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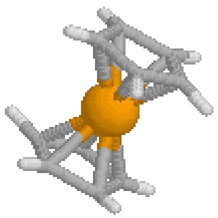
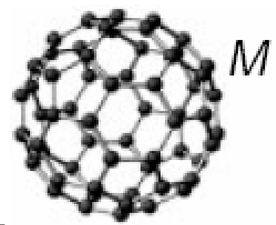
for Theoretical Physics

M.N.Kiselev

Kondo Shuttling



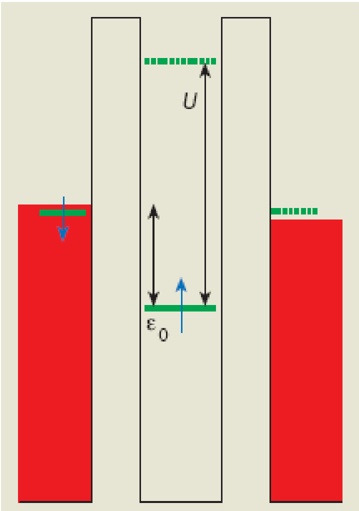


Workshop on Quantum Pumping, Haifa, January 8, 2007

Single orbital level coupled to two leads

$$H = H_{leads} + H_{tun} + H_{dot}$$

$$H_{leads} = \sum_{k,\sigma\alpha=L,R} [\epsilon_k - \mu_\alpha] c^\dagger_{k,\sigma\alpha} c_{k,\sigma\alpha}$$

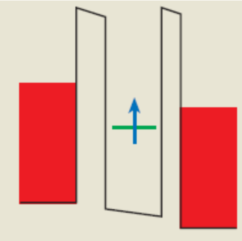


$$H_{tun} = \sum_{k,\sigma\alpha} [V_\alpha(t) c^\dagger_{k,\sigma\alpha} d_\sigma + H.c.]$$

$$H_{dot} = \sum_\sigma \varepsilon_0 d^\dagger_\sigma d_\sigma + U(n-N)^2$$

Tunneling width $\Gamma_\alpha(t) = \pi\rho|V_\alpha|^2(t)$

Single orbital level coupled to two leads



Time-dependent Glazman-Raikh rotation

$$\begin{pmatrix} c_{k\sigma L} \\ c_{k\sigma R} \end{pmatrix} = U_t \begin{pmatrix} c_{k\sigma +} \\ c_{k\sigma -} \end{pmatrix} \qquad U_t = \begin{pmatrix} \cos\theta_t & -\sin\theta_t \\ \sin\theta_t & \cos\theta_t \end{pmatrix}$$

$$\tan\theta_t = \left|\frac{V_R(t)}{V_L(t)}\right| \qquad |V|^2(t) = |V_L|^2(t) + |V_R|^2(t)$$

$$H_{Berry} = \sum_{k,\sigma\gamma=\pm} \left(c^\dagger_{k,\sigma+} c^\dagger_{k,\sigma-}\right) \underbrace{\left[-iU_t^{-1}\frac{\partial U_t}{\partial t}\right]}_{a_t} \begin{pmatrix} c_{k,\sigma+} \\ c_{k,\sigma-} \end{pmatrix}$$

Gauge potential

$$a_t = \frac{d\theta_t}{dt}\begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix}$$

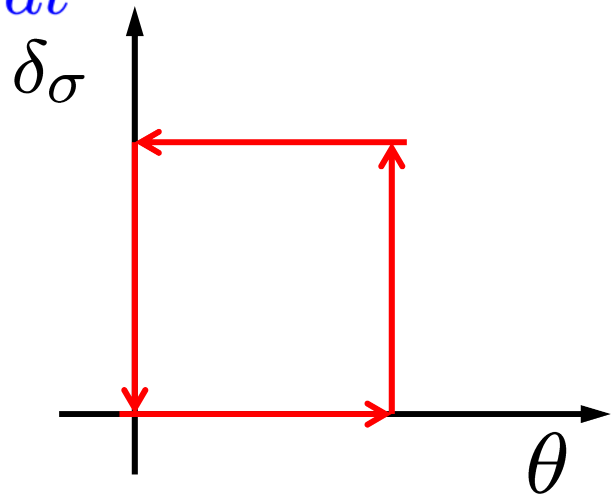
Tomosuke Aono, 2004

Adiabatic current and pumped charge per cycle at T=0

$$I_\sigma = \frac{e}{2\pi}\left[-\frac{d\theta_t}{dt}\sin(2\theta_t)\sin(2\delta_\sigma(t)) + \frac{d\delta_\sigma}{dt}\cos(2\theta_t)\right]$$

Scattering phase shifts at the Fermi level in the leads

$$Q_\sigma = \oint dt I_\sigma(t) = \frac{e}{2\pi}\oint dt(1-T_\sigma)\frac{d\Upsilon_\sigma}{dt}$$



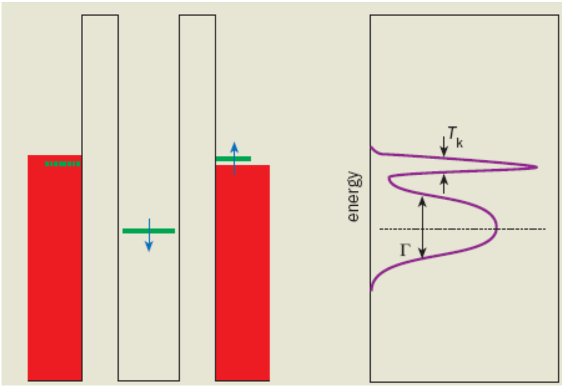
$$T_\sigma = \sin^2(2\theta_t)\sin^2\delta_\sigma(t)$$

$$\Upsilon_\sigma = \arctan[\cos^2(2\theta_t)\tan\delta_\sigma(t)]$$

$$Q_\sigma = \frac{e}{2\pi}\oint(\cos(2\theta)d\delta_\sigma - \sin(2\theta)\sin(2\delta_\sigma)d\theta)$$

Adiabaticity $\hbar\Omega \ll \min[\Gamma(t)]$ **M.Büttiker et al, 1994**

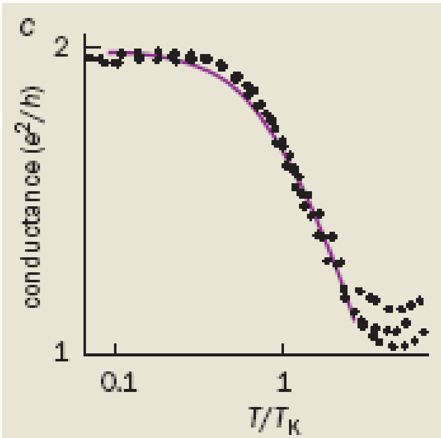
Adiabatic pumping at the Kondo regime



$$\delta_\sigma \rightarrow \frac{\pi}{2}$$

Nozieres Fermi Liquid regime

$$T_K = \sqrt{(\Gamma_L + \Gamma_R)U/\pi} \exp\left[-\frac{\pi U}{4(\Gamma_L + \Gamma_R)}\right]$$



Pumped charge

$$Q_c = Q_\uparrow + Q_\downarrow = 0$$

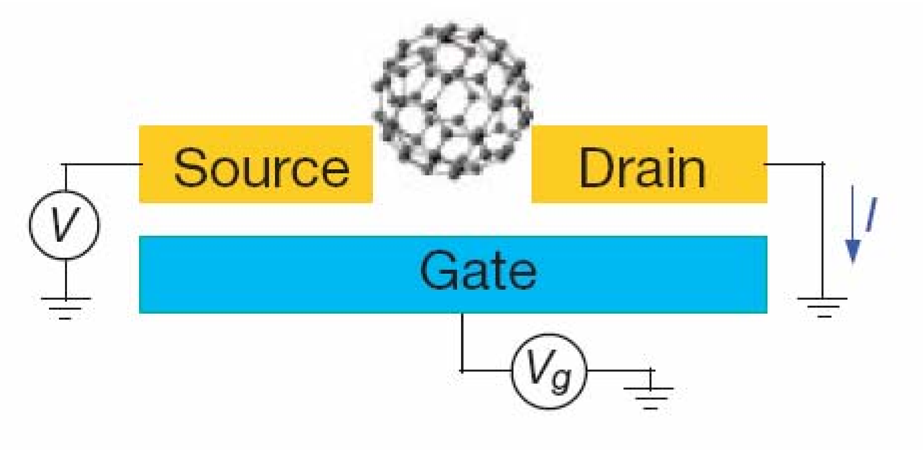
Pumped spin

$$Q_s = Q_\uparrow - Q_\downarrow \neq 0$$

Kondo Pump = Resonance Spin Diode

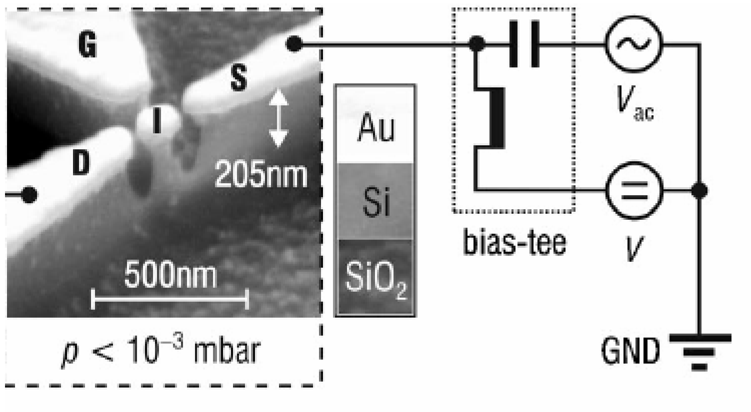
What if $\Gamma(t)$ is due to a nanomechanics?

Molecular Transistor



H.Park et al, Nature 2000

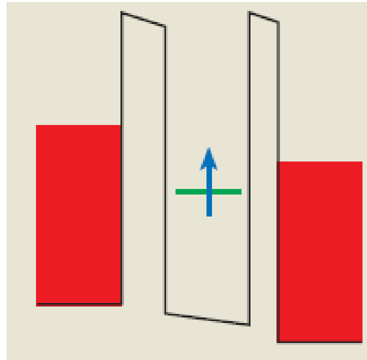
Nano-Pendulum



D.Sheible and R.Blick 2004

NanoElectroMechanical Pump = Shuttle

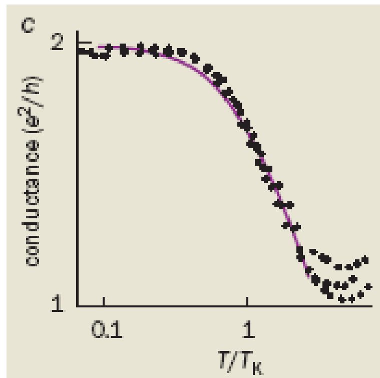
Why do we look for the Kondo effect in nano-devices ?

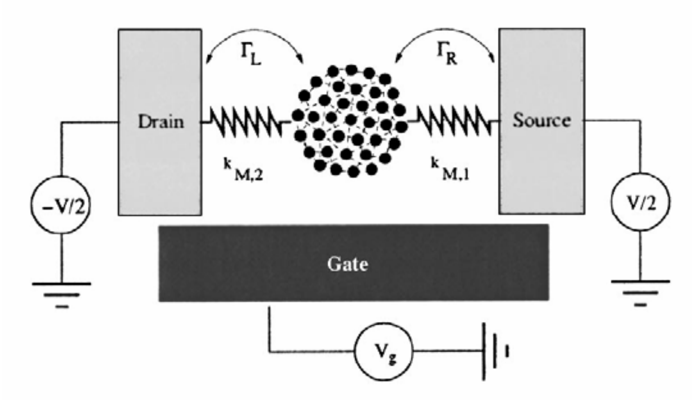


- The Kondo effect makes it easier for states belonging to the two opposite electrodes to mix

- Reasonably high Kondo temperatures > 1 K

- SETs are highly controllable (by bias, magnetic field etc) devices





Keeping in mind Pumping …

I will speak about Shuttling.

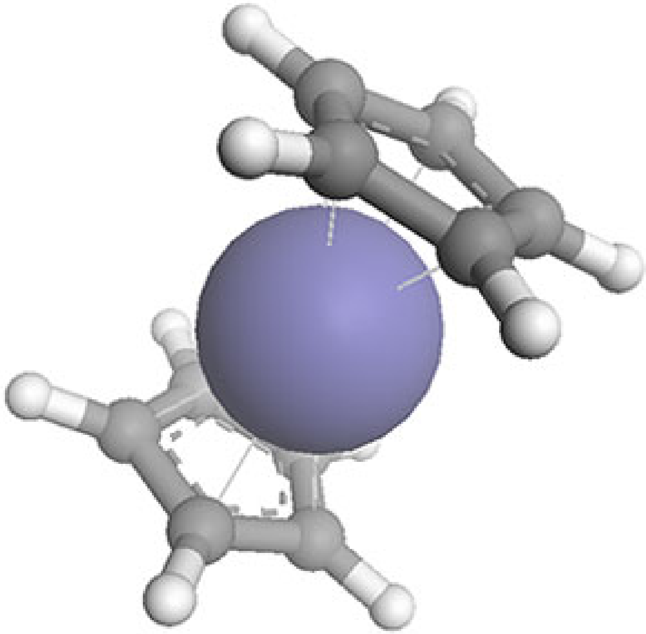
How to make the Kondo effect work in the Nanoelectromechanical devices?

How is the KE influenced by the NEM?

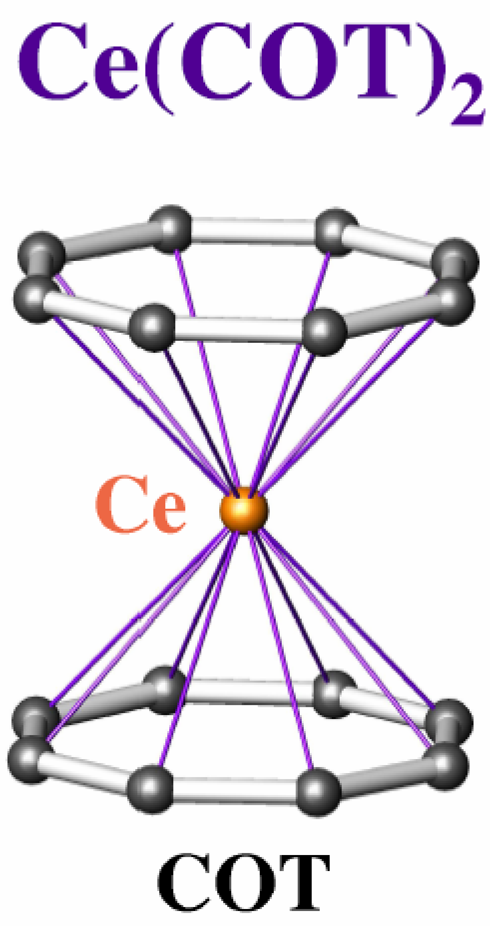
- the nano-device changes its shape in the process of the tunneling
- the nano-devise is nano-machined by external periodic force

K.Kikoin, MK and M.R.Wegewijs, PRL 2006
MK, K.Kikoin, R.Shekhter and V.Vinokur, PRB 2006

Ferrocene $Fe(C_5H_5)_2$



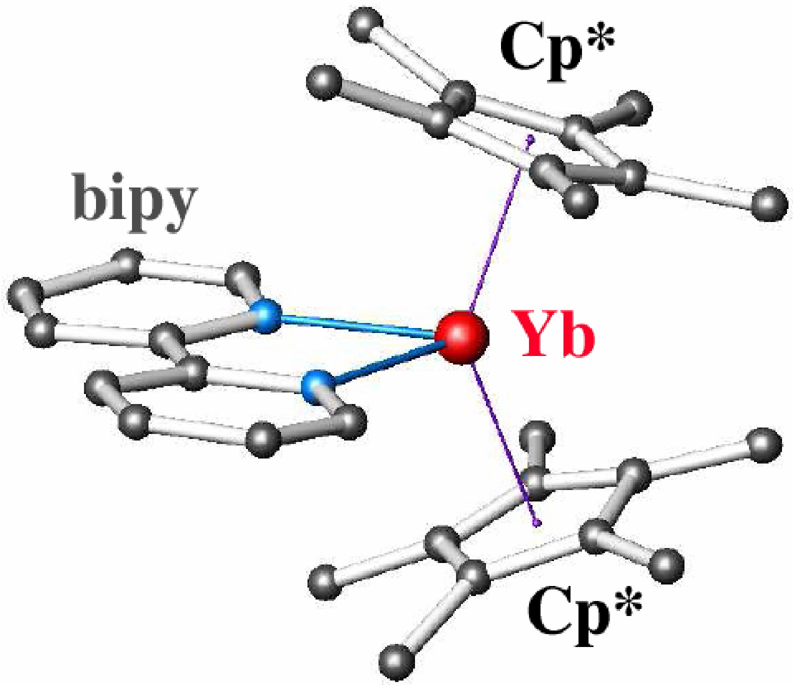
Cerocene $Ce\left(C_8H_8\right)_2$



COT = C8H8

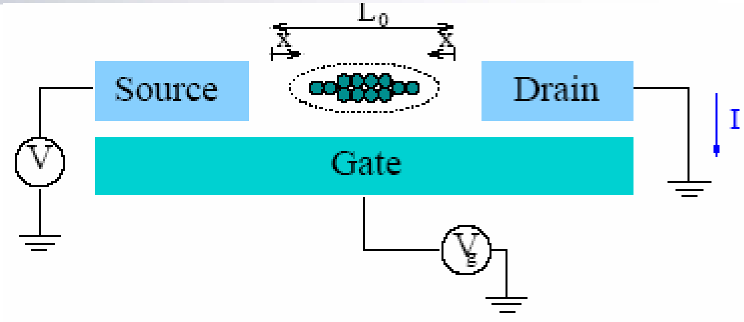
Ytterbocene

$Cp^*_2Yb(bipy)$

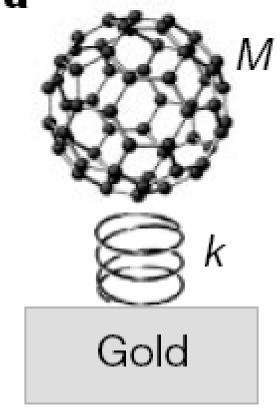


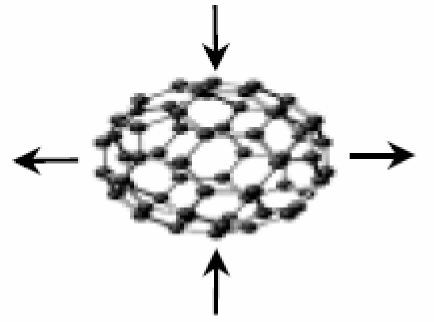
Cp* = C5Me5, bipy = (NC5H4)2]

Fullerenes

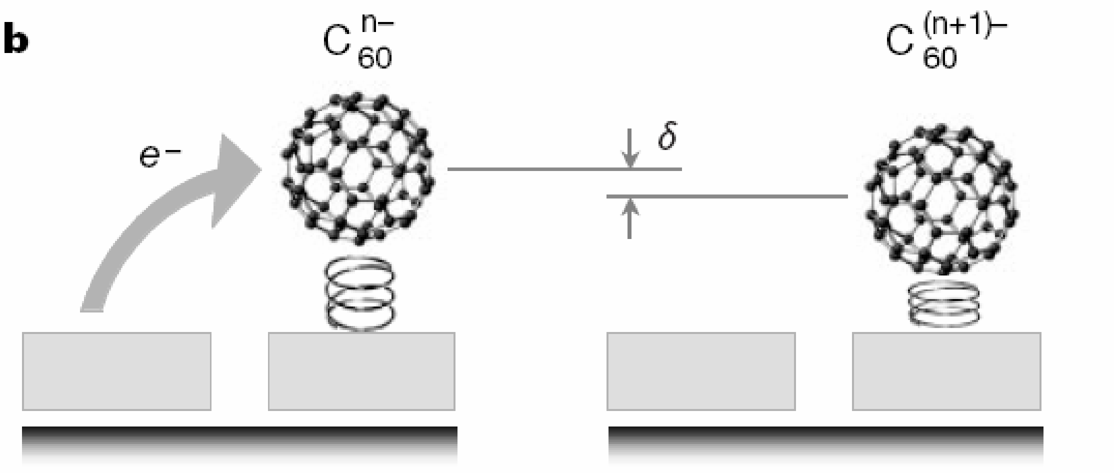


a



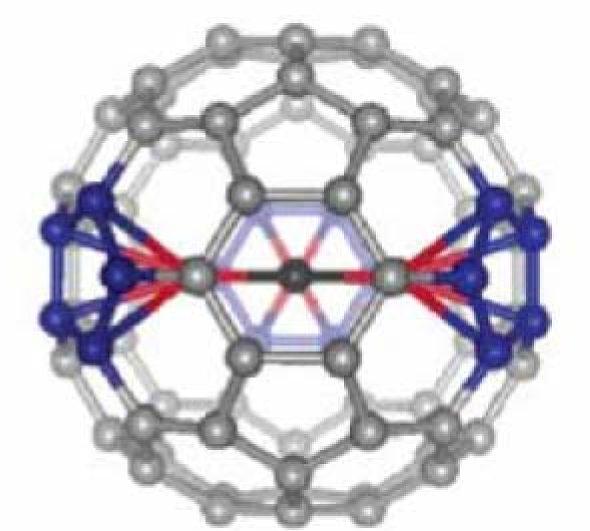


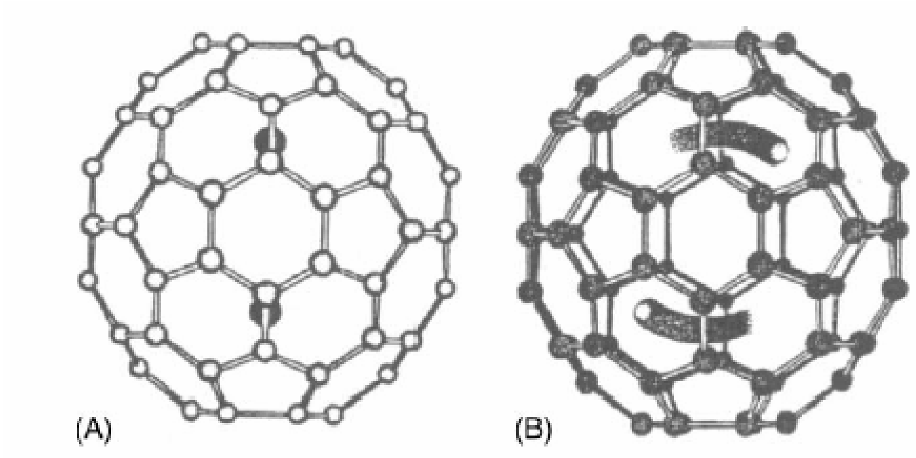
b

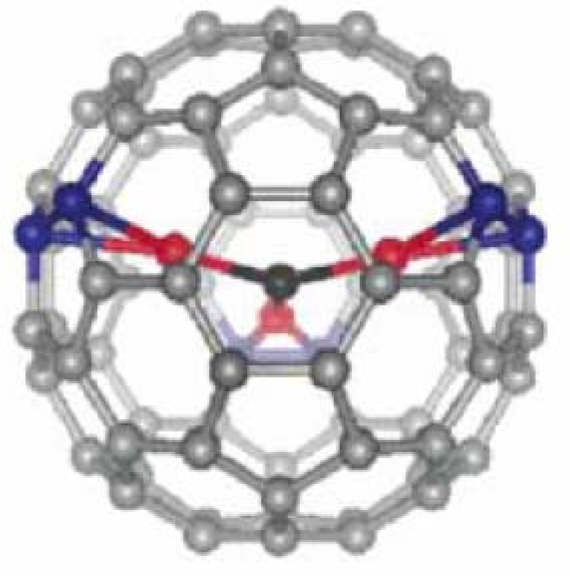


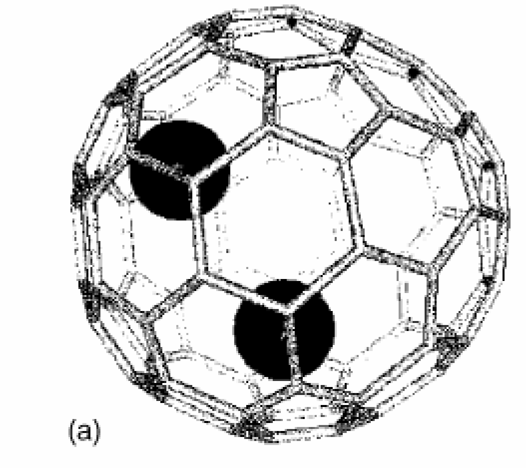
H.Park et al, Nature 2000

Transition metals inside fullerens

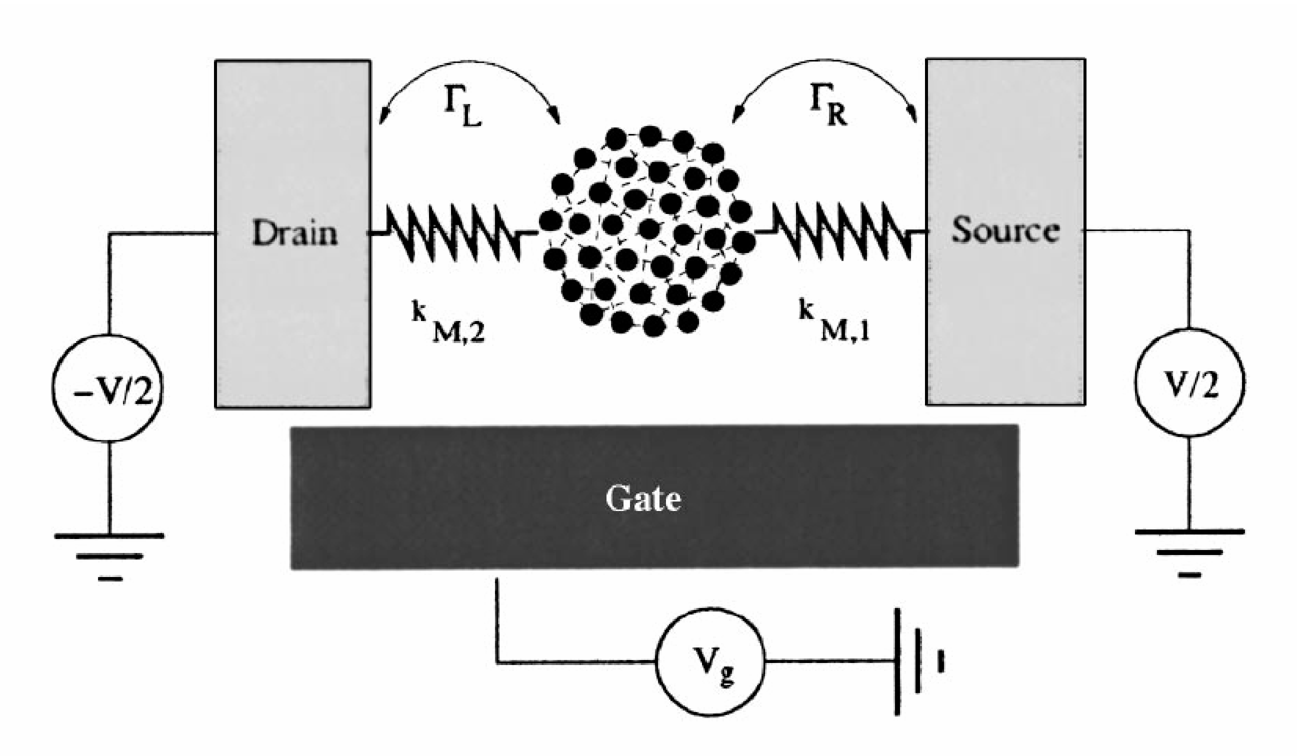








Transport through molecular transistors



Q: Whether phonons support or destroy Kondo effect?

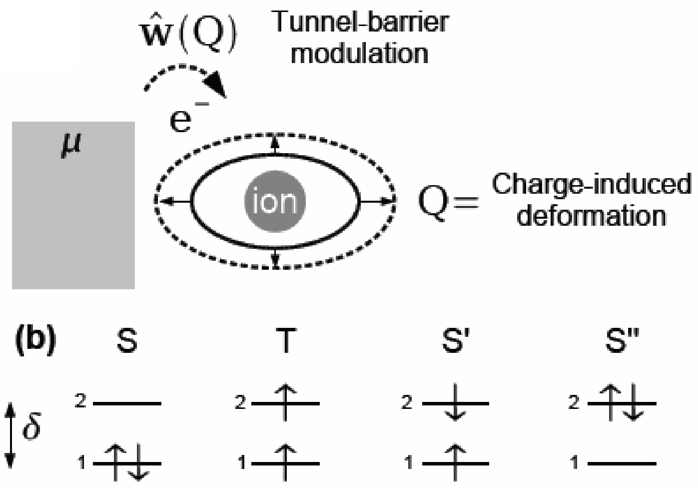
A: Usually they destroy it due to the energy transfer and the decoherence effects.

Q: Can phonons assist a resonance tunneling?

A: Yes, they can do it through dynamical symmetries.

Phonons + Kondo = "Phondo"

Effective model

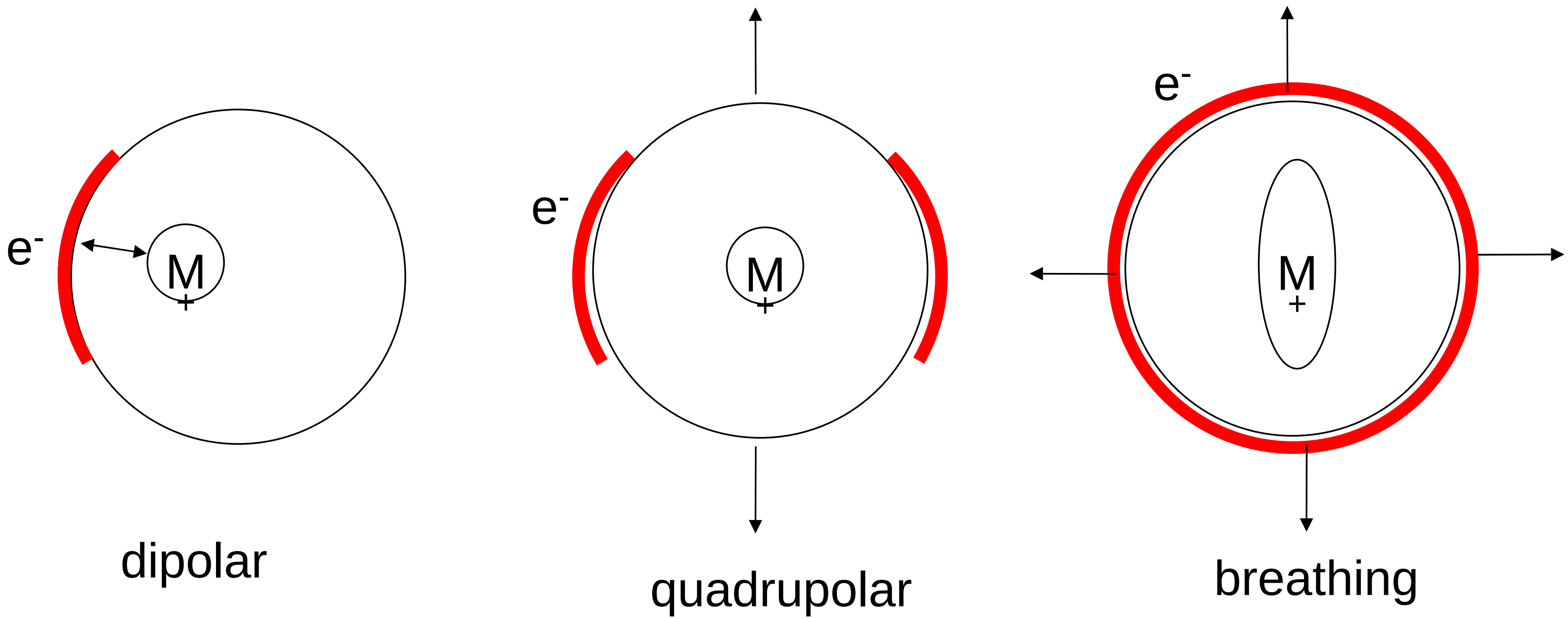


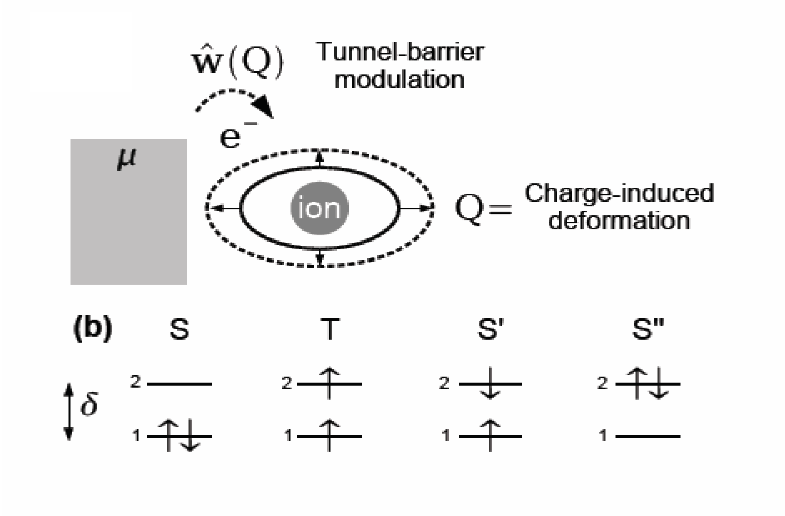
$$H = H_{mol} + H_{res} + H_{tun}$$

$$H_{mol} = H_Q^{(N)} + H_Q^{(N+1)} + H_Q^{(N-1)} + T_n$$

$$H_{res} + H_{tun} = \sum_{k\sigma} \epsilon_k c_{k\sigma}^\dagger c_{k\sigma} + \hat{w}_Q \sum_{k\mu\sigma} \left(\tilde{d}_{\mu\sigma}^\dagger c_{k\sigma} + H.c. \right)$$

cage MO = localized | cage MO = delocalized

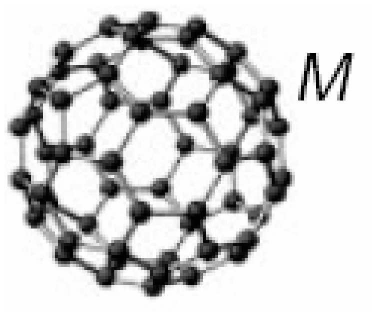




$$\Delta \equiv E_T - E_S = \delta - I > T_K$$

Triplet | Singlet | Exchange

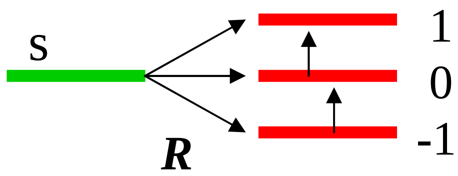
TMOC = Transition Metal + Organic Complex (cage)



$$H_{mol}^{(N)} = \sum_{\Lambda=S,T0,T\pm} E_\Lambda(Q)|\Lambda\rangle\langle\Lambda|$$

Singlet Triplet

Assumption: even electron occupation number



Singlet is a ground state

SO(4) symmetry

$$H_{tun} = \hat{w}(Q)\sum_k {\sum_{\Lambda\gamma\sigma}}' [|\Lambda\rangle\langle\gamma|c_{k\sigma} + H.c.]$$

$$H_{eff} = H_{res} + \frac{1}{2}\Delta \mathbf{S}^2 + \hat{J}_S \mathbf{S}\cdot\mathbf{s} + \hat{J}_R \mathbf{R}\cdot\mathbf{s} + \frac{\Omega}{2}P^2$$

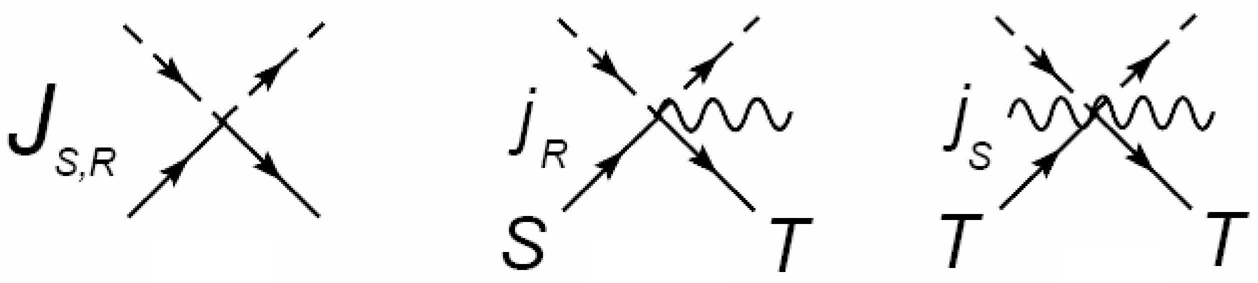
Local phonon can be emitted or absorbed in a co-tunneling processes

The main source of phonon emission/absorption is the tunneling rate

Vibration assisted tunneling

$$H_{eff} = H_{res} + \frac{1}{2}\Delta \mathbf{S}^2 + \hat{J}_S \mathbf{S}\cdot\mathbf{s} + \hat{J}_R \mathbf{R}\cdot\mathbf{s} + \frac{\Omega}{2}P^2$$

$$\hat{J}_S(Q) = J_S + j_S Q^2, \qquad \hat{J}_R(Q) = J_R + j_R Q$$

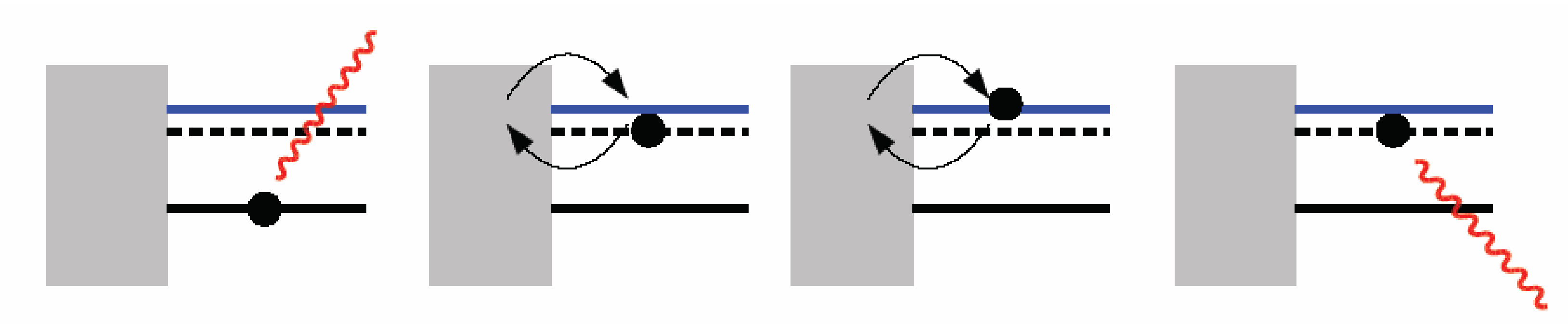


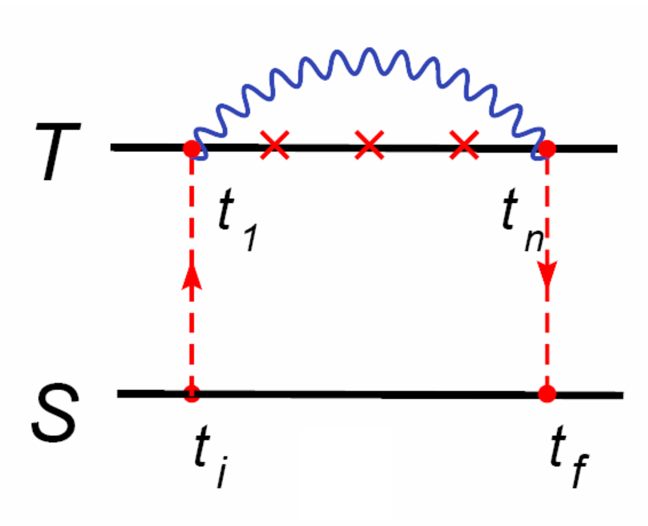
single phonon

two-phonon

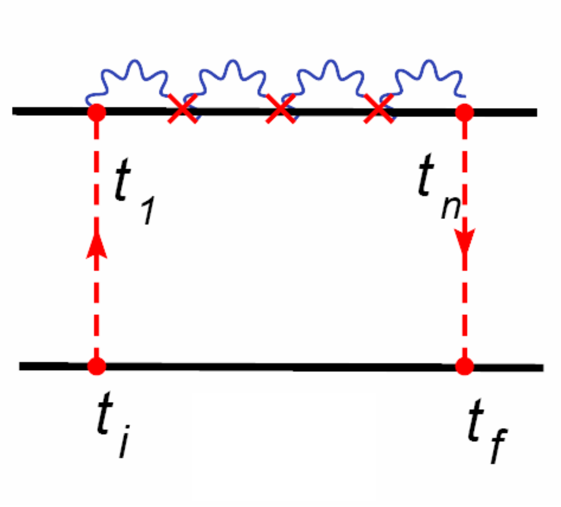
$$j_S \ll j_R$$

Phonon assisted processes



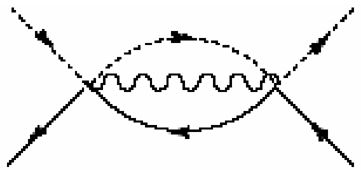


single-phonon

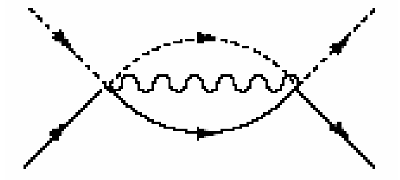


two-phonon

Single phonon processes

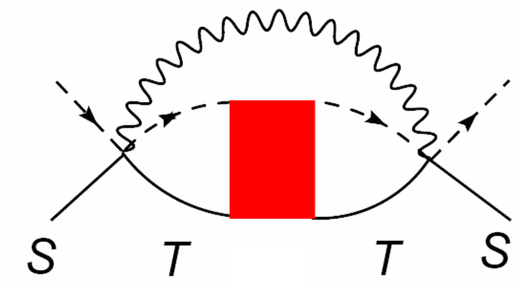


$$\gamma^{(1)} \sim j_R^2 \int \frac{d\epsilon}{2\pi} \int \frac{d\omega}{2\pi} \tanh\left(\frac{\epsilon}{2T}\right) Im\mathcal{G}^R(\epsilon) Re\bar{G}^R(\omega) ImD^R(\epsilon-\omega) \coth\left(\frac{\epsilon-\omega}{2T}\right)$$



$$\gamma^{(1)} = \gamma^{(2)} \sim \rho j_R^2 \log\left(\frac{D}{max[T, |\Delta - \Omega_0|]}\right)$$

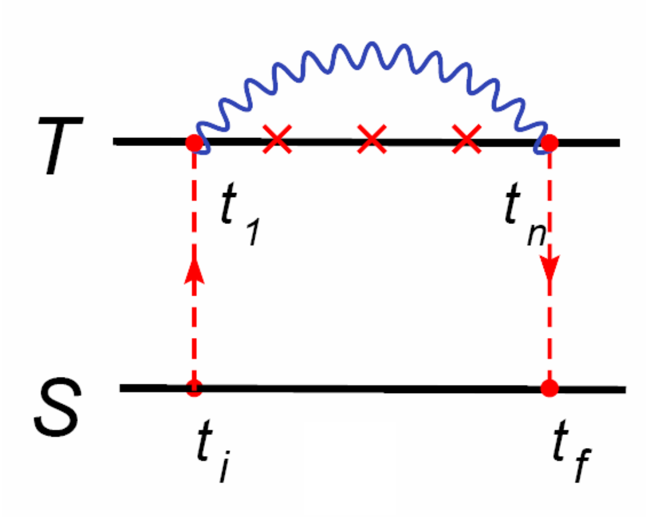
$$\gamma^{(2)} \sim j_R^2 \int \frac{d\epsilon}{2\pi} \int \frac{d\omega}{2\pi} \tanh\left(\frac{\epsilon}{2T}\right) Im\mathcal{G}^R(\epsilon) Re\bar{G}^R(\omega) ImD^R(-\epsilon-\omega) \coth\left(\frac{\epsilon+\omega}{2T}\right)$$



Summation of “parquet” diagrams

$$\gamma_1 \sim j_R^2 \int \frac{d\epsilon}{2\pi} \coth\left(\frac{\epsilon}{2T}\right) \left[Re\left[\frac{\Pi(-\epsilon)}{1 - J_0^T \bar{\Pi}(-\epsilon)}\right]^R ImD^R(\epsilon) + ReD^R(-\epsilon) Im\left[\frac{\Pi_i(\epsilon)}{1 - J_0^T \bar{\Pi}(\epsilon)}\right]^R \right]$$

Single phonon processes



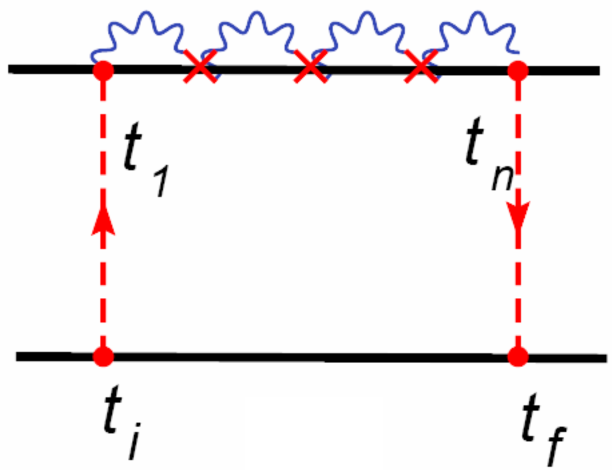
$$\gamma_1 \sim (j_R)^2 \rho \left[\frac{\log\left(\frac{D}{\max[T, |\Delta - \Omega|]}\right)}{1 - J_S A \rho \log\left(\frac{D}{\max[T, |\Delta - \Omega|]}\right)} \right]$$

$$T_K^{(1)} \sim D \exp\left(-\frac{1}{A\rho J_S}\right)$$

Messages:

- Single phonon processes assist the Kondo tunneling
- Kondo temperature does not depend on the phonon coupling
- Differential conductance is logarithmically enhanced approaching the Kondo regime

Two-phonon processes



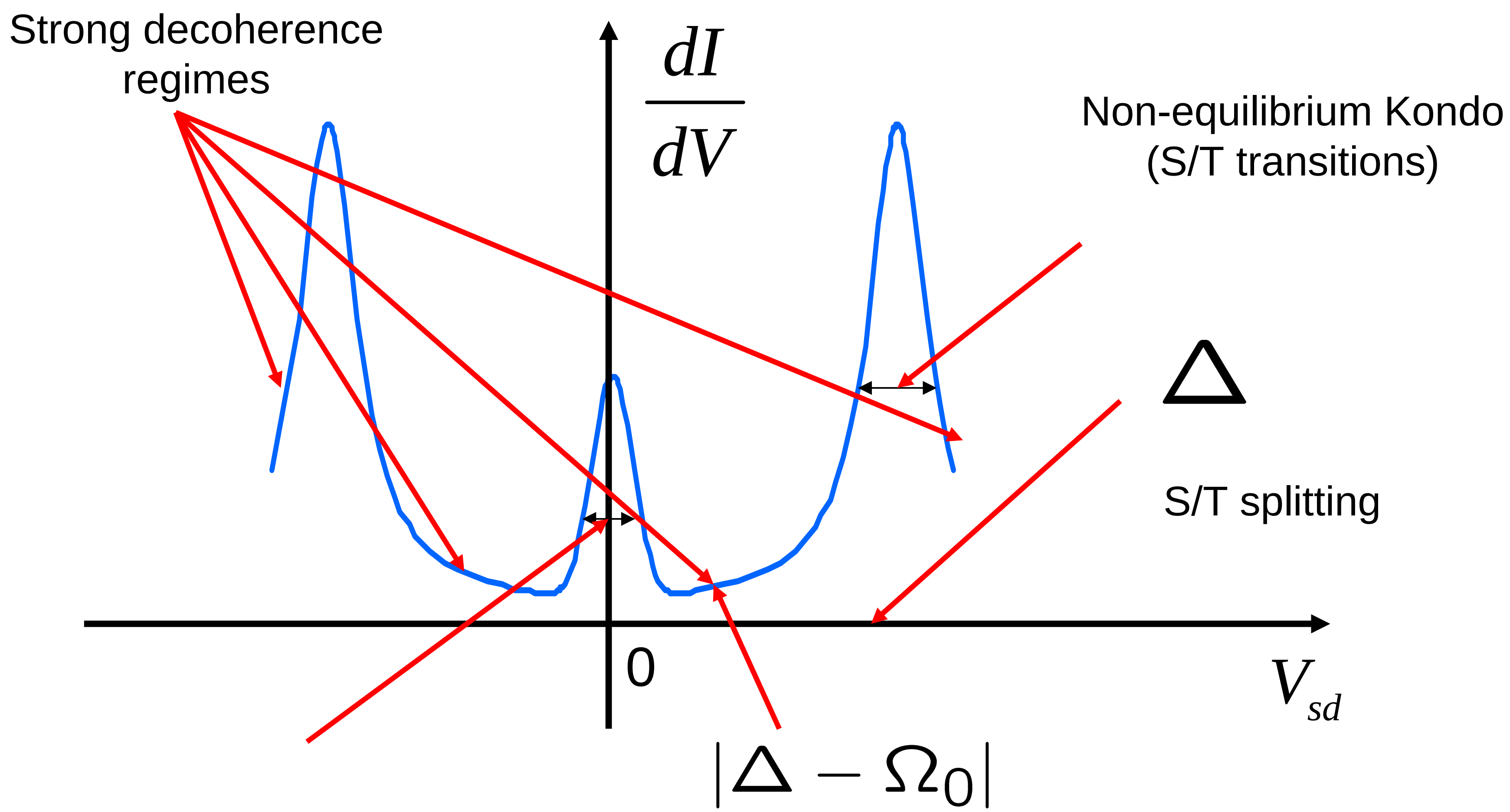
$$\gamma_2 \sim (j_R)^2 \rho \left[\frac{\log\left(\frac{D}{\max[T, |\Delta - \Omega|]}\right)}{1 - j_S A' \rho \log\left(\frac{D}{\max[T, |\Delta - \Omega|]}\right)} \right]$$

$$T_K^{(2)} \sim D \exp\left(-\frac{1}{A' \rho j_S}\right) \ll T_K^{(1)}$$

Messages:

- Two-phonon processes also assist the Kondo tunneling, however
- Kondo temperature **depends** on the phonon coupling
- The two phonon scenario leads to much smaller Kondo temperatures

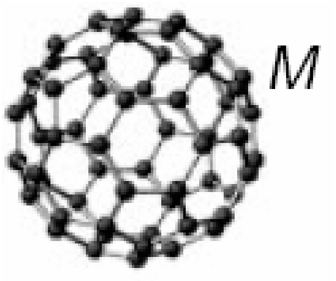
Differential Conductance



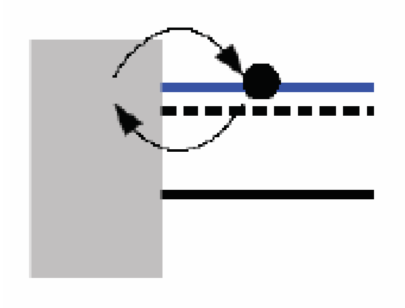
Equilibrium Kondo temperature (triplet state)

Log-scaling of peaks is a manifestation of the Kondo effect

A resonance condition



$$|\Omega_0 - \Delta| \ll T_K$$

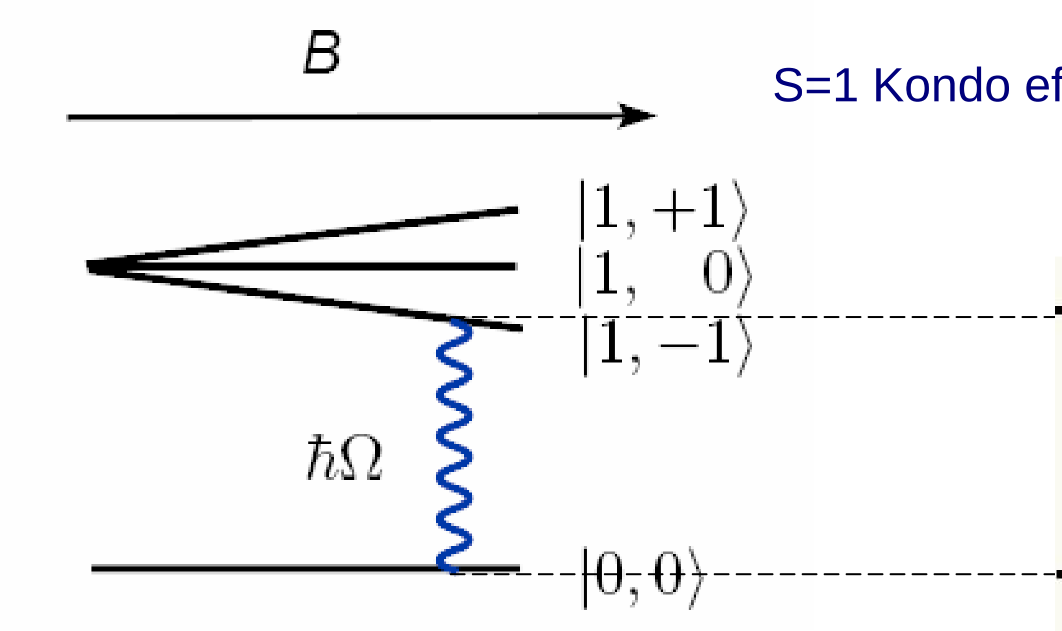


… narrows a group of the TMOC with "Phondo".

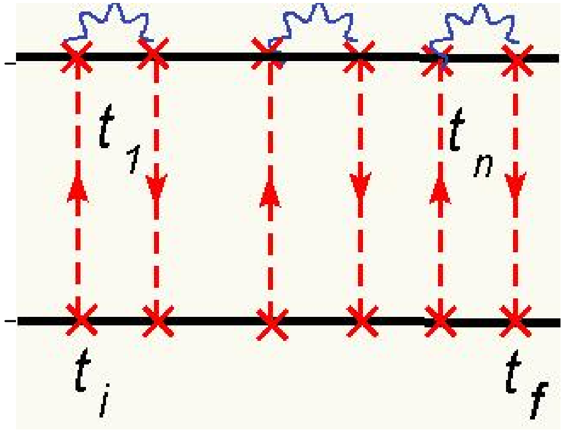
What happens if $T_K < |\Omega_0 - \Delta| \ll \Delta$ **?**

Fine tuning tool is necessary to control the resonance

Magnetic Field Effects



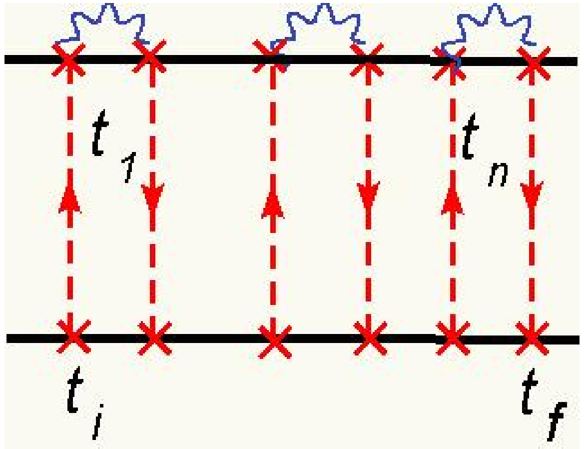
S=1 Kondo effect → S=1/2 Kondo effect



Magnetic field as a fine tuning tool

M.Pustilnik, Y.Avishai, K.Kikoin, PRL 2000

Single-phonon processes in magnetic field



$$\gamma_B \sim \left[\frac{(j_R)^2 \rho \log \left(\frac{D}{\max[T, B, |\Delta - \Omega - B|]} \right)}{1 - (j_R A_B \rho)^2 \log^2 \left(\frac{D}{\max[T, B, |\Delta - \Omega - B|]} \right)} \right]$$

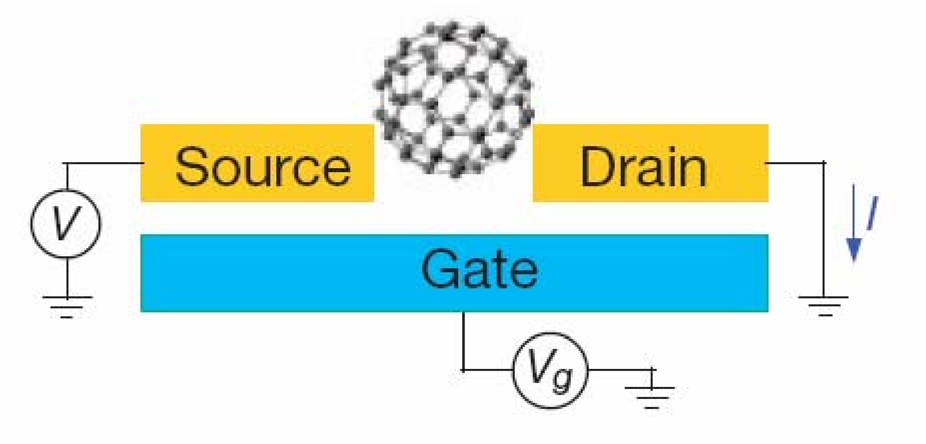
$$T_K^{(2)} \ll T_K^{(B)} \sim D \exp\left(-\frac{1}{A_B \rho j_R} \right) \ll T_K^{(1)}$$

Messages:

- Single-phonon processes assist the Kondo tunneling, however
- Kondo temperature **depends** on the phonon coupling
- Magnetic field provides a tool for the fine tuning of the TMOC

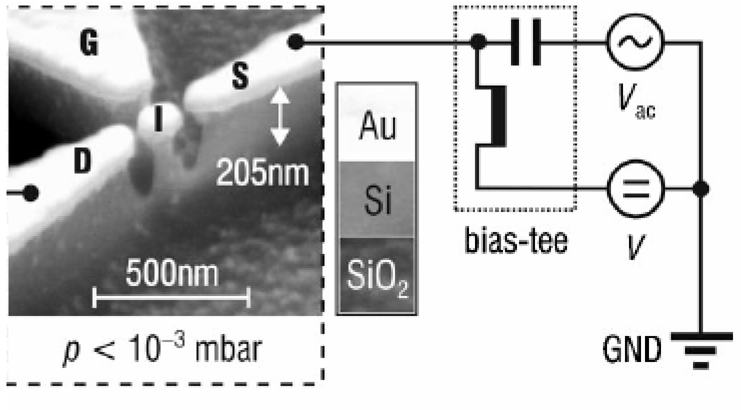
NEM-SET with center-of-mass motion
= Mobile Kondo Impurity

Molecular Transistor



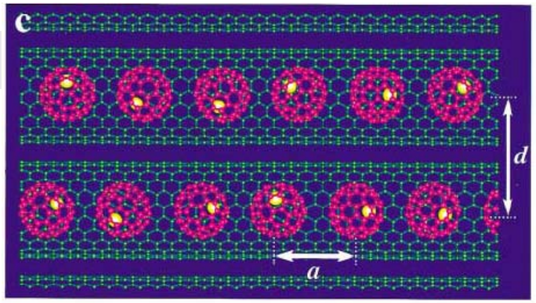
H.Park et al, Nature 2000

Nano-Pendulum

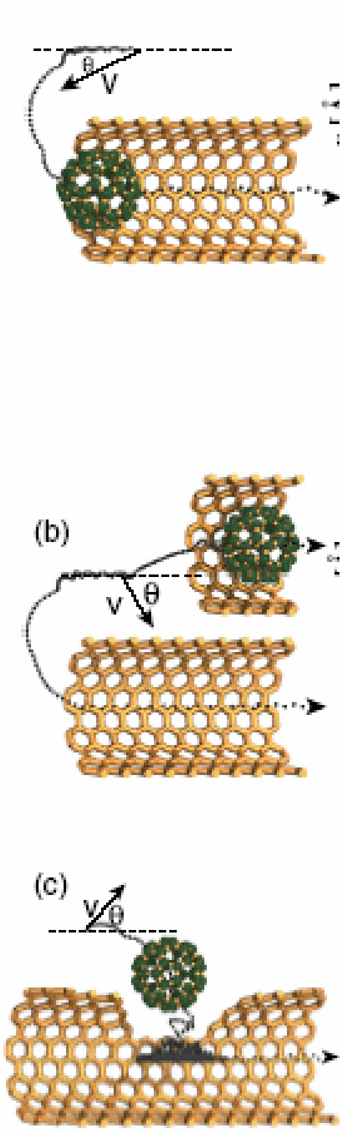


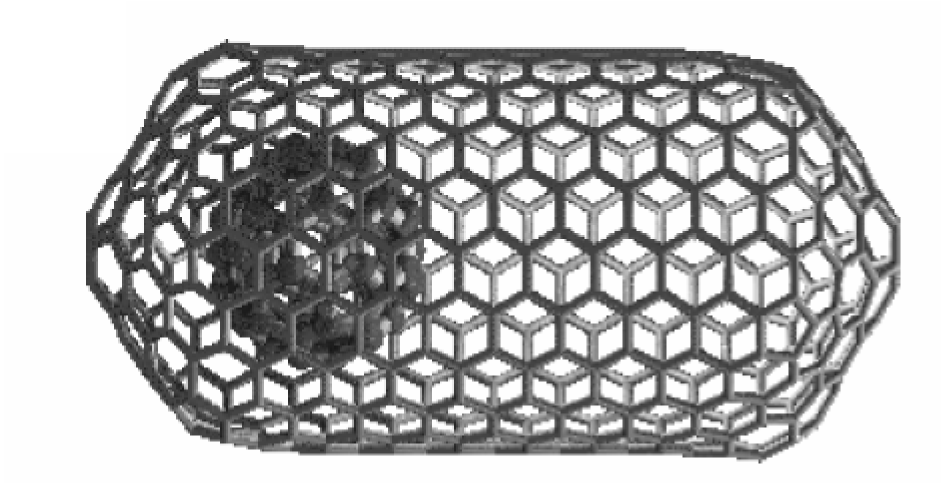
D.Sheible and R.Blick 2004

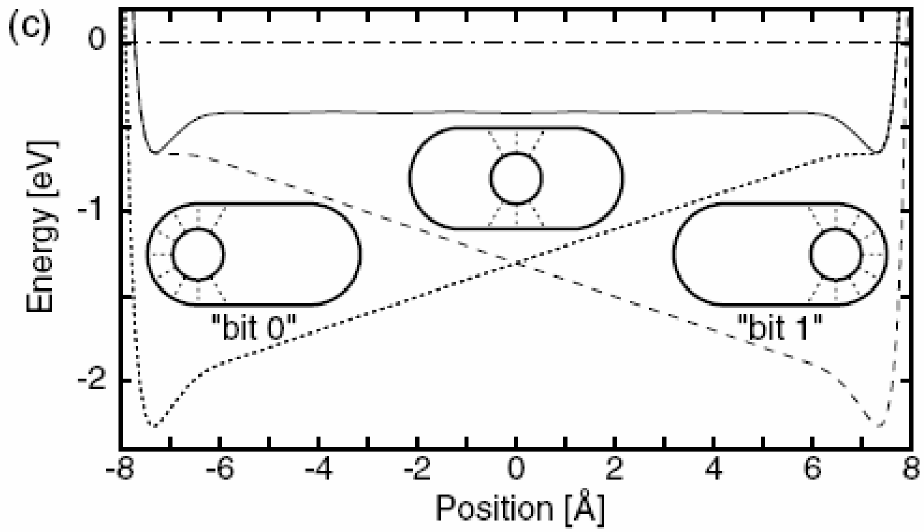
Nanotube peapods: C_{60} @ CNT



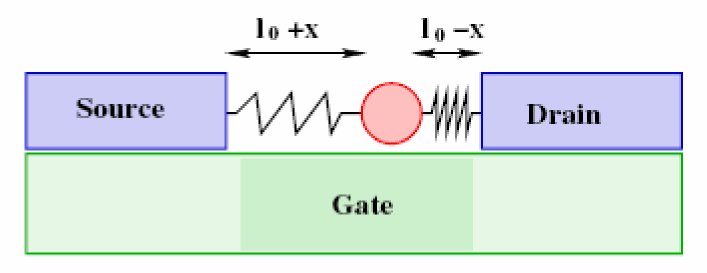
(a)







The model



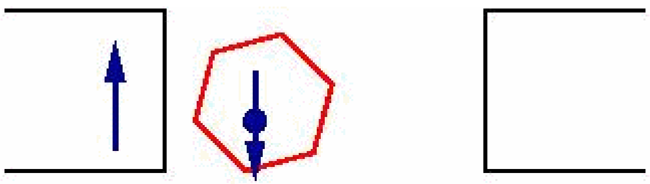
$$H_0 = \sum_{k,\alpha} \varepsilon_{k\sigma,\alpha} c^{\dagger}_{k\sigma,\alpha} c_{k\sigma,\alpha} + \sum_{i\sigma} [\epsilon_i - e\mathcal{E}x] d^{\dagger}_{i\sigma} d_{i\sigma} + Un^2$$

$$H_{tun} = \sum_{ik\sigma,\alpha} [V^{(i)}_{\alpha}(x) c^{\dagger}_{k\sigma,\alpha} d_{i\sigma} + H.c],$$

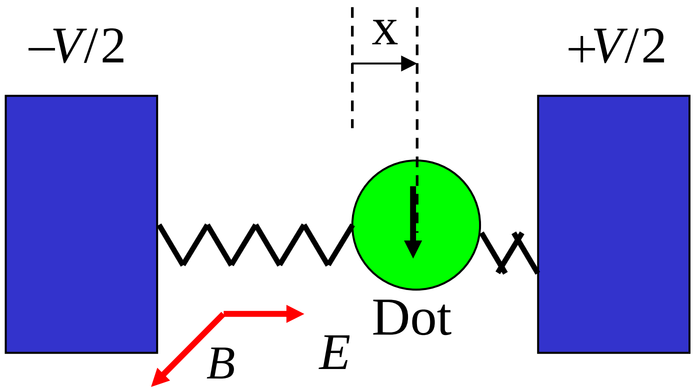
SW transformation

$$H = H_0 + \sum_{k\alpha\sigma,k'\alpha'\sigma'} \mathcal{J}_{\alpha\alpha'}(t)[\vec{\sigma}_{\sigma\sigma'}\vec{S} + \frac{1}{4}\delta_{\sigma\sigma'}] c^{\dagger}_{k\sigma,\alpha} c_{k'\sigma',\alpha'}$$

$$\mathcal{J}_{\alpha,\alpha'}(t) = \sqrt{\Gamma_{\alpha}(t)\Gamma_{\alpha'}(t)}/(\pi\rho_0 E_d(t)) \qquad \Gamma_{\alpha}(t) = 2\pi\rho_0 |V_{\alpha}(x(t))|^2$$



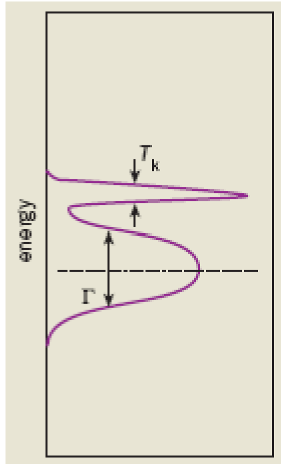
Odd-spin Kondo shuttle



Competition between

Breit-Wigner Resonance

$$G = \frac{2e^2}{h}\left\langle \frac{4\Gamma_L(t)\Gamma_R(t)}{(\Gamma_L(t)+\Gamma_R(t))^2}\right\rangle$$

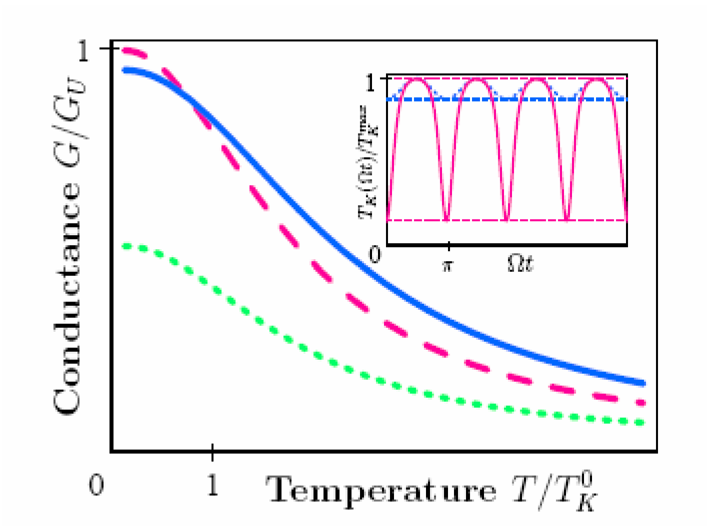


Abrikosov-Suhl Resonance

$$G(T) = \frac{3\pi^2}{16}G_U\left\langle \frac{4\Gamma_L(t)\Gamma_R(t)}{(\Gamma_L(t)+\Gamma_R(t))^2}\frac{1}{[\ln(T/T_K(t))]^2}\right\rangle$$

$$T_K(t) = D(t)\exp\left[-\frac{\pi U}{8\Gamma_0\cosh(2x(t)/\lambda_0)}\right]$$

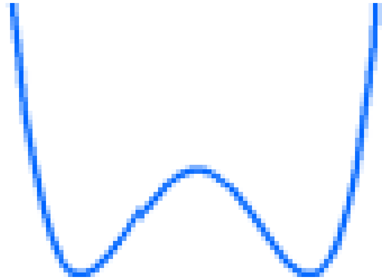
$$\langle T_K\rangle = T_K^0\left\langle \exp\left[\frac{\pi U}{4\Gamma_0}\frac{\sinh^2(x(t)/\lambda_0)}{1+2\sinh^2(x(t)/\lambda_0)}\right]\right\rangle$$

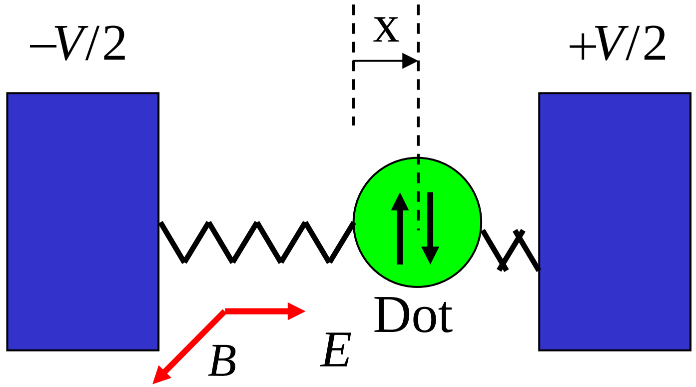


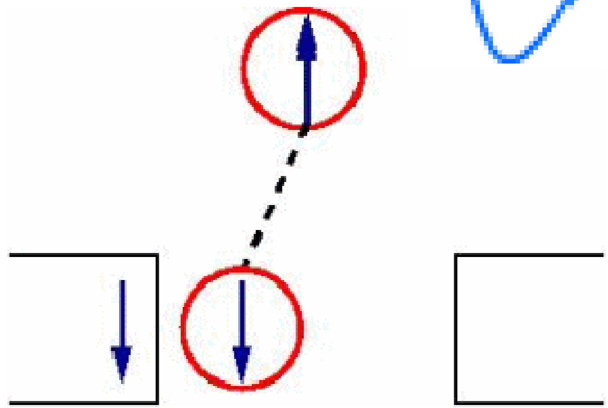
Adiabaticity $\hbar\Omega \ll T_K \ll \Gamma$

Time-dependent Kondo temperatures

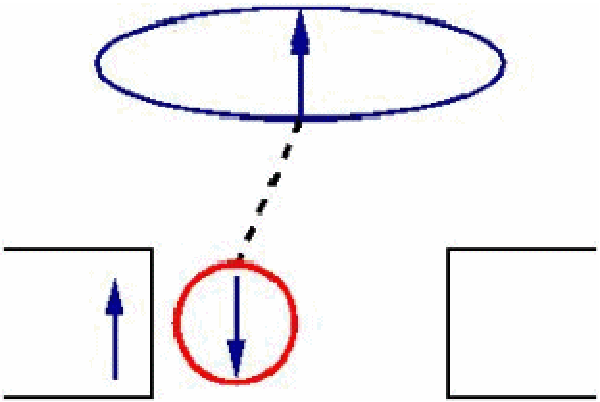
Even-spin Kondo shuttle



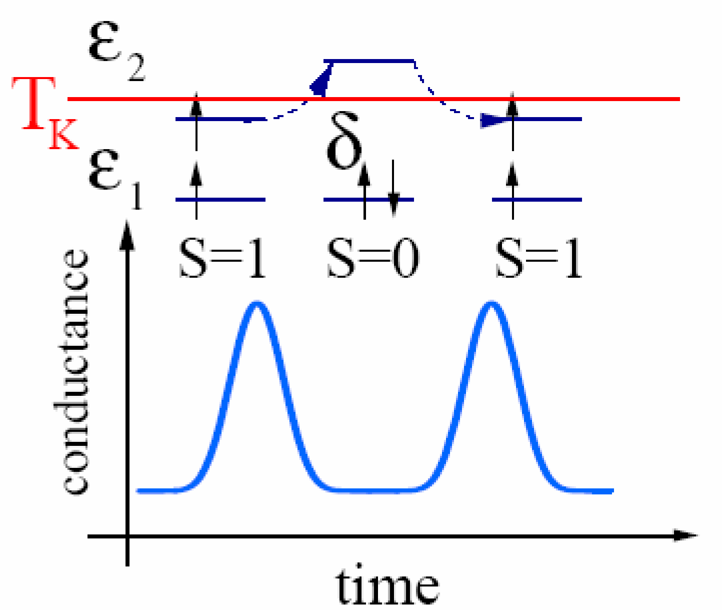




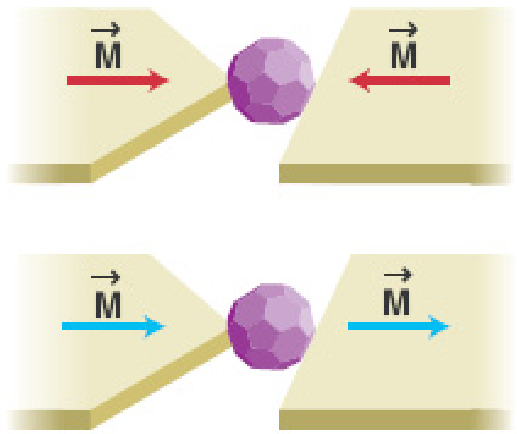
Singlet shuttling: No Kondo effect



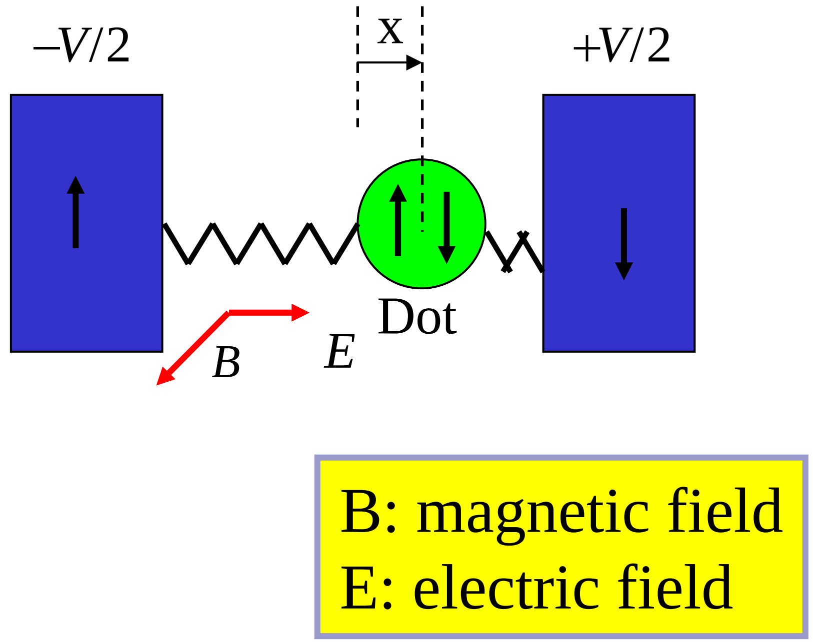
Triplet Kondo Shuttling



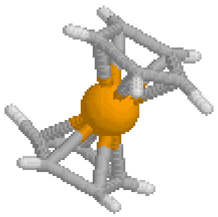
Perspectives



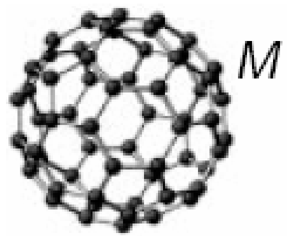
A. Pasupathy et al., Science ***306***,*86 (2004)*



- NEM-SET between spin-polarized leads
- NEM spin manipulation
- Rotating pendulum
- Coupled NEM-SET devices (DQD, TQD)

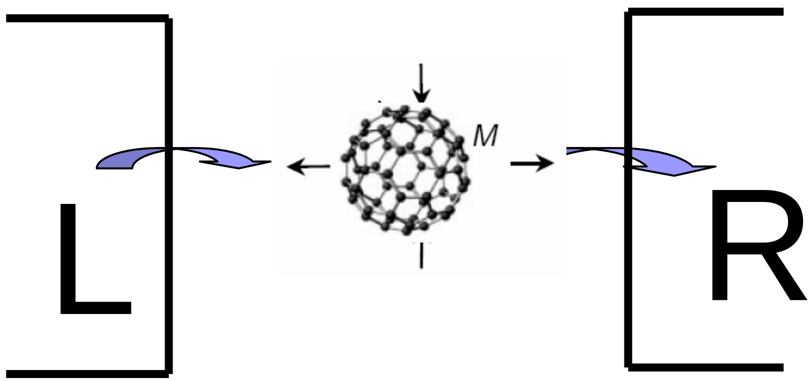


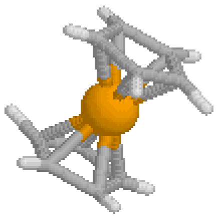
Conclusions



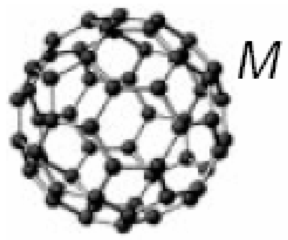
Molecular Transistor

- Phonon emission/absorption induces the Kondo tunneling
- Dynamical symmetries allow Kondo effect in excited triplet state
- Decoherence due to vibration does not destroy the Kondo effect





Conclusions



Molecular Transistor

- Phonon emission/absorption induces the Kondo tunneling
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Kondo shuttle

- Kondo shuttling allows the spin manipulation by NEM motion
- Kondo NEM-SET is a Mobile Quantum Impurity
- Dynamical symmetries influence the Kondo shuttling in S/T setups