

## Observation of Photon-Assisted Noise in a Diffusive Normal Metal–Superconductor Junction

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We report measurements of nonequilibrium noise in a diffusive normal metal–superconductor (N-S) junction in the presence of both dc bias and high-frequency ac excitation. We find that the shot noise of a diffusive N-S junction is doubled compared to a normal diffusive conductor. Under ac excitation of frequency  $\nu$  the shot noise develops features at bias voltages  $|V| = h\nu/(2e)$ , which bear all the hallmarks of a photon-assisted process. Observation of these features provides clear evidence that the effective charge of the current carriers is  $2e$ , due to Andreev reflection.

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Recent research in the area of mesoscopic superconductivity has yielded a number of interesting and often surprising results. Reentrant behavior of the conductance of a diffusive normal metal–superconductor (N-S) junction, supercurrent in a normal wire between two superconducting reservoirs, and large magnetic flux modulation of the conductance of the Andreev interferometer are some of the effects recently discovered in hybrid N-S structures [1]. Most of the effort focused on dc transport properties. Much less is known about time-dependent processes in mesoscopic N-S systems.

In this Letter we report measurements of the shot noise in a diffusive N-S junction in the presence of both high-frequency ac excitation and a dc bias. We find that the shot noise in a diffusive N-S junction is doubled compared to a normal diffusive conductor. We observe for the first time an effect similar to photon-assisted noise in a normal mesoscopic conductor [2], except in the N-S device the features in the nonequilibrium noise occur at bias voltages  $|V| = h\nu/(2e)$ . Observation of this effect provides clear evidence that the effective charge of the current carriers is  $2e$ . This is the first clear and quantitative experimental evidence of effective charge  $2e$  in an N-S junction obtained in a high-frequency ac measurement, and also in the measurement of a dynamic quantity, noise. It is also the first observation where the Josephson frequency manifests itself in a device with only one superconducting reservoir and no weak links, where no true Josephson effect takes place.

In an N-S junction at energies below the gap of the superconductor, the current flows via the Andreev reflection process [3], where two electrons are simultaneously transferred from the normal metal into the superconductor and form a Cooper pair. For a ballistic N-S junction with a perfectly transparent interface, the conductance at subgap voltages is doubled due to the doubled effective charge, as compared to the normal-state conductance of the junction [4]. In contrast, in a diffusive N-S junction the conductance is only weakly enhanced by the proximity effect compared to the normal-state value, due to the contributions of modes with small transmission probabilities [5]. For a diffusive

N-S junction, the doubled effective charge due to Andreev reflection is predicted to have a much stronger effect on the shot noise than on the conductance. The shot noise of a diffusive N-S junction is predicted [6] to be doubled compared to the normal diffusive conductor. Noise larger than expected for a normal diffusive wire was observed in a normal metal film with two superconducting contacts [7].

Another manifestation of the charge of  $2e$  is expected to occur in the nonequilibrium noise of an N-S junction with a high-frequency ac bias. In a normal phase-coherent conductor under a high-frequency bias, the shot noise develops features at dc bias voltages corresponding to multiples of the photon energy,  $|V| = nh\nu/e$  [2,8]. These photon-assisted noise features have the same physical origin as the photon-assisted tunneling (PAT) features in the conductance of a nonlinear device [9]. In the N-S device, due to the doubled effective charge, the features in the shot noise are predicted to occur at bias voltages  $|V| = nh\nu/(2e)$  [10]. Observation of this effect provides evidence that the effective charge of the current carriers is  $2e$ , and is also a signature of elastic transport in the N-S device. As we discuss later, such observation provides a proof of effective charge  $2e$  which is more uniquely indicative than the doubling of the shot noise.

Lesovik *et al.* [10] calculated the shot noise of an N-S junction subject to both dc and ac bias. After averaging over the transmission channels in the diffusive conductor, their equation (11) for the current spectral density  $S_I$  can be written for a diffusive N-S junction as

$$S_I(V) = 4k_B T G_{NS} (1 - \eta) + 2\eta G_{NS} \sum_{n=-\infty}^{\infty} J_n^2(\alpha) \times \left\{ (2eV + nh\nu) \coth \left[ \frac{2eV + nh\nu}{2k_B T} \right] \right\}, \quad (1)$$

where  $\alpha = 2eV_{ac}/(h\nu)$ ,  $G_{NS} = G_N$  is the differential conductance of the device at voltages small compared to  $E_C/e$ , and  $\eta = 1/3$  is the shot noise suppression factor for a normal diffusive conductor. Equation (1) is valid when  $eV$ ,  $kT$ , and  $h\nu$  are all smaller than the gap of the superconductor  $\Delta$  and the Thouless energy  $E_C = \hbar D/L^2$ ;  $D$  is the diffusion constant and  $L$  is the wire length.

Equation (1) can be formally obtained by replacing the charge of the electron  $e$  by  $2e$  in the formula for the normal conductor [8]. This charge-doubling scheme is expected to be valid when the electrons and Andreev-reflected holes are coherent, that is, at energies  $E < E_C$ . The complete theory for the nonequilibrium noise in an N-S junction at arbitrary energies is not developed yet. Especially interesting is the question of whether the features in the noise at  $|V| = h\nu/(2e)$  survive when the transit time  $\tau = L^2/D$  becomes comparable to or larger than the period of ac excitation [11], i.e., when  $h\nu \gtrsim E_C$ . In our experiments,  $\Delta \approx 1.3$  meV,  $E_C \approx 25$   $\mu$ eV,  $k_B T \approx 8$   $\mu$ eV,  $h\nu = 40$ – $160$   $\mu$ eV.

If there is no ac bias and  $eV \gg k_B T$ , the shot noise of a diffusive N-S junction is  $S_I = (1/3)4e|I| = (1/3)2q_{\text{eff}}|I|$ , where  $q_{\text{eff}} = 2e$  is the effective charge of the current carriers (for “classical” shot noise  $S_I = 2q_{\text{eff}}I$ ; the sensitivity of shot noise to  $q_{\text{eff}}$  was used to provide evidence of fractionally charged excitations in the fractional quantum Hall effect regime [12]). The effective noise temperature  $T_N = S_I R_{\text{diff}}/(4k_B)$  is

$$T_N = q_{\text{eff}}|V|/(6k_B) = (2e)|V|/(6k_B). \quad (2)$$

The geometry of our sample is shown in Fig. 1. The device is a 10 nm thick Au wire 280 nm long and 100 nm wide in contact with a 60 nm thick Au contact pad on one side and 70 nm thick Nb pad on the other side. The thin Au wire and thick Au pad were deposited using a double-angle evaporation technique [13] in a single vacuum pump down to ensure a transparent interface. The surface of the Au wire was *in situ* ion beam cleaned immediately before Nb sputter deposition to ensure a transparent interface between Au and Nb. The diffusion constant of the thin Au film is about 30 cm<sup>2</sup>/sec which results in a nearly temperature-independent sheet resistance of about 15  $\Omega/\square$ . We estimate the interface resistance between Au and Nb to be  $R_{\text{interface}} \leq 5$   $\Omega$ , so the resistance of the device ( $\sim 40$   $\Omega$ ) is dominated by the diffusive Au wire. This corresponds to the case of a diffusive N-S junction with a transparent N-S interface [14]. At low temperatures the differential resistance of the device displays reentrant behavior vs both bias voltage (inset in Fig. 2) and temperature (not shown), as expected for a diffusive N-S device with a transparent interface. At  $T < 1$  K the energy relaxation length  $L_e$  is dominated by

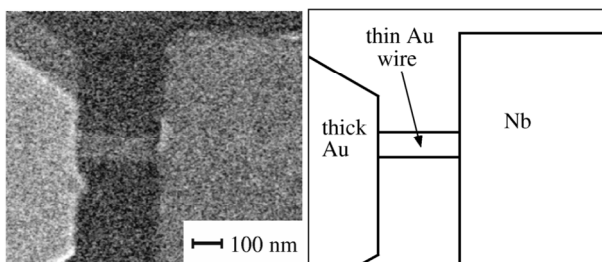


FIG. 1. SEM picture of the device and device schematic.

electron-electron inelastic scattering and should be greater than 2  $\mu$ m at 100 mK [15].

Measurements were performed in a dilution refrigerator at mixing chamber temperatures down to 50 mK. The current fluctuations in a frequency band from 1.25 to 1.75 GHz were measured using a cryogenic high electron mobility transistor amplifier. A bias modulation scheme [16] was used to measure the differential noise power. The device was well matched to the 50  $\Omega$  amplifier; the differential resistance of the device at bias voltages  $|V| < 0.6$  mV varied between 39  $\Omega$  and 41.5  $\Omega$ , which corresponds to a relative change of less than 1% in the rf power coupled from the device to the amplifier. We used a 20 dB microwave isolator between the device and the amplifier to ensure that the contribution of the amplifier’s noise was independent of the device resistance. A broadband directional coupler was installed between the device and the amplifier to provide the ac bias for the device.

We first performed detailed measurements of the noise with no ac excitation. Figure 2 shows the measured differential noise  $dT_N/dV$  vs bias voltage for the N-S device and for the same device driven normal by a magnetic field of 5 T. The solid lines are the theoretical predictions with no adjustable parameters. The error of the experimental data is less than 5%. In Fig. 2 the asymptotic value of the experimentally observed  $dT_N/dV$  for the N-S junction is 3.9 K/mV, in good agreement with the expected  $dT_N/dV = e/(3k_B) = 3.87$  K/mV. Our data show that the nonequilibrium noise of a diffusive N-S junction is doubled compared to the noise of a normal diffusive conductor, in agreement with shot noise theory.

The doubling of the nonequilibrium noise for a diffusive N-S device compared to a normal diffusive conductor, however, might occur due to a different mechanism. Shot noise occurs in a diffusive wire if the wire length  $L$  is smaller than the energy relaxation length  $L_e$ . For

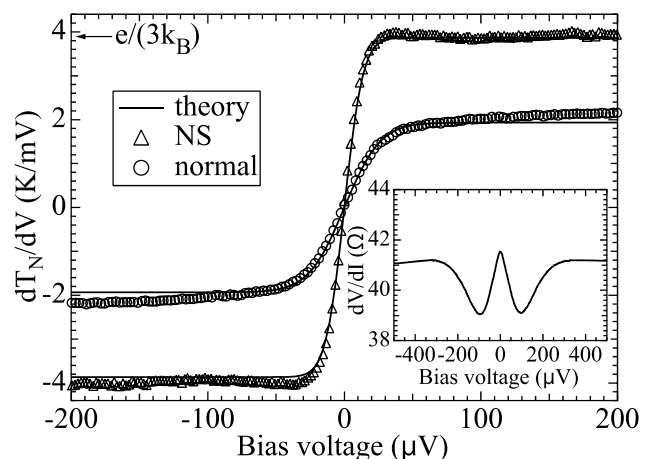


FIG. 2. Differential shot noise  $dT_N/dV$  vs bias voltage for an N-S device at  $T = 70$  mK and for the same device driven normal ( $T = 100$  mK) and the theoretical predictions with no adjustable parameters. The inset shows the differential resistance of the device vs bias voltage at  $T = 70$  mK.

our sample at zero bias voltage  $L \ll L_e \approx L_{ee}$ ;  $L_{ee}$  is the electron-electron inelastic length. However, in order to measure shot noise one has to apply large bias voltages ( $eV \gg k_B T$ ), which can reduce  $L_{ee}$ . If the device is in the regime  $L_{ee} < L < L_{e-ph}$ , where  $L_{e-ph}$  is the electron-phonon length, then the noise will be due to hot electrons [17]. For a diffusive normal wire at  $eV \gg k_B T$  this hot-electron noise is  $T_N = (\sqrt{3}/8)eV/k_B$ . For the diffusive N-S junction with  $L_{ee} < L < L_{e-ph}$ , the heat can flow out of only one end, and the hot-electron noise is *doubled* compared to the value for the normal wire:  $T_N^{NS} = (\sqrt{3}/4)eV/k_B$ . Numerically this is close to the prediction of Eq. (2). Additional complications arise due to the heating of the reservoirs, which can strongly affect the magnitude of shot noise and make it often difficult in experiments to convincingly distinguish between “true” shot noise and hot-electron noise [18]. These factors greatly complicate extraction of the effective charge  $2e$  from the magnitude of nonequilibrium noise alone.

To obtain clear evidence of an effective charge of  $2e$ , we performed noise measurements of the N-S device in the presence of high-frequency ac excitation. If the transport is elastic, in the presence of ac excitation of frequency  $\nu$ , the shot noise is expected to develop features at bias voltages  $|V| = h\nu/(2e)$ . The location of these features should be independent of ac power. In contrast, if the transport is inelastic, no photon-assisted features should occur. We measured the derivative of the noise vs bias voltage with ac excitation at  $\nu = 34$  GHz, at different levels of ac power. Figures 3(a) and 3(b) show the predicted and observed derivative of the noise temperature vs dc bias voltage for several levels of ac power. To see the features more clearly, we plot in Fig. 3(c) the second derivative  $d^2T_N/dV^2$  obtained by numerical differentiation of the experimental data. With no ac excitation,  $d^2T_N/dV^2$  has a peak at  $V = 0$ . With ac excitation, the sidebands of this peak are clearly evident at  $|V| = h\nu/(2e)$ . The sideband locations are power independent [19], which further argues that the structure is due to a photon-assisted process. The magnitude of  $d^2T_N/dV^2$  at  $V_{dc} = 0$  displays oscillatory [roughly  $\sim J_0^2(\alpha)$ ] behavior vs ac excitation amplitude (not shown), which is another hallmark of a photon-assisted process.

The most convincing evidence of the photon-assisted nature of the observed effects is the dependence of the voltage location of the sideband peak on the frequency of the ac excitation. We performed measurements of the shot noise at several different frequencies of ac bias, both in zero magnetic field and at  $B = 5$  T. At 5 T the device is normal and the effective charge is  $e$ . Figure 4(a) shows the second derivative of shot noise power vs bias voltage for  $\nu = 10$  and 20 GHz at  $B = 0$  (solid lines) and for the same device at  $B = 5$  T (dotted lines). The solid and dotted straight lines are the expected peak positions for the N-S and normal cases, respectively. The peak locations clearly follow the theoretical predictions  $|V| = h\nu/(2e)$  in the case of the N-S device and  $|V| = h\nu/e$  in the case

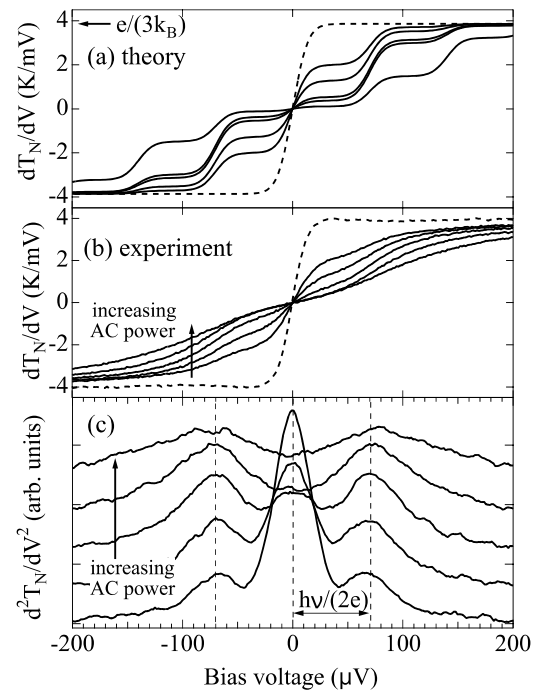


FIG. 3. Predicted and observed shot noise of an N-S device vs bias voltage without ac bias and at different powers of ac excitation at 34 GHz: (a) theory for  $dT_N/dV$  at  $T = 100$  mK with no ac (dashed line) and with ac excitation at  $\alpha = 1.1, 1.4, 1.7, 2.2, 2.8$  (solid lines); (b) experimentally measured  $dT_N/dV$  with no ac bias (dashed line) and with ac excitation powers differing by 2 dB and corresponding to the above values of  $\alpha$  (solid lines); (c)  $d^2T_N/dV^2$  obtained by numerical differentiation of data in (b).

of the device driven normal. Figure 4(b) shows the peak locations for a number of different ac excitation frequencies at  $B = 0$  and  $B = 5$  T. The solid and dotted lines are theoretical predictions with no adjustable parameters.

The presence of the photon-assisted noise features for our N-S device provides evidence of elastic transport in the device at large ( $eV \gg k_B T$ ) bias voltages. We conclude that we indeed observe shot noise in the regime of elastic transport, not hot-electron noise. In contrast to the magnitude of shot noise, the voltage location of the photon-assisted noise features is not affected by heating. Thus, our observation of photon-assisted noise sidebands at  $|V| = h\nu/(2e)$  provides evidence of the effective charge being  $2e$  which is clearer and more direct than the observation of noise doubling alone.

For the normal conductor PAT features in the conductance are not observed because  $dI/dV$  is constant. For an N-S device, the PAT features in the conductance are expected to occur along with features in shot noise. For example, the sidebands of the conductance minimum at  $V = 0$  would appear at  $|V| = h\nu/(2e)$  [20]. We measured the conductance of the device under ac excitation, but observed no PAT features. One possible explanation for the absence of PAT features in the conductance is heating. We estimate the lead resistance to be about  $2 \Omega$ , so

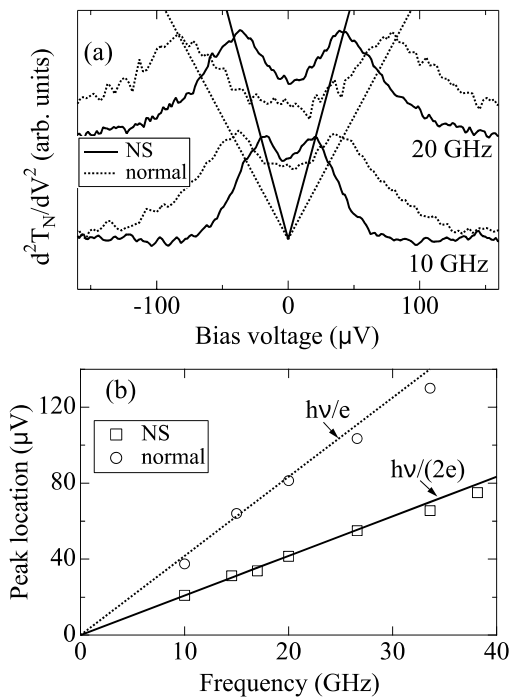


FIG. 4. (a)  $d^2T_N/dV^2$  vs bias voltage at  $B = 0$  (solid lines) and at  $B = 5$  T (dotted lines) with ac excitation at  $\nu = 10$  and 20 GHz. The curves are offset vertically by an amount proportional to frequency. The solid straight lines mark the expected peak locations for the N-S case (at  $B = 0$ ):  $|V_{\text{peak}}| = h\nu/(2e)$ ; the dotted straight lines mark the expected peak locations for a normal device (at  $B = 5$  T):  $|V_{\text{peak}}| = h\nu/e$ ; (b) peak location vs frequency for  $B = 0$  and  $B = 5$  T; the solid and the dotted straight lines are  $V_{\text{peak}} = h\nu/(2e)$  and  $V_{\text{peak}} = h\nu/e$ , respectively.

the rf power corresponding to  $\alpha = 2$  at 34 GHz will cause the temperature in the leads near the device to rise to about 200 mK. The broadening of the  $I$ - $V$  curve features due to heating suppresses sidebands in the conductance. The noise, on the other hand, has a much stronger nonlinearity,  $T_N \sim |V|$ , which survives this temperature increase. The shot noise data are noticeably broadened compared to theory, likely due to the heating of the leads.

Equation (1) was derived for the case of short transit time:  $\nu \ll 1/(2\pi\tau) = E_C/h$ . However, for our sample the diffusion transit time  $\tau = L^2/D$  is long and corresponds to frequency  $1/(2\pi\tau) \approx 5$  GHz, less than the excitation frequency. Our results show that the photon-assisted features in the noise persist when the transit time of the electrons is larger than the period of the ac excitation.

In summary, we have observed a novel signature of phase-coherent electron dynamics in a diffusive N-S junction which bears all the hallmarks of a photon-assisted process but manifests itself in the shot noise rather than in the conductance. Observation of the photon-assisted noise in a diffusive N-S junction provides evidence that the effective charge is  $2e$  due to Andreev reflection. The photon-assisted noise features occur at voltages which satisfy Josephson relation  $2e|V| = h\nu$ . This is the first ob-

servation where the Josephson frequency manifests itself in a system with only one superconducting reservoir and with no weak links.

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