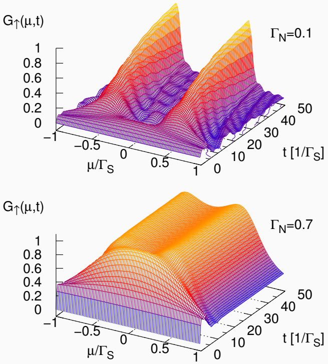
Dynamical effects of correlated superconducting nanostructures

Tadeusz DOMAŃSKI

M. Curie-Skłodowska University, Lublin



JEMS, Warsaw **29 July 2022**

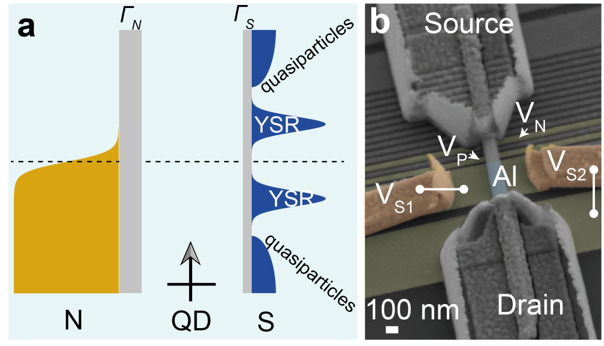
Superconducting nanostructures

Superconducting nanostructures

a few examples ...

HETEROSTRUCTURES WITH SUPERCONDUCTOR(S)

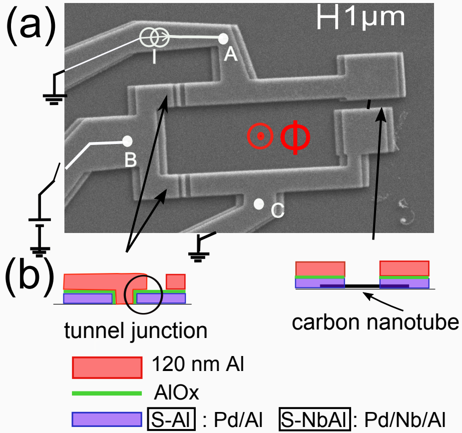
Normal metal (N) – Quantum Dot (QD) – Superconductor (S)



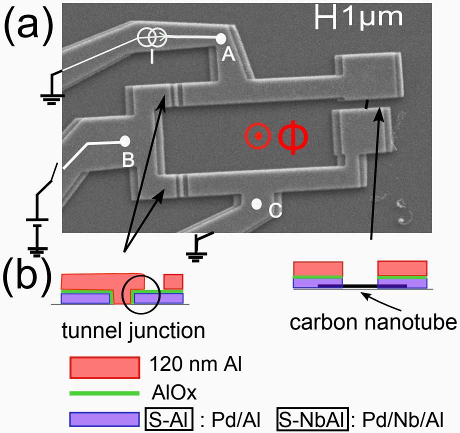
J. Estrada Saldaña, A. Vekris, V. Sosnovtseva, T. Kanne, P. Krogstrup, K. Grove-Rasmussen and J. Nygård, Commun. Phys. 3, 125 (2020).

HETEROSTRUCTURES WITH SUPERCONDUCTOR(S)

Superconductor – Quantum Dot – Superconductor



Superconductor – Quantum Dot – Superconductor



Josephson junction

R. Delagrange et al, Phys. Rev. B 93, 195437 (2016).

SUPERCONDUCTING PROXIMITY EFFECT

- **Coupling of the localized (QD) to itinerant (SC) electrons induces:**

$\Longrightarrow$ **on-dot pairing**

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SUPERCONDUCTING PROXIMITY EFFECT

- **Coupling of the localized (QD) to itinerant (SC) electrons induces:**

$\Longrightarrow$ **on-dot pairing**

- **This is manifested spectroscopically by:**

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

- **originating from:**

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

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

Why are we interested in this ?

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recent headlines ...

SUPERCONDUCTING QUBITS

Applied Physics Letters PERSPECTIVE scitation.org/journal/apl

A perspective on semiconductor-based superconducting qubits

Cite as: Appl. Phys. Lett. **117**, 240501 (2020); doi: 10.1063/5.0024124
Submitted: 4 August 2020 · Accepted: 9 November 2020 ·
Published Online: 14 December 2020

View Online Export Citation CrossMark

Ramón Aguado[a)]

AFFILIATIONS

Instituto de Ciencia de Materiales de Madrid (ICMM), Consejo Superior de Investigaciones Científicas (CSIC), Sor Juana Inés de la Cruz 3, 28049 Madrid, Spain

Quantum bits (qubits) can be constructed out of in-gap bound states, using either the Josephson junctions (transmons) or the semiconducting-superconducting hybrids (gatemons).

REPORT

QUANTUM DEVICES

Coherent manipulation of an Andreev spin qubit

M. Hays[1*], V. Fatemi[1*], D. Bouman[2,3], J. Cerrillo[4,5], S. Diamond[1], K. Serniak[1†], T. Connolly[1], P. Krogstrup[6], J. Nygård[6], A. Levy Yeyati[5,7], A. Geresdi[2,3,8], M. H. Devoret[1*]

Two promising architectures for solid-state quantum information processing are based on electron spins electrostatically confined in semiconductor quantum dots and the collective electrodynamic modes of superconducting circuits. Superconducting electrodynamic qubits involve macroscopic numbers of electrons and offer the advantage of larger coupling, whereas semiconductor spin qubits involve individual electrons trapped in microscopic volumes but are more difficult to link. We combined beneficial aspects of both platforms in the Andreev spin qubit: the spin degree of freedom of an electronic quasiparticle trapped in the supercurrent-carrying Andreev levels of a Josephson semiconductor nanowire. We performed coherent spin manipulation by combining single-shot circuit–quantum-electrodynamics readout and spin-flipping Raman transitions and found a spin-flip time T_S = 17 microseconds and a spin coherence time T_{2E} = 52 nanoseconds. These results herald a regime of supercurrent-mediated coherent spin-photon coupling at the single-quantum level.

Hays *et al.*, *Science* **373**, 430–433 (2021)   23 July 2021

Recent evidence for experimental realization

SUPERCONDUCTING QUBITS

PRX QUANTUM **2,** 040347 (2021)

Yu-Shiba-Rusinov Qubit

Archana Mishra,[1,*] Pascal Simon,[2,†] Timo Hyart,[1,3,‡] and Mircea Trif[1,§]

[1] *International Research Centre MagTop, Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, Warsaw PL-02668, Poland*

[2] *Université Paris-Saclay, CNRS, Laboratoire de Physiques des Solides, Orsay 91405, France*

[3] *Department of Applied Physics, Aalto University, Aalto, Espoo 00076, Finland*

(Received 15 June 2021; accepted 2 November 2021; published 7 December 2021)

Magnetic impurities in *s*-wave superconductors lead to spin-polarized Yu-Shiba-Rusinov (YSR) in-gap states. Chains of magnetic impurities offer one of the most viable routes for the realization of Majorana bound states, which hold promise for topological quantum computing. However, this ambitious goal looks distant, since no quantum coherent degrees of freedom have yet been identified in these systems. To fill this gap, we propose an effective two-level system, a YSR qubit, stemming from two nearby impurities. Using a time-dependent wave-function approach, we derive an effective Hamiltonian describing the YSR-qubit evolution as a function of the distance between the impurity spins, their relative orientations, and their dynamics. We show that the YSR qubit can be controlled and read out using state-of-the-art experimental techniques for manipulation of the spins. Finally, we address the effect of spin noise on the coherence properties of the YSR qubit and show robust behavior for a wide range of experimentally relevant parameters. Looking forward, the YSR qubit could facilitate the implementation of a universal set of quantum gates in hybrid systems where they are coupled to topological Majorana qubits.

Conventional and/or topological superconducting qubits

Are there any characteristic time-scales ?

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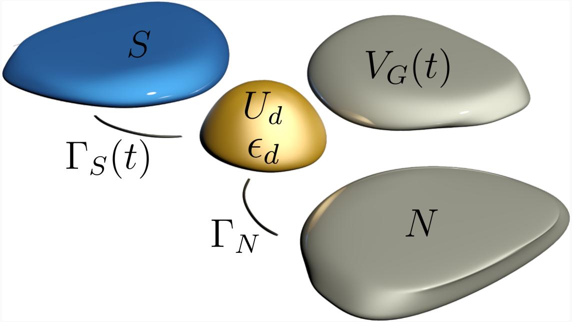
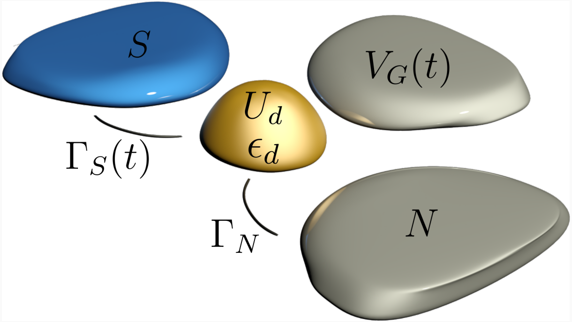
(of importance for operations on qubits)



Possible quench protocols:

QUENCH DRIVEN DYNAMICS



Possible quench protocols:

$\Rightarrow$ **sudden coupling to superconductor** $0 \rightarrow \Gamma_S$

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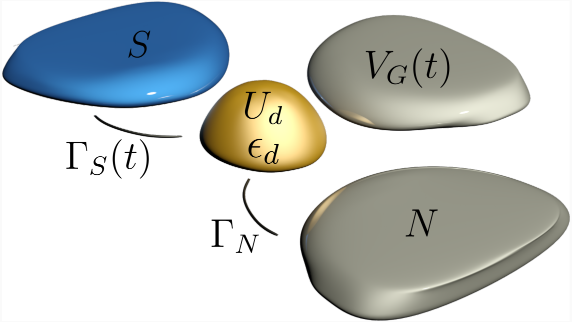


Possible quench protocols:

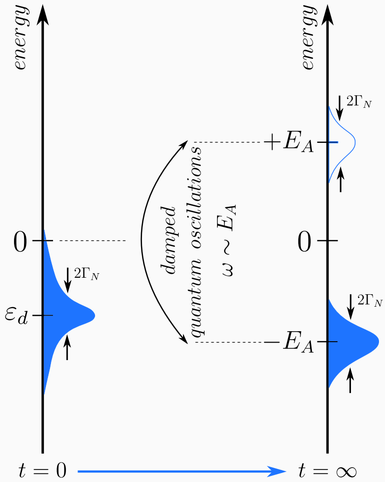
⇒ **sudden coupling to superconductor** $0 \rightarrow \Gamma_S$

⇒ **abrupt application of gate potential** $0 \rightarrow V_G$

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

BUILDUP OF IN-GAP STATES

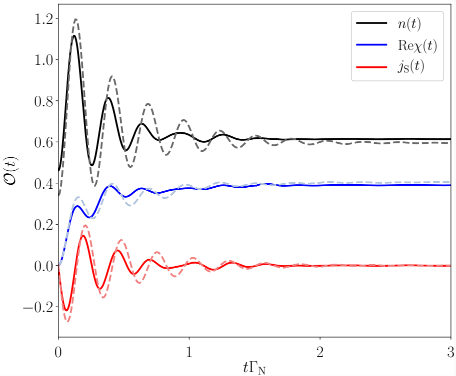
Schematics of the Andreev states formation induced by quench $\mathbf{0 \rightarrow \Gamma_S}$



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 $0 \to \Gamma_S$



solid lines - time dependent NRG

dashed lines - Hartree-Fock-Bogolubov

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

Singlet-doublet (quantum phase) transition

Singlet-doublet (quantum phase) transition

(static version)

SINGLY OCCUPIED VS BCS-TYPE CONFIGURATIONS

Quantum dot proximitized to superconductor can described by

$$\hat{H}_{QD} = \sum_{\sigma} \epsilon_d \, \hat{d}^{\dagger}_{\sigma} \, \hat{d}_{\sigma} \; + \; U_d \, \hat{n}_{d\uparrow} \hat{n}_{d\downarrow} - \left(\Gamma_S \, \hat{d}^{\dagger}_{\uparrow} \hat{d}^{\dagger}_{\downarrow} + \text{h.c.} \right)$$

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Eigen-states of this problem are represented by:

$|\uparrow\rangle$ **and** $|\downarrow\rangle$ $\Leftarrow$ **doublet states (spin $\frac{1}{2}$)**

$$\left. \begin{array}{l} u\,|0\rangle - v\,|\uparrow\downarrow\rangle \\ v\,|0\rangle + u\,|\uparrow\downarrow\rangle \end{array} \right\} \Leftarrow$$ **singlet states (spin 0)**

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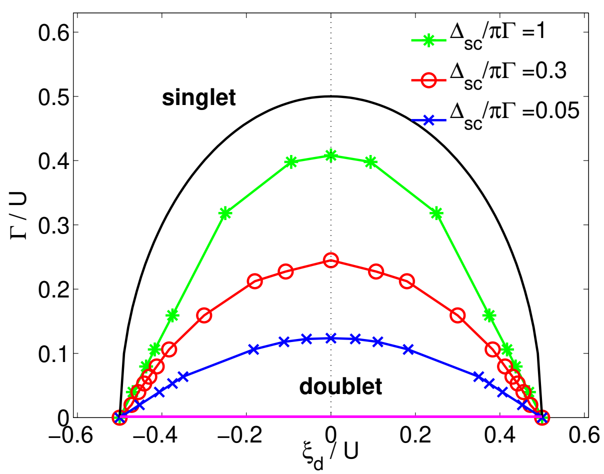
Upon varrying the parameters ε_d, U_d or Γ_S there can be induced a transition between these doublet/singlet ground states.

QUANTUM PHASE TRANSITION (STATIC VERSION)

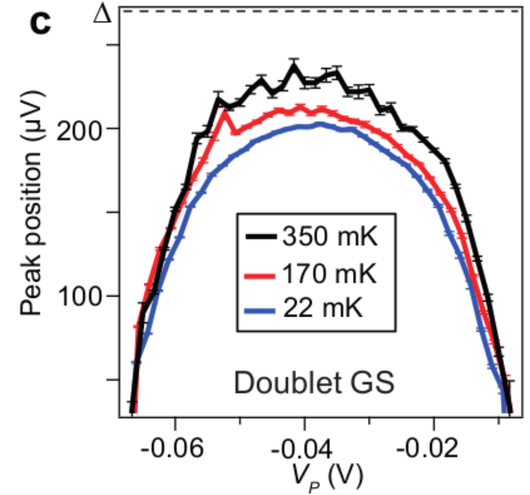
Singlet-doublet quantum (phase transition): NRG results



$$\xi_d \equiv \varepsilon_d - U/2$$

J. Bauer, A. Oguri & A.C. Hewson, J. Phys.: Condens. Matter 19, 486211 (2007).

QUANTUM PHASE TRANSITION: EXPERIMENT



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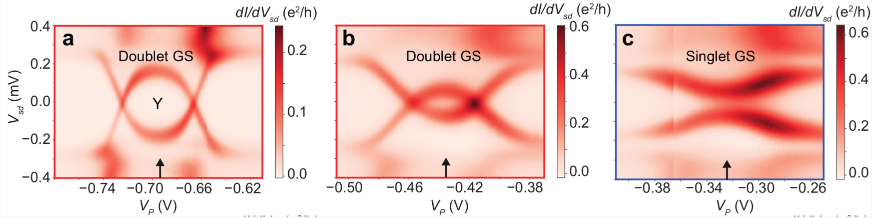
SINGLET VS DOUBLET: EXPERIMENT

Differential conductance vs source-drain bias V_{sd} (vertical axis) and gate potential V_p (horizontal axis) measured for various Γ_S/U

$U \gg \Gamma_s$ $\quad$ $U \geq \Gamma_s$ $\quad$ $U < \Gamma_s$



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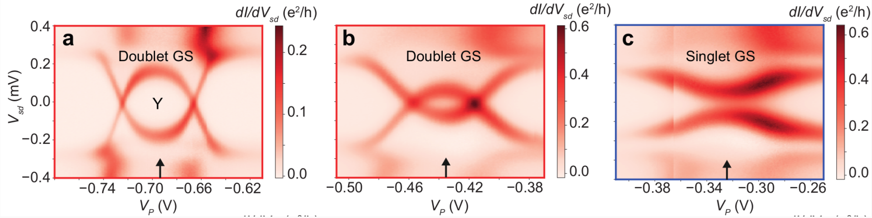

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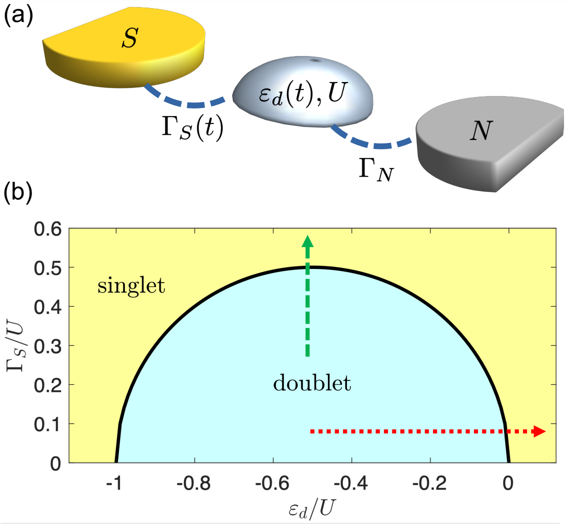
Crossings of in-gap states correspond to the singlet-doublet QPT.

Dynamical singlet-doublet transition

QUANTUM QUENCHES ACROSS QPT



K. Wrześniewski, I. Weymann, N. Sedlmayr & T. Domański, Phys. Rev. B 105, 094514 (2022).

DYNAMICS IMPOSED BY QUANTUM QUENCH

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Loschmidt amplitude

STATIONARY VS DYNAMICAL PHASE TRANSITION

Idea: M. Heyl, A. Polkovnikov, S. Kehrein, Phys. Rev. Lett. 110, 135704 (2013).

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$$L(t) = \left| \left\langle \Psi_0 | e^{-it\hat{H}} | \Psi_0 \right\rangle \right|^2$$

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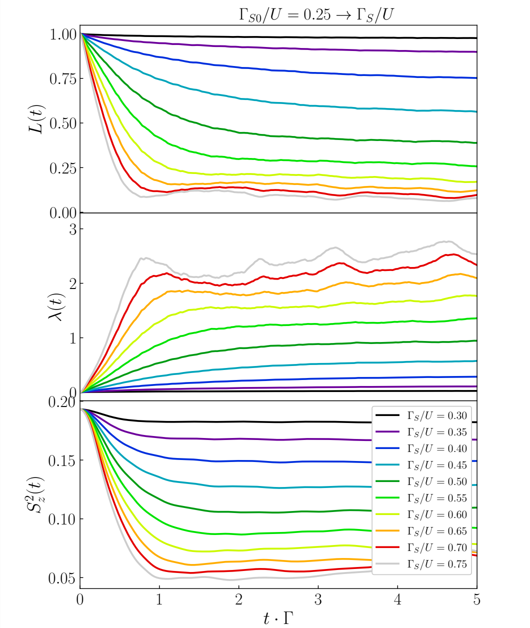
tNRG RESULTS: ABRUPT CHANGE OF Γ_S



Loschmidt amplitude

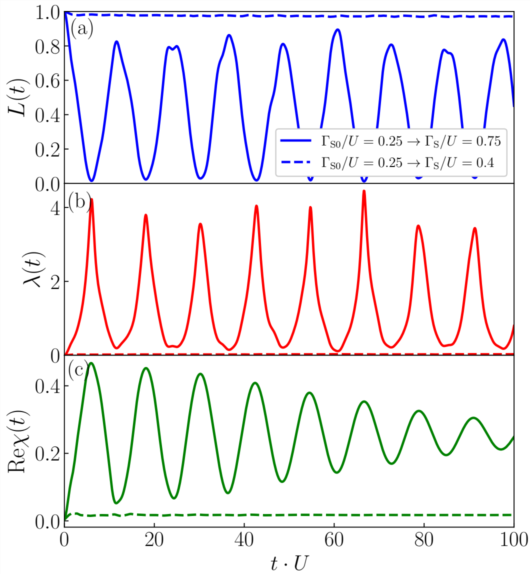
$L(t) \equiv |\langle \Psi(0)|\Psi(t)\rangle|^2$

Return rate

$\lambda(t) = -\frac{1}{N} \log [L(t)]$

The squared magnetic moment $\langle S_z^2(t) \rangle$

tNRG RESULTS: ABRUPT CHANGE OF Γ_S



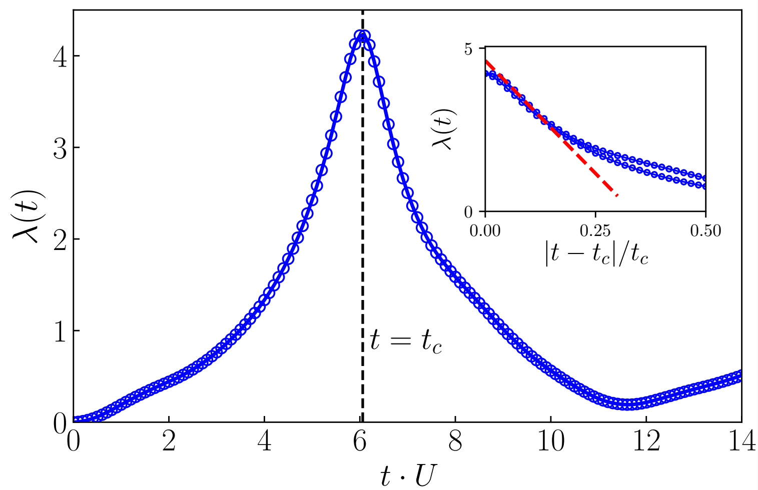
$\varepsilon_d = -U/2$

$\Gamma_N = U/100$

K. Wrześniewski, I. Weymann, N. Sedlmayr & T. Domański, Phys. Rev. B 105, 094514 (2022).

tNRG RESULTS: ABRUPT CHANGE OF Γ_S

Return-rate nearby the first critical time t_c (rounding due to finite-size).



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SUMMARY (PART 1)

Quench imposed onto the nanostructure consisting of normal metal – quantum dot – superconductor:

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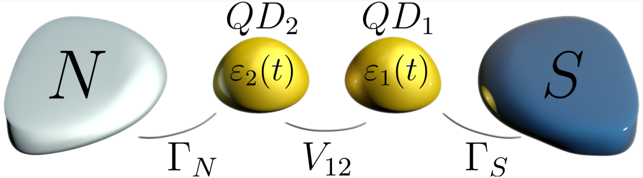
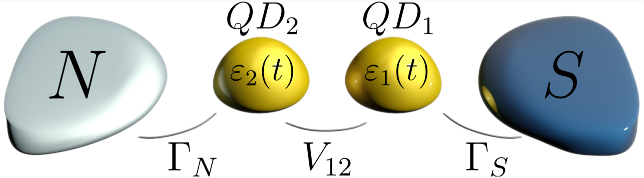
These phenomena are detectable in charge transport properties.

QUENCH IN DOUBLE QUANTUM DOTS



Physical issues:

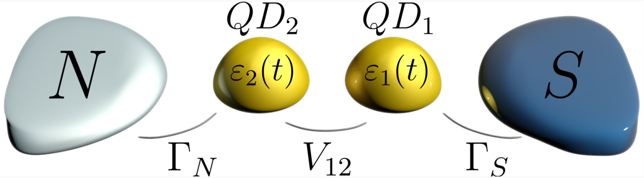
QUENCH IN DOUBLE QUANTUM DOTS



Physical issues:

$\Rightarrow$ **role of initial conditions**

QUENCH IN DOUBLE QUANTUM DOTS



Physical issues:

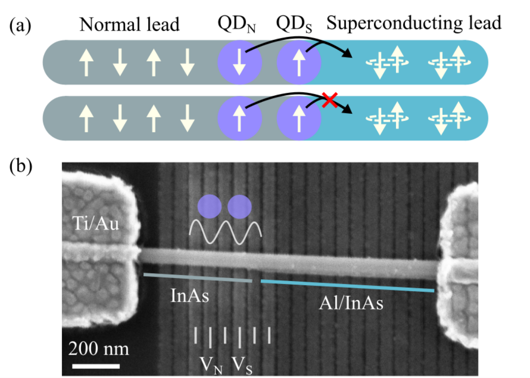
⇒ **role of initial conditions**

⇒ **blocking of superconducting proximity effect**

R. Taranko, K. Wrześniewski, B. Baran, I. Weymann, T. Domański, Phys. Rev. B 103, 165430 (2021).

B. Baran, R. Taranko, T. Domański, Scientific Reports 11, 11148 (2021).

ANDREEV BLOCKADE

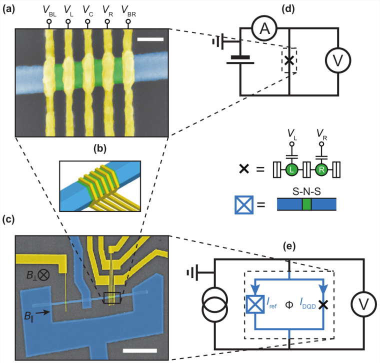


N = Au, DQD=InAs, S=Al

Suppression of Andreev reflection by spin-triplet configuartion of DQD

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

TRIPLET BLOCKADE IN JOSEPHSON JUNCTION



DQD=InAs, S=Al

Triplet-blockaded Josephson supercurrent in double quantum dots

D. Bouman, R.J.J. van Gulik, G. Steffensen, D. Pataki, P. Boross, P. Krogstrup, J. Nygård, J. Paaske, A. Pályi, A. Geresdi, Phys. Rev. B 102, 220505(R) (2020).

SUMMARY (PART 2)

Quantum quench imposed onto the nanostructure consisting of normal metal – double quantum dot – superconductor:

- **prevents any charge flow for initial triplet configuration**

SUMMARY (PART 2)

Quantum quench imposed onto the nanostructure consisting of normal metal – double quantum dot – superconductor:

- prevents any charge flow for initial triplet configuration
- such Andreev blockade is gradually eliminated by coupling Γ_N

SUMMARY (PART 2)

Quantum quench imposed onto the nanostructure consisting of normal metal – double quantum dot – superconductor:

- prevents any charge flow for initial triplet configuration
- such Andreev blockade is gradually eliminated by coupling Γ_N
- dynamical phenomena reveal quantum beating effects

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- dynamical singlet-doublet phase transition

$\Longrightarrow$ K. Wrześniewski (Poznań), I. Weymann (Poznań),

N. Sedlmayr (Lublin),

- dynamics of in-gap states (transients effects, etc.)

$\Longrightarrow$ R. Taranko (Lublin), B. Baran (Lublin).