Observation of "Photon-Assisted" Shot Noise in a Phase-Coherent Conductor

R. J. Schoelkopf, A. A. Kozhevnikov, and D. E. Prober
Departments of Applied Physics and Physics, Yale University, New Haven, Connecticut 06520-8284

M. J. Rooks
Cornell Nanofabrication Facility, Knight Laboratory, Cornell University, Ithaca, New York 14853

(Received 17 November 1997)

We observe a novel signature of coherent transport in the nonequilibrium current fluctuations of a diffusive metallic conductor shorter than the electron phase-breaking length. Under illumination with monochromatic microwaves, the shot noise develops features at voltages corresponding to the photon energies, $V = nh\nu/e$, which are oscillatory functions of the microwave power, while the conductance and the I-V curve are unaffected. The observed effect bears a strong resemblance to photon-assisted tunneling, although this marks the first demonstration in a *linear* system, and in a system without an explicit tunnel barrier. [S0031-9007(98)05538-0]

PACS numbers: 73.50.Td, 73.23.Ps, 73.50.Mx, 73.50.Pz

Studies of the nonequilibrium current fluctuations have recently emerged as a probe of various mesoscopic systems [1]. The nature of the shot noise can reveal information about the transport which is not evident merely by examining the conductance or the time-averaged transport. For example, correlations due to the Fermi statistics of the electrons can lead to a partial suppression of the shot noise [2,3]. It has been demonstrated [4,5] that even a metallic wire will produce shot noise, provided that its length is short compared to the electron-electron inelastic length, L_{ee}. Time-dependent phenomena in nanostructured systems have also become an active area of research lately [6], and it is interesting to ask what the effect of a time-dependent potential on the current fluctuations might be. Indeed, Lesovik and Levitov [7] recently proposed a new two-particle interference phenomenon, the "nonstationary Aharonov-Bohm effect," which should be observable in the shot noise of a phase-coherent conductor under a high-frequency excitation. As we describe below, this phenomenon is formally identical to the process of "photon-assisted tunneling" (PAT) [8], but applied to shot noise of the system rather than its current-voltage characteristic.

In this Letter, we present measurements of the nonequilibrium noise of a diffusive, phase-coherent metallic conductor in the presence of both a high-frequency (2–40 GHz) ac excitation and a dc bias. The noise displays features generated by the time-dependent excitation that bear all the hallmarks of photon-assisted tunneling. Because of the linear nature of the conductance in this mesoscopic system, however, the photon-assisted signatures appear only in the noise, not in the conductance.

The theory of photon-assisted tunneling [8] was developed some time ago to explain the features observed [9] in superconducting tunnel junctions when they were illuminated with microwave radiation. It was extended to derive the quantum-limited performance [10] of heterodyne detectors based on these devices. More recently, PAT has been demonstrated in a variety of systems, including semiconductor quantum dots [11], metallic single-electron transistors [12], semiconductor superlattices [13], and other dual-barrier semiconductor devices [14]. In all of these systems, the conductance displays a strong nonlinearity, which then develops "sidebands" in the presence of monochromatic radiation. These sidebands are offset from the main nonlinearity by a voltage which is proportional to integer multiples of the photon energy, $\Delta V = nh\nu/e$, but is independent of illumination power. The amplitude of any given sideband is a nonmonotonic function of the photon flux, and a photon energy larger than the width of the energy levels involved is generally required to resolve the sidebands.

In their paper, Lesovik and Levitov (LL) [7] considered the case of the coherent conductor with two contacts which is bent into an "open," singly connected loop and threaded by a time-varying Aharonov-Bohm flux [see inset of Fig. 1(a)]. This flux causes a time-varying phase shift in the scattering amplitudes for transmission of electrons from one contact to another. Because of the lack of closed electron trajectories enclosing the flux, neither the one-particle wave functions nor the conductance are modified by the flux. However, both the two-particle wave functions and the shot noise, which is a two-particle observable, have a dependence on this time-varying flux. Note that this gedanken experiment differs from the usual Aharonov-Bohm effect, since the time-varying nature of the flux ensures that there will always be a nonzero electric field felt by the electrons. In fact, the time-varying flux is completely equivalent to an alternating voltage applied to the contacts, with a magnitude $V_{\mathrm{ac}} = -c^{-1} d\Phi(t)/dt$. Nonetheless, the predicted modulation of the noise does arise because the flux adds a time-dependent phase factor, or equivalently, a shift in the incident energy levels by multiples of the photon energy. The modulation does not

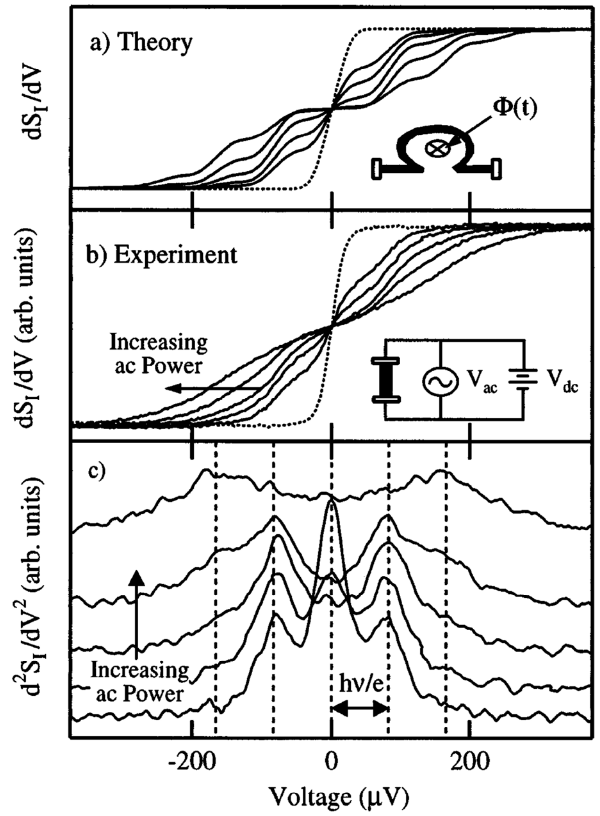

FIG. 1. Theoretical and experimental variation of differential shot noise versus voltage, with 20 GHz ac excitation. (a) Theoretical dependence of dS_I/dV for mesoscopic conductor at 50 mK. Dotted line shows behavior without ac excitation ($\alpha = 0$), solid curves are for ac excitations with $\alpha = 1.1$, 1.4, 1.7, 2.2, and 2.8. (b) Measured curves of dS_I/dV for Au wire at 50 mK base temperature and a 20 GHz microwave excitation with powers differing by 2 dB, corresponding to the values of alpha given above. (c) Measured second derivative of the shot noise (d^2S_I/dV^2). Dashed vertical lines show expected locations of sidebands at $V = nh\nu/e$ for $n = 0, \pm 1, \pm 2$.

arise from simple modification of the electron trajectories, which are confined within the conductor. While there are many parallels between shot noise in mesoscopic systems and quantum optics, effects in electron systems due to external fields or vector potentials [15] have no optical analogs, and are therefore of much interest.

For a coherent conductor consisting of a single conducting channel with transmission probability D, the low-frequency current spectral density derived by LL, in the presence of an oscillatory excitation at frequency ν, is

$$S_I(0) = D^2 \frac{2e^2}{h} 4kT + D(1 - D) \frac{2e^2}{h} \times \sum_{\pm} \sum_{n=0}^{\infty} J_n^2(\alpha) \left\{ (eV \pm nh\nu) \coth\left[\frac{eV \pm nh\nu}{2kT} \right] \right\}, \tag{1}$$

where n is an integer, T is the temperature of the electrons in the contacts, and α is the amplitude of the time-dependent flux normalized to the flux quantum, $\alpha = \Phi_{ac}/\Phi_0$. In terms of the equivalent ac voltage across the contacts, α is given by $\alpha = eV_{ac}/h\nu$. The factor of $D(1 - D)$ arises from the Fermi statistics of the electrons [16]. In the case of a conductor with multiple transmitting modes, an additional sum should be performed over the m conducting modes, each with transmission probability D_m. For a diffusive conductor with many allowed modes, the net result of the averaging over the m modes is to reduce the voltage-dependent portion of the noise by the ensemble-averaged factor of 1/3 [17]; for $V_{ac} = 0$, one has $S_I(0) = (1/3)2eI$ when $|V| \gg kT/e$.

The form of Eq. (1) has many similarities to that derived for PAT [8], where the current response under illumination consists of a sum of terms, weighted by the Bessel functions $J_n^2(\alpha)$, of the response at all voltages displaced by multiples of the photon energy. The usual shot noise has a linear dependence, $S_I \propto |I|$, on current at large biases ($e|V| \gg kT$), giving rise to the steplike behavior of dS_I/dV at zero voltage. This step [dotted line in Fig. 1(a)] is rounded on the scale $eV \sim kT$ at finite temperature. In the presence of a high-frequency excitation, such that $h\nu \gg kT$, Eq. (1) predicts the formation of sidebands on this step, occurring at the voltages $V = \pm nh\nu/e$. The predicted shape of the dS_I/dV curves for a 20 GHz modulation at a temperature of 50 mK is shown in Fig. 1(a) for several values of the excitation strength α. Note that coherent transport must be maintained even under strongly nonequilibrium conditions, when both the ac and dc potentials are several times greater than kT/e, in order to observe the effect.

The sample used for the measurements described here [18] consisted of a thin (10 nm) Au wire approximately 40 nm wide, whose length (200 nm) was defined by wide, thicker (80 nm) Au contacts [cf. inset of Fig. 3(a) shown below]. The wire had a diffusion constant of 40 cm^2/s and a nearly temperature-independent sheet resistance of $\sim 9\ \Omega/\text{square}$, giving a resistance of 47 Ω. The dominant phase-breaking mechanism below 1 K is electron-electron scattering, and we expect that the electron-electron inelastic length, L_{ee}, should be greater than 2 μm at 100 mK, so that $L \ll L_{ee}$ for all the measurements described here. Shot noise was indeed observed [4] in Ag wires shorter than L_{ee}, with the expected magnitude [17] of 1/3 the Schottky limit of $2eI$. Our earlier measurements on this Au wire [5] investigated the frequency dependence of this shot noise.

Measurements of nonequilibrium noise of the mesoscopic wire were performed in a dilution refrigerator at 50 mK. The sample was mounted in a "flip-chip" [19] configuration which allowed an efficient coupling to a 50 Ω coaxial cable over the entire frequency range from dc to 40 GHz. The current fluctuations were measured in the band from 1.25–1.75 GHz using a cooled high-electron-mobility transistor (HEMT) amplifier with a noise temperature of 7 K, located at the other end of the cable in the main He bath. The measurement frequency was small enough ($h\nu \sim kT$) to allow comparison with zero-frequency limits. A directional coupler between the device and the amplifier was used to introduce a monochromatic microwave voltage across the wire at frequencies between 2 and 40 GHz. An isolator with a directivity of 20 dB at the amplifier's input helped to ensure that the amplifier's noise contribution was independent of the impedance at its input; in any case the sample itself was well matched, with $R = 47\ \Omega$. Four-wire measurements of the dc conductance, using a bias tee located at the mixing chamber, showed that the sample's resistance was constant under all conditions to within a few parts in 10^3.

All the noise measurements were performed using a bias modulation technique [2,5]. The total system noise in the 500 MHz band at 1.5 GHz was rectified, and the change in this power (the "differential noise") which occurred synchronously with a small change (typically $\pm 20\ \mu\text{V}$) in the dc bias across the sample was detected with a lock-in amplifier, thus effectively measuring the derivative of the sample's noise, dS_I/dV, with voltage. Several of the measured dS_I/dV curves, for differing powers of a 20 GHz microwave drive, are shown in Fig. 1(b). While it is difficult to calibrate the absolute excitation strength at the device, the smallest power level shown is estimated as a fraction of a nanowatt, in reasonable agreement with $\alpha = 1$. As the strength of the microwave drive is increased, a kink in the dS_I/dV curve develops.

The behavior of the differential noise can be seen more clearly in Fig. 1(c), where we display the second derivative of the noise, d^2S_I/dV^2, obtained by numerical differentiation of the data in Fig. 1(b). For small powers, d^2S_I/dV^2 has a large peak at zero bias. As the microwave amplitude increases, "sidebands" of this peak develop at about $\pm 80\ \mu\text{V}$, which corresponds to the photon energy via $V = h\nu/e$. The location of the sidebands is independent of the power, although their amplitude does depend on the power. At the very highest power levels, a broadened peak can be seen at $\pm 160\ \mu\text{V}$, corresponding to twice the photon energy. The independence of the sideband voltages on power is strong evidence that they are due to PAT, rather than classical heating or rectification.

The second hallmark of a photon-assisted process is a nonmonotonic dependence of the sideband amplitude on the applied power. The variation of dS_I/dV, at a constant bias voltage of about 40 μV, is shown as a function of the applied microwave power in Fig. 2. For a high-frequency (20 GHz) drive, the differential noise is indeed an oscillatory function of the power. The expected dependence, which is roughly like $J_0^2(\alpha)$, is calculated from Eq. (1) and shown with a dashed line. Also shown are the measured and predicted dependence for an applied microwave frequency of 2.5 GHz ($h\nu \sim kT$), for which no oscillations are expected or observed. The 20 GHz oscillations are damped more rapidly than predicted, however, and for sufficiently large powers, all photon-assisted features disappear. It is not known whether this results from an enhanced phase-breaking mechanism in this nonequilibrium situation, or simply a heating of the sample chip. Heating could be a problem even if the wire remains phase coherent. At the second minimum in dS_I/dV, a power (V_{ac}^2/R) of order several nanowatts is dissipated in the region near the wire. We estimate that the total thermal conductance from the contacts to the mixing chamber, which is mostly through the sample leads, to be ~20 nW/K. This implies a temperature rise of several hundred millikelvin in the contacts. The increase in temperature would make it difficult to fulfill the condition required for distinct sidebands, that the photon energy should be much larger than kT, and would also increase the rounding of the PAT features, as is seen in Fig. 1(b) at high ac excitations.

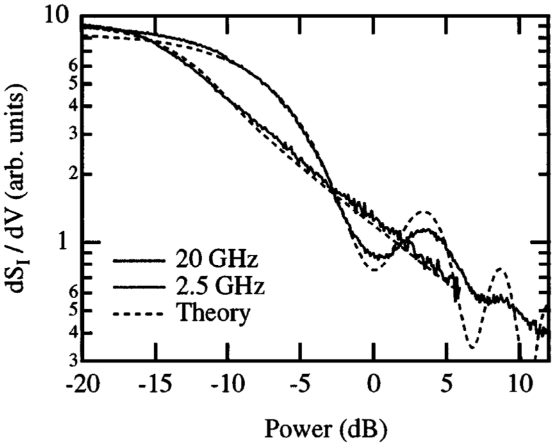

FIG. 2. Differential noise (dS_I/dV) at a voltage of ~40 μV as a function of the applied microwave power. Solid curves show the measured noise for microwave frequencies of 20 and 2.5 GHz, while the dashed lines are calculated according to Eq. (1). For high applied frequencies, the data show a damped oscillatory behavior consistent with the expected Bessel functions.

Conclusive evidence that the observed noise sidebands are generated by photon-assisted transport is gained by examining the sidebands as a function of the frequency of the applied microwaves. Measured values of d^2S_I/dV^2 are displayed in Fig. 3(b) for frequencies ranging from 2.5 to 40 GHz, and the curves are vertically offset by an amount proportional to the frequency. For all frequencies greater than 10 GHz, the $n = \pm 1$ photon peaks can be easily observed, and move progressively to higher voltages as the frequency is increased. The peak positions follow the expected scaling, seen in Fig. 3(a), with no adjustable parameters [20]. The presence of these frequency-dependent features shows that the transport in our wire remains coherent, and that the only allowed inelastic process is the absorption or emission of photons from the incident field.

The photon-assisted effect we observe indicates that the bias-dependent noise seen in these wires is indeed shot noise, rather than an effect due to heating. Interestingly,

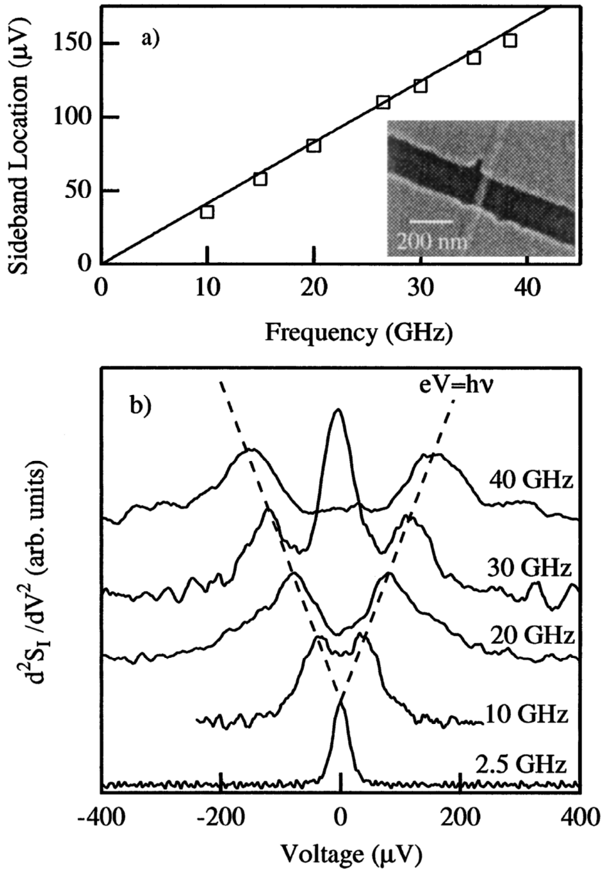

FIG. 3. Dependence of photon-assisted noise with frequency of the applied microwaves. (a) Observed voltage of the sidebands as a function of the frequency of applied microwaves. Solid line gives the scaling $\Delta V = h\nu/e$ expected for PAT. Inset is electron micrograph of device, showing 200 nm long Au wire and Au contacts. (b) Measured second derivatives of the shot noise (d^2S_I/dV^2) for various frequencies. Curves have been offset vertically by an amount proportional to the frequency, so that the dashed lines show the linear variation of sideband location with frequency.

the noise does not display any dramatic deviations from Eq. (1), which was derived ignoring electron-electron interactions and finite transit times for the electrons. The transit time for diffusive transport in the sample ($\tau = L^2/D = 10$ ps) corresponds to a frequency ($1/2\pi\tau$) of roughly 20 GHz. The possible effects of an even longer transit time ($\nu \gg 1/2\pi\tau$) are unknown and remain an interesting topic for future study.

In summary, we have observed the effect of photon-assisted transport on the nonequilibrium current fluctuations (shot noise) of a phase-coherent wire. While the conductance is completely unaffected by the presence of the high-frequency excitation, the shot noise displays frequency-dependent features bearing all the hallmarks of photon-assisted tunneling. This phenomenon marks the first observation of PAT in a *linear* system, and in one without an explicit tunnel barrier for the electron transport. The observed phenomenon can also be interpreted as a two-particle interference effect, which is visible only in two-particle observables such as the shot noise.

The authors wish to acknowledge L. S. Levitov, K. K. Likharev, M. Reznikov, and R. G. Wheeler for useful discussions. This work was supported by NSF Grants No. DMR-9216121, No. AST-9320387, and No. DMR-9701427.

[1] M. J. M. de Jong and C. W. J. Beenakker, in *Proceedings of Advanced Study Institute on Mesoscopic Electron Transport,* edited by L. L. Sohn, L. P. Kouwenhoven, and G. Schön (Kluwer, Dordrecht, 1997).
[2] M. Reznikov *et al.,* Phys. Rev. Lett. **75**, 3340 (1995).
[3] A. Kumar *et al.,* Phys. Rev. Lett. **76**, 2778 (1996).
[4] A. H. Steinbach, J. M. Martinis, and M. H. Devoret, Phys. Rev. Lett. **76**, 3806 (1996).
[5] R. J. Schoelkopf *et al.,* Phys. Rev. Lett. **78**, 3370 (1997).
[6] L. P. Kouwenhoven *et al.,* in *Proceedings of Advanced Study Institute on Mesoscopic Electron Transport* (Ref. [1]).
[7] G. B. Lesovik and L. S. Levitov, Phys. Rev. Lett. **72**, 538 (1994).
[8] P. K. Tien and J. P. Gordon, Phys. Rev. **129**, 647 (1963).
[9] A. H. Dayem and R. J. Martin, Phys. Rev. Lett. **8**, 246 (1962).
[10] J. R. Tucker, IEEE J. Quantum Electron. **QE-15**, 1234 (1979); J. R. Tucker and M. J. Feldman, Rev. Mod. Phys. **57**, 1055 (1985).
[11] L. P. Kouwenhoven *et al.,* Phys. Rev. B **50**, 2019 (1994); L. P. Kouwenhoven *et al.,* Phys. Rev. Lett. **73**, 3443 (1994); T. H. Oosterkamp *et al.,* Phys. Rev. Lett. **78**, 1536 (1997); R. H. Blick *et al.,* Appl. Phys. Lett. **67**, 3924 (1995).
[12] R. J. Fitzgerald, Ph.D. thesis, Harvard University, 1996; E. H. Visscher, Ph.D. thesis, Delft University of Technology, 1996.
[13] B. J. Keay *et al.,* Phys. Rev. Lett. **75**, 4098 (1995).
[14] S. Verghese *et al.,* Phys. Rev. B **52**, 14 834 (1995).
[15] M. Büttiker, Phys. Rev. B **46**, 12 485 (1992); Phys. Rev. Lett. **68**, 843 (1992).
[16] V. A. Khlus, Sov. Phys. JETP **66**, 1243 (1987); G. B. Lesovik, JETP Lett. **49**, 592 (1989).
[17] C. W. J. Beenakker and M. Büttiker, Phys. Rev. B **46**, 1889 (1992).
[18] The sample was patterned by direct-write *e*-beam lithography, evaporation, and lift-off for each layer (wire and contacts); measurements on the same device were reported in Ref. [5].
[19] P. J. Burke *et al.,* Appl. Phys. Lett. **68**, 3344 (1996).
[20] For both quantum dots and single-electron transistors, there can be an asymmetry in the division of the microwave voltage in the device. This requires a scale factor between photon and bias energies, although PAT features which vary linearly with frequency have been convincingly observed.