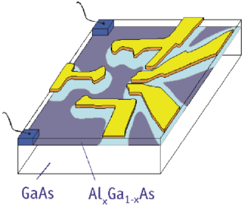
Quench dynamics and counting statistics in interacting nanojunctions: Quasi-particles trapping

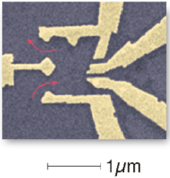
Rubén Seoane Souto
Normal case: Rèmi Avriller, Rosa Carmina Monreal, Álvaro Martín Rodero and Alfredo Levy Yeyati
Superconducting: Álvaro Martín Rodero and Alfredo Levy Yeyati

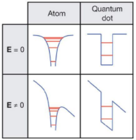
September 20, 2016

Introduction(I): Why time-dependent?

Systems with confined electrons: quantum dots, nanowires, single molecules,...







Several applications: high efficient electronic devices, medicine,...

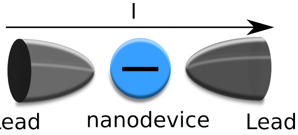
Problem of quantum transport through a quantum dot

- Quench dynamics
- Counting statistics

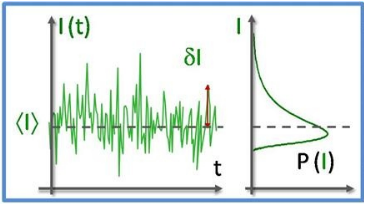
Role of interactions

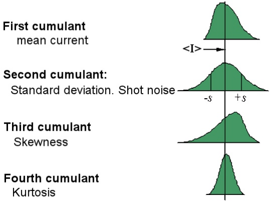
Introduction(I): Why time-dependent?

Electronic transport through nanoscaled devices



electron transport properties

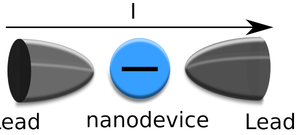




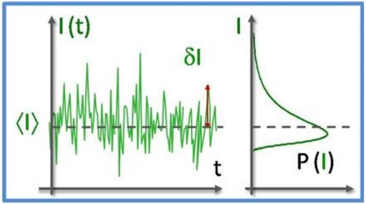
Time-dependent evolution?

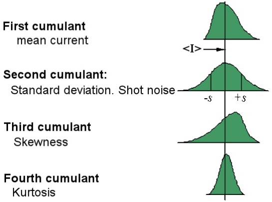
Introduction(I): Why time-dependent?

Electronic transport through nanoscaled devices



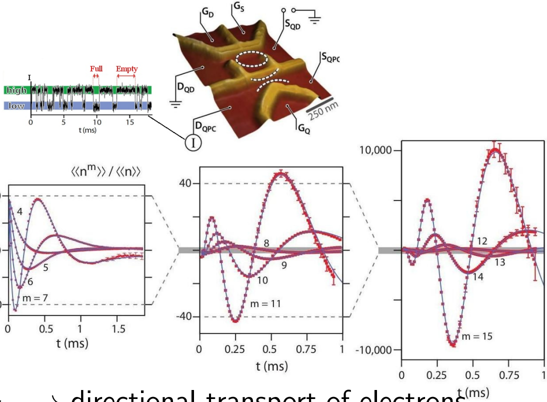
electron transport properties





Time-dependent evolution?

Transient regime: Flindt et al.[†]

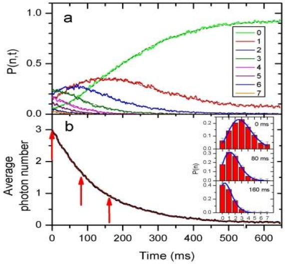


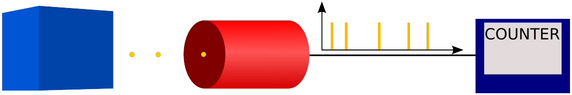
- Large V_{bias} → directional transport of electrons
- Sequential regime
- Non-interacting model

[†]PNAS, 10116 (2009)

Introduction(II): Why counting?

Counting photons statistics $\rightarrow$ since 70's.





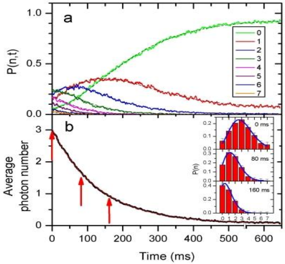
t-evolution probabilities of number of photons[†]

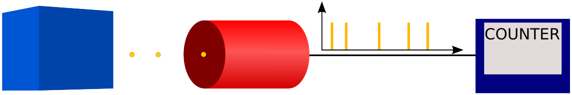
What about electrons?

[†] Phys. Rev. Lett. **101**, 240402 (2008)

Introduction(II): Why counting?

Counting photons statistics $\rightarrow$ since 70's.





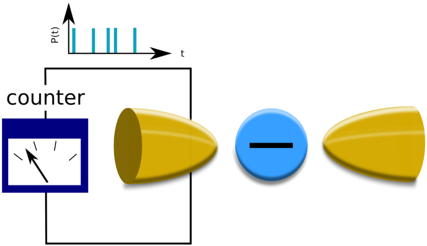
t-evolution probabilities of number of photons[†]

What about electrons?

[†]Phys. Rev. Lett. **101**, 240402 (2008)

Electron Counting Statistics

- Detector Coupled to the System
- No directional flux of electrons
- **Role of interactions**



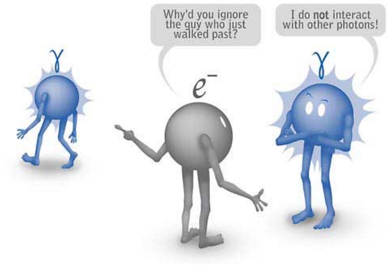
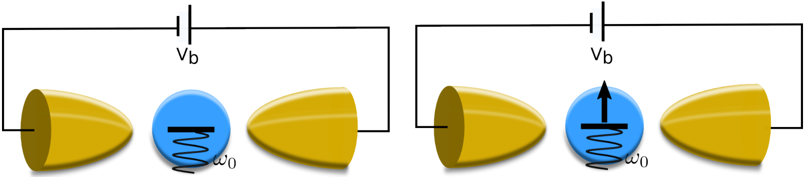


Table of contents

Anderson-Holstein comprises different kind of nanojunctions: single molecule transistors, nanowires, carbon nanotubes,...

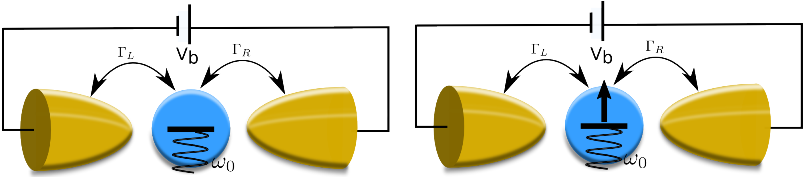
- Single spinless level
- Localized vibrational mode



$$H = H_{Leads} + \epsilon_0 d^\dagger d + \omega_0 a^\dagger a + \lambda d^\dagger d (a + a^\dagger)$$

Anderson-Holstein comprises different kind of nanojunctions: single molecule transistors, nanowires, carbon nanotubes,...

- Single spinless level
- Localized vibrational mode



$$H = H_{Leads} + \epsilon_0 d^\dagger d + \omega_0 a^\dagger a + \lambda d^\dagger d (a + a^\dagger) + H_T \theta(t), \quad \Gamma_i = \pi \rho_{Fi} t_i^2 \quad (i = L, R)$$

Generating function

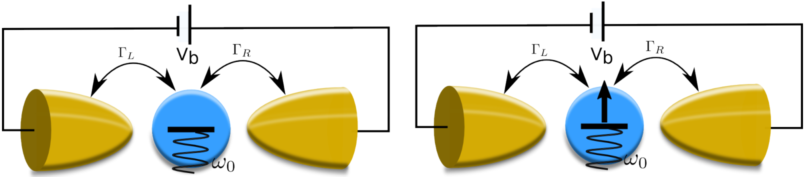
$$Z(\chi, t) = \sum_n P_n(t) e^{i\chi n}$$

$$\langle c_n(t) \rangle = \left. \frac{\partial^n \mathrm{Log}\left(Z(\chi, t)\right)}{\partial \chi^n} \right|_{\chi=0}$$

Anderson-Holstein Model

Anderson-Holstein comprises different kind of nanojunctions: single molecule transistors, nanowires, carbon nanotubes,...

- Single spinless level
- Localized vibrational mode



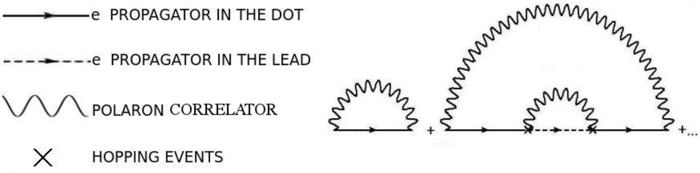
$$H = H_{Leads} + \epsilon_0 d^\dagger d + \omega_0 a^\dagger a + \lambda d^\dagger d (a + a^\dagger) + H_T \theta(t), \quad \Gamma_i = \pi \rho_{Fi} t_i^2 \quad (i = L, R)$$

Generating function

$$Z(\chi, t) = \sum_n P_n(t) e^{i\chi n}$$

$$\langle c_n(t) \rangle = \left. \frac{\partial^n \mathrm{Log}\,(Z(\chi, t))}{\partial \chi^n} \right|_{\chi=0}$$

Dressed Tunneling Approximation: Diagramatic resummation of dominant Feynman diagrams†



- Equilibrium population of phonons

† R. Seoane Souto et. al. Phys. Rev. B **89**, 085412 (2014)

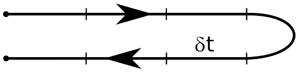
Generating function:

$$Z(\chi, t) = \left\langle T_c e^{i \int_c H_{T\chi} dt} \right\rangle$$

Functional determinant→Discretized in time contour[†]

$$Z(\chi, t) = \frac{\det\left[\hat{g}_0^{-1}(t) - \hat{\Sigma}(\chi, t)\right]}{\det\left[\hat{g}_0^{-1}(t) - \hat{\Sigma}(\chi = 0, t)\right]}$$

$\hat{g}_0$ →Green function of the dot
$\hat{\Sigma}$ → Self-energy (coupling to the electrodes)



[†]Rev. Mod. Phys. **81** (2009)

Mukamel formula

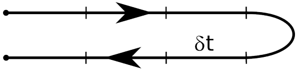
Generating function:

$$Z(\chi, t) = \left\langle T_c e^{i \int_c H_T \chi dt} \right\rangle$$

Functional determinant→Discretized in time contour†

$$Z(\chi, t) = \frac{\det\left[\hat{g}_0^{-1}(t) - \hat{\Sigma}(\chi, t)\right]}{\det\left[\hat{g}_0^{-1}(t) - \hat{\Sigma}(\chi = 0, t)\right]}$$

$\hat{g}_0$ →Green function of the dot
$\hat{\Sigma}$ → Self-energy (coupling to the electrodes)

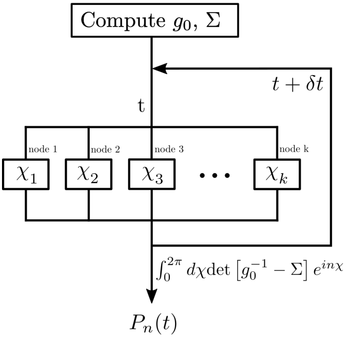


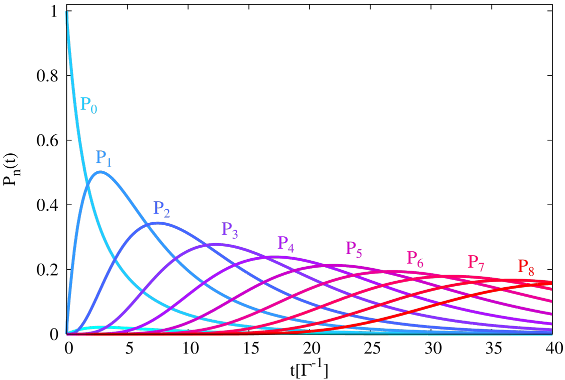
† Rev. Mod. Phys. **81** (2009)

Probability of electrons transfered

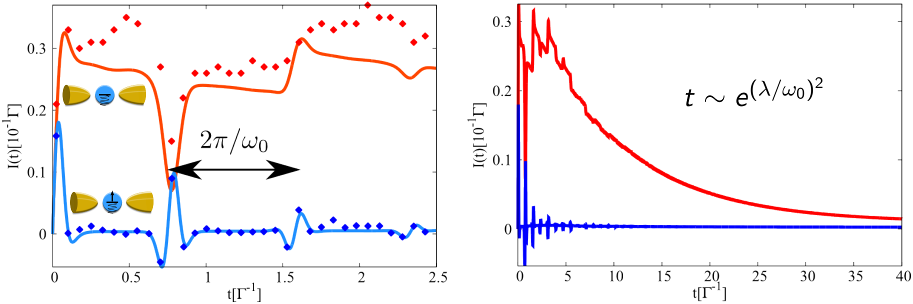
$$P_n = \int_0^{2\pi} d\chi \, Z(\chi, t) e^{in\chi} = \frac{\int_0^{2\pi} d\chi \, \det\left[\hat{g}_0^{-1}(t) - \hat{\Sigma}(\chi, t)\right] e^{in\chi}}{\det\left[\hat{g}_0^{-1}(t) - \hat{\Sigma}(\chi = 0, t)\right]}$$

Strong scaling≈1





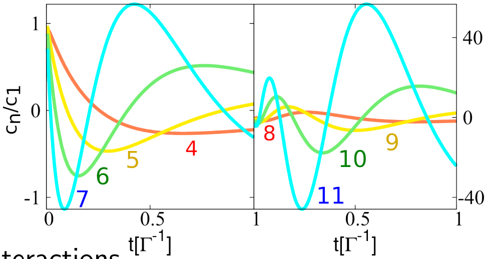
Current evolution. Quantum Monte Carlo data†



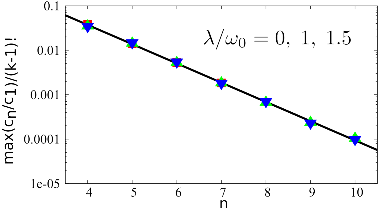
- ~~Bistability~~
- Polaronic effects causes long transient behavior

†K. F. Albretch et al. Phys. Rev. B **87**, 085127 (2013)

Universal oscillatory behavior at short times. Experiments †



independent of interactions



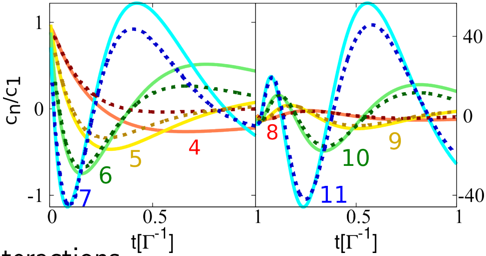
$$\langle c_n(t)\rangle = \left.\frac{\partial \mathrm{Log}[Z(\chi,t)]}{\partial \chi^n}\right|_{\chi=0}$$

$$Z(\chi,t) = c_1(t)\left(e^{i\chi} - 1\right)$$

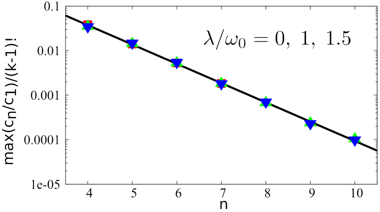
$$\max(c_n/c_1) = (n-1)!e^{-\pi}$$

† PNAS, 10116 (2009)

Universal oscillatory behavior at short times. Experiments †



independent of interactions



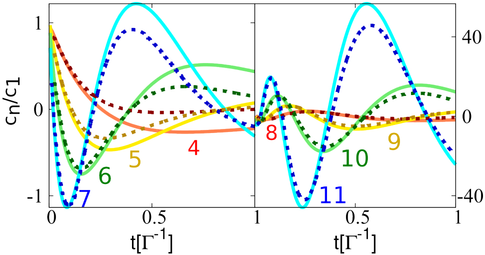
$$\langle c_n(t)\rangle = \left.\frac{\partial \mathrm{Log}[Z(\chi,t)]}{\partial \chi^n}\right|_{\chi=0}$$

$$Z(\chi,t) = c_1(t)\left(e^{i\chi}-1\right)$$

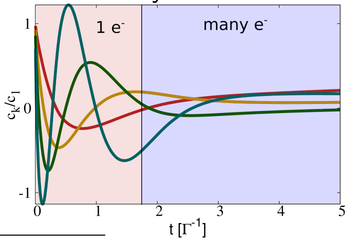
$$\max(c_n/c_1) = (k-1)!e^{-\pi}$$

† PNAS, 10116 (2009)

Universal oscillatory behavior at short times. Experiments

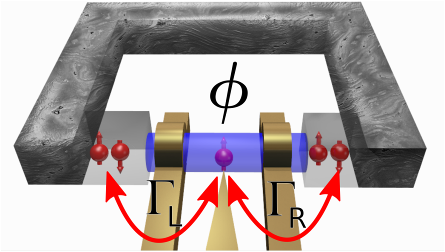


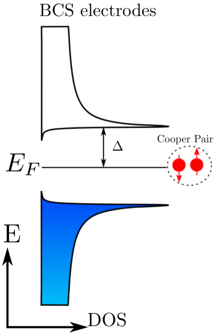
Many electrons→Broken universality †



† R. Seoane et al. PRB 92 (12) 125435, 2015 ;Accepted in Fortschritte der Physik

Phase driven superconducting junction

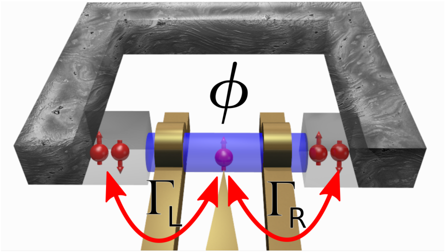


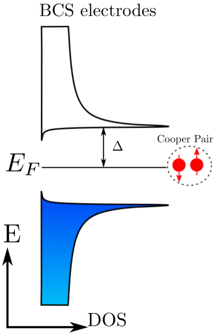


$\phi \rightarrow$ Magnetic flux through the loop

$$H = H_{BCS\ Leads} + \epsilon_0 \sum_{\sigma=\uparrow,\downarrow} d_\sigma^\dagger d_\sigma + H_T \theta(t)$$

Phase driven superconducting junction



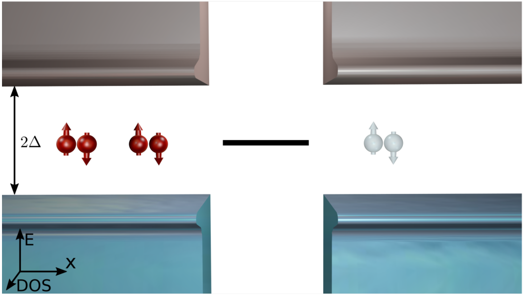


$\phi \rightarrow$ Magnetic flux through the loop

$$H = H_{BCS\ Leads} + \epsilon_0 \sum_{\sigma=\uparrow,\downarrow} d_\sigma^\dagger d_\sigma + H_T \theta(t)$$

electron-hole reflections→ Andreev reflections

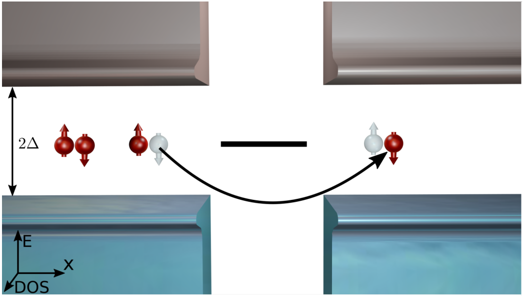
$$H = H_{BCS\ Leads} + \epsilon_0 \sum_{\sigma=\uparrow,\downarrow} d^\dagger_\sigma d_\sigma + H_T \theta(t)$$



Multiple Andreev reflections→ Andreev Bound states

electron-hole reflections→ Andreev reflections

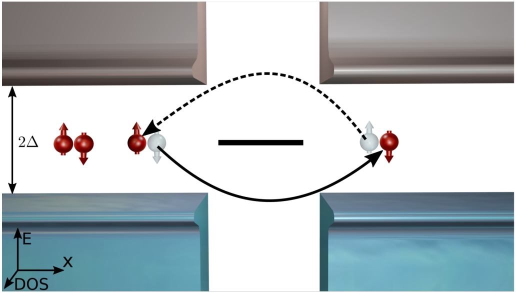
$$H = H_{BCS\ Leads} + \epsilon_0 \sum_{\sigma=\uparrow,\downarrow} d_\sigma^\dagger d_\sigma + H_T \theta(t)$$



Multiple Andreev reflections→ Andreev Bound states

electron-hole reflections→ Andreev reflections

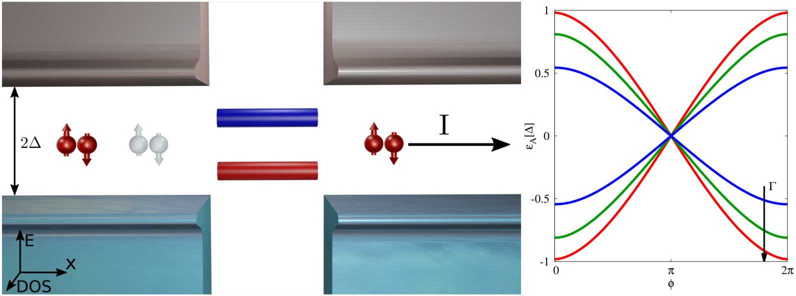
$$H = H_{BCS\ Leads} + \epsilon_0 \sum_{\sigma=\uparrow,\downarrow} d_\sigma^\dagger d_\sigma + H_T\theta(t)$$



Multiple Andreev reflections→ Andreev Bound states

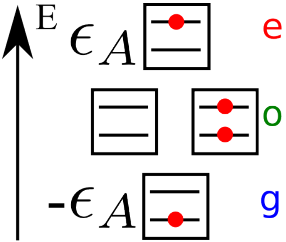
electron-hole reflections→ Andreev reflections

$$H = H_{BCS\ Leads} + \epsilon_0 \sum_{\sigma=\uparrow,\downarrow} d^\dagger_\sigma d_\sigma + H_T \theta(t)$$



Multiple Andreev reflections→ Andreev Bound states

Transport dominated by the presence of the Andreev Bound States[†]

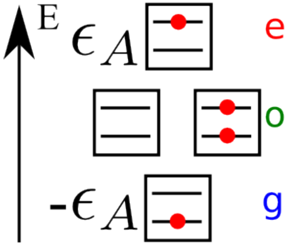


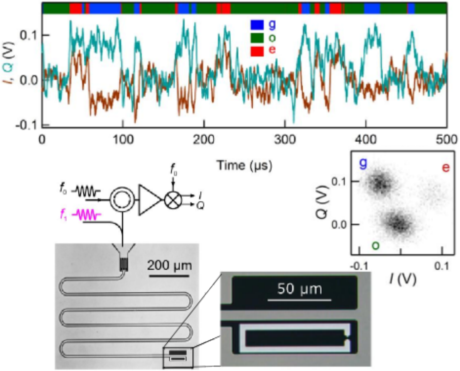
$I(t) \propto n_{ground}(t) - n_{excited}(t)$
T=0: only the *ground* state is populated.

[†]Science **349**, 1199 (2015)

Andreev physics

Transport dominated by the presence of the Andreev Bound States†



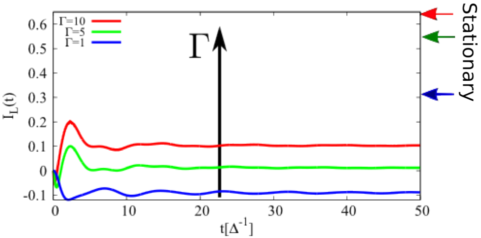


$I(t) \propto n_{ground}(t) - n_{excited}(t)$

T=0: only the *ground* state is populated.

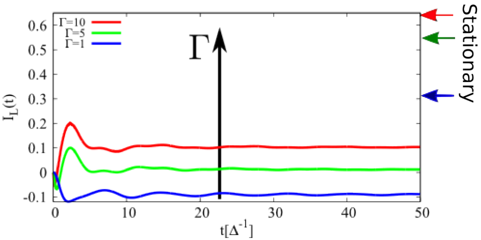
†Science **349**, 1199 (2015)

Current is not converging to the stationary value (even with adiabatic switching)

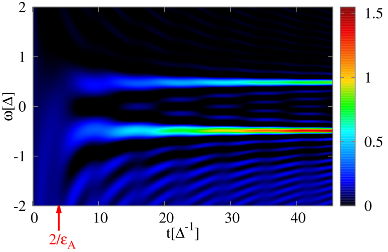


Non-interacting Andreev Bound states→ non-equilibrium population

Current is not converging to the stationary value

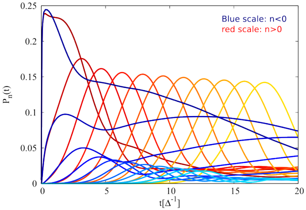


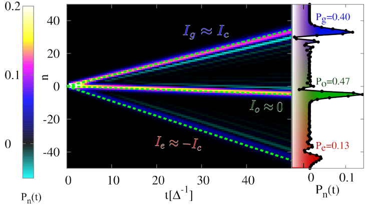
Non-interacting Andreev Bound states→ non-equilibrium population



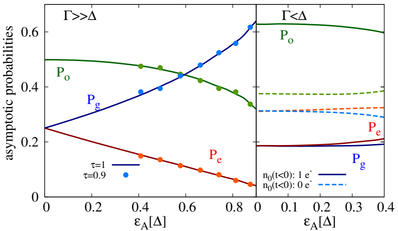
Counting statistics

Counting statistics→contributions from the four Fock states



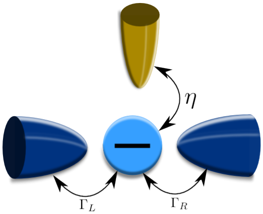


Quasi-particles trapped in the system. Universal behavior at $\Gamma \gg \Delta$†



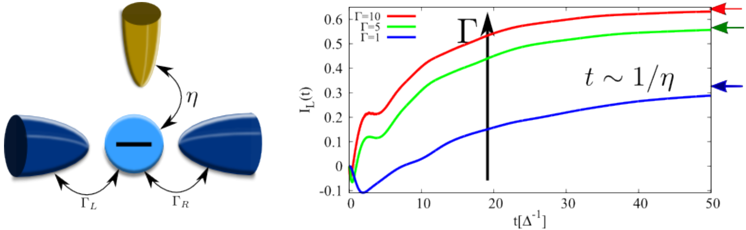
†Submitted to Phys. Rev. Lett.

Relaxation mechanism: weak coupling to a third normal electrode



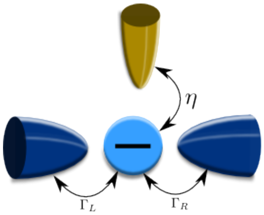
Population of the excited state relaxes

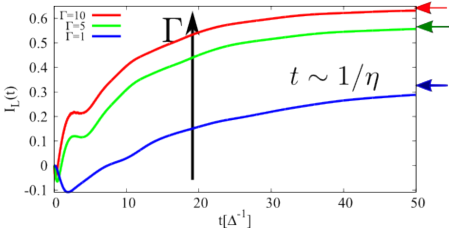
Relaxation mechanism: weak coupling to a third normal electrode



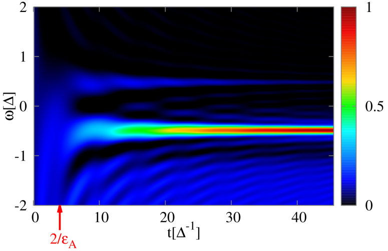
Population of the excited state relaxes

Relaxation mechanism: weak coupling to a third normal electrode





Population of the excited state relaxes



Conclusions

Electron counting statistics in transient regime

- Holstein model
  - Long transient dynamics
  - Universal oscillations in higher current cumulants
- Superconducting electrodes
  - Non-equilibrium population of Andreev bound states
  - Extra relaxation mechanism to reach stationary

Future

- Stationary regime
- Coherent control of the system$\rightarrow$ Andreev qubit

Acknoledgements

Computational resources

Funding

Our group in Madrid


Alfredo Levy


Rosa C. Monreal


Álvaro Martín

Bordeaux


Rémi Avriller

Thank you!