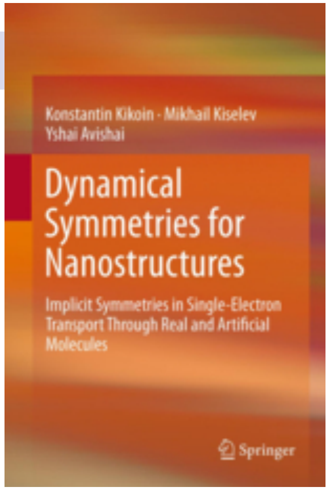
The Abdus Salam International Centre
for Theoretical Physics

Михаил Киселев

Эффект Кондо
в наноструктурах и сильно-коррелированных системах

**46- я Школа ФГБУ ПИЯФ по Физике Конденсированного Состояния,
Райвола, 12-17 Марта 2012**

References:



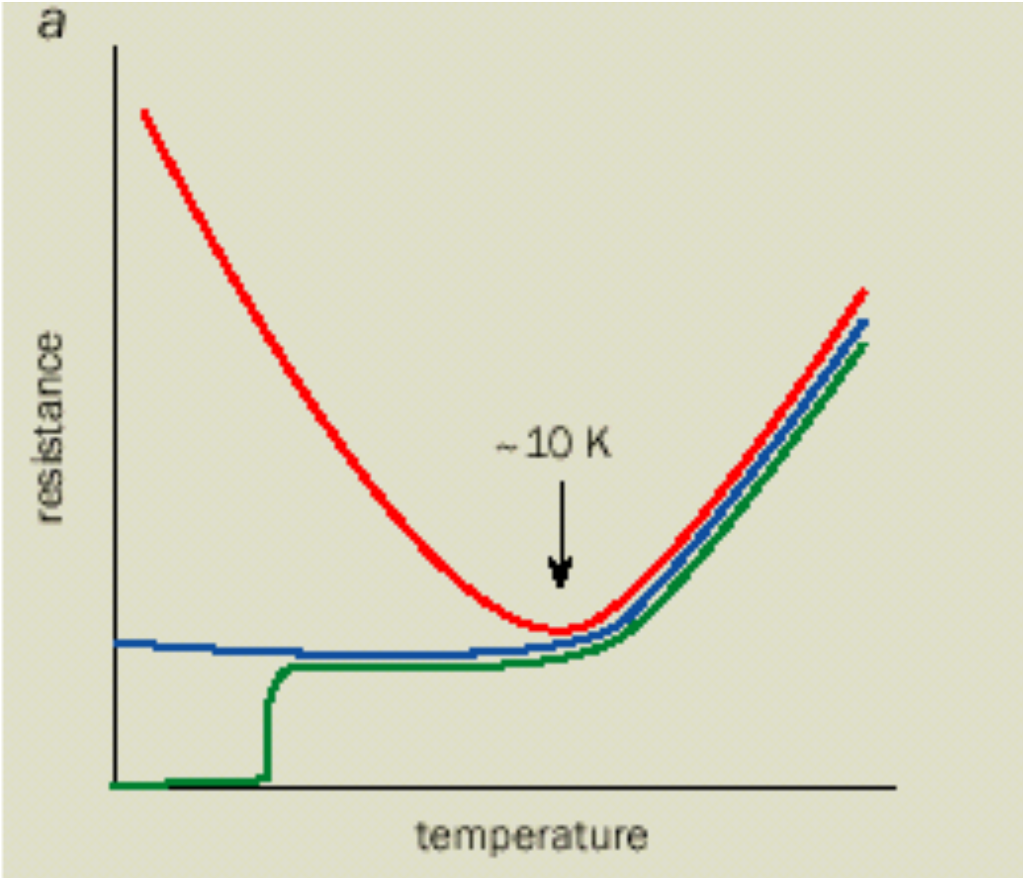
Books

A.Hewson.
The Kondo Problem to Heavy Fermions.
Cambridge University Press (1993)

K.Kikoin, M.N.Kiselev and Y.Avishai.
Dynamical Symmetries for Nanostructures
Springer (2012)

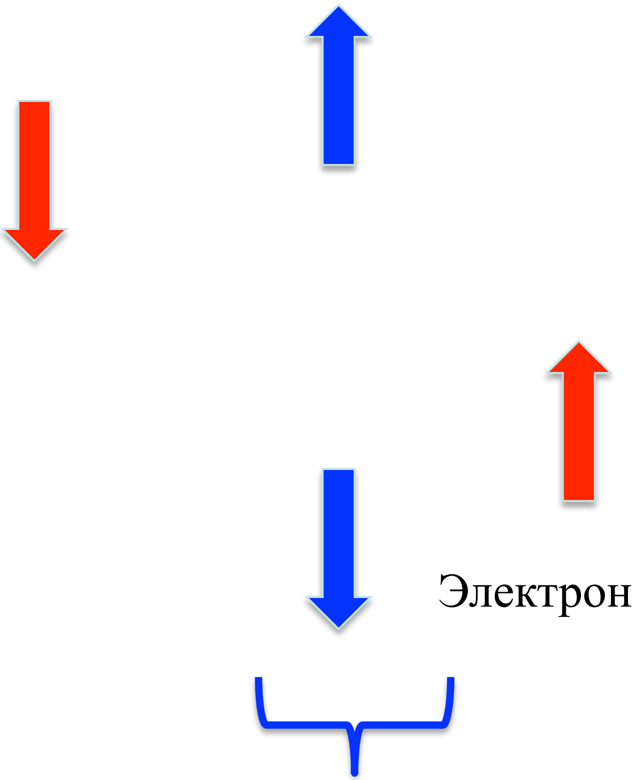
Transport through QDs: W.G. van der Wiel et al, RMP 75 (2003)
SET and Coulomb blockade: M.A.Kastner, RMP 64 (1992)
Popular reading: Leo Kouwenhoven and Charles Marcus, Physics World 1998
See also in the web Lecture courses of Ya. Blanter, Y. Gefen, Yu. Galperin

Эффект Кондо



$$\rho = \rho_c + c_m \ln\left(D/T\right) + bT^5$$

Эффект Кондо



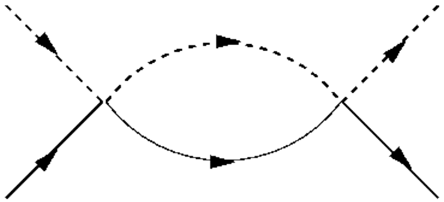
$$H_{Kondo} = J \sum_i \vec{S}_i \vec{s}_i$$

Электрон проводимости в чистом немагнитном металле: Au, Ag ...

Локальный момент: Mn, Co, Fe, Ni, Ce …

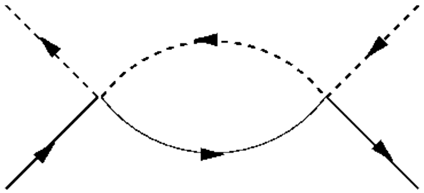
Эффект Кондо по теории возмущений (слабая связь)

$$H_{Kondo} = J\Psi^{\dagger}_{\alpha}(0)\vec{\sigma}_{\alpha\alpha'}\Psi_{\alpha'}(0)\vec{s}$$

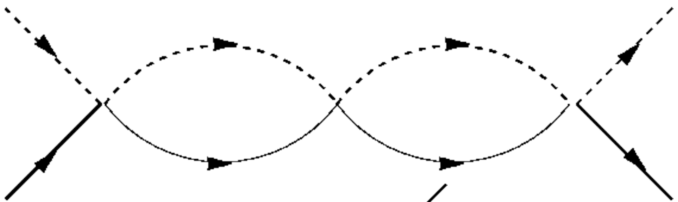


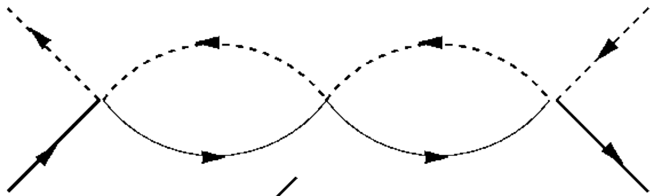
$$[S(S+1)\delta_{\sigma\sigma'}\delta_{mm'} - \sigma_{\sigma'\sigma}S_{m'm}]J^2\sum_k \frac{1-n_k}{\omega-\xi_k}$$

$$\propto J^2/D\ln\left(\frac{D}{\max[T,\omega]}\right)$$

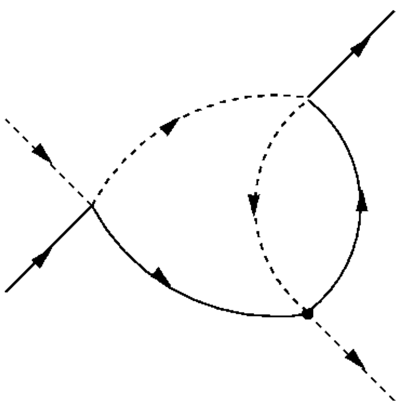


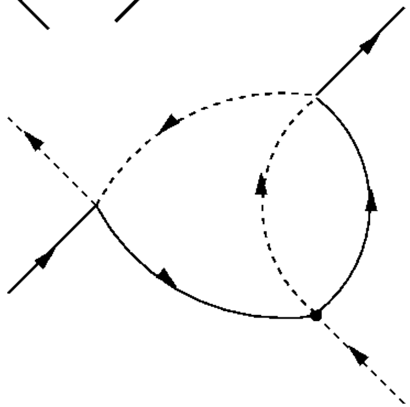
$$[S(S+1)\delta_{\sigma\sigma'}\delta_{mm'} + \sigma_{\sigma'\sigma}S_{m'm}]J^2\sum_k \frac{n_k}{\omega-\xi_k}$$





$$\propto J^3/D^2\ln^2\left(\frac{D}{\max[T,\omega]}\right)$$

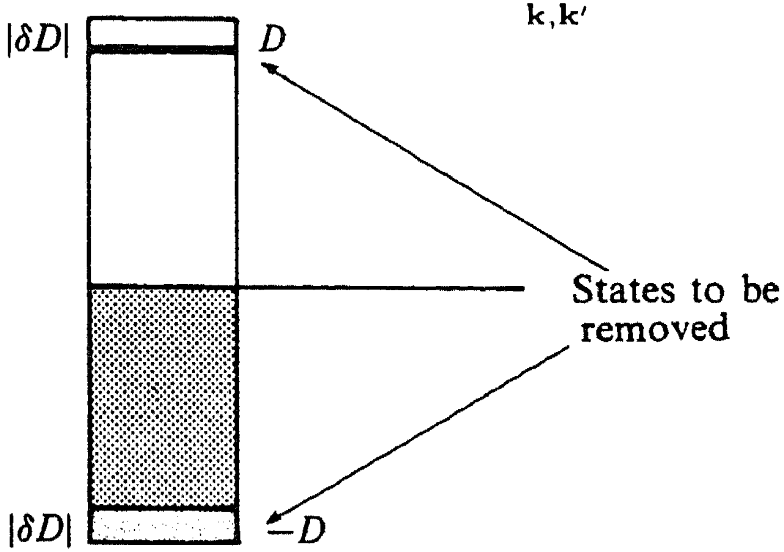


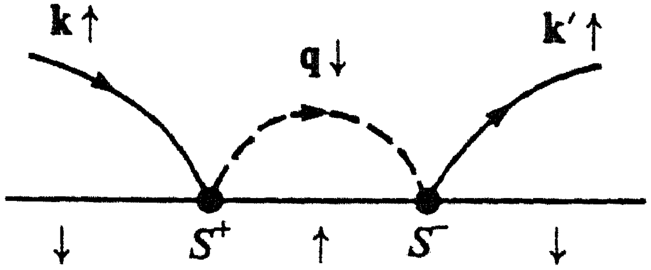


$$\propto J^3/D^2\ln^2\left(\frac{D}{\max[T,\omega]}\right)$$

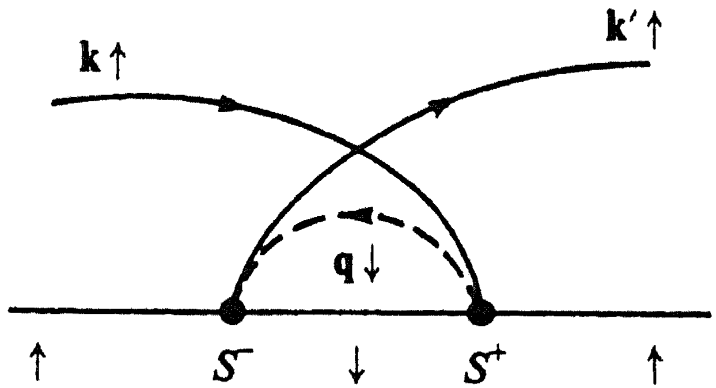
Poor man's scaling (Anderson)

$$H = \sum_{\mathbf{k},\mathbf{k}'} J_+ S^+ c^\dagger_{\mathbf{k},\downarrow} c_{\mathbf{k}',\uparrow} + J_- S^- c^\dagger_{\mathbf{k},\uparrow} c_{\mathbf{k}',\downarrow} + J_z S_z (c^\dagger_{\mathbf{k},\uparrow} c_{\mathbf{k}',\uparrow} - c^\dagger_{\mathbf{k},\downarrow} c_{\mathbf{k}',\downarrow}).$$





(i)

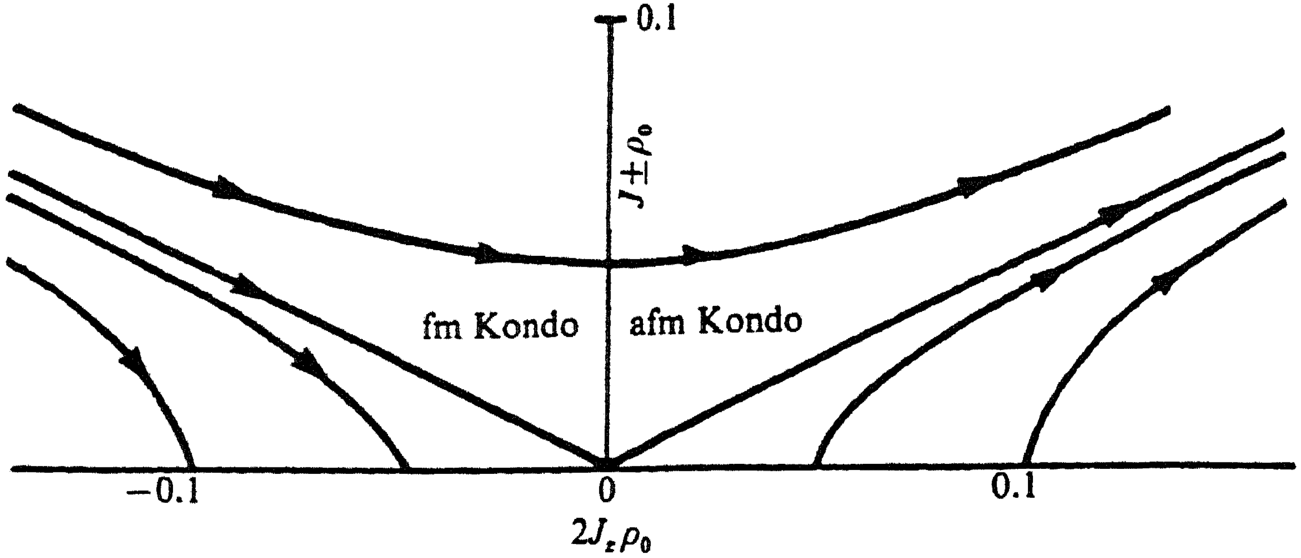


(ii)

Ренорм-группа

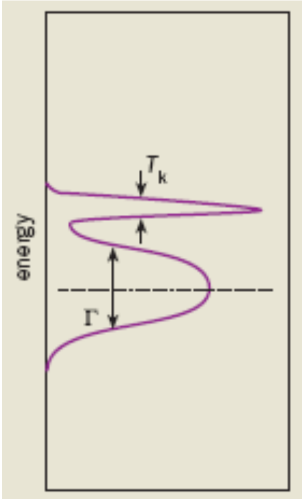
$$\frac{dJ_\pm}{d\ln D} = -2\rho_0 J_z J_\pm \quad \text{and} \quad \frac{dJ_z}{d\ln D} = -2\rho_0 J_\pm^2.$$

$$J_z^2 - J_\pm^2 = \text{const}..$$



Эффект Кондо в слабой связи

$$H_K = \sum_{k\alpha\sigma, k'\alpha'\sigma'} J_{\alpha\alpha'}[\vec{\sigma}_{\sigma\sigma'}\vec{S} + \frac{1}{4}\delta_{\sigma\sigma'}]c^{\dagger}_{k\sigma,\alpha}c_{k'\sigma',\alpha'}$$



$$J \to \mathcal{J} = \frac{J}{1-\nu J \ln(D/T)}$$

$$T_K = D \exp\left(-\frac{1}{\nu J}\right)$$

$T \gg T_K$ Слабая связь, работает теория возмущений

$T \ll T_K$ Сильная связь, теория возмущений неприменима

Феноменологическая теория Ферми-жидкости (Нозиер)

Эффект Кондо (сильная связь) $T \ll T_K$

Фаза рассеяния $\delta_\uparrow + \delta_\downarrow = 0.$ $\delta_\uparrow - \delta_\downarrow = \pi.$ $\delta_s = s\frac{\pi}{2}$

Т-матрица $-\pi\nu T_s(0) = \frac{1}{2i}\left(\mathbb{S}_s - 1\right), \quad \mathbb{S}_s = e^{2i\delta_s}$

Эффективная модель в режиме сильной связи

$$H_{\text{fixed point}} = \sum_{ks} \xi_k \varphi^\dagger_{ks}\varphi_{ks} - \sum_{kk's} \frac{\xi_k + \xi_{k'}}{2\pi\nu T_K}\varphi^\dagger_{ks}\varphi_{k's} + \frac{1}{\pi\nu^2 T_K}\rho_\uparrow\rho_\downarrow .$$

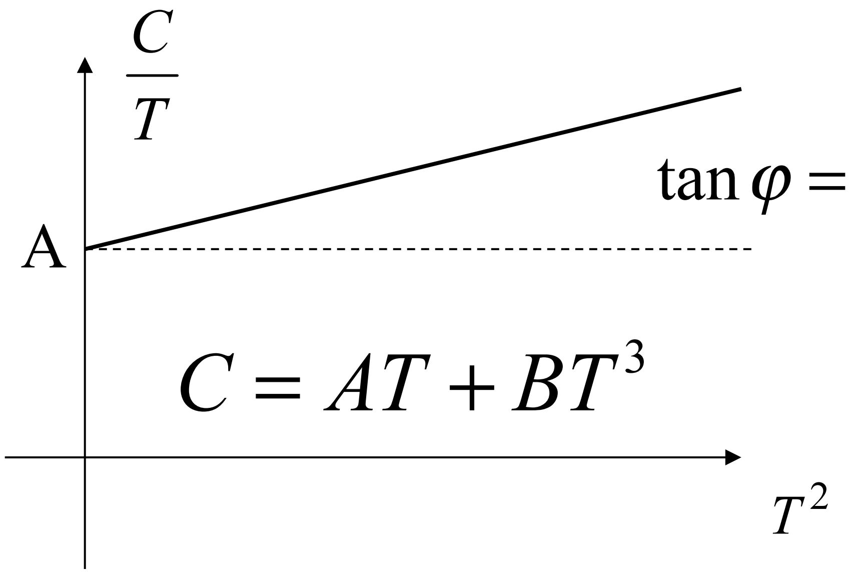
$$-\pi\nu \widetilde{T}_{in}(\omega) = i\,\frac{\omega^2 + \pi^2 T^2}{2\,T_K^2} . \qquad -\pi\nu \,\mathrm{Im}\, T_s(\omega) = 1 - \frac{3\omega^2 + \pi^2 T^2}{2\,T_K^2} .$$

Кондактанс при низких температурах (ферми-жидкость)

$$G = G_0\left[1 - (\pi T/T_K)^2\right], \quad T \ll T_K$$

Эффект Кондо
в сильно-коррелированных системах

Теплоемкость



$$E = 2V \int \epsilon(p) n(\epsilon_p) \frac{d^3p}{(2\pi\hbar)^3}$$

$$C = V^{-1} \left(\frac{\partial E}{\partial T}\right)_V = 2 \int \epsilon(p) \left(\frac{\partial n(\epsilon_p)}{\partial T}\right) \frac{d^3p}{(2\pi\hbar)^3}$$

$$C = \frac{\pi^2}{3}\rho(0)T = \gamma T \qquad \gamma = \frac{p_F m^*}{3\hbar^3} \qquad \rho(0) = \frac{p_F m^*}{\pi^2\hbar^3}$$

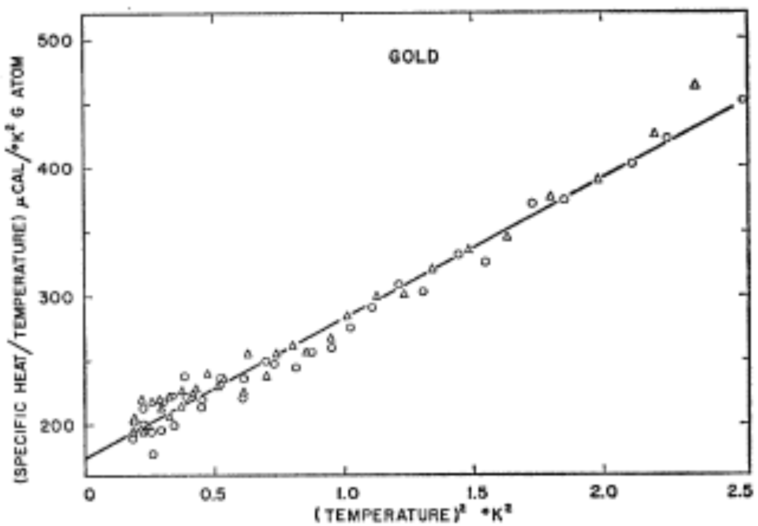
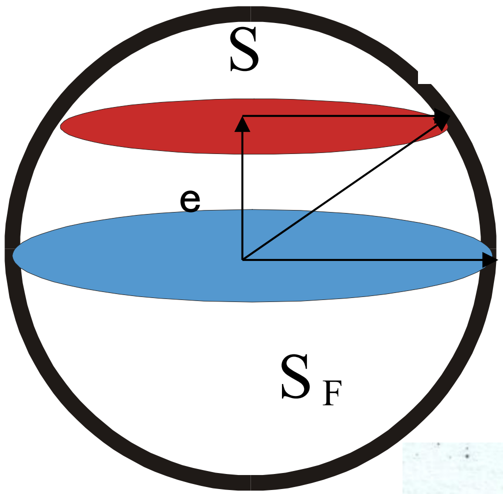


FIG. 1. Plot of (specific heat/temperature) versus (temperature²) for gold.

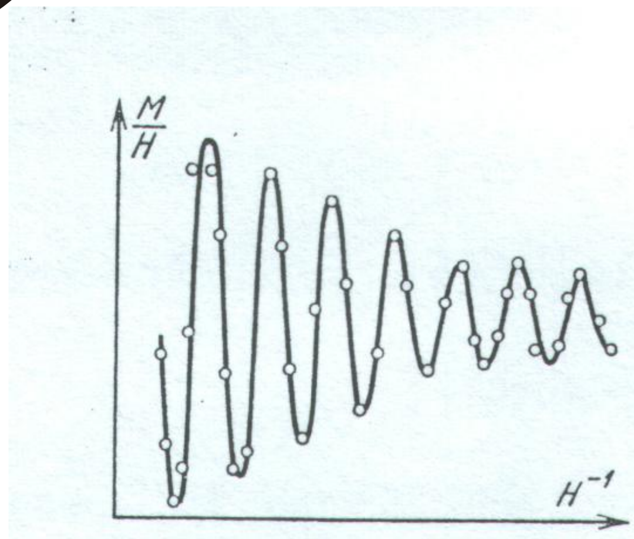
	N/V $[cm^{-3}]$	ϵ_F [eV]	T_F [K]	m^*/m
Li	4.6×10^{22}	4.7	5.5×10^4	2.3
Na	2.5	3.1	3.7	1.3
K	1.34	2.1	2.4	1.2
Cu	8.5	7.0	8.2	1.3
Ag	5.76	5.5	6.4	1.1
Au	5.9	5.5	6.4	1.1

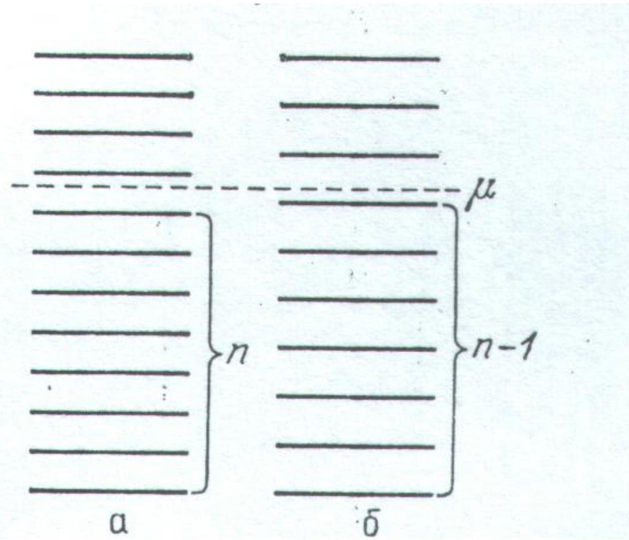
Эффект де Гааза - ван Альфена (dHvA)



$$M \approx T\sqrt{\frac{2e\hbar}{\pi^3 cH}}\sum_m S_m \left|\frac{\partial^2 S_m}{\partial p_z^2}\right| \exp\left(-\frac{2\pi^2 T c m^*}{e\hbar H}\right)\sin\left(\frac{cS_m}{e\hbar H}\pm\frac{\pi}{4}\right)\cos\left(\frac{\pi m^*}{m}\right)$$

$$m^* = \frac{1}{2\pi}\frac{\partial S}{\partial \epsilon}$$

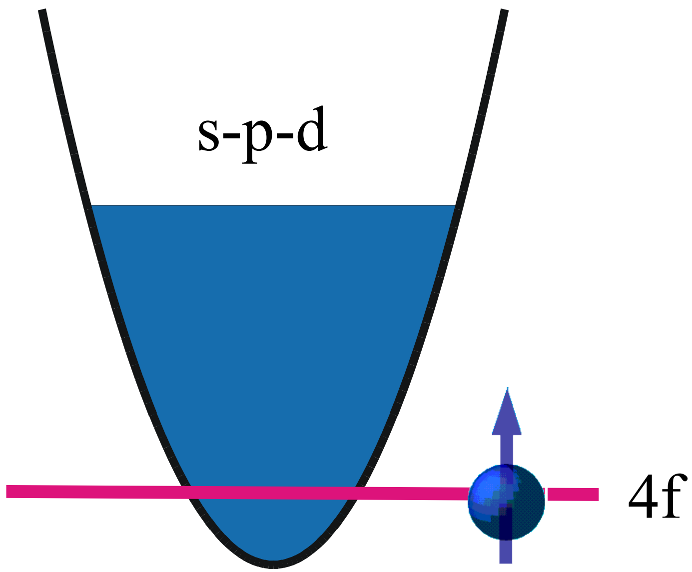


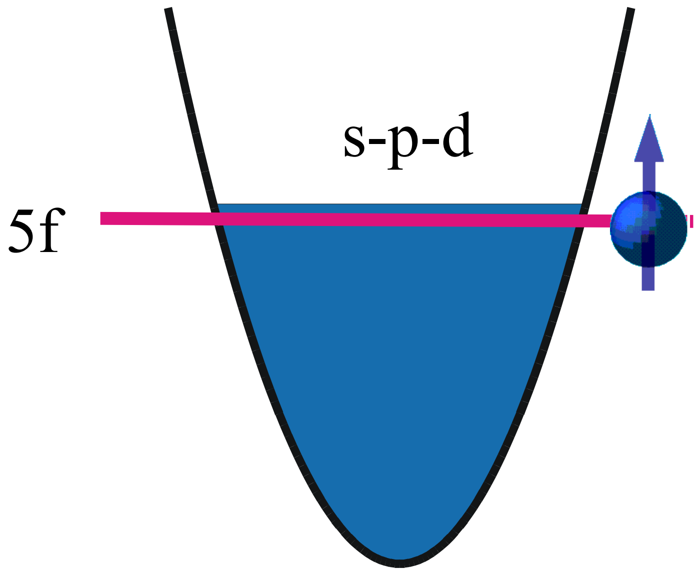


"Тяжелые" фермионы (heavy fermions)

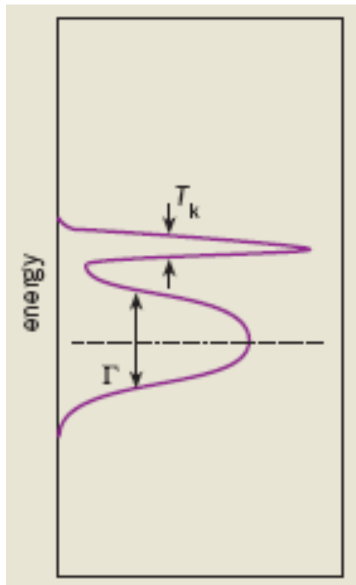
Type	Material	T^*	$T_c,\ x_c,\ B_c$	Properties	ρ	γ_n $mJmol^{-1}K^{-2}$	Ref.
Metal	$CeCu_6$	$10K$	-	Simple HF Metal	T^2	1600	[1]
Super-conductors	$CeCu_2Si_2$	$20K$	T_c=0.17K	First HFSC	T^2	800-1250	[2]
	UBe_{13}	2.5K	T_c=0.86K	Incoherent metal→HFSC	$\rho_c \sim$ 150$\mu\Omega$cm	800	[3]
	$CeCoIn_5$	38K	T_c=2.3K	Quasi 2D HFSC	T	750	[4]
Kondo Insulators	$Ce_3Pt_4Bi_3$	$T_\chi \sim 80K$	-	Fully Gapped KI	$\sim e^{\Delta/T}$	-	[5]
	$CeNiSn$	$T_\chi \sim 20K$	-	Nodal KI	Poor Metal	-	[6]
Quantum Critical	$CeCu_{6-x}Au_x$	$T_0 \sim 10K$	$x_c = 0.1$	Chemically tuned QCP	T	$\sim \frac{1}{T_0} \ln\left(\frac{T_0}{T}\right)$	[7]
	$YbRh_2Si_2$	$T_0 \sim 24K$	$B_\perp$=0.06T $B_\parallel$=0.66T	Field-tuned QCP	T	$\sim \frac{1}{T_0} \ln\left(\frac{T_0}{T}\right)$	[8]
SC + other Order	UPd_2Al_3	110K	T_{AF}=14K, T_{sc}=2K	AFM + HFSC	T^2	210	[9]
	URu_2Si_2	75K	T_1=17.5K, T_{sc}=1.3K	Hidden Order & HFSC	T^2	120/65	[10]

"Тяжелые" фермионы (heavy fermions)





System	γ_0 (J/K^2mol)	T_F K	m^*/m	T_c K	T_K K
$CeCu_6$	1.6	300	500	-	5
$CeAl_2$	0.14	4000	42	-	3.9
$CeCu_2Si_2$	1.1	350	450	0.8	10
$CeRu_2Si_2$	0.35	1200	100	-	20
UBe_{13}	0.72	700	260	-	8
UPt_3	0.42	1100	180	5	80
UCd_{11}	1.42	400	425	5	-
U_2Zn_{17}	0.42	1100	180	10	-



Решетка Кондо

$$H = \sum_k \varepsilon(k) c^+_{k,\sigma} c_{k,\sigma} + J \sum_i \vec{S}_i \vec{s}_i + \sum_{ij} I_{ij} \vec{S}_i \vec{S}_j$$

$CeRu_2Si_2$

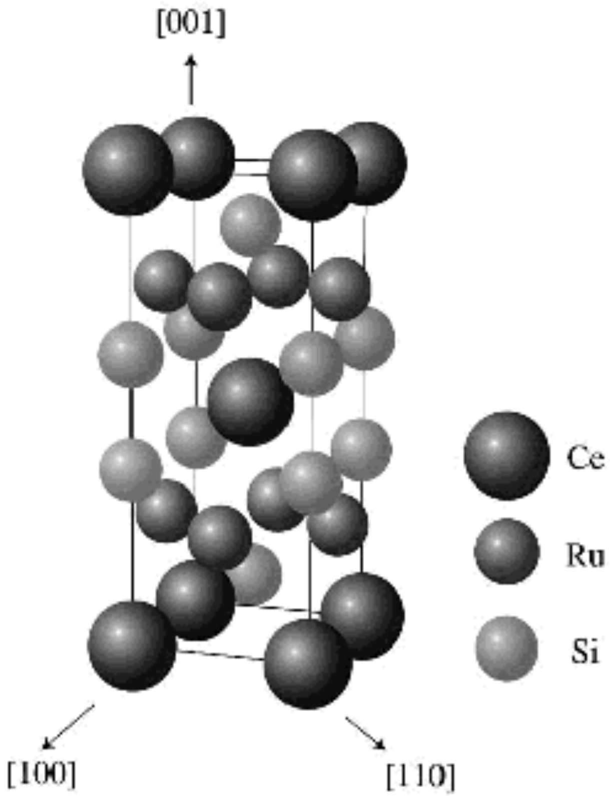
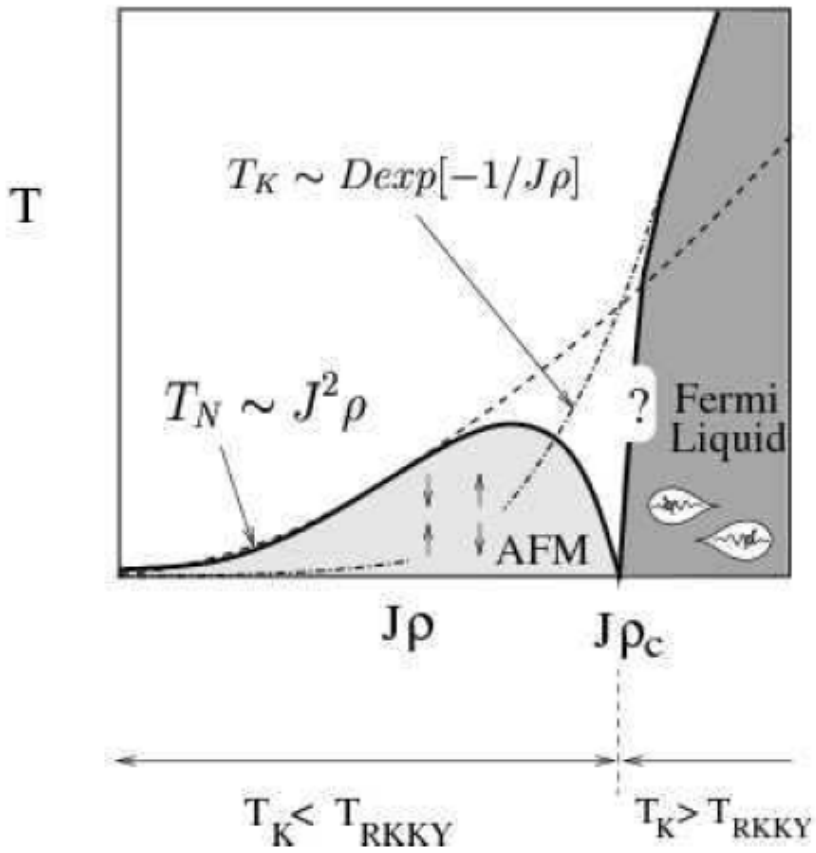


Fig. 10. Crystal structure of $CeRu_2Si_2$.

$$H_{Kondo} = J \sum_i \vec{S}_i \vec{s}_i$$

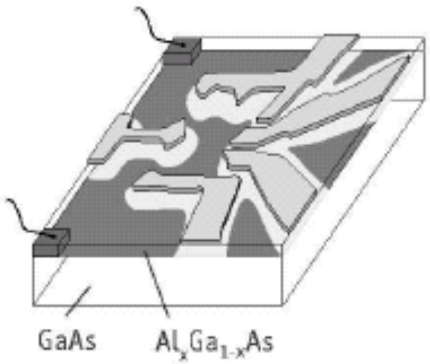
$$H_{RKKY} = \sum_{i,j} I_{ij} \vec{S}_i \vec{S}_j$$

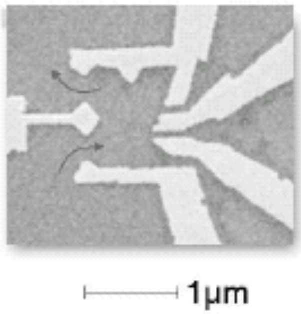
Тяжелые фермионы: фазовая диаграмма

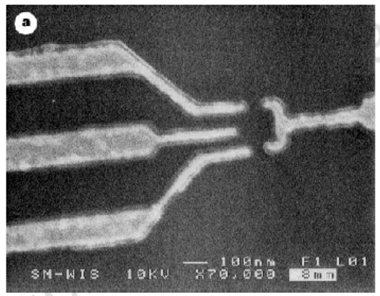


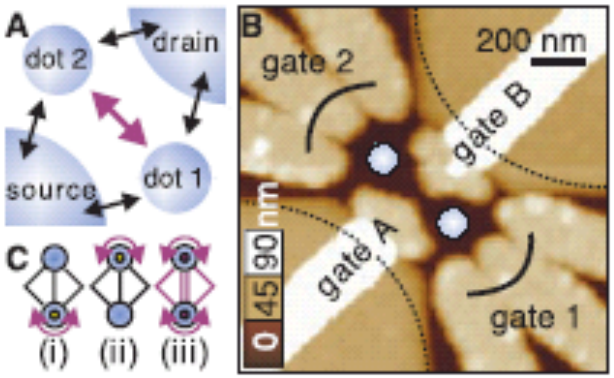
Эффект Кондо в наноструктурах

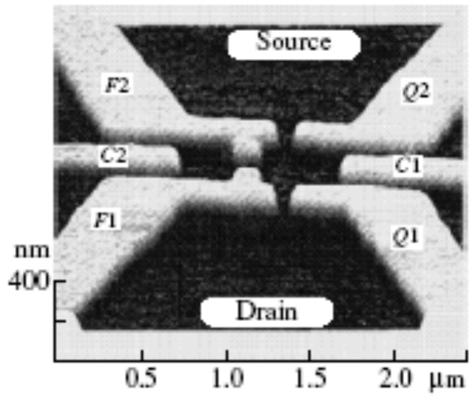
Квантовые точки

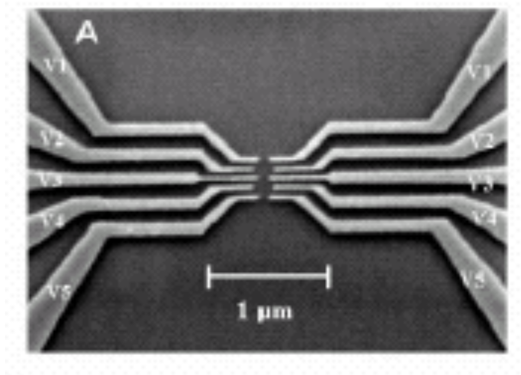












D.Goldhaber-Gordon et al (1998)

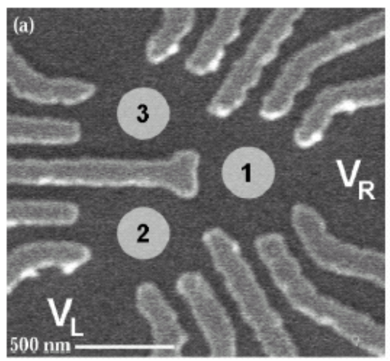
J.P.Kotthaus (1995)

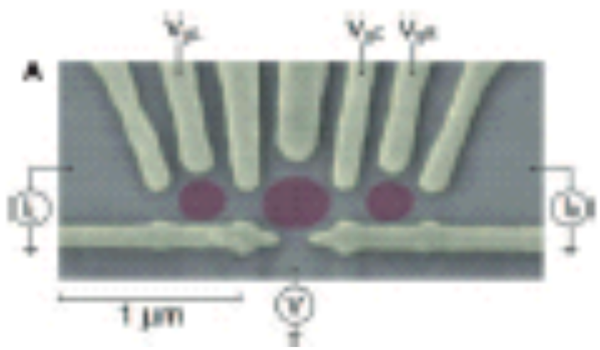
A.Holleitner et al (2002)

L.W.Molenkamp et al (1995)

H.Jeong et al (2001)

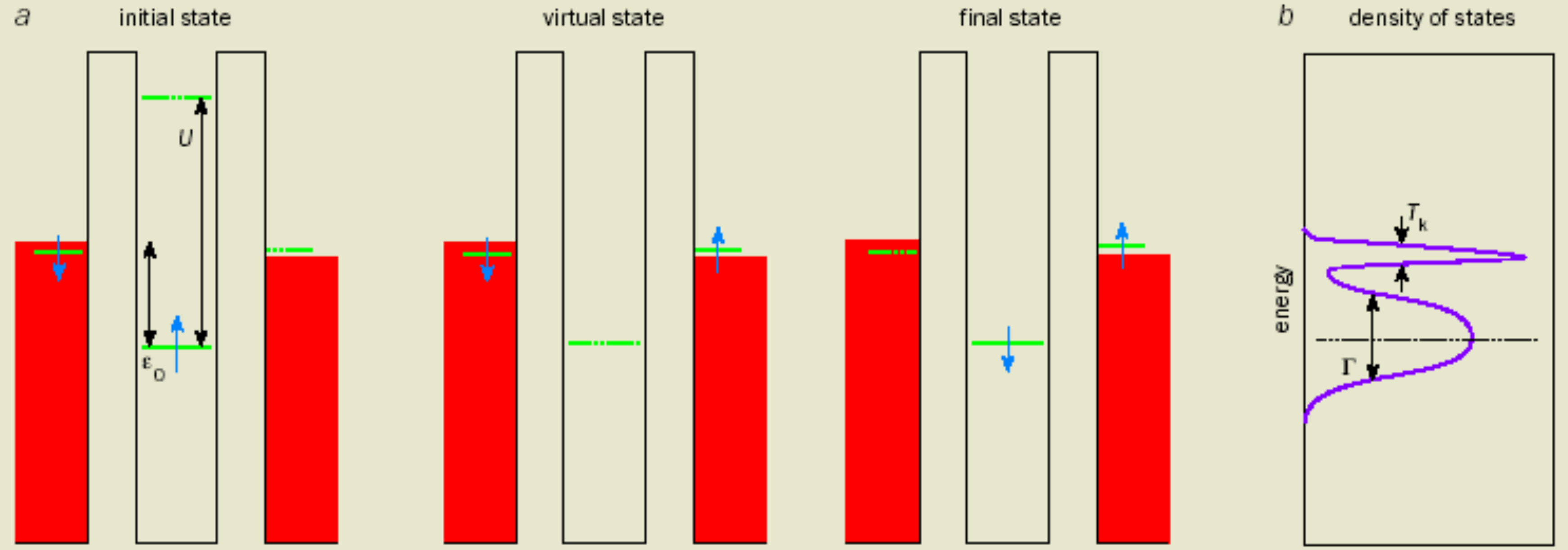
C.Marcus et al (2003)





Эффект Кондо в квантовых точках

2 Spin flips

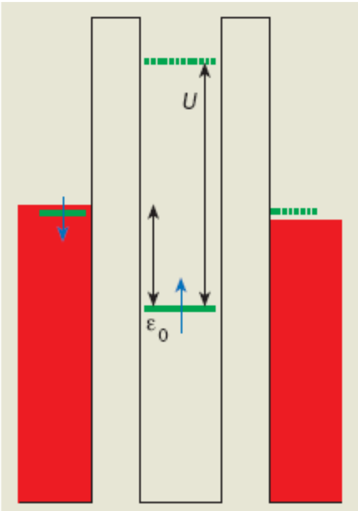


(*a*) The Anderson model of a magnetic impurity assumes that it has just one electron level with energy ε_0 below the Fermi energy of the metal (red). This level is occupied by one spin-up electron (blue). Adding another electron is prohibited by the Coulomb energy, *U*, while it would cost at least $|\varepsilon_0|$ to remove the electron. Being a quantum particle, the spin-up electron may tunnel out of the impurity site to briefly occupy a classically forbidden "virtual state" outside the impurity, and then be replaced by an electron from the metal. This can effectively "flip" the spin of the impurity. (*b*) Many such events combine to produce the Kondo effect, which leads to the appearance of an extra resonance at the Fermi energy. Since transport properties, such as conductance, are determined by electrons with energies close to the Fermi level, the extra resonance can dramatically change the conductance.

Single orbital level coupled to two leads

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

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

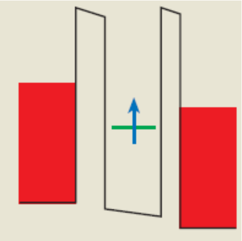


$$H_{tun} = \sum_{k,\sigma\alpha} [V_\alpha c^\dagger_{k,\sigma\alpha} d_\sigma + H.c.]$$

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

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

Single orbital level coupled to two leads



Glazman-Raikh rotation

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

$$\tan\theta = \left|\frac{V_R}{V_L}\right| \qquad |V|^2 = |V_L|^2 + |V_R|^2$$

Only symmetric combination of the leads is coupled to the dot

Single level Anderson model is reduced to Kondo model

From Anderson model to Kondo model

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

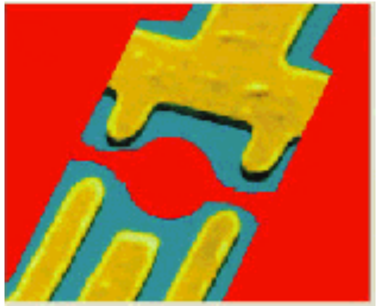
$$H_K = W H' W^\dagger \qquad W = \exp(V)$$

$$V = \sum_{k\sigma\alpha} [\left(w^{(1)}_{k\alpha}(1 - n_{-\sigma}) + w^{(2)}_{k\alpha} n_{-\sigma} \right) d^\dagger_\sigma c_{k\sigma\alpha} + h.c.]$$

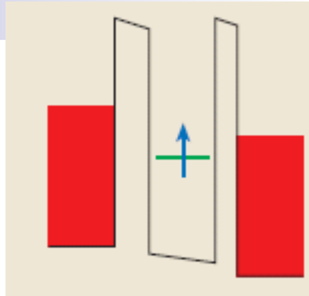
$$0 = H_{tun} + [V, H_{dot} + H_{leads}]$$

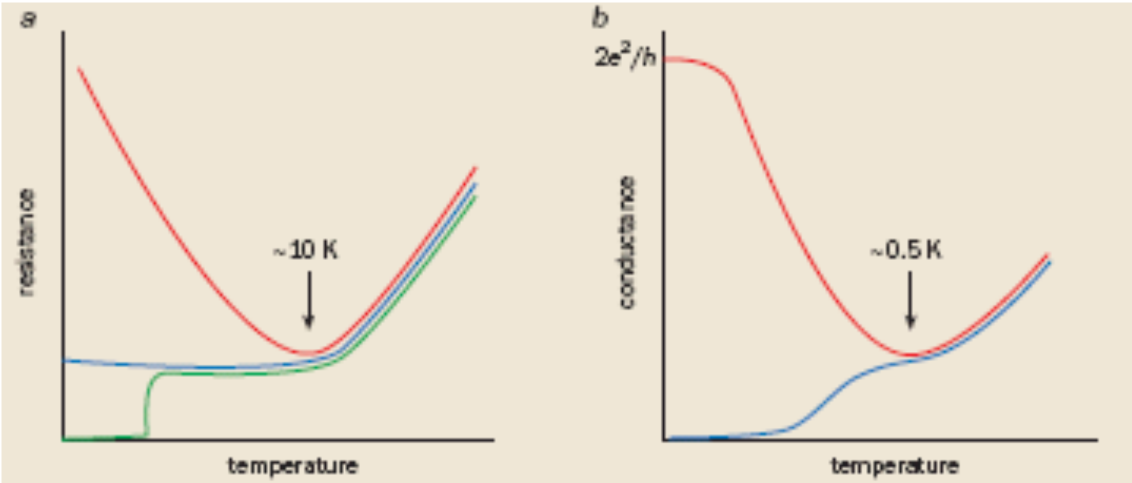
$$H_K = \sum_{k\alpha\sigma,k'\alpha'\sigma'} J_{\alpha\alpha'} [\vec{\sigma}_{\sigma\sigma'} \vec{S} + \frac{1}{4}\delta_{\sigma\sigma'}] c^\dagger_{k\sigma,\alpha} c_{k'\sigma',\alpha'}$$

$$J_{\alpha,\alpha'} = \sqrt{\Gamma_\alpha \Gamma_{\alpha'}}/(\pi\rho_0 E_d)$$

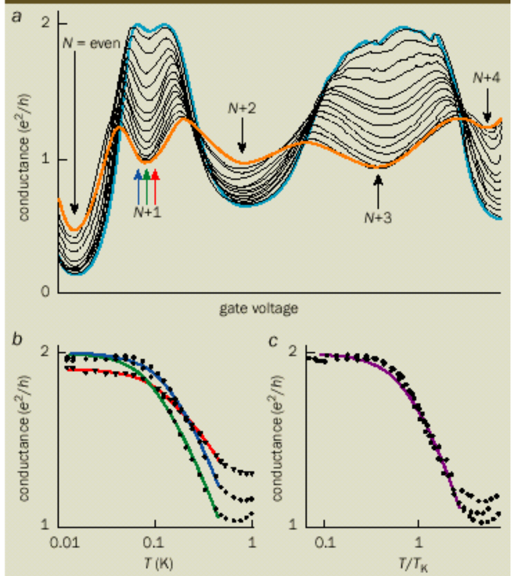


Масштабная инвариантность (скейлинг)





5 Universal scaling

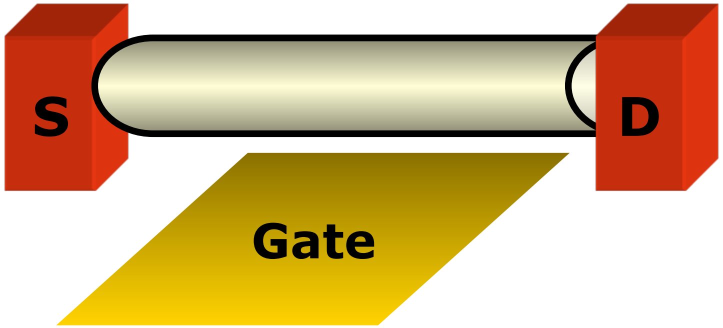


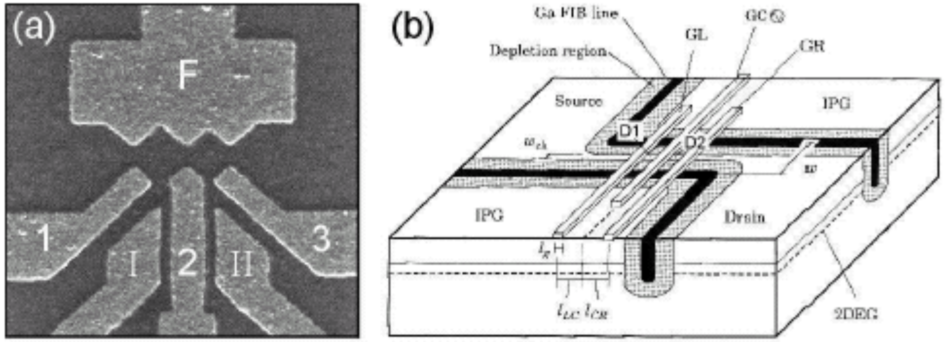
(*a*) The conductance (*y*-axis) as a function of the gate voltage, which changes the number of electrons, *N*, confined in a quantum dot. When an even number of electrons is trapped, the conductance decreases as the temperature is lowered from 1 K (orange) to 25 mK (light blue). This behaviour illustrates that there is no Kondo effect when *N* is even. The opposite temperature dependence is observed for an odd number of electrons, i.e. when there is a Kondo effect. (*b*) The conductance for *N* + 1 electrons at three different fixed gate voltages indicated by the coloured arrows in (*a*). The Kondo temperature, T_K, for the different gate voltages can be calculated by fitting the theory to the data. (*c*) When the same data are replotted as a function of temperature divided by the respective Kondo temperature, the different curves lie on top of each other, illustrating that electronic transport in the Kondo regime is described by a universal function that depends only on T/T_K.

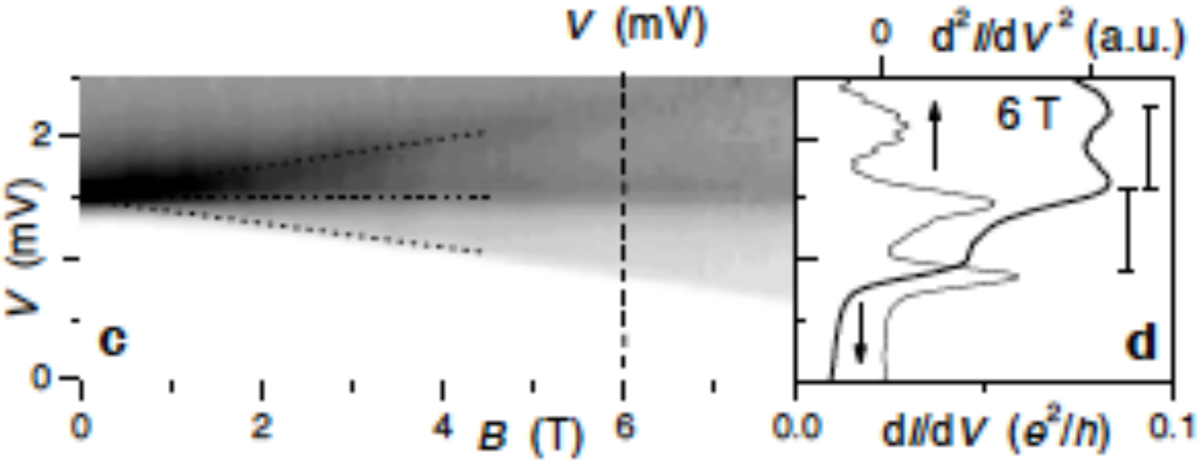
$$G/G_0 \propto \ln^{-2}\left(\max[T/T_K]\right)$$

$$T_K = \frac{1}{2}(\Gamma U)^{1/2}\exp\left(\pi\varepsilon_0\frac{\varepsilon_0+U}{\Gamma U}\right)$$

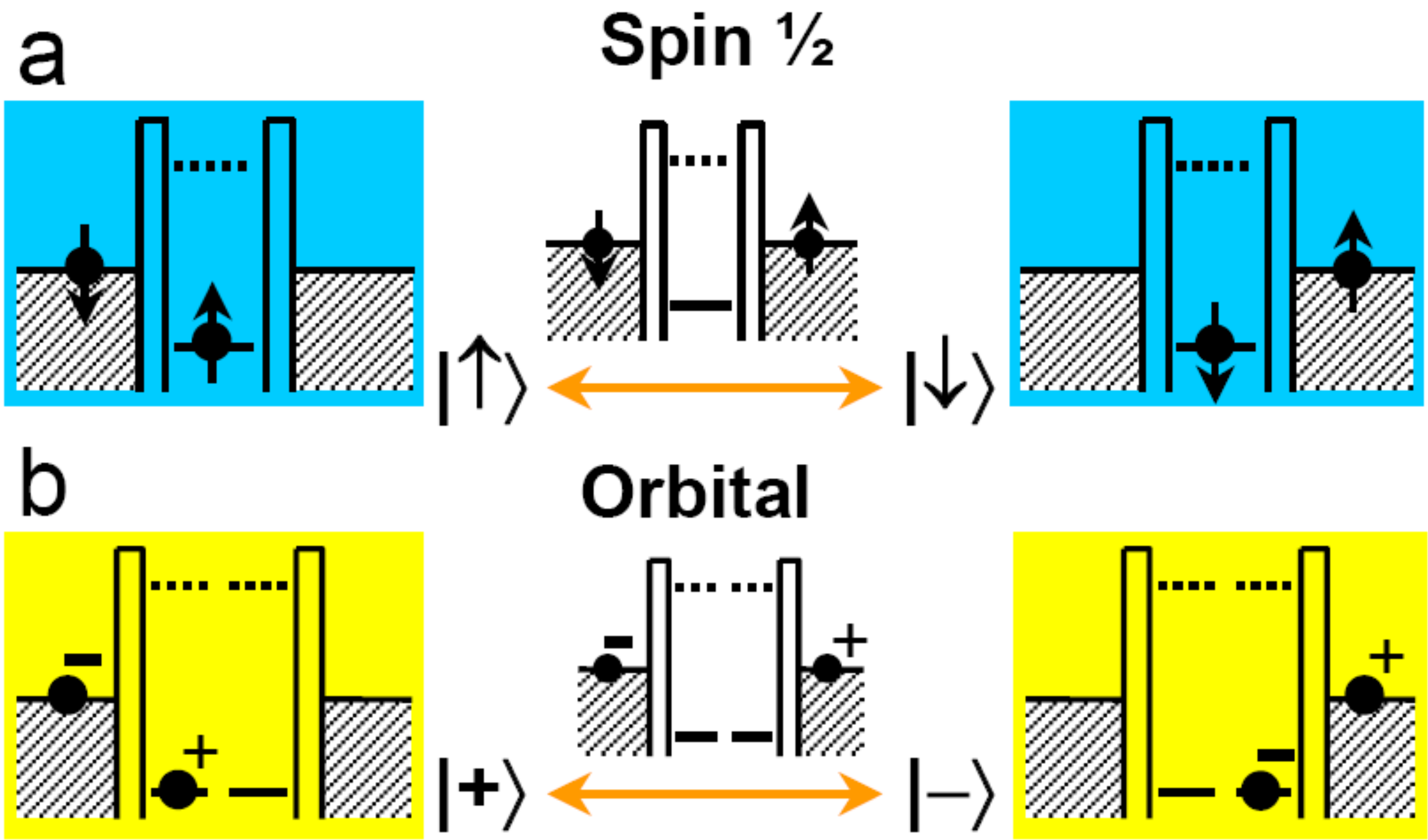
Экзотические эффекты Кондо

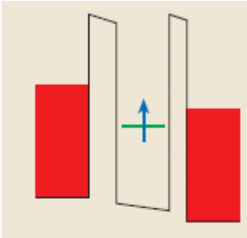




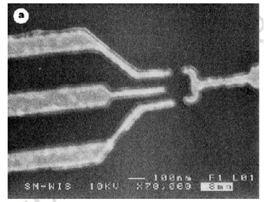


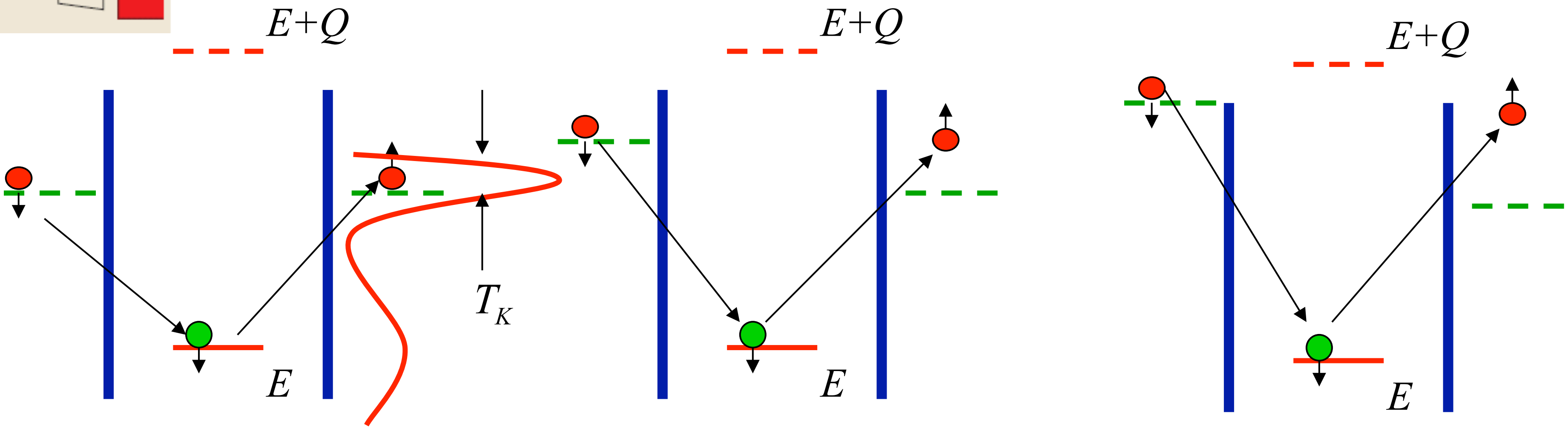
Спиновый и орбитальный эффекты Кондо





Kondo effect: coherence and decoherence





Zero-bias (equilibrium)

$$T_K$$

Small bias (quasi-equilibrium)

$$eV \ll T_K$$

Large bias (out of equilibrium)

$$eV \gg T_K$$

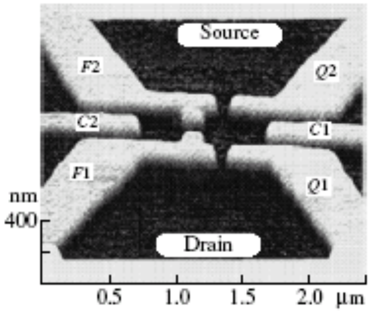
Effects of decoherence

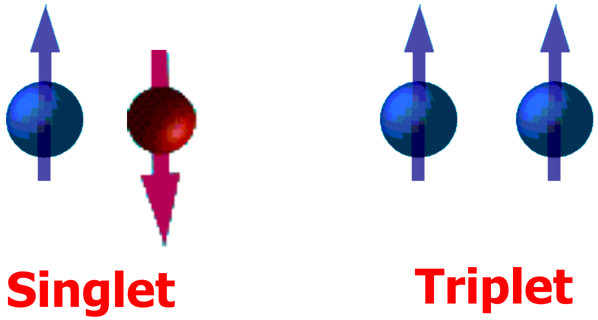
$$\Gamma_{rel} \sim eV$$

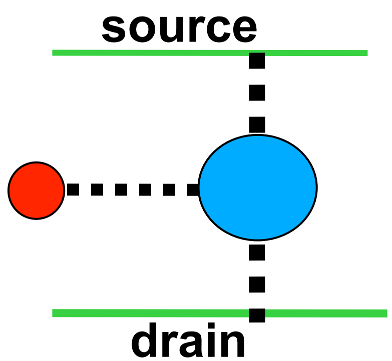
$$\Gamma_{rel} \sim eV / \ln^2 \left(eV / T_K \right)$$

There is no strong coupling (Kondo) regime at low T in out of equilibrium

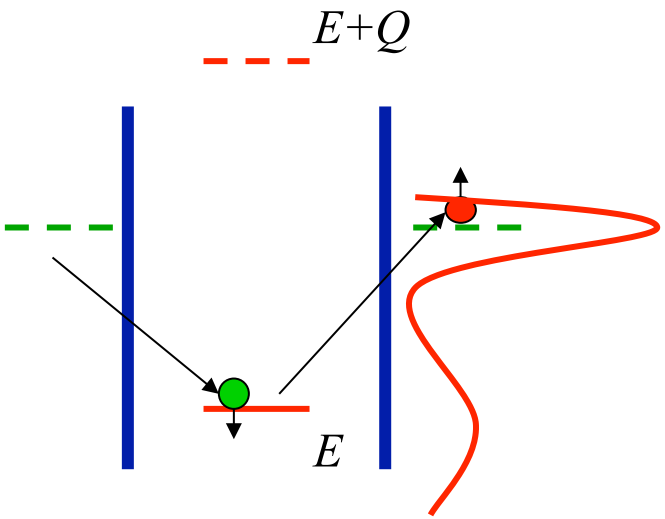
From Single Quantum Dot to Double Quantum Dot

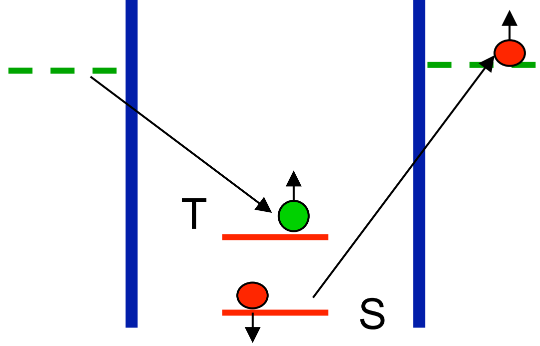


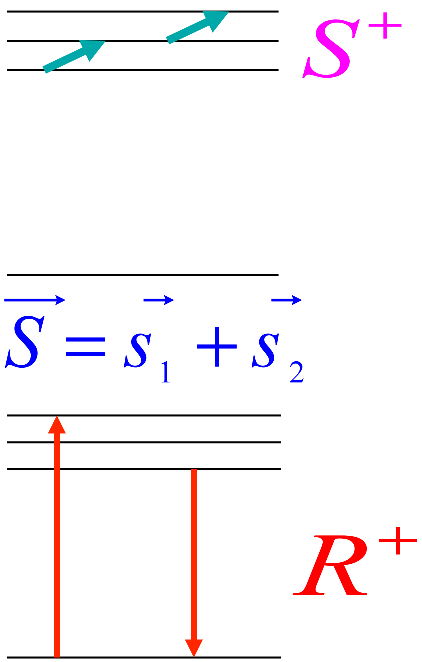




- Kondo co-tunneling through QD: N=1
- Kondo co-tunneling through DQD: N=2







$\vec{S} = \vec{s}_1 + \vec{s}_2$

Kondo Hamiltonian

$H = J\,(\mathbf{S}\,\mathbf{s})$

$S=1/2$

Generalized Kondo Hamiltonian

$H = J_1\,(\mathbf{S}\,\mathbf{s}) + J_2\,(\mathbf{R}\,\mathbf{s})$

$S=1$ (triplet) plus $S=0$ (singlet)

Non-universal Kondo temperature

$$\Delta_{TS} \sim T_K(\Delta_{TS})$$

$\vec{R} = \vec{s}_1 - \vec{s}_2$

“Simple” knowledge about Kondo Effect

- Kondo effect exists if the total number of electrons in a dot is odd

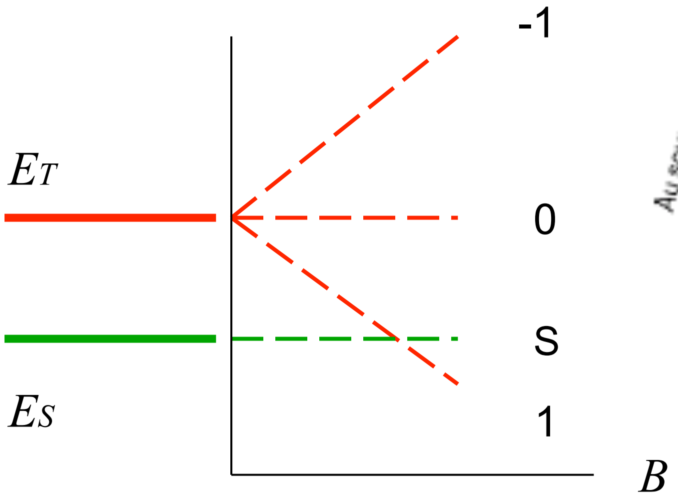
- Kondo effect is destroyed by external magnetic field

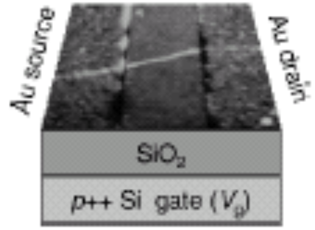
- Relaxation effects associated with the non-equilibrium conditions eliminate the Kondo peak

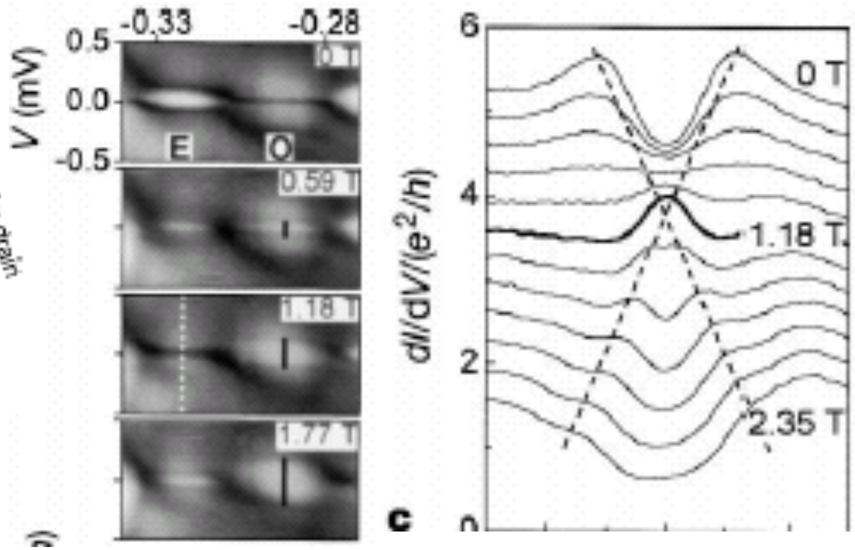
Is it always true?

S/T transition: Magnetic field induced Kondo effect

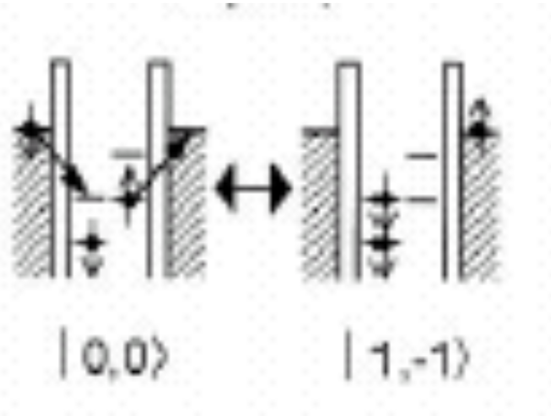
Symmetry reduction from SO(4) to SU(2)







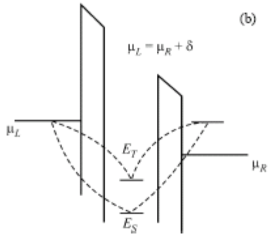
$$H_{Kondo} = J\left(\vec{R} \bullet \vec{s}\right)$$



Kondo effect due to the dynamical symmetry of DQD

M. Pustilnik, Y. Avishai & K.Kikoin (2000)

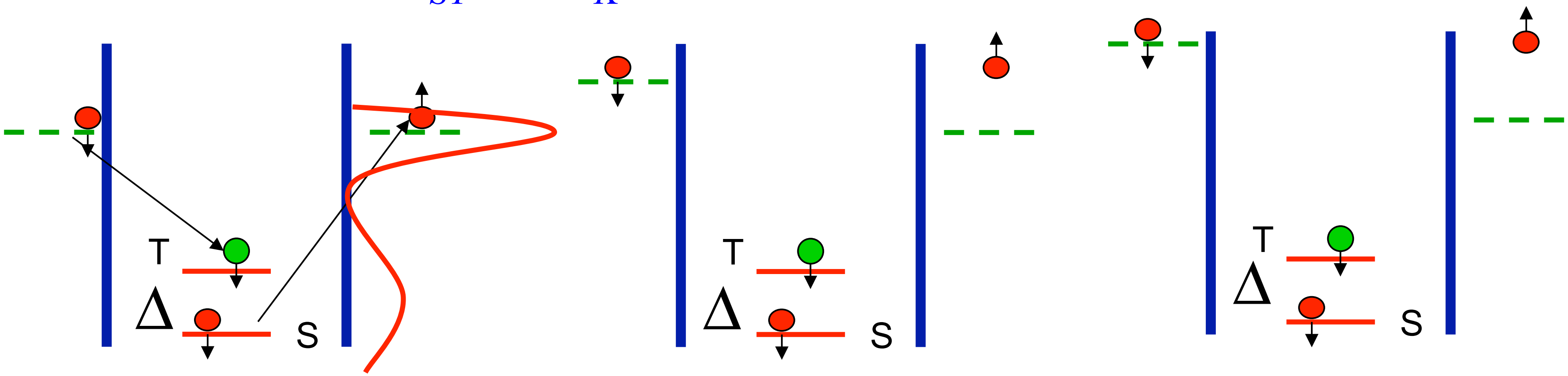
D. Kobden et al (2000)



Non-equilibrium Kondo effect in DQD

$\Delta_{ST} \ll T_K^{EQ}$ **Underscreened S=1 NEK**

$\Delta_{ST} \gg T_K^{EQ}$ **Is Kondo effect possible?**

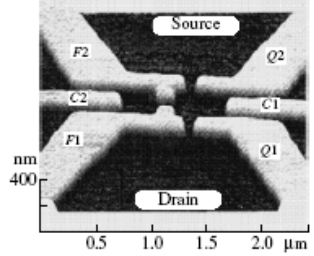


Zero-bias (equilibrium)	Small bias (quasi-equilibrium)	Large bias (out of equilibrium)
T_K^{EQ}	$eV \ll T_K^{EQ}$	$eV \gg T_K^{EQ}$
Effects of decoherence	$\Gamma_{rel} \sim eV$	**?**

What happens if $eV \sim \Delta_{ST}$ **?**

$$\Delta_{ST} \gg T_K^{EQ}$$

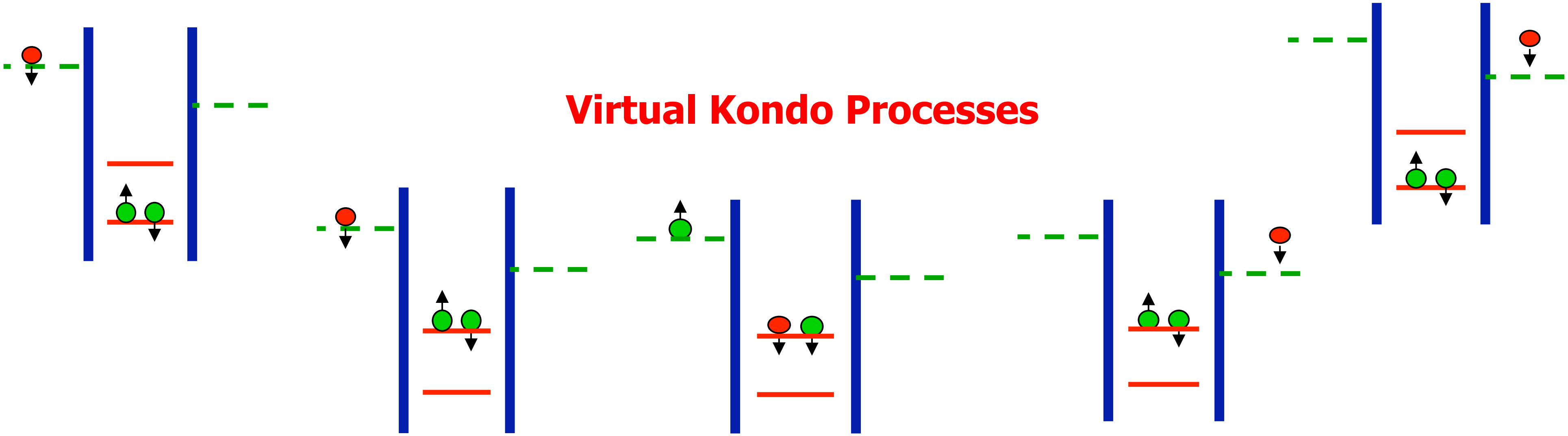
Non-equilibrium Kondo effect in DQD



$$G/G_0 \propto \ln^{-2}\left(\max\left[(eV-\Delta),T\right]/T_K\right)$$

initial **final**

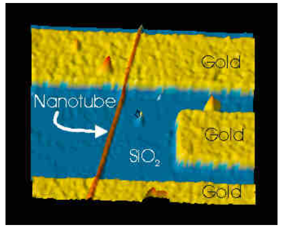
Virtual Kondo Processes

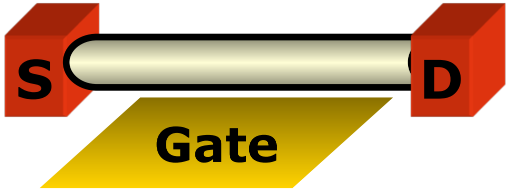


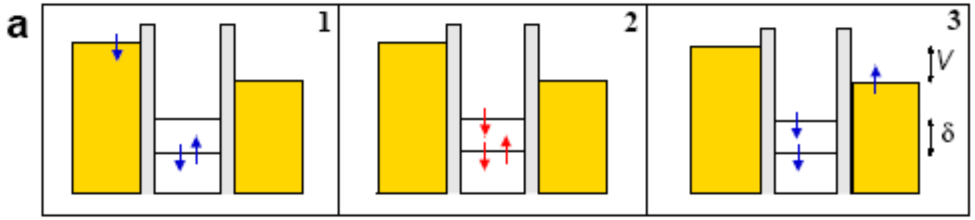
$$T_K^{NEQ} = D\exp\left(-\frac{1}{\nu J_0^T}\right) = \left(T_K^{EQ}\right)^2 / D$$

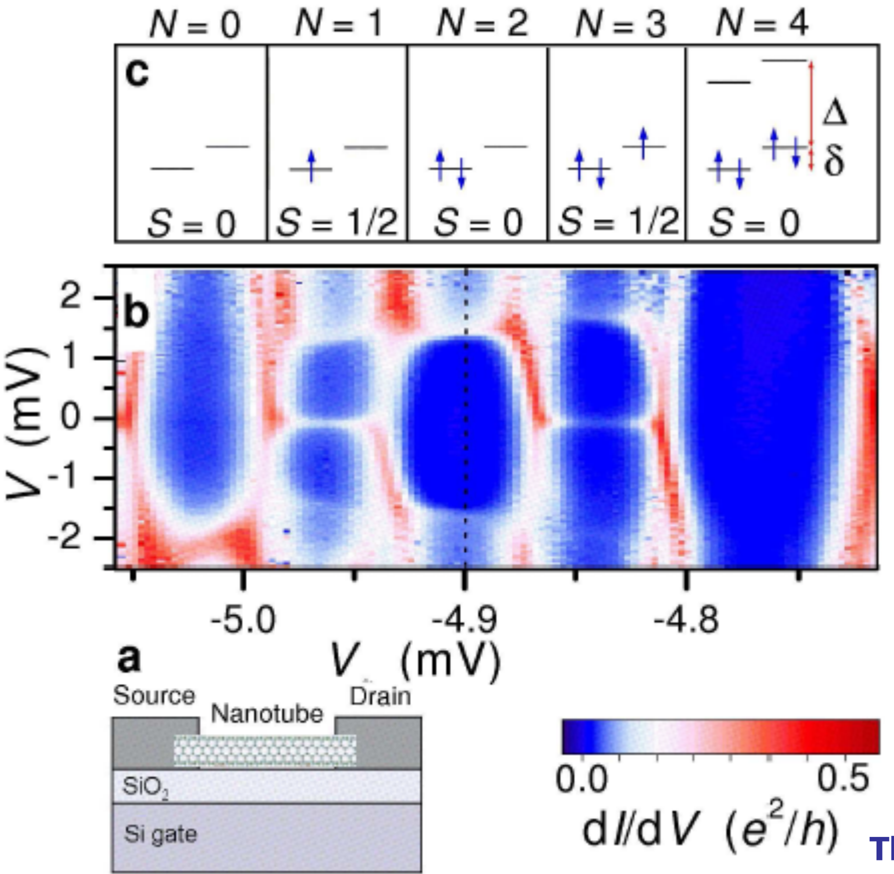
MK, K.Kikoin and L.W.Molenkamp JETP Lett 2003
MK, K.Kikoin and L.W.Molenkamp, PRB 2003

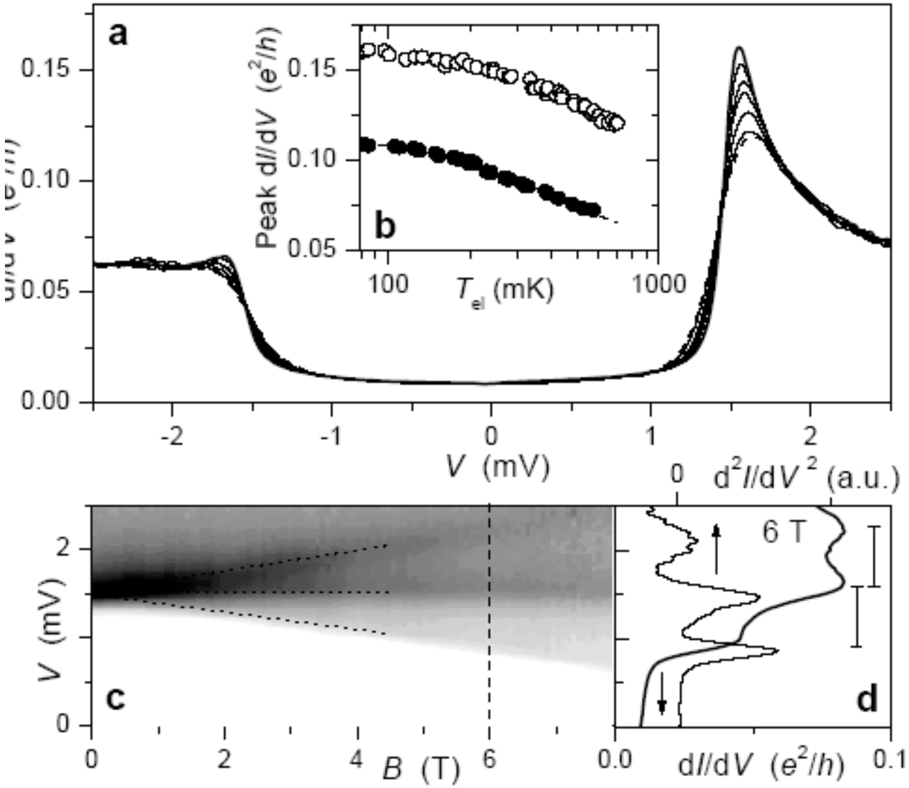
Singlet/Triplet finite bias Kondo effect in Carbon Nanotubes





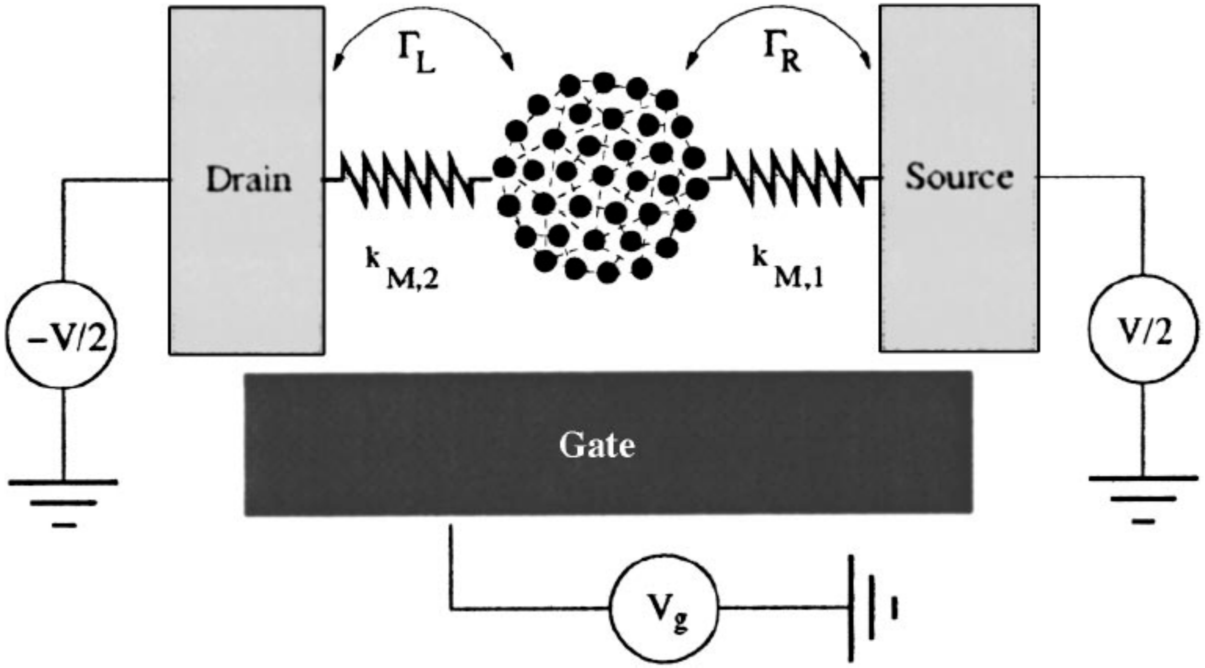






Theory DQD: MK, K.Kikoin and L.W.Molenkamp, PRB 2003
Experiment+Theory CNT: J.Paaske et al, Nature Physics 2006

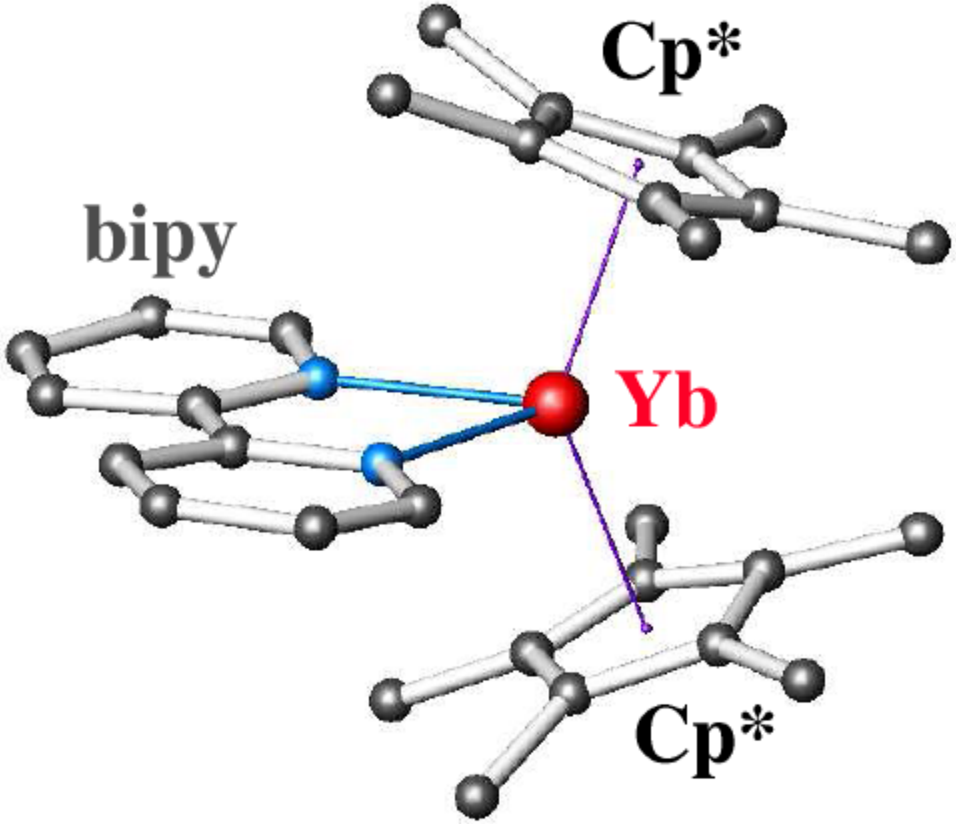
Эффект Кондо в молекулярном транзисторе



Ytterbocene

Cerocene

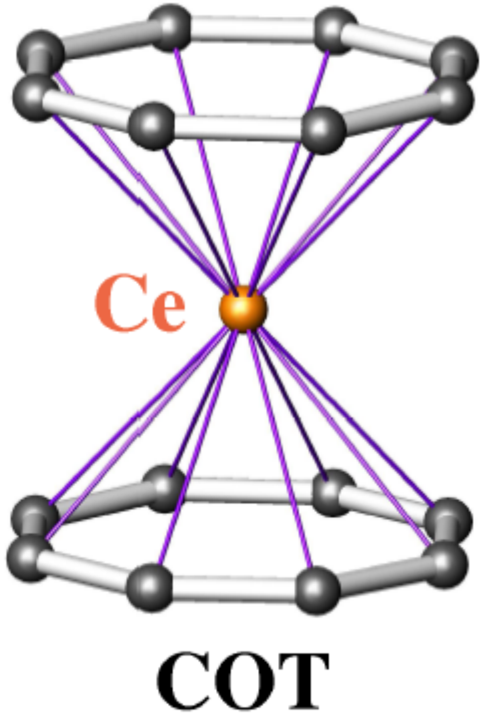
$Cp^*_2Yb(bipy)$



Cp* = pentamethylcyclopentadienyl = C5Me5,

bipy = 2,2′ -bipyridyl = (NC5H4)2]

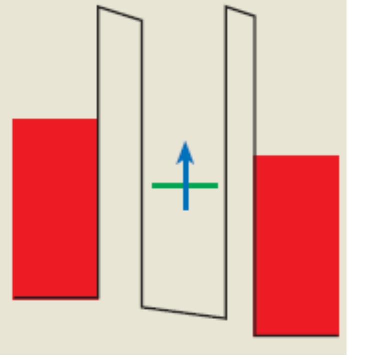
$Ce(COT)_2$



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

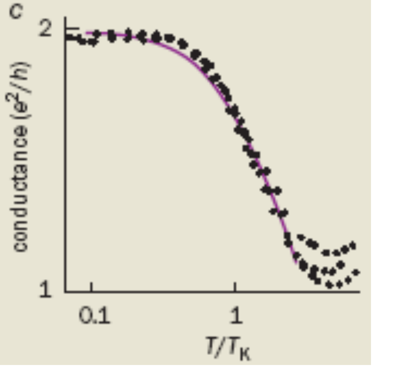
COT = cyclooctatetraene

Why do we look for the Kondo effect in molecular devices ?

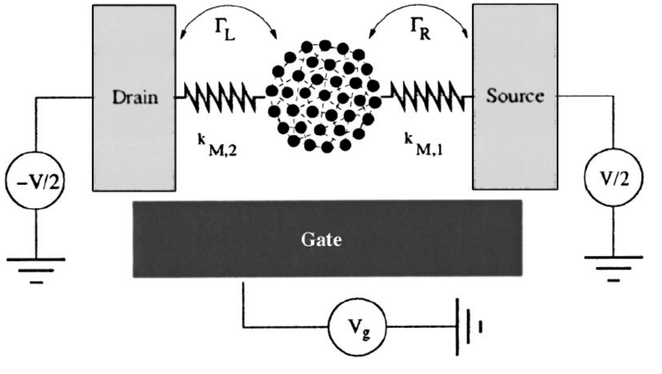


• The Kondo effect makes it easier for states belonging to the two opposite electrodes to mix

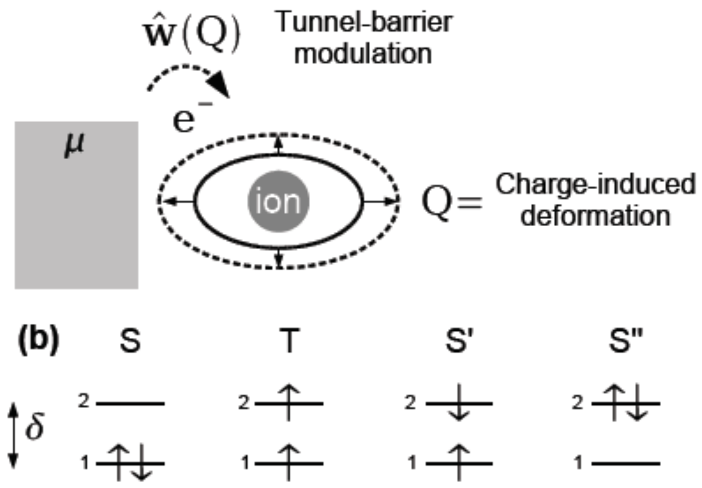
• Reasonably high Kondo temperatures > 10 K (compared to 100 mK- 1 K for QDs)



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



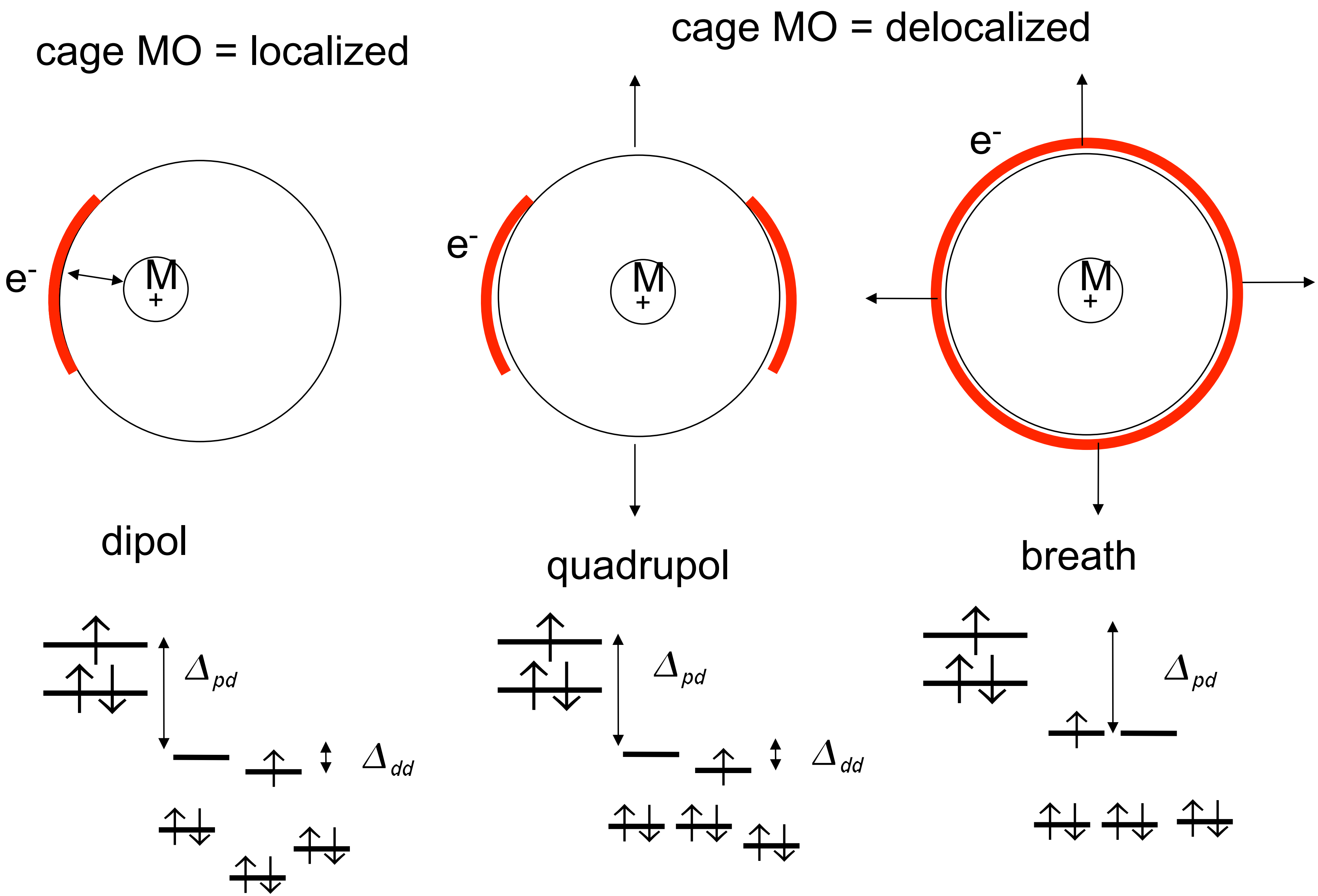
Эффект Кондо индуцированный фононами



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

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

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


cage MO = localized
cage MO = delocalized
e-
M
+
e-
M
+
e-
M
+
dipol
quadrupol
breath
Δpd
Δdd
Δpd
Δdd
Δpd

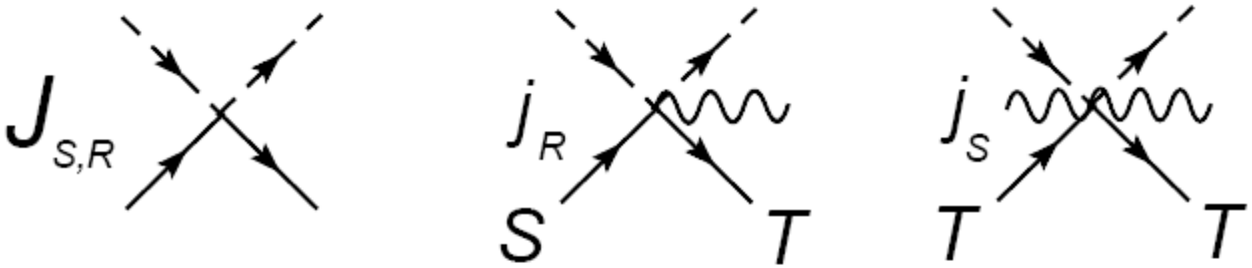
Vibration assisted tunneling

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

$$\hat{J}_{S,R}(Q) \approx \sum_\gamma |\hat{w}(Q)|^2/|E_T - E_\gamma|$$

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

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

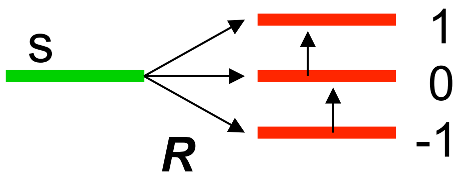


Singlet Triplet

single phonon

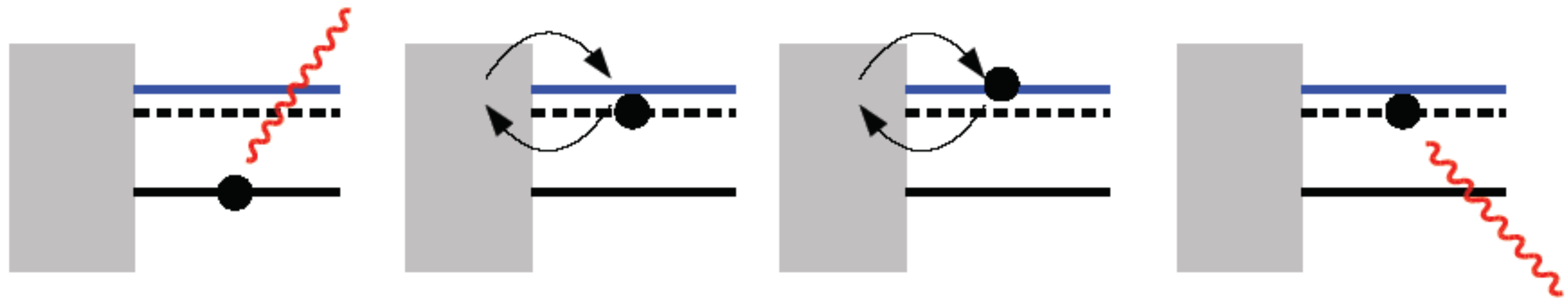
two-phonon

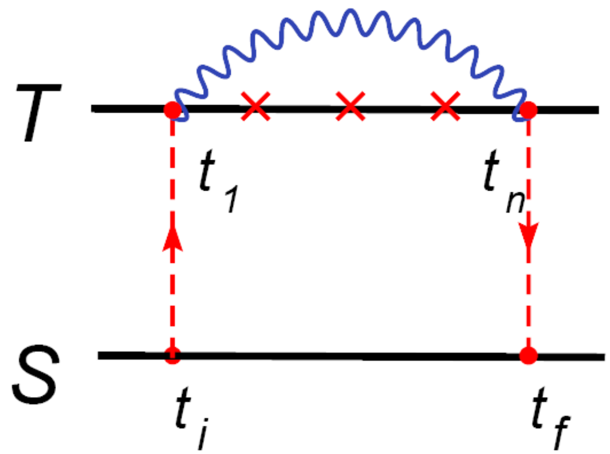
$$j_S \ll j_R$$



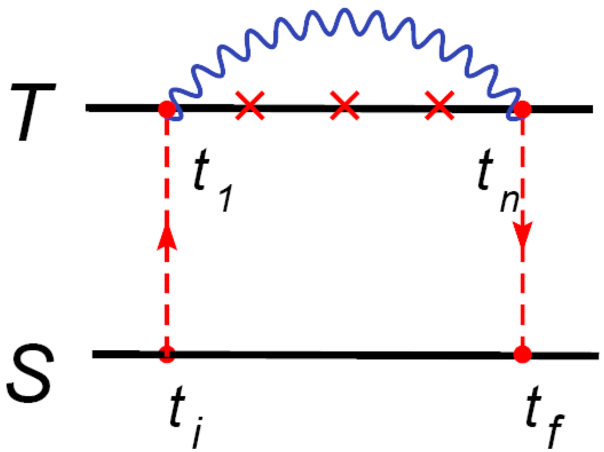
$$\Delta \equiv E_T - E_S = \delta - I > T_K$$

Single phonon processes





Single phonon processes



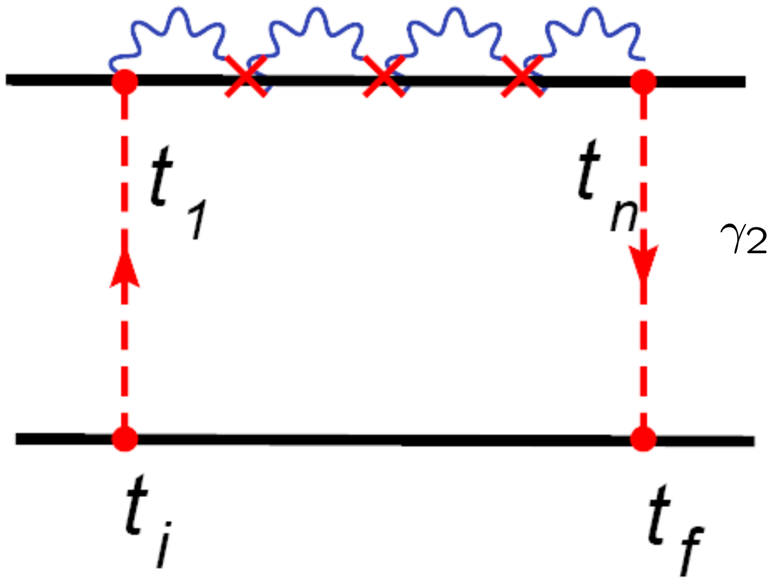
$$\gamma_1 \sim (j_R)^2 \rho \left[\frac{\log\left(\frac{D}{\max[T, |\Delta - \Omega|]}\right)}{1 - J_S A \rho \log\left(\frac{D}{\max[T, |\Delta - \Omega|]}\right)} \right]$$

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

Messages:

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

Two-phonon processes



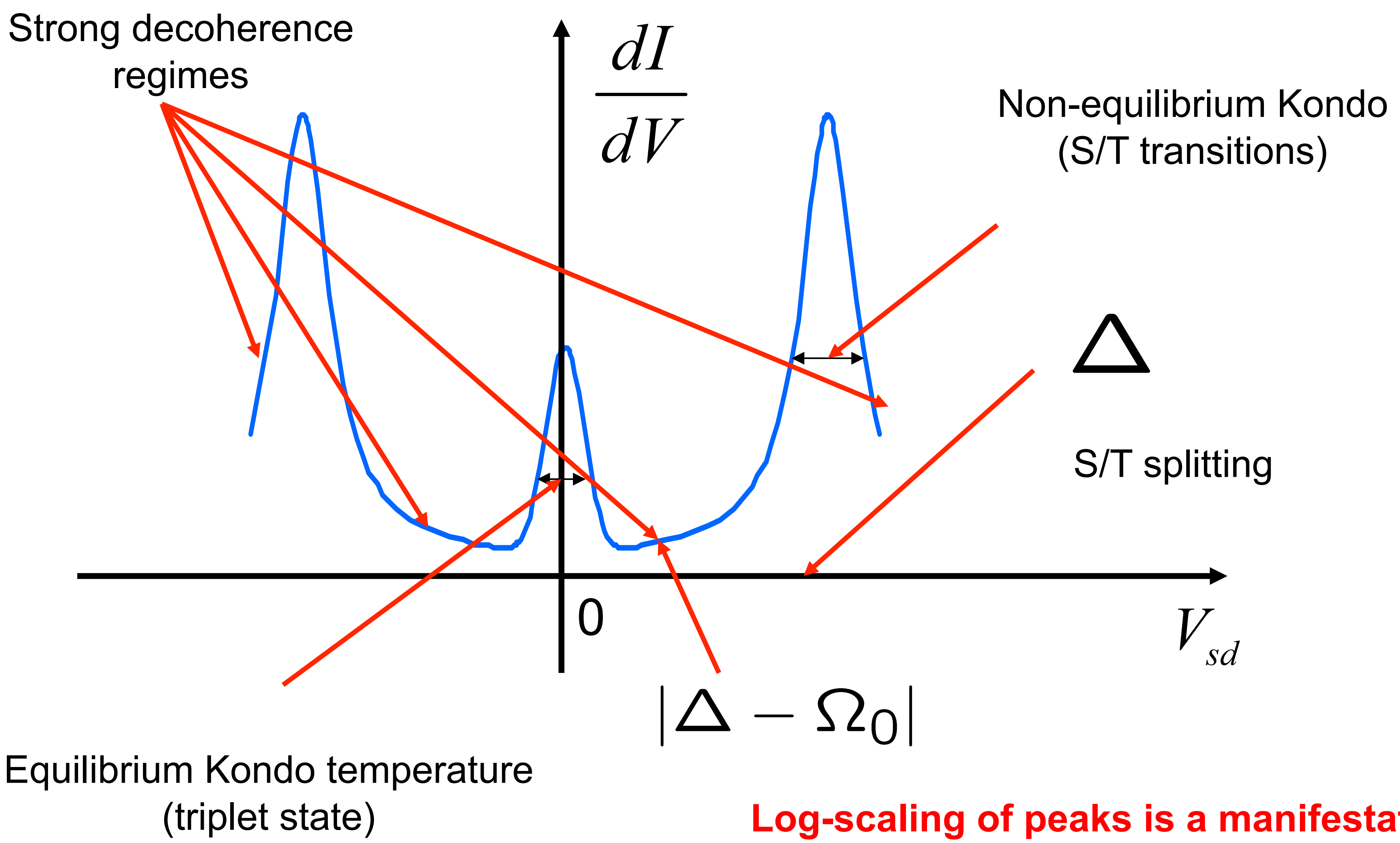
$$\gamma_2 \sim (j_R)^2 \rho \left[\frac{\log\left(\frac{D}{\max[T, |\Delta - \Omega|]}\right)}{1 - j_S A' \rho \log\left(\frac{D}{\max[T, |\Delta - \Omega|]}\right)} \right]$$

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

Messages:

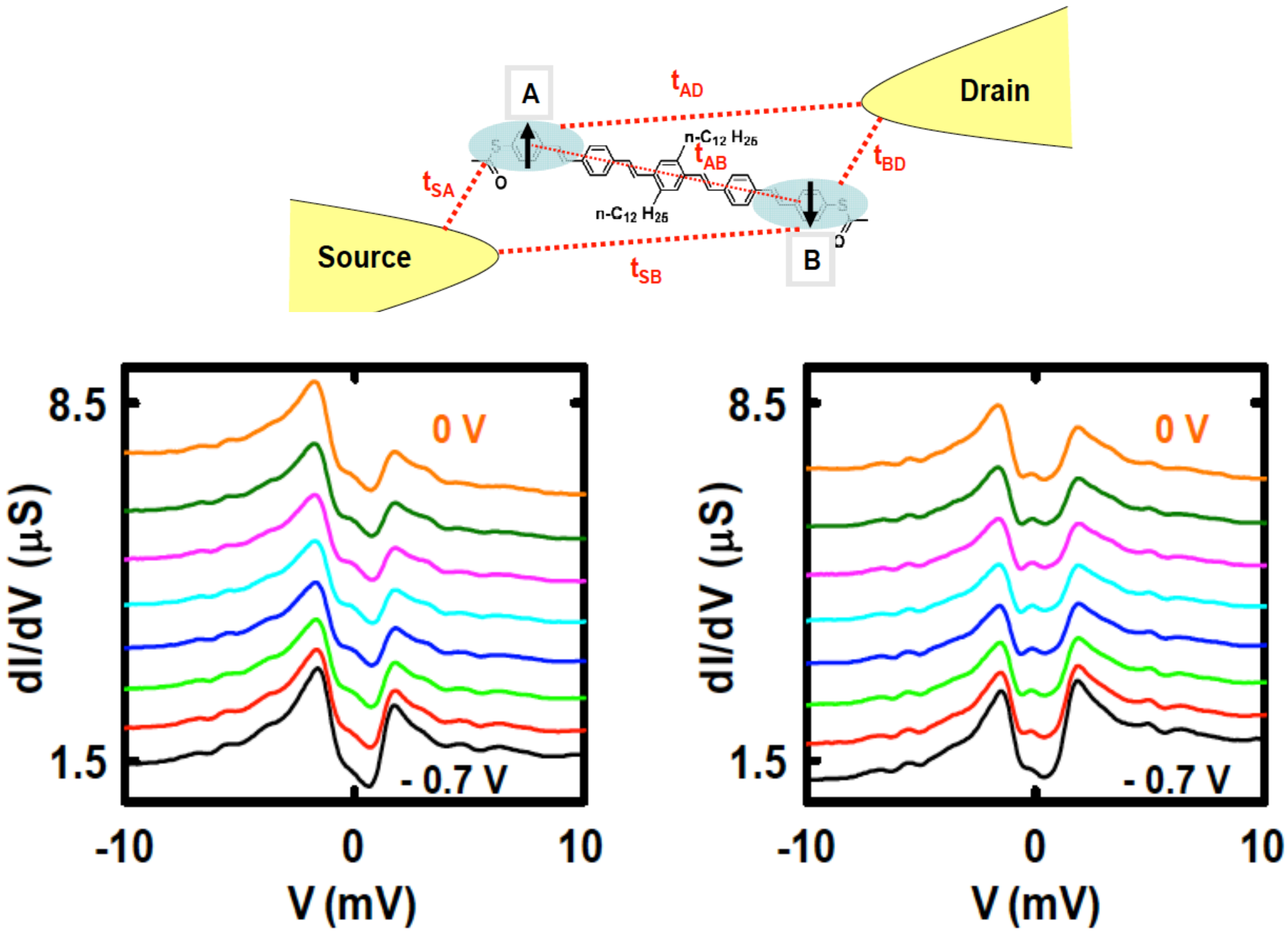
- Two-phonon processes also assist Kondo tunneling, however
- Kondo temperature depends on phonon coupling
- The two phonon scenario leads to much smaller Kondo temperatures

Differential Conductance: Theory



Log-scaling of peaks is a manifestation of Kondo effect

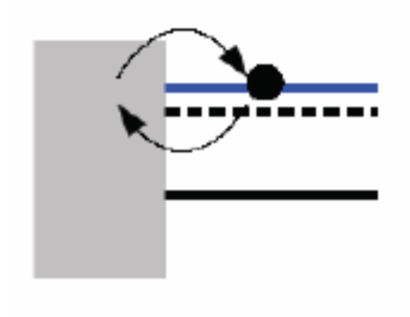
Differential Conductance: Experiment



Theory: K.Kikoin, M.N.Kiselev and M.Wegewijs, PRL 2006
Experiment: van der Zant et al, Nanoletters, 2007

A resonance condition

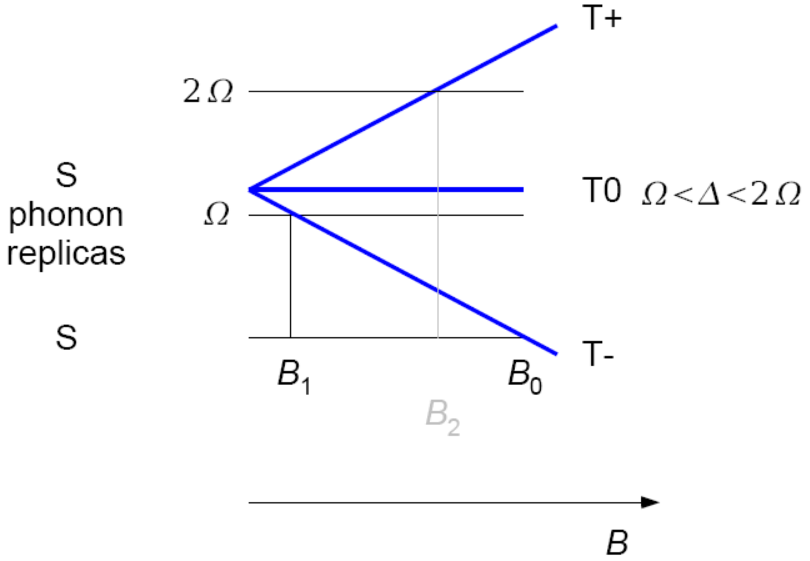
$$|\Omega - \Delta| \ll T_K$$

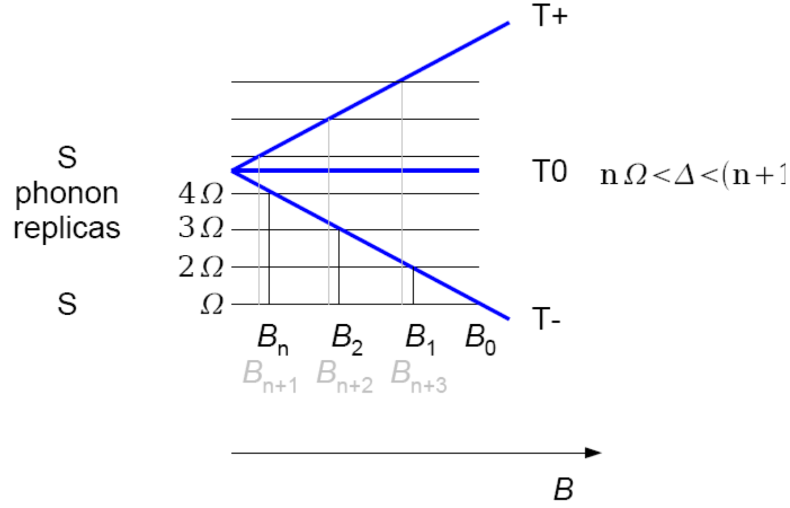


… narrows a group of the TMOC with "Phondo".

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

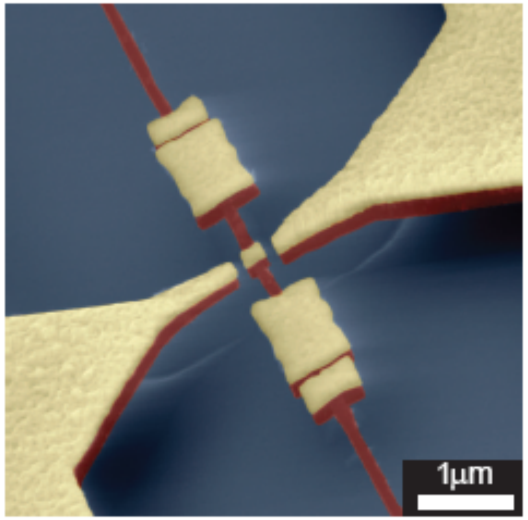
Fine tuning tool is necessary to control the resonance

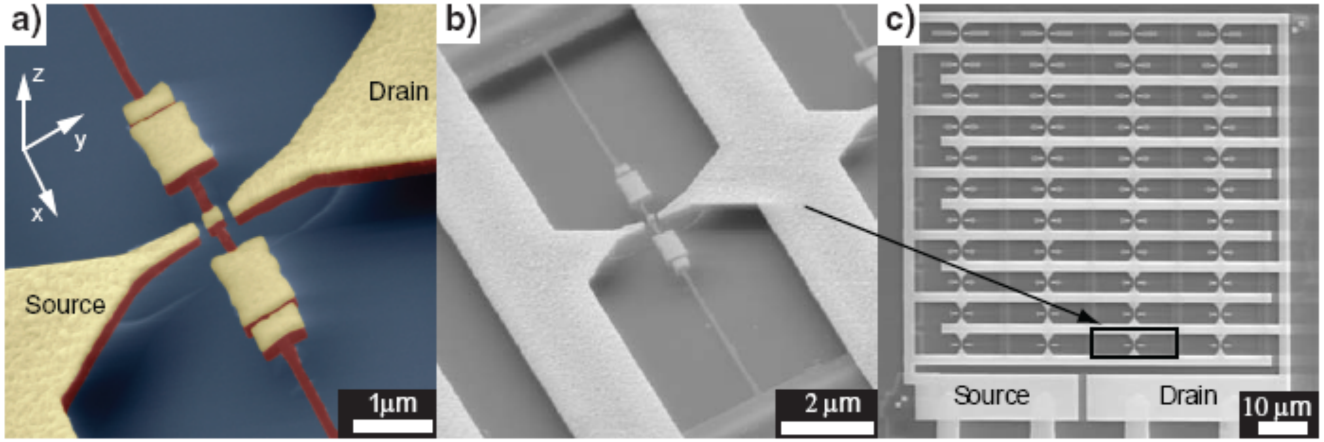




Magnetic field induced Kondo at phonon replicas of B_0
pseudo spin ½ Kondo
Which T_{Kn} dependence on n (or B field)

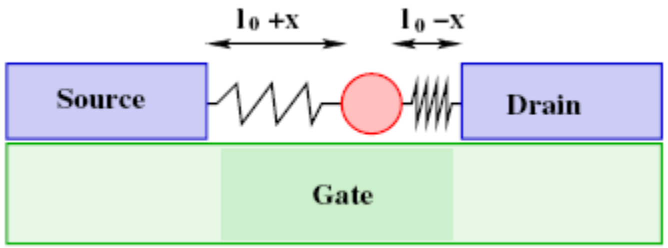
Nanoelectromechanical shuttling: QD devices





J. Kotthaus et al, Nature Nanotechnology 2008

The model



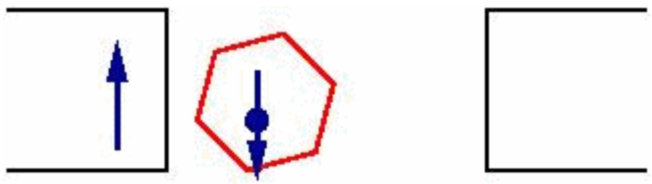
$$H_0 = \sum_{k,\alpha} \varepsilon_{k\sigma,\alpha} c^{\dagger}_{k\sigma,\alpha} c_{k\sigma,\alpha} + \sum_{i\sigma} [\epsilon_i - e\mathcal{E}x] d^{\dagger}_{i\sigma} d_{i\sigma} + U n^2$$

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

SW transformation

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

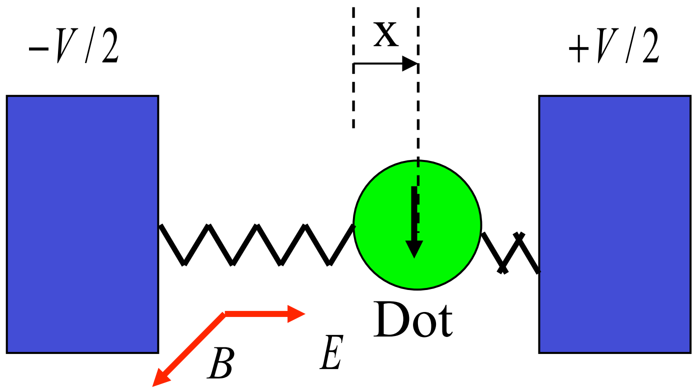
$$\mathcal{J}_{\alpha,\alpha'}(t) = \sqrt{\Gamma_{\alpha}(t)\Gamma_{\alpha'}(t)}/(\pi\rho_0 E_d(t)) \qquad \Gamma_{\alpha}(t) = 2\pi\rho_0 |T_{\alpha}(x(t))|^2$$



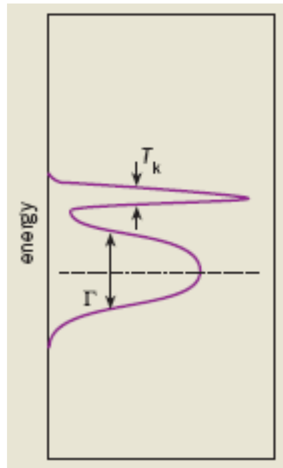
Classical shuttling trajectories

$$\langle x^2 \rangle \gg \hbar/(m\Omega)$$

Odd-spin Kondo shuttle



Competition between



Breit-Wigner Resonance

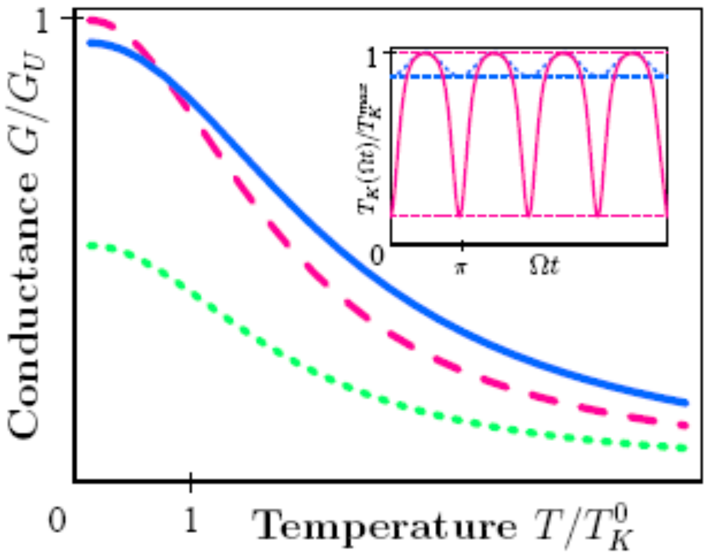
$$G = \frac{2e^2}{h}\left\langle \frac{4\Gamma_L(t)\Gamma_R(t)}{(\Gamma_L(t)+\Gamma_R(t))^2}\right\rangle$$

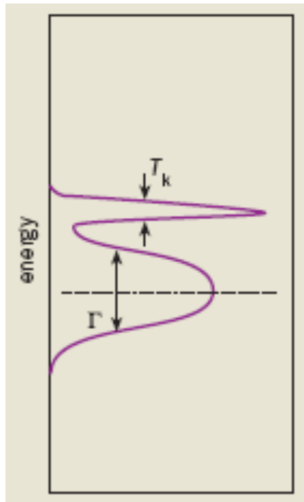
Abrikosov-Suhl Resonance

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

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

Time-dependent Kondo temperature





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

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

$$G(T) = G_K^0 \left\langle \left(\frac{1}{1-2\alpha^2(T)\sinh^2[x(t)/\lambda_0]}\right)^2 \right\rangle, \qquad \frac{\delta G_K}{G_K^0} = \frac{G(T)-G_K^0}{G_K^0} = 2\frac{\delta T_K}{T_K^0}\frac{1}{\ln(T/T_K^0)}.$$

Konstantin Kikoin · Mikhail Kiselev · Yshai Avishai

Dynamical Symmetries for Nanostructures

Implicit Symmetries in Single-Electron Transport Through Real and Artificial Molecules

Group theoretical concepts elucidate fundamental physical phenomena, including excitation spectra of quantum systems and complex geometrical structures such as molecules and crystals. These concepts are extensively covered in numerous textbooks. The aim of the present monograph is to illuminate more subtle aspects featuring group theory for quantum mechanics, that is, the concept of dynamical symmetry. Dynamical symmetry groups complement the conventional groups: their elements induce transitions between states belonging to different representations of the symmetry group of the Hamiltonian. Dynamical symmetry appears as a hidden symmetry in the hydrogen atom and quantum rotator problem, but its main role is manifested in nano and meso systems. Such systems include atomic clusters, large molecules, quantum dots attached to metallic electrodes, etc. They are expected to be the building blocks of future quantum electronic devices and information transmitting algorithms. Elucidation of the electronic properties of such systems is greatly facilitated by applying concepts of dynamical group theory.

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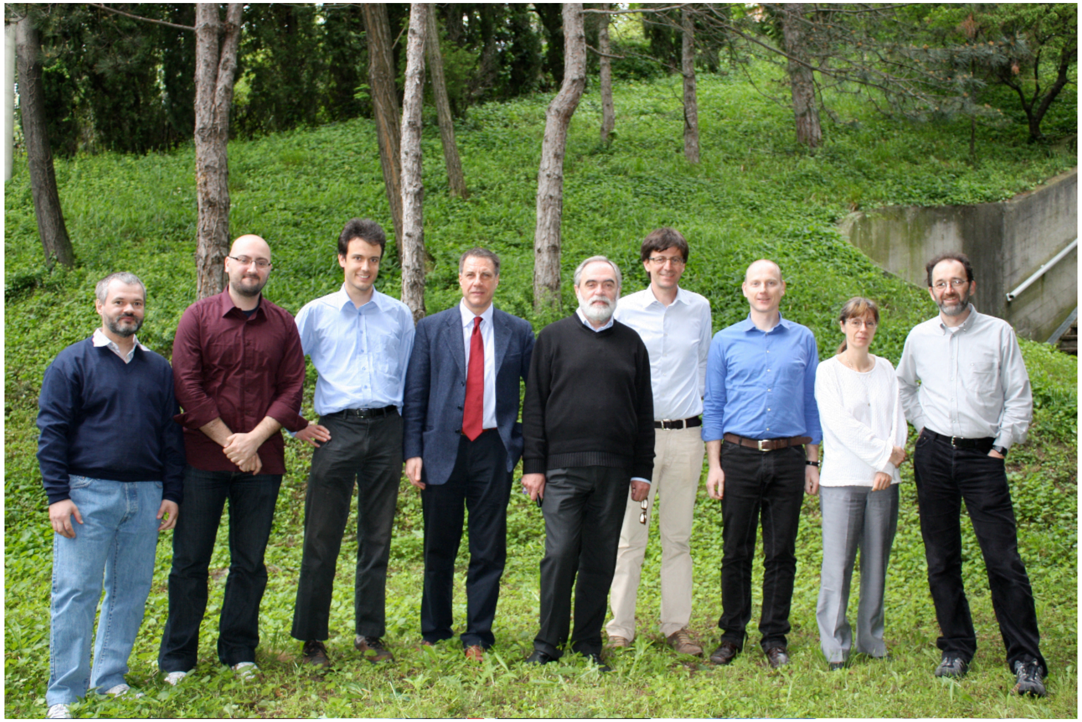

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