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# Shuttling of Single Electrons and Cooper Pairs


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*In collaboration with:*

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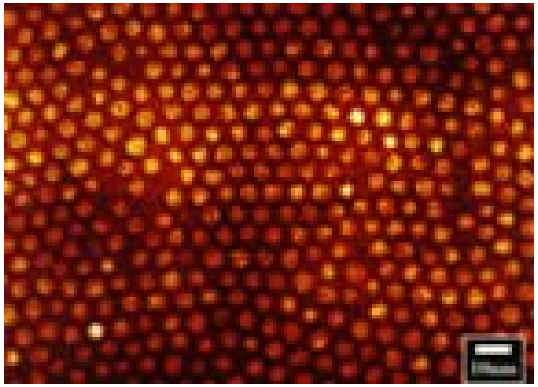
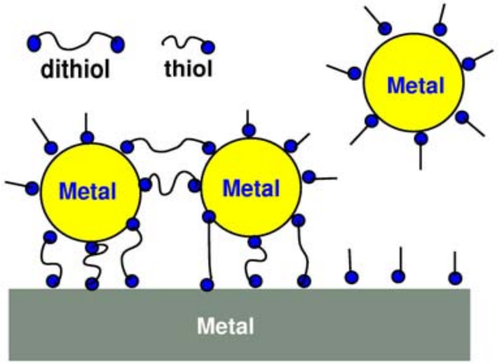
- Electromechanical coupling in Coulomb Blockade structures
- Shuttling of electrons by a movable dot (PRL,1998)
- Shuttling of Cooper pairs by a movable Single Cooper Pair Box (Nature (2001); PRL (2002) )
- Shuttling of Magnetization between nanomagnets
- Discussion and conclusion

# *Motivation*

Molecular manufacturing – a way to design materials on the nanometer scale



Encapsulated 4 nm Au particles self-assembled into a 2D array supported by a thin film, Anders *et al*., 1995




Scheme for molecular manufacturing

## *Basic characteristics*

**Materials properties:**

**Electrical – heteroconducting**

**Mechanical - heteroelastic**

**Electronic features:**

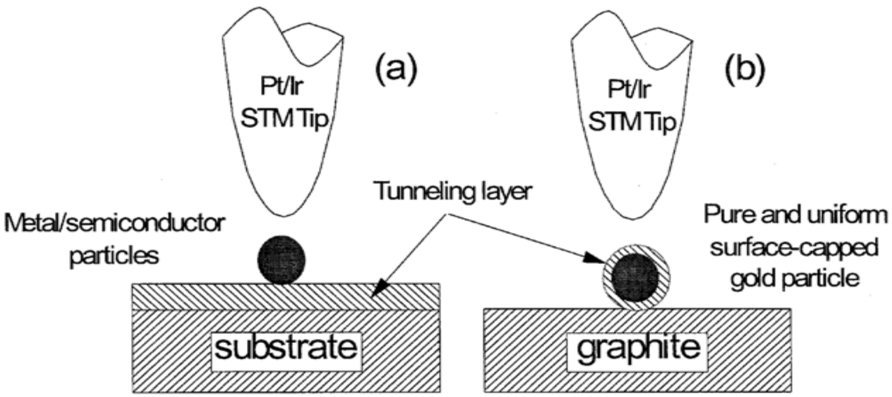
**Quantum coherence**

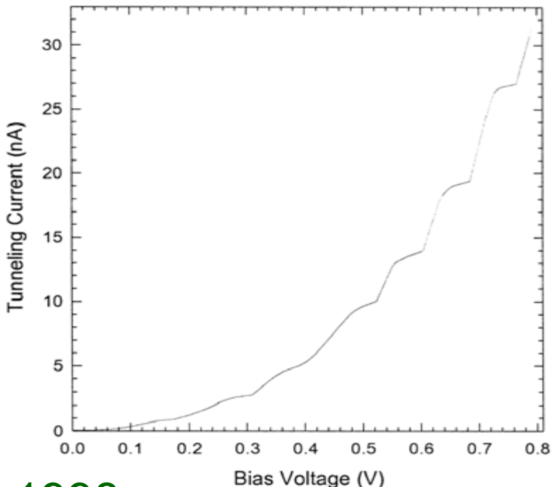
**Coulomb correlations**

**Electromechanical coupling**

$$\tau_{\mathrm{R}} = RC, \quad \omega_M \tau_R \approx 1, \quad \omega_M \approx 10^{11} - 10^{12}\ \mathrm{s}^{-1}$$

# *Tunneling through a metal-organic single-electron device (experiment)*



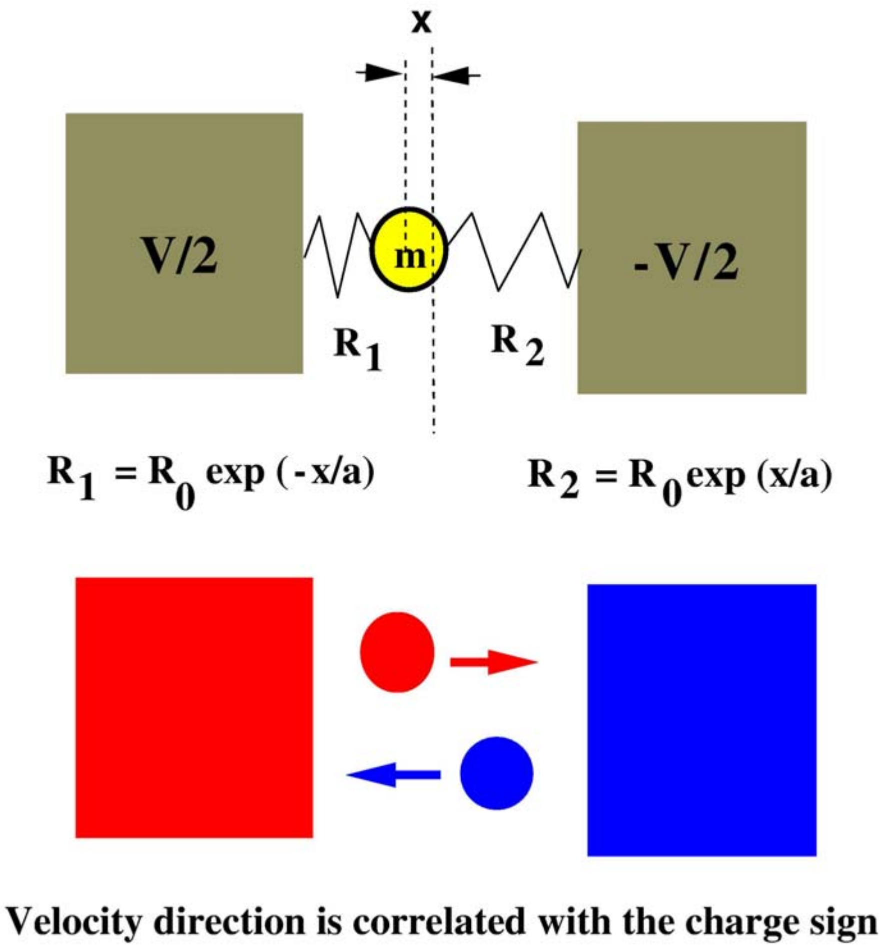




From Han et al., Chem. Phys. Lett. 1998

**<u>Specifics of Coulomb Blockade (CB) in molecularly coated dots:</u>**

- More emphasized (flat plateaus, sharp edges)
- More pronounced with bias increase
- In some cases – hysteretic I-V curves

# *Electro-mechanical instability*



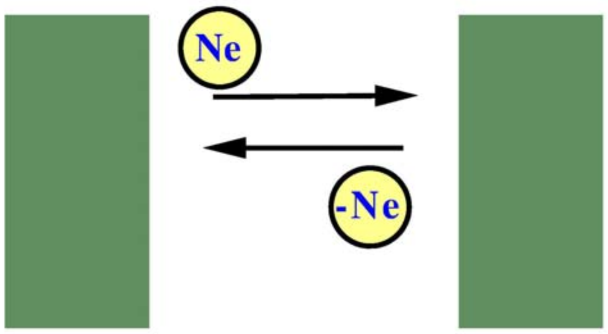

$$W = \frac{E}{T}\int_0^T dt\, Q(t)\,\dot{X}(t) > 0$$

If W exceeds the dissipated power an instability occurs

Gorelik et al., PRL 1998

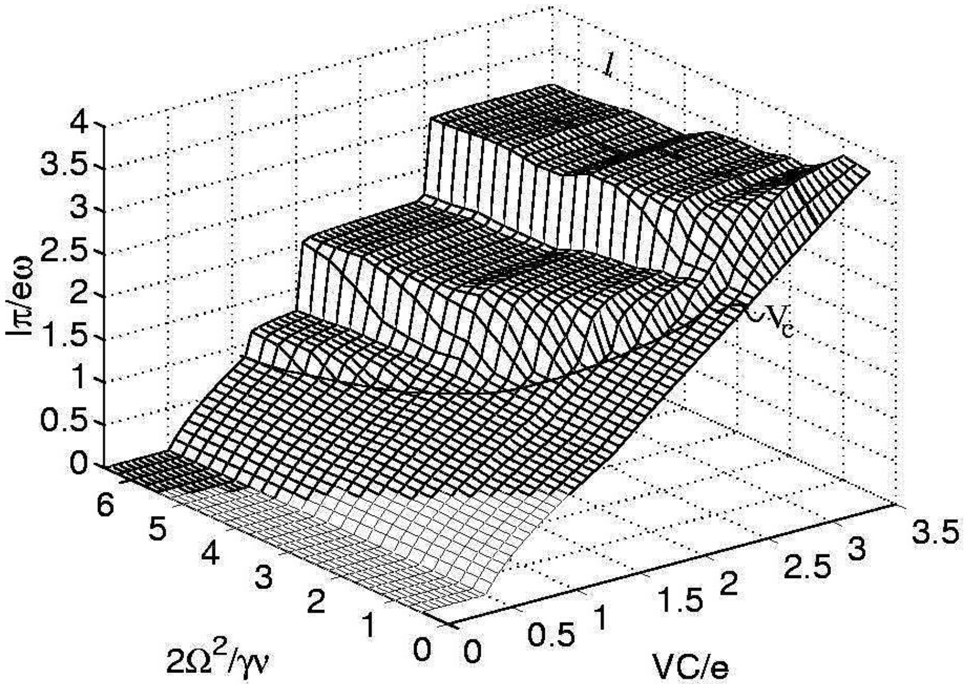
# *Shuttling of electronic charge*

Instability occurs at $V > V_c$ and develops into a limit cycle of dot vibrations. Both $V_c$ and vibrational amplitude are determined by dissipation.

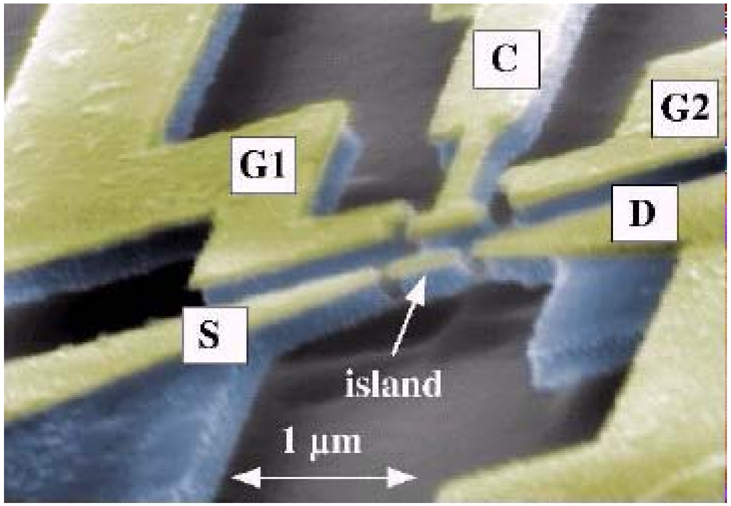



$$I = 2eN\omega$$

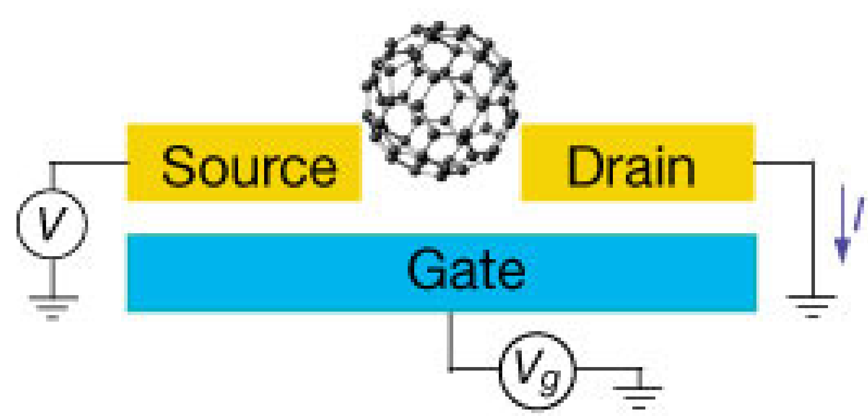
$$N = \mathrm{Int}\,[\frac{VC}{2e}]$$



Quantum ”bell” Single $\mathbf{C_{60}}$ Transistor




A. Erbe *et al*., PRL **87**, 96106 (2001)




H. Park *et al*., Nature **407**, 57 (2000)

*Conclusion*: Strong electroelastic effects imply that electrical and mechanical phenomena are coupled on the nanometer length scale – *new physics*!

*Here*: Nanoelectromechanics caused by or associated with single-charge tunneling effects

# *Electromechanical coupling*

Experiments:

• Artificial systems - mechanical oscillator, f=340 Hz, Tuominen *et al*., PRL 1999

• Tunneling through a vibrating $C_{60}$ molecule, f=1.2 THz, Park *et al*., Nature 2000

• Mechanical manufacturing of nanoshuttle, Erbe *et al.,* PRL 2001

Theory:

• Gate controlled shuttling, Nishiguchi, PRB 2001

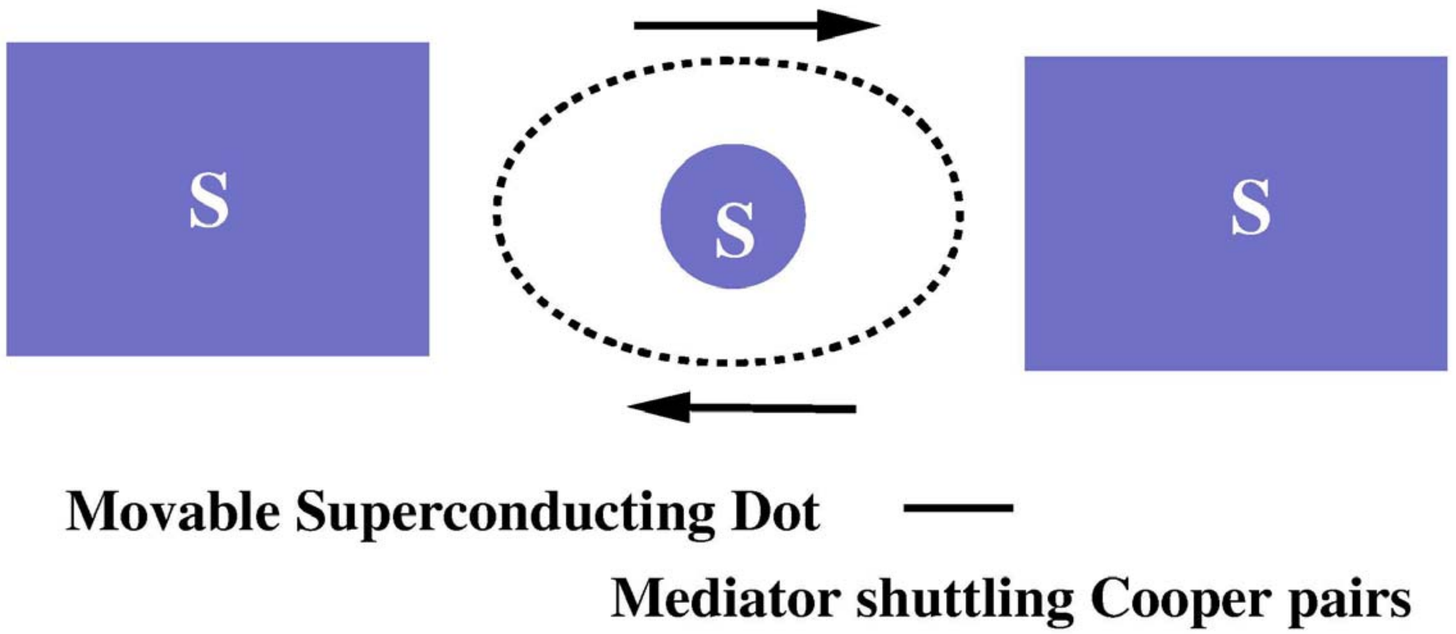
• Shuttle instability induced by a resonantly tunneling electron, Fedorets *et al*., Europhys. Lett. 2002

• Quantum shuttle, Armour *et al.,* PRB, 2002

• Shuttling of Cooper pairs by a movable single-Cooper- pair box, Gorelik et al., Nature 2001; Isacsson et al., PRL (in press)

*How does mechanics contribute to tunneling of Cooper pairs?*

Is it possible to maintain a mechanically-assisted supercurrent?

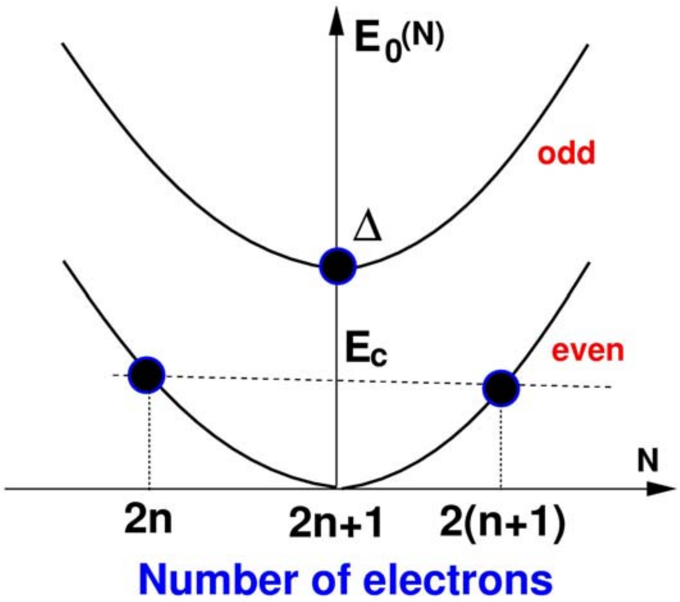


To preserve phase coherence only few degrees of freedom must be involved.

This can be achieved provided:

- No quasiparticles are produced $\rightarrow \hbar\omega << \Delta$
- Large fluctuations of the charge are suppressed by the Coulomb blockade: $\rightarrow E_J << E_C$

# *Coulomb Blockade of Cooper Pair Tunneling*



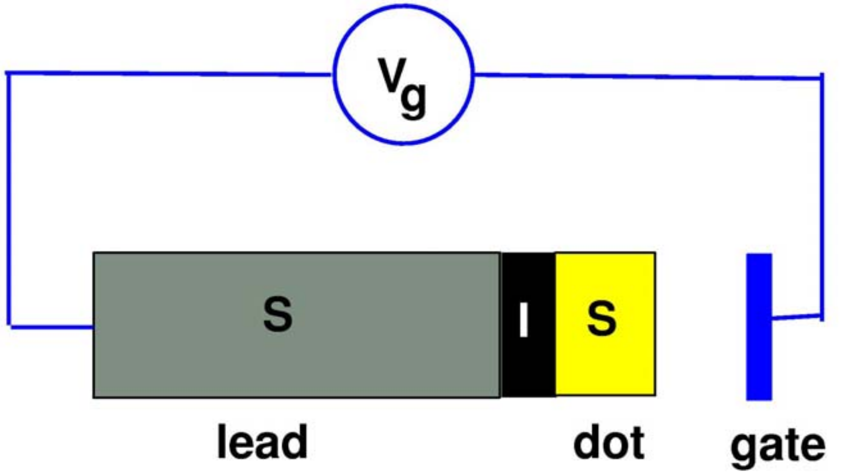

$$E_0(N) = E_c(N - \alpha V_g)^2 + \Delta_N$$

$$\Delta_N = \begin{cases} 0, & N = 2n \\ \Delta, & N = 2n+1 \end{cases}$$ Parity Effect

At $\alpha V_g = 2n+1$ Coulomb Blockade is lifted, and the ground state is degenerate with respect to addition of one extra Cooper Pair

$| \Psi \rangle = \gamma_1 | n \rangle + \gamma_2 | n+1 \rangle$ Single Cooper Pair Box

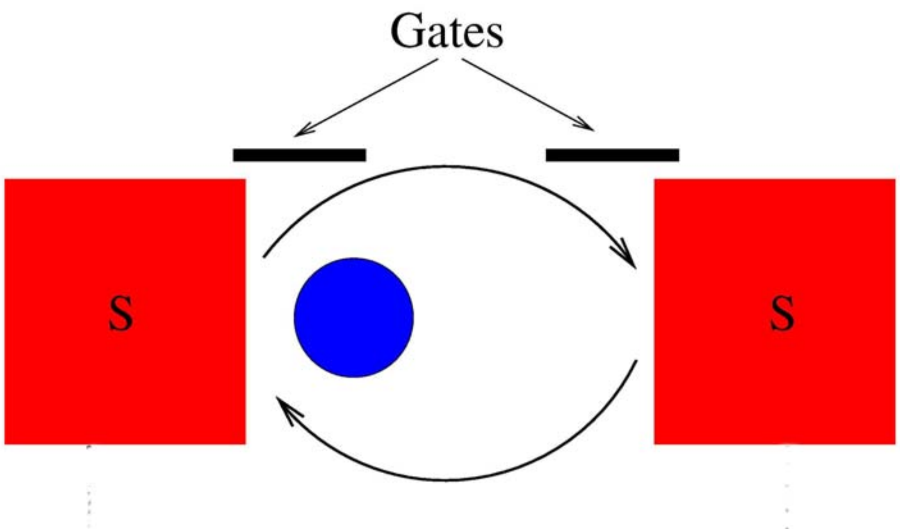
# *Single Cooper Pair Box*




Coherent superposition of two succeeding charge states can be created by choosing a proper gate voltage which lifts the Coulomb Blockade,

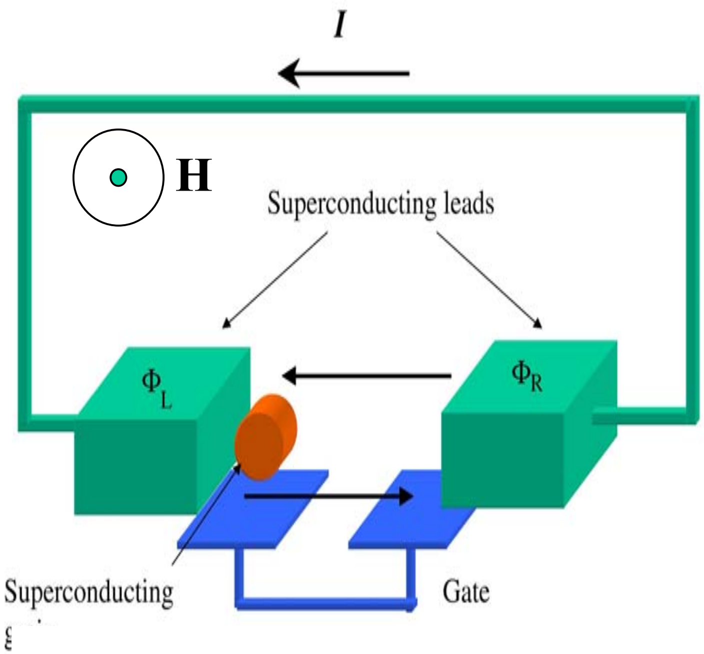
Nakamura et al., Nature 1999

# *Movable Single Cooper Pair Box*

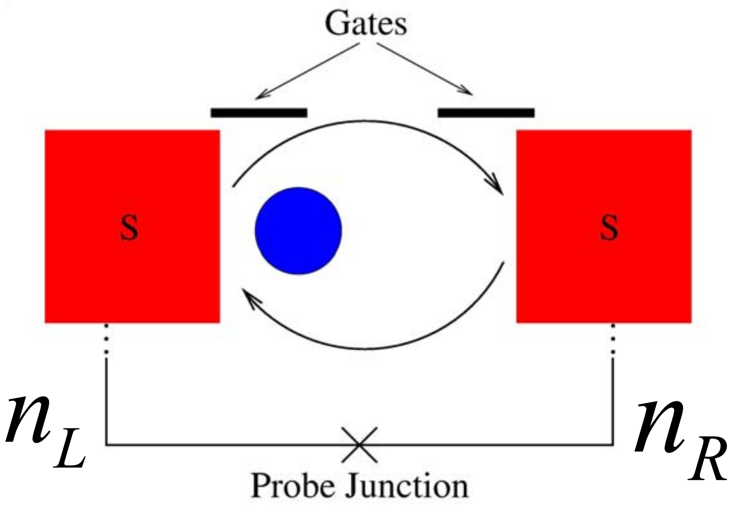



Josephson hybridization is produced at the trajectory turning points since near these points the CB is lifted by the gates.

# *Possible setup configurations*




Supercurrent between the leads kept at a fixed phase difference




Coherence between isolated remote leads created by a single Cooper pair shuttling

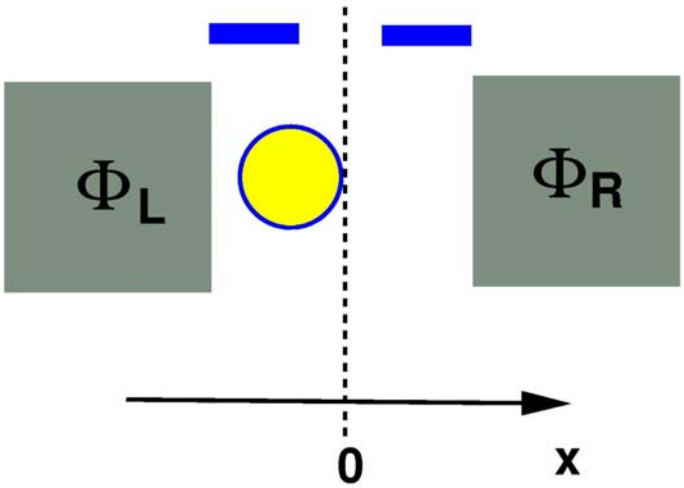
# *Shuttling between coupled superconductors*

$$H = H_C + H_J$$

$$H_C = \frac{e^2}{2C(x)}\left[2n + \frac{Q(x)}{e}\right]^2$$

$$H_J = -\sum_{s=L,R} E_J^s(x)\cos(\Phi_s - \hat{\Phi})$$

$$E_J^{L.R}(x) = E_0 \exp\left(\pm\frac{\delta x}{\lambda}\right)$$

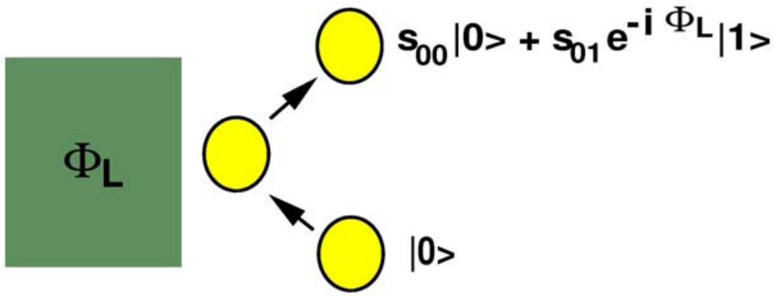


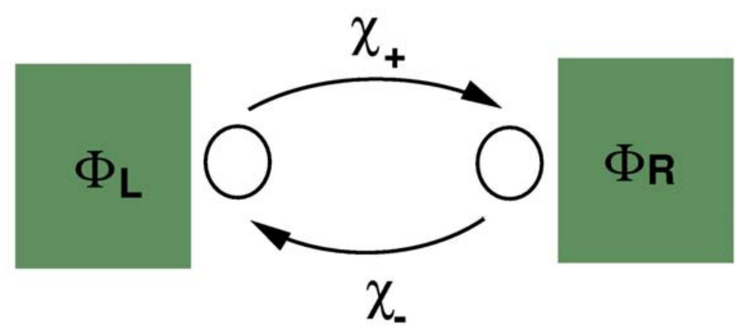

Dynamics: Louville-von Neumann equation

$$\frac{\partial \rho}{\partial t} = -i[H,\rho] - \nu[\rho - \rho_0(H)]$$

Relaxation suppresses the memory of initial conditions.

# *How does it work?*




Between the leads Coulomb degeneracy is lifted producing an additional "electrostatic" phase shift

$$\chi_\pm = \int dt\,[E_0(1) - E_0(0)]$$

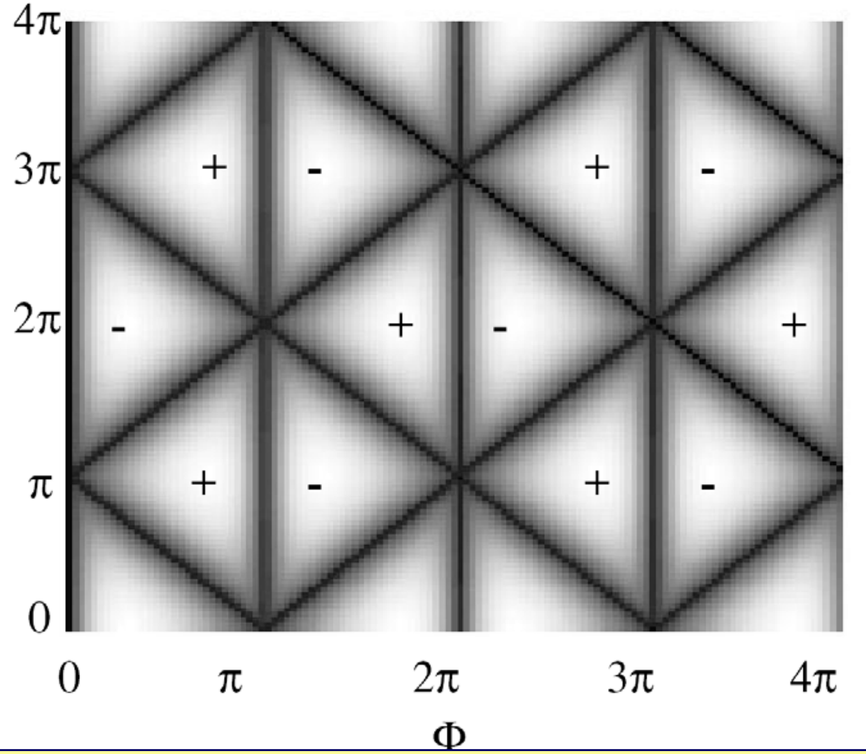
# Resulting expression for the current:

$$\frac{\bar{I}}{I_0} = \frac{\cos\vartheta \sin^3\vartheta \sin\Phi\,(\cos\chi + \cos\Phi)}{1 - (\cos^2\vartheta \cos\chi - \sin^2\vartheta \cos\Phi)^2}\,.$$

**Main features:**

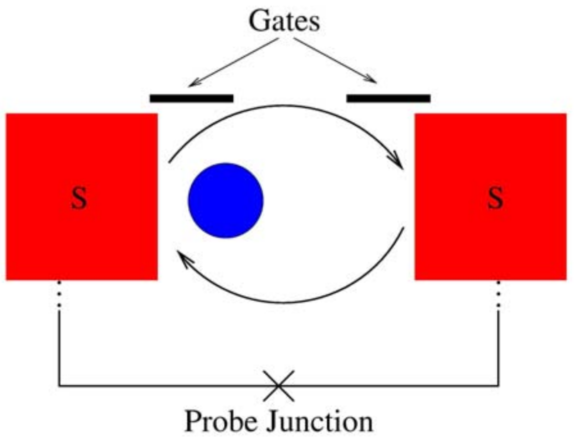
- The oscillating dependence of the dc current on the phase difference $\Phi_R - \Phi_L$ $\to$ the coherent states are controlled by the phase difference $\Phi$;
- If there is no phase difference, $\Phi_L = \Phi_R$, but the grain's trajectory is *asymmetric*, $\chi_+ \neq \chi_-$, the current still does not vanish.
- If the grain's trajectory embeds some magnetic flux created by external magnetic field with vector-potential $\mathbf{A}(\mathbf{r})$, an extra item $(2\pi/\Phi_0)\oint \mathbf{A}(\mathbf{r})\cdot d\mathbf{r}$ enters the expression for the phase difference $\Phi$ which must be gauge-invariant.

Average current in units $I_0 = 2ef$ as a function of electrostatic, $\chi$, and superconducting, $\Phi$, phases




Black regions – no current. The current direction is indicated by signs

# *Mechanically-assisted superconducting coupling*




The distribution function of the phase difference as a function of number of grain excursions is studied. It is defined through the states

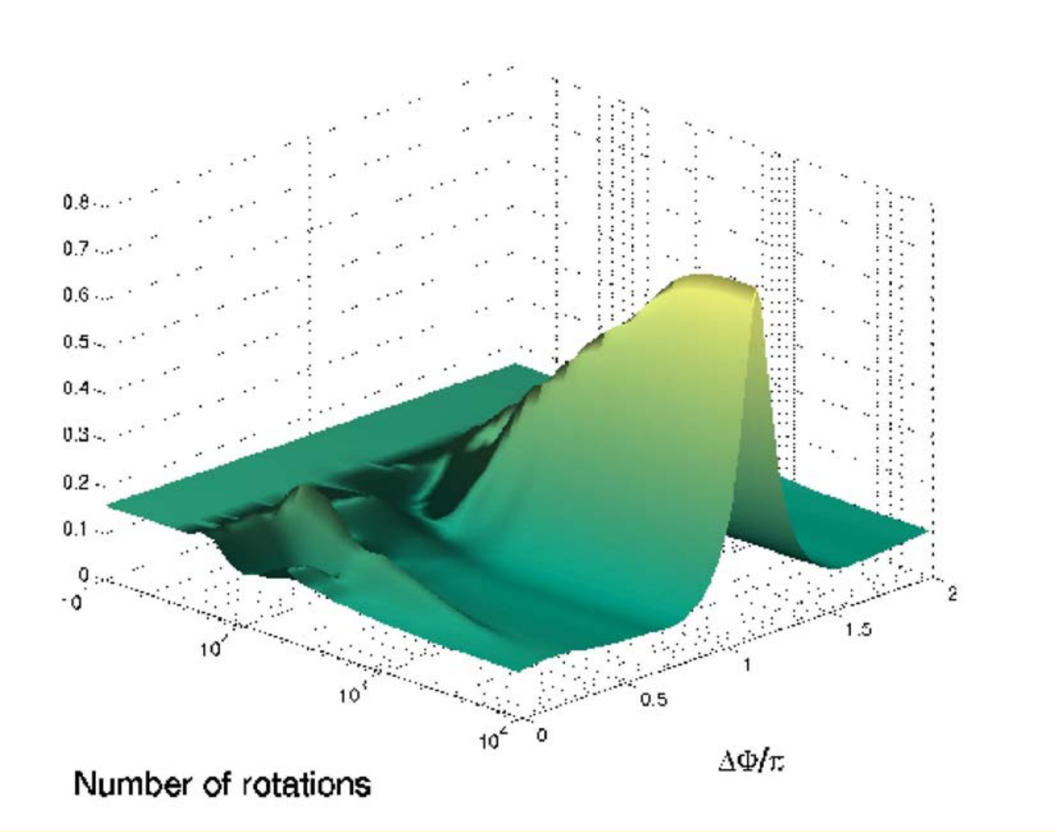
$$|\Phi,\phi\rangle = \frac{1}{2\pi}\sum_{n=0,1}\sum_{N_L=-N}^{N-n} e^{-iN_L\Phi}e^{-in\phi}\,|n\rangle\,|N_L\rangle\,|-N_L-n\rangle\ .$$

as the average

$$f(\Phi) \equiv \int_0^{2\pi} d\phi\ \langle\Phi,\phi|\,\rho\,|\Phi,\phi\rangle\ .$$

where $\rho$ is the density matrix.

# *Distribution of phase differences as a function of number of rotations. Suppression of quantum fluctuations of phase difference*



## *To avoid decoherence:*

- Electromagnetic perturbations should be screened
- Gates should be free from dynamic charged defects
- Single-electron tunneling should be suppressed

Estimates from below can be extracted from the experiment by Nakamura et al., Nature 2000:

$$\tau_{\phi} = 10^{-9} - 10^{-8}\ \mathrm{s}$$

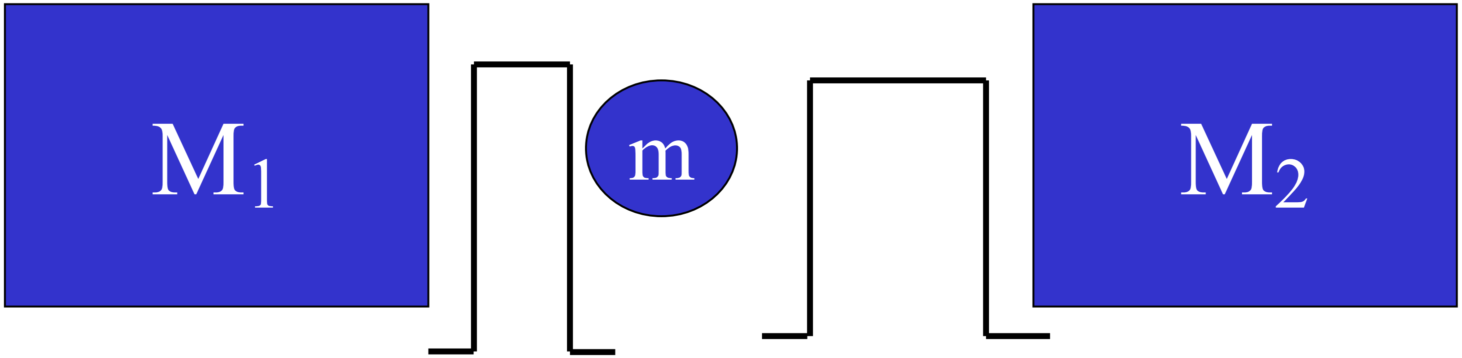
Recent experiments by Saclay group demonstrate even longer decoherence times,

D. Vion et al., cond-mat/0205343

$$\tau_{\varphi} \approx 10^{-6}\ s$$

# *What about shuttling magnetization?*

Is it possible to control the effective magnetic coupling between two magnets by means of a mediator nanomagnet?




By mechanically controlling the tunnel barriers and hence the exchange coupling between the magnetic moments $\mathbf{M}_{1,2}$ and **m** at the turning points the effective interaction between $\mathbf{M}_1$ and $\mathbf{M}_2$ can be made *ferromagnetic* or *antiferromagnetic*

# Conclusions

- Electronic and mechanical degrees of freedom of nanometer-scale structures can be coupled.
- Such a coupling may result in an electro-mechanical instability and “shuttling” of electric charge
- Phase coherence between remote superconductors can be supported by shuttling of Cooper pairs.
- Magnetization can be shuttled by a mediator nanomagnet to provide controllable FM or AFM coupling between cluster magnetic moments