \) is any integer. Thus, in addition one gets generalized spectral densities \( S_\omega,m = \langle \hat{j}\omega\hat{j}_{m\Omega-\omega} \rangle \), an integer parameter family of functions. Among them there is the ’ordinary’ \( m = 0 \) spectral density \( S_\omega = S_{\omega,0} = \langle \hat{j}\omega\hat{j}_{-\omega} \rangle \), the one easiest to access experimentally. In what follows we concentrate on it and do not study other \( S_{\omega,m} \), \( m \neq 0 \).

To compute the noise one has to average the product of two current operators over the distribution in the reservoirs. Evaluation of the average is similar to Refs. [2,3,4], so we do not need to repeat it here. General expression simplifies quite substantially in the practically interesting limit of \( t_f \), the time of flight through the barrier \( U(x,t) \) being much shorter than \( 2\pi/\Omega \) and \( \hbar/eV \). The point is that \( \hbar/t_f \) defines the characteristic scale of energy dependence of the scattering amplitudes, so the condition \( t_f\Omega \ll 1 \) enables one to neglect the energy dependence of \( A_{L(R),n} \) in the interesting energy domain \( E_F \pm \max[eV,\hbar\Omega] \). We also assume \( E_F \gg \max[eV,\hbar\Omega] \), which allows to neglect the difference of \( k_n/m \) and \( k/m \), the velocities of scattered and incident states, and set \( k_n/m = v_F \). It should be remarked that the physical picture we discuss below is not really dependent on any of these assumptions, they only make our expressions more compact. The more general case of arbitrary relation between \( \hbar/t_f, E_F, eV, \hbar\Omega \) presents no difficulty.

With the above assumptions made it becomes convenient to use Fourier transform of the amplitudes \( A \) and \( B \). Let us define \( A_\alpha(t) = \sum_n A_{\alpha,n}\exp(-in\Omega t) \), \( \alpha = L, R \). Similarly we introduce \( B_\alpha(t) \), and rewrite Expr.(1) as

\[
I(t) = \sum_{m=-\infty}^{\infty} I_m \exp(-im\Omega t) ,
\]
\[
\psi_{L,k}(x,t) = \begin{cases} 
e V, 
 e^{ikx} + B_L(t + x/v_F)e^{-ikx} & x < -d 
 e^{-ikx} + B_R(t - x/v_F)e^{ikx} & x > d
\end{cases}
\]

\[
\psi_{R,k}(x,t) = \begin{cases} 
e V, 
 A_R(t + x/v_F)e^{-ikx} & x < -d 
 e^{-ikx} + B_R(t - x/v_F)e^{ikx} & x > d
\end{cases}
\] (3)

(To obtain (3) from (1) we substitute \(k_n = k + n\Omega/v_F\) in the phase shifts \(e^{ik_nx}\) and then do the sum over \(n\).) The amplitudes \(A_{L(R)}(t), B_{L(R)}(t)\) have clear meaning of the transmission and reflection amplitudes at given instant of time for a slowly varying potential. The retarded time \(t - |x|/v_F\) in Expr.(3) accounts for the finite speed of motion after scattering. The unitarity relation now takes the form

\[
|A_{L(R)}(t)|^2 + |B_{L(R)}(t)|^2 = 1, \quad A_L(t)B_R(t) + B_L(t)A_R(t) = 0.
\]

To clarify the character of the simplification thus achieved let us remark that with Expr.(3) the formula (2) for the current \(I(t)\) becomes just \(I(t) = 2\frac{e^2}{h} |A(t)|^2 eV\) which means that the current 'adiabatically' follows time variation of the transparency of the barrier according to the Landauer formula. Now we shall compute noise and find that, unlike \(I(t)\), it is not reduced to anything trivially related with the static limit. Let us write the average of two currents \(\langle \langle \dot{j}(t_1)\dot{j}(t_2) \rangle \rangle = \)

\[
\frac{2e^2}{\hbar^2} \sum_{E,E'} e^{-i(E_k - E_d)(t_1 - t_2)} [|A(t_1)A(t_2)|^2(n_L(E')(1 - n_L(E)) + n_R(E')(1 - n_R(E)))
\]

\[+B(t_1)A(t_2)B(t_2)n_R(E')(1 - n_L(E)) + A(t_1)B(t_1)B(t_2)A(t_2)n_L(E')(1 - n_R(E))].
\]

To compute \(S_\omega\) we have to do Fourier transform and substitute Fermi distributions \(n_{L(R)}(E)\). Explicit calculation yields the result

\[
S_\omega = \frac{2e^2}{\pi} \sum_n 2N_0(\omega - n\Omega)|(|A|^2)_n|^2 + N_1(\omega, n\Omega + eV)(AB)_n|^2,
\] (4)

where

\[
N_0(x) = \int(n(E - x) + n(E + x))(1 - n(E))dE = x\coth(x/2T),
\]

\[
N_1(x, y) = N_0(x + y) + N_0(x - y) = \frac{x \sinh(x/2T) - y \sinh(y/2T)}{\cosh(x/2T) - \cosh(y/2T)},
\]

and (...)_n denotes Fourier components, e.g., \((AB)_n = \frac{2}{2\pi} \int A(t)B(t)e^{in\Omega t}dt\). Expr.(4) describes the noise as function of \(eV, \Omega, \omega\) and \(T\). The behavior is simplest at \(T = 0\) when \(N_0(x) = |x|, \quad N_1(x, y) = |x + y| + |x - y|\). Given by Expr.(4) as a weighted sum of terms like \(|n\Omega + eV \pm \omega|, |\omega - n\Omega|\) the noise \(S_\omega\) will then depend on \(V, \Omega, \omega\) in a piecewise linear way, changing from one slope to another when \(n\Omega + eV \pm \omega\) or \(\omega - n\Omega\) equals 0. This
condition defines the locations where $S_\omega$ has singularities. They are cusps, sharp at $T = 0$ and rounded on the scale $T$ at $T > 0$.

With the general Expr.(4) one can explore the noise in all possible limiting situations that one obtains for different combinations of $eV$, $\Omega$, $\omega$ and $T$. Particularly interesting for us will be the case $T = 0$, $\omega = 0$ corresponding to the noise $S_0 = \langle \langle j_\omega j_\omega \rangle \rangle_{\omega \to 0}$ measured at low frequency. Let us remark here that setting $\omega = 0$ means only that $\omega$ is small compared to the parameters $eV$ and $\Omega$ that define the width of the frequency band of the excess noise. Such $\omega$ may still be much higher than the band width for other sources of noise, e.g., the $1/f$. Let us concentrate on the dependence of $S_0$ on $V$. It is a piecewise linear function which is easiest to characterize by its derivative,

$$\frac{\partial S_0}{\partial V} = \frac{2e^3}{\pi} \sum_n \lambda_n \theta(eV - nh\Omega),$$

where $\lambda_n = |(\bar{A}_L B_R)_n|^2$ and $\theta(x) = 1$ for $x > 0$, $-1$ otherwise. The function $\partial S_0/\partial V$ rises in positive steps at all $V_n = h\Omega n/e$ (see Fig. [1]), the property that can be alternatively formulated as convexity of $S_0(V)$ in $V$.

The meaning of the singularities in $S_0(V)$ was clarified recently in a study of the statistics of transmitted charge [11]. The generating function of the charge distribution was expressed through the single-particle scattering matrix, and it was found that the distribution arises from Bernoulli statistics (i.e., it is a generalized binomial distribution). The frequencies of attempts were given as function of $V$ and $\Omega$. The probabilities of outcomes of a single attempt were found in terms of many-particle scattering amplitudes, and it was shown that they change at the thresholds $V_n = nh\Omega/e$ in a discontinuous way due to statistical correlation in the outgoing channels of the scattering. The discontinuity manifests itself in the second moment of the distribution that corresponds to the noise $S_0(V)$ discussed above.

There is an interesting and simple example where one can explicitly evaluate the heights of the steps. Let us consider a junction with ideal leads bent into a loop of length $L$ (see inset of Fig. [2]) and placed into an external magnetic field varying with time. In this problem the junction is the only source of scattering. For simplicity let us assume that only one scattering channel is involved and that the junction is symmetric, $A_L = A_R = A$, $B_L = B_R = B$. The ac bias is supplied by the alternating flux of the magnetic field through the loop, $\Phi(t) = \Phi_a \sin(\Omega t)$. Also let us suppose that the magnetic field is quasistatic, i.e., the time of flight through the system, $t_f = L/v_F$ is much shorter than $2\pi/\Omega$, that makes it possible to introduce the time dependent amplitudes $A_{L(R)}(t)$, $B_{L(R)}(t)$ as it was discussed above. As is common, in such a situation the vector potential can be treated semiclassically, and one can write the wavefunction as $\psi(x,t) = \exp(\frac{ie}{\hbar} \int_{-\infty}^{x} A(x')dx') \psi_0(x,t)$, where $x$ is the coordinate along the lead and $\psi_0(x,t)$ is found by solving the Schrödinger equation in the absence of the magnetic field. Thus all the dependence on the magnetic flux can be accumulated in the phase of the transmission amplitude,

$$A_{R(L)}(t) = \exp(\pm i\Phi(t)/\Phi_0) A, B_{R(L)}(t) = B,$$

where $\Phi_0 = hc/e$ is single electron flux quantum. Since $|A(t)|^2 = D = const$ the current is time independent: $I = \frac{2e^2}{\hbar} DV$. According to Expr.(4) $S_\omega$ is written through the Fourier components of $A_L(t)B_R(t)$ in this case given by the Bessel functions: $(\bar{A}_L B_R)_n = J_n(2\pi \Phi_a/\Phi_0)AB$. Thus we find
\[ S_\omega = \frac{2e^2}{\pi} [2N_0(\omega)D^2 + \sum_n N_1(\omega, n\Omega + eV)D(1 - D)J_n^2(2\pi\Phi_a/\Phi_0)]. \]  

(6)

The heights \( \lambda_n \) of the steps in \( \partial S_0/\partial V \) are then given by

\[ \lambda_n = D(1 - D)J_n^2(2\pi\Phi_a/\Phi_0). \]  

(7)

They oscillate as function of \( \Phi_a/\Phi_0 \) and vanish at the nodes of Bessel functions.

Exprs. (6),(7) illustrate one important feature of the noise in the ac biased system, the sensitivity to the phase of the transmission amplitude \( A \). By varying the amplitude \( \Phi_a \) of the alternating flux one can make \( \lambda_n \) vanish separately for each harmonic \( n\Omega \) of the ac frequency. This should be compared with the case of the dc bias where the noise is expressed only through \( |A|^2 \) and thus cannot be phase dependent. We call the oscillating dependence (6),(7) non-stationary Aharonov-Bohm effect. To compare it with the usual A-B effect let us recall that the latter is observed as an oscillation of the dc conductance under variation of flux in the situation when one has interference of transmission amplitudes corresponding to different classical trajectories of a quantum system, e.g., in a conductor with multiply connected leads forming one or several closed loops. The dc A-B effect cannot be observed in the single path geometry like Fig.1. Alternatively, the non-stationary A-B effect appears as a result of interference of the right and left scattering states travelling in the opposite directions along same path and having energies shifted by \( n\Omega \). It is clear from our discussion that such interference does not contribute to the ac conductance but is important for the noise and, therefore, one obtains the non-stationary A-B effect in the noise even in the topologically trivial situation of Fig.1.

One can derive a sum rule:

\[ \sum_n \lambda_n = \frac{\Omega}{2\pi} \int_0^{2\pi/\Omega} D(t)(1 - D(t))dt, \]  

(8)

where \( D(t) = |A(t)|^2 \). For \( \lambda_n \) given by Expr.(7) it follows from the definition of the Bessel functions. In the general case of Expr.(5) the sum rule is obtained by applying Plancherel’s formula to Fourier components of \( A(t)\overline{B(t)} \). The sum rule clarifies the relation of our problem with the previous calculation [3,4] of the noise in the pure dc case for which the result does not depend on the phase of \( A(t) \). When the limit is taken \( \Omega \to 0, V = \text{const} \), the steps in \( \partial S_0/\partial V \) do not vanish but just move closer to zero, thus effectively condensing then all together in a single step at \( V = 0 \). The height of this step is not phase sensitive and is simply given by the expression (8) for the dc noise averaged over the period \( 2\pi/\Omega \).

It is worth mentioning that our results for \( S_\omega \) are quite general. Indeed, it is clear after what have been said that the singularities at \( V = nh\Omega/e \) are only due to the sharp edge of the Fermi distribution, and not related with any specific geometry assumed for the junction. Because of that the phenomenon should be displayed by any coherent conductor, provided that the main source of inelastic scattering is the ac potential. The reason is that an elastic scattering, if any, can smear the Fermi distribution of momenta but it will not affect the sharpness of the step in the energies distribution, and our effect is sensitive only to the latter. The same remark applies to the oscillating dependence of the singularities on the amplitude of the ac signal.
Let us briefly discuss a generalization of the system shown in Fig.1 where the loop is not an ideal lead but a real metallic wire with disorder, i.e., instead of one scatterer there are now many of them uniformly distributed over the bulk of the wire. Most interesting is the case of a purely coherent conductor for which the energy relaxation time $\tau_E$ and the phase breaking time $\tau_\phi$ are much longer than the flight time $t_f$. (One can estimate $t_f \approx \bar{\hbar}/E_c$, where $E_c$ is Thouless’ energy $\hbar D/L^2$.) In such a system transport is described by channels of the scattering matrix with transmission coefficients $T_m$ assigned to each channel \[7\]. In the dc case the noise can be written \[4\] in terms of $T_m$ as $S_0 = \frac{2e^2}{\pi} \sum_m T_m(1-T_m)eV$. In the presence of the alternating flux the extension of our formalism can be carried out easily and one obtains expressions similar to (6) and (7), with $D^2$ and $D(1-D)$ replaced by $\sum_m T_m^2$ and $\sum_m T_m(1-T_m)$ respectively. However, the limitations under which the result is valid, $eV \ll \hbar/t_f$, $\Omega \ll 1/t_f$, are now slightly more stringent than for Exprs.(6),(7) because the flight time $t_f$ is longer.

A more fundamental limitation to the general validity of our calculation is in the assumption that the flux threads only the phase coherent part of the conductor. It would certainly be of interest to better understand the opposite limit when the ac voltage increases smoothly over a distance much larger than the phase breaking length $L_\phi = \sqrt{\tau_\phi/D}$.

To summarize, we studied current and noise in a conductor driven by dc and ac and we expressed them through time-dependent one particle scattering amplitudes. In the quasistatic limit of short time of flight through the conductor the current is given by the Landauer formula with time-dependent transmission coefficient, i.e., by a trivial generalization of the static case. The situation with the noise is quite different because of the two-particle interference. Spectral density of the noise $S_\omega$ depends on the scattering amplitudes in such a way that the phases do not drop out, and this leads to a non-stationary Aharonov-Bohm effect. Because of the way the Fermi statistics affects the two-particle interference the noise measured at $T = 0$ is singular at $\omega = \pm eV/\hbar + m\Omega$, where $m$ is any integer. To illustrate the phase sensitivity of the noise we consider a conducting metallic loop in which the ac signal is supplied by an oscillating magnetic flux. Because of the sensitivity to the phase of transmission amplitude the strengths of the singularities in the noise display oscillatory dependence on the amplitude of the ac flux given by squares of the Bessel functions.

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FIGURES

FIG. 1. Differential noise $\partial S_0/\partial V$ at $T = 0$ given by Exprs.(5),(7) is plotted against $V$ for three flux amplitudes: (1) $\Phi_a = 5\Phi_0/4\pi$; (2) $\Phi_a = 7\Phi_0/2\pi$; (3) $\Phi_a = 23\Phi_0/4\pi$. (Inset: Junction with leads bent in a loop through which alternating magnetic flux is applied.)