The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

International Atomic Energy Agency

SMR 1760 - 3

COLLEGE ON

PHYSICS OF NANO-DEVICES

10 - 21 July 2006

Nanoelectromechanics of Magnetic and Superconducting Tunneling Devices

Presented by:

Robert Shekhter

Göteborg University, Sweden

*

Mechanically Assisted Single-Electronics

Robert Shekhter

Göteborg University, Sweden

Lecture 3

Nanoelectromechanics of Magnetic and Superconducting Tunneling Devices

Outline

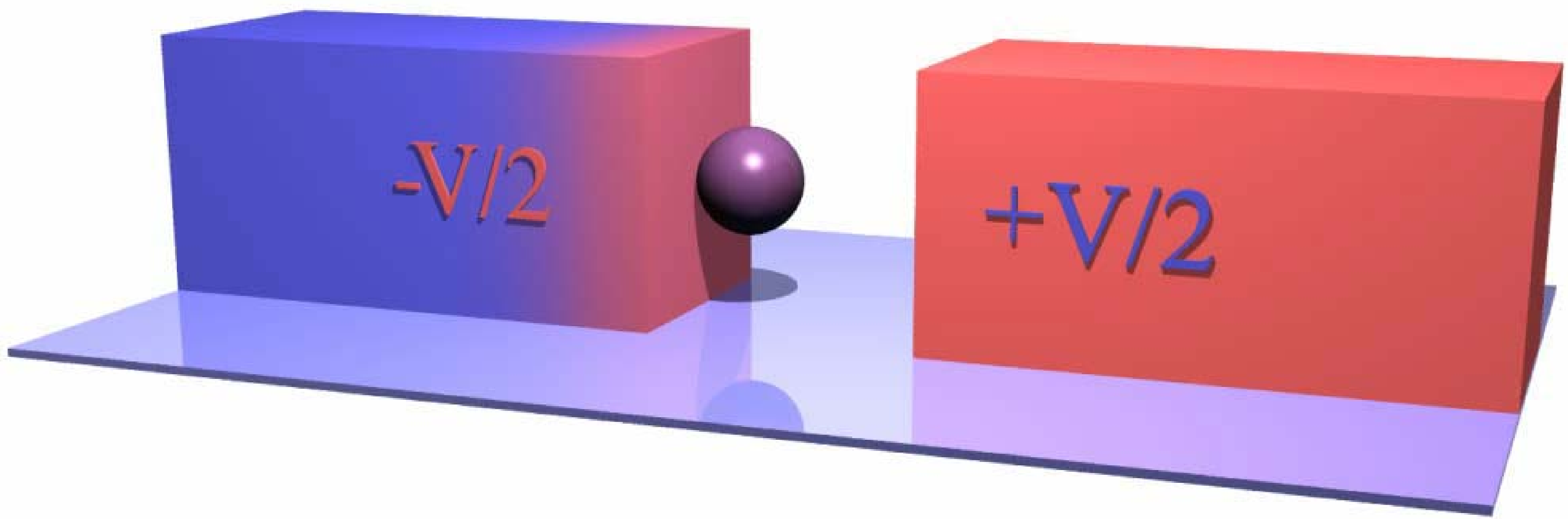
Nanoelectromechanics with spin-polarized electrons

- *Half-metals - magnetic conductors- materials with spin-polarized electrons*
- *Spintronics of a NEM-SET device*
- *Shuttling of a spin-polarized electrons*

Nanomechanically assisted superconductivity

- *Supercurrent due to shuttling of Cooper pairs*
- *Nanomechanically assisted Josephson coupling*

The Electronic Shuttle



Nanoelectromechanics with spin-polarized electrons

Nanoelectromechanics come from a coupling between electronic **charge** and mechanical degrees of freedom

What about electronic **spin**?

Could we have a spin-controlled nanoelectromechanics?

Spintronics of Nanomechanical Performance

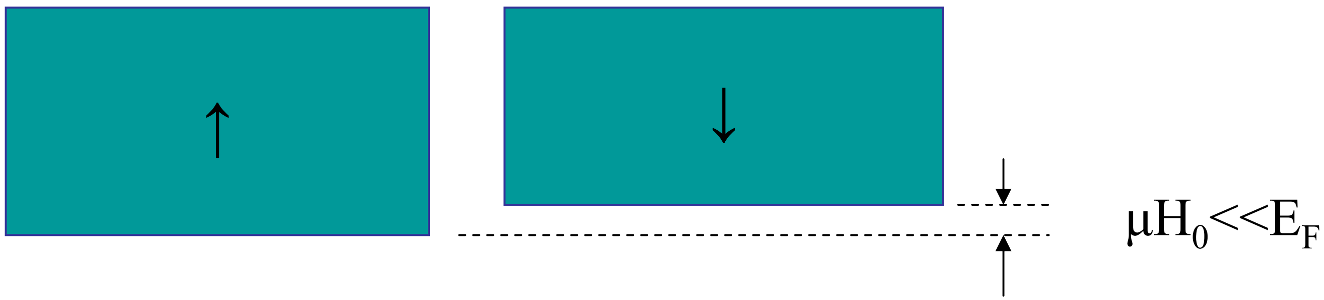
Electronic spin can be coupled to mechanical degrees of freedom

This is the case when tunneling electrons are spin-polarized

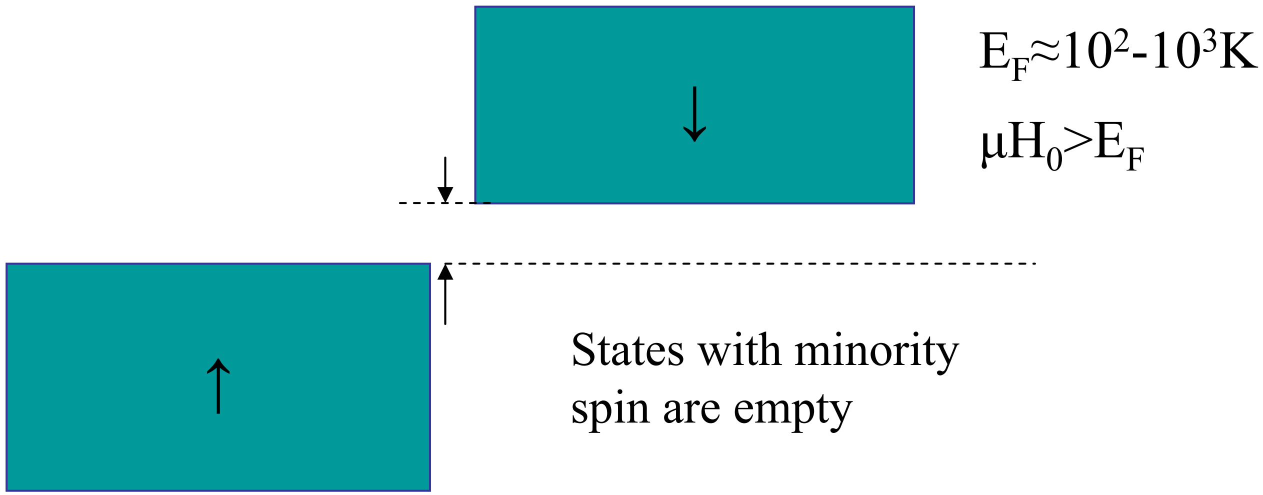
What is a spin polarization of the electronic states ?

Half-Metallic Conductors

Ferromagnetic Metal



Half-Metallic Conductors

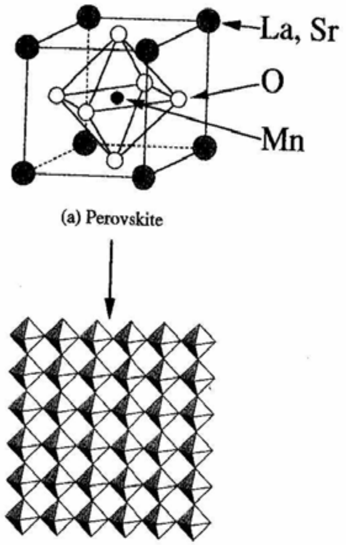


Metal – w.r.t. to majority spin electrons; Semiconductor w.r.t. minority spin electrons

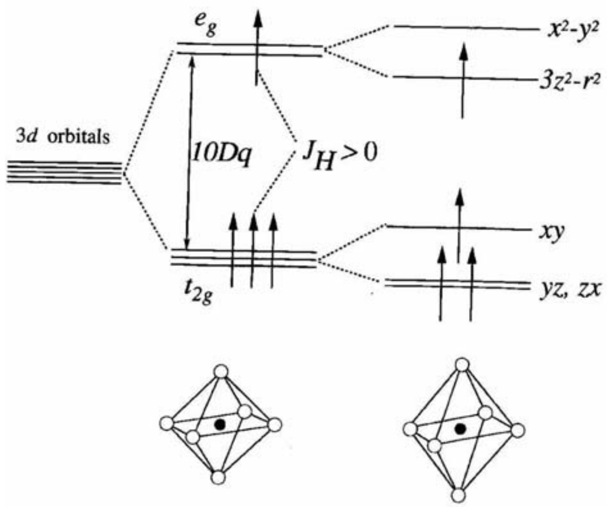
Perovskite Manganese Oxides

$RE_{1-x}AE_xMnO_3$

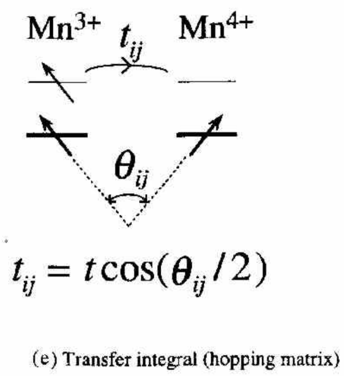
RE: trivalent rare earth element (La, Y, Cd, ...)
AE: divalent alkaline earth ions (Sr, Ba, Ca, Pb^{2+}, ...)



Ex: $La_{1-x}Pb_xMnO_3$



Ligand-field splitting of five-fold degenerate atomic 3d levels into lower t_{2g} (triply degenerate) and higher e_g (doubly degenerate) levels. Jahn-Teller distortion of MnO_6 further lifts each degeneracy

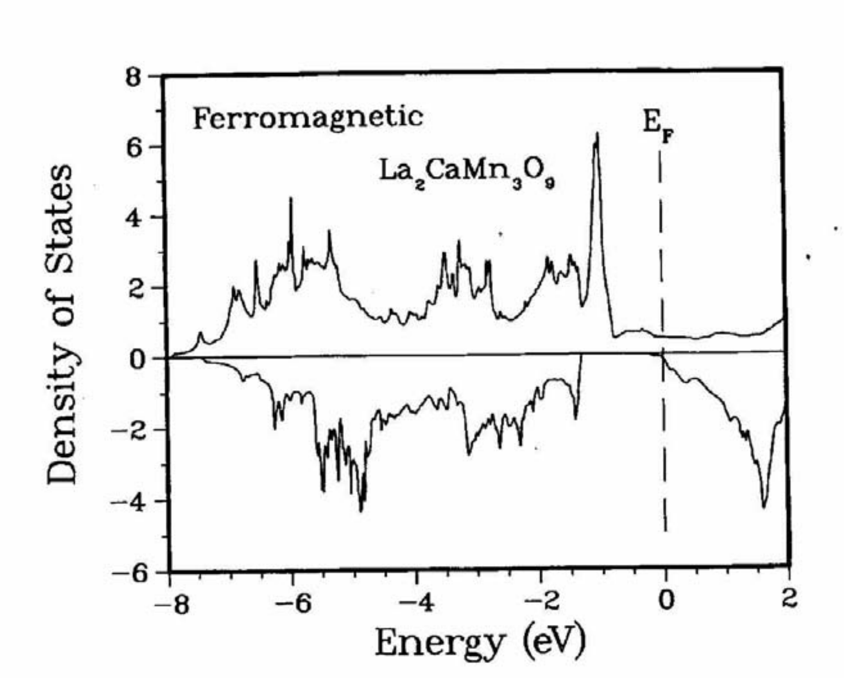


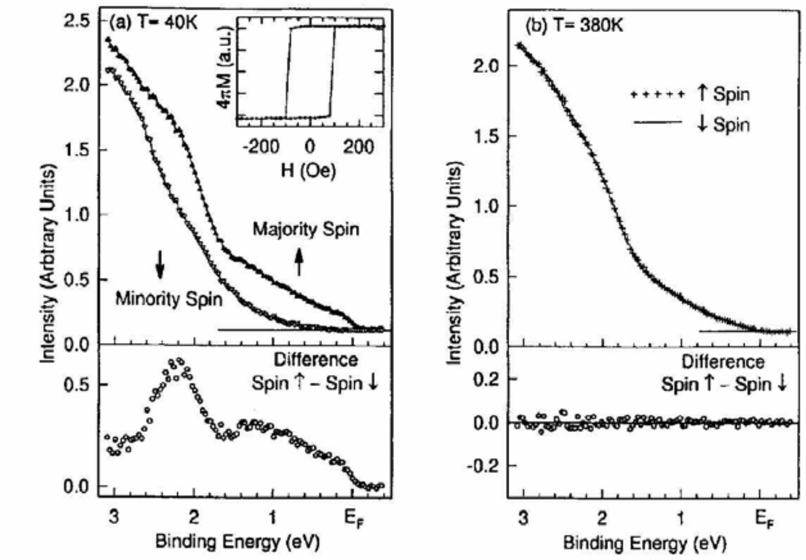
Double-exchange Interaction (Zenner)
P.W. Anderson and H. Hasegawa, PR **100**, 67 (1955).

e_g – itinerant electrons; t_{2g} – localized electrons

Strong exchange coupling: $J_H \approx$ 2-3 eV >> E_F

Half-Metallic Electronic Structure of Manganites

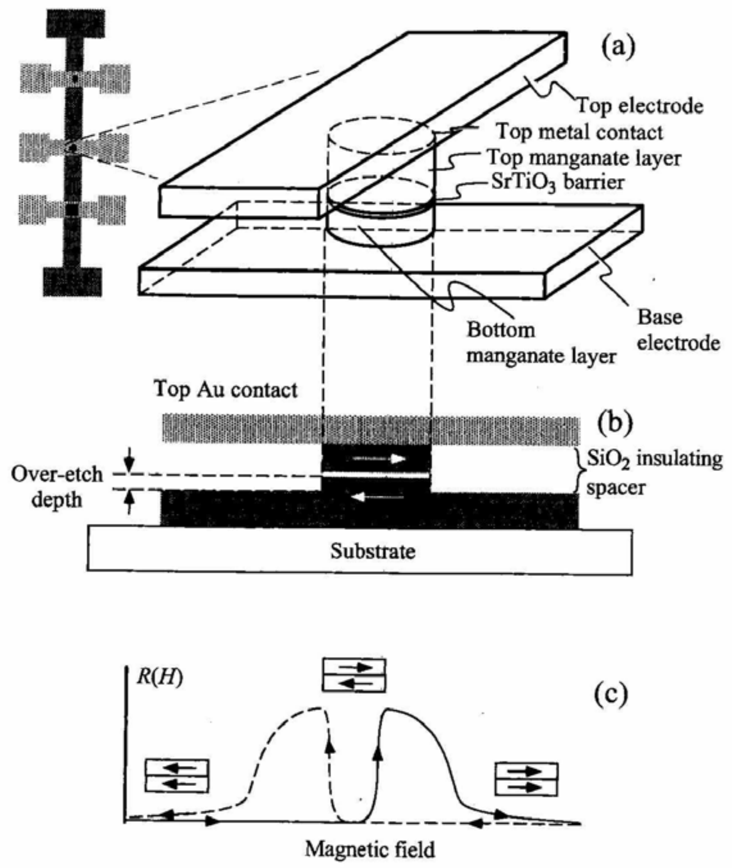




Density of states (in states per Mn per eV) for feromagnetic $La_{2/3}Ca_{1/3}MnO_3$. Majority spin Is shown as positive and minority spin as negative, and E_F=0.

Spin-resolved photoemission spectra of a thin film of $La_{0.7}Sr_{0.3}MnO_3$ (T_c ~ 350 K) near E_F at (left) 40 K and (right) 380 K. The majority and minority spin directions are defined with respect to the magnetization direction. The bottom panels show the difference between the majority and minority spin spectra. The inset shows the M(H) hysteresis loop for the film.

Spin Dependent Tunneling Between Manganites



Schematic view of the LSMO-barrier-LSMO Trilayer thin film junction structure. (a) top view (b) Side view (c) junction resistance as a function of sweeping magnetic field

J.Z. Sun *et al*. Appl. Phys. Lett. **69**, 3266 (1966); *ibid*. **70**, 1769 (1997).

Y. Lu *et al*. Phys. Rev. **54**, R8357 (1996).

$$H_{eff} \approx 0.5kOe$$

$$d \approx 1-10nm$$

$H_{\rm eff}$ – coercitivity, which depends on:

- *Shape of the contact*
- *Stress of the contact area*
- *Multidomain structure of the leads*

Possible Experimental Realization

Small-size magnetic tunnel junctions with resonant impurity states in the barrier

Resonant tunneling of spin-polarized electrons was detected in nanocontacts (d ~80nm) Ni-NiO-Co at T~1.6 – 4.2 K
(E.Y.Tsymbal et al. PRL, **90,** 186602-1 (2003))

Spin-dependent tunneling through 2D quantum dots

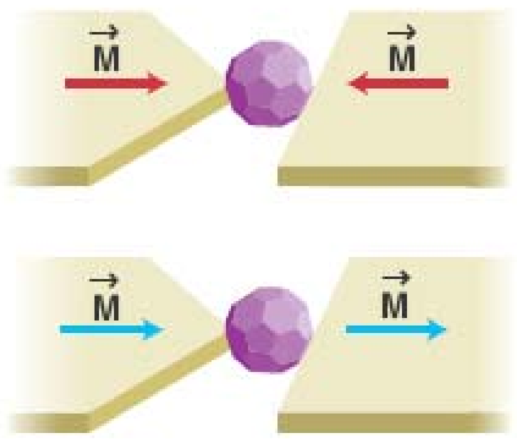
Was observed in a number of experiments:
(See f.e. M. Ciorga et al. PRB **61**, R16315, (2000))

New Mechanism for Low-Field Magnetoresistance

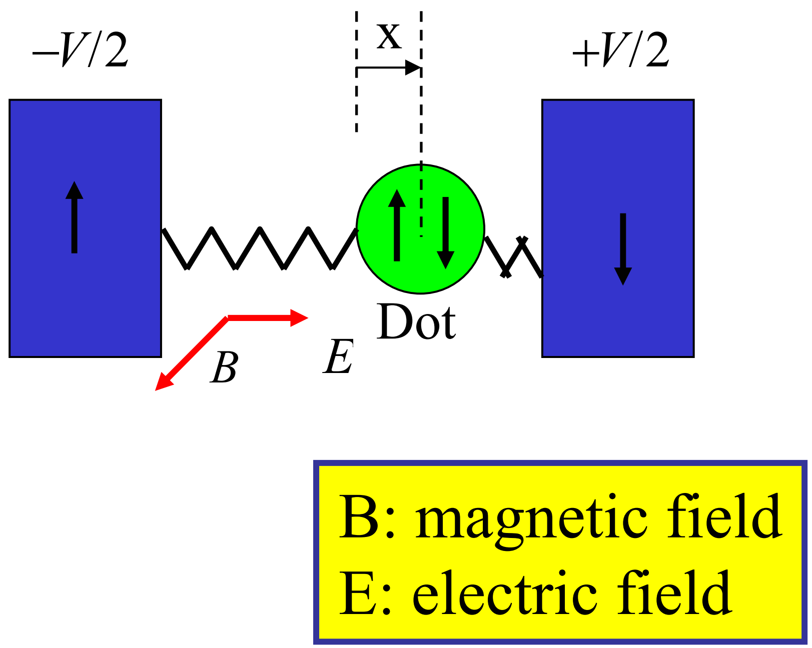
In order to get higher magnetosensitivity one may manipulate (by a magnet field) the *spin* of the tunneling electron rather than the orientation of magnetization in the leads.

A mesoscopic tunnel junction with shuttling of electrons is an example of a system where such a manipulation can naturally be arranged

Magnetic NEM-SET



A. Pasupathy et al., Science **306**,86 (2004)



Formulation of the Problem

$$H = H_{Leads} + H_T + H_{Dot} + H_{bath} + H_{bath-osc}$$

$$H_{Leads} = \sum_{\alpha,k} \varepsilon_{\alpha k} a^{+}_{\alpha k} a_{\alpha k}, \quad H_T = \sum_{\alpha,k} T_\alpha(x)\left[a^{+}_{\alpha k} c_\alpha + c^{+}_\alpha a_{\alpha k}\right]$$

$$H_{Dot} = (\varepsilon_0 - xd)\left[c^{+}_\uparrow c_\uparrow + c^{+}_\downarrow c_\downarrow\right] + U c^{+}_\uparrow c_\uparrow c^{+}_\downarrow c_\downarrow - \frac{h}{2}\left[c^{+}_\uparrow c_\downarrow + c^{+}_\downarrow c_\uparrow\right] +$$

$$\frac{1}{2}\left[p^2 + x^2\right]$$

Density Matrix for the "Spin-polarized" Shuttle

Four basic vectors for the electronic space

$$|0\rangle \quad |\uparrow\rangle \equiv c_{\uparrow}^{+}|0\rangle \quad |\downarrow\rangle \equiv c_{\downarrow}^{+}|0\rangle \quad |2\rangle \equiv c_{\downarrow}^{+}c_{\uparrow}^{+}|0\rangle$$

Density matrix

$$\hat{\rho}_0 = \langle 0|\hat{\rho}|0\rangle$$

$$\hat{\rho}_2 = \langle 2|\hat{\rho}|2\rangle$$

$$\hat{\rho}_1 = \begin{Bmatrix} \hat{\rho}_{\uparrow} & \hat{\rho}_{\uparrow\downarrow} \\ \hat{\rho}_{\downarrow\uparrow} & \hat{\rho}_{\downarrow} \end{Bmatrix}$$

$$\hat{\rho}_{\uparrow} = \langle \uparrow|\hat{\rho}|\uparrow\rangle$$

$$\hat{\rho}_{\uparrow\downarrow} = \langle \uparrow|\hat{\rho}|\downarrow\rangle$$

Spin-vibrational Dynamics

$$\partial_t \hat{\rho}_0 = -i[H_v + eE\hat{x}, \hat{\rho}_0] - \frac{1}{2}\{\Gamma_L(\hat{x}), \hat{\rho}_0\} + \sqrt{\Gamma_R(\hat{x})}\hat{\rho}_1\sqrt{\Gamma_R(\hat{x})} + \Lambda_\gamma \hat{\rho}_0$$

$$\partial_t \hat{\rho}_2 = -i[H_v - eE\hat{x}, \hat{\rho}_2] - \frac{1}{2}\{\Gamma_L(\hat{x}), \hat{\rho}_2\} + \sqrt{\Gamma_L(\hat{x})}\hat{\rho}_\downarrow\sqrt{\Gamma_L(\hat{x})} + \Lambda_\gamma \hat{\rho}_2$$

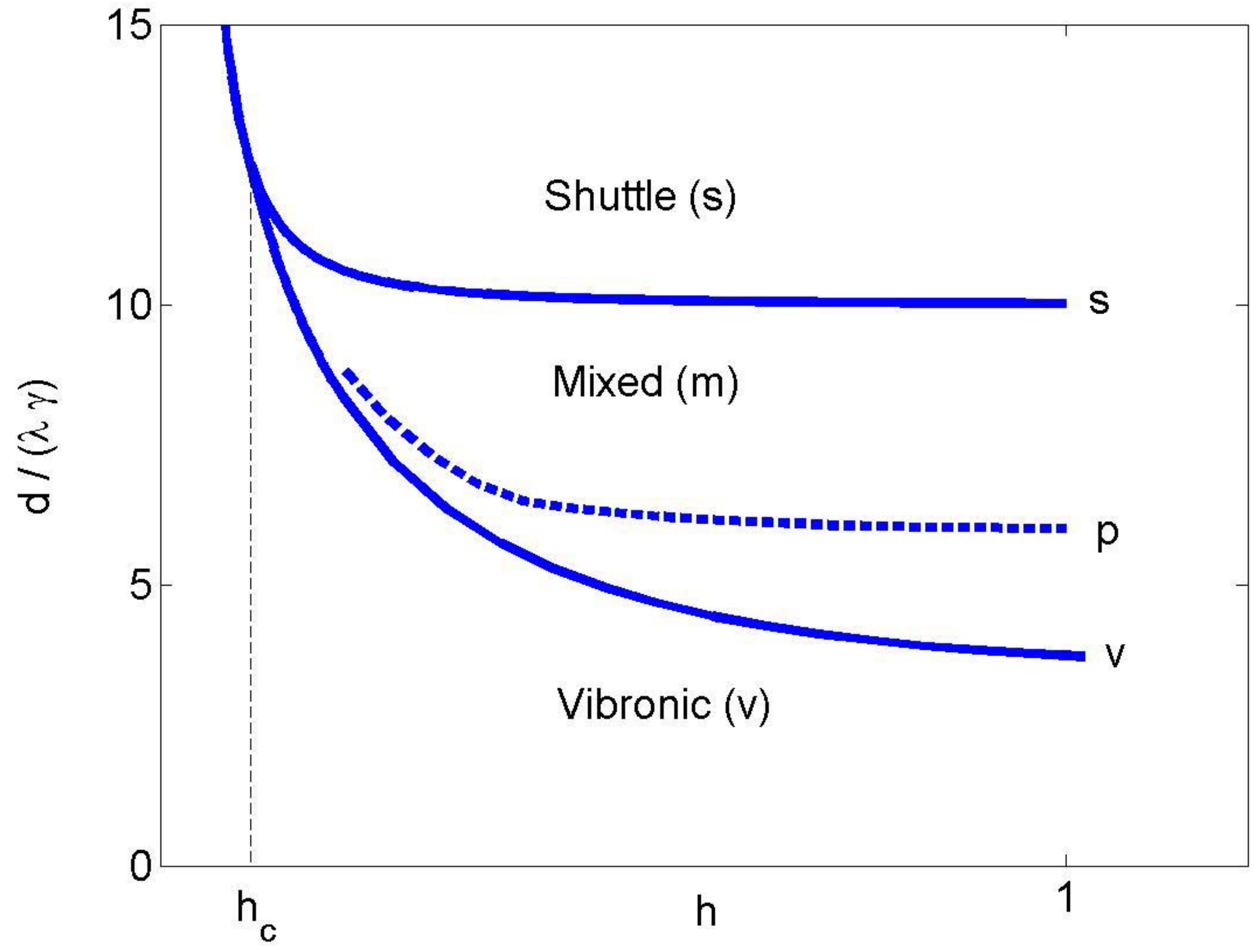
$$\partial_t \hat{\rho}_\downarrow = -i[H_v, \hat{\rho}_\downarrow] + ih(\hat{\rho}_{\uparrow\downarrow} - \hat{\rho}_{\downarrow\uparrow}) - \frac{1}{2}\{\Gamma_+(\hat{x}), \hat{\rho}_\downarrow\} + \Lambda_\gamma \hat{\rho}_\downarrow$$

$$\partial_t \hat{\rho}_\uparrow = -i[H_v, \hat{\rho}_\uparrow] - ih(\hat{\rho}_{\uparrow\downarrow} - \hat{\rho}_{\downarrow\uparrow}) + \sqrt{\Gamma_L(\hat{x})}\hat{\rho}_0\sqrt{\Gamma_L(\hat{x})} + \sqrt{\Gamma_R(\hat{x})}\hat{\rho}_2\sqrt{\Gamma_R(\hat{x})} + \Lambda_\gamma \hat{\rho}_\downarrow$$

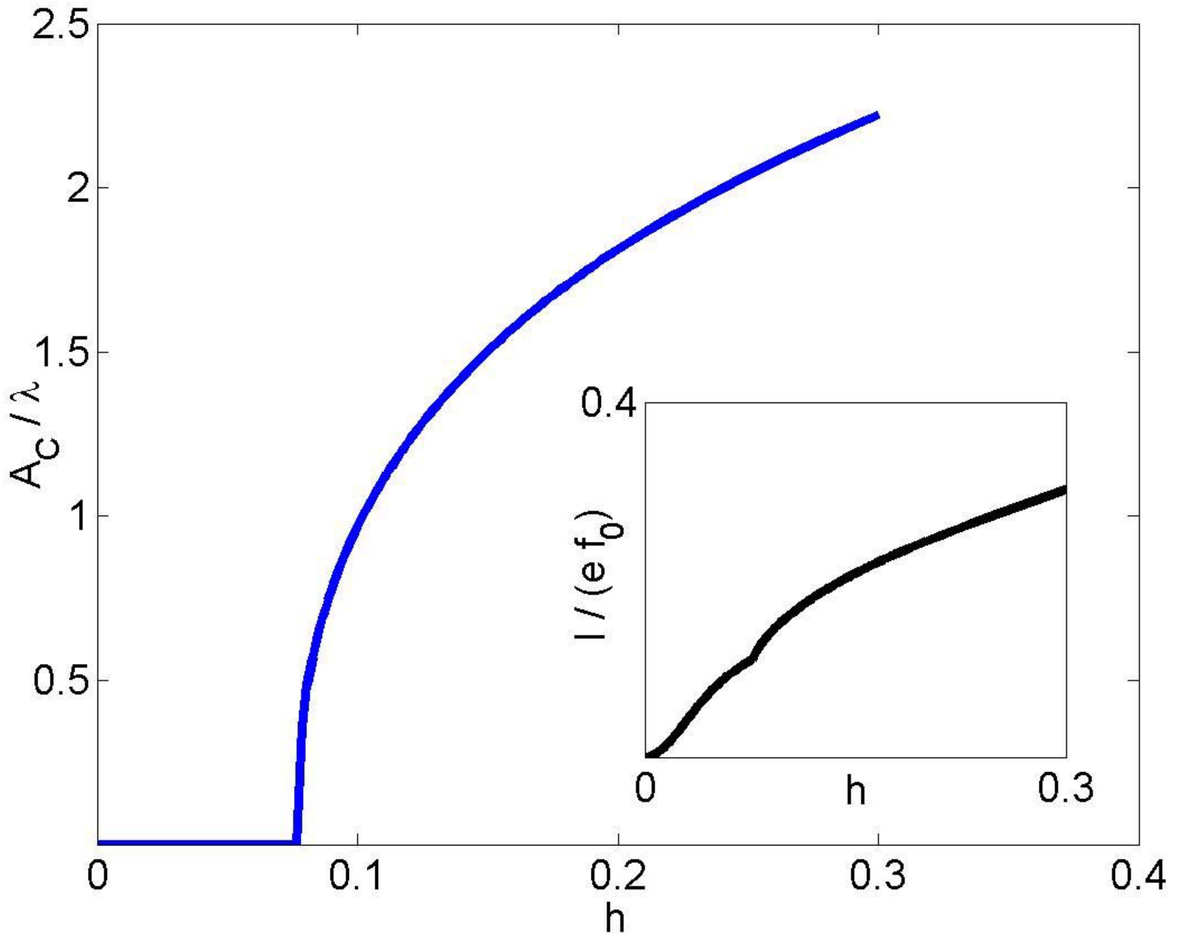
$$\partial_t \hat{\rho}_{\downarrow\uparrow} = -i[H_v, \hat{\rho}_{\downarrow\uparrow}] - ih(\hat{\rho}_\downarrow - \hat{\rho}_\uparrow) - \frac{1}{2}\Gamma_+(\hat{x})\rho_{\downarrow\uparrow} + \Lambda_\gamma \hat{\rho}_{\downarrow\uparrow}$$

$$\partial_t \hat{\rho}_{\uparrow\downarrow} = -i[H_v, \hat{\rho}_{\uparrow\downarrow}] + ih(\hat{\rho}_\downarrow - \hat{\rho}_\uparrow) - \frac{1}{2}\Gamma_+(\hat{x})\hat{\rho}_{\uparrow\downarrow} + \Lambda_\gamma \hat{\rho}_{\uparrow\downarrow}$$

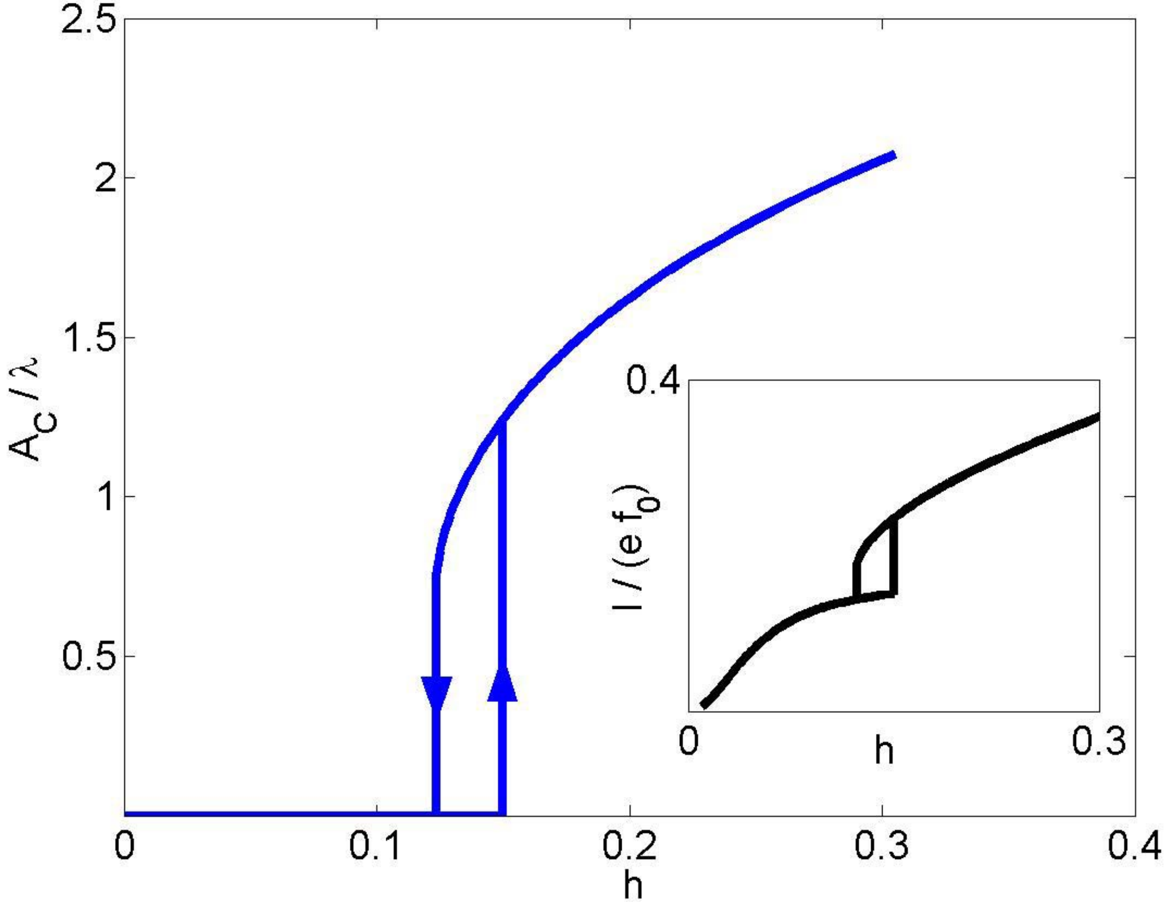
”Phase diagram” of Shuttle Vibrations



”Soft” Onset of Shuttle Vibrations



”Hard” Onset of Shuttle Vibrations



Conclusion

Magnetic Field Controlled Nanomechanics:

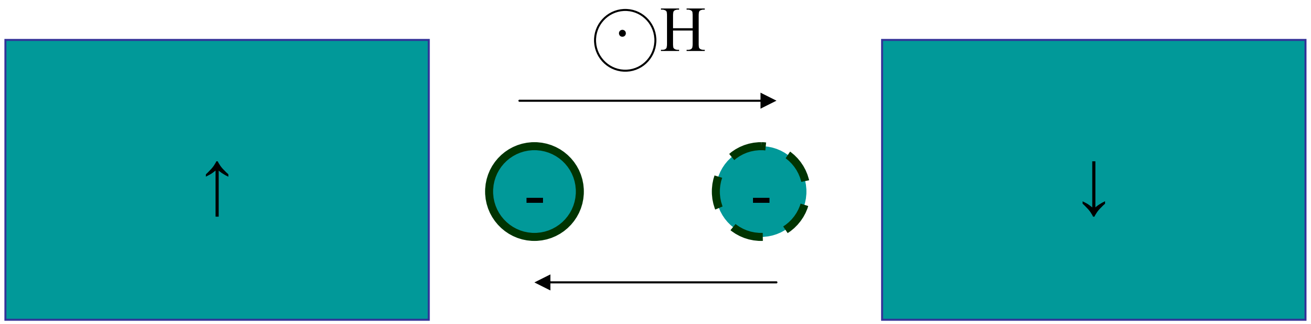
Nanomechanical instability and different stable regimes of the spintronic NEM-SET operation can be achieved depending on magnitude of external magnetic field.

What about mechanically assisted magnetotransport?

Shuttling of spin-polarized electrons

Shuttling of Spin-Polarized Electrons

Mechanism: Quantum transmission of electrons through single energy level on vibrating dot



ω; $\Omega = \mu H/\hbar$

The quantum evolution can be viewed as a sequence of two alternating events:

(i) Tunneling: Transfer of electron between left or right lead and dot (time for tunneling $\tau \approx \pi/\omega$)

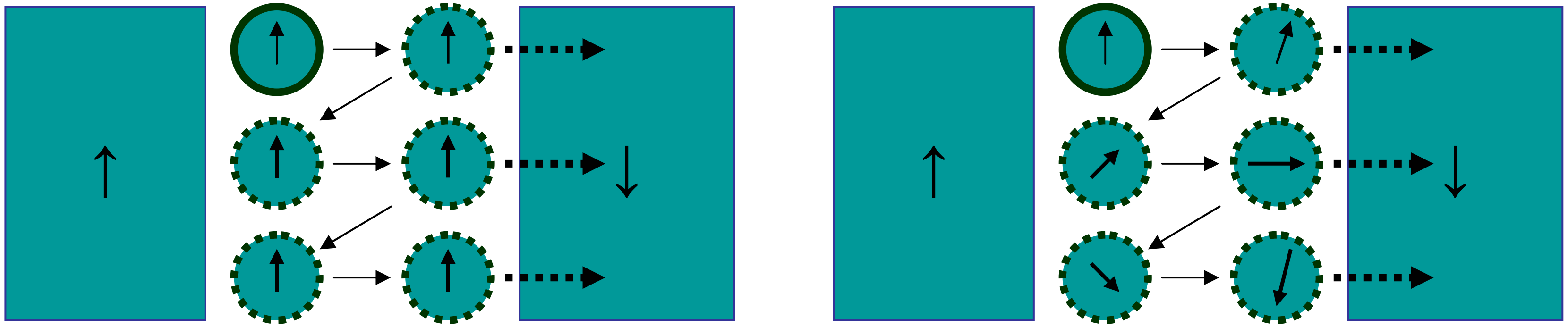
(i) Free evolution: On-site electronic state is disconnected from the leads. In this stage the spin of the electron precesses in the external magnetic field H.

Natural scale for H: $\Delta H \approx \hbar\omega/\mu$; $(\Omega/\omega = 1/2)$. ***But this is not the only scale here!***

L.Y.Gorelik et al., Phys.Rev.,**B71**, 35327 (2005)

Mechanical Transmission of Spin-polarized Electrons

$t_n^R = (2n+1)\pi/\omega; \quad t_n^L = 2n\pi/\omega; \quad n_{eff} \approx \omega/\Gamma$



$\Omega\, t(n_{eff}) \ll 1 \; (\delta H \leq (\hbar\omega/\mu)(1/n_{eff})$

$\Omega\, t(n_{eff}) \gg 1$

Spin polarization

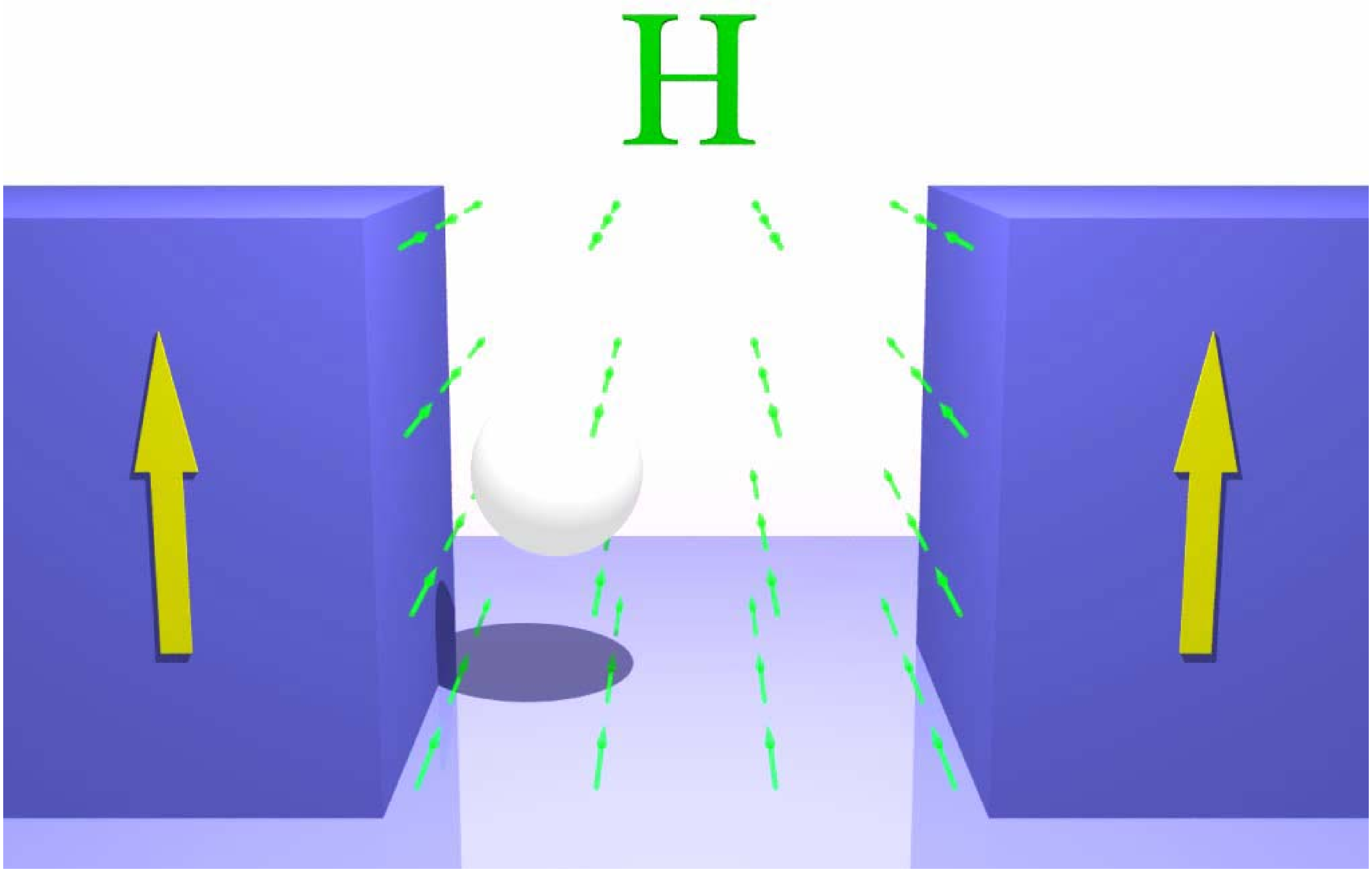
Spin equilibrization

Two scales for magnetic field

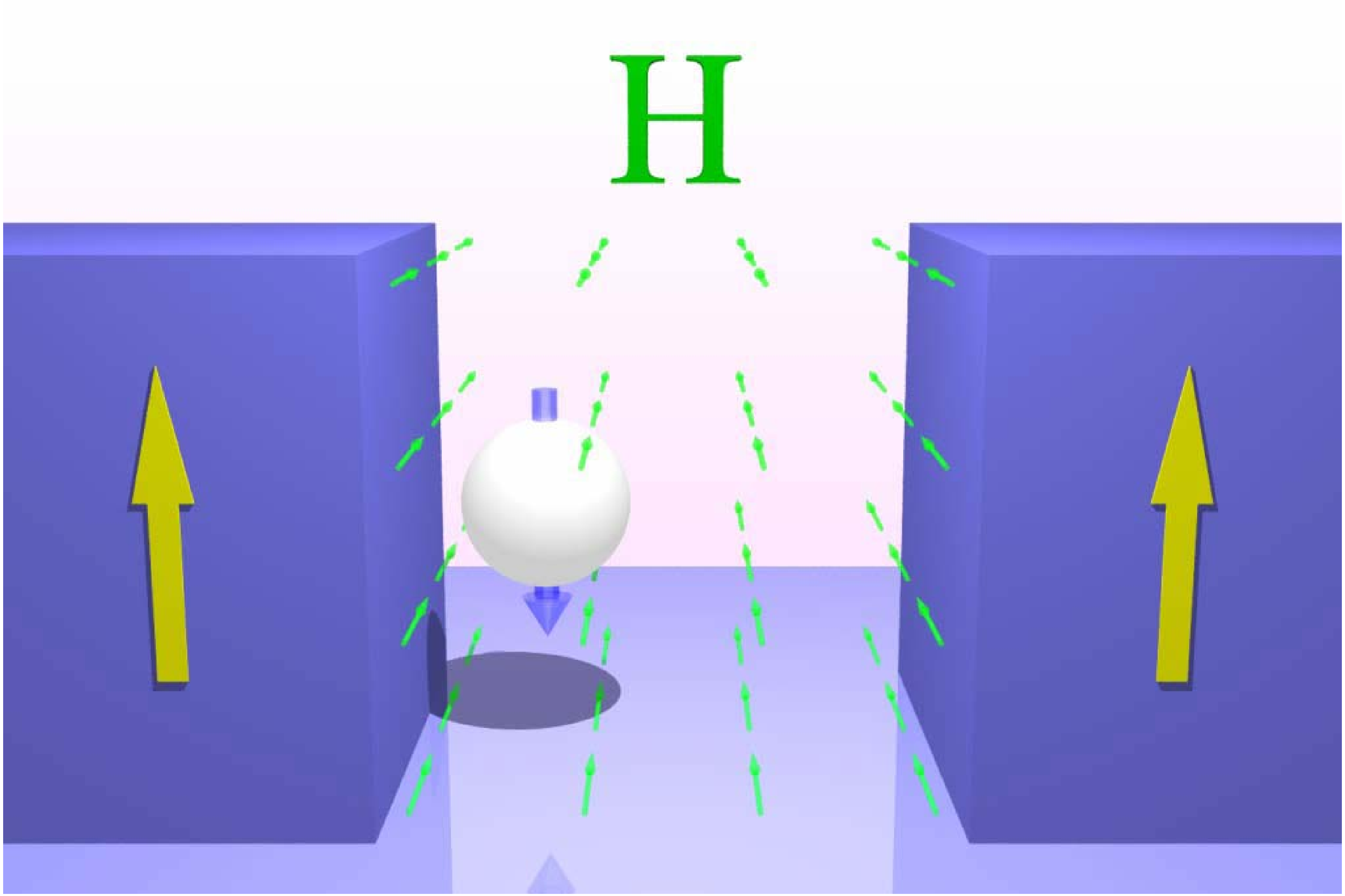
$\delta H \propto \Gamma / \mu$

$\Delta H \propto \hbar\omega / \mu$

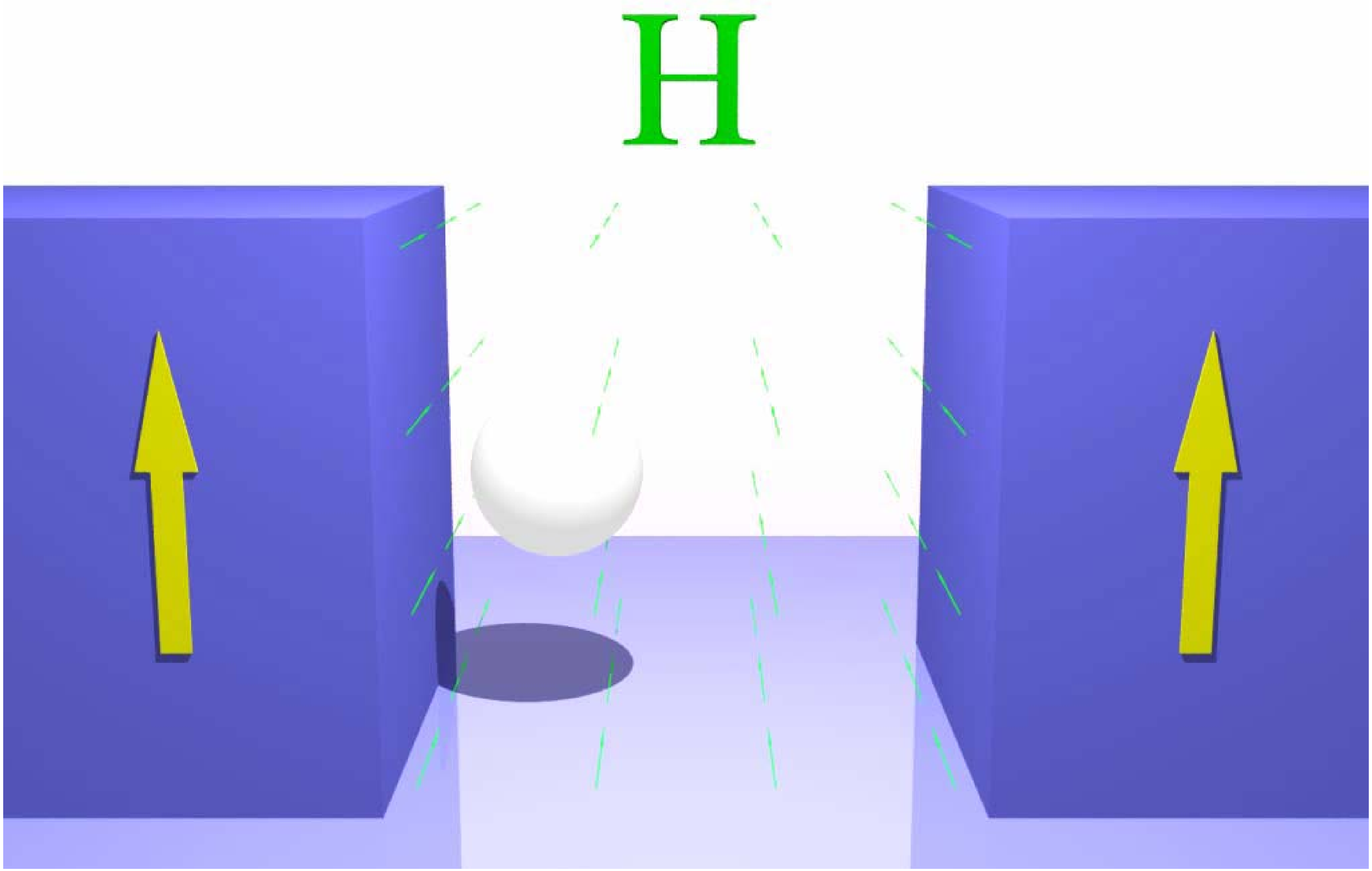
Spin-dependent Shuttling



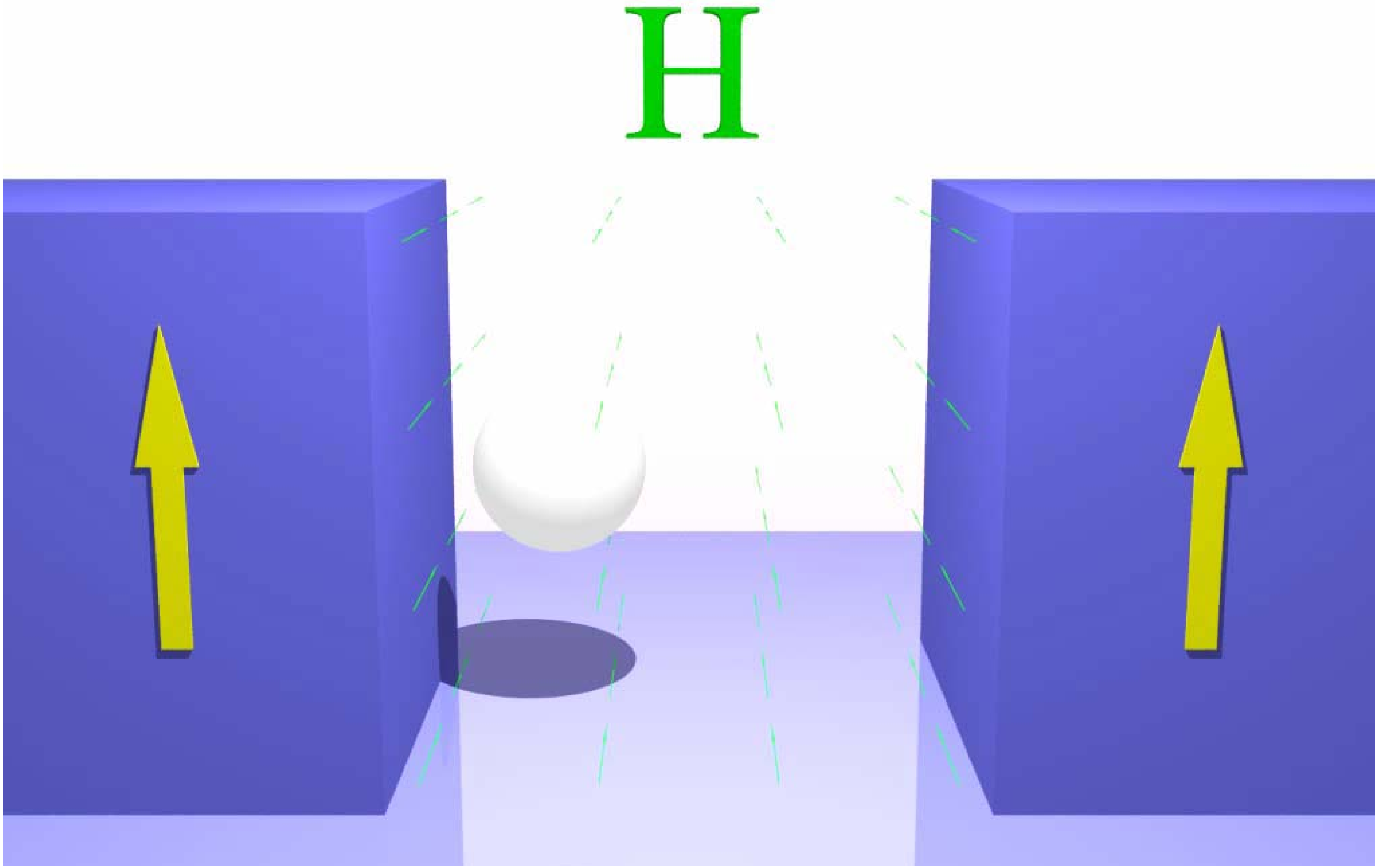
Spin-dependent Shuttling



Spin-dependent Shuttling



Spin-dependent Shuttling



Spin Dynamics of Tunneling Electron

$$\partial_t \rho_0 = -\Gamma_L(x)\rho_0 + \Gamma_R(x)\rho_\downarrow$$

$$\partial_t \rho_2 = \Gamma_L(x)\rho_2 + \Gamma_L(x)\hat{\rho}_\downarrow$$

$$\partial_t \rho_\downarrow = ih(\rho_{\uparrow\downarrow} - \rho_{\downarrow\uparrow}) - \Gamma_+(x)\rho_\downarrow$$

$$\partial_t \rho_\uparrow = -ih(\rho_{\uparrow\downarrow} - \rho_{\downarrow\uparrow}) + \Gamma_L(x)\rho_0 + \Gamma_R(x)\rho_2$$

$$\partial_t \rho_{\downarrow\uparrow} = -ih(\rho_\downarrow - \rho_\uparrow) - \frac{1}{2}\Gamma_+(x)\rho_{\downarrow\uparrow}$$

$$\partial_t \rho_{\uparrow\downarrow} = ih(\rho_\downarrow - \rho_\uparrow) - \frac{1}{2}\Gamma_+(x)\rho_{\uparrow\downarrow}$$

Electrical Current

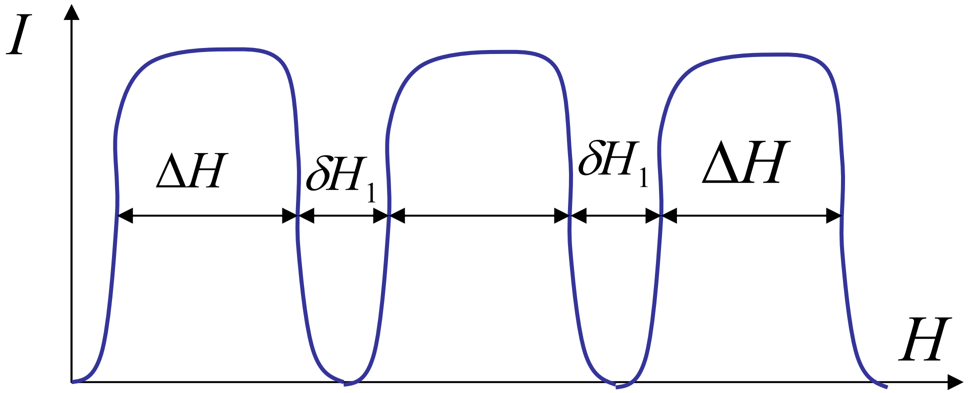
$$I = \frac{e\omega}{2\pi} \int_0^{\frac{2\pi}{\omega}} dt \Gamma_L(x_t)\{\rho_0 + \rho_\downarrow\} \qquad \Gamma_{L,R} = \Gamma\delta[1 \pm Sin\,\omega t]$$

$$I = \frac{e\omega}{\pi} \frac{\sin^2(\theta)\tanh(\Gamma/4\hbar\omega)}{\sin^2(\theta) + \tanh^2(\Gamma/4\hbar\omega)}$$

$$\theta = \pi\frac{\mu H}{\hbar\omega}$$

Two scales for magnetic field: $\delta H = \frac{\Gamma}{\mu}$ $\quad$ $\Delta H = \frac{\hbar\omega}{\mu}$

Spectroscopy of Nanomechanical Vibrations



$$\delta H_1 = \Gamma / \mu$$

$$\Delta H = 2\hbar\omega / \mu$$

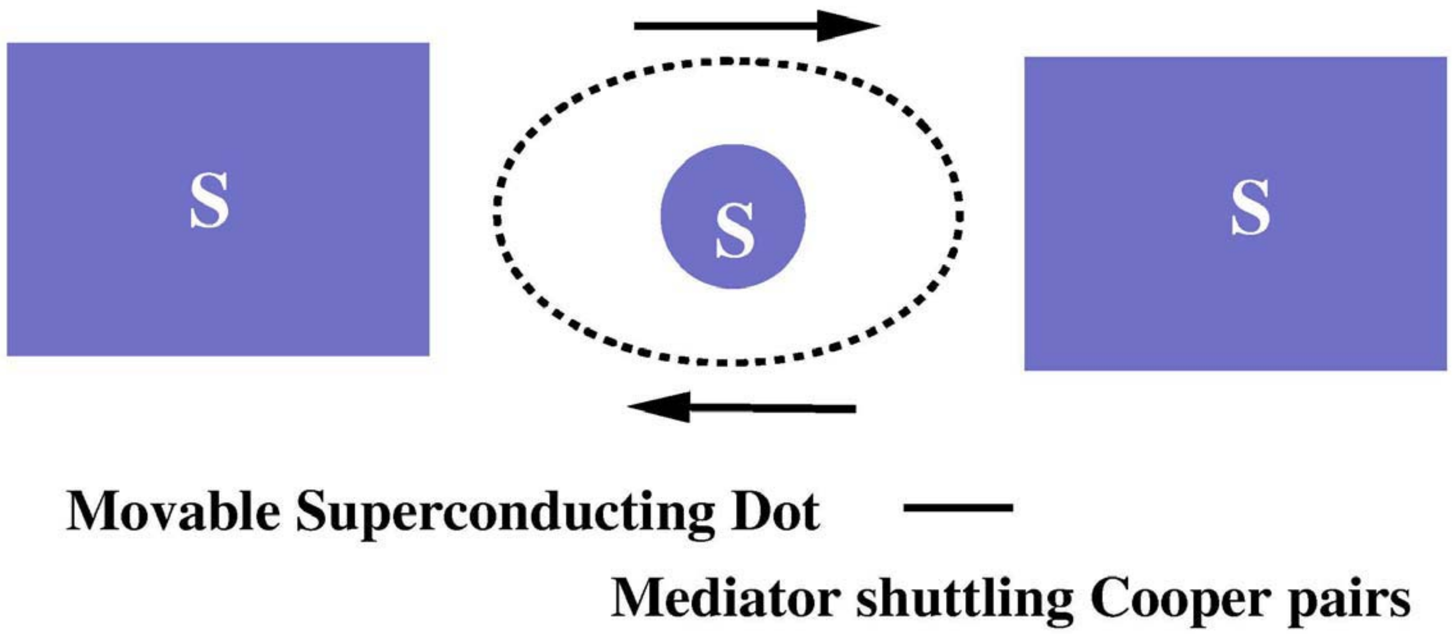
Study of magnetoresistance makes it possible DC spectroscopy of nanomechanical vibrations

Giant magnetoresistance: $\delta H \approx 10\, Oe$ for Gohm tunnel resistance

Nanomechanically assisted superconductivity

How Does Mechanics Contribute to Tunneling of Cooper Pairs?

Is it possible to maintain a mechanically-assisted supercurrent?



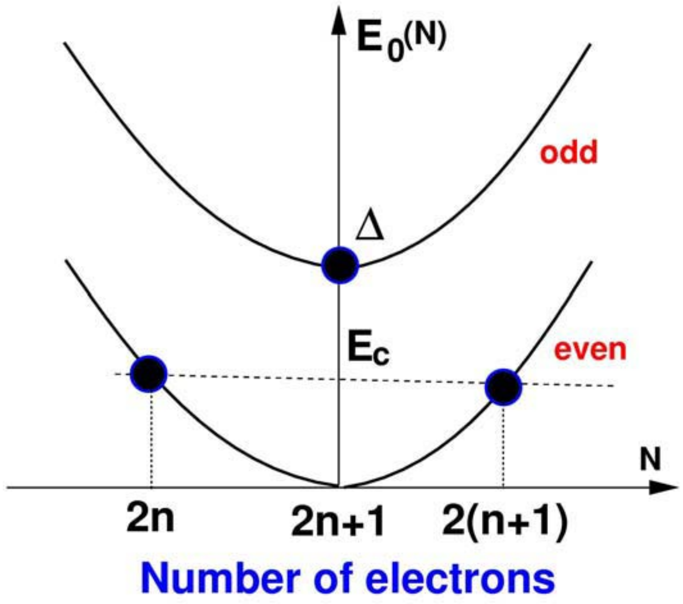
L.Gorelik et al. Nature 2001; A. Isacsson *et al.* PRL **89**, 277002 (2002)

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

<u>This can be achieved provided:</u>

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

Coulomb Blockade of Cooper Pair Tunneling



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

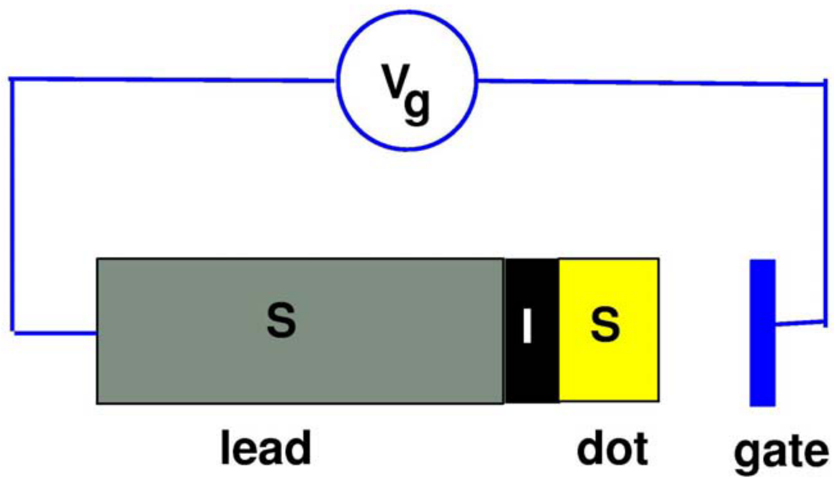
$$\Delta_N = \begin{cases} 0, & N = 2n \\ \Delta, & N = 2n+1 \end{cases}$$

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

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

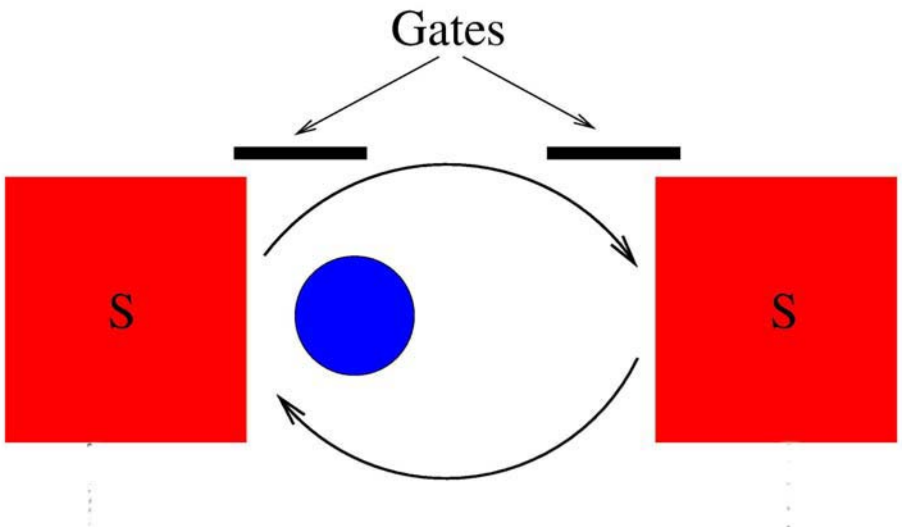
Single Cooper Pair Box



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

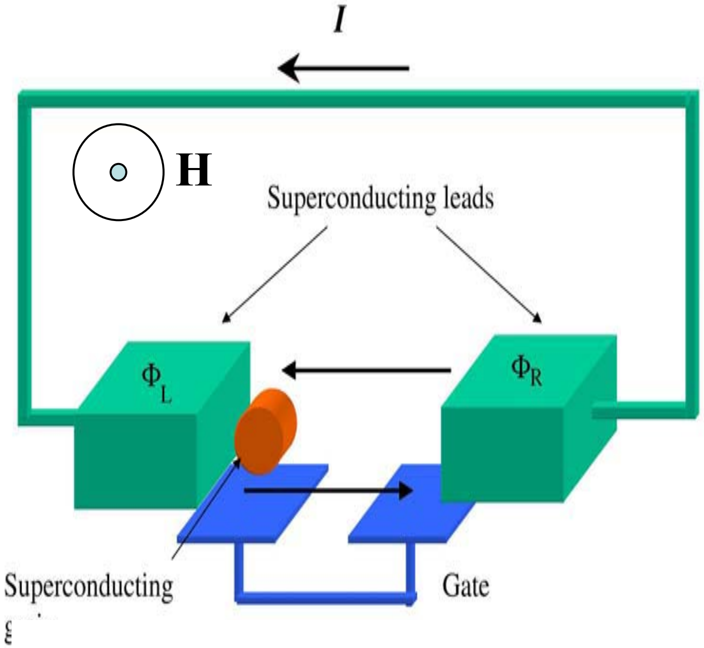
Nakamura et al., Nature 1999

Movable Single Cooper Pair Box

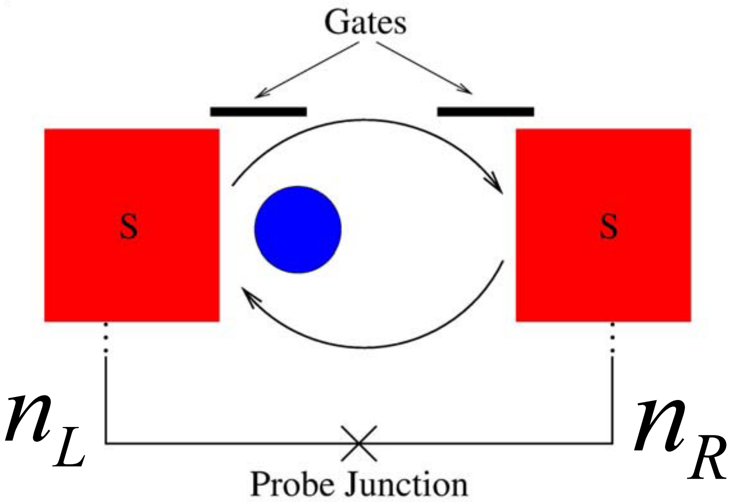


Josephson hybridization is produced at the trajectory turning points since near these points the CB is lifted by the gates.

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

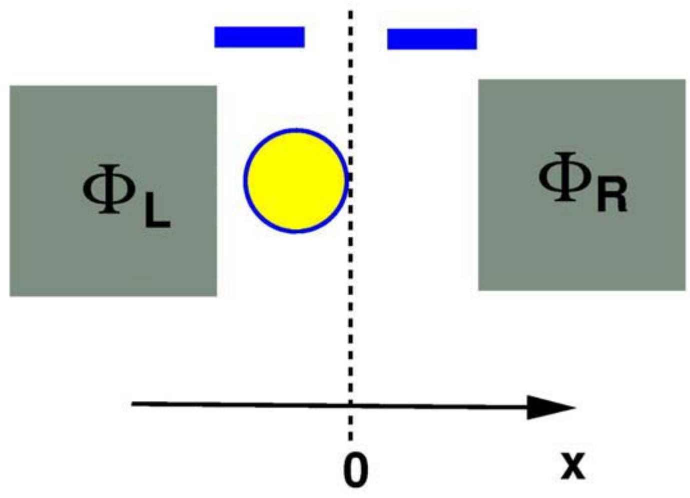
Shuttling Between Coupled Superconductors

$$H = H_C + H_J$$

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

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

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

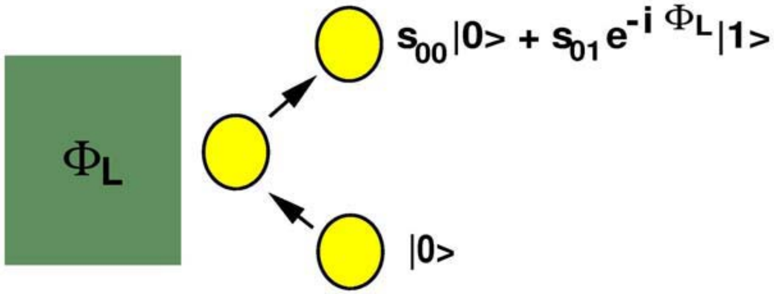


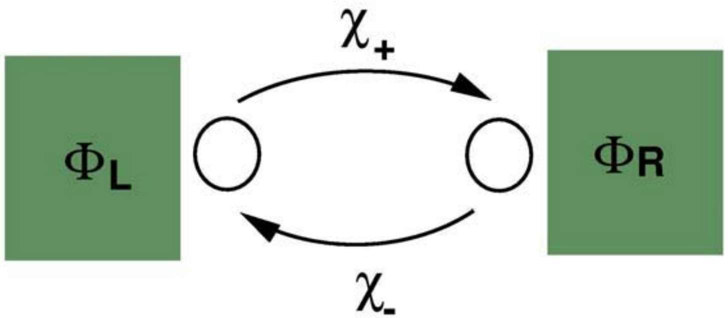
Dynamics: Louville-von Neumann equation

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

Relaxation suppresses the memory of initial conditions.

How Does It Work?





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

$$\chi_{\pm} = \int dt \left[E_0(1) - E_0(0) \right]$$

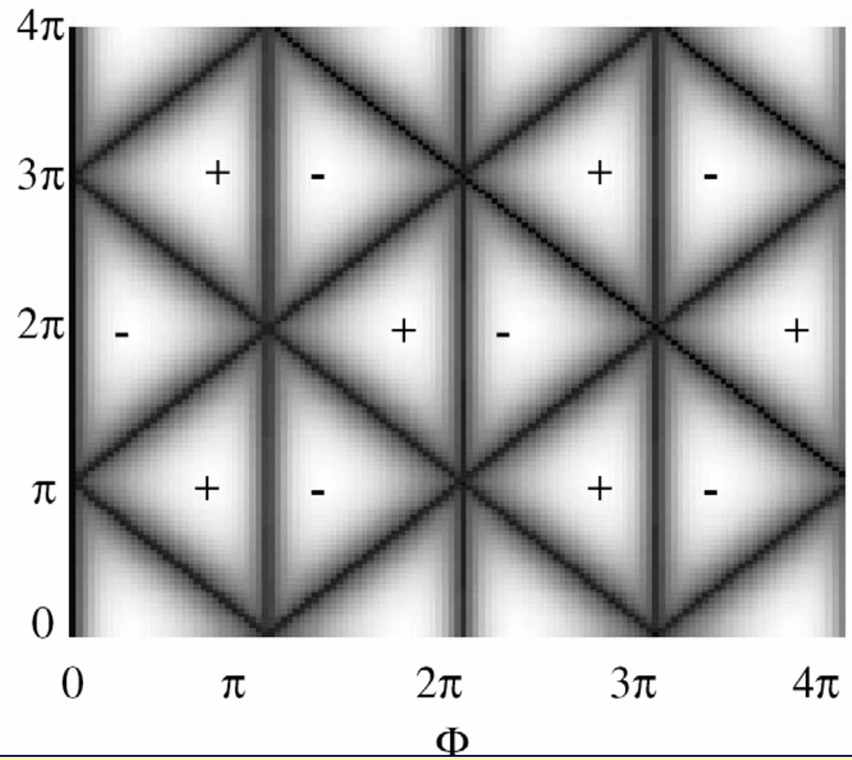
Resulting expression for the current:

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

Main features:

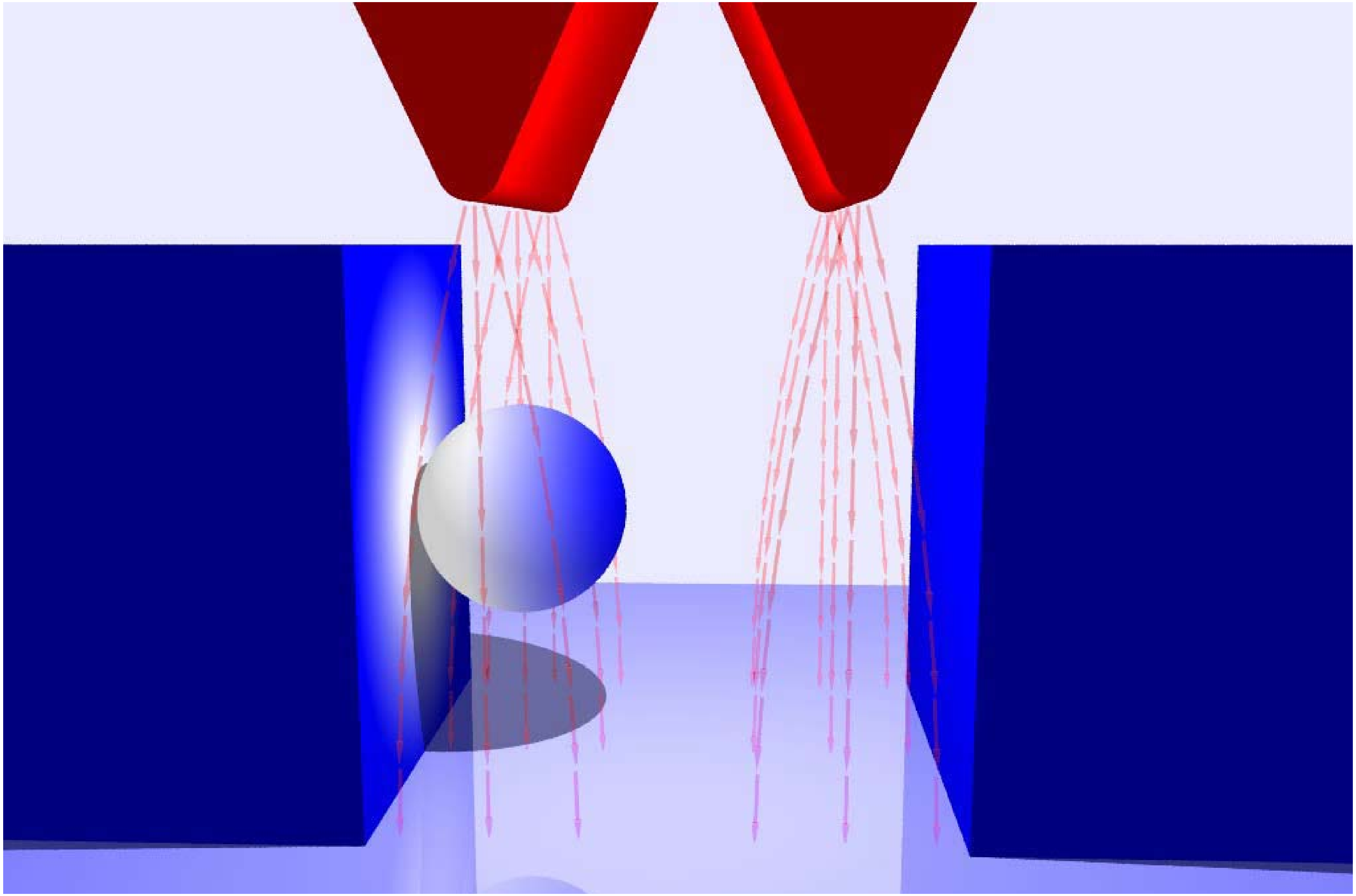
- The oscillating dependence of the dc current on the phase difference $\Phi_R - \Phi_L$ $\rightarrow$ the coherent states are controlled by the phase difference Φ;
- If there is no phase difference, $\Phi_L = \Phi_R$, but the grain's trajectory is *asymmetric*, $\chi_+ \neq \chi_-$, the current still 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 Φ which must be gauge-invariant.

Average current in units $I_0 = 2ef$ as a function of electrostatic, χ, and superconducting, Φ, phases

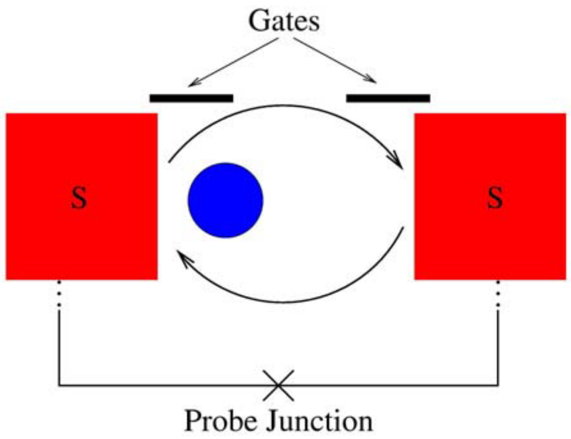


Black regions – no current. The current direction is indicated by signs

Shuttling of Cooper Pairs



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 ρ is the density matrix.

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