Thermally induced subgap features in the cotunneling spectroscopy of a carbon nanotube

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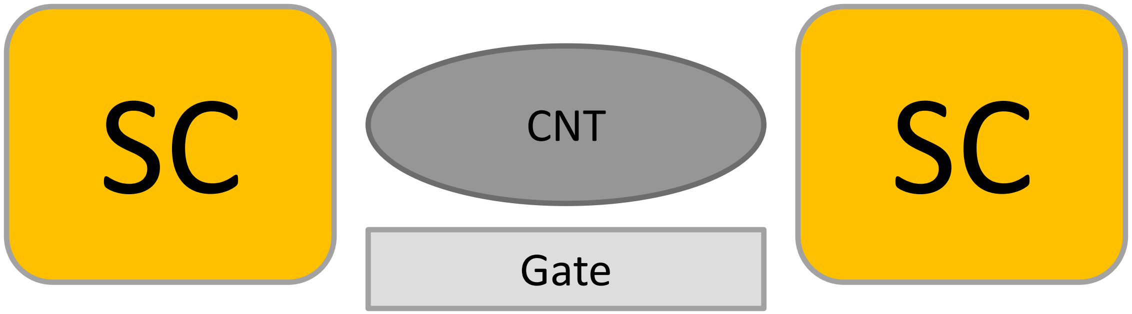

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Several phenomena

Hybrid SC quantum dot devices in the Coulomb Blockade regime show several transport phenomena:

- Supercurrent transport carried by **Cooper pairs**

  L. I. Glazman, and K. A. Matveev, *JETP Lett.* **49**, 659 (1989)
  J. Baselmans, A. F. Morpurgo, et al., *Nature* **43**, 397 (1999)
  A. V. Rozhkov, D. P. Arovas, and F. Guinea, *Phys. Rev. B* **64**, 233301 (2001)
  P. Jarillo-Herrero, J. A. van Dam, and L. Kouwenhoven, *Nature* **439**, 953 (2006)

- Coherent electron transport in terms of **multiple** **Andreev reflections**

  E. Scheer, W. Belzig, et al., *Phys. Rev. Lett.* **86**, 284 (2001)
  M. R. Buitelaar,W. Belzig, et al., *Phys. Rev. Lett.* **91**, 057005 (2003)
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  F. Deon, V. Pellegrini, et al., *Phys. Rev. B* **84**, 100506 (2011)

- **Quasi-particle** transport

  A. Levy Yeyati, J. C. Cuevas, et al., *Phys. Rev. B* **55**, 6137 (1997)
  V. N. Golovach and D. Loss, *Phys. Rev. B* **69**, 245327 (2004)
  J. A. van Dam, Y. V. Nazarov , et al., *Nature* **442**, 667 (2006)
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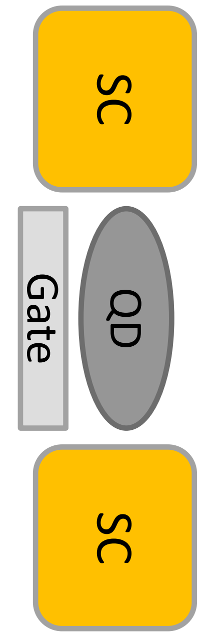
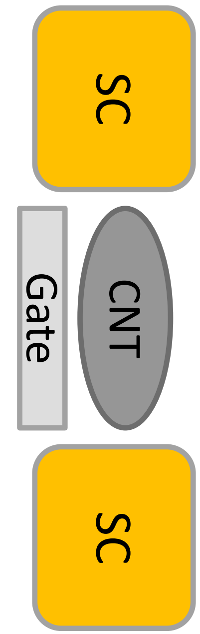
  K. Grove-Rasmussen, H. I. Jørgensen et al., Phys. Rev. B 79 134518 (2009)
  S. De Franceschi S, L. Kouwenhoven, et al., *Nat. Nanotechnol.* **5**, 703(2010)
  S. Pfaller, A. Donarini , and M. Grifoni, *Phys. Rev. B* **87**, 155439 (2013)
  M. Gaass, S. Pfaller, et al., *Phys. Rev. B* **89**, 241405 (2014)



A specific transport regime

A few energy scales define the hybrid junction:

Temperature	T	24 – 1700 mK
Lead-dot (bare) tunnelling rate	$\hbar\Gamma$	0.1 meV
Superconducting gap	Δ	0.26 (1.2) meV
Charging energy	U	15 meV



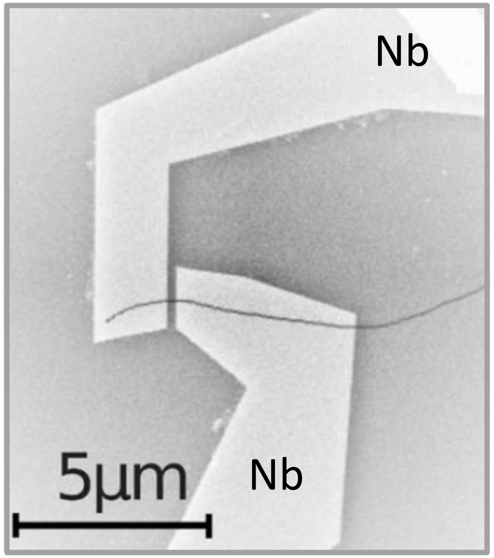
$\hbar\Gamma < \Delta$ ➡ Suppression of Andreev reflection

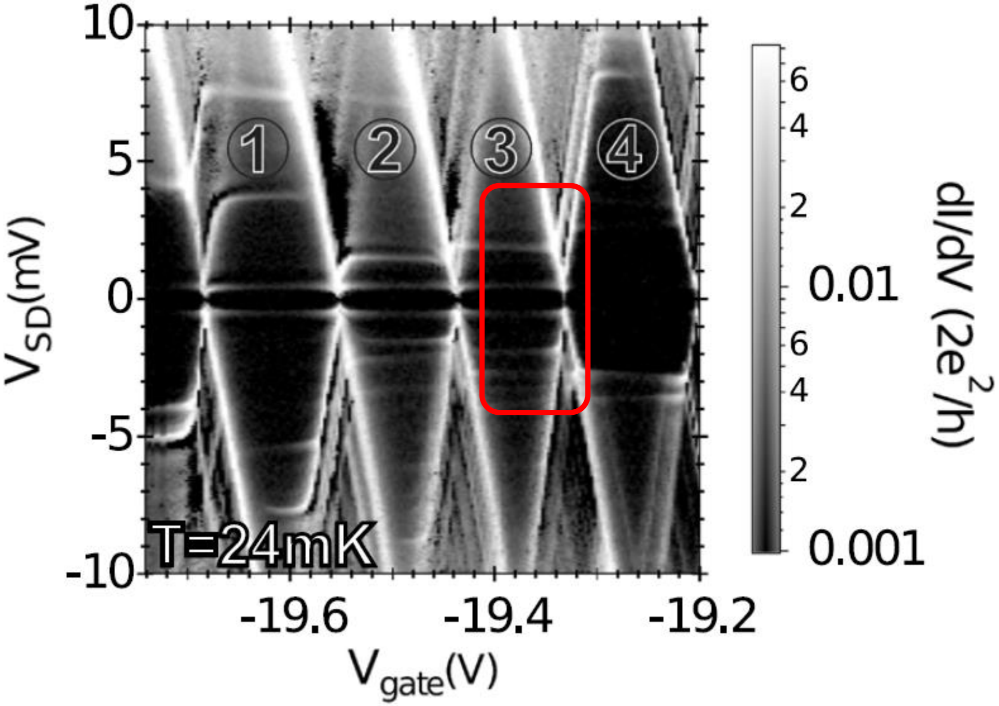
$\hbar\Gamma \ll U$ ➡ Suppression of multiple quasiparticle tunnelling

$k_B T \approx \Delta$ ➡ Thermal excitation of quasiparticles

Sequential tunnelling and **cotunnelling** processes suffice for the description of the system dynamics

Motivation





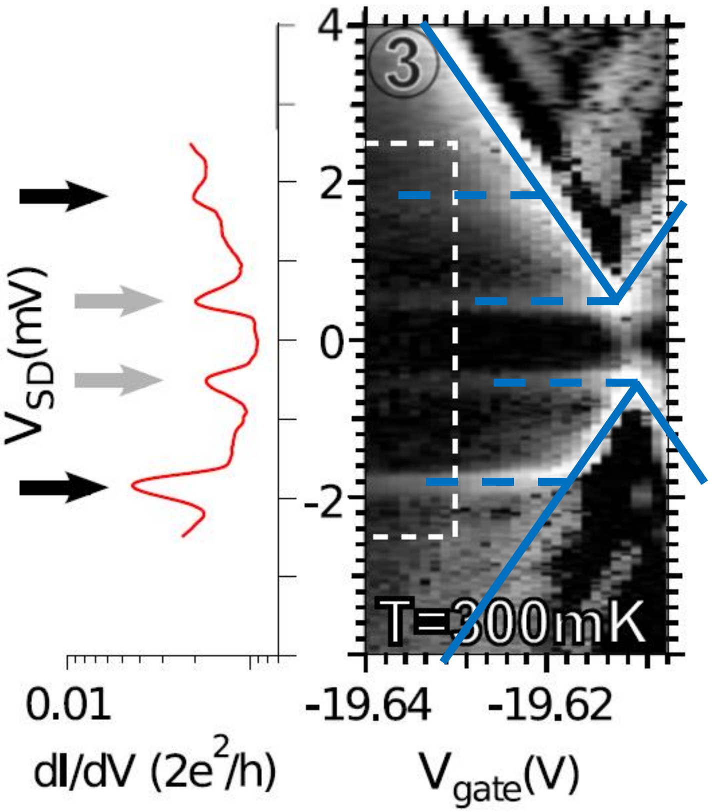
Cotunnelling lines are visible at:

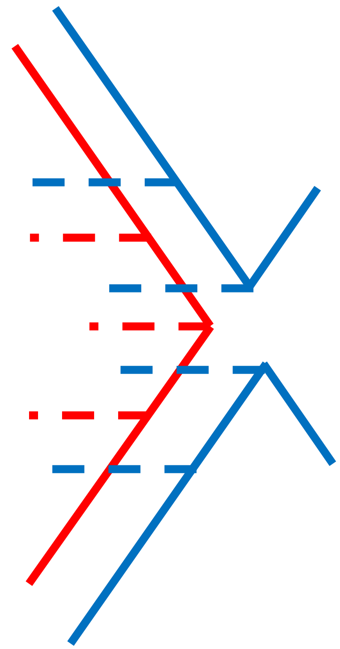
$$V_b = \pm 2\Delta/e$$ Elastic cotunnelling

$$V_b = \pm(2\Delta + \delta_m)/e$$ Inelastic cotunnelling

$\{\delta_m\}$ is the set of excitation energies for the quantum dot with N particles

Thermallly induced effects





Standard sequential tun.

Standard cotunnelling

Therm. induced sequential tun.

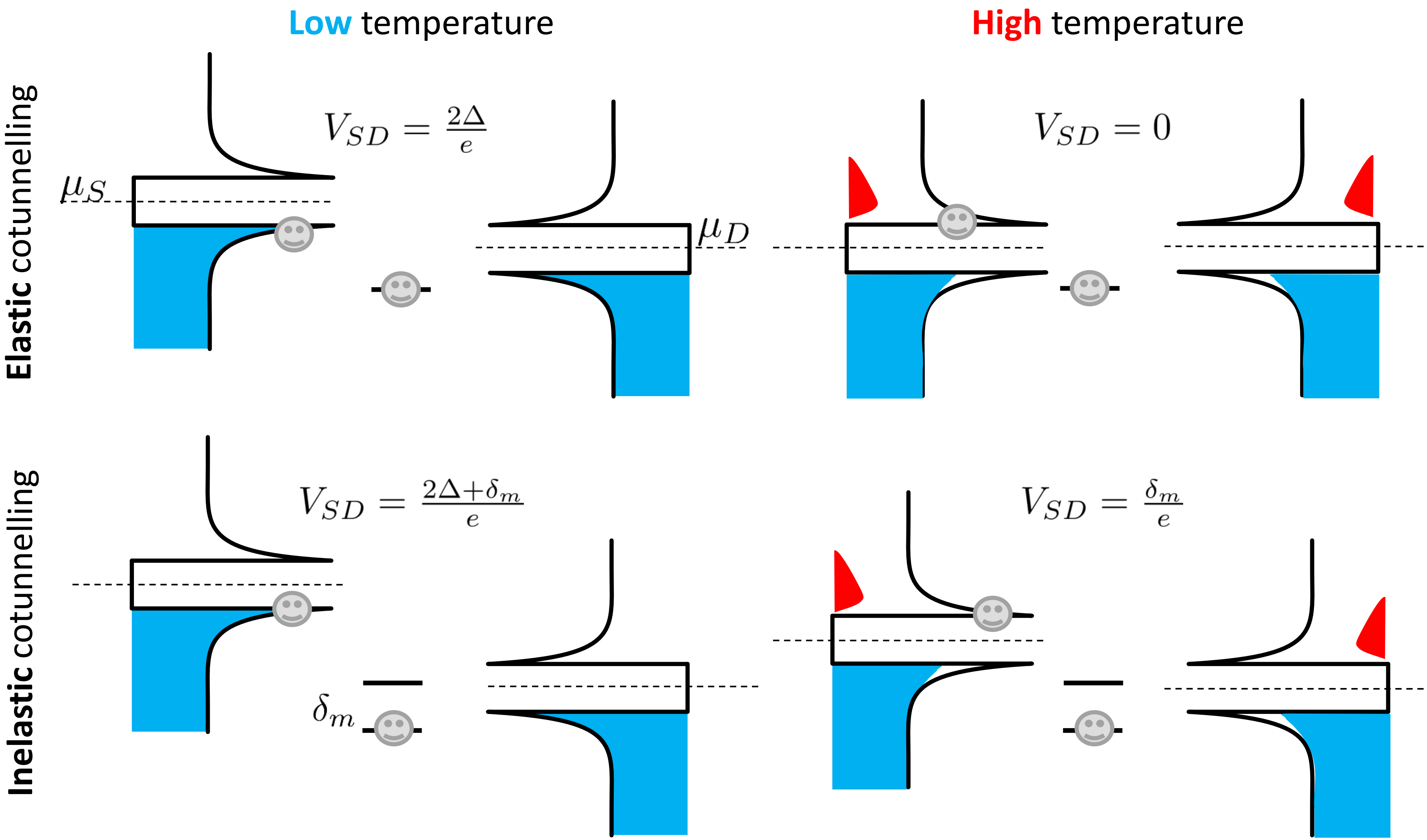
Therm. induced cotunnelling.

M. Gaass, et al. *Phys. Rev. B* **89**, 241405(R) (2014)

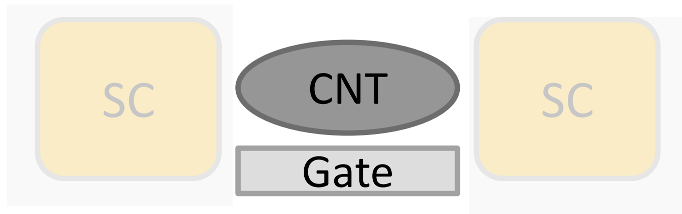
S. Pfaller et al., *Phys. Rev. B* **87**, 155439 (2013)

S. Ratz et al., *New J. Phys.* **16**, 123040 (2014)

Cotunnelling processes



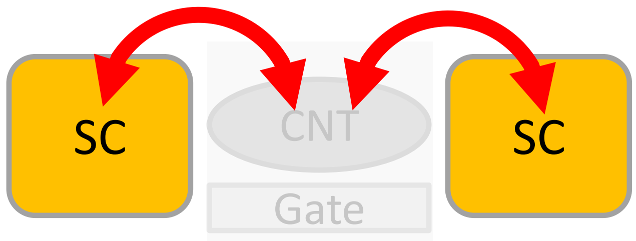
Model



$$\hat{H}_{\mathrm{CNT}} = \underbrace{\sum_{m\sigma} E_{m\sigma} \hat{d}^{\dagger}_{m\sigma} \hat{d}_{m\sigma}}_{\text{Single shell + spin orbit and KK‘ mixing}} + \underbrace{\frac{U}{2} \hat{N} \left(\hat{N} - 1 \right)}_{\text{Constant interaction}} - \underbrace{\alpha e V_{\mathrm{gate}} \hat{N}}_{\text{Gate shift}}$$

$$E_{m\sigma} = \epsilon_d + \frac{1}{2} m \sigma \delta$$

Model



$$\hat{H}_l = E_l^0 + \underbrace{\sum_{\vec{k}\sigma} E_{l\vec{k}}\, \hat{\gamma}^\dagger_{l\vec{k}\sigma} \hat{\gamma}_{l\vec{k}\sigma}}_{\text{Quasiparticle excitations}} + \mu_l \hat{N}_l$$

Quasiparticle excitations

$$E_{l\vec{k}} = \sqrt{(\epsilon_{\vec{k}} - \mu_l)^2 + \Delta^2}$$

The gap equation

$$\Delta \equiv |V| \sum_{\vec{k}} \left\langle \hat{S}_l^\dagger \hat{c}_{l-\vec{k}\downarrow} \hat{c}_{l\vec{k}\uparrow} \right\rangle$$

$$\hat{H}_{T,l} = T_l \sum\nolimits_{\vec{k}\sigma m} \left(\hat{d}^\dagger_{m\sigma} \hat{c}_{l\vec{k}\sigma} + \text{h.c.} \right)$$

Bogolioubov – Valatin
particle conserving transformation

$$\hat{c}^\dagger_{l\vec{k}\sigma} = u_{l\vec{k}} \hat{\gamma}^\dagger_{l\vec{k}\sigma} + \sigma v^*_{l\vec{k}} \hat{S}_l^\dagger \hat{\gamma}_{l-\vec{k}\bar{\sigma}}$$

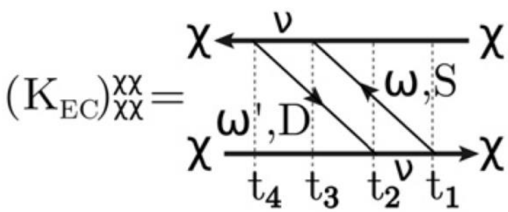
$$\hat{c}_{l\vec{k}\sigma} = u^*_{l\vec{k}} \hat{\gamma}_{l\vec{k}\sigma} + \sigma v_{l\vec{k}} \hat{S}_l \hat{\gamma}^\dagger_{l-\vec{k}\bar{\sigma}}$$

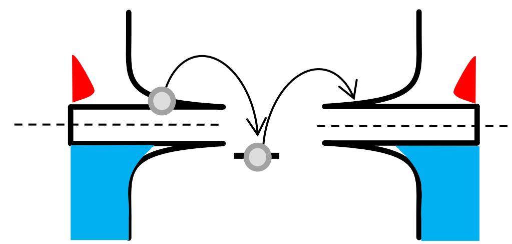
Transport calculation

The dynamics is described by the generalized master equation

$$\dot{\hat{\rho}}_{\text{red}}(t) = -\frac{i}{\hbar}\left[\hat{H}_{\text{CNT}}, \hat{\rho}_{\text{red}}(t)\right] + \int_{t_0}^{t} \mathrm{d}\tau \hat{K}(t-\tau)\hat{\rho}_{\text{red}}(\tau)$$

Exemplarily, one elestic cotunnelling contribution to the evolution kernel reads:



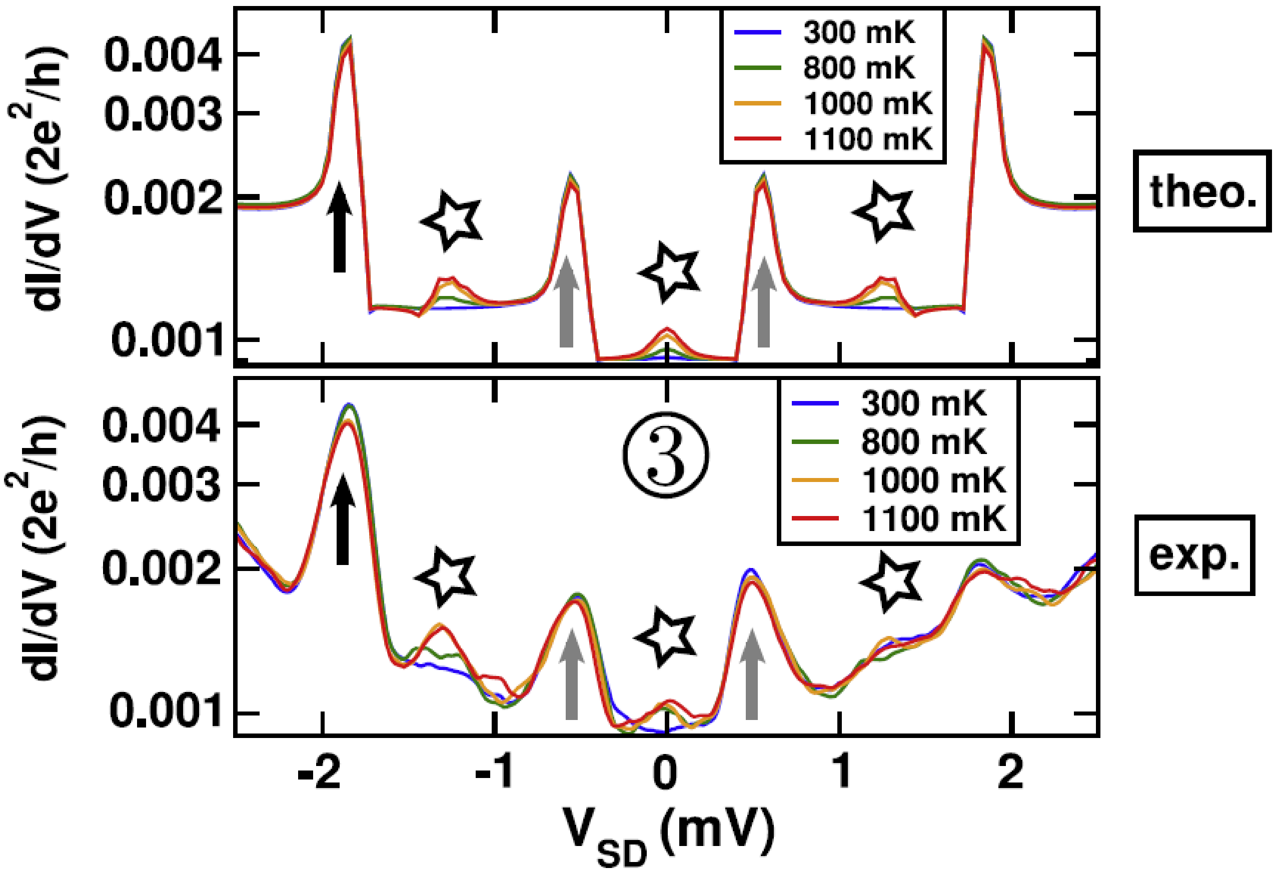


$$\left(\hat{K}_{EC}\right)^{\chi\chi}_{\chi\chi} \equiv -i\hbar\Gamma_S\Gamma_D \sum_{\nu} \int \frac{\mathrm{d}\omega}{2\pi}\frac{\mathrm{d}\omega'}{2\pi} D_S(\omega, \Delta) D_D(\omega', \Delta)$$

$$\times \frac{f_S(\omega)\left(1 - f_D(\omega')\right)}{\left(-\omega + \delta E + i0^+\right)\left(\omega' - \omega + i0^+\right)\left(\omega' - \delta E + i0^+\right)}$$

Theory vs. Experiment

Φ(R)



Conclusions and outlook

- We report on **new transport properties** of a CNT contacted with two superconducting Nb leads.

- **Thermal replicas** of the elastic and inelastic cotunnelling resonances are observed for a temperature above 600 mK ($k_B T \approx \Delta$) : i.e. an extra **zero-bias peak** and **inelastic peak** corresponding to the lower excitation energy.

- We develope a generalized master equation for the reduced density matrix in the charge-conserved regime applicable to **any intradot interaction** and **finite** superconducting gap.

- A model of the CNT with a low energy interacting spectrum gives **remarkable agreement** with the experimental results.

- Further developments of the theory to include multiple Andreev reflections and supercurrent transport carried by Cooper pairs is envisaged.