QUANTUM LIMIT OF HEAT FLOW ACROSS A SINGLE ELECTRONIC CHANNEL

Sébastien JEZOUIN


Laboratoire de Photonique et Nanostructures (LPN)
CNRS / Univ. Paris Diderot, Marcoussis, France
Quantum limits of conductance

Quantum conductor $\iff$ Parallel 1D waveguides

Landauer, Büttiker, Martin
Electrical conductance of a single channel

- Electrons $G_{el} \leq \frac{e^2}{h}$

Indep. material/geometry!

Quantum conductor $\iff$ Parallel 1D waveguides

Landauer, Büttiker, Martin

QUANTUM LIMITS OF CONDUCTANCE
QUANTUM LIMITS OF CONDUCTANCE

Electrical conductance of a single channel

- Electrons \( G_{el} \leq \frac{e^2}{h} \)

  Indep. material/geometry!

  ... but depends on the particle:

- Anyons \( G_{el} \leq \nu \frac{e^2}{h} \)

Landauer, Büttiker, Martin
QUANTUM LIMITS OF CONDUCTANCE

Electrical conductance of a single channel

- Electrons \( G_{el} \leq \frac{e^2}{h} \)

Indep. material/geometry!

... but depends on the particle:

- Anyons \( G_{el} \leq \nu \frac{e^2}{h} \)

Thermal conductance of a single channel

- Electrons
- Anyons
- Photons
- Phonons
- ...

Quantum conductor \( \iff \)
Parallel 1D waveguides

Landauer, Büttiker, Martin
QUANTUM LIMITS OF CONDUCTANCE

Electrical conductance of a single channel
- Electrons \( G_{el} \leq \frac{e^2}{h} \)
  
  Indep. material/geometry!
  
  ... but depends on the particle:
  - Anyons \( G_{el} \leq \nu \frac{e^2}{h} \)

Thermal conductance of a single channel
- Electrons
- Anyons
- Photons
- Phonons
- ...

\( G_{th} \leq \frac{\pi^2 k_B^2}{3h} T \)

Universal to any known particle!
QUANTUM LIMIT OF INFORMATION TRANSFER?

\[ \frac{N}{T} \leq 2 \ln 2 \times \pi^2 P \bigg/ 3h \]

1 W \Rightarrow \text{max } 10^{17} \text{ bit/s}

Root of quantum limit:
\[ \Delta E \cdot T \geq \hbar \]

Heat ↔ Entropy ↔ Information

Bosons:
Caves & Drummond, Rev. Mod. Phys. (1994)

Rego & Kirczenow, PRB (1999)
Blencowe & Vitelli, PRA (2000)
EXPERIMENTAL SITUATION

**PHONONS**


\[ G_Q = \frac{\pi^2 k_B^2}{3h} T \approx (1 \text{ pW/K}^2) T \]

\[ G_{th} = 16 \times G_Q \]
EXPERIMENTAL SITUATION

PHONONS

\[ G_Q = \frac{\pi^2 k_B^2}{3h} T \]
\[ \sim (1 \text{ pW/K}^2) T \]

\[ T \rightarrow 0 : 4x4 \text{ modes} \]

\[ G_{th} = 16 \times G_Q \]

PHOTONS

\[ G_{th} \leq (1/2) \times G_Q \]
EXPERIMENTAL SITUATION

**PHONONS**

\[ G_Q = \frac{\pi^2 k_B^2}{3h} T \]

\[ \sim (1 \text{ pW/K}^2) T \]

\[ T \rightarrow 0 : 4 \times 4 \text{ modes} \]

\[ G_{th} = 16 \times G_Q \]

**ELECTRONS**
Molenkamp et al., PRL (1992)

**PHOTONS**

\[ G_{th} \leq (1/2) \times G_Q \]

AuPd / Al on Si

Qualitative order of mag. estimate
EXPERIMENTAL SITUATION

**PHONONS**

\[ G_Q = \frac{\pi^2 k_B^2}{3h} T \sim (1 \text{ pW/K}^2) T \]

\[ T \to 0 : \text{4x4 modes} \]

\[ G_{th} = 16 \times G_Q \]

**ELECTRONICS**
Molenkamp et al., PRL (1992)

Chiatti et al., PRL (2006)

Qualitative order of mag. estimate

**PHOTONS**

\[ G_{th} \leq \left( \frac{1}{2} \right) \times G_Q \]

AuPd / Al on Si

\[ G_{th} \propto \# \text{ channels} \]

\[ G_{th} = 16 \times G_Q \]
ELECTRONIC CHANNELS REVEALED WITH QPCs

Van Wees et al., PRL (1988)
ELECTRONIC CHANNELS REVEALED WITH QPCs

Van Wees et al., PRL (1988)

Quantization of the tranverse wavefunction
ELECTRONIC CHANNELS REVEALED WITH QPCs

Quantization of the tranverse wavefunction

Van Wees et al., PRL (1988)
Heat balance: \[ J_Q = n \times J_Q^e(T_\Omega, T_0) + J_Q^{e-ph}(T_\Omega, T_0) \]
Heat balance:

\[ J_Q = n \times J_Q^e(T_\Omega, T_0) + J_Q^{e-\text{ph}}(T_\Omega, T_0) \]

Separate electronic heat flow:

\[ J_Q + \Delta J_Q = (n + 1) J_Q^e(T_\Omega, T_0) + J_Q^{e-\text{ph}}(T_\Omega, T_0) \]
Heat balance:

\[ J_Q = n \times J_Q^e(T_\Omega, T_0) + J_Q^{e-ph}(T_\Omega, T_0) \]

Separate electronic heat flow:

\[ J_Q + \Delta J_Q = (n + 1) J_Q^e(T_\Omega, T_0) + J_Q^{e-ph}(T_\Omega, T_0) \]

\[ \Delta J_Q \bigg|_{T_\Omega \text{ cst}} = J_Q^e(T_\Omega, T_0) \]
EXPERIMENTAL IMPLEMENTATION

Joule power:

\[ J_Q = \frac{V_{DC}^2}{2R_{sample}} \]

\( \Delta S_I = \frac{2k_B(T_\Omega - T_0)}{R_{sample}} \)

0.2 nV/\sqrt{Hz}


2DEG:

\[ \begin{align*} 
    n &= 2.5 \times 10^{15} / \text{m}^2 \\
    \mu &= 55 \text{ m}^2 / \text{V.s} 
\end{align*} \]

Exp\textsuperscript{tal} challenges

- Noise sensitivity
- \( \Omega \) contact: Low resistance
  - Thermal distrib.: Large
  - Small e-ph: Small

Noise thermometry:

\[ \Delta S_I = \frac{2k_B(T_\Omega - T_0)}{R_{sample}} \]
NOISE THERMOMETRY

- Acq. time : 10 min/pt
- Resol. : $10^{-30}$ A$^2$/Hz

Convert to :

$$T_\Omega = T_0 + \frac{R_{\text{sample}}}{2k_B} \Delta S_I$$

$$J_Q = \frac{V_{dc}^2}{2R_{\text{sample}}}$$

$$B = 3.58 \text{ T (} n = 3\text{)}$$
$$T_0 = 24 \text{ mK}$$
NOISE THERMOMETRY

Calibrated separately

\[ B = 3.58 \, T \quad (\nu = 3) \]
\[ T_0 = 24 \, \text{mK} \]

\[ \approx I - V \quad \text{characteristics} \]
MODELING THE FULL HEAT FLOW

\[
\begin{align*}
J_Q^{e-ph} &= \Sigma \Omega (T_\Omega^5 - T_0^5) \\
n J_Q^e &= n \frac{\pi^2 k_B^2}{6h} (T_\Omega^2 - T_0^2)
\end{align*}
\]

See e.g. Giazotto et al., Rev. Mod. Phys. (2006)

\[B = 3.58 \text{ T (} v = 3)\]
\[T_0 = 24 \text{ mK}\]
MODELING THE FULL HEAT FLOW

\[
\begin{align*}
J_Q e^{-ph} &= \Sigma \Omega (T_\Omega^5 - T_0^5) \\
n J_Q^e &= n \frac{\pi^2 k_B^2}{6h} (T_\Omega^2 - T_0^2)
\end{align*}
\]

Same found at \( T_0 = 40 \) mK

Compatible within 20\% at \( B = 2.67 \) T \( (\nu = 4) \)

\( B = 3.58 \) T \( (\nu = 3) \)

\( T_0 = 24 \) mK

See e.g. Giazotto et al., Rev. Mod. Phys. (2006)
EXTRACTING ELECTRONIC HEAT FLOW

\[
\Delta J_Q \bigg|_{T_\Omega \text{ cst}} = J_{Q}^e(T_\Omega, T_0) \\
\text{with } n \to n + 1
\]

\[B = 3.58 \text{ T (} \nu = 3)\]
\[T_0 = 24 \text{ mK}\]
EXTRACTING ELECTRONIC HEAT FLOW

\[ \Delta J_Q \bigg|_{T_\Omega \text{ cst}} = J_Q^e(T_\Omega, T_0) \]

\[ n \rightarrow n + 1 \]

\[ B = 3.58 \, \text{T (} v = 3) \]

\[ T_0 = 24 \, \text{mK} \]
EXTRACTING ELECTRONIC HEAT FLOW

\[ \Delta J_Q \bigg|_{T_\Omega \text{ cst}} = J_{Qe}^e(T_\Omega, T_0) \]

\[ n \rightarrow n + 1 \]

\[ B = 3.58 \, T \,(\nu = 3) \]

\[ T_0 = 24 \, \text{mK} \]
QUANTUM LIMIT OF ELECTRONIC HEAT FLOW

\[ J_Q^e = \frac{\pi^2 k_B^2}{6h} (T_\Omega^2 - T_0^2) \]

Predictions:

\[ B = 3.58 \, T \,(\nu = 3) \]
QUANTUM LIMIT OF ELECTRONIC HEAT FLOW

\[ J_Q^e = \frac{\pi^2 k_B^2}{6h} (T_\Omega^2 - T_0^2) \]

Predictions:

\[ B = 3.58 \, T \, (\nu = 3) \]
QUANTUM LIMIT OF ELECTRONIC HEAT FLOW

\[ J_Q^e = \frac{\pi^2 k_B^2}{6\hbar} \left( T_\Omega^2 - T_0^2 \right) \]

Predictions:

\( B = 3.58 \text{T} \quad (\nu = 3) \)

\( B = 2.67 \text{T} \quad (\nu = 4) \)
QUANTUM LIMIT OF ELECTRONIC HEAT FLOW

\[ B = 3.58 \, T \, (\nu = 3) \]

Fitted slope \( \left( \frac{\pi^2 k_B^2}{6\hbar} \right) \)

\[ B = 2.67 \, T \, (\nu = 4) \]

Predictions:

\[ J_Q^e = \frac{\pi^2 k_B^2}{6\hbar} \left( T_\Omega^2 - T_0^2 \right) \]
QUANTUM LIMIT OF ELECTRONIC HEAT FLOW

\[ \frac{J_Q^e}{T_\Omega^2 - T_0^2} = (1.06 \pm 0.07) \times \frac{\pi^2 k_B^2}{6h} \]

Fitted slope \( \left( \frac{\pi^2 k_B^2}{6h} \right) \)

\( B = 3.58 \, \text{T} \, (\nu = 3) \)

\( B = 2.67 \, \text{T} \, (\nu = 4) \)

Stat. error on mean value
QUANTUM LIMIT $J_Q^e$ FROM FULL HEAT FLOW

\[ 4J_Q^e + (n - 4)J_Q^e \]

(model-dependent) \hspace{5cm} (model-free)

\[
\frac{J_Q^e}{T_{\Omega}^2 - T_0^2} = (0.98 \pm 0.02) \times \frac{\pi^2 k_B^2}{6h}
\]

Stat. error on mean value
CONCLUSION & PERSPECTIVES

1st meas. of $G_Q$ on electronic channel

< 10 % accuracy

Extends Wiedemann-Franz law down to single channel

Heat quantum interference

Jezouin et al., Science 342, 601 (2013)
Thank you for your attention
AMPLIFICATION CHAIN CIRCUIT

Simplified Description:

Practical Implementation:
AMPLIFICATION CHAIN CALIBRATION
EQUIVALENT CONFIGURATIONS

\[
\Delta S | (10^{23} \text{ A}^2/\text{Hz})
\]

\[
v=3, \ T_0 = 24 \text{ mK}
\]

\[
\Delta S | (10^{23} \text{ A}^2/\text{Hz})
\]

\[
v=4, \ T_0 = 22.5 \text{ mK}
\]
FULL JOULE POWER SPAN

Full heat flow fit up to 90 fW:

\[
\begin{align*}
n &= 4.04 \\
p &= 4.8
\end{align*}
\]
DATA AT $\nu=4$

Full heat flow fit up to 20 fW: \[
\begin{align*}
n &= 4.2 \\
\Sigma \Omega &= 6.5 \text{ nW/K}^5
\end{align*}
\]

Full heat flow fit up to 90 fW: \[
\begin{align*}
n &= 3.6 \\
p &= 4.8
\end{align*}
\]
DATA AT 40 mK

Full heat flow fit: \[
\begin{align*}
  n &= 3.8 \\
  \Sigma \Omega &= 5.5 \text{ nW/K}^5
\end{align*}
\]

Phonons are cold