Thermoelectric performance of a quantum-dot pump

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JARA - Fundamentals of Future Information Technology

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Outline

Introduction

- Quantum dots
- Time-dependent driving of quantum dots
- Quantum dots as heat engines

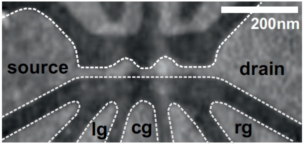
Performance of quantum-dot pumps

- Charge pumping against a bias:

⇒ Study the energy balance to extract efficiencies!

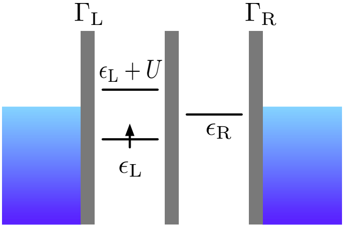
- Heat transport
- Cooling device - Heat engine

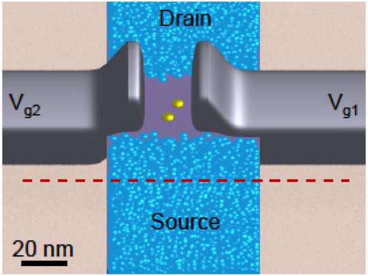
(Double) quantum dots



RWTH Aachen

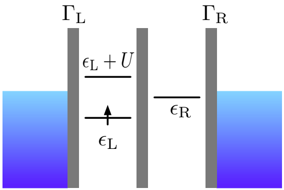
- Well-defined energy levels: occupied by single particles
- Spin-degree of freedom
- Tuneable, e.g. via gates
- Connect to reservoirs
- Realisation of a peristaltic pump



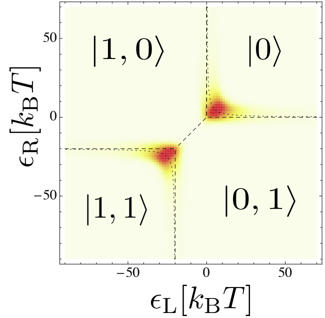


CEA Grenoble

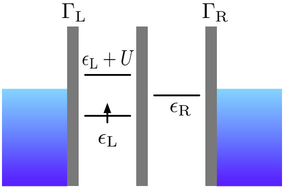
Double dot - stability diagram



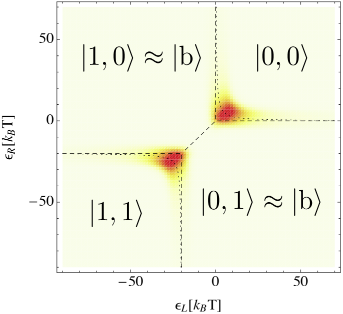
- Stable regions for different gate voltages



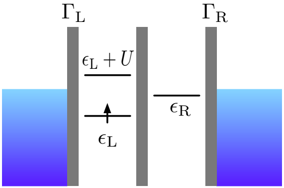
Double dot - stability diagram



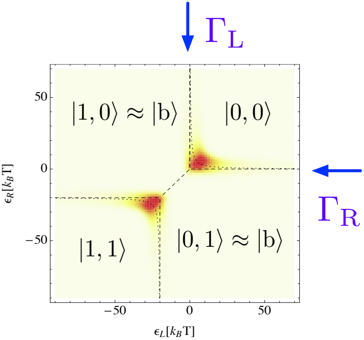
- Stable regions for different gate voltages
- Hybrid states due to interdot coupling



Double dot - stability diagram

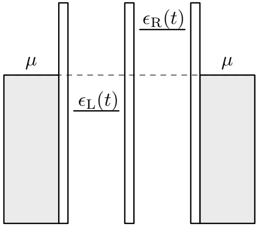


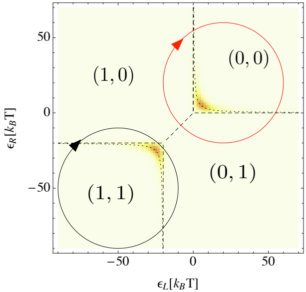
- Stable regions for different gate voltages
- Hybrid states due to interdot coupling
- Coupling and decoupling to different reservoirs
- Transport only when levels are aligned!



Time-dependent driving – Peristaltic pumping

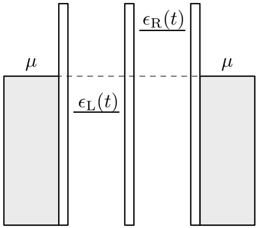
- Peristaltic electron pumping

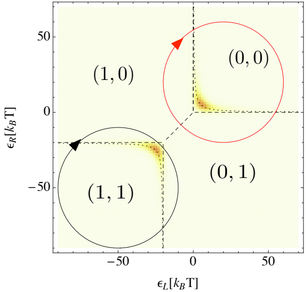




- First realisations (with metallic islands)
  Pothier, *et. al.*, Europhys. Lett. **17**, 249 (1992).
- Promising for metrology: Current standard with very high precision
  M. D. Blumenthal, B. Kaestner, L. Li, S. Giblin, T. J. B. M. Janssen, M. Pepper, D. Anderson, G. Jones, and D. A. Ritchie, Nature Physics **3**, 343 (2007);
  V. F. Maisi, Y. A. Pashkin, S. Kafanov, J.-S. Tsai, and J. P. Pekola, New J. Phys. 11, 113057 (2009);
  etc.

Time-dependent driving – Peristaltic pumping



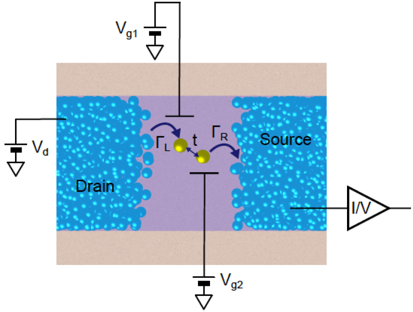


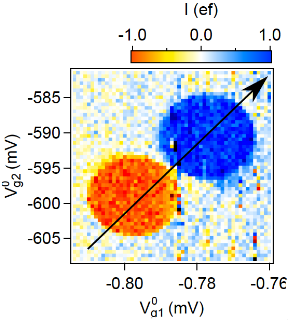
- Strong Coulomb interaction is crucial!
- **Adiabatic** pumping, low frequencies

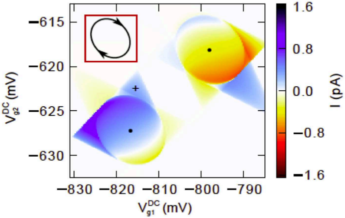
$$\Omega \ll \frac{1}{\text{lifetime}}$$

- Important to guarantee particle transfer

Adiabatic/Nonadiabatic pumping







- Pumping through two atoms!
- Control over single Phosphor dopants in a silicon bar.

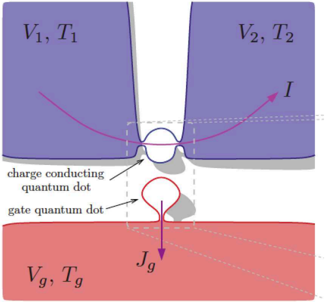
B. Roche, R.-P. Riwar, B. Voisin, E. Dupont-Ferrier, R. Wacquez, M. Vinet, M. Sanquer, J. Splettstoesser, and X. Jehl, Nat. Commun. **4**, 1581 (2013). (Experiments done at CEA Grenoble)

⇒ In addition: Fast driving ⇔ strong heating...

Quantum dot heat engines

Quantum dot heat engine

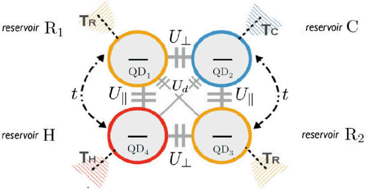
Conversion of energy quanta to current



R. Sánchez and M. Büttiker, Phys. Rev. B **83**, 085428 (2011).

Quantum dot refrigerator

Minimal self-contained implementation



D. Venturelli, R. Fazio, and V. Giovannetti, Phys. Rev. Lett. **110**, 256801 (2013).

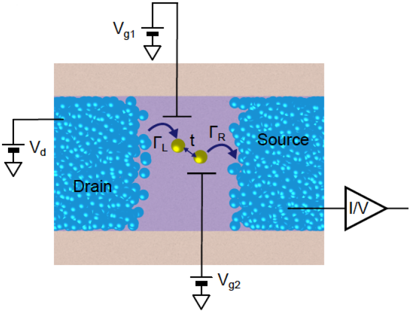
Performance of quantum-dot pumps

- Charge pumping against a bias:

⇒ Study the energy balance! – useful work done?

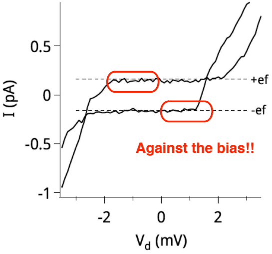
- Heat transport
- Cooling device - Heat engine

Pump against a bias

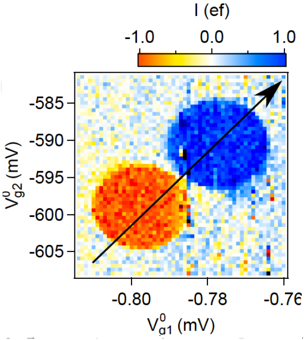


- Pumping through two atoms!
- Control over single Phosphor dopants in a silicon bar.
- Pumping against the bias.

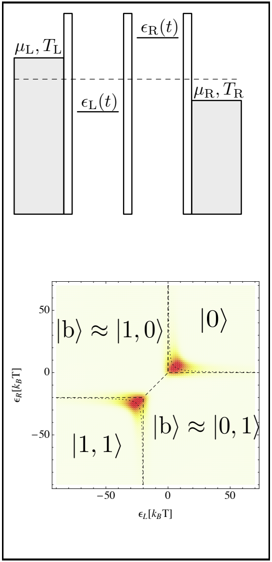
B. Roche, R.-P. Riwar, B. Voisin, E. Dupont-Ferrier, R. Wacquez, M. Vinet, M. Sanquer, J. Splettstoesser, and X. Jehl, Nat. Commun. **4**, 1581 (2013). (Experiments done at CEA Grenoble)

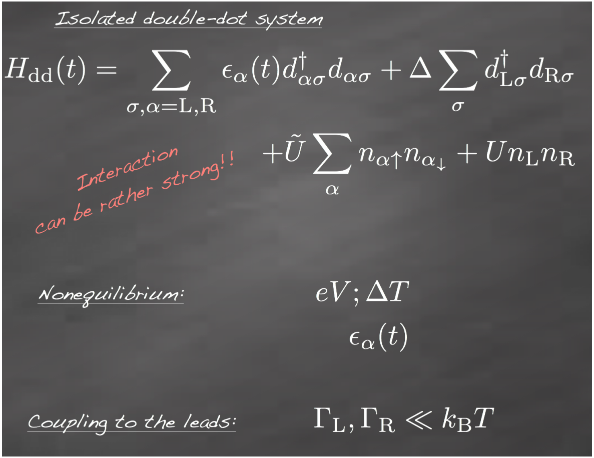


Against the bias!!



How to proceed theoretically...





Isolated double-dot system

$$H_{dd}(t) = \sum_{\sigma,\alpha=L,R} \epsilon_\alpha(t) d^\dagger_{\alpha\sigma} d_{\alpha\sigma} + \Delta \sum_\sigma d^\dagger_{L\sigma} d_{R\sigma}$$

$$+\tilde{U} \sum_\alpha n_{\alpha\uparrow} n_{\alpha\downarrow} + U n_L n_R$$

Interaction can be rather strong!!

Nonequilibrium: $eV; \Delta T$

$\epsilon_\alpha(t)$

Coupling to the leads: $\Gamma_L, \Gamma_R \ll k_B T$

Generalised Master equation:

J. König, H. Schoeller, and G. Schön, Phys. Rev. Lett. **76**, 1715 (1996); J. Splettstoesser, M. Governale, J. König, and R. Fazio, Phys. Rev. B **74**, 085305 (2006), F. Cavaliere, M. Governale, and J. König, Phys. Rev. Lett. **103**, 136801 (2009).

How to proceed theoretically...

Kinetic equation for double-dot occupation probabilities:

$$0 = \boldsymbol{W}_t \boldsymbol{P}_t^{(0)} \quad , \qquad \frac{d}{dt}\boldsymbol{P}_t^{(k-1)} = \boldsymbol{W}_t \boldsymbol{P}_t^{(k)}$$

- $\boldsymbol{P}_t^{(0)}$, instantaneous solution, frozen parameters
- $\boldsymbol{P}_t^{(1)}$, adiabatic correction, slight lagging behind
- $\boldsymbol{P}_t^{(2)}$, second order: important for heating

Charge and heat currents

Charge currents

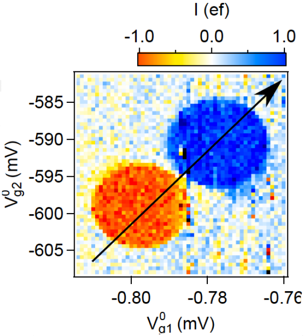
$I^{(0)}(t) = \mathrm{e}^{\mathrm{T}} \boldsymbol{W}^{I}_{t} \boldsymbol{P}^{(0)}_{t}$	Current due to a stationary bias/temperature gradient
$I^{(1)}(t) = \mathrm{e}^{\mathrm{T}} \boldsymbol{W}^{I}_{t} \boldsymbol{P}^{(1)}_{t}$	Pumping current!

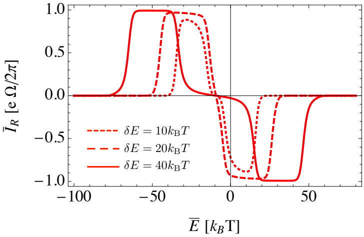
Heat currents

$$J_\alpha(t) = I^E_\alpha(t) - \mu_\alpha I^N_\alpha(t)$$

$J^{(0)}(t)$	Heat current due to a stationary bias/temperature gradient
$J^{(1)}(t)$	Adiabatically pumped heat
$J^{(2)}(t)$	Important contribution for heating!

Battery charger



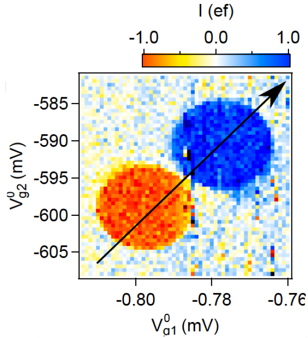


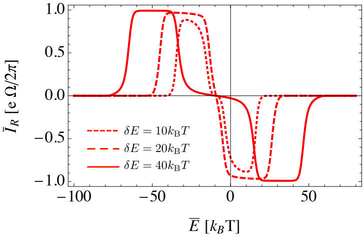
Energy flow

$$\frac{d}{dt}\langle E\rangle^{(k-1)} = J_\mathrm{L}^{(k)}(t) + J_\mathrm{R}^{(k)}(t) \underbrace{+ \sum_{\alpha=\mathrm{L,R}} \frac{d\epsilon_\alpha}{dt}\langle\hat{n}_\alpha\rangle_t^{(k-1)}}_{\mathcal{P}_\mathrm{ac}} \underbrace{+VI^{(k)}(t)}_{\mathcal{P}_\mathrm{dc}}$$

S. Juergens, F. Haupt, M. Moskalets, and J. Splettstoesser, Phys. Rev. B **87**, 245423 (2013).

Battery charger





Energy flow

$$\frac{d}{dt}\langle E\rangle^{(k-1)} = J_{\mathrm{L}}^{(k)}(t) + J_{\mathrm{R}}^{(k)}(t) + \underbrace{\sum_{\alpha=\mathrm{L,R}} \frac{d\epsilon_\alpha}{dt}\langle\hat{n}_\alpha\rangle_t^{(k-1)}}_{\mathcal{P}_{\mathrm{ac}}} + \underbrace{V I^{(k)}(t)}_{\mathcal{P}_{\mathrm{dc}}}$$

Efficiency

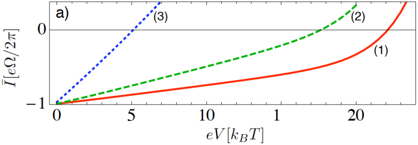
Limited by counterflow

$$\eta_{\mathrm{charger}} = \frac{-I\ V}{\mathcal{P}_{\mathrm{ac}}}$$

Limited by heating

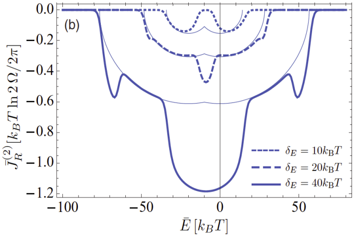
Limiting effects – heating and counterflow

Counterflow



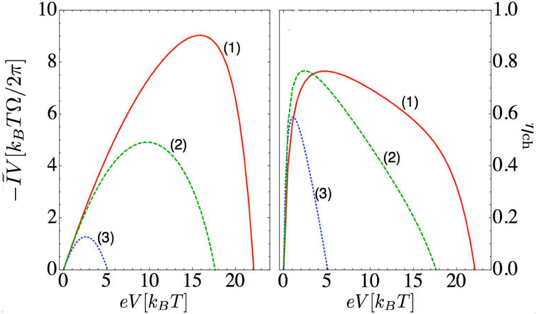
- Both levels in the bias window → stationary current flow
- Critical bias at which pumping gets fully cancelled

Heating



- Heating proportional to frequency and velocity of the level position

Battery charger



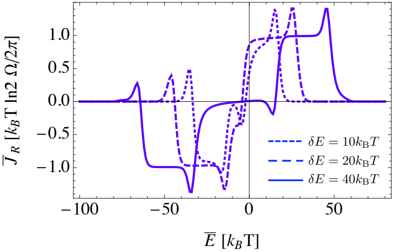
Efficiency

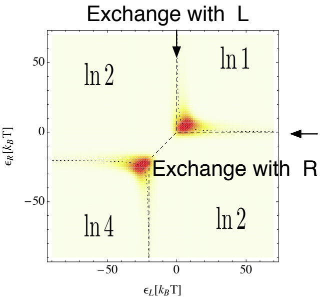
Limited by counterflow

$$\eta_{\text{charger}} = \frac{-I\ V}{\mathcal{P}_{\text{ac}}}$$

Limited by heating

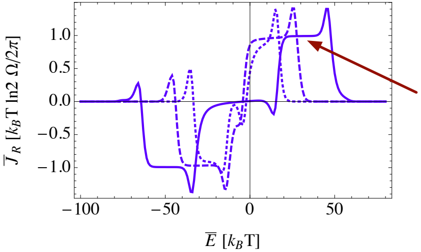
Heat transport



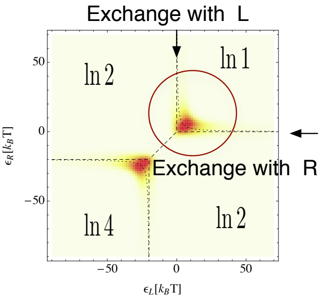


- Plateaux in the pumped heat!
- Related to the entropy change during a cycle.

Heat transport

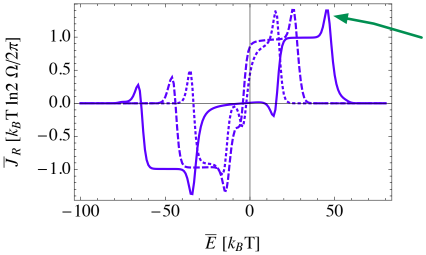


$= k_{\mathrm{B}} T \ln(2)$

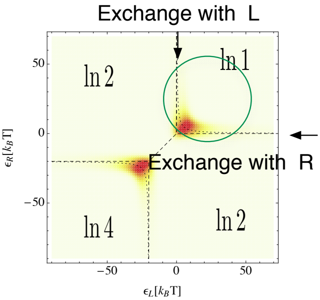


- Exchange with left lead:
  $k_{\mathrm{B}} T\,(\ln 1 - \ln 2)$
- Exchange with right lead:
  $k_{\mathrm{B}} T\,(\ln 2 - \ln 1)$

Heat transport



$\approx k_{\mathrm{B}}T\ln(3)$

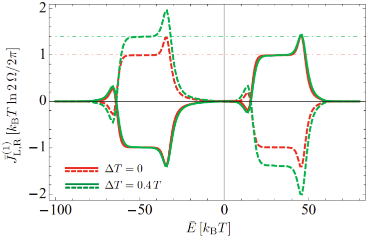


- Transfer takes place, when states with different occupation number are degenerate!
- Exchange with both leads!

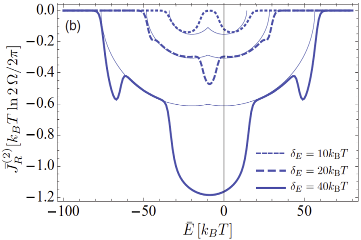
Heat transport

Heat current is directly given by the driving frequency!

- Plateaux are temperature-dependent.

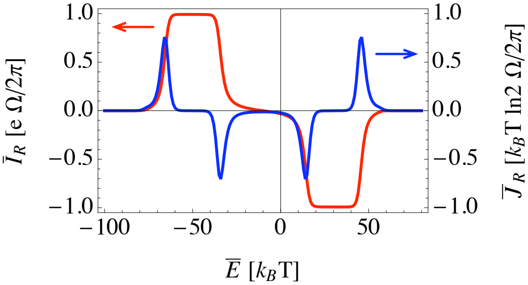


- Plateaux are unstable with respect to heating



Heat transport

$\Rightarrow$ Switch off the heat pump with a magnetic field!



- Switching on a magnetic field:

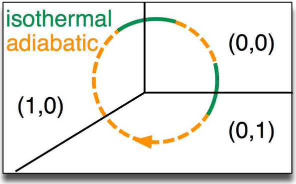
$\Rightarrow$ Lifts the spin degeneracy of the states in all stable regions!

$\Rightarrow$ No change in entropy in plateau regions!

Control heat currents/heat engines
R. Sánchez and M.Büttiker, Phys. Rev. B **83**, 085428 (2011); D. Venturelli, R. Fazio, and V. Giovannetti, Phys. Rev. Lett. **110**, 256801 (2013); A. N. Jordan, B. Sothmann, R. Sánchez, and M. Büttiker, Phys. Rev. B **87**, 075312 (2013); etc.

Heat engine

Perfect (reverse) heat engine has Carnot efficiency!

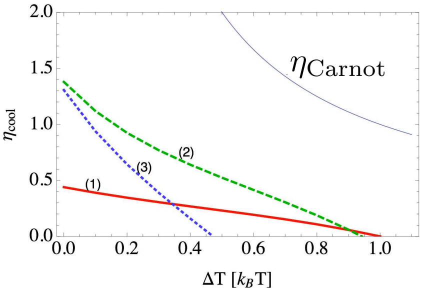


Example: Cooling device

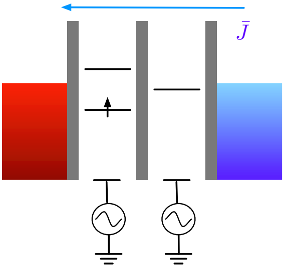
$$\eta_{\mathrm{cooling}} = \frac{-J_{\mathrm{cold}}}{J_{\mathrm{cold}} + J_{\mathrm{hot}}} = \frac{k_B T_{\mathrm{cold}} \ln(2)}{k_B T_{\mathrm{hot}} \ln(2) - k_B T_{\mathrm{cold}} \ln(2)} = \frac{T_{\mathrm{cold}}}{T_{\mathrm{hot}} - T_{\mathrm{cold}}}$$

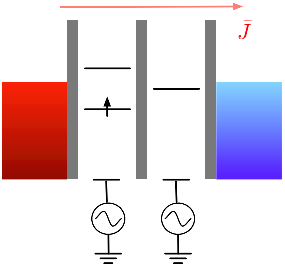
A realistic device is not infinitely slow!!

- Heating due to finite frequency
- Leakage currents due to stationary gradient



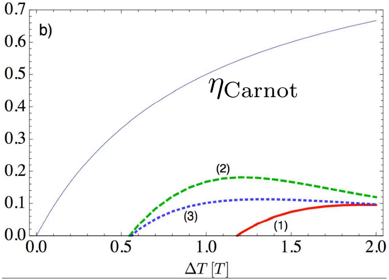
Heat engine - extract work with a temperature gradient





- Use the pump to cool down the cold contact
- Extract work from the pump by transporting heat into the cold reservoir

$$\eta = \frac{-\bar{\mathcal{P}}_{\mathrm{ac}}}{\bar{J}_{\mathrm{hot}}}.$$



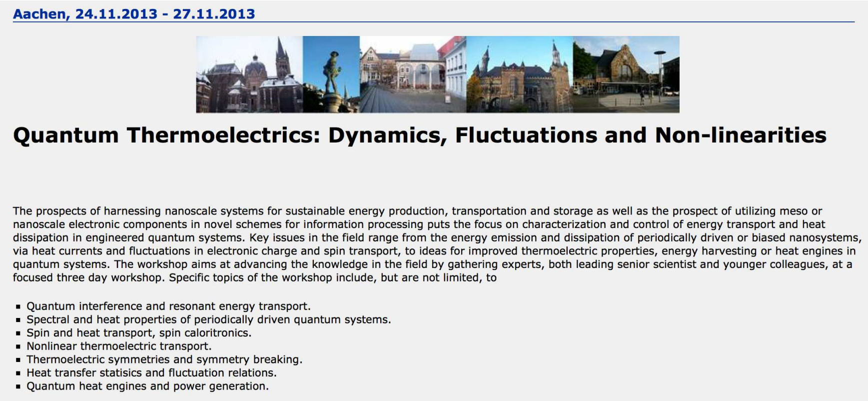
How to extract work – quantum motor?

R. Bustos-Marún, G. Refael, and F. von Oppen, arXiv:1304.4969

Conclusions

- Quantum dots are intriguing candidates for the implementation of quantum engines
- (Rather) efficient quantised charge pumping against a bias
- Plateaus in the heat current due to degeneracies
  (Control by a magnetic field)
- Implementation of heat engines due to controlled decoupling of the double-dot levels

Stefan Juergens, Federica Haupt, Michael Moskalets, and Janine Splettstoesser,
Phys. Rev. B **87**, 245423 (2013).



Aachen, 24.11.2013 - 27.11.2013

Quantum Thermoelectrics: Dynamics, Fluctuations and Non-linearities

The prospects of harnessing nanoscale systems for sustainable energy production, transportation and storage as well as the prospect of utilizing meso or nanoscale electronic components in novel schemes for information processing puts the focus on characterization and control of energy transport and heat dissipation in engineered quantum systems. Key issues in the field range from the energy emission and dissipation of periodically driven or biased nanosystems, via heat currents and fluctuations in electronic charge and spin transport, to ideas for improved thermoelectric properties, energy harvesting or heat engines in quantum systems. The workshop aims at advancing the knowledge in the field by gathering experts, both leading senior scientist and younger colleagues, at a focused three day workshop. Specific topics of the workshop include, but are not limited, to

- Quantum interference and resonant energy transport.
- Spectral and heat properties of periodically driven quantum systems.
- Spin and heat transport, spin caloritronics.
- Nonlinear thermoelectric transport.
- Thermoelectric symmetries and symmetry breaking.
- Heat transfer statisics and fluctuation relations.
- Quantum heat engines and power generation.

Aachen, 24.11. – 27.11.2013

See webpage:
http://www.physik.rwth-aachen.de/thermo2013/