SU(2) & SU(4) Kondo Effects in a Carbon Nanotube Probed by Shot-Noise

Meydi Ferrier

Université Paris sud, Orsay
R. Delagrange, R. Debloch, H. Bouchiat
R. Weil

Osaka University
T. Arakawa, T. Hata, R. Fujiwara, K. Kobayashi
Theory
R. Sakano, ISSP, Tokyo
A. Oguri, Osaka city University
Quick reminder

Shot noise

Kondo effect in CNT

Linear shot noise of SU(2) and SU(4) Kondo effect

Direct signature of the symmetry class

Non-linear noise:

Observation of 2-particle scattering induced by interactions out of equilibrium
Origin of shot noise

Fluctuations due to the partition of scattered particles

\[ S_I = 2eF I \]

with

\[ F = \frac{\sum T_n (1-T_n)}{\sum T_n} \]

\( e \) = charge of the particle
\( F \) = Fano factor = statistics of the particles

Nature of the quasiparticle and the scattering mechanism
Experimental set-up for noise measurement

DC measurement + resonant circuit for noise

Sensitivity $\sim 10^{-29}$ A$^2$/Hz

Signature of the Kondo effect

Spin screening induced by electron interaction

Macroscopic sample

Quantum dot (1 electron)

Scattering enhanced

Delocalization enhanced

Probe locally a many body state
Interaction and Non-equilibrium Kondo physics

« First order » correction:
Non-linear conductance
Scaling with $T, B, V$


Higher order: 2-particle scattering induced by residual interaction

Non-linear noise \hspace{1cm} Enhanced current fluctuations

Zarchin et al, PRB (2008)
Yamauchi et al, PRL (2011)

not quantitative
Nanotube dot = 2 different Kondo states

nanotube band structure

\[ K \quad K' \]

\[ 4 \text{ e}^- \text{ per shell} \]

2 « spin » are screened

2 transport channels

\[ \text{SU}(4) \text{ symmetry} \]

Disorder, spin-orbit = splitting

\[ K \quad K' \]

\[ 2 \text{ e}^- \text{ per shell} \]

Only the usual spin is screened

1 transport channel

\[ \text{SU}(2) \text{ symmetry} \]

Signature of interaction depends on the symmetry class
Part 1

Noise in the linear regime

\[ eV \ll k_B T_K \]

Kondo state = Fermi-liquid constituted of non-interacting quasi-particles

Signature of the symmetry class of the Fermi-liquid
SU(2) or SU(4)
Carbon Nanotube in the SU(2) Kondo state

Unitary limit reached at low T

$B=0.08T$ to destroy superconductivity
Shot noise

Coulomb blockade

Kondo regime

Nonlinear Noise

Linear Noise

Shot noise

dI/dV $\propto (2e^2/h)$

$I$ (nA)

$S_I(10^{-27}\text{A}^2/\text{Hz})$

$T_K = 2K$

$S_I(10^{-27}\text{A}^2/\text{Hz})$

$I$ (nA)
Linear Noise (eV \ll T_K) in the Coulomb Valley

No interaction:

\[ G = G_Q T \]
\[ F = 1 - T \]

Conventional Poissonian tunneling
Linear Noise ($eV \ll T_K$) on the Kondo ridge

Silent impurity around $V=0$

Perfect transmission through resonance (no partition)

Kondo regime: $F \ll 1$
Different Kondo effect in the same Nanotube

\[ T_0 = 1.4 \text{ K} \]
\[ T_0 = 1.6 \text{ K} \]
\[ T_K > 10 \text{ K} \]
The SU(4) Kondo state

Coulomb diamond

Kondo resonance for $N=1,2$ and 3 electrons
Screening of spin & orbit degrees of freedom

1 electron: 4 degenerate states

2 electrons: 6 degenerate states

2 channels participates for transport

Kondo screening for odd and even number of electrons
Shot noise and SU(4) Kondo effect

\[ G = G_Q (T_1 + T_2) \]
\[ F = \frac{\sum T_n (1 - T_n)}{\sum T_n} \]

2 channels with \( T = 1/2 \)

\[ G = G_Q \quad F \approx 0.5 \]


2 perfect channels: Noise \( \approx 0 \)

\[ G = 1.82 G_Q \quad F = 0.15 \]

Odd and Even SU(4) Kondo effect unambiguously observed
Comparison with NRG calculation

Anderson model with 2 orbitals

2 parameters: U/G and L/R asymmetry

Fixed: same as SU(2)

Very good agreement in the linear regime
Summary for the linear shot noise

**SU(2)**

- $16 \text{ mK}$
- $780 \text{ mK}$

- $N = 1$, $N = 2$, $N = 3$

**SU(4)**

- Symmetry distinguished by the linear shot noise
Noise contains more information than conductance!

\[ G = G_Q \times 1 \]

\[ G = G_Q \times \left( \frac{1}{2} + \frac{1}{2} \right) \]

**SU(2) odd**

**SU(4) odd**

**SU(2) = 1 perfect channel = NO NOISE**

\[ F = 1 - 1 \]

**SU(4) = 2 channels with T = 1/2 strong partition = strong shot noise**

Very difficult to distinguish experimentally

\[ F = 2 \times \left( 1 - \frac{1}{2} \right) \]

Scattering is fundamentally different
Part 2

What about non-linear Noise?

Observation of 2-quasi-particle scattering induced by interaction
Is non-linear noise only due to non-linear conductance?

Kondo effect: Transmission depends strongly on energy

\[ \frac{dI}{dV} = G_Q T(V) \]

Without interaction non-linearities appear in noise:

\[ S(V) = 2G_Q \int_0^{eV} T(\epsilon) (1 - T(\epsilon)) \, d\epsilon = 2 \int_0^{eV} G(\epsilon) \left(1 - \frac{G}{G_Q}(\epsilon)\right) \, d\epsilon \]
Non-linear Fano factor for non-interacting particles

\[ S(V^3) = 2eF_K I(V^3) \]

Non-linear conductance:

\[ T(\epsilon) = 1 - \alpha \epsilon^2 \]
\[ I(V) = G_Q V - \frac{\alpha}{3} G_Q V^3 \]

Non-interacting quasi-particle picture:

\[ S(V) = 2G_Q \int_0^e V T(\epsilon) (1 - T(\epsilon)) d\epsilon = 2e \frac{\alpha e^2 G_Q}{3} V^3 \]

\[ F_K = 1 \]

\( F_K \) measures the probability for 2-particle scattering
Direct observation of the many-body effect

Shot noise contains signature of 2 e scattering which is not in the $dI/dV$

compute the noise

$S = 2G_Q \int_0^{eV} T(1-T)d\varepsilon$

$S = F_K * 2G_Q \int_0^{eV} T(1-T)d\varepsilon$

Free particle scattering

2 particles scattering
Non-linear Fano factor: «effective charge»

\[ S(V^3) = 2eF_K I(V^3) \]

\[ F_K = \frac{P_1 + 4P_2}{P_1 + 2P_2} \]

Not normalized! \( P_1 + P_2 \neq 1 \)

No interaction \( P_2 = 0 \)

\[ F_K = 1 \]

Sela et al, PRL 97 086601 (2006)

\[ F_K = \frac{5}{3} \]

\[ P_1 = P_2 \]

\[ F_K = \frac{3}{2} \]

Mora et al, PRB 80 (2009)

Sakano et al PRB 83 (2011)

\[ F_K \text{ measures the probability for 2-particle scattering} \]
Extraction of non-linear Fano factor

Back scattered current

\[ I_K = G(0)V - I \]

Nonlinear noise

\[ S_K = S_I - S_{\text{linear}} \]

\[ S_K = 2e F_K I_K \]
Measurement of Kondo Fano factor

Nonlinear component

\[ S_K = S_I - S_{\text{linear}} \]

Other experiments

Zarchin et al, PRB (2008)
Yamauchi et al, PRL (2011)
not quantitative

Asymmetric dot, low \( T_K \)

Back scattered current

\[ I_K = G(0)V - I \]

Quantitative agreement with theory
Evolution of Kondo shot noise

2 particles scattering destroyed by magnetic field and temperature
Scaling properties of $F_K$

Seems to be logarithmic

$g\mu_B B/2k_B T_K$, $T/T_K$

Same scaling properties as the conductance
$F_K$ for SU(4) $N=2$ electrons

$1.35 < F_K < 1.55$

3/2 predicted for SU(4):
Mora et al PRB 80, 155322 (2009)

Interaction decreases when degeneracy increases
Significance of these experiments

Around equilibrium

Kondo state = non interacting quasi-particles

Noise = Landauer-Buttiker theory

Out of equilibrium

Interaction between quasi-particles shows up

Noise is non-linear and strongly enhanced

$F_K >1$ appears

Very good quantitative agreement with theory

Extension of Fermi-liquid theory out of equilibrium demonstrated experimentally
CONCLUSION

On-chip collision experiment: Probe dynamical behaviors of a quantum many body system

Noise shows the symmetry class

Direct evidence of 2 quasi-particles scattering due to interaction

\[ F_K \approx 1.7 \text{ for two different kind of SU}(2) \]
\[ F_K \approx 1.5 \text{ for SU}(4) @ N=2 \]

Cross-over in the symmetry class monitored by shot noise

Also tuned by the magnetic field
Next...

Effect of Superconducting leads:

See Tokuro Hata’s poster

Mixing Kondo and Andreev states

Noise in the Coulomb regime: bunching effect $F=1.5$