Non-equilibrium signatures of electron pairing in quantum dots coupled to superconductors

Tadeusz Domański

M. Curie-Skłodowska University

Lublin, Poland

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OUTLINE

Physical issue:

1. time-resolved phenomena

(observable for in-gap bound states)

2. out-of-equilibrium transport

(realized via Andreev scattering)

SUPERCONDUCTING PROXIMITY EFFECT

Quantum dot (QD) coupled to itinerant electrons of bulk superconductor (SC) is affected by:

$\Rightarrow$ **on-dot pairing**

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spectroscopically manifested by:

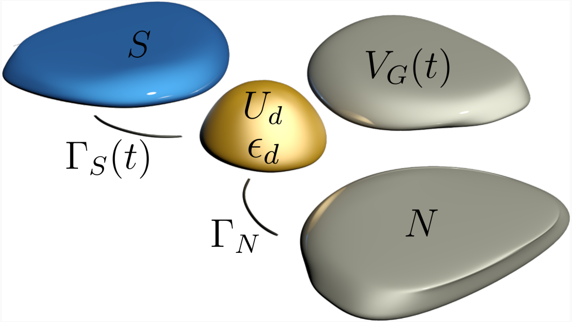
$\Rightarrow$ **in-gap bound states**

which originate from:

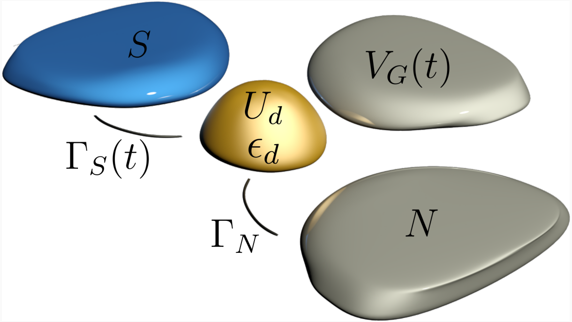
$\Rightarrow$ **leakage of Cooper pairs on QD** **(Andreev)**

$\Rightarrow$ **exchange int. of QD with SC** **(Yu-Shiba-Rusinov)**

DYNAMICS OF IN-GAP STATES



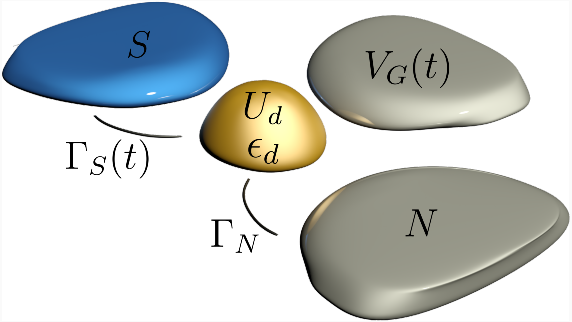
Empirical protocols of time-resolved phenomena:



Empirical protocols of time-resolved phenomena:

$\Rightarrow$ **variation of the coupling Γ_S to superconductor**

DYNAMICS OF IN-GAP STATES



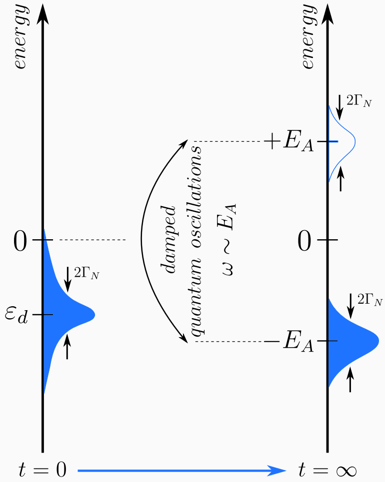
Empirical protocols of time-resolved phenomena:

$\Longrightarrow$ **variation of the coupling Γ_S to superconductor**

$\Longrightarrow$ **change of the gate potential V_G**

BUILDUP OF IN-GAP STATES

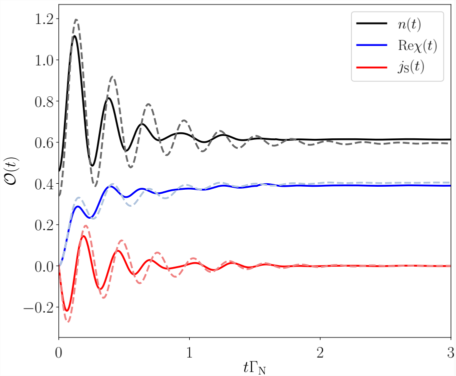
Sudden coupling of QD to superconductor $0 \rightarrow \Gamma_S$



K. Wrześniewski, B. Baran, R. Taranko, T. Domański & I. Weymann, PRB 103, 155420 (2021).

BUILDUP OF IN-GAP STATES

Time-dependent observables driven by the quantum quench $0 \to \Gamma_S$



$n(t)$ **electron number**

$\chi(t) = \left\langle \hat{d}_\downarrow \hat{d}_\uparrow \right\rangle$ **on-dot pairing**

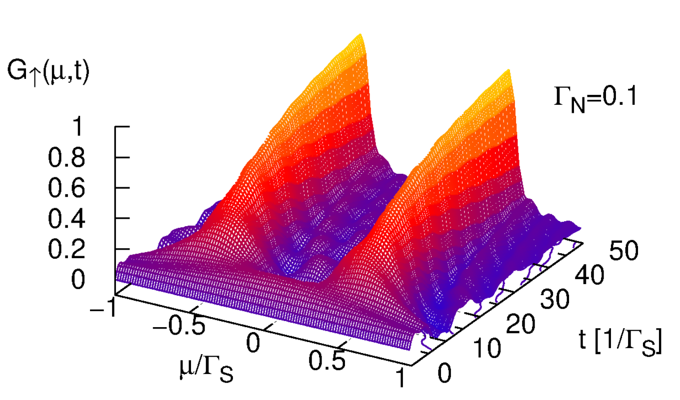
$j_S(t)$ **charge current**

solid lines - time dependent NRG

dashed lines - Hartree-Fock-Bogolubov

K. Wrześniewski, B. Baran, R. Taranko, T. Domański & I. Weymann, PRB 103, 155420 (2021).

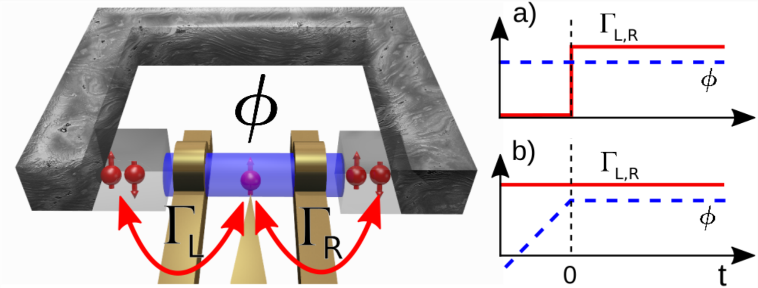
TIME-DEPENDENT TUNNELING CONDUCTANCE



Subgap tunneling conductance $G_\sigma = \frac{\partial I_\sigma}{\partial t}$ vs time (t) and voltage (μ)

K. Wrześniewski, B. Baran, R. Taranko, T. Domański & I. Weymann, PRB 103, 155420 (2021).

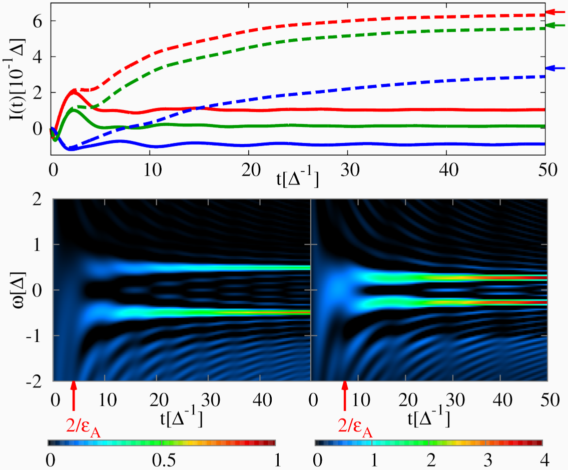
Quantum quench imposed on QD in Josephson junction geometry



R. Seoane Souto, A. Martín-Rodero, A. Levy Yeyati, Phys. Rev. Lett. 117, 267701 (2016).

ANDREEV STATES IN JOSEPHSON JUNCTION

Transient current and quasiparticle spectrum obtained for different ratios of Γ/Δ (from top to bottom: 10, 5 and 1).



R. Seoane Souto, A. Martín-Rodero, A. Levy Yeyati, Phys. Rev. Lett. 117, 267701 (2016).

IN-GAP STATES OF CLASSICAL IMPURITY

communications
physics

ARTICLE

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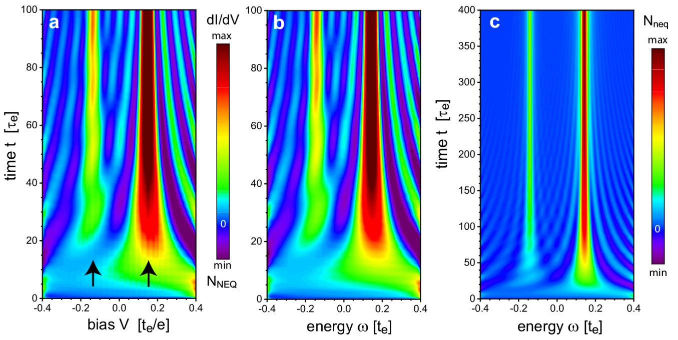
https://doi.org/10.1038/s42005-022-01050-7 OPEN

Emergence and manipulation of non-equilibrium Yu-Shiba-Rusinov states

Jasmin Bedow[1], Eric Mascot[1,2] & Dirk K. Morr[1]✉



Triplet (Andreev) blockade

[in double-quantum-dot junctions]

STATIC REALIZATION: N-DQD-S

SciPost Phys. 11, 081 (2021)

Theory of Andreev blockade in a double quantum dot with a superconducting lead

David Pekker, Po Zhang and Sergey M. Frolov

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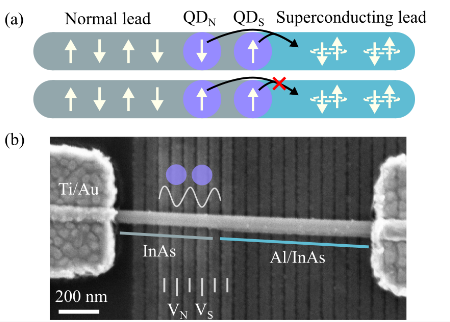

P. Zhang, H. Wu, J. Chen, S.A. Khan, P. Krogstrup, D. Pekker, and S.M. Frolov, Phys. Rev. Lett. 128, 046801 (2022).

STATIC REALIZATION: S-DQD-S

PHYSICAL REVIEW B **102**, 220505(R) (2020)

Rapid Communications

Triplet-blockaded Josephson supercurrent in double quantum dots

Daniël Bouman,[1] Ruben J. J. van Gulik,[1] Gorm Steffensen,[2] Dávid Pataki,[3] Péter Boross,[4] Peter Krogstrup,[2] Jesper Nygård,[2] Jens Paaske,[2] András Pályi,[3] and Attila Geresdi[1,5,*]

[1]*QuTech and Kavli Institute of Nanoscience, Delft University of Technology, NL-2600 GA Delft, The Netherlands*

[2]*Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark*

[3]*Department of Theoretical Physics and MTA-BME Exotic Quantum Phases Research Group, Budapest University of Technology and Economics, H-1111 Budapest, Hungary*

[4]*Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, P.O. Box 49, H-1525 Budapest, Hungary*

[5]*Quantum Device Physics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-41296 Gothenburg, Sweden*

(Received 12 August 2020; accepted 2 December 2020; published 21 December 2020)

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[4]*Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, P.O. Box 49, H-1525 Budapest, Hungary*
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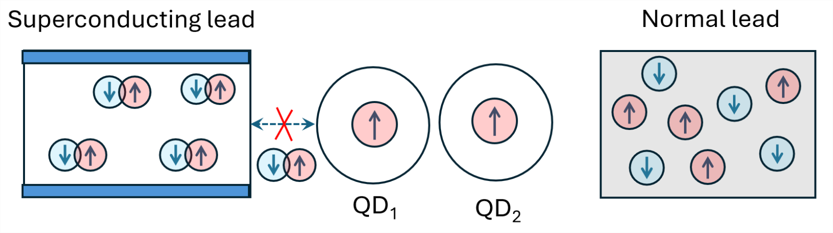
Conclusion: **"magnetic field dependence of the supercurrent amplitude in the even occupied state reveals the presence of a supercurrent blockade in the spin-triplet ground state"**

DYNAMICAL ANDREEV BLOCKADE



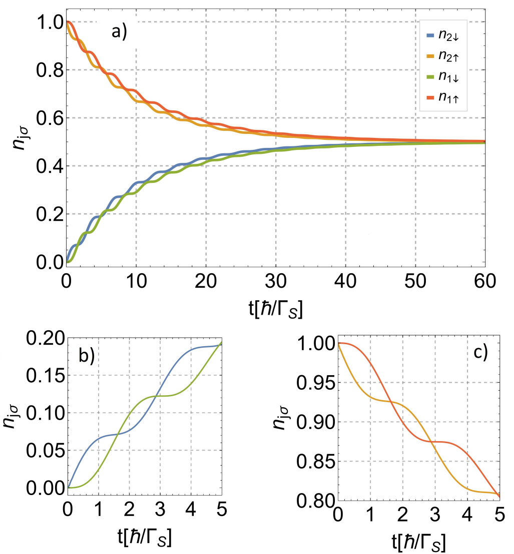
Superconducting proximity effect is blocked:

⇒ **when both quantum dots are singly occupied**

⇒ **by the same spin (for example ↑) electrons**

R. Taranko, J. Barański, A. Jankiewicz, K. Wrześniewski, I. Weymann & T. Domański [submitted (2025)].

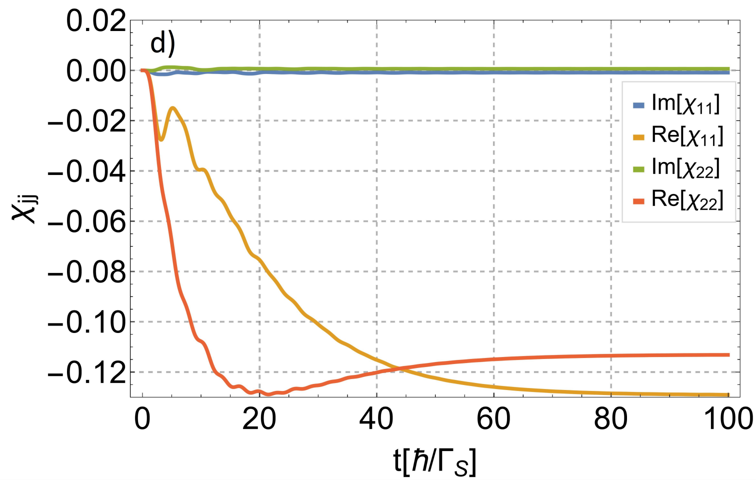
TRANSIENT BLOCKADE



Occupancy of the quantum dots initially occupied by ↑ electrons.

TRANSIENT BLOCKADE

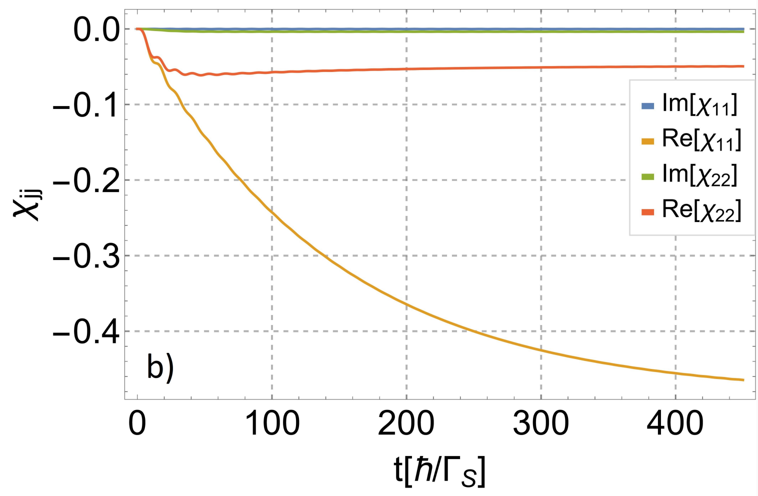
Results for $\chi_{jj}(t) \equiv \langle \hat{d}_{j\downarrow}\hat{d}_{j\uparrow} \rangle$ in the strong inter-dot coupling $V_{12} = \Gamma_S$.



Pairing in the quantum dots initially occupied by ↑ electrons

TRANSIENT BLOCKADE

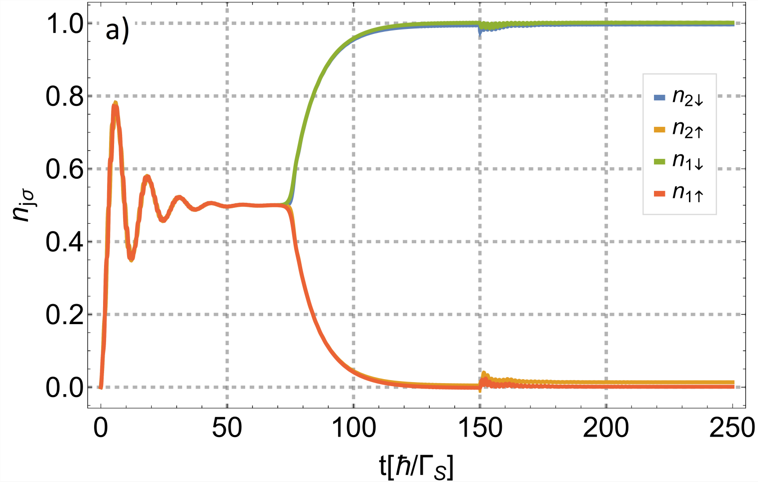
Results for $\chi_{jj}(t) \equiv \langle \hat{d}_{j\downarrow}\hat{d}_{j\uparrow} \rangle$ in the weak inter-dot coupling $V_{12} = 0.1\Gamma_S$.



Pairing in the quantum dots initially occupied by ↑ electrons

ZEEMAN INDUCED BLOCKADE

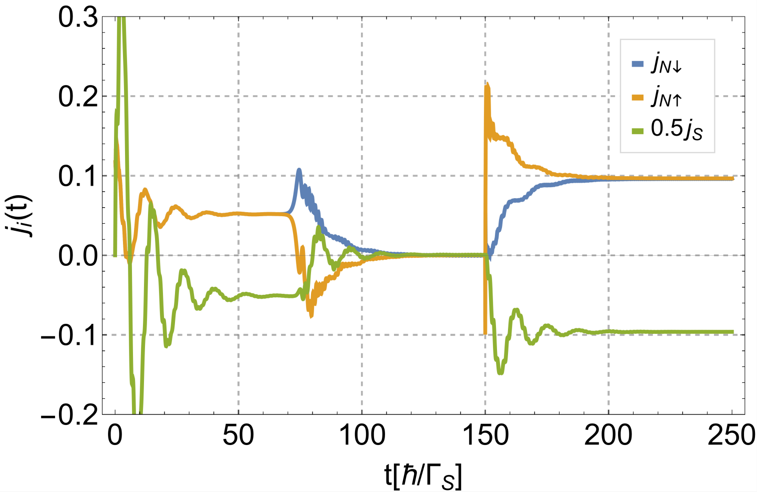
Magnetic field $B = 10\Gamma_S/\mu_B$ is switched on at $t = 75\Gamma_S/\hbar$



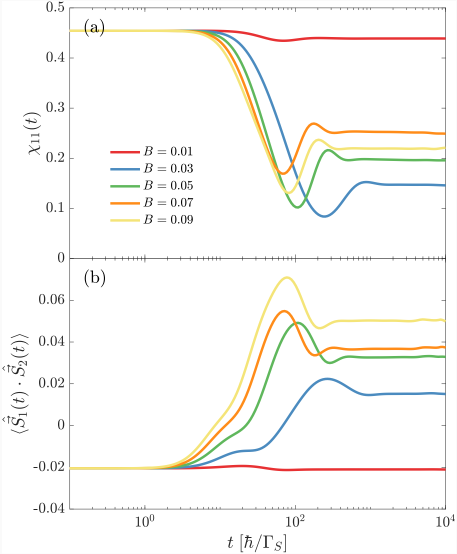
Occupancy of the initially empty quantum dots.

NON-EQUILIBRIUM CHARGE TRANSPORT

Magnetic field $B = 10\Gamma_S/\mu_B$ is switched on at $t = 75\Gamma_S/\hbar$ and bias voltage is strongly amplified at $t = 150\Gamma_S/\hbar$



Results obtained by time-dependent NRG calculations



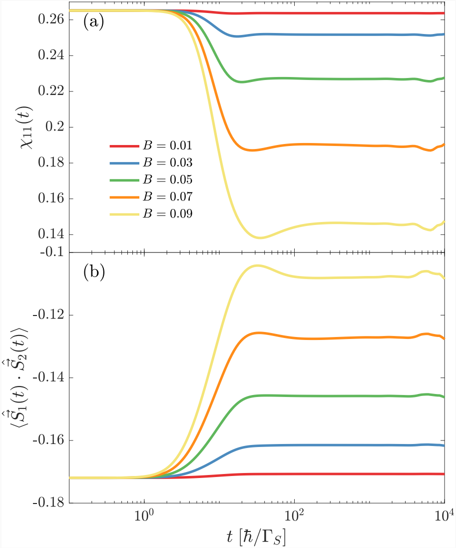
Model parameters:

$U_1 = 0.9\Gamma_S, \quad U_2 = 0,$

$\varepsilon_1 = -U_1/2, \quad \varepsilon_2 = 0,$

$V_{12} = 0.045\Gamma_S$

Results obtained by time-dependent NRG calculations



Model parameters:

$U_1 = 0.9\Gamma_S, \quad U_2 = 0,$

$\varepsilon_1 = -U_1/2, \quad \varepsilon_2 = 0,$

$V_{12} = 0.225\Gamma_S$

SUMMARY

By attaching the quantum impurity to bulk superconductor (or when its energy level / coupling strength is varried):

- **Rabi-type oscillations are induced** **(due to particle-hole mixing)**
- **leading to buildup (re-arrangement) of the in-gap states**
- **dynamical phase transition can occur** **(changeover of ground state)**

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By attaching the quantum impurity to bulk superconductor (or when its energy level / coupling strength is varried):

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These phenomena could be detected in the charge transport measurements, using time-resolved Andreev spectroscopy.