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Shot Noise Measurements in Diffusive Normal Metal - Superconductor (N-S) Junctions.

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We report on the measurements of non-equilibrium noise in diffusive normal metal - superconductor (N-S) junctions. We observe that at bias voltages less than the gap voltage the shot noise is doubled compared to the normal diffusive conductor, in agreement with theoretical predictions. We also observe that the crossover from the thermal to shot noise occurs at bias voltages smaller than for the normal conductor, in qualitative agreement with theory.

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1. INTRODUCTION

The proximity effect in mesoscopic systems has been extensively studied, both theoretically and experimentally, in recent years. Much of the effort was focused on transport properties (for a review, see, for example[1] and references to it), while much less is known about time-dependent processes in mesoscopic normal metal - superconductor (N-S) systems. Non-equilibrium noise measurements can probe the time-dependent properties of the system and provide information which one cannot extract from the transport measurements. For example, the Poissonian shot noise has current spectral density $S_I = 2q_{eff}I$ where I is the current and q_{eff} is the charge of the current carriers. Thus, shot noise is sensitive to the magnitude of the charge of the current carriers. This property of shot noise was used to provide evidence of fractionally charged excitations in the FQHE regime.[2] Shot noise is also sensitive to the quantum statistics of the current carriers.[3]

In this paper, we report on the measurements of shot noise in diffusive

N-S junctions. We observe that the shot noise in a diffusive N-S junction is doubled compared to the normal diffusive conductor, and also that the crossover from thermal to shot noise occurs at bias voltages smaller than expected for a normal diffusive conductor.

At $T = 0$ in an N-S junction biased below the gap of the superconductor all current flows via Andreev reflection process,[4] 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 because of the doubled effective charge.[5] In contrast, in a diffusive N-S junction the conductance is only weakly enhanced by the proximity effect due to the contributions of modes with different transparencies.[6] The doubled effective charge due to Andreev reflection, however, is predicted to have a much stronger effect on the shot noise of a diffusive N-S junction than on the conductance. The shot noise of a diffusive N-S junction is predicted[7] to be doubled compared to the normal diffusive conductor because of the effective charge of $2e$. The expression for the non-equilibrium noise of a diffusive N-S junction was derived in[7] and can be formally obtained by replacing electron charge e by $2e$ in the formula for the normal diffusive conductor,[9] so one expects for the normal diffusive conductor:

$$S_I(V) = 4k_BTG_N(1-\eta) + 2\eta eVG_N \coth\left[\frac{eV}{2k_BT}\right] \tag{1}$$

and for the diffusive N-S junction:

$$S_I(V) = 4k_BTG_{NS}(1-\eta) + 2\eta(2e)VG_{NS} \coth\left[\frac{eV}{k_BT}\right] \tag{2}$$

Here $G_{NS} = G_N$ 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 2 was derived for the case when eV, k_BT are smaller than the gap of the superconductor Δ and Thouless energy $E_C = \hbar D/L^2$ (L is the length of the normal metal wire and D is the diffusion constant of quasiparticles in normal metal). The same equation is predicted to be valid when $eV, k_BT \gg E_C$,[8] however, to our best knowledge, there are no predictions for the case $E \sim E_C$. Besides doubling of the shot noise, Equations 1 and 2 predict that the crossover from the thermal regime to the shot noise regime for an N-S junction is determined by the ratio (eV/k_BT) and not $(eV/2k_BT)$ as in the case of the normal diffusive conductor. Therefore, the crossover from Johnson-Nyquist to shot noise for the N-S device is expected to occur at bias voltages 2 times smaller than for the normal conductor.

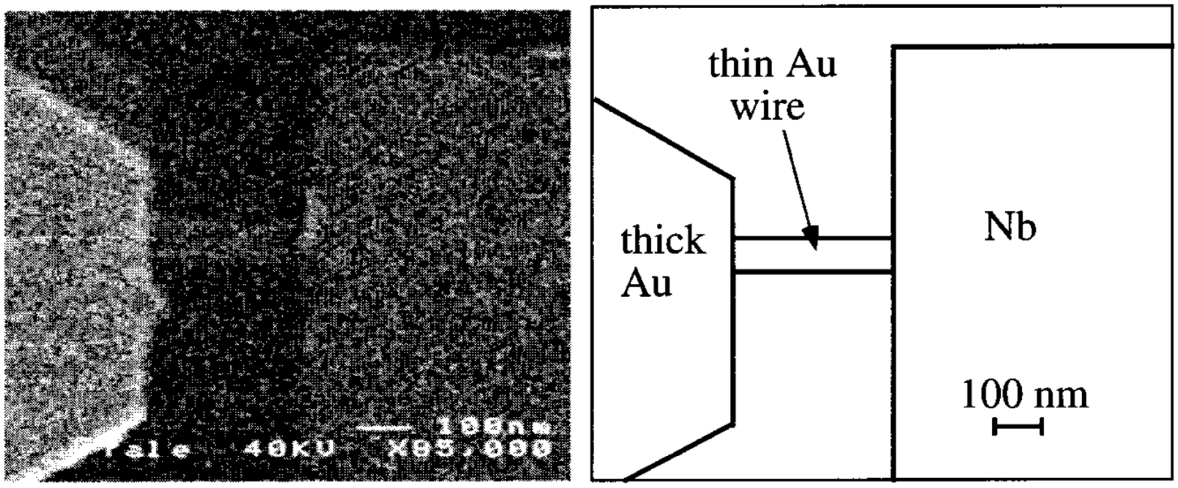

Fig. 1. SEM picture of the device and device schematics.

2. DEVICE FABRICATION AND PARAMETERS.

Our device is a 10 nm thick Au wire in contact with 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 evaporated using a double-angle evaporation technique[10] in a single vacuum pumpdown to ensure good interface quality. To ensure a transparent interface between the Au wire and the Nb contact, the surface of the Au was *in situ* ion beam cleaned immediately before Nb sputtering. The diffusion constant of thin Au film is about 30 cm^2/sec, which results in a nearly temperature-independent sheet resistance of about 15 $\Omega/\square$. Based on known R_{device}, $R_\square$ and the dimensions of the device, we estimate the Au-Nb interface resistance to be $R_{interface} \leq 5\ \Omega$, so the resistance of the device ($\sim 40\ \Omega$) is dominated by the resistance of the diffusive Au wire. This means that the conductance of the device should behave similarly to that of a diffusive N-S device with a perfectly transparent interface.[11] Our observations of reentrant behavior of the differential resistance of the device (see below) further argue that we have a diffusive N-S device with a transparent interface between the normal metal and the superconductor. At $T < 1$ K the phase-breaking length L_ϕ is dominated by electron-electron inelastic scattering and should be greater than 2 μm at 100 mK.[12] We performed shot noise measurements on 2 devices of different lengths (0.28 μm and 0.22 μm). The conductance and the noise of both devices displayed similar behavior, so we present the results of measurements of only one of the 2 devices, with length L =0.28 μm. The geometry of the device is shown in Fig. 1.

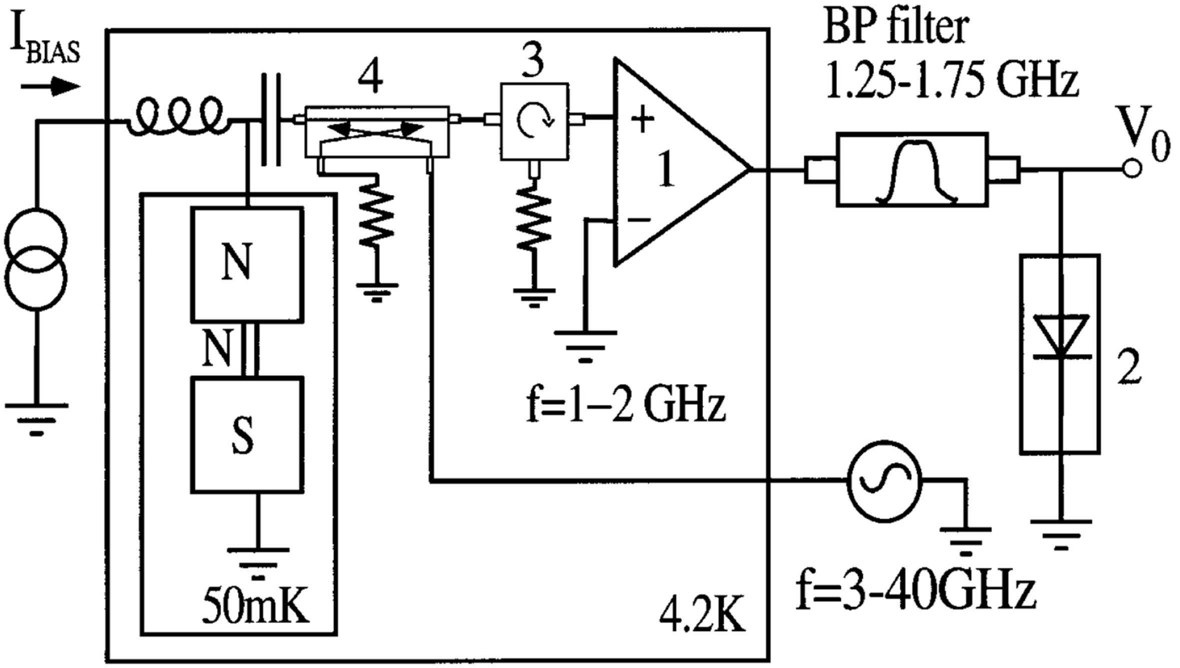

Fig. 2. Block-diagram of experimental setup.

3. MEASUREMENT SETUP.

Measurements were performed in a dilution refrigerator at mixing chamber temperatures down to 50 mK. Fig. 2 shows the block-diagram of our measurement setup. The current fluctuations in a frequency band from 1.25 to 1.75 GHz were measured using a cryogenic HEMT amplifier (1) and a bandpass filter, the amplified signal was rectified by a diode (2), and a bias modulation scheme[13] was used to measure the differential resistance and differential noise power simultaneously. The device was well-matched to the 50 Ω amplifier; the differential resistance of the device changed from 39 Ω to 41.5 Ω over the range of bias voltages $|V| < 0.6$ mV. This corresponds to < 1 % relative change in the RF power coupled from the device to the amplifier. We used a 20 dB microwave isolator (3) between the device and the amplifier to further ensure that the contribution of the amplifier's noise was independent of the device resistance. A broadband directional coupler (4) was installed between the device and the amplifier to apply the RF excitation to the device. We performed the calibration of the gain and noise temperature of the measurement setup by changing the mixing chamber temperature and using the Johnson-Nyquist noise of the device as a calibrating signal.

4. RESULTS OF THE MEASUREMENTS.

As expected for a diffusive normal metal wire in good contact with a superconductor, the differential resistance of the device displays reentrant behavior vs. both bias voltage and temperature (see Fig. 3(b)). The minimum of dV/dI occurs at $V_{bias} = 97\ \mu$V; while the expected location of the resistance minimum is about $5E_c/e \approx 125\ \mu$V, so the observed location of resistance minimum is in reasonable agreement with the expected value.

We performed measurements of shot noise of an N-S device vs. bias voltage at different mixing chamber temperatures. Fig. 3(a) presents the derivative of the shot noise power vs. bias voltage at several different temperatures (the shot noise power is expressed in temperature units: $T_N = S_I R_{diff}/(4k_B)$). Theory predicts that at large bias voltages ($eV \gg k_B T$) the noise depends linearly on the bias voltage, and the slope is $dT_N/dV = e/3k_B = 3.87$ K/mV. At lower temperatures (70 and 200 mK) the data in Fig. 3(a) have asymptotic values which are in good agreement (within < 10 %) with theoretical predictions. The error in the experimental data is dominated by a systematic error of the the gain of the measurement setup and is smaller than 5 %.

To make detailed comparison of the shot noise in the diffusive N-S junction and normal diffusive conductor we also performed shot noise measurements at magnetic field $B = 5$ T, when the Nb contact is driven normal, and the device is a normal diffusive conductor. Fig. 4 shows the derivative of the shot noise power vs. bias voltage dT_N/dV for the N-S device ($B = 0$) and for the same device driven normal ($B = 5$ T), and the theoretical predictions with no adjustable parameters. The doubling of the shot noise for the N-S device compared to the normal diffusive conductor is clearly seen. Note also that for the N-S device, dT_N/dV saturates to the asymptotic value at smaller bias voltages than for the normal case, in agreement with theory.

5. DISCUSSION AND CONCLUSIONS.

Our measurements show that the non-equilibrium noise in an N-S junction at bias voltages $eV \gg k_B T$ is doubled compared to the case of the normal diffusive conductor. A somewhat subtle issue is how to provide unambiguous evidence that the observed non-equilibrium noise is indeed the shot noise. The shot noise is present in diffusive mesoscopic wire if the transport is elastic, that is, if the wire length L is shorter than the electron energy relaxation length L_e. If the wire length is intermediate between the electron-electron inelastic length L_{ee} and the electron-phonon length L_{e-ph} ($L_{ee} < L < L_{e-ph}$), the diffusive wire displays "hot-electron" noise.[14] For the normal diffusive conductor both shot noise and "hot-electron" noise are linearly dependent on the bias current when $eV \gg k_B T$: $S_I = (2/3)eI$ for shot noise and $S_I = (\sqrt{3}/4)eI$ for hot-electron noise. Because of the large

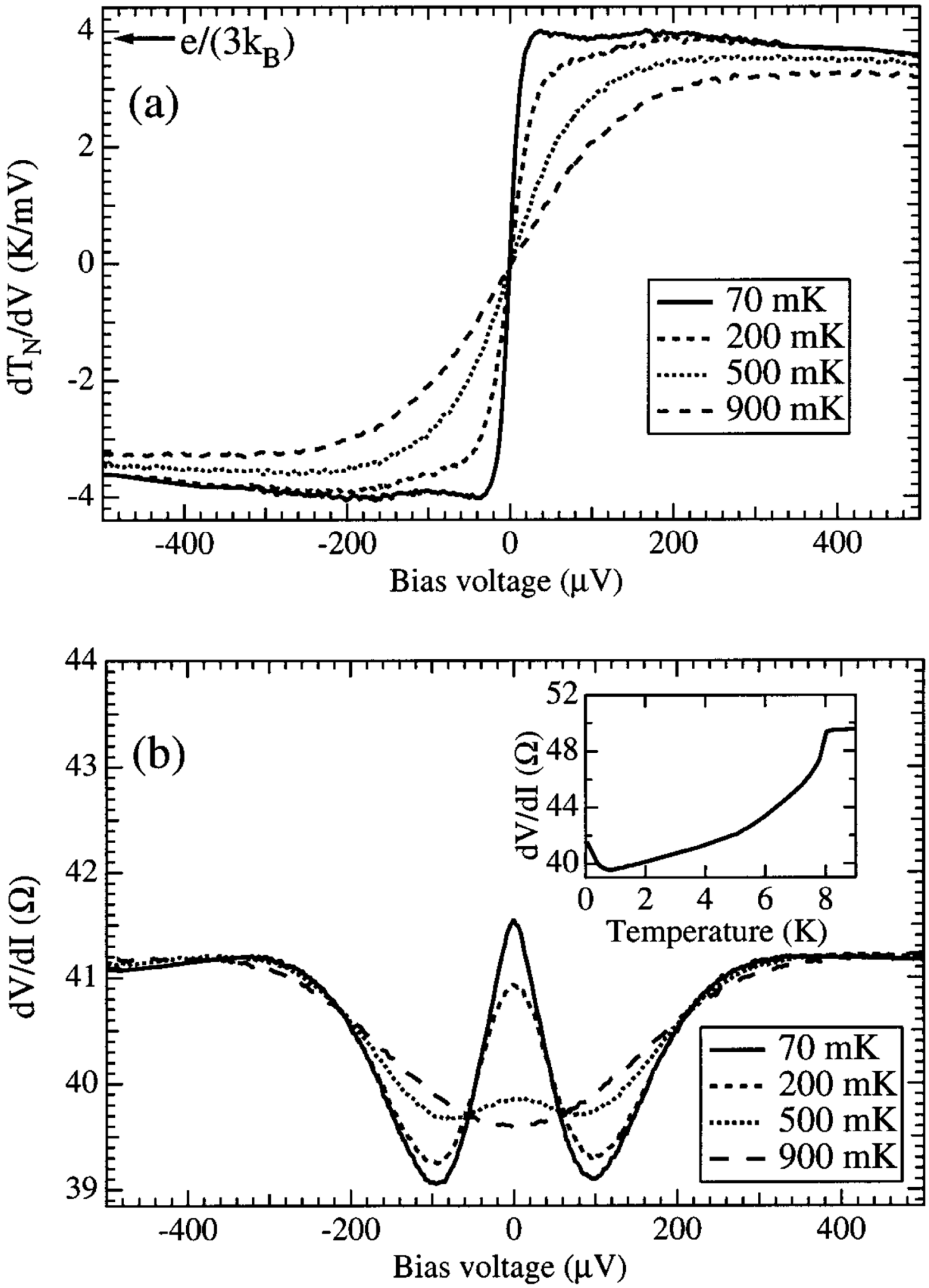

Fig. 3. (a) Derivative of shot noise vs. bias voltage dT_N/dV for the N-S device at different temperatures. The theoretically predicted asymptotic value $dT_N/dV = e/(3k_B)$ =3.87 K/mV is marked with arrow. (b) Differential resistance vs. bias voltage at several different temperatures. The inset shows the temperature dependence of zero-bias differential resistance.

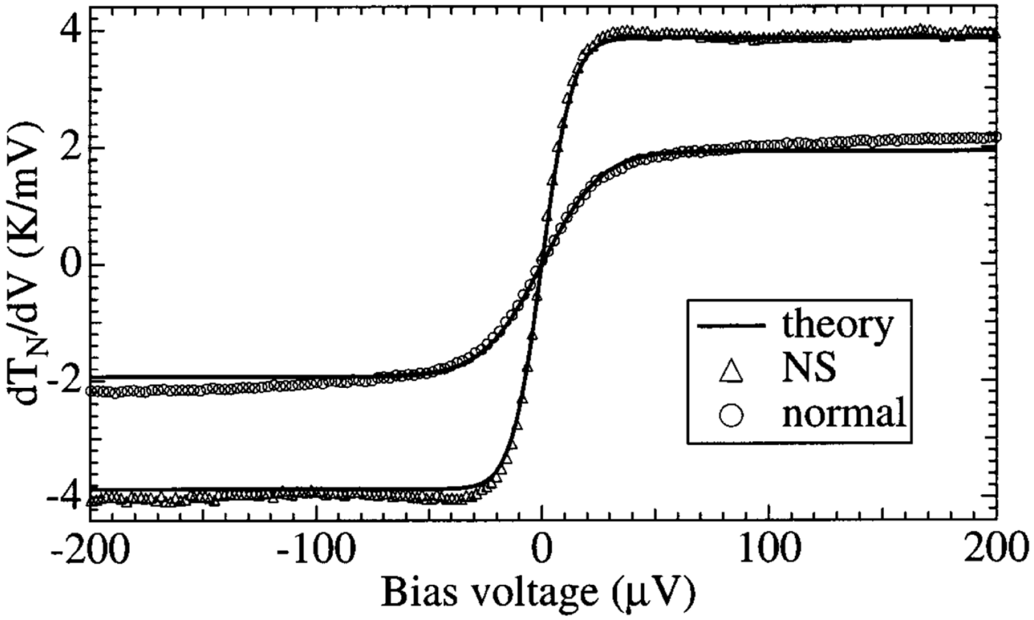

Fig. 4. Shot noise for an N-S device at T=70 mK and for the same device driven normal (T=100 mK) and the theoretical predictions with no adjustable parameters.

($eV \gg k_B T$) bias voltages which cause heating of the reservoirs of the device and may cause additional effects due to phonon emission it is often difficult in experiments[15] to convincingly distinguish between "true" shot noise and "hot-electron" noise. Moreover, making one of the contacts superconducting should lead to doubling of both shot noise (because of Andreev reflection and charge $2e$) and "hot-electron" noise (because of a decrease of electron heat conductance to the leads by a factor of 2).

Applying RF excitation to the device and observation of photon-assisted features in the noise under RF irradiation[16] provides clear evidence that our device is in the regime of elastic transport at large ($eV \gg k_B T$) bias voltages, so the observed nonequilibrium noise is indeed shot noise.

In conclusion, we performed shot noise measurements in diffusive N-S junctions. We observed an increase of shot noise by a factor of 2 compared to the normal diffusive conductor in good agreement with theoretical predictions. The crossover from Johnson-Nyquist to shot noise occurs at bias voltages smaller than for the normal diffusive conductor in qualitative agreement with theory.

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REFERENCES

1. D. Esteve *et al.* in *Proceedings of Advanced Study Institute on Mesoscopic Elecron Transport*, edited by L.L. Sohn, L.P. Kouwenhoven and G. Schon (Kluwer, Dordrecht, 1997).
2. L. Saminadayar *et al.*, Phys. Rev. Lett. **79**, 2526 (1997); R. de-Picciotto *et al.*, Nature (London) **389**, 162 (1997).
3. M. Buttiker, Phys. Rev. B **46**, 12485 (1992).
4. A.F. Andreev, Sov. Phys. JETP **19**, 1228 (1964).
5. G.E. Blonder, M. Tinkham, T.M. Klapwijk, Phys. Rev. B **25**, 4515 (1982).
6. H. Courtois *et al.*, Phys. Rev. Lett. **76**, 130 (1996).
7. V.A. Khlus, Zh. Eksp. Teor. Fiz. **93**, 2179 (1987) [Sov. Phys. JETP **66**, 1243 (1987)]; M.J.M. de Jong, C.W.J. Beenakker, Phys. Rev. B **49**, 16070 (1994); B.A. Muzykantskii and D.E. Khmelnitskii, Phys. Rev. B **50**, 3982 (1994).
8. D. Ivanov, unpublished.
9. K.E. Nagaev, Phys. Lett. A**169**, 103 (1992).
10. T.A. Fulton and G.J. Dolan, Phys. Rev. Lett. **59**, 109 (1987).
11. H. Courtois *et al.*, cond-mat/9902014 (1999). Note that the transparency of the interface *per se* is not the relevant parameter; the propagation of superconducting correlations in the diffusive normal metal depends only on the ratio of $R_{device}/R_{interface}$ (at least as far as transport in concerned).
12. B.L. Al'tshuler, A.G. Aronov and D.E. Khmelnitskii, J. Phys. C **15**, 7367 (1982).
13. M. Reznikov *et al.*, Phys. Rev. Lett. **75**, 3340 (1995); R. Schoelkopf *et al.*, Phys. Rev. Lett. **78**, 3370 (1997).
14. A.H. Steinbach, J.M. Martinis, M.H. Devoret, Phys. Rev. Lett. **76**, 3806 (1996).
15. M. Henny *et al.*, Phys. Rev. B **59**, 2871 (1999).
16. A.A. Kozhevnikov, R.J. Schoelkopf, D.E. Prober, in preparation.