From Sequential to Resonant Tunneling through a Quantum Level in a Dissipative Environment

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Environmental Coulomb blockade in a tunneling junction

Tunneling across a junction into resistive leads excites electromagnetic modes.

Zero-bias conductance is proportional to the probability of not exciting the environment. Conductance is suppressed at low $T$, $V_{\text{BIAS}}$: $G \sim \max (eV_{\text{BIAS}}, k_B T)^\alpha$

This is an example of the zero-bias anomaly (ZBA) in tunneling.

The effect is also related to “tunneling with dissipation”: the resistive leads serve as a dissipative environment.

Coupling strength is controlled by the leads resistance: $\alpha = 2e^2 R_{\text{leads}} / h$
Environmental Coulomb blockade in a nanotube with resistive leads

Distinct regimes:
- Nanotube as a lumped tunneling junction
- Nanotube as quantum dot with a single resonant level

Nanotube ≠ Luttinger liquid

Several kΩ

T >> \Gamma \quad \text{sequential tunneling}
T << \Gamma \quad \text{resonant tunneling}
Schottky barriers as tunable tunneling barriers

![Graph showing Schottky barriers as tunable tunneling barriers](image)
Elastic co-tunneling regime - tunneling through a virtual state

Tunneling is (almost) energy independent on the scales $< U, \Delta$. Any energy dependence on smaller scales is due to environmental blockade.
Zero-bias anomaly in tunneling (ZBA)

Data in X and Y valleys scale onto each other.

Nanotube serves as a lump tunneling junction with gate-controlled transparency.
$G \sim \text{max} \left( eV_{SD}, k_B T \right)^\alpha$ where $\alpha \approx 0.22$

Consistent with the lead resistance of several k$\Omega$
Resonant peaks with dissipation

\[ G(V) \]

- \( T < \Gamma \) peak \( W \) resonant tunneling
- \( T > \Gamma \) peak \( N \) sequential tunneling

\[ V_{\text{gate}} \text{ (V)} \]

- Tunnel in
- Tunnel out
- Wait…
Sequential tunneling: $T > \Gamma$

“Narrow peak”
Sequential tunneling with $\Gamma$ which depends on $T$

$G_{\text{peak}} \propto \frac{1}{T} \frac{\Gamma_L(T) \Gamma_R(T)}{\Gamma_L(T) + \Gamma_R(T)} \sim \frac{\Gamma_R(T)}{T} \sim T^{-\alpha_R-1} \rightarrow \alpha_R \approx 0.15$

Quantum dot with Luttinger liquid leads: sequential tunneling works with $T$-dependent $\Gamma$ (as long as $T \gg \Gamma$)

$\Gamma_{L,R} \sim T^{\alpha_{L,R}}$

$\alpha_{L,R} = 2e^2 R_{L,R}/h$

$\alpha_L + \alpha_R \approx 0.22$
From sequential tunneling ($T > \Gamma$) to resonant tunneling ($T < \Gamma$)

"Wide peak"
Peak width and height vs. temperature

Nazarov & Glazman
PRL 2003,
Polyakov & Gornyi
PRB 2003.
QD with Luttinger liquid leads and asymmetric barriers. Width saturates, Height drops as:
\[ \Gamma_L, R \sim T^{\alpha_R + \alpha_L} \]
\[ \alpha_L + \alpha_R = \alpha \approx 0.22 \]

Conventional expression would not work:
\[ G_{\text{peak}} \propto \frac{\Gamma_L \Gamma_R}{(\Gamma_L + \Gamma_R)^2} \sim \frac{\Gamma_R(T)}{\Gamma_L(T)} \sim T^{\alpha_R - \alpha_L} \]
Back to a lumped junction

Temperature washes away the zero bias suppression => peak grows
Summary

Environmental Blockade in tunneling through a nanotube

- Elastic co-tunneling: reproduced lumped junction case
- Sequential tunneling: $\Gamma(T)$ modifies the peak height
- Resonant tunneling: nonmonotonic $T$ dependence
Kondo Box in a Carbon Nanotube

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Signature of an extra electron
Unexpected gap in co-tunneling spectrum

Odd electron valley + an extra electron
Cotunneling Spectroscopy

\[ (\text{case } T_K \ll \Delta) \]
Odd electron valley + extra electron - Revisited

Kondo-box singlet
Suppressed G

vs.

Nanotube-lead Kondo singlet
Enhanced G

G ($e^2/h$)

Vgate (V)

Vsd (mV)
Two-stage Kondo effect

Vsd (mV)

G (e^2/h)

Vgate = -3.38 V

25 mK

85 mK

200 mK

400 mK

1 K

Vgate = -3.31 V

Vgate = -3.35 V

Vsd (mV)
Summary

- Kondo box in CNT - evidence for extra spins
- Confirmed sequence of the many-body states when \( T_K \sim \Delta \)
- Competition of the two Kondo effects: [Nanotube-leads] and [Kondo box]
- Two stage Kondo effect
Origin of extra electrons