Spin pumping : control of electrons and nuclei in nanostructures

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Outline

- **Introduction : - quantum pumping and its history**
  - charge pumping
  - spin pumping

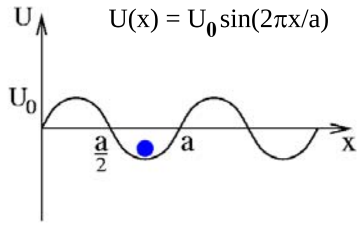
- **Pumping of electrons in the quantum Hall regime : transport of electrons and control of nuclei**

- **Discussion**

Introduction

Idea behind pumping : to generate motion of particles by slow **periodic modulations** of their environment, e.g. their confining potential or a magnetic field.

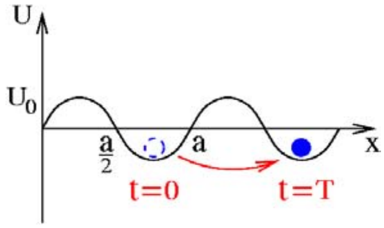
Thouless pump, 1983 : adiabatic transport of electrons in 1D periodic potential



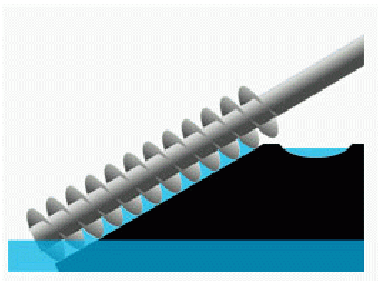
For **moving** potential, **every minimum is shifted by a** after each period T:

$$U(x+vt) = U_0 \sin(2\pi x/a) \cos(2\pi t/T) + U_0 \cos(2\pi x/a) \sin(2\pi t/T)$$

Superposition of two standing waves with a phase difference can produce pumping



Archimedean screw

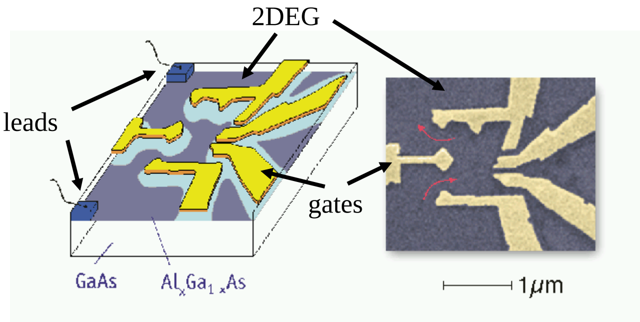


- over 2000 years old
- used for irrigation

‘s Hertogenbosch, NL

Charge pumping in condensed matter systems

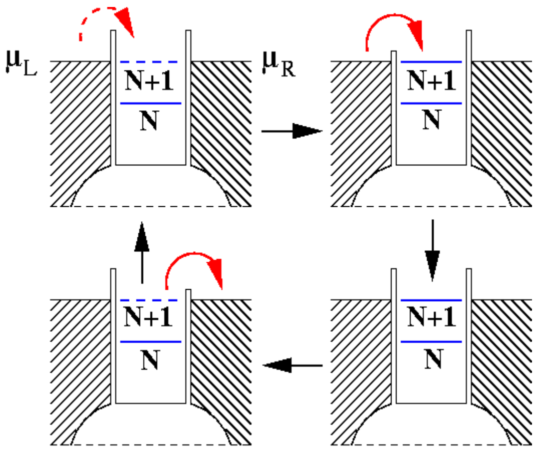
Quantum dot = small island in a metal or semiconductor material (two-dimensional electron gas, 2DEG), confined by gates and connected to leads via quantum point contacts (QPCs).



Elastic scattering length l_e ~ 100 μm, ballistic transport

Quantum dots can be **open** (wide QPCs) or **closed** (QPCs pinched off).

First electron pump : turnstile



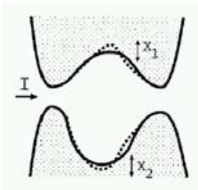
- **Oscillating tunnel barriers by rf modulation**
- **Electrons transported one by one, pumped charge is quantized**
- **"classical" pumping**

Kouwenhoven *et al.*, PRL **67**, 1626 (1992)
Pothier *et al.*, Europhys. Lett. **17**, 249 (1992)

Quantum pumping in quantum dots : idea

Spivak *et al*, PRL **51**, 13226 (1995)

Open quantum dot



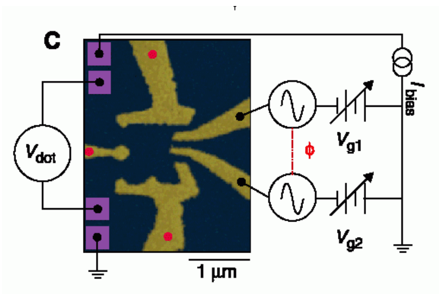
Current generated by adiabatic periodic variation of parameters X_1 and X_2 (gate voltage, magnetic field) with a phase difference

Physical picture : infinitesimal change of system parameters δX_i during a time δt leads to a **redistribution of charge** δQ_i within the system (due to changing electrostatic landscape). This redistribution produces electron flows $I_i = \delta Q_i / \delta t$

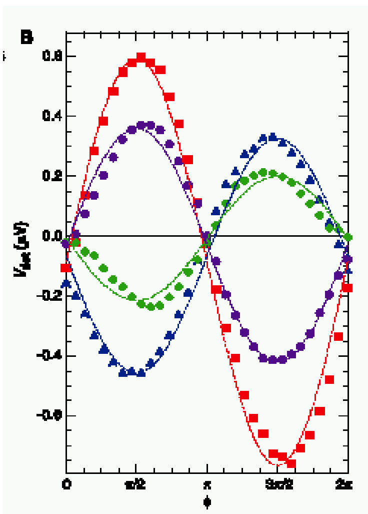
- pumped charge **depends on the interference of electron wavefunctions** in the system.
- current in general **not quantized** and its **direction** depends on microscopic properties of the (chaotic) system
- reversing phase difference reverses the direction of the current

Quantum pumping experiment

Switkes *et al.*, Science **283**, 1905 (1999)



Experimental set-up, open quantum dot



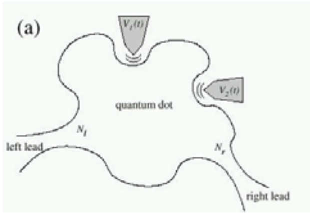
Pumped current vs. phase difference ϕ

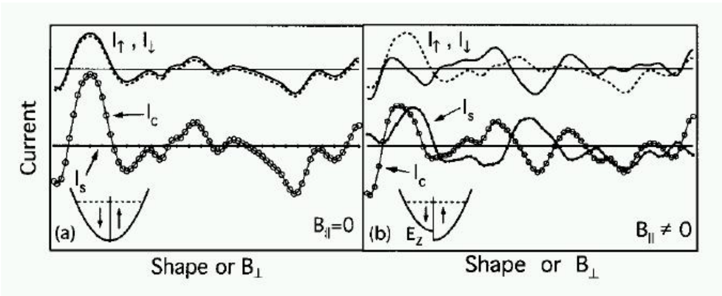
Red gates control the conductance of the point contacts

Black gates are used for pumping

Spin pumping in quantum dots

Quantum dot in parallel magnetic field

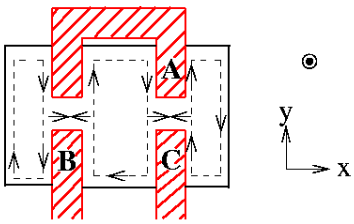




Watson *et al.*, PRL **91**, 258301 (2003)
Mucciolo *et al.*, PRL **89**, 146802 (2002)

Spin pumping in the quantum Hall regime

Hall bar



Characteristics :

- electrons travel along the edges of the sample (edge channels)
- quantized energy levels (Landau levels)
- # of edge channels corresponds to the # of (partially) filled Landau levels ν
- separation of “left-movers” and “right-movers”
- electrons can be **scattered** from one side to another

Idea : investigate pumping of electrons across a Hall bar and the effect on the nuclei via hyperfine interaction

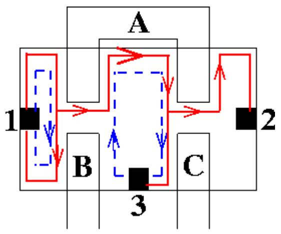
Motivation : era of quantum computing and quantum information processing. **Spins**, electronic but also nuclear, are promising candidates for qubits because of their long coherence times.

Drawback : difficult to measure spin effects directly, easier to measure charge

Ideally : manipulate and read-out spin processes via charge

Here : contribution towards manipulation and read-out of nuclear spins via pumped current

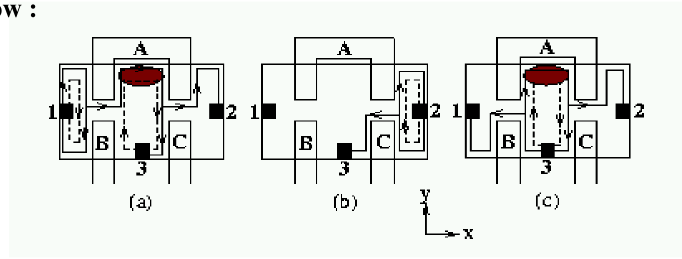
Charge pumping in a Hall bar



- AB and AC form 2 quantum point contacts (QPC's)
- $\nu = 2$: spin-split Landau levels, one for **spin-up** and one for **spin-down**

- the QPC's transmit at most one edge channel
- time-varying voltages applied to B and C form pumping parameters

Current flow :



The pumped current

Dynamics of electrons in absence of gates is described by Hamiltonian :

$$\mathcal{H} = \frac{1}{2m^*}(i\hbar\vec{\nabla}+e\vec{A})^2+V(y)+\frac{1}{2}g^*\mu_B B\sigma+\frac{1}{2}A\langle I_z\rangle\sigma$$

For harmonic potential V(y) = ½ $m^* \omega_0^2 y^2$ the Schrödinger equation is exactly solvable $\rightarrow$ Landau levels

$$\begin{aligned}
\psi_{\lambda,\sigma}(x,y,t) &= C_\lambda \chi_\lambda(y)\, e^{i(kx-\frac{E_{\lambda,\sigma}}{\hbar}t)}, \\
\chi_\lambda(y) &= e^{\frac{1}{2l_m^2}(y+\frac{\omega_c^2}{\omega_0^2+\omega_c^2}y_k)^2}\left(\frac{\partial}{\partial y}\right)^\lambda e^{-\frac{1}{l_m^2}(y+\frac{\omega_c^2}{\omega_0^2+\omega_c^2}y_k)^2} \\
E_{\lambda,\sigma} &= (\lambda+\frac{1}{2})\hbar\sqrt{\omega_0^2+\omega_c^2}+\frac{1}{2}m^*\frac{\omega_0^2\omega_c^2}{\omega_0^2+\omega_c^2}y_k^2 \\
&\quad +\frac{1}{2}g^*\mu_B B\sigma+\frac{1}{2}A\langle I_z\rangle\sigma, \quad \lambda = 0, 1, 2, \ldots
\end{aligned}$$

Model QPC's as δ-function barriers and use Floquet theory to find pumped current into contact 1, 2 and 3:

$$I_\alpha = \frac{e}{h}\int dE f(E)\sum_{E_n>0}\left(|t_{\alpha\beta}(E_n,E)|^2-|t_{\beta\alpha}(E_n,E)|^2\right)$$

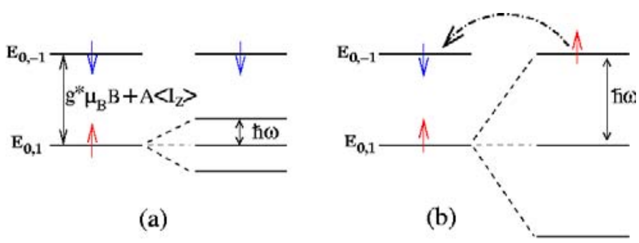
Floquet theory describes pumping in terms of **gain or loss of energy quanta ħω** at the two oscillating barriers

Incoming particle with energy E leaves with energy $E_n \equiv E + n\hbar\omega$

The Floquet scattering matrix is obtained by matching wave functions

$$\psi(x,t) = \sum_{n=-\infty}^{\infty}(a_n e^{ik_n x}+b_n e^{-ik_n x})e^{-i(E_{0,1}+n\hbar\omega)t/\hbar}$$

Energy level diagrams

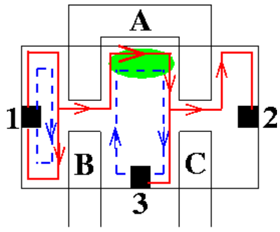


$\hbar\omega \ll g^*\mu_B B + A\langle I_z\rangle$ $\quad$ $\hbar\omega \sim g^*\mu_B B + A\langle I_z\rangle$

effective Zeeman gap

For $\hbar\omega \sim g^*\mu_B B + A\langle I_z\rangle$:

- **transitions** between the two Landau levels may occur
- Simultaneously, nuclear spins are flipped



Control of nuclear polarization via quantum pumping

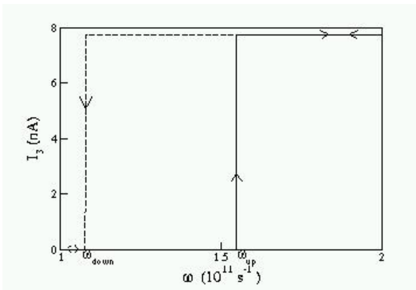
Pumped current :

$$
\begin{aligned}
I_1 &= 2\frac{e}{h}\mu\frac{q^2}{k_0^2}\left(-2+\beta-\beta^2+O(\frac{p^2}{k_0^2})\right)\\
I_2 &= 2\frac{e}{h}\mu\frac{q^2}{k_0^2}\left(2-2\beta+\beta^2+O(\frac{p}{k_0})\right)\\
I_3 &= 2\beta\frac{e}{h}\mu\frac{q^2}{k_0^2}\left(1+O(\frac{p}{k_0})\right).
\end{aligned}
$$

Measure I_3 as a function of ω :

$$\omega_{up} = g^*\mu_B B/\hbar$$

Sweep $\omega(t) = \omega(0) + \alpha t$



• I_3 ~ 1-10 nA, and 20 % shift of Zeeman gap for typical parameters

• Difference $\Delta\omega = \omega_{up} - \omega_{down}$ direct measure of local nuclear polarization

$$\Delta\omega = \frac{M}{\hbar(M - \hbar\alpha)}\left[2|g^*|\mu_B B - 2\hbar\omega(0) - \hbar\alpha(2t_{\text{sweep}} + t_{\text{dwell}})\right]$$

• Nuclear polarization set by the sweep time and sweep rate

Perspectives

• Quantum pumping useful "tool" to study electron transport at the edge of a 2DEG in the quantum Hall regime

• Provides new technique to accurately **manipulate** and **monitor** local dynamic nuclear polarization

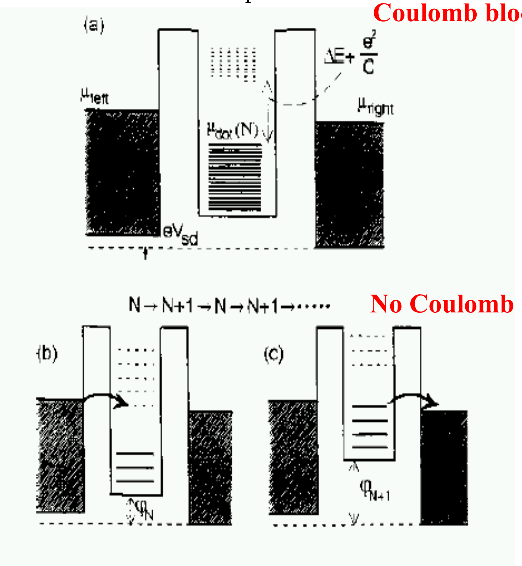
• Interesting as possibility for e.g. memory storage in solid-state systems

Reference: condmat/0307166

Transport through tunnel-coupled quantum dots: Coulomb blockade

Potential landscape of a dot

Coulomb blockade



No Coulomb blockade

ϕ_N = electrostatic potential of dot occupied by N electrons

$V_{sd} = (\mu_{left} - \mu_{right})/e$

Energy required to add an electron:
$\mu_{dot}(N+1) - \mu_{dot}(N) = \Delta E + e^2/C$

ΔE = energy level spacing, typically 10 μeV.
In order to resolve the energy levels ΔE must be larger than the thermal energy, $\Delta E \gg k_B T$.
So temperature must be less than ~ 10 mK