Quantum Partition Noise of photon excited electron-hole pairs

Is it possible to observe quantum partition noise without net electron transport?

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(ordinary) **Transport Shot Noise**

In general, shot noise requires non-equilibrium conditions. In nearly all present works, non-equilibrium is provided by a voltage bias.

### Incoming current:

\[ I_0 = e (eV / h) \]

### Transmitted current:

\[ I = DI_0 = D \frac{e^2}{h} V \]

### Current shot noise power:

\[ S_I = 2eI_0(D(1-D)) = 2eI(1-D) \]

\[ S_I(\omega) = \int I(t)I(t+\tau)\cos(\omega\tau)d\tau \]
Other non-equilibrium cases are however possible while no electrons flow through the conductor (non-transport shot noise):

- heating one of the reservoirs.
  Sukhorukov and Loss PRB (1999)
  \[ S_f = 2k_B T \frac{e^2}{h} \left[D^2 + 2\ln(2)D(1-D)\right] \]
  (no measurements yet available)

- coherent rf pumping of electron emitted from one side of the conductor.

(this presentation)
Partition noise of photon-created Electron-hole pairs
(non-transport Shot Noise)

an incoming electron can be either
 un pumped ( prob. $P_0$ )

or pumped ( prob. $P_1$ )

un pumped electrons do not
 generate noise (ground state)

pumped electrons do generate noise
 as e - h pairs are dissociated by the
 elastic scatter.
current of pumped incoming electrons:

\[ I_0^{(e)} = P_1 \frac{e}{h} (h\nu) \]

current of pumped incoming holes:

\[ I_0^{(h)} = -I_0^{(e)} \]

the associated electron and hole shot noise powers are respectively:

\[ S_I^{(e)} = 2e I_0^{(e)} D (1 - D) \quad \text{and} \quad S_I^{(h)} = 2e I_0^{(h)} D (1 - D) = S_I^{(e)} \]

they add independently to give the electron-hole partition shot noise:

\[ S_I = 4h\nu \frac{e^2}{h} P_1 D (1 - D) \]

while the mean current: \[ I = 0 \]
Not a simple thermal effect!

For an energy relaxation length shorter than the conductor:

\[ S_I = 4\hbar\nu \frac{e^2}{h} \left\{ P_1 D (1 - D) + P_1 (1 - P_1) D^2 \right\} \]

Electron hole partitioning

While Photon assisted process gives:

\[ S_I = 4\hbar\nu \frac{e^2}{h} P_1 D (1 - D) \]
for a doubly non-equilibrium, when both a d-c voltage $V$ and RF are applied, the slope of the transport shot noise variation with $V$ was predicted to show a singularity at $eV = \hbar \nu$

Applying DC bias and RF

electron transport shot noise

electron-hole non-transport shot noise

\[ \text{slope} = 2 \frac{e^2}{h} D(1 - D)(1 - 2P_I) \]
a complete formula have been derived by Levitov and Lesovik (PRL 94):

\[ S_I = 4 \hbar \left( \sum_i l P_i \right) \frac{e^2}{h} \sum_l D_n (1 - D_n) \]

where \( P_i = J_i^2 (\phi / \phi_0) \)

\( \phi(t) = \phi_0 \cos \omega t \) and \( \phi_0 = \hbar / e \)

“a-c Aharanov-Bohm effect”

later Pedersen et al. (98) have considered the equivalent case of an a-c potential applied to one contact:

\[ V_{a-c}(t) = V_{a-c} \cos \omega t \text{ with } P_i = J_i^2 (eV_{a-c} / \hbar \omega) \]

\[ V_{a-c}(t) = \frac{d\phi(t)}{dt} \]

At Finite Temperature:

\[ T_N = \frac{S_I}{4G k_B} = T \left( \frac{\sum D_n^2}{\sum D_n} \right) + \sum_n D_n (1 - D_n) \sum_{l=0}^{\infty} \sum_{\pm} \frac{(eV \pm l \hbar \nu)}{2k_B} J_i^2(\alpha) \coth \left( \frac{eV \pm l \hbar \nu}{2k_B T} \right) \]

One needs \( k_B T \ll \hbar \nu \)

\[ 17 \text{ GHz} \approx 850 \text{ mK} \]
The singularity was observed by Schoelkopf et al. (PRL 98) in the doubly non-equilibrium regime (RF and V bias) using:

- a diffusive system (and later a S-diffusive junction)
- measuring the derivative of the transport noise versus d-c bias voltage V
- they provide the first evidence of photon-assisted processes in shot noise, supporting Lesovik’s model.

→ the Fano factor was fixed by the bimodal statistics of the transmission probabilities of a diffusive conductor:

\[
F = \frac{\left\langle \sum_n D_n (1 - D_n) \right\rangle}{\left\langle \sum_n D_n \right\rangle} = \frac{1}{3}
\]

→ no possibility to measure the total shot noise at zero bias (non-transport electron-hole pair shot noise)
• ballistic QPC to control the transmission and vary the Fano factor

• total shot noise measurements to probe the V=0 non transport electron-hole pairs shot noise

• allows for quantitative test of the scattering theory

- 2 to 4 kHz cross-correlation voltage noise measurements.

- ~17 GHz rf excitation.
Quantum Point Contact
(tuning the transmission probability of the first two modes)

2D electron gas in GaAs/GaAlAs
\( \mu = 8.1 \times 10^5 \text{cm}^2/\text{Vs} \)
\( n_s = 4.8 \times 10^{11} \text{ cm}^{-2} \)

\[ G = \frac{dI}{dV} = \frac{2e^2}{h} \sum D_n \]
\( h/e^2 = 25812 \Omega \)

\( T = 80 \text{ mK} \)

\( D_1 = 1, D_2 = 1 \)

Tuning of the mode transmissions

Split gate

++ ++ ++ + Si ++ + + + AlGaAs

2D gas

GaAs

100 nm

Vg

100 nm

V

L = 30 \mu m

mean free path ~ 9 \mu m

Transit time ~ 0.4 ns
Calibration using Johnson-Nyquist Noise at D = 1

Cross correlated power spectrum
\[ S_{V_1V_2}(\omega) = \int V_1(t)V_2(t+\tau)\cos(\omega\tau)\,d\tau \]
\[ S_I = S_{V_1V_2}(\omega)G^2 \quad \text{2 to 4 kHz frequency range} \]

Sensitivity: 10 min. acq. time leads to 5 mK noise temperature accuracy at D = 1

\[ T_N = \frac{S_I}{4k_BG} \]

(12906 \Omega)
1 - check for possible heating by RF power  (no bias voltage, i.e. no current )

At transmission 1 or 2 no electron-hole partition noise is expected!

\[ D_1 = 1 \quad D_2 = 1 \]

\[ D_1 = 1 \quad D_2 = 0 \]

\[ \Delta T_{\text{NOISE}} = \frac{1}{2} \left( mW^{1/2} \right) \]

\[ 0,00 \quad 0,47 \quad 0,94 \quad 1,40 \quad 1,87 \quad 2,34 \quad 2,81 \quad 3,27 \]

\[ \alpha = eV_{\text{ac}} / h \]

\[ \nu = 17.32 \text{ GHz} \]

\[ T_0 = 98 \text{ mK} \]

\[ \text{Determination of } T = T_0 + \Delta T_N \]
2 - check for possible e-h partition noise at $1/2$ transmission:

$$D_1 = 0.5 \quad \text{and} \quad D_{n>1} = 0$$

$$\alpha \propto \sqrt{P}$$

$\Delta T_{\text{NOISE}}$(K) vs $P^{1/2}$ (mW$^{1/2}$)

- good fit with theory gives a calibration of $\alpha = eV_{ac}/h\nu$ with RF power

$T_0 = 98$ mK

17.32 GHz

Determination of the coupling parameter $\alpha$
Quantum or Classical?

\[ V(t) = V_{a-c} \sin(2\pi vt) ; \quad \alpha = eV_{a-c} / \hbar \]

**Low frequency approximation:**

\[ S_{I,\text{moy}} = 2e^2 \frac{e^2}{h} \overline{V(t)}D(1-D) = 4\hbar e^2 \frac{e^2}{h} D(1-D) \frac{\alpha}{\pi} \]

Photon assisted processes:

\[ S_I = 4\hbar e^2 \frac{e^2}{h} D(1-D) \left( \sum_l l J_l^2(\alpha) \right) \]

Same result if \( \alpha >> 1 \)
Quantum!
3 - Is this really the partition noise of photon-created electron-hole pairs?

( no dc V bias, no current! )

QPC allows to measure the Fano factor of the e-h partition noise

\[
\frac{S_I}{4Gk_B} = T \left( J_0^2(\alpha) + \sum \frac{D_n^2}{D_n} (1 - J_0^2(\alpha)) \right) + \frac{h\nu}{k_B} \left( \sum lJ_i^2(\alpha) \right) \frac{\sum D_n (1 - D_n)}{\sum D_n}
\]

\( \alpha, D_n, T \) are known: perfect agreement without adjustable parameter
4 - additional confirmation of photon-created e-h pairs: RF and dc voltage V

Transmission 1/2

\[ T_N = \frac{S_I}{4G k_B} = T \left( \sum_n \frac{D_n^2}{\sum D_n} \right) + \sum_n \frac{D_n (1 - D_n)}{\sum D_n} \sum_{l=0}^{\infty} \frac{(eV \pm lh\nu)}{2k_B} J_l^2(\alpha) \coth \left( \frac{eV \pm lh\nu}{2k_B T} \right) \]

\( \alpha, D_n, T \) are known: perfect agreement without adjustable parameter
transmission 1/2, various rf power (or $\alpha$), two different frequencies

(no fits, just comparison data / theory)

$\rightarrow$ quantitative test of quantum scattering model of photo-assisted shot noise
CONCLUSION

partition noise of photo-created Electron-hole pairs (non-transport Shot Noise)

the Fano factor has been accurately measured

radiofrequency provide a new way to probe q-particles without necessary transport

at finite dc voltage and under various transmissions and r-f powers we have made an accurate test of the photon-assisted shot noise scattering theory