Single-particle interference and two-particle collisions

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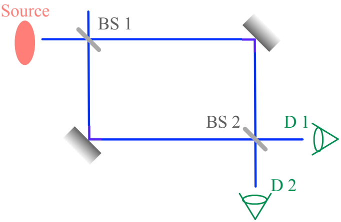
Outline

- Introduction
  - Electronic interferometers in the QH regime
  - Single-electron sources
  - Tunable two-particle effects
- Single-electron coherence from Mach-Zehnder interferometry
- Single-particle interference versus two-particle collision
  - Two-particle effects in the charge current
  - Confirmation of observed effects from the noise
- Counter-intuitive results from the energy current

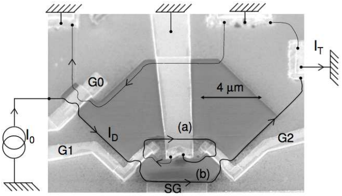
Introduction

Electronic interferometer in the quantum Hall regime

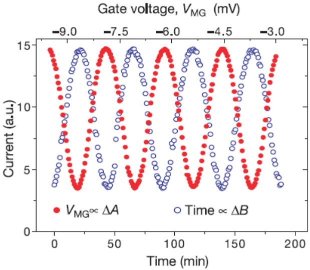


⇒ Interference pattern as a coherence effect.

Electronic realization in a Quantum Hall setup

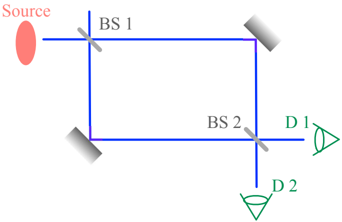


Y. Ji, *et al.*, Nature **422**, 415 (2003); P. Roulleau, *et al.*, Phys. Rev. B **76**, 161309(R) (2007).



Visibility as a measure of coherence!

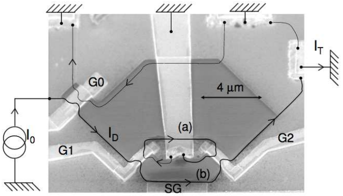
Electronic interferometer in the quantum Hall regime

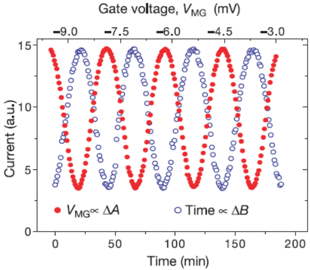


- Particles emitted into quantum Hall edges (waveguides)
- Particles are scattered at quantum point contacts (beam splitters)

⇒ Interference pattern as a coherence effect.

Electronic realization in a Quantum Hall setup





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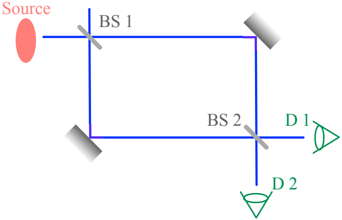
Electronic interferometer in the quantum Hall regime

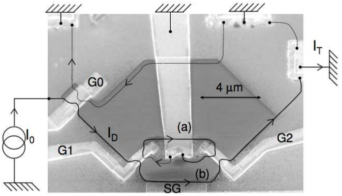


- Particles emitted into quantum Hall edges (waveguides)
- Particles are scattered at quantum point contacts (beam splitters)
- *Coherent* single-particle sources ⇒ ???

⇒ "Quantum optics with electrons."

⇒ Interference pattern as a coherence effect.

Electronic realization in a Quantum Hall setup



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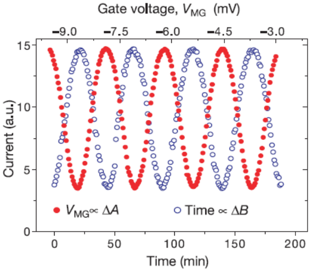
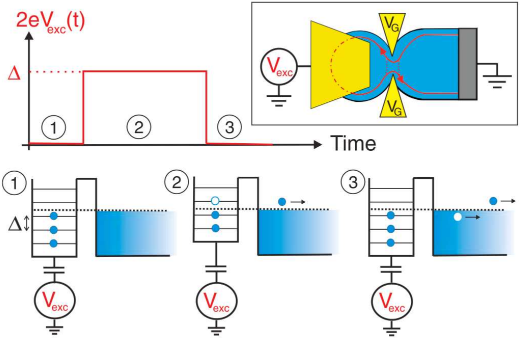


Visibility as a measure of coherence!

Single-electron sources

Aim: Inject single, well-separated electrons into an electronic circuit.

- (Superconducting) single-electron turnstiles
  see, e.g., J. Pekola, *et al.*, Nat. Phys. **4**, 120 (2008).
- Single-electron pumps
  see, e.g., H. Pothier, *et al.*, Europhys. Letts. **17**, 249 (1992); B. Kaestner, *et al.*, Phys. Rev. B **77**, 153301 (2008); B. Roche, et al., Nat. Comm. **4**, 1581 (2013)
- Gate-tuned mesoscopic capacitor



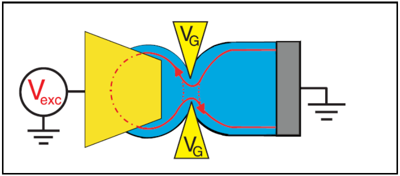
G. Fève, *et al.*, Science **316**, 1169 (2007).

- Time-dependent bias-pulses (Levitons)

J. Dubois, *et al.*, Nature **502**, 659 (2013).

Single-electron sources

Here: **adiabatically driven mesoscopic capacitor** (∼ Levitons)



Adiabaticity condition:

$$\Omega \ll T/\tau$$

with driving frequency Ω, QPC transmission T, time of flight τ.

Relate incoming and outgoing states to this (and other!) setups by a time-dependent/Floquet scattering matrix:

$$S(t,t') \Leftrightarrow S(t,E) \Leftrightarrow S(E+m\hbar\Omega, E)$$

Adiabatic limit **for the source**: ⇒ Frozen scattering matrix:

$$S_{\rm SES}(t) = \frac{\pm(t-t^{\rm e/h}) - i\sigma}{\pm(t-t^{\rm e/h}) + i\sigma}$$

Here: Neglect Coulomb interaction (strong screening due to top gates)
otherwise, see e.g. C. Wahl, J. Rech, T. Jonckheere, and T. Martin, Phys. Rev. Lett. **112**, 046802 (2014) [interaction between edge states]; J. Schulenborg, R. B. Saptsov, F. Haupt, J. Splettstoesser, and M. R. Wegewijs, Phys. Rev. B **93**, 081411(R) (2016) [Onsite Coulomb interaction].

Single-electron sources

Scattering matrix adds a **phase** to the wave-function

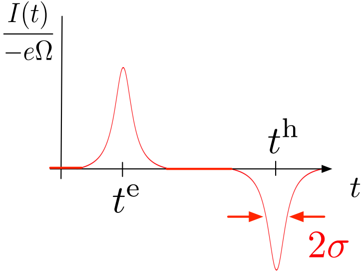
$$\Psi_E(t,x) = S_{\mathrm{SES}}\left(t - x/v_{\mathrm{D}}, E\right)\, e^{i(k_E x + \omega t)}$$

which has a nontrivial effect on the current:

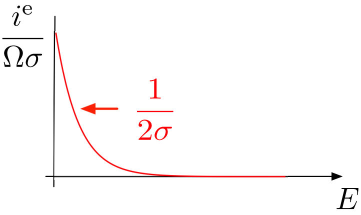
$$I_{\mathrm{SES}}(t,x) = \frac{-ie}{2\pi} S_{\mathrm{SES}}(t - x/v_{\mathrm{D}}, \mu) \frac{\partial S^*_{\mathrm{SES}}(t - x/v_{\mathrm{D}}, \mu)}{\partial t}$$

Pulses of duration $2\sigma \sim$ Emission/absorption of particles!

Lorentzian time-dependence



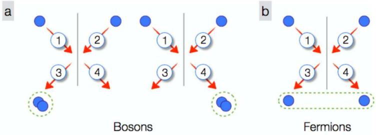
Exponential energy-distribution

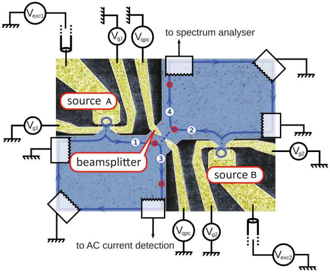


Up to here: Single-particle properties.

Tunable two-particle (exchange) effects

Hong-Ou-Mandel effect for electrons (antibunching)



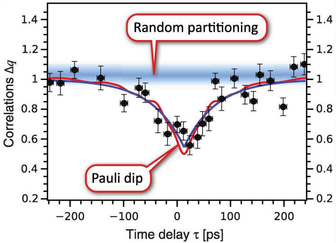


Charge current noise (correlations):

$$\mathcal{P} = \frac{e^2}{\mathcal{T}} T(1-T)$$

$$\left(1 - \frac{4\sigma_{\mathrm{A}}\sigma_{\mathrm{B}}}{(t^{\mathrm{e}}_{\mathrm{A}} - t^{\mathrm{e}}_{\mathrm{B}})^2 + (\sigma_A + \sigma_B)^2}\right)$$

S. Ol'khovskaya, J. Splettstoesser, M. Moskalets, and M. Büttiker, Phys. Rev. Lett. **101**, 166802 (2008).



Figures from Experiment: E. Bocquillon, V. Freulon, J. M. Berroir, P. Degiovanni, B. Plaçais, A. Cavanna, Y. Jin, and G. Fève, Science **339**, 1054 (2013).

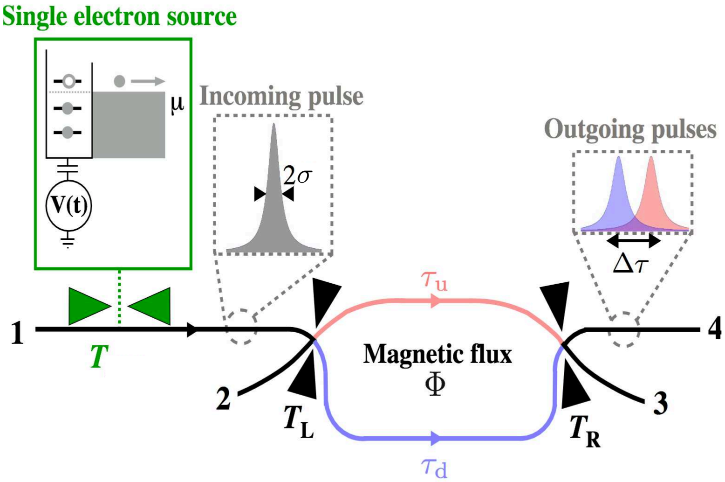
Single-electron coherence from Mach-Zehnder interferometry

Single-electron coherence from Mach-Zehnder interferometry

Spectral analysis of emitted signal - some alternative approaches:

- Full quantum state tomography from noise
  C. Grenier, R. Hervé, E. Bocquillon, F. D. Parmentier, B. Plaçais, J.-M. Berroir, G. Fève, P. Degiovanni, New J. Phys. **13**, 093007 (2011).
- Energy current, power fluctuations and mixed noise
  F. Battista, F. Haupt, and J. Splettstoesser, Phys. Rev. B **90**, 085418 (2014);
  F. Battista, F. Haupt, and J. Splettstoesser, J. Phys.: Conf. Ser. **568**, 052008 (2014).
  N. Dashti, M. Misiorny, P. Samuelsson, and J. Splettstoesser, in preparation;
  N. Dashti, P. Samuelsson, M. Misiorny, and J. Splettstoesser, in preparation.

Single-electron coherence from Mach-Zehnder interferometry



G. Haack, M. Moskalets, J. Splettstoesser, and M. Büttiker, Phys. Rev. B **84**, 081303(R) (2011).

Single-electron coherence from Mach-Zehnder interferometry

$$I_4(t,\Phi) = I_4^{(\mathrm{cl})}(t) + I_4^{(\mathrm{int})}(t,\Phi)$$

$$I_4^{(\mathrm{int})}(t,\Phi) \propto \mathrm{Re}\left\{ e^{-i\phi} \mathcal{C}_{\mathrm{SES}}(t,\Delta\tau) \right\}$$

Single-particle coherence:

$$\mathcal{C}_{\mathrm{SES}}(t^-,\Delta\tau) = \frac{1}{1 - i\,\Delta\tau/\sigma}$$

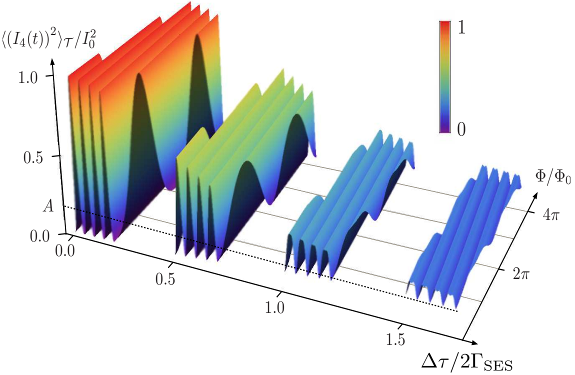
Extract

Single-particle coherence length

$$\Lambda = v_{\mathrm{D}}\sigma$$

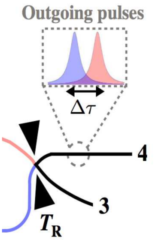
from the visibility of a time-averaged measurement.

G. Haack, M. Moskalets, J. Splettstoesser, and M. Büttiker, Phys. Rev. B **84**, 081303(R) (2011).



Single-electron coherence from Mach-Zehnder interferometry

Two interpretations:



Large detuning $\Delta\tau \gg \sigma$:

No overlap between wave packets

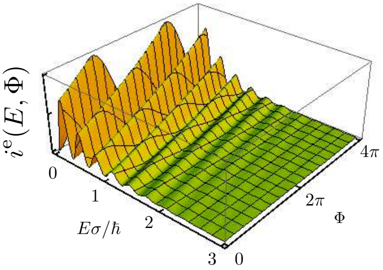
⇒ knowledge of path taken by the particle

⇒ Interference suppression.

G. Haack, M. Moskalets, J. Splettstoesser, and M. Büttiker, Phys. Rev. B **84**, 081303(R) (2011).

Channelled spectrum

(oscillations on a scale $\hbar/\Delta\tau$):



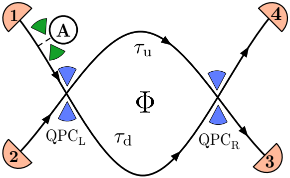
Averaging effect of phase-shifted contributions of the distribution function at different energies.

G. Rosselló, F. Battista, M. Moskalets, and J. Splettstoesser, Phys. Rev. B **91**, 115438 (2015).

⇒ Particle interpretation of a superposition of plane waves (wave packet)

[Strong energy-dependence of MZI-transmission leads to different currents of electrons and holes!]

Single-electron coherence from Mach-Zehnder interferometry



$$\mathcal{P} = \frac{1}{2}\int_0^{\mathcal{T}} \frac{dt'}{\mathcal{T}} \int_{-\infty}^{\infty} d(t-t') \left[\langle \hat{I}_3(t)\hat{I}_4(t') + \hat{I}_3(t')\hat{I}_4(t)\rangle - 2\langle \hat{I}_3(t)\rangle\langle \hat{I}_4(t')\rangle\right]$$

Noise of a **single-particle** process (partition noise $\propto T(1-T)$):

$$\boxed{\mathcal{P} = -\frac{e^2}{\mathcal{T}} T_{41}^{\mathrm{eff}} T_{31}^{\mathrm{eff}}}$$

Interpretation of the classical part:

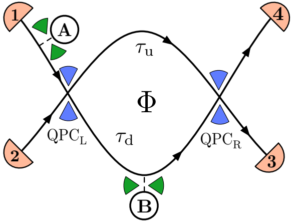
$$\propto T_{\mathrm{R}}R_{\mathrm{R}} + T_{\mathrm{L}}R_{\mathrm{L}}\left(T_{\mathrm{R}} - R_{\mathrm{R}}\right)^2$$

Noise of QPC R Noise of QPC L (in presence of QPC R)

G. Rosselló, F. Battista, M. Moskalets, and J. Splettstoesser, Phys. Rev. B **91**, 115438 (2015).

Single-particle interference versus two-particle collision

Single-particle interference versus two-particle collision



Two electrons collide at QPC R:

$$\Delta t_{\mathsf{u}}^{\mathsf{ee}} = 0$$

Two electrons collide at source B:

$$\Delta t_{\mathsf{d}}^{\mathsf{ee}} = 0$$

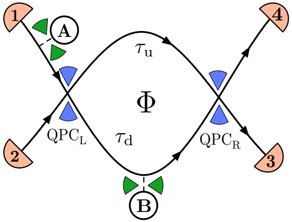
Time-averaged charge current

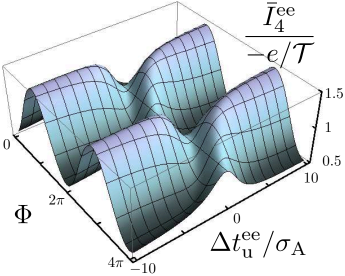
$$\frac{\bar{I}_4^{\mathsf{ee}}}{-e/\mathcal{T}} = R_{\mathsf{L}}R_{\mathsf{R}} + T_{\mathsf{L}}T_{\mathsf{R}} + T_{\mathsf{R}}$$
$$-2\gamma\mathbb{R}\mathrm{e}\left\{e^{-i\phi}\frac{-2i\sigma_{\mathsf{A}}}{\Delta\tau - 2i\sigma_{\mathsf{A}}}\left(1 - \frac{-2i\sigma_{\mathsf{B}}}{\Delta t_{\mathsf{u}}^{\mathsf{ee}} - i\left(\sigma_{\mathsf{A}} + \sigma_{\mathsf{B}}\right)}\right)\right\}$$

Two-particle effect visible in a single-particle quantity!
(Similar for h-h collision at QPC R and
for e-h collision (absorption) at source B)

S. Juergens, J. Splettstoesser, and M. Moskalets, EPL **96**, 37011 (2011).

Single-particle interference versus two-particle collision





Two interpretations:

1.) Collision of electrons at QPC R suppresses fluctuations due to the Hong-Ou-Mandel effect!

Noise at $\Delta t_\mathrm{u}^\mathrm{ee} = 0$:

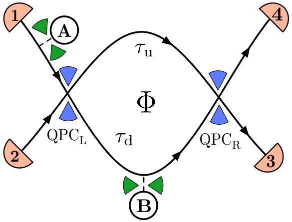
$$2T_\mathrm{L} \cdot T_\mathrm{R}R_\mathrm{R} + T_\mathrm{L}R_\mathrm{L}\left(T_\mathrm{R} - R_\mathrm{R}\right)^2$$

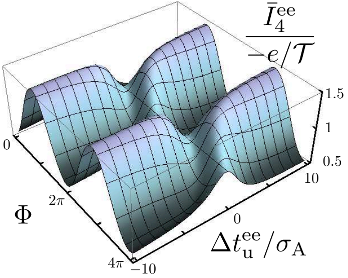
Noise of two particles at QPC R Noise of QPC L (in presence of QPC R)

$\Rightarrow$ Which-path detection suppressing interference.

S. Juergens, J. Splettstoesser, and M. Moskalets, EPL **96**, 37011 (2011); G. Rosselló, F. Battista, M. Moskalets, and J. Splettstoesser, Phys. Rev. B **91**, 115438 (2015).

Single-particle interference versus two-particle collision





Two interpretations:

1.) Collision of electrons at QPC R suppresses fluctuations due to the Hong-Ou-Mandel effect!
⇒ Which-path detection suppressing interference.

2.) Time-deference Δt_d^{ee} introduces new energy-scale $\hbar/\Delta t_d^{ee}$ on which the spectral current oscillates.
⇒ Averaging effect from the channelled spectrum of the **combined** time-dependent scatterer (MZI + Source B).

S. Juergens, J. Splettstoesser, and M. Moskalets, EPL **96**, 37011 (2011); G. Rosselló, F. Battista, M. Moskalets, and J. Splettstoesser, Phys. Rev. B **91**, 115438 (2015).

Counter-intuitive results from the energy current

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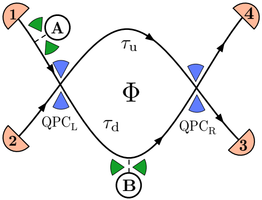


Energy current J

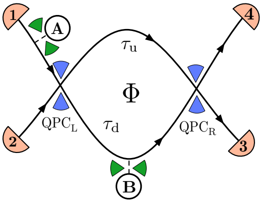
carried by electrons (and holes)
in the vicinity of e-e collision

Independent transmission/reflection of energy injected from the sources.

$$
\begin{aligned}
\bar{J}^{\mathsf{ee}} = {} & \frac{\hbar}{2\sigma_\mathsf{A}\mathcal{T}}\left(R_\mathsf{L}R_\mathsf{R}+T_\mathsf{L}T_\mathsf{R}\right)+\frac{\hbar}{2\sigma_\mathsf{B}\mathcal{T}}T_\mathsf{R} \\
& +T_\mathsf{L}T_\mathsf{R}\left(\frac{\hbar}{2\sigma_\mathsf{A}\mathcal{T}}+\frac{\hbar}{2\sigma_\mathsf{B}\mathcal{T}}\right)\frac{4\sigma_\mathsf{A}\sigma_\mathsf{B}}{\Delta t_\mathsf{d}^{\mathsf{ee}\,2}+\left(\sigma_\mathsf{A}+\sigma_\mathsf{B}\right)^2} \\
& -2\gamma\frac{\hbar}{2\sigma_\mathsf{A}\mathcal{T}}\mathbb{R}\mathrm{e}\left\{e^{-i\phi}\left(\frac{-2i\sigma_\mathsf{A}}{\Delta\tau-2i\sigma_\mathsf{A}}\right)^2\left(1-\frac{-2i\sigma_\mathsf{B}}{\Delta t_\mathsf{u}^{\mathsf{ee}}-i\left(\sigma_\mathsf{A}+\sigma_\mathsf{B}\right)}\right)\right\} \\
& +2\gamma\frac{\hbar}{2\sigma_\mathsf{B}\mathcal{T}}\mathbb{R}\mathrm{e}\left\{e^{-i\phi}\frac{-2i\sigma_\mathsf{A}}{\Delta\tau-2i\sigma_\mathsf{A}}\left(\frac{-2i\sigma_\mathsf{B}}{\Delta t_\mathsf{u}^{\mathsf{ee}}-i\left(\sigma_\mathsf{A}+\sigma_\mathsf{B}\right)}\right)^2\right\}
\end{aligned}
$$

G. Rosselló, F. Battista, M. Moskalets, and J. Splettstoesser, Phys. Rev. B **91**, 115438 (2015).

Counter-intuitive results from the energy current



Energy current J

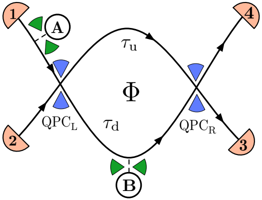
carried by electrons (and holes)
in the vicinity of e-e collision

Increased energy current when particle B is injected **on top** of particle A.

$$
\begin{aligned}
\bar{J}^{\mathsf{ee}} \quad = \quad & \frac{\hbar}{2\sigma_{\mathsf{A}}\mathcal{T}}\left(R_{\mathsf{L}}R_{\mathsf{R}}+T_{\mathsf{L}}T_{\mathsf{R}}\right)+\frac{\hbar}{2\sigma_{\mathsf{B}}\mathcal{T}}T_{\mathsf{R}} \\
& +T_{\mathsf{L}}T_{\mathsf{R}}\left(\frac{\hbar}{2\sigma_{\mathsf{A}}\mathcal{T}}+\frac{\hbar}{2\sigma_{\mathsf{B}}\mathcal{T}}\right)\frac{4\sigma_{\mathsf{A}}\sigma_{\mathsf{B}}}{\Delta t_{\mathsf{d}}^{\mathsf{ee}\,2}+\left(\sigma_{\mathsf{A}}+\sigma_{\mathsf{B}}\right)^{2}} \\
& -2\gamma\frac{\hbar}{2\sigma_{\mathsf{A}}\mathcal{T}}\mathbb{R}\mathrm{e}\left\{e^{-i\phi}\left(\frac{-2i\sigma_{\mathsf{A}}}{\Delta\tau-2i\sigma_{\mathsf{A}}}\right)^{2}\left(1-\frac{-2i\sigma_{\mathsf{B}}}{\Delta t_{\mathsf{u}}^{\mathsf{ee}}-i\left(\sigma_{\mathsf{A}}+\sigma_{\mathsf{B}}\right)}\right)\right\} \\
& +2\gamma\frac{\hbar}{2\sigma_{\mathsf{B}}\mathcal{T}}\mathbb{R}\mathrm{e}\left\{e^{-i\phi}\frac{-2i\sigma_{\mathsf{A}}}{\Delta\tau-2i\sigma_{\mathsf{A}}}\left(\frac{-2i\sigma_{\mathsf{B}}}{\Delta t_{\mathsf{u}}^{\mathsf{ee}}-i\left(\sigma_{\mathsf{A}}+\sigma_{\mathsf{B}}\right)}\right)^{2}\right\}
\end{aligned}
$$

G. Rosselló, F. Battista, M. Moskalets, and J. Splettstoesser, Phys. Rev. B **91**, 115438 (2015).

Counter-intuitive results from the energy current



Energy current J

carried by electrons (and holes)
in the vicinity of e-e collision

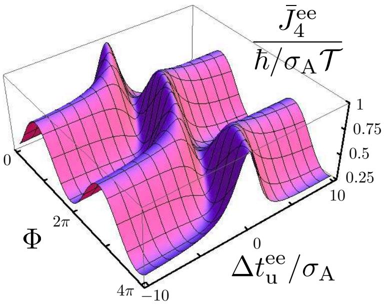
Impact on interference part - **but no suppression!!** -
when electrons collide at QPC R.

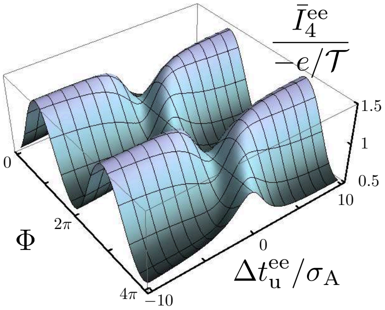
$$\begin{aligned}
\bar{J}^{\mathsf{ee}} \quad = \quad & \frac{\hbar}{2\sigma_\mathsf{A}\mathcal{T}}\left(R_\mathsf{L}R_\mathsf{R}+T_\mathsf{L}T_\mathsf{R}\right)+\frac{\hbar}{2\sigma_\mathsf{B}\mathcal{T}}T_\mathsf{R} \\
& +T_\mathsf{L}T_\mathsf{R}\left(\frac{\hbar}{2\sigma_\mathsf{A}\mathcal{T}}+\frac{\hbar}{2\sigma_\mathsf{B}\mathcal{T}}\right)\frac{4\sigma_\mathsf{A}\sigma_\mathsf{B}}{\Delta t_\mathsf{d}^{\mathsf{ee}\,2}+\left(\sigma_\mathsf{A}+\sigma_\mathsf{B}\right)^2} \\
& -2\gamma\frac{\hbar}{2\sigma_\mathsf{A}\mathcal{T}}\mathbb{R}\mathrm{e}\left\{e^{-i\phi}\left(\frac{-2i\sigma_\mathsf{A}}{\Delta\tau-2i\sigma_\mathsf{A}}\right)^2\left(1-\frac{-2i\sigma_\mathsf{B}}{\Delta t_\mathsf{u}^{\mathsf{ee}}-i\left(\sigma_\mathsf{A}+\sigma_\mathsf{B}\right)}\right)\right\} \\
& +2\gamma\frac{\hbar}{2\sigma_\mathsf{B}\mathcal{T}}\mathbb{R}\mathrm{e}\left\{e^{-i\phi}\frac{-2i\sigma_\mathsf{A}}{\Delta\tau-2i\sigma_\mathsf{A}}\left(\frac{-2i\sigma_\mathsf{B}}{\Delta t_\mathsf{u}^{\mathsf{ee}}-i\left(\sigma_\mathsf{A}+\sigma_\mathsf{B}\right)}\right)^2\right\}
\end{aligned}$$

G. Rosselló, F. Battista, M. Moskalets, and J. Splettstoesser, Phys. Rev. B **91**, 115438 (2015).

Counter-intuitive results from the energy current

Impact on interference part - **but no suppression!!** -
when electrons collide at QPC R.

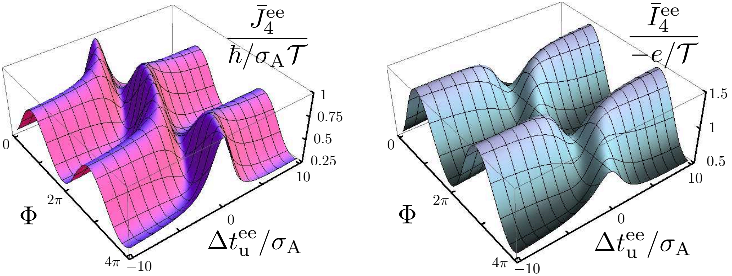




Separation of charge/energy current due to the electronic HOM effect!

G. Rosselló, F. Battista, M. Moskalets, and J. Splettstoesser, Phys. Rev. B **91**, 115438 (2015).

Counter-intuitive results from the energy current



For electron-electron collisions ($\Delta t_{\text{u}}^{\text{ee}} \approx 0$):

- Interference in energy current - **no** interference in charge current.
  No consistent particle picture can be employed!
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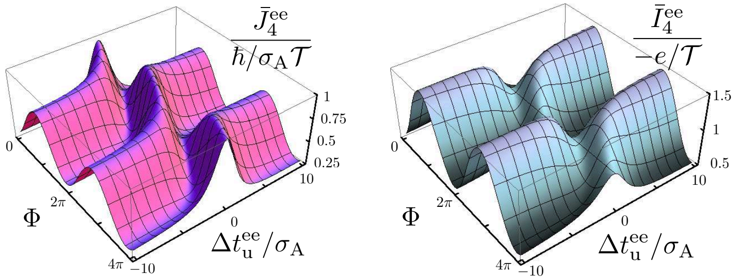

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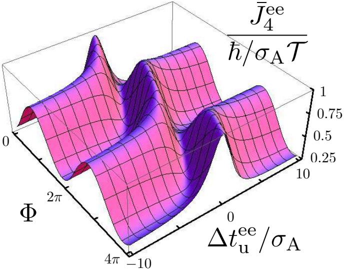

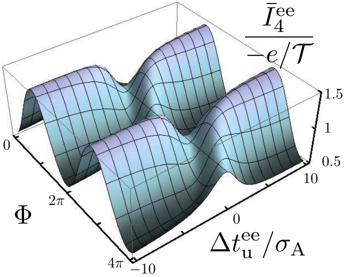

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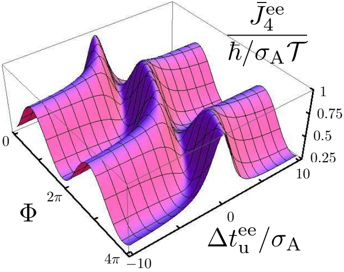

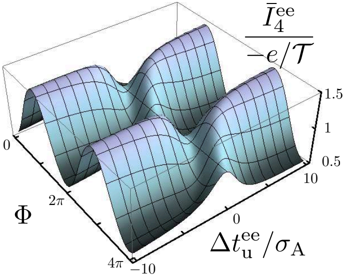

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- (Particle picture continues to hold for e-h absorption.)

G. Rosselló, F. Battista, M. Moskalets, and J. Splettstoesser, Phys. Rev. B **91**, 115438 (2015).

Conclusion

Quantum optics with electrons:

- Single-particle sources allow to access single-particle coherence properties.
- Tunable few-particle effects.
- Proposals for on-chip fermionic single- and few-particle interference experiments.

- Time-dependent setup: Two-particle effects are visible in single-particle quantities.
- Charge/energy current separation.
- Particle-picture leads to paradoxical statements when considering the energy current.

G. Haack, M. Moskalets, J. Splettstoesser, and M. Büttiker, Phys. Rev. B **84**, 081303(R) (2011);
S. Juergens, J. Splettstoesser, and M. Moskalets, EPL **96**, 37011 (2011);
G. Rosselló, F. Battista, M. Moskalets, and J. Splettstoesser, Phys. Rev. B **91**, 115438 (2015).

Length scale estimates

Metallic (biased) source:

- Applied bias: $1\mu V$
- Single-particle coherence time: $h/eV \approx 4ns$
- Drift velocity $\approx 10^4 m/s$

$\Rightarrow \Lambda \approx 40\mu m$

Single-electron source:

- Driving frequency: $\Omega \approx GHz$
- Transmission of the QOC, defining the source: $T \approx 0.1$
- Pulse width - Single-particle coherence time: $T/\Omega \approx 10^{-10}s$

$\Rightarrow \Lambda = v_D \Gamma \approx 1\mu m$

Single-particle coherence

$$\boxed{\mathcal{C}_{\mathrm{SES}}(t,\Delta\tau) = \frac{-i\,e}{2\pi I_{\mathrm{max}}}\,\frac{S_{\mathrm{SES}}(t-\tau_{\mathrm{u}},\mu)S^{*}_{\mathrm{SES}}(t-\tau_{\mathrm{d}},\mu)-1}{\Delta\tau}}$$

with

$$\Delta\tau = \tau_{\mathrm{up}} - \tau_{\mathrm{down}}$$

and

$$S_{\mathrm{SES}} = S_{\mathrm{SES}}(t) = \frac{\pm(t-t^{\pm}) - i\Gamma_{\mathrm{SES}}}{\pm(t-t^{\pm}) + i\Gamma_{\mathrm{SES}}}$$

Spectral current with e-e collision

$$\begin{aligned}
i^{\mathrm{ee}}(E,\Phi) \quad = \quad & R_{\mathrm{L}}R_{\mathrm{R}}i_{\mathrm{A}}^{\mathrm{e}}(E) + T_{\mathrm{L}}T_{\mathrm{R}}i_{\mathrm{A}}^{\mathrm{e}}(E)\mathbb{R}\mathrm{e}\Bigg\{1 + \frac{4\sigma_{\mathrm{A}}\sigma_{\mathrm{B}}}{\Delta t_{\mathrm{d}}^{\mathrm{ee}\,2} + (\sigma_{\mathrm{A}} - \sigma_{\mathrm{B}})^2} \\
& -2i\sigma_{\mathrm{B}}\frac{\Delta t_{\mathrm{d}}^{\mathrm{ee}} - i(\sigma_{\mathrm{A}} + \sigma_{\mathrm{B}})}{\Delta t_{\mathrm{d}}^{\mathrm{ee}\,2} + (\sigma_{\mathrm{A}} - \sigma_{\mathrm{B}})^2}e^{-iE\left(\Delta t_{\mathrm{d}}^{\mathrm{ee}} + i(\sigma_{\mathrm{A}} - \sigma_{\mathrm{B}})\right)/\hbar}\Bigg\} \\
& +R_{\mathrm{L}}T_{\mathrm{R}}i_{\mathrm{B}}^{\mathrm{e}}(E) + T_{\mathrm{L}}T_{\mathrm{R}}i_{\mathrm{B}}^{\mathrm{e}}(E)\mathbb{R}\mathrm{e}\Bigg\{1 + \frac{4\sigma_{\mathrm{A}}\sigma_{\mathrm{B}}}{\Delta t_{\mathrm{d}}^{\mathrm{ee}\,2} + (\sigma_{\mathrm{A}} - \sigma_{\mathrm{B}})^2} \\
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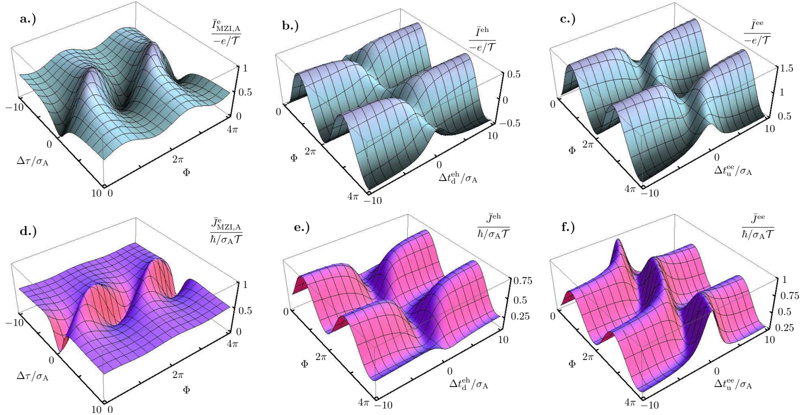
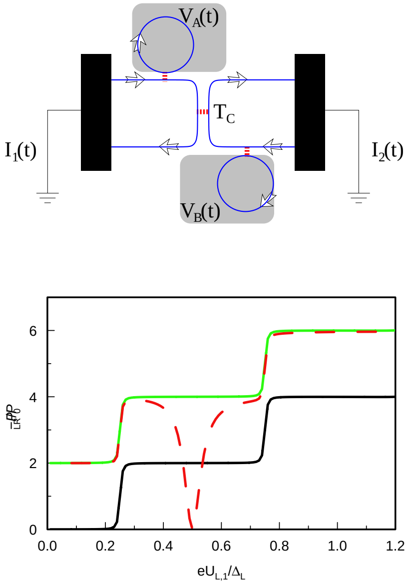
& -2\gamma i_{\mathrm{A}}^{\mathrm{e}}(E)\mathbb{R}\mathrm{e}\Bigg\{e^{-i\Phi}e^{-iE\Delta\tau}\Bigg[1 + \frac{2i\sigma_{\mathrm{B}}}{\Delta t_{\mathrm{d}}^{\mathrm{ee}} + i\left(\sigma_{\mathrm{A}} - \sigma_{\mathrm{B}}\right)} \\
& \left(1 - e^{-iE\left(\Delta t_{\mathrm{d}}^{\mathrm{ee}} + i(\sigma_{\mathrm{A}} - \sigma_{\mathrm{B}})\right)/\hbar}\right)\Bigg]\Bigg\}
\end{aligned}$$

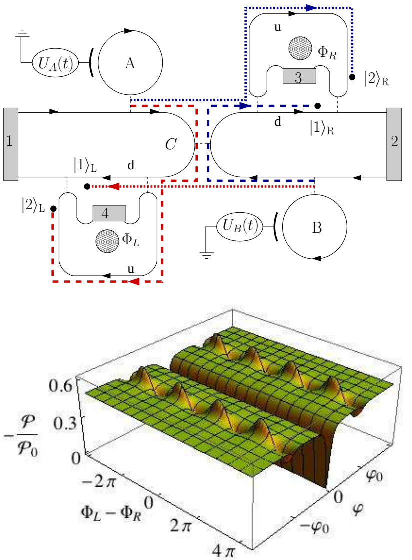
Currents in the presence of absorptions and collisions



Tunable two-particle effects



S. Ol’khovskaya, J. Splettstoesser, M. Moskalets, and M. Büttiker, Phys. Rev. Lett. **101**, 166802 (2008).



J. Splettstoesser, M. Moskalets, and M. Büttiker, Phys. Rev. Lett. **103**, 076804 (2009).