Interplay of electromagnetic noise and Kondo effect in quantum dots

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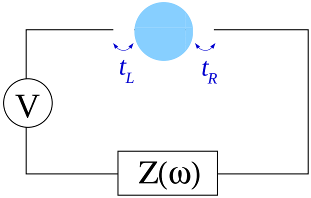
Motivation

$\longrightarrow$ transport through nanostructure

quantum dot in Kondo regime:

– *unitary conductance*

– *spin screening*



$\longrightarrow$ environmental effects

circuit characterized by impedance $Z(\omega)$:

– Dynamical Coulomb blockade

– low-energy equivalence to Luttinger liquid for ohmic environment

$\Rightarrow$ influence of electromagnetic environment on *transport*?

Outline

- Introduction:
  - $\longrightarrow$ Kondo physics in quantum dots (QD)
  - $\longrightarrow$ Dynamical Coulomb blockade (DCB) induced by environment

- Kondo effect in presence of DCB:
  - $\longrightarrow$ theoretical description
  - $\longrightarrow$ transport analysis
  - $\longrightarrow$ *Experimental proposal*

The Kondo effect: a short overview

Kondo Hamiltonian:

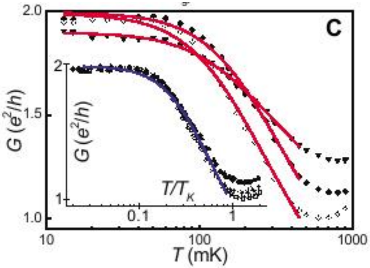
$$H_K = J\,\vec{S}\cdot \sum_{\sigma\sigma',\gamma\gamma'} c^\dagger_{\sigma\gamma}(0)\frac{\vec{\tau}_{\sigma\sigma'}}{2}c_{\sigma'\gamma'}(0) + \sum_{k\sigma\gamma}(\epsilon_k c^\dagger_{k\sigma\gamma}c_{k\sigma\gamma} + \mathrm{H.c.})$$

– *universal scaling* in $T_K = De^{-D/J}$

– signatures in transport:

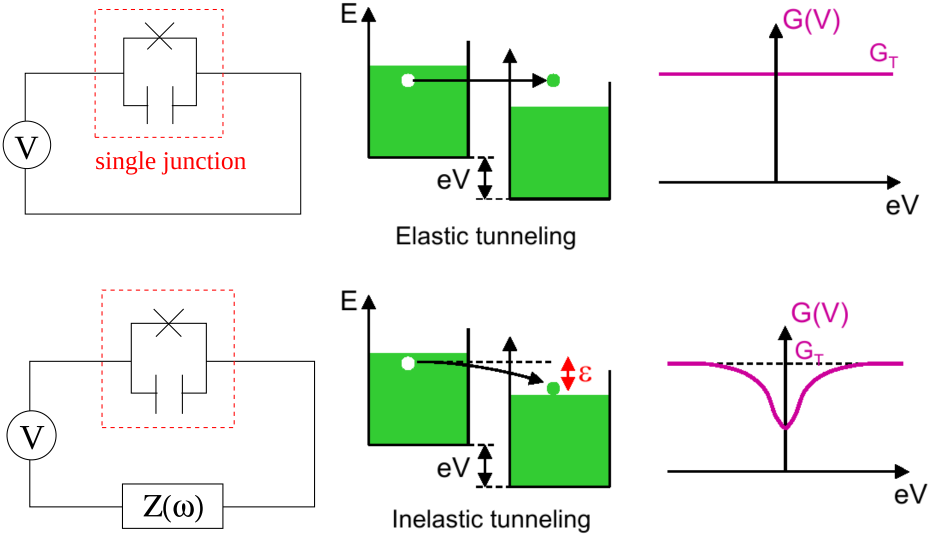
$$G(T) = \frac{2e^2}{h}[1-(\frac{T}{T_K})^2] \quad (T \ll T_K)$$

$$G(T) \sim \frac{1}{\log^2(T/T_K)} \quad (T \gg T_K)$$



Kouwenhoven and Glazman '01

Environmental effects: Tunneling



→ appearance of zero-bias anomaly

Dynamical Coulomb blockade: theoretical description

tunneling amplitudes dressed by environmental modes via phase

$$\varphi(t) = e \int_{-\infty}^{t} \delta V(t') dt'$$

describing circuit voltage fluctuations $\delta V(t')$ in terms of *bosonic* excitations with distribution function

$$P(E) = \frac{1}{2\pi} \int_{-\infty}^{\infty} dt \; e^{J_\varphi(t) + iEt}$$

with $J_\varphi(t) \equiv \langle (\varphi(t) - \varphi(0))\varphi(0) \rangle$ $\quad \rightarrow$ *"P(E) theory"*

$\Rightarrow$ effective circuit theory including $Z(\omega)$ by distribution function of bosonic excitations

Devoret, Grabert; Ingold, Nazarov '92

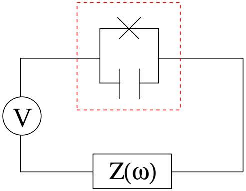
Ohmic environment and low-energy equivalence to LL

$$Z(\omega = 0) = R \quad \rightarrow \quad J_\varphi(t) \equiv \langle(\varphi(t) - \varphi(0))\varphi(0)\rangle \sim -2r \ln(i\omega_c t)$$

$$\text{with} \;\; \omega_c = \frac{1}{RC} \;\; \text{and} \;\; r = \frac{R}{R_K} = R\frac{e^2}{h}$$

$\rightarrow \;\; P(E) \sim A_r \frac{E^{2r-1}}{\omega_c^{2r}}$ for $E \ll \omega_c$ describes also weak link in LL!

$\Rightarrow$ non-linear transport: $\frac{dI}{dV} \sim \left(\frac{V}{E_c}\right)^{2r}$



ohmic environment

$Z(\omega = 0) = R$

exact

MAPPING

for $\omega < \omega_c$

Luttinger liquid with

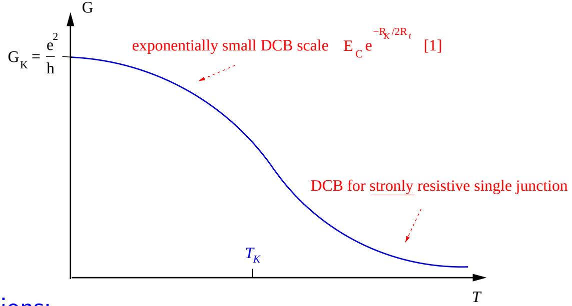
$K = 1/(1 + 2r)$

Matveev '95, Safi and Saleur '04, Le Hur '04

Environmental effect on transport through Kondo quantum dot

– one mode environment   Kaminski, Nazarov, Glazman '99

– ohmic environment: competing phenomena

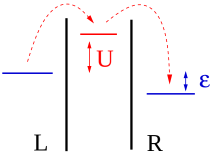


⇒ Key questions:

- *relevant energy scales* → influence of dissipation on T_K
- *fixed points* → determination of different conduction regimes

[1] Panyukov and Zaikin '91, Nazarov '99, Golubov and Zaikin '01

Theoretical description: Model



Hamiltonian $H = H_{\mathrm{dot}} + H_{\mathrm{leads}} + H_{\mathrm{tun}} + H_{\mathrm{env}}$

with H_{env} = collection of harmonic oscillators

→ effective Kondo Hamiltonian in *quasi-elastic approximation* $\omega_{\mathrm{bath}} \ll U$

$$H_K = \sum_{\gamma\gamma'} J_{\gamma\gamma'}\, e^{i(\varphi_\gamma - \varphi_{\gamma'})} \sum_{k\sigma,k'\sigma'} c^\dagger_{k\sigma\gamma} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{k'\sigma'\gamma'} \cdot \vec{S} \qquad (\gamma, \gamma' = L, R)$$

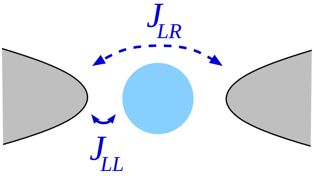
with $J_{\gamma\gamma'} \approx 2 t_\gamma t_{\gamma'} \left(\frac{-1}{\epsilon_d} + \frac{1}{U+\epsilon_d} \right)$ and $\vec{S}$ local spin on quantum dot

processes described by Kondo couplings:

– J_{LL}, J_{RR} charge conserving

– J_{LR}, J_{RL} charge transfer (tunneling)

⇒ *affected by DCB*



Results: weak-coupling analysis

RG flow equations as a function of energy scale Λ:

$$\frac{dj_{LL}}{d\log\Lambda} = -j_{LL}^2 - j_{LR}^2 \int_0^\Lambda dE\; P(E) \qquad \textit{“spin screening”}$$

$$\frac{dj_{LR}}{d\log\Lambda} = -j_{LR}(j_{LL} + j_{RR}) \qquad \textit{“transparency”}$$

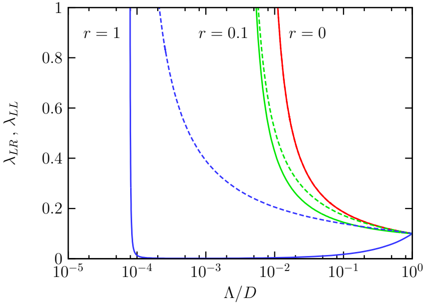
with dimensionless spin-exchange interactions $j_{\gamma\gamma'} = \rho_0 J_{\gamma\gamma'}$

$\longrightarrow$ low-energy description for $\Lambda \lesssim \omega_c$

$$\frac{d\lambda_{LL}}{d\log\Lambda} = -\lambda_{LL}^2 - \lambda_{LR}^2$$

$$\frac{d\lambda_{LR}}{d\log\Lambda} = -\lambda_{LR}(\lambda_{LL} + \lambda_{RR} - r)$$

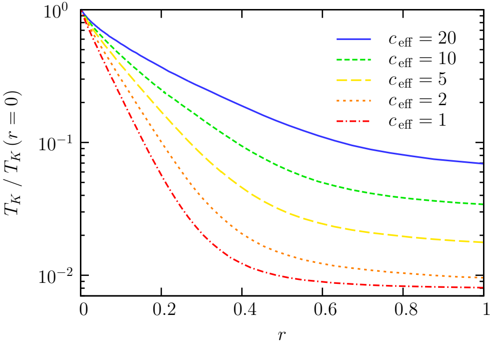
with reduced couplings $\lambda_{\gamma\gamma'}$



different low-energy behavior depending on dissipation r

Results: weak-coupling analysis

Kondo temperature T_K



($c_{eff} = R_K C$)

– systematic decrease of T_K with increasing $r \longrightarrow$ reduction of Kondo

– significant dependence on circuit impedance $Z(\omega)$
via distribution function $P(E)$ of environmental modes

Results: strong-coupling analysis

extension of low-energy mapping to double junction:

equivalence to Kondo model between Luttinger liquid leads

with effective interaction parameter

$$K = \frac{1}{1+2r}$$

$\longrightarrow$ singlet Kondo groundstate (spin screening) survives dissipation

due to divergence of j_{LL} and j_{RR}

BUT transport strongly affected and gate-voltage dependent via j_{LR}

Distinction of two conduction regimes:

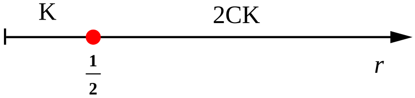
− $r < \frac{1}{2}$: fully transparent transport *only* for p-h symmetry

− $r > \frac{1}{2}$: non-ohmic transport characterized by DCB $\rightarrow$ *power laws*

Results: strong-coupling analysis

Transport characterized by non-ohmic DCB behavior

$\rightarrow$ *weak dissipation* for $r < \frac{1}{2}$:



$$\frac{dI}{dV} \approx a \left(\frac{eV}{T^*}\right)^{2r}$$

$$\frac{dI}{dV} \approx 2G_K \left(1 - b\left(\frac{eV}{T_K}\right)^{2r}\right)$$ *fully transparent* for p-h symmetry

$\rightarrow$ *strong dissipation* for $r > \frac{1}{2}$:

in general Kondo effect *only* in strongest coupled electrode

$$\frac{dI}{dV} \approx c \left(\frac{eV}{T_{1CK}}\right)^{2r} \quad \text{for} \quad J_{LL} \neq J_{RR}$$

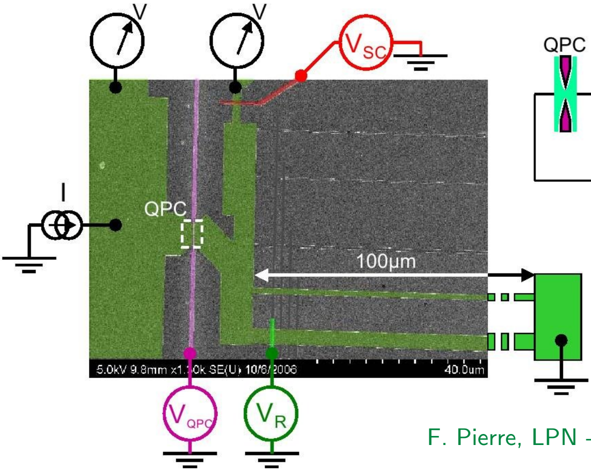
for balanced couplings **2-channel Kondo** (partial screening of spin)

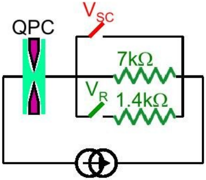
$$\frac{dI}{dV} \approx d \left(\frac{eV}{T_{2CK}}\right)^{2r-1} \quad \text{for} \quad J_{LL} = J_{RR}$$

Experimental proposal

environmental effects:

- reduction of T_K
- non-linearities in $I(V)$ characteristics $\rightarrow$ extension to QD setup





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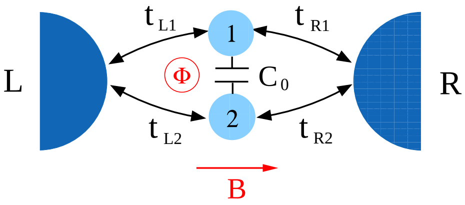
Environmental effects on orbital Kondo



entangled spin and orbital

degrees of freedom

Simon and Feinberg, PRL '06

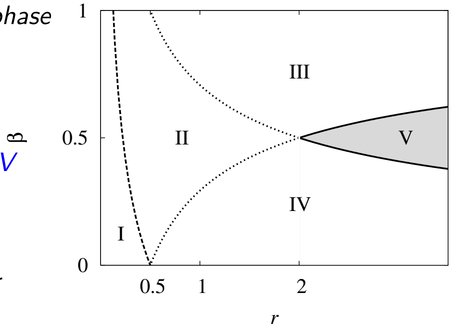
different Kondo fixed points and localized phase

geometric asymmetry $\beta \sim C_{L1}C_{R2} - C_{R1}C_{L2}$

$\rightarrow$ vanishing of Kondo screening in phase V

due to coupling of φ to charge states!

$\Rightarrow$ reduced *efficiency* of device as spin-filter



Summary

transport through quantum dot	*environmental effects*
in Kondo regime:	*(DCB)*
– spin screening	→ *survives*
– unitary conductance	→ *affected*

⇒ *anomalous low-T transport properties*

References:

Florens, Simon, Andergassen, and Feinberg, Phys. Rev. B **75**, 155321 (2007)
Andergassen, Simon, Florens, and Feinberg, Phys. Rev. B **77**, 045309 (2008)