QUANTUM PHASE BATTERY & QUANTUM PUMPS

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SPIN

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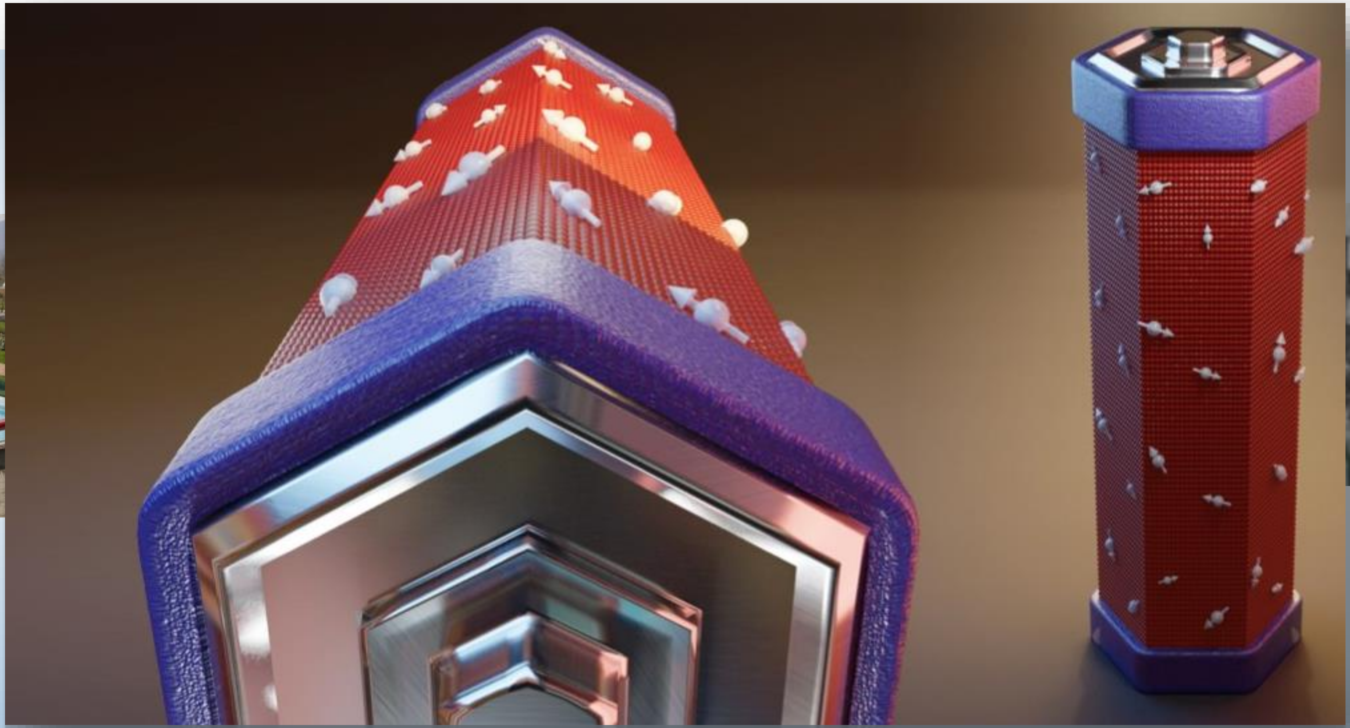
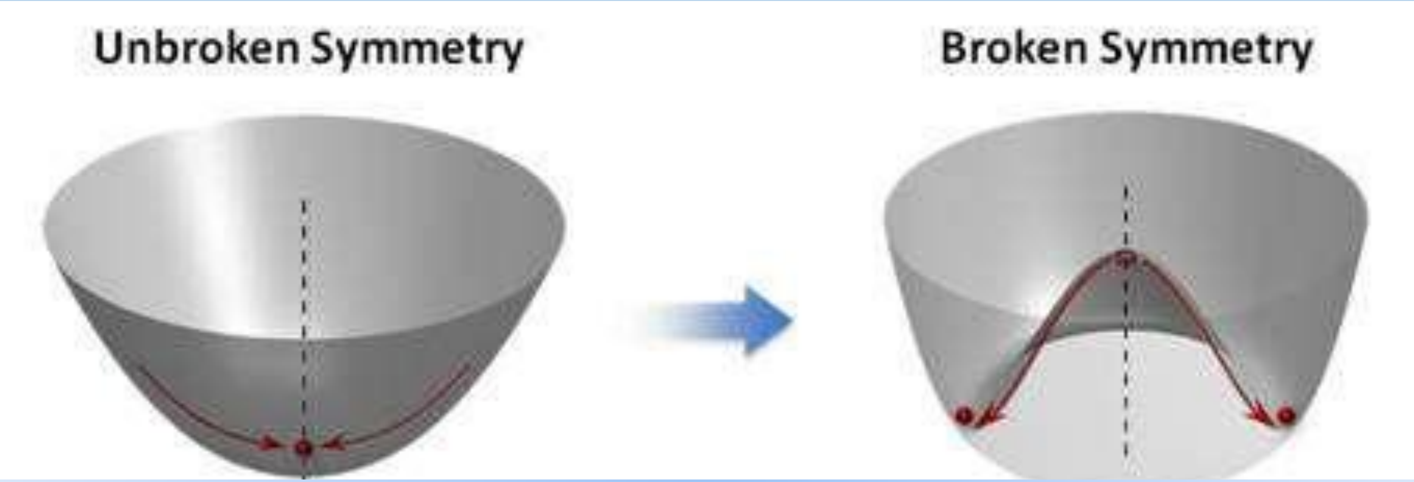


Nat.Phys. 12, 350 2016

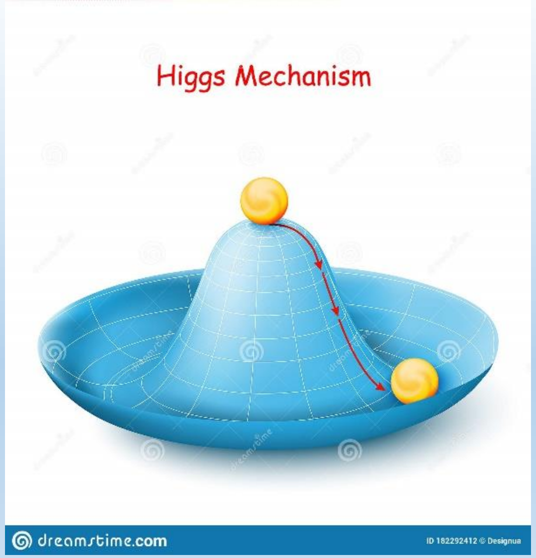
107° CONGRESSO NAZIONALE SIF
13-17 SETTEMBRE 2021

THE ESSENCE OF SYMMETRIES BREAKING IN PHYSICS

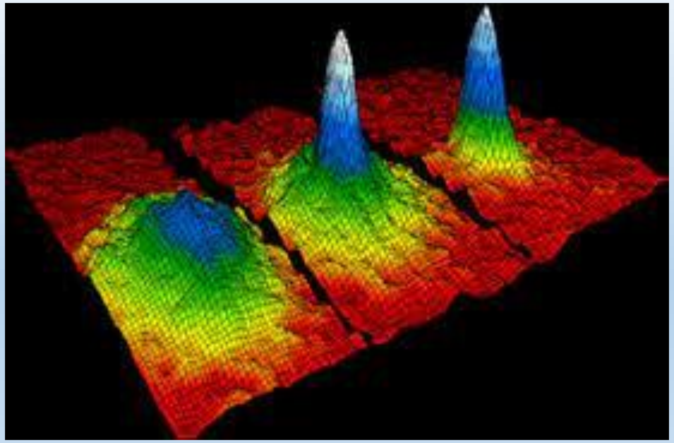
Small fluctuations acting on a system crossing a critical point decide the system's fate



Symmetry is the essential basis of nature, which gives rise to conservation laws



BEC CONDENSATE



SUPERCONDUCTIVITY

«More is different»

Vol. 1, 1972

Using the idea of symmetry breaking to show that **reductionism** is true.

…but implications and assessment of symmetry breaking on modern technologies are unquestionable!

Quantum phase battery & Quantum pumps

OUTLINE

- ✓ THE QUANTUM PHASE BATTERY
- ✓ A MACROSCOPIC QUANTUM PHENOMENON: THE JOSEPHSON EFFECT
  The current-phase relation and the anomalous Josephson effect
- ✓ THE HYBRID QUANTUM CIRCUIT
- ✓ THEORETICAL MODELING OF A PHASE BATTERY: EFFECT OF MAGNETIC IMPURITIES

- ✓ THE QUANTUM PUMP: ORIGIN AND BASICS
- ✓ AN ATOMIC IMPLEMENTATION : SPIN AND MASS PUMPS

PERSPECTIVES & CONCLUSIONS

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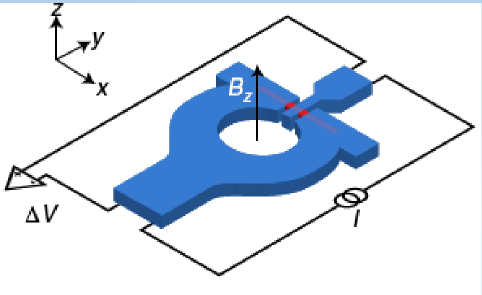
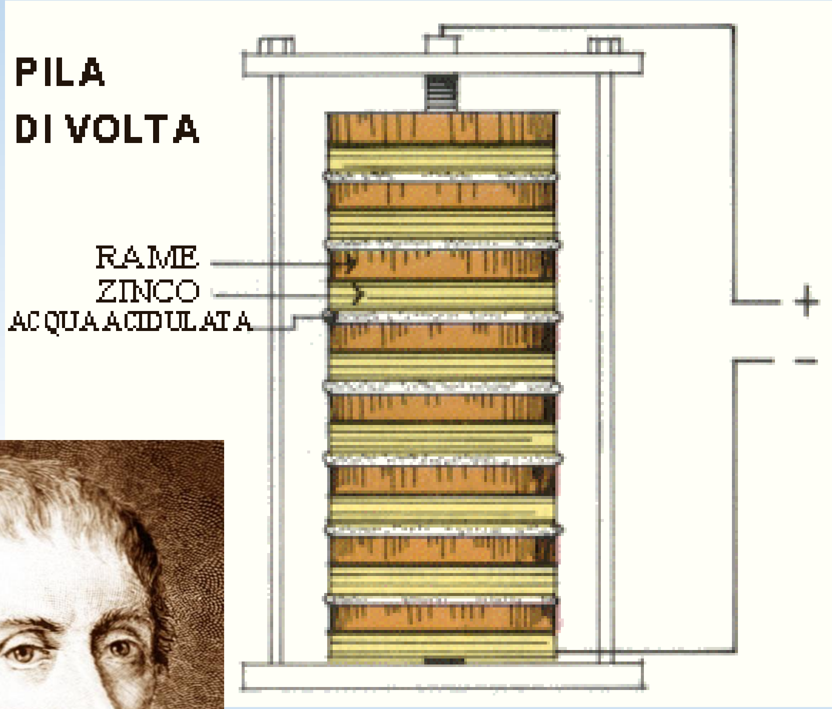
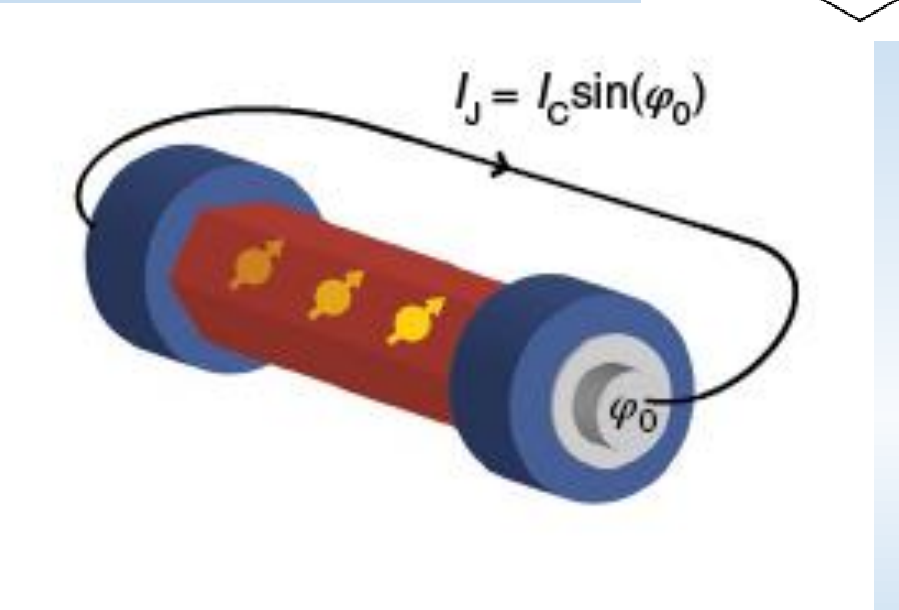
PERSPECTIVES & CONCLUSIONS

THE CLASSICAL *VS* THE QUANTUM PHASE BATTERY







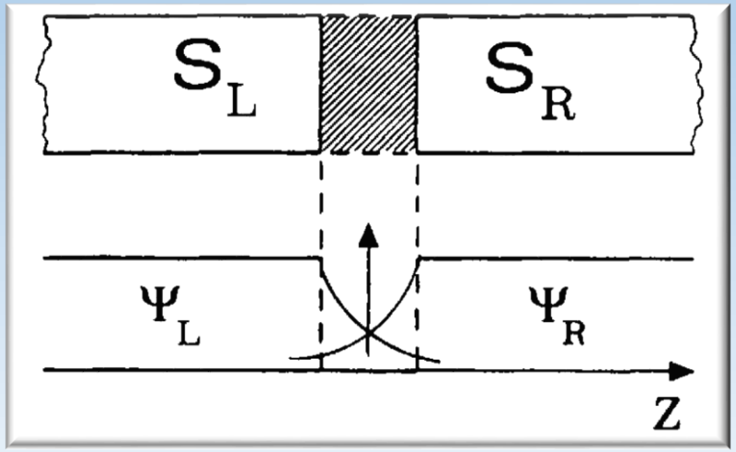
It converts chemical energy into a voltage bias that gives power to electronic circuits

It provides a **persistent phase bias** to the wavefunction of the quantum circuits. It converts the polarization of unpaired spins in a phase bias φ_0

This phenomenon is intimately connected to an **anomalous Josephson current**

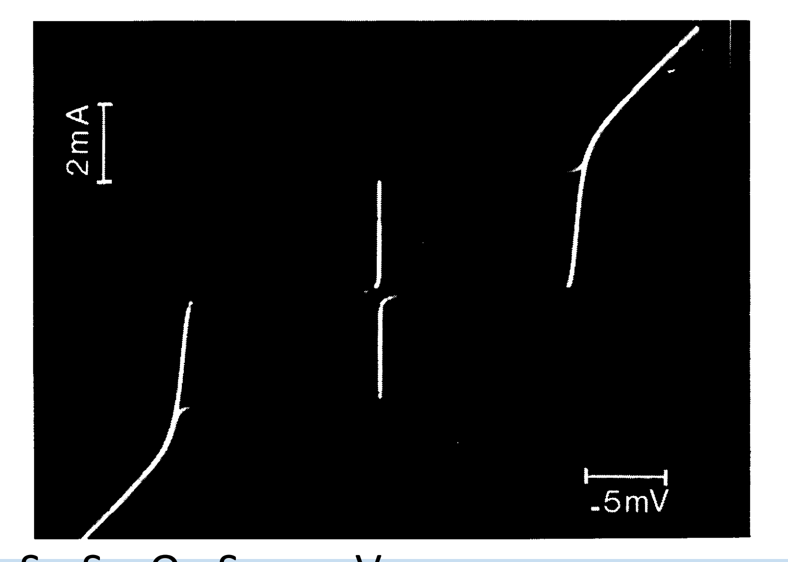
THE JOSEPHSON EFFECT

B.D. Josephson, 1962



Two superconductors separated by a thin insulator

I



Sn-SnxOy-Sn V

In the presence of d.c. bias V

$$j\hbar\frac{\partial\psi_R}{\partial t}=-eV\psi_R+K\psi_L$$

$$j\hbar\frac{\partial\psi_L}{\partial t}=eV\psi_L+K\psi_R$$

$$\psi_L=\rho_L^{1/2}e^{j\varphi_L}\qquad \psi_R=\rho_R^{1/2}e^{j\varphi_R}$$

$$J\equiv\frac{\partial\rho_L}{\partial t}=-\frac{\partial\rho_R}{\partial t}$$

Current-phase relationship (CPR)

$$J=\frac{2K}{\hbar}\sqrt{\rho_L\rho_R}\sin\varphi$$

$$\varphi=\varphi_L-\varphi_R$$

$$\frac{\partial\varphi}{\partial t}=\frac{2eV}{\hbar}$$

$$J=J_1\sin\left(\varphi_0+\frac{2e}{\hbar}Vt\right)$$

An open JJ (J=0) cannot provide a phase bias

We are interested in the anomalous JJ here!

SYMMETRIES OF JOSEPHSON CURRENT

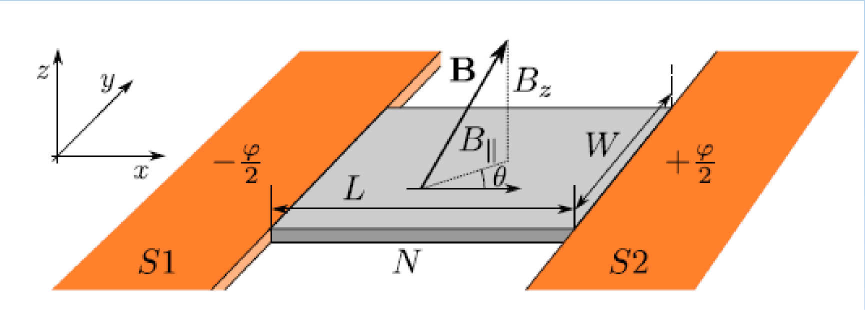
Free-energy of the junction:

$$F = -T \ln \mathrm{Tr}\{e^{-H/T}\}$$

The **supercurrent** is calculated through the thermodynamic relation:

$$I_s(\varphi) = \frac{2e}{\hbar}\frac{\partial F}{\partial \varphi}$$

$$I_{c+} = \max_{\varphi} I_s(\varphi) \quad \text{and} \quad I_{c-} = \min_{\varphi} I_s(\varphi)$$



$$\mathcal{H}_{\mathrm{SOI}} = \left\{\frac{\alpha}{\hbar}(-p_y\sigma_x + p_x\sigma_y) + \frac{\beta}{\hbar}(-p_x\sigma_x + p_y\sigma_y)\right\}\tau_z$$

Symmetry argument: $H = U H' U^\dagger$ → Relation between *Is* and *Is'*

If $F(\varphi) = F(-\varphi)$ is symmetric under $\varphi \to -\varphi$

→ $I_s(\varphi) = -I_s(-\varphi)$

Thus investigating all the cases in which there exist a transformation such that:

$U H(\varphi) U^\dagger = H(-\varphi)$ Allows to determine the conditions for **anomalous Josephson current** $I_s(\varphi = 0) \neq 0$ to exist

Symmetry operations U protecting $H(\varphi) = H(-\varphi)$

$UH(\varphi)U^\dagger = H(-\varphi)$	Broken by
$P_y P_x$	α,
$\sigma_z P_y P_x$	B_x, B_y
$\sigma_x P_y T$	B_x, α,
$\sigma_y P_y T$	B_y.

$T = i\sigma_y K$

THE JOSEPHSON CURRENT AND SYMMETRIES

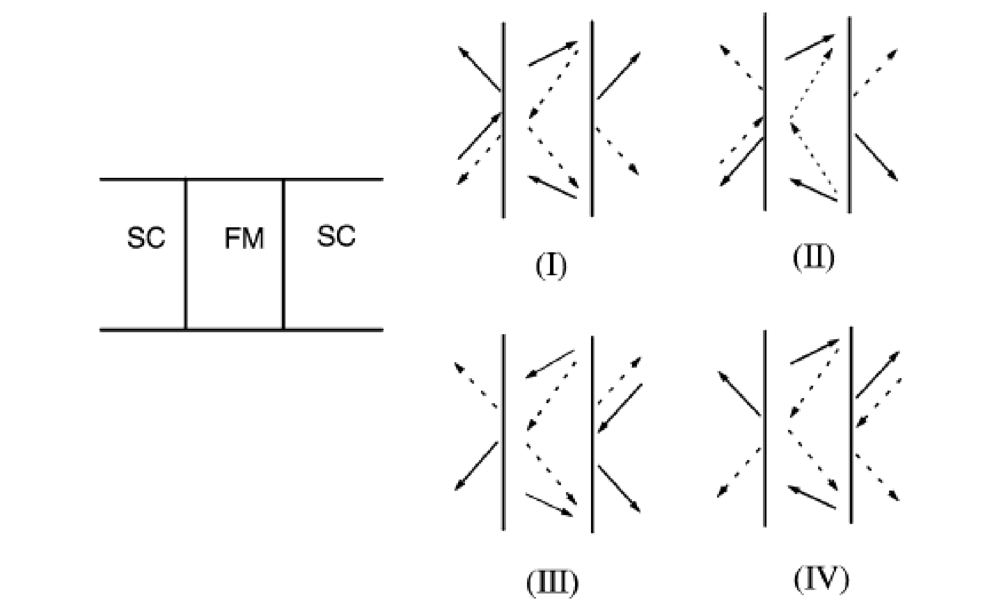
Time-reversal symmetry	Reflection symmetry
(t→ —t)	r→ —r

$$I_J(\varphi) = I_C \sin(\varphi)$$

Implementation of phase battery is prevented by the symmetries! Phase rigidity

Time-reversal symmetry	Reflection symmetry
(t→ —t)	r→ —r

$0-\pi$ Transition



Golubov, A. A., et al., Rev. Mod. Phys. 76, 411–469 (2004).

THE JOSEPHSON CURRENT AND SYMMETRIES

Time-reversal symmetry	Reflection symmetry
($t \to -t$)	$\mathbf{r} \to -\mathbf{r}$

$0 < \varphi_0 < \pi$ Finite phase shift

$$I_J(\varphi) = I_C \sin(\varphi + \varphi_0).$$

- It will generate a constant phase-bias in an open circuit

$$\varphi = -\varphi_0$$

- Inserted in a closed sc circuit $I = I_C \sin(\varphi_0).$

Anomalous Josephson current in absence of finite phase difference.

Question: How do we break the inversion and time-reversal symmetry in a sc circuit**?**

Question: How do we break the inversion and time-reversal symmetry in a sc circuit?

Answer: A combination of **Rashba spin-orbit coupling, magnetic field or exchange field** are the good compromise!

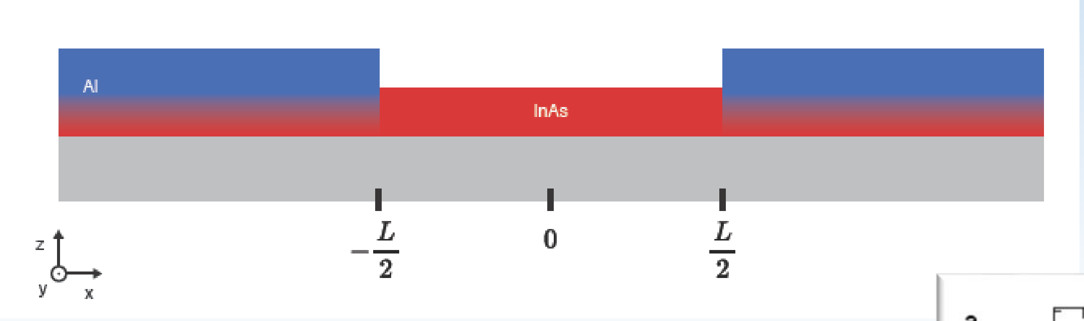
compromise!

THE LATERAL HYBRID JOSEPHSON JUNCTION

- ✓ **Lateral hybrid junctions** made of a wire with strong Rashba **spin-orbit interaction** or **topological insulators**: ideal candidates for φ_0 junctions

- ✓ The lateral arrangement breaks the inversion symmetry and since the wire lies on a substrate plane it provides a natural polar axis **z perpendicular to current direction** (**uniaxial asymmetry**)

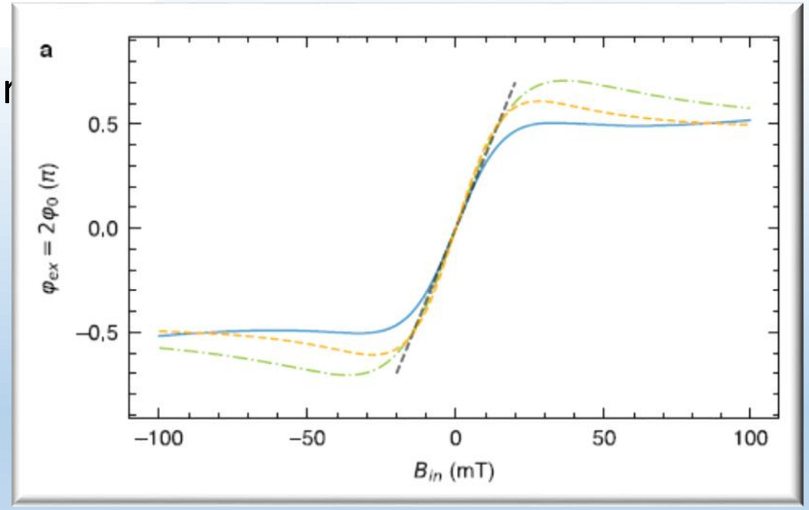
- ✓ The presence of an **exchange field** due to magnetic impurities breaks the **time-reversal symmetry**



Diffuse nanowire

The presence of **Rashba spin-orbit coupling** allows for a differential operator

$$C_k^a \partial_k \sim (\hat{z} \times \nabla)^a$$



From linearized **Usadel equation** for the condensate function

$$f = f_s + i f_t \mathrm{sgn}\omega \sigma^y$$

(high transparent interface, ideal SNS junction)

$$\varphi_0 = \frac{\tau m^{*2} E_Z (\alpha L)^3}{3\hbar^6 D}$$

S. Bergeret et al., EPL 110 (2015)

THE FREE ENERGY

The shifts φ_0 are ruled by a **Lifshitz-type invariant** of the free energy of the form

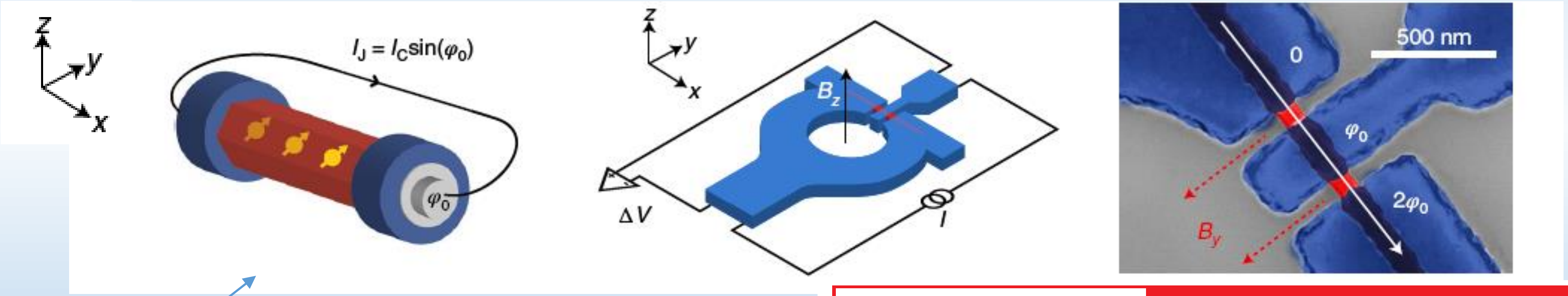
$$F_L \approx f(\alpha, h)(\mathbf{n_h} \times \hat{\mathbf{z}}) \cdot \mathbf{v_s},$$

S. Bergeret, EPL 110 (2015)

Odd function of SO coefficient and Zeeman field

Superfluid velocity

Conceptual scheme for the phase battery



InAs nanowire embedded between two sc Al poles

nature nanotechnology

LETTERS

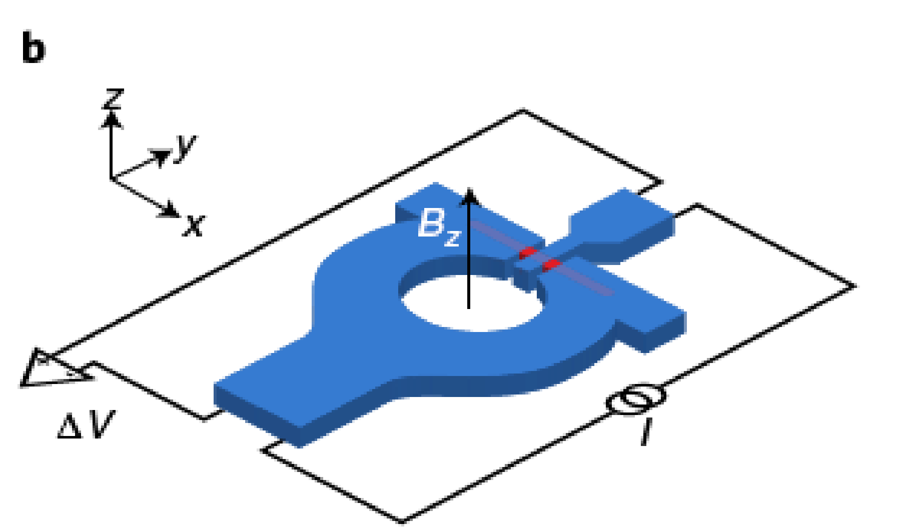
https://doi.org/10.1038/s41565-020-0712-7

Check for updates

A Josephson phase battery

Elia Strambini[1]✉, Andrea Iorio[1]✉, Ofelia Durante[2], Roberta Citro[2], Cristina Sanz-Fernández[3], Claudio Guarcello[2,3], Ilya V. Tokatly[4,5], Alessandro Braggio[1], Mirko Rocci[1,7], Nadia Ligato[1], Valentina Zannier[1], Lucia Sorba[1], F. Sebastián Bergeret[3,6]✉ and Francesco Giazotto[1]✉

SQUID AS A PHASE SENSITIVE INTERFEROMETER

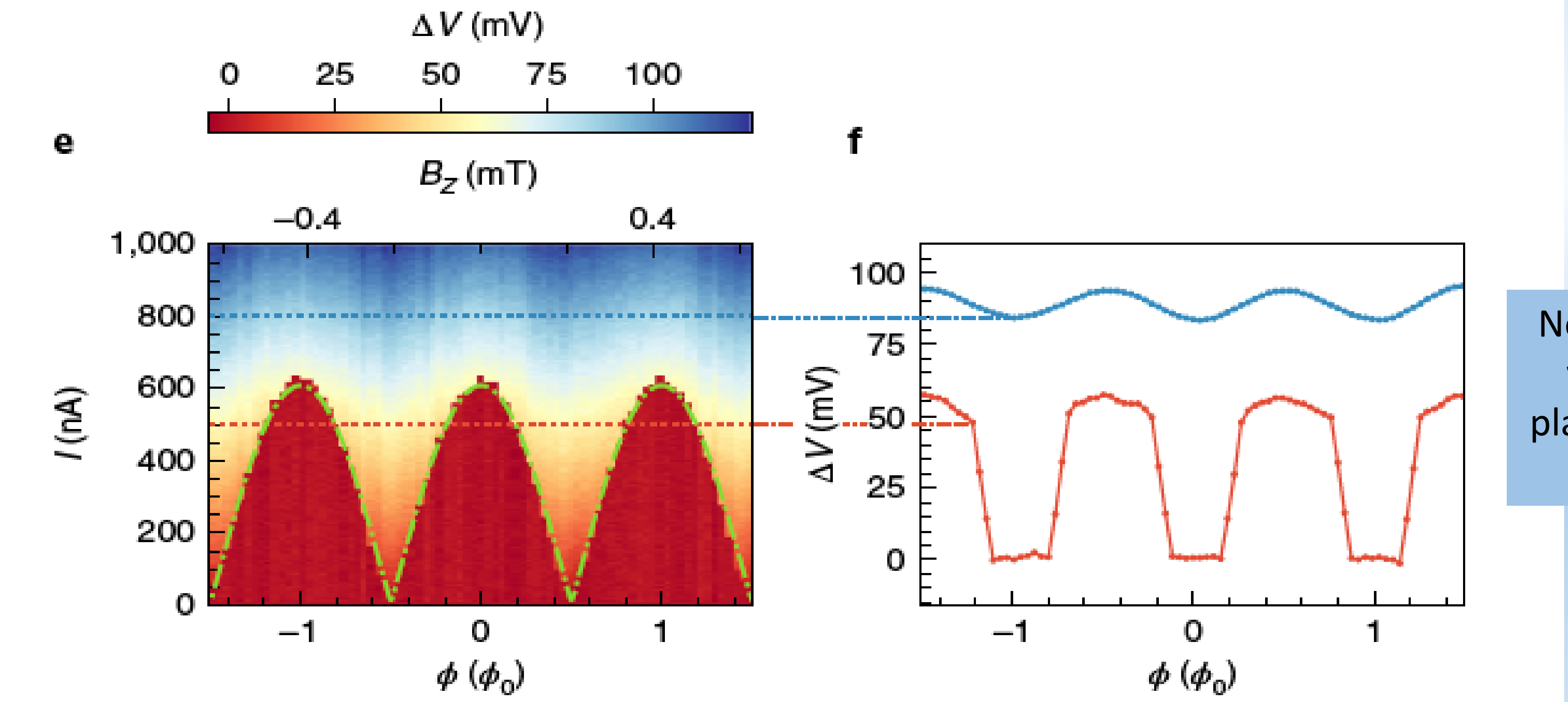


$$I_S(\Phi) = 2I_C\left|\cos\left(\pi\frac{\Phi}{\Phi_0} + \frac{\varphi_{tot}}{2}\right)\right|;$$

Phase shift

$\varphi_{tot} = 2\varphi_0$

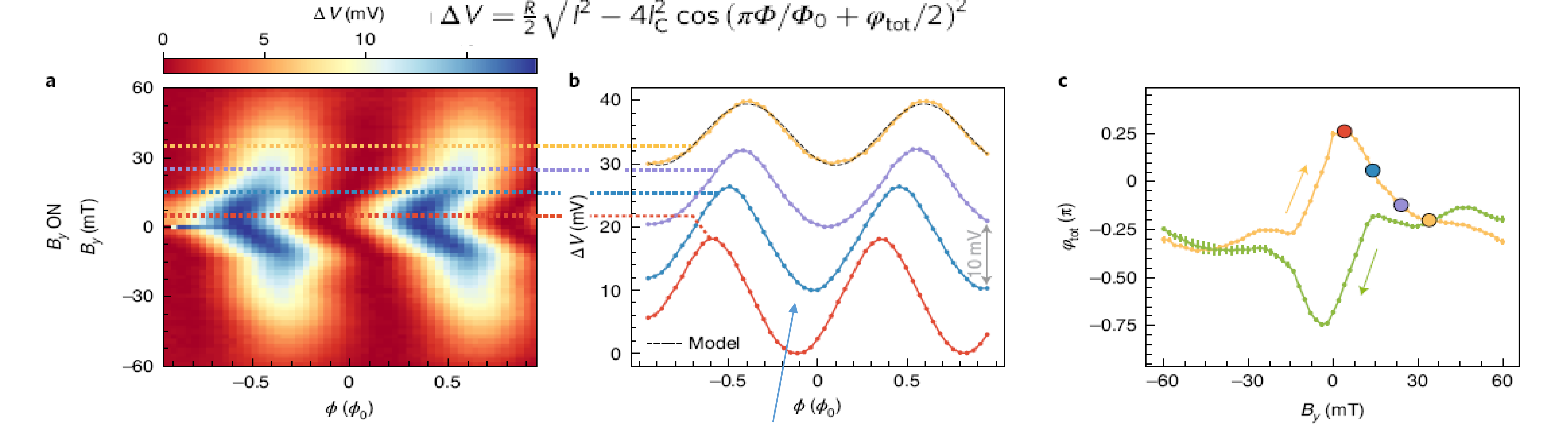
Anomalous phase is zero for the **out of plane** magnetic field

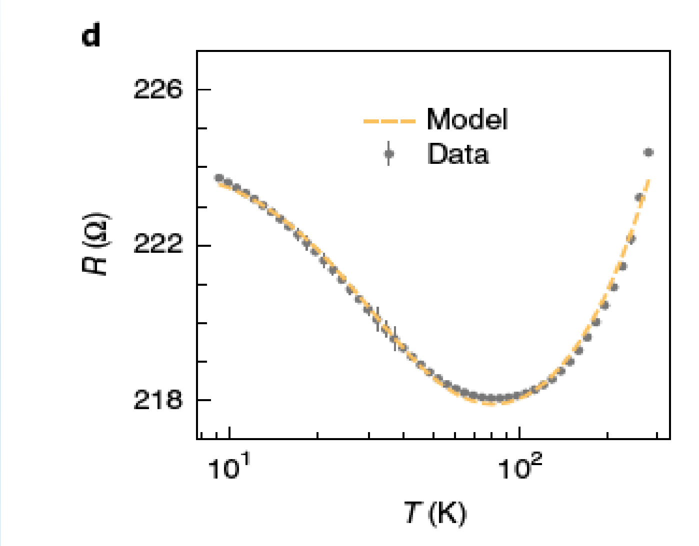


No phase shift with out of plane magnetic field

EFFECT OF POLARIZED IMPURITIES

$$\Delta V = \frac{R}{2}\sqrt{I^2 - 4I_C^2\cos\left(\pi\Phi/\Phi_0 + \varphi_{tot}/2\right)^2}$$





Evidence of a phase shift with an **in plane magnetic field**

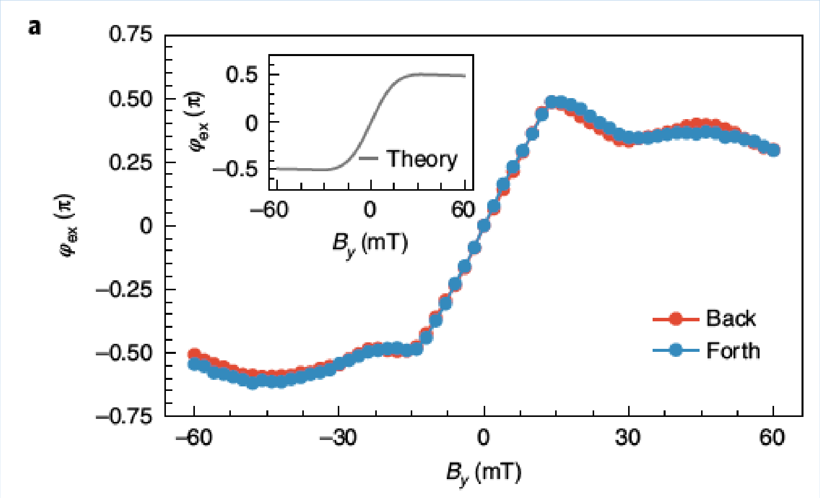
ruled by polarized impurities

$$F_L \approx f(\alpha, h)(\mathbf{n_h} \times \hat{\mathbf{z}}) \cdot \mathbf{v_s}, \quad \neq 0$$

Kondo effect

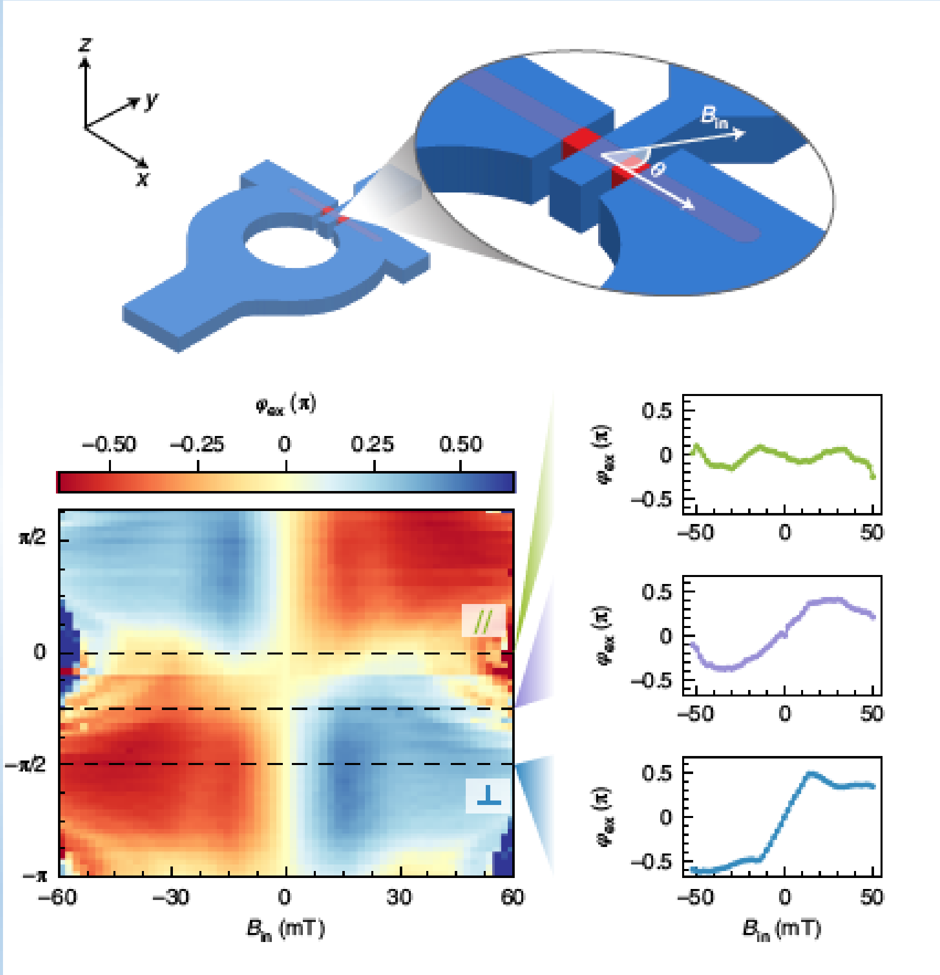
Impurities

INTRINSIC VS EXTRINSIC PHASE SHIFT



The extrinsic phase is odd symmetric non-hysteretic contribution

$$\varphi_{ex} \approx C_1 \alpha^3 B_{in} \sin(\theta) + O(B_{in}^3),$$



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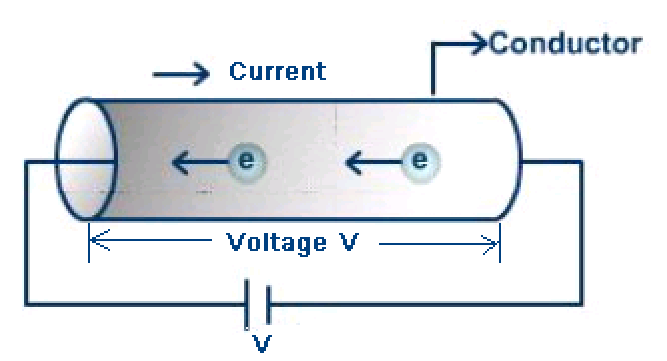
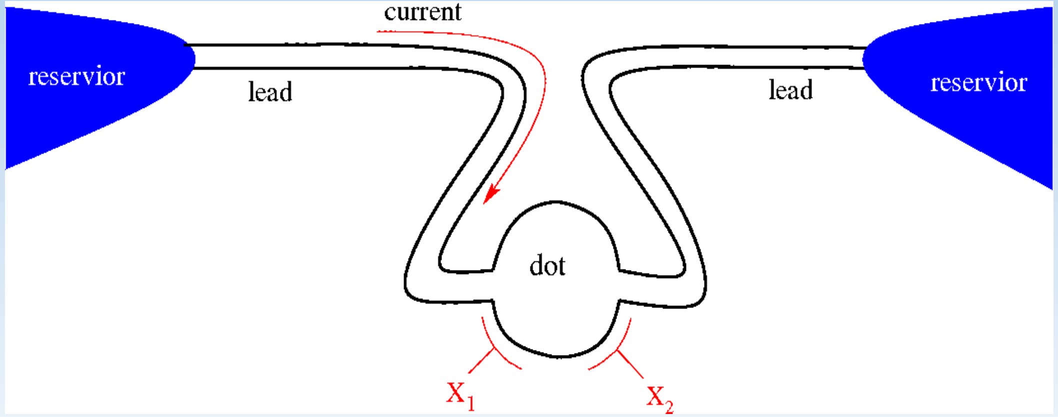
PERSPECTIVES & CONCLUSIONS

Quantum pump basic idea...





A direct current (dc) is usually associated to a dissipative flow of the electrons in response to an applied bias voltage.

In systems of mesoscopic scale a dc current can be generated *even at zero bias* (e.g. in semiconductor nanostructures of nm size and tens of atoms) in the presence of slow periodic perturbations

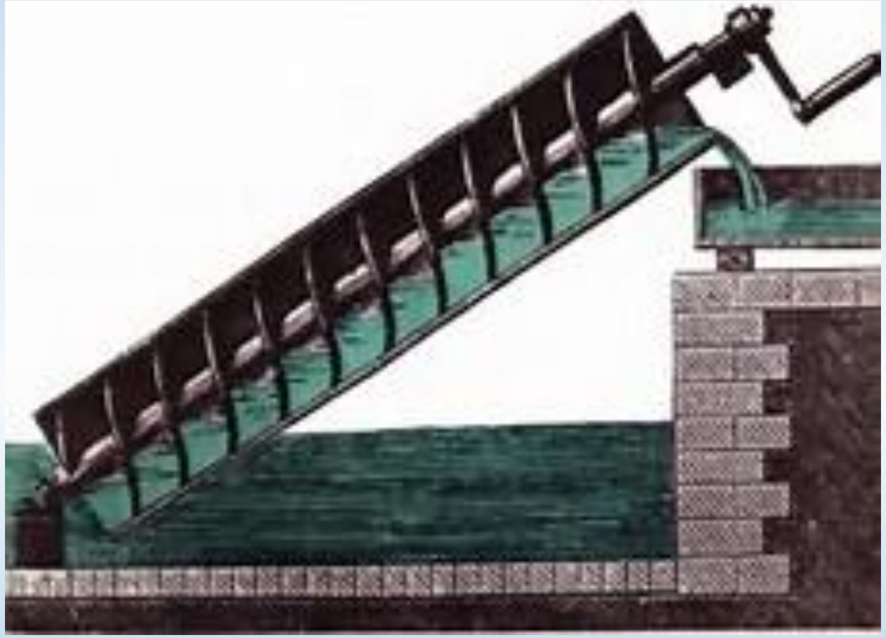
This quantum coherent effect is called **quantum pumping**

(*quantum charge pumping*)

Applications: sources and minimal-noise current standards; diagnostic tools for mescoscopic devides

The classical pump idea...

a way of generating a directional motion obtained by using a periodic modulation of a system parameter…already Archimede thought about that

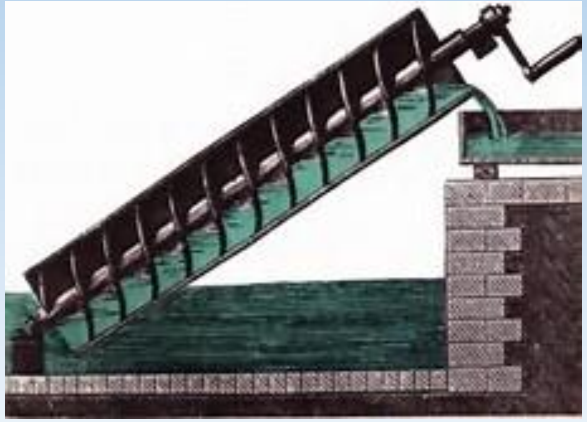


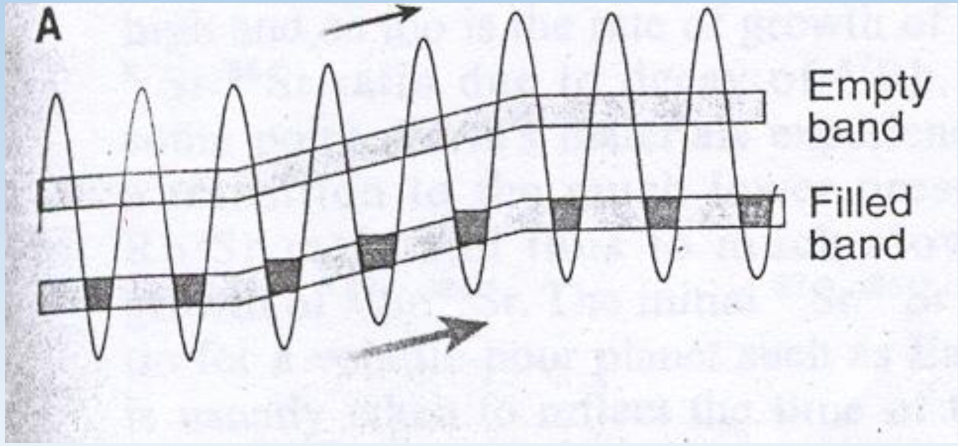
The Archimedean screw

The Thouless pump

Thouless, PRB (1983)

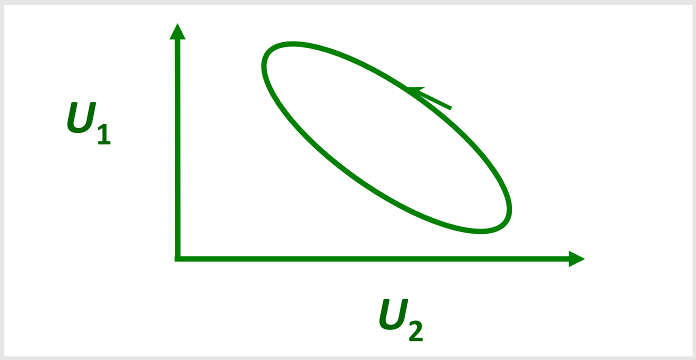
Spinless electrons in a sliding periodic potential U(x-vt), with spatial period a





The sliding potential: interfering standing waves

$$U(x-vt) = U_1(t)\sin(2\pi x/a) + U_2(t)\cos(2\pi x/a)$$
$$U_{1,2}(t) = U_0\cos(2\pi t/T + \phi_{1,2})$$



The number of electrons pumped per cycle of a quantum pump is an integer as long as the bulk is gapped

$I = nev$ $Q = Ne$

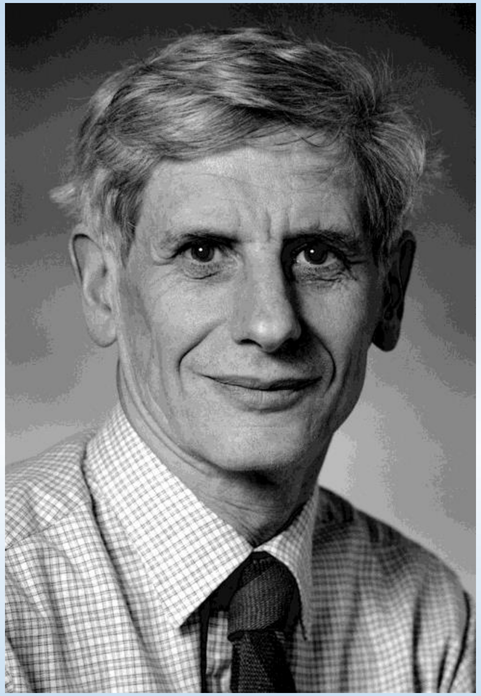
Time-evolution of the potential-closed trajectory in the parameter space $U_{1,2}$

The pumped charge is the contour integral of some "vector potential" [topological invariant]

The quantum pump and the dynamical version of the Interger Quantum Hall Effect [Thouless, PRB 27, (1983)]

The quantum pump is intimately connected to the integer quantum Hall effect

Klaus von Klitzing, Nobel 1985

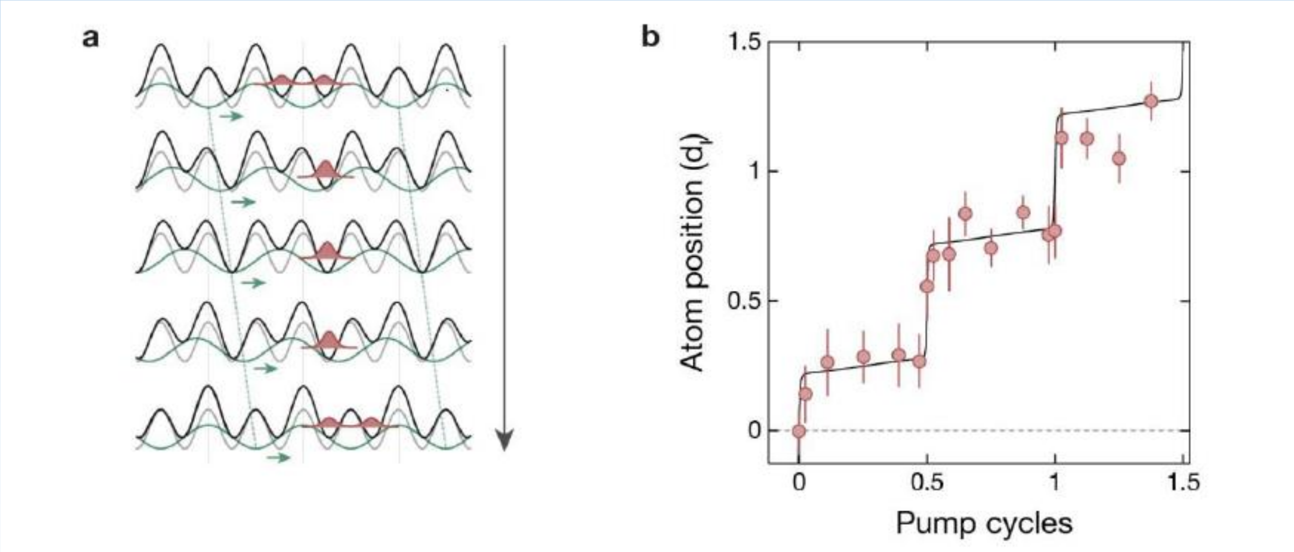


David J. Thouless, Nobel 2016

A similar phenomenon could also be observed in one-dimensional quantum systems if their parameters are varied periodically. The dynamic version of QHE enables transport without external bias.

The ultracold atoms in optical lattices…ideal system for a quantum pump

Implementation of the topological pump in optical superlattices with bosons and fermions



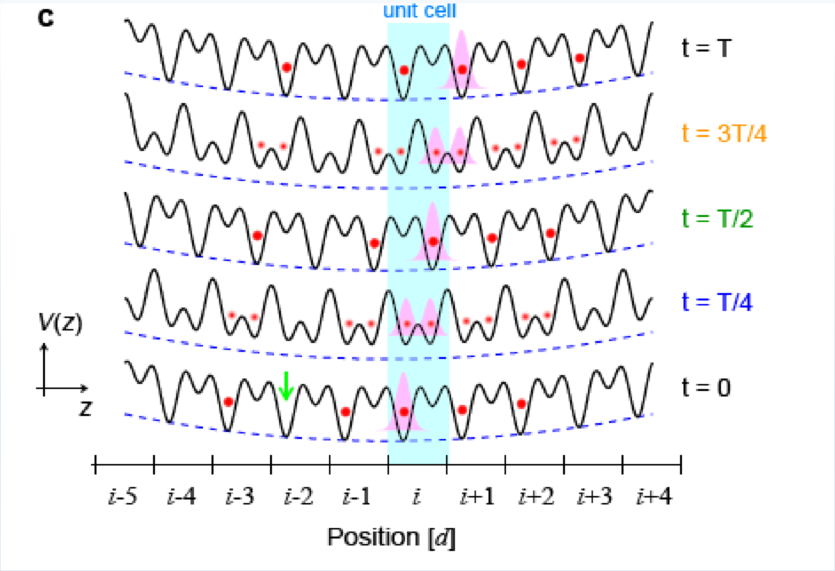
$$V_s \sin^2(\pi x/d_s + \pi/2) + V_l \sin^2(\pi x/d_l - \varphi/2)$$

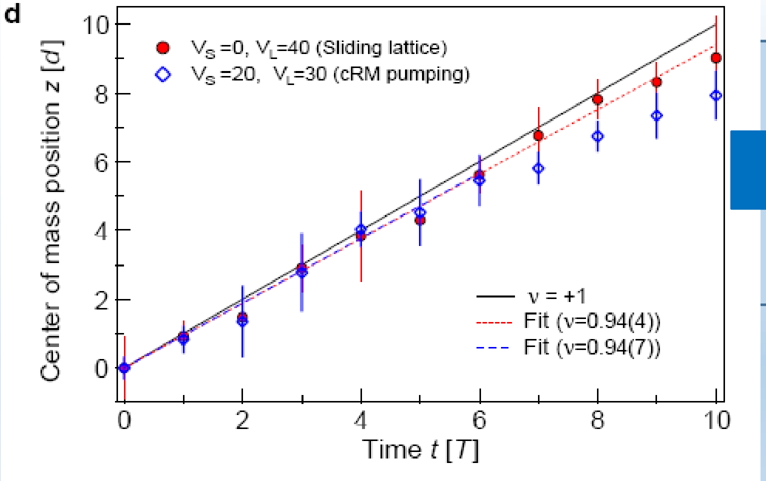
[87] Rb atoms

Bloch's group, Nat. Phys. 12, 350 (2016);

the c.o.m. moves by exactly one period of the long lattice d_l in a cycle: motion occurs in discrete steps.

$\delta x = 2\pi\, dl\, C$ → **Pumped charge**





$$C = \frac{1}{2\pi}\int_0^T dt \int_{-\pi/d}^{\pi/d} dk\, \Omega(k,t),$$

CHERN NUMBER: topological invariant

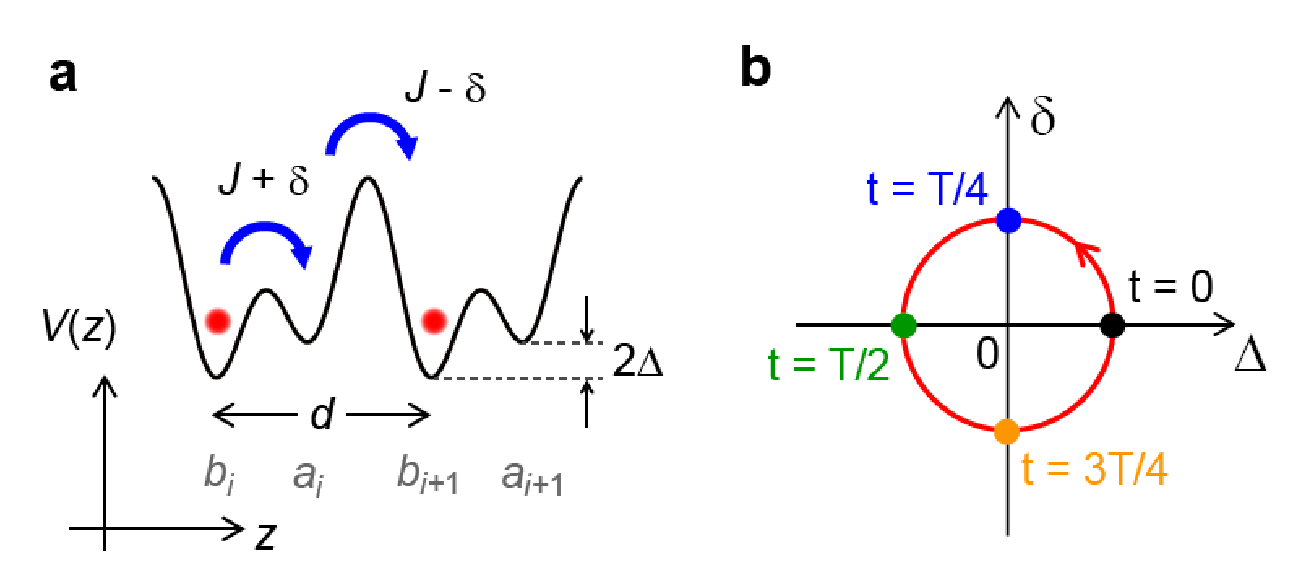
Nakajima et., Nature Phys. (2016)

[171] Li atoms

The Rice-Mele model

A pictorial way to understand the pumping scheme with superlattice is to consider the **tight-binding Rice-Mele model [**M. J. Rice and E. J. Mele, PRL **49**, (1982)] [superlattice model]

$$\hat{\mathcal{H}} = \sum_i \left(-(J+\delta)\hat{a}_i^\dagger \hat{b}_i - (J-\delta)\hat{a}_i^\dagger \hat{b}_{i+1} + \text{h.c.} + \Delta(\hat{a}_i^\dagger \hat{a}_i - \hat{b}_i^\dagger \hat{b}_i) \right)$$



$(\delta,\Delta) \rightarrow \delta(\phi), \Delta(\phi)$

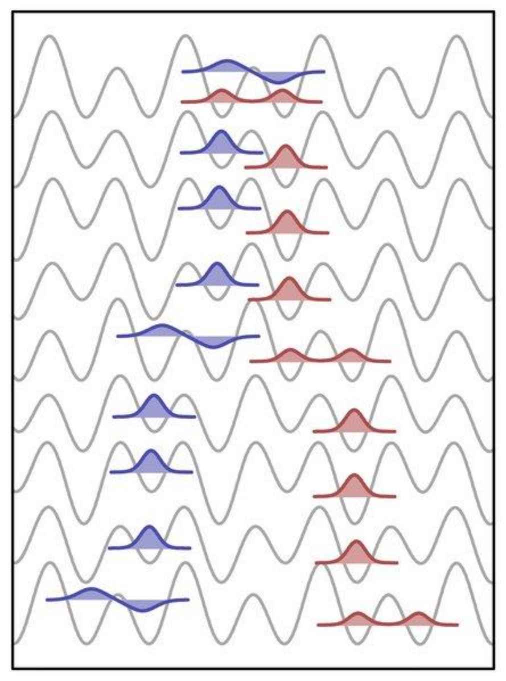
$\phi = 2\pi t/T$

*A pump can be induced by an adiabatic periodic modulation of the potential [dimerization+tilt] which corresponds to a loop in the parameter space of the RM model around the degeneracy point.

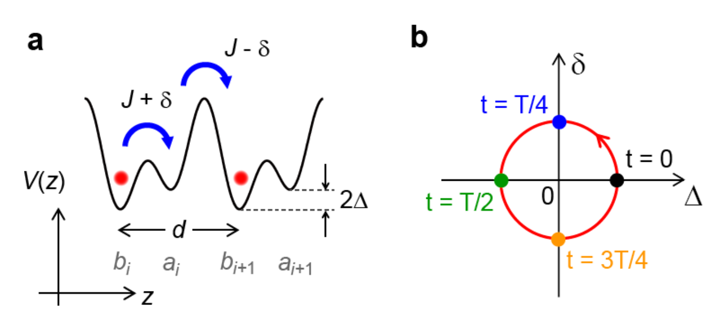
*Periodically changing δ, Δ is equivalent to **change the optical path difference** between two sublattices

THE QUANTUM SPIN PUMP

A quantum spin pump can be implemented with ultracold atoms in two hyperfine states in **a spin-dependent controlled optical superlattice**



^{87} Rb atoms



$U \gg J$ Induces couplings between the two spin-components

$$\hat{\mathcal{H}} = -\frac{1}{4}\sum_m (J_{\rm ex} + (-1)^m \delta J_{\rm ex})(\hat{S}_m^+ \hat{S}_{m+1}^- + {\rm H.c.}) + \frac{\Delta}{2}\sum_m (-1)^m \hat{S}_m^z$$

Alternating exchange coupling

Spin dependent tilt

$$\tfrac{1}{2}(J_{\rm ex} \pm \delta J_{\rm ex}) \simeq (J \pm \delta J)^2/U$$

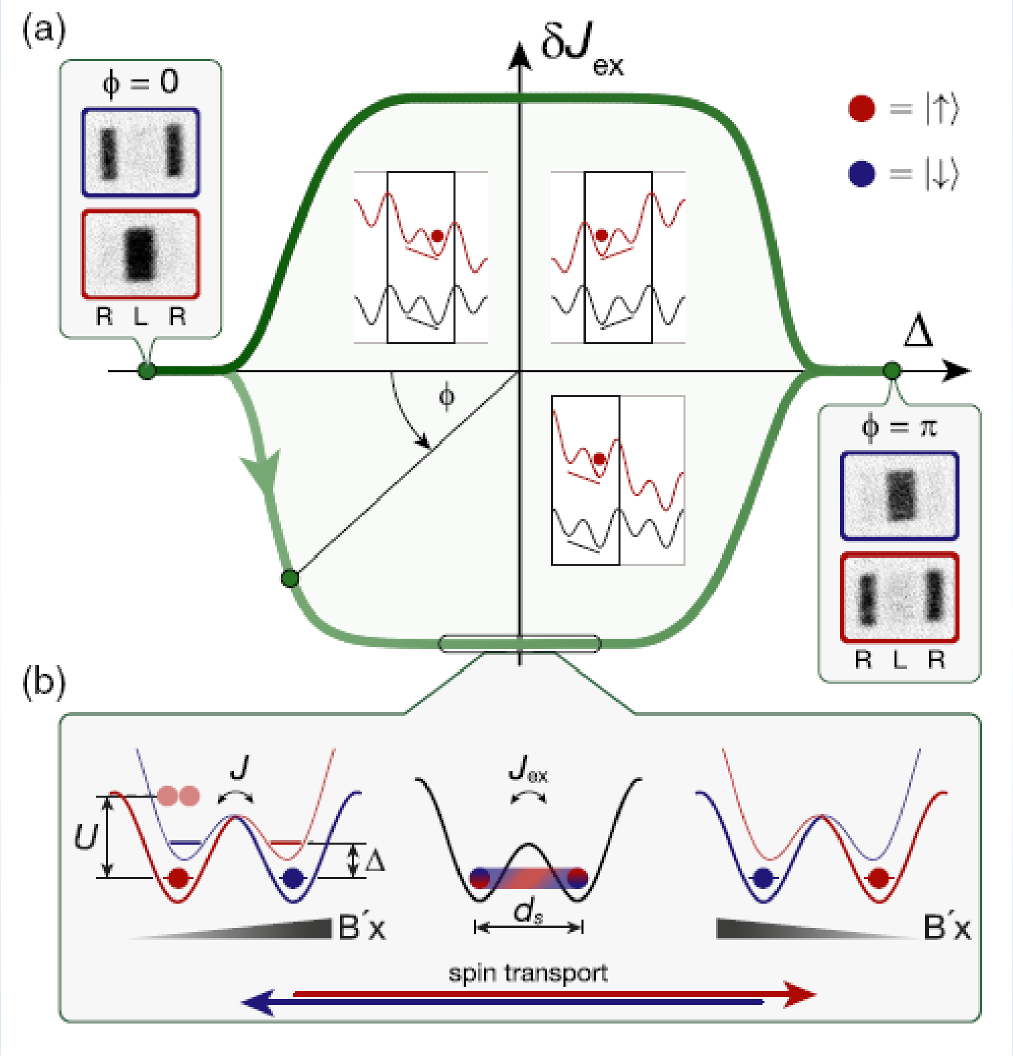
$\Delta \gg \frac{1}{2}(J_{\rm ex} + \delta J_{\rm ex})$ Antiferromagnetically ordered spins

$\frac{1}{2}(J_{\rm ex} + \delta J_{\rm ex}) \gg \Delta$ Dimerized entangled pairs

Varying δJ and Δ during the pump cycle modulates (δJex, Δ) in the interacting 1D spin chain which corresponds to a closed loop in the parameter space

NOTE: time-reversal symmetry is retained !

THE SPIN PUMP CYCLE



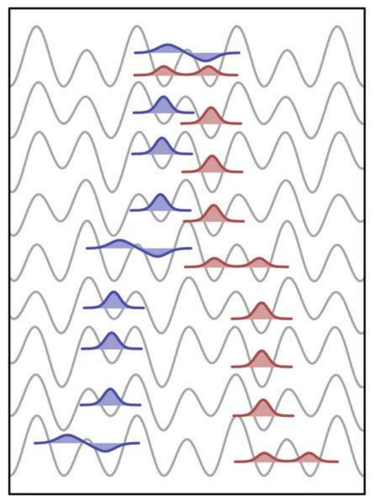
Evolution of the two particle ground state in a double well

When pump cycle encircles the degeneracy point (Jex=0, Δ=0) and modulation is adiabatic: quantized transport described by the Z2 invariant [Kane & Mele PRL, 2005].

$$C_{sc} = \nu_{\uparrow} - \nu_{\downarrow}$$

Spin exchange their position by a delocalized triplet state

After a full pump cycle the two spin components have moved in opposite directions



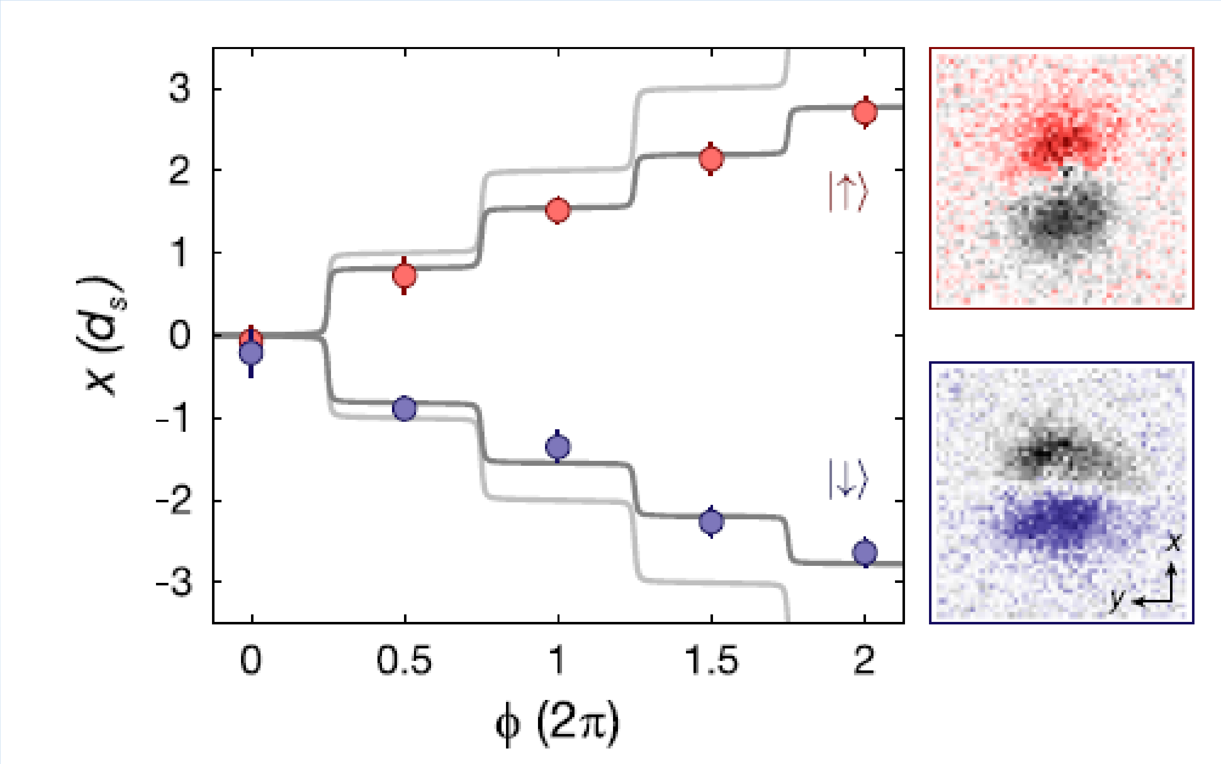
^{87}Rb atoms

C. Schweizer, RC et al., PRL 117, 170405 (2016)

SHIFT OF THE SPIN CENTER OF MASS

Evidence for the spin separation and measure of the total spin currents come from spin center of mass position from *in situ* absorption images

Motion of the spins occurs in discrete steps



Errors coming from reduced ground state occupation
Pump efficiency ~89%

C. Schweizer, RC et al., PRL 117, 170405 (2016)

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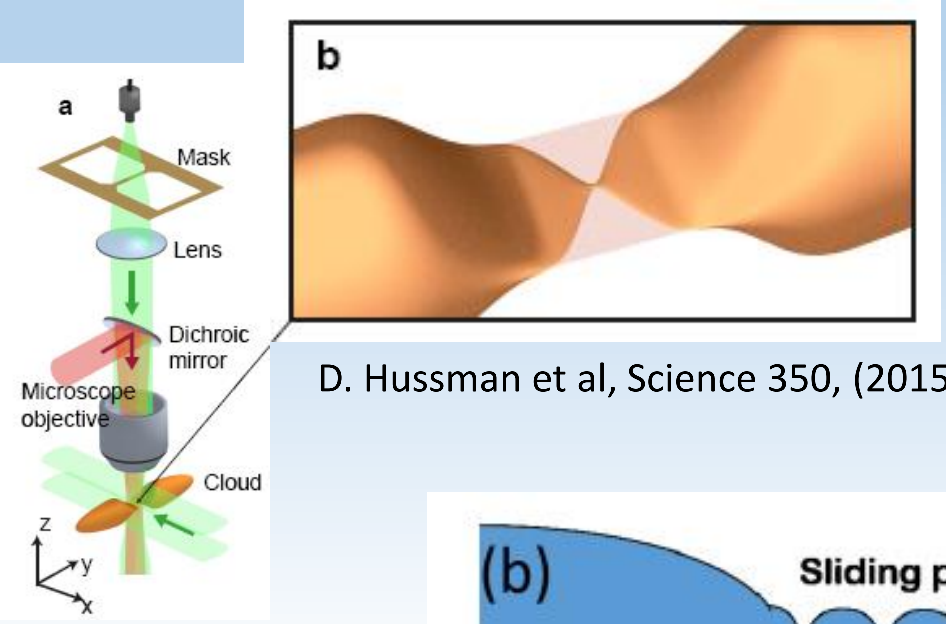
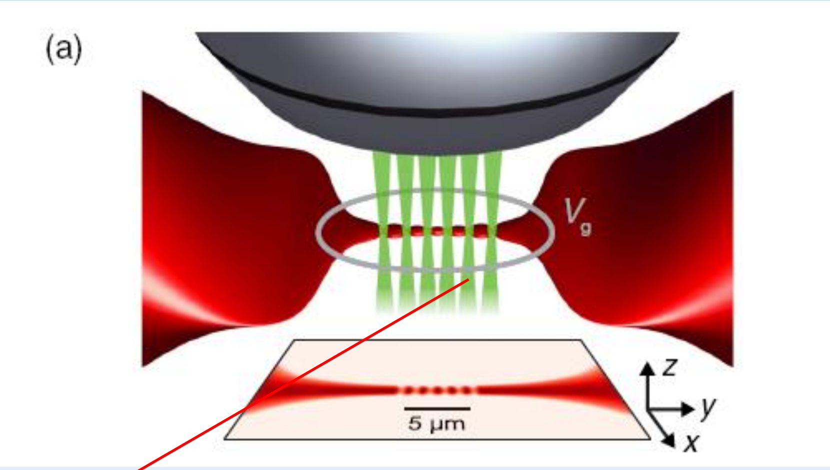
THE PERISTALTIC QUANTUM PUMP

Connecting two superfluids of ^{6}Li atoms

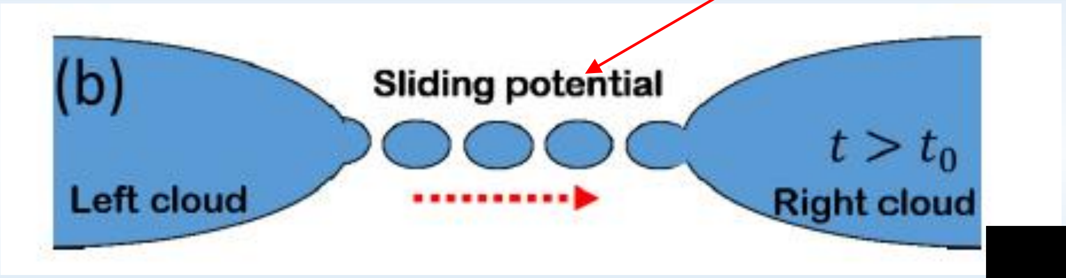


D. Hussman et al, Science 350, (2015)



L. Lebrat et al., PRX 8, 011053 (2018)

Projection of thin barrieirs



Conveyor belt

$$H_0 = \sum_n \epsilon c_n^\dagger c_n - J \sum_n (c_{n+1}^\dagger c_n + \mathrm{H.c.})$$

Time-dependent potential

$$V_j^0 + V_j \cos(\omega t + \varphi_j)$$

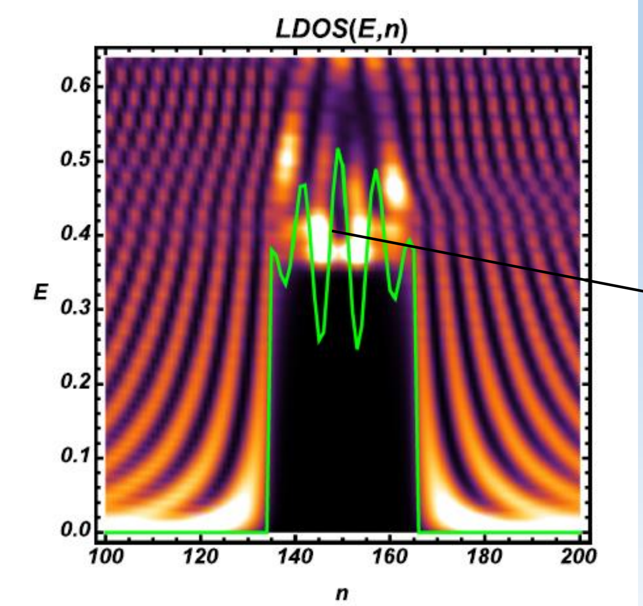
$$H_V = \sum_{j \in A} V_j(t) n_j$$

THE POTENTIAL AND LOCAL DENSITY OF STATES

$$[\hat{V}(t=0)]_{ln} = \left\{V + U_P\left[1 - \left(\frac{n-n_0}{W}\right)^2\right]\cos(Kan)\right\}\delta_{ln}$$

$V > E_F$

$2W > \lambda_F$



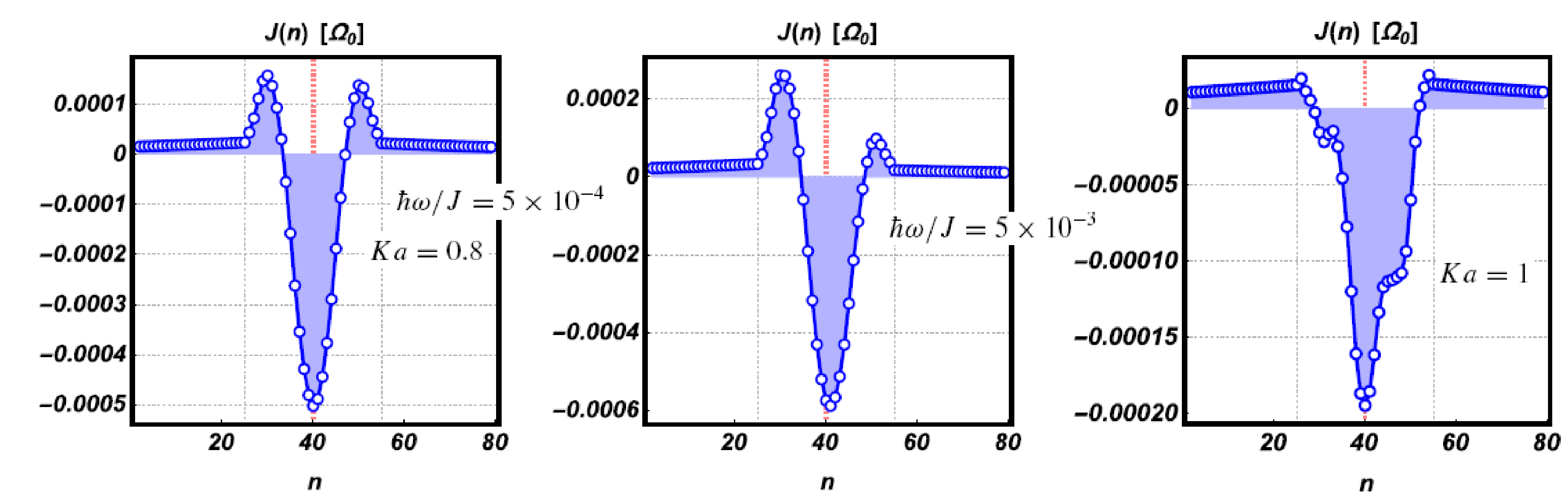
$V = 0.38J, U_P = 0.14J, Ka = 0.8, W = 15$

Localized quantum states

2W defines the distance from the clouds

The site current

$\Omega_0 = 2J/\hbar.$

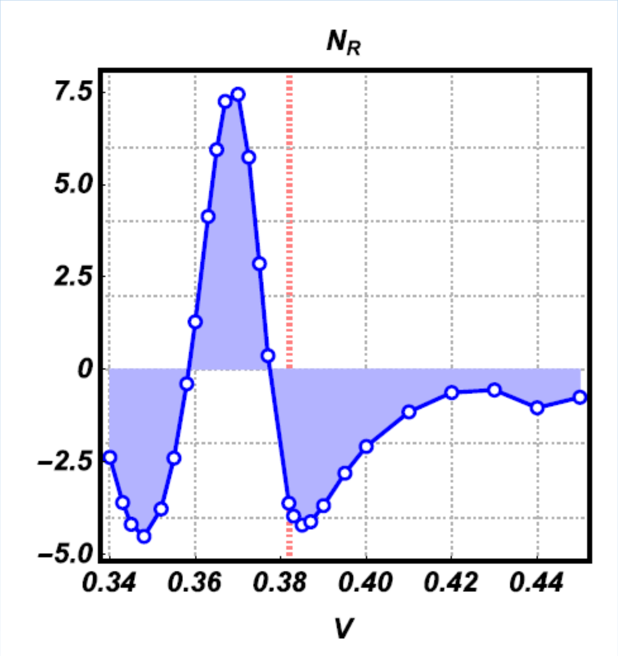


F. Romeo, **RC**
PRB **97**,
184519 (2018)

Simulations for N=80 lattice sites

THE PUMP EFFICIENCY

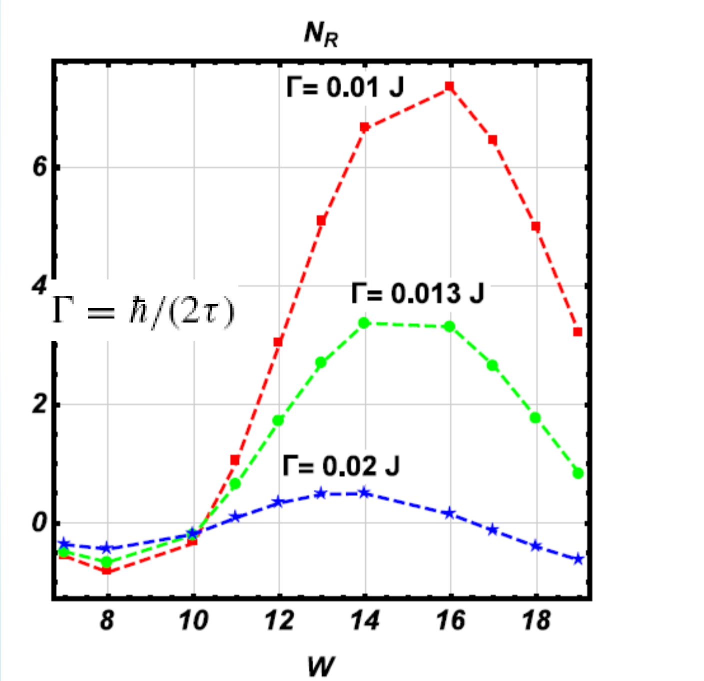
$$\mathcal{N}_{L/R} = 2\pi\, \mathcal{J}_{L/R}/\omega$$

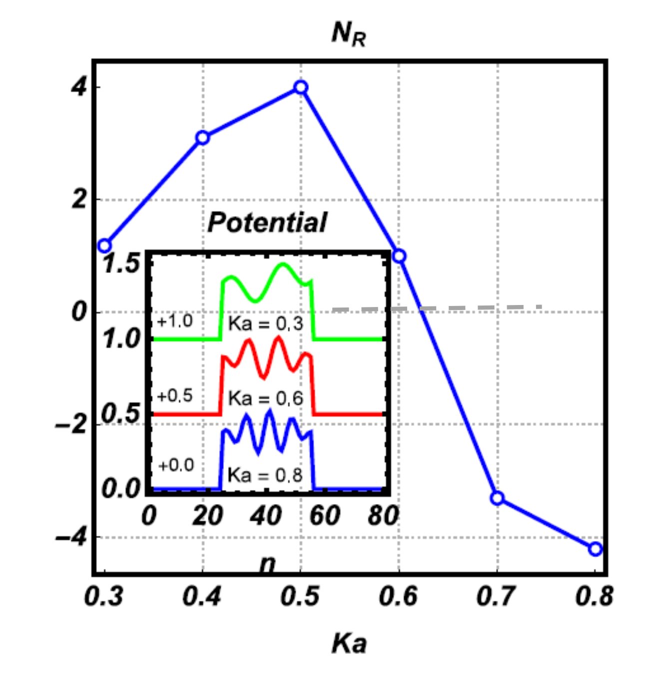


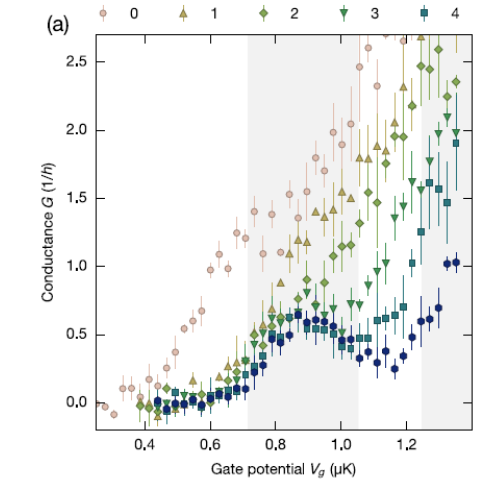
Effect of barrier height

Effect of relaxation

Effect of fingers number







F. Romeo, et al. PRB 97, 184519 (2018)

Phase battery --Acknowledgments

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The peristaltic pump
Theory

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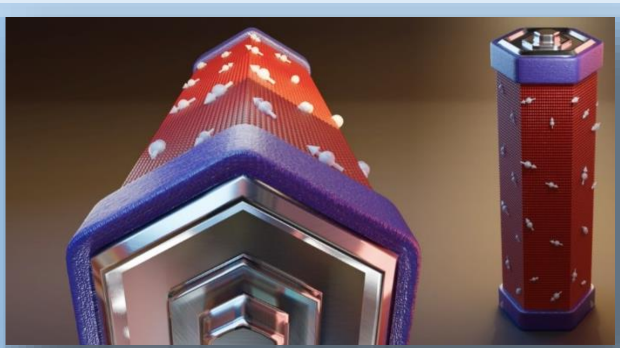
Experiment on spin pump

More details on

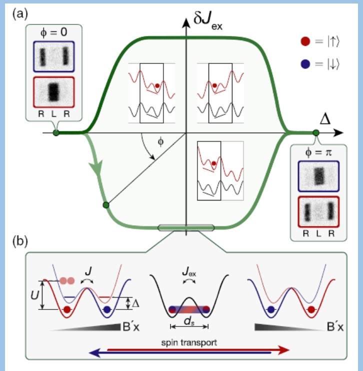
P. Marra et al., Phys. Rev. B 93, 220507(R) (2015)
P. Marra & **RC**, EPJ ST **226**, 2781 (2017)
C. Schweizer, M. Lohse, **RC**, I. Bloch, PRL **117**, 170405 (2016)
F. Romeo, **RC**, PRB **97**, 184519 (2018)

Conclusions

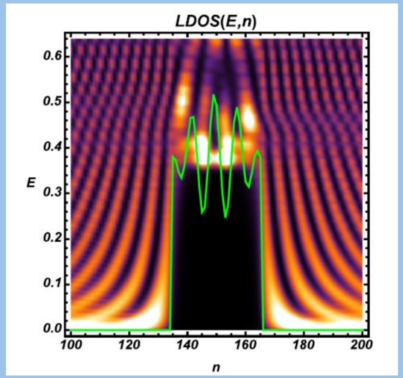
Symmetry breaking and invariant concepts hold great potential for the study of fundamental physics and high-performance in quantum devices



- ***Quantum phase battery***: **Provides a controllable phase bias; applications as a qubit, sc quantum memories**



- **The *spin pump* in optical superlattice and spin current: adiabatic change of the system parameters generates a current**



- **The *peristaltic pump* and its efficiency**


Thank you for your attention