Shot-Noise Signatures of 0.7 Structure and Spin in a Quantum Point Contact

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We report simultaneous measurement of shot noise and dc transport in a quantum point contact as a function of source-drain bias, gate voltage, and in-plane magnetic field. Shot noise at zero field exhibits an asymmetry related to the 0.7 structure in conductance. The asymmetry in noise evolves smoothly into the symmetric signature of spin-resolved electron transmission at high field. Comparison to a phenomenological model with density-dependent level splitting yields good quantitative agreement.

Shot noise, the temporal fluctuation of current resulting from the quantization of charge, is sensitive to quantum statistics, scattering and many-body effects.1,2 Pioneering measurements3-5 of shot noise in quantum point contacts (QPCs) observed the predicted6 suppression of shot noise below the Poisson value due to Fermi statistics. In regimes where many-body effects are strong, shot noise measurements have been exploited to directly observe quasiparticle charge in strongly correlated systems7-9 as well as to study coupled localized states in mesoscopic tunnel junctions10 and cotunneling in nanotube-based quantum dots11.

Paralleling these developments, a large literature has emerged concerning the surprising appearance of an additional plateau in transport through a QPC at zero magnetic field, termed 0.7 structure. Experiment12-14 and theory15,16 suggest that 0.7 structure is a many-body spin effect. Its underlying microscopic origin, however, remains an outstanding problem in mesoscopic physics. This persistently unresolved issue is remarkable given the simplicity of the device.

In this Letter, we report simultaneous measurements of the shot noise at 2 MHz and dc transport in a QPC, exploring the noise signature of the 0.7 structure and its evolution with in-plane magnetic field B∥. A suppression of the noise relative to that predicted by theory for spin-degenerate transport16 is observed near 0.7 × 2e²/h at B∥ = 0, in agreement with results from Roche et al.17 obtained at kHz frequencies. This suppression evolves smoothly with increasing B∥ into the signature of spin-resolved transmission. We find quantitative agreement between noise data and a phenomenological model for a density-dependent level splitting16, with model parameters extracted solely from conductance.

Measurements are performed on a gate-defined QPC fabricated on the surface of a GaAs/Al₂₀.₃Ga₇₀.₀₇As heterostructure grown by molecular beam epitaxy (see micrograph in Fig. 1). The two-dimensional electron gas 190 nm below the surface has a density of 1.7 × 10⁻¹¹ cm⁻² and mobility 5.6 × 10⁶ cm²/Vs. All data reported here were taken at 290 mK, the base temperature of a ³He cryostat.

The differential conductance g = dI/dVsd (where I is the current and Vsd is the source-drain bias) is measured by lock-in technique with an applied 25 µVrms excitation at 430 Hz17. The resistance Rg in series with the QPC is subtracted at every applied B∥ (see Fig. 2(a))18.

The QPC is first characterized at zero and finite B∥ using dc conductance measurements. Figure 2(a) shows linear-response conductance g₀ = g(Vsd ~ 0) as a function of gate voltage Vg2, for B∥ = 0 to 7.5 T in steps of 0.5 T. The QPC shows the characteristic quantization of conductance in units of 2e²/h at B∥ = 0, and the appearance of spin-resolved plateaus at multiples of 0.5 × 2e²/h at B∥ = 7.5 T. Additionally, at B∥ = 0, a shoulder-like 0.7 structure is evident, which evolves smoothly into the 0.5 × 2e²/h spin-resolved plateau at high B∥.

Figures 2(b) and 2(c) show g as a function of Vsd for evenly spaced Vg2 settings at B∥ = 0 and 7.5 T, respectively. In this representation, linear-response plateaus in Fig. 2(a) appear as accumulated traces around Vsd = 0 at multiples of 2e²/h for B∥ = 0, and at multiples of 0.5 × 2e²/h for B∥ = 7.5 T. At finite Vsd, additional

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capacitor resonator that performs current-to-voltage conversion. Each channel consists of a transconduc-
tance stage using a high electron mobility transistor (HEMT) cooled to 4.2 K, followed by 50 Ω amplification at room temperature. The amplified noise signals from both channels are sampled simultaneously by a digitizer, and their cross-spectral density calculated by fast-Fourier-transform.

The cross-spectral density is maximal at resonance, with a value

\[ X_R^0 = G_X^2 \left( S'_I \left( \frac{R_{\text{eff}}}{1 + gR_s} \right)^2 + 4k_B T_e R_{\text{eff}} \right), \]  

where \( G_X \) is the geometric mean of the voltage gain of the amplification channels, \( T_e \) is the electron temperature and \( R_{\text{eff}} \) is the effective resistance (at 2 MHz) between the HEMT gates and ground. \( R_{\text{eff}} \) is measured from the half-power bandwidth of the cross-spectral density [17]. \( S'_I \) is extracted from simultaneous measurements of \( X_R^0 \) and \( R_{\text{eff}} \) following calibration of \( G_X \) and \( T_e \) using thermal noise. At \( V_{sd} = 0 \), where \( S'_I \) vanishes, \( X_R^0 = G_X^2 \cdot 4k_B T_e R_{\text{eff}} \). At elevated temperatures (3 to 5 K), where electrons are well thermalized to a calibrated thermometer, a measurement of \( X_R^0 \) as a function of \( R_{\text{eff}} \) (tuned through \( V_{g2} \)) allows a calibration of \( G_X = 790 \text{ V}/\text{V} \). This gain is then used to determine from similar measurements the base electron temperature \( T_e = 290 \text{ mK} \).

Figure 3 shows \( S'_I \) at \( B_{//} = 0 \) and fixed \( V_{g2} \) for \( V_{sd} \) between -150 μV and +150 μV (blue regions in Figs. 2(b) and 2(c)). With an integration time of 60 s at each bias point, the resolution in \( S'_I \) is 1.4 x 10^-20 A^2/Hz, equivalent to full shot noise 2eI of \( I \approx 40 \text{ pA} \). Open markers superimposed on the linear conductance trace in Fig. 3(a) indicate \( V_{g2} \) settings for which corresponding noise data are shown in Fig. 3(b). \( S'_I \) vanishes with the QPC pinched off \( (g(V_{sd}) = 0) \), or on linear conductance plateaux, which shows that bias-dependent electron heating is not significant [4]. In contrast, for \( g \approx 0.5 \) and \( 1.5 \times 2e^2/h, S'_I \) grows with \( |V_{sd}| \) and shows a transition from quadratic to linear dependence [3, 4, 7], demonstrating the absence of noise from resistance fluctuations.

Solid curves superimposed on the \( S'_I \) data in Fig. 3(b) are fits to the form

\[ S'_I (V_{sd}) = \frac{2e^2}{h N} \left[ e V_{sd} \coth \left( \frac{e V_{sd}}{2k_B T_e} \right) - 2k_B T_e \right], \]  

with the noise factor \( N \) as the only free fitting parameter. Note that \( N \) relates \( S'_I \) to \( V_{sd} \), in contrast to the Fano factor, which relates \( S'_I \) to \( I \) [1, 2]. The form of this fitting function is motivated by mesoscopic scattering theory [3], where transport is described by transmission coefficients \( \tau_{n,\sigma} \) (\( n \) is the transverse mode index and \( \sigma \) denotes spin) and partition noise originates from

![Graph](image-url)
there is a reduction in the maximum amplitude of energy-independent scattering theory in two ways. First, the shape of a dome, reaching a maximum near odd multiples of $2\pi e^2/h$, and vanishing at multiples of $2\pi e^2/h$. The observed $\mathcal{N}(g_{\text{avg}})$ deviates from the spin-degenerate, energy-independent scattering theory in two ways. First, there is a reduction in the maximum amplitude of $\mathcal{N}$ below 0.25. Second, there is an asymmetry in $\mathcal{N}$ with respect to $0.5 \times 2e^2/h$, resulting from a noise reduction near the 0.7 feature. A similar but weaker asymmetry is observed about $1.5 \times 2e^2/h$.

The dependence of $\mathcal{N}(g_{\text{avg}})$ on $B_{\parallel}$ is shown in Fig. 4(d). $\mathcal{N}$ is seen to evolve smoothly from a single asymmetric dome at $B_{\parallel} = 0$ to a symmetric double-dome at 7.5 T, the latter a signature of spin-resolved electron transmission. Notably, near $0.7 \times 2e^2/h$, $\mathcal{N}$ appears insensitive to $B_{\parallel}$,
in contrast to the dependence of $N$ near $0.3 \times 2e^2/h$.

We find that all features in noise data are well accounted for within a simple phenomenological model in which the twofold degeneracy of QPC mode $n$ is lifted by a splitting $\Delta \varepsilon_{n,\sigma} = \sigma \cdot \rho_n \cdot \gamma_n$, that grows linearly with 1D density $\rho_n$ (with proportionality $\gamma_n$) within that mode. Here, $\sigma = \pm 1/2$ and $\rho_n \propto \sum_\sigma \sqrt{\mu - \varepsilon_{n,\sigma}}$ ($\mu$ is the chemical potential). The lever arm converting from $V_{sd}$ to energy (and hence $\rho_n$) as well transverse mode spacing are extracted from transconductance ($dg/dV_{sd}$) data (Fig. 4(b)). Assuming an energy-dependent transmission, $t_{n,\sigma}(\varepsilon) = 1/(1 + e^{2\pi(\varepsilon - \varepsilon_{n,\sigma})/\hbar \omega_x})$, appropriate for a saddle-point potential with curvature parallel to the current described by $\omega_x[21]$, the value for $\omega_x$ is found by fitting linear conductance below $0.5 \times 2e^2/h$ (below $1.5 \times 2e^2/h$ for the second mode), and $\gamma_n$ is obtained from a fit to conductance above $0.5(1.5) \times 2e^2/h$, where (within the model) the splitting is largest (see Fig. 4(c)). For the QPC studied, we find $\hbar \omega_x \sim 500(300) \mu eV$ and $\gamma_{1(2)} \sim 0.012(0.008) e^2/4\pi e\hbar$ for the first (second) transverse modes. Note that the splitting is two orders of magnitude smaller than the direct Coulomb energy of electrons spaced by $1/\rho_n$.

Using these parameters, model values for $S^P_{1y}(V_{sd})$ are then calculated using the full Eq. (3), and $N$ is extracted by fitting the model $S^P_{1y}(V_{sd})$ to Eq. (2). The resulting model values of $N(Q_{avg})$ at $B_{||} = 0$ are shown along with the experimental data in Fig. 4(a). Also shown for comparison are the model values only accounting for energy dependent transmission but no splitting ($\gamma_n = 0$). The overall reduction of $N$ arises from a variation in transmission across the $150 \mu V$ bias window, which is comparable to $\hbar \omega_x$. Asymmetry of the model values for $N$ about 0.5 and $1.5 \times 2e^2/h$ require nonzero $\gamma_n$.

We include magnetic field in the model with corresponding simplicity by assuming a $g$-factor of 0.44 and adding the Zeeman splitting to the density-dependent splitting [24] maintaining the parameters obtained above. The resulting model values for $N$ are shown in Fig. 4(e), next to the corresponding experimental data (Fig. 4(d)). Experimental and model values for $N$ show comparable evolution in $B_{||}$: the asymmetric dome at $B_{||} = 0$ evolves smoothly into a double dome at $7.5 \ T$, and for conductance $\gtrsim 0.7 \times 2e^2/h$, the curves for all magnetic fields overlap closely. Some differences are observed between data and model, particularly for $B_{||} = 7.5 \ T$. While the experimental double-dome is symmetric with respect to the minimum at $0.5 \times 2e^2/h$, the theory curve remains slightly asymmetric with a less pronounced minimum. We find that setting the $g$-factor to approximately 0.6 in the model reproduces the measured symmetrical double-dome as well as the minimum value of $N$ at $0.5 \times 2e^2/h$. This observation is consistent with previous reports of an enhanced $g$-factor in a QPC at low-density [12].

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