Dynamical phase transitions in superconducting nanostructures

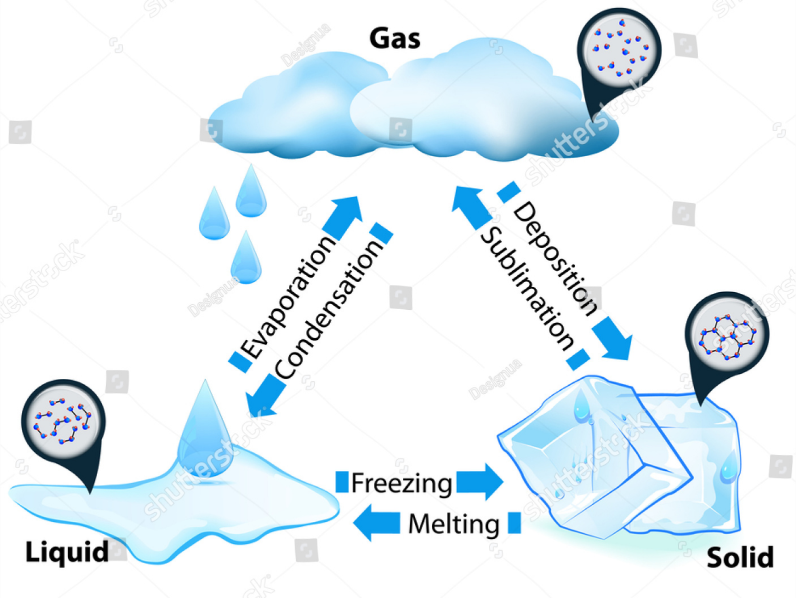
Tadeusz DOMAŃSKI

UMCS, Lublin

Politechnika Warszawska

28 March 2023

EVERY-DAY EXAMPLES OF PHASE TRANSITIONS



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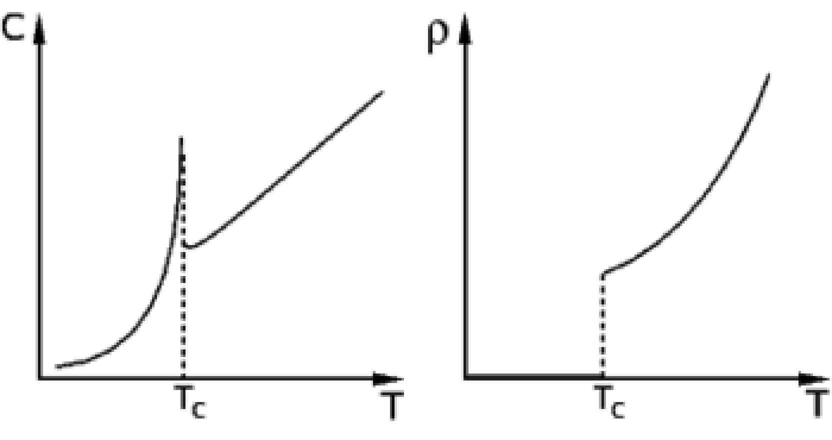
$\Rightarrow$ **phase transitions in time-domain**

1. TRANSITION TO SUPERCONDUCTING STATE

Phase transition is manifested by non-analytic behaviour appearing at critical temperature T_c in the specific heat



Transition is manifested by λ shape of the specific heat

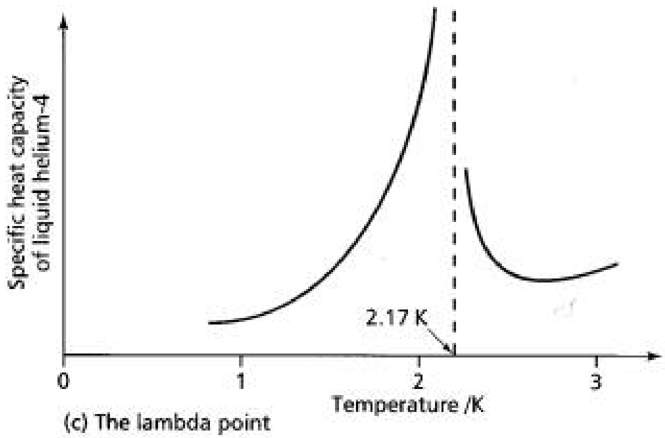


Fig. 11.6E Liquid helium as a superfluid

I. Dynamical quantum phase transition

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[general idea]

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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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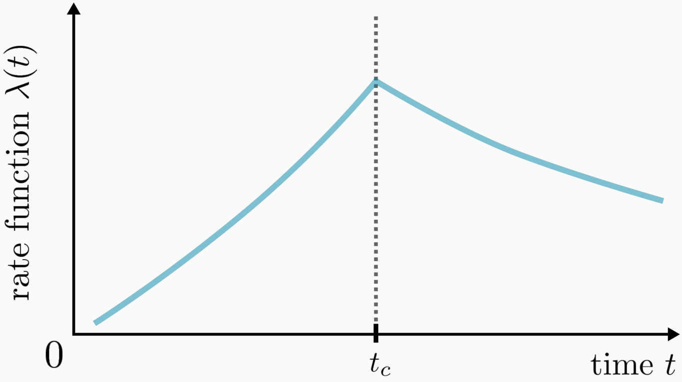
CRITICAL TIME

At critical time t_c the rate function $\lambda(t)$ of $L(t) \equiv e^{-N\lambda(t)}$ has a kink, or other types of nonanalytic behaviour.



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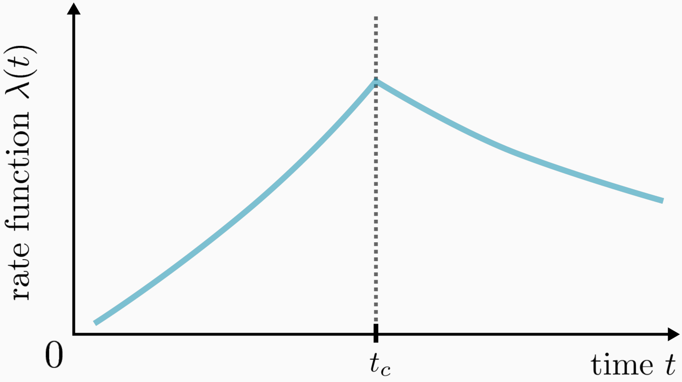
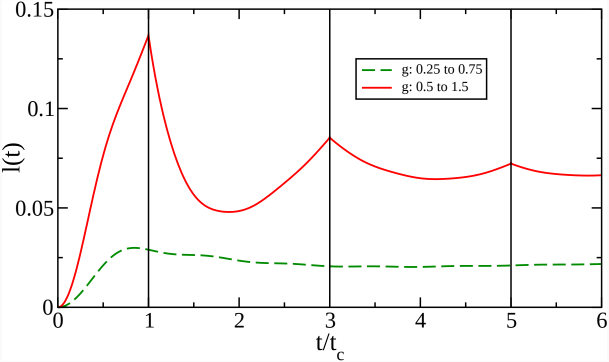


At this time-instant $\psi(t_c)$ might be orthogonal to initial $\psi(t_0)$.

A few examples ...

ISING MODEL: CHANGE OF MAGNETIC FIELD

Post-quench return rate of the Ising model ($g \equiv h/J$)



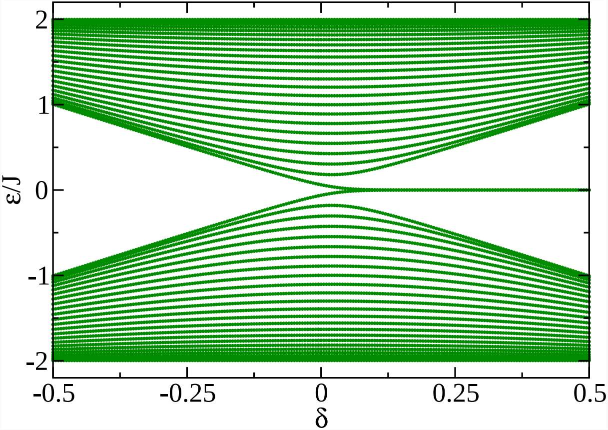
$$\hat{H} = -\frac{J}{2}\sum_{j=1}^{N-1} \hat{\sigma}_j^z \; \hat{\sigma}_{j+1}^z + \frac{h}{2}\sum_{j=1}^{N} \hat{\sigma}_j^x$$

solid red line - **across a phase transition ($g_c = 1$)**

dashed green line - inside the same phase

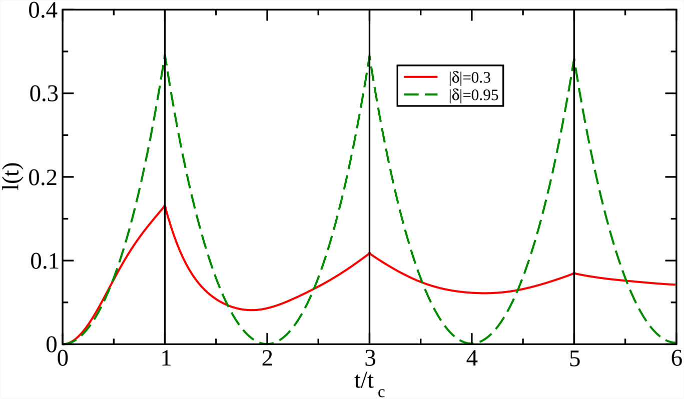
SU-SCHRIEFFER-HEEGER MODEL

Quasiparticle spectrum of the SSH model under stationary conditions.



$$\hat{H} = -J \sum_j \left[\left(1 + \delta e^{i\pi j} \right) \hat{c}_j^\dagger \, \hat{c}_{j+1} \; + \; \text{h.c.} \right]$$

SSH MODEL: QUENCH DRIVEN TRANSITION



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solid red line: $\delta = -0.3 \longrightarrow \delta = +0.3$

dashed green line: $\delta = 0.95 \longrightarrow \delta = -0.95$

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$\Rightarrow$ **at equidistant critical times**

(in most cases, but not always)

$\Rightarrow$ **and can survive at finite temperatures**

(when they are no longer sharp)

Finite-size systems

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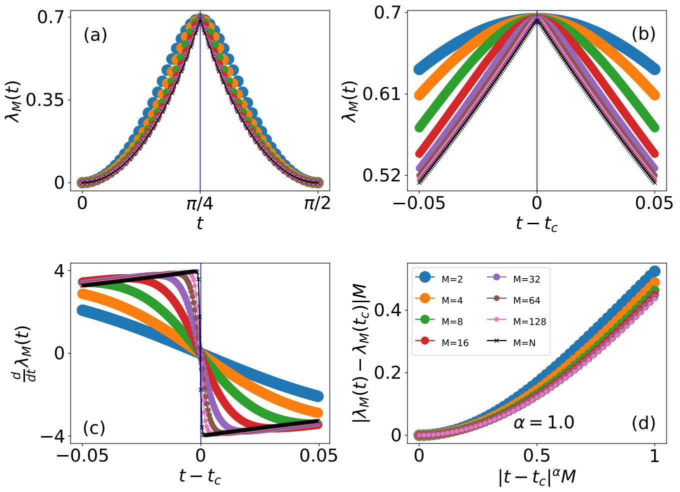
(possible observability)

ISING MODEL: DQPT OF FINITE-SIZE SYSTEM



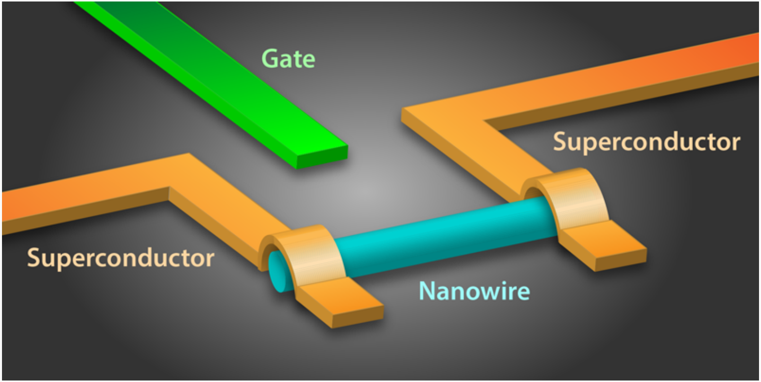
"Local measures of dynamical quantum phase transitions"

J.C. Halimeh, D. Trapin, M. Damme & M. Heyl, Phys. Rev. B 104, 075130 (2021).

II. Application to superconducting nanostructures

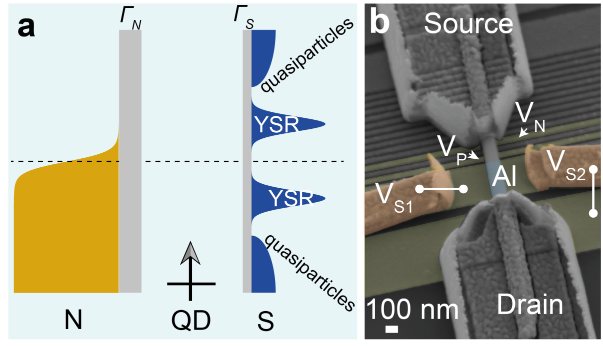
HETEROSTRUCTURES WITH SUPERCONDUCTOR(S)

superconductor (S) - quantum dot (QD) - superconductor (S)



Tunneling of Cooper pairs via bound states in Josephson junction.

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).

SUPERCONDUCTING PROXIMITY EFFECT

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

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- This is manifested spectroscopically by:

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- 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 issue ?

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Selected headlines ...

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).

SUPERCONDUCTING QUBITS

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

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.

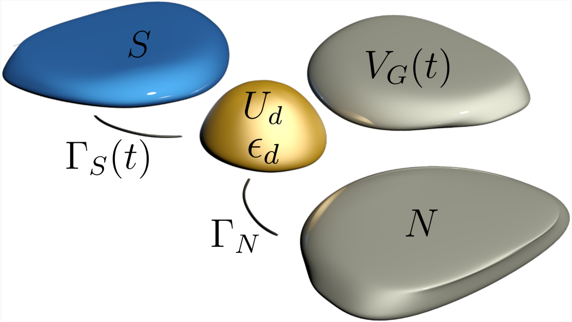
Conventional and/or topological superconducting qubits

Characteristic time-scales

Characteristic time-scales

(relevant to operations on sc qubits)

DYNAMICS OF A SINGLE QUANTUM DOT



Quantum quench protocols:

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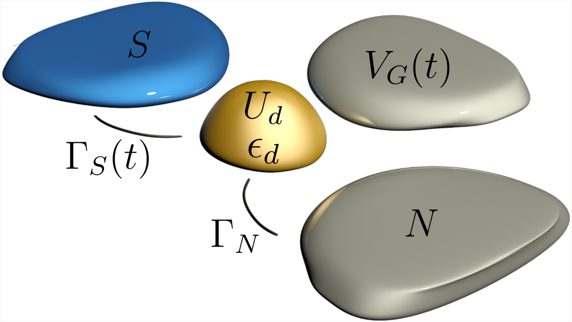

Quantum quench protocols:

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

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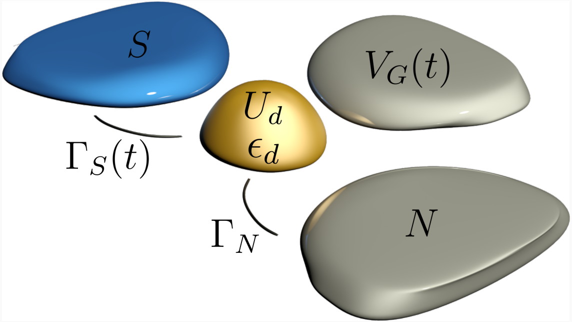


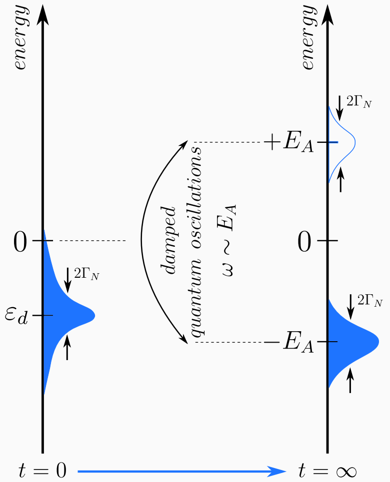
Quantum quench protocols:

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

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

BUILDUP OF IN-GAP STATES

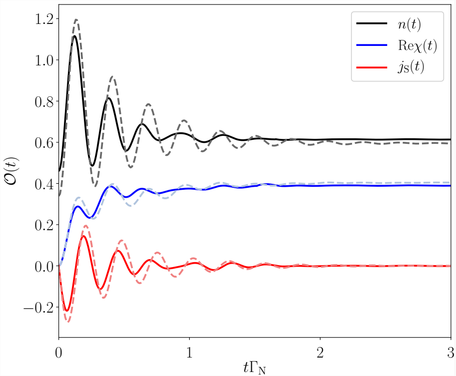
Schematics of the Andreev states formation induced by quench $0 \rightarrow \Gamma_S$



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 super-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).

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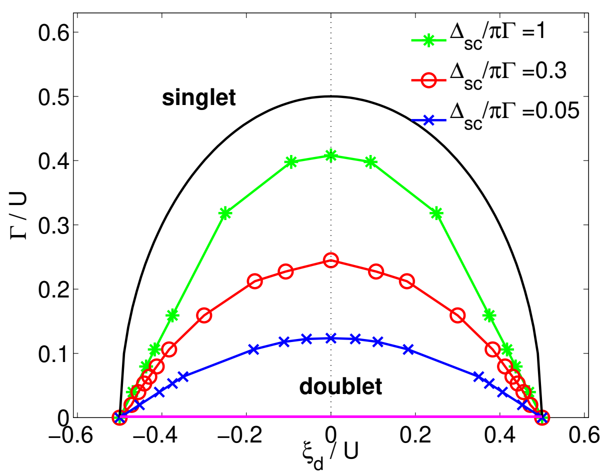
Upon varrying the parameters ε_d, U_d or Γ_S there can be induced phase transition between these doublet/singlet ground states.

QUANTUM PHASE TRANSITION (STATIC VERSION)

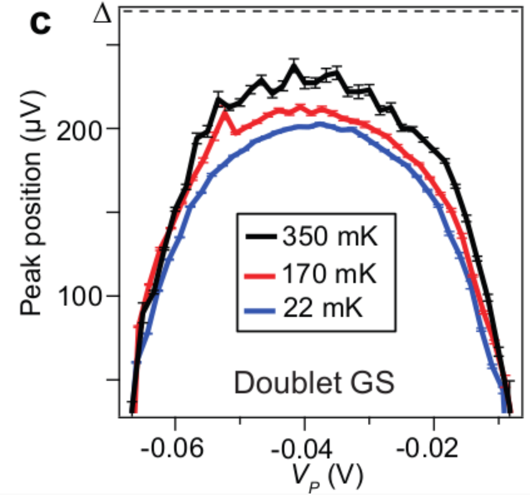
Singlet-doublet quantum (phase transition): NRG results



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

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

QUANTUM PHASE TRANSITION: EXPERIMENT



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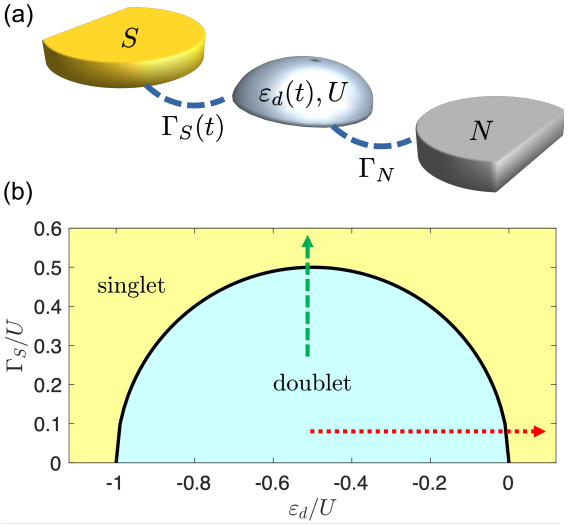
Singlet-doublet (quantum phase) transition

Singlet-doublet (quantum phase) transition

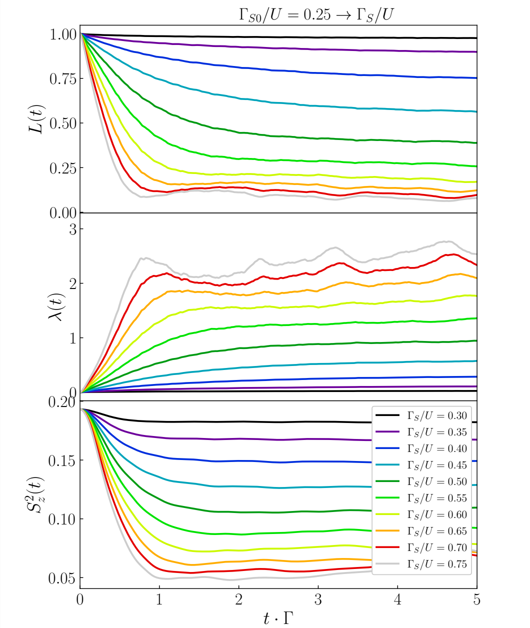
[dynamical realization]

QUANTUM QUENCHES ACROSS STATIC QPT



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

DYNAMICAL QUANTUM PHASE TRANSITION



Loschmidt echo

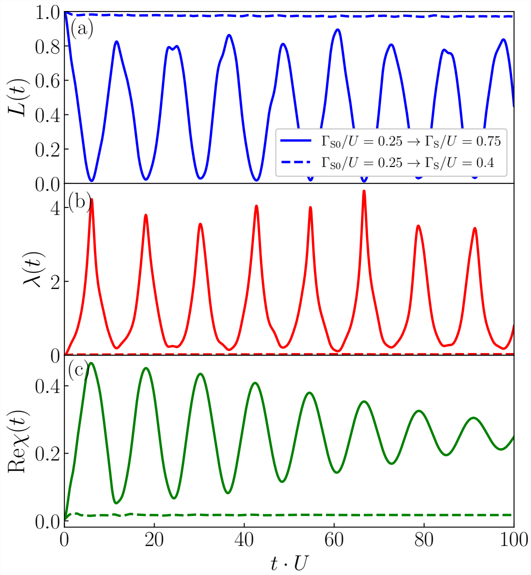
$$L(t) \equiv |\langle \Psi(t)|\Psi(0)\rangle|^2$$

Return rate

$$\lambda(t) = -(1/N)\log L(t)$$

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

tNRG RESULTS: ABRUPT CHANGE OF Γ_S

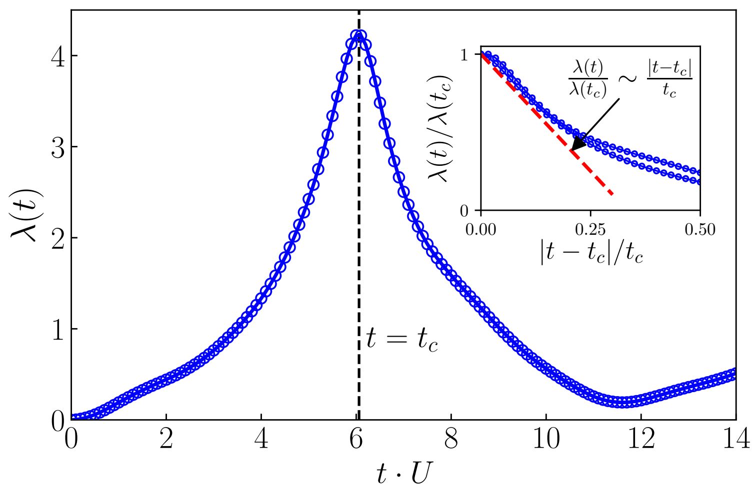


$\varepsilon_d = -U/2$

$\Gamma_N = U/100$

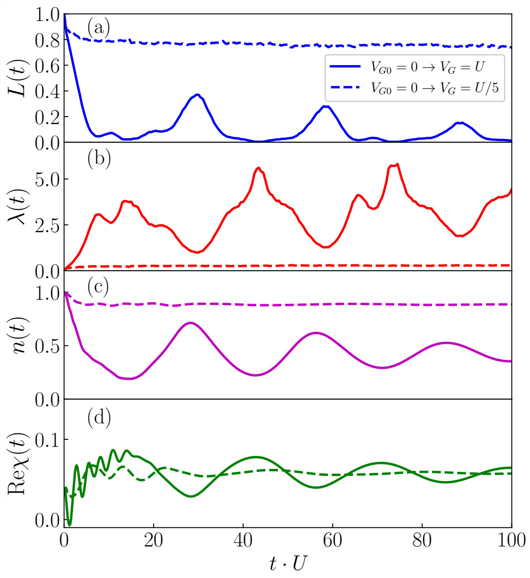
K. Wrześniewski, I. Weymann, N. Sedlmayr & T. Domański, Phys. Rev. B 105, 094514 (2022).

tNRG RESULTS: ABRUPT CHANGE OF Γ_S



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

tNRG RESULTS: QUANTUM QUENCH $\varepsilon_d \to \varepsilon_d + V_G$



$\Gamma_S = U/5$

$\Gamma_N = U/100$

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

ISSUES TO BE SPECIFIED

Means to detect dynamical singlet-doublet transition(s):

- **measurement of the time-dependent charge current**

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Quantitative results will be provided . . . . (on-going project)

SIMILAR IDEAS: #1 ULTRACOLD SUPERFLUIDS

Annals of Physics 435 (2021) 168554

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Loschmidt echo of far-from-equilibrium fermionic superfluids

Colin Rylands [a,*,1], Emil A. Yuzbashyan [b,1], Victor Gurarie [c,1], Aidan Zabalo [b,1], Victor Galitski [a,1]

[a] *Joint Quantum Institute and Condensed Matter Theory Center, University of Maryland, College Park, MD 20742, USA*

[b] *Department of Physics and Astronomy, Center for Materials Theory, Rutgers University, Piscataway, NJ 08854, USA*

[c] *Department of Physics and Center for Theory of Quantum Matter, University of Colorado, Boulder, CO 80309, USA*

Rapid change across the BCS-BEC limits in the ultracold atom superfluids.

SIMILAR IDEAS: #2 DYNAMICS OF SHIBA STATES

communications
physics

ARTICLE

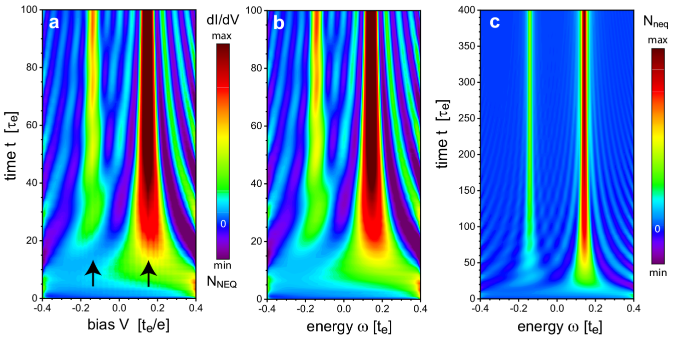
Check for updates

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]✉



SIMILAR IDEAS: #3 HIGGS & GOLDSTONE MODES

PHYSICAL REVIEW RESEARCH **2**, 022068(R) (2020)

Rapid Communications

Signatures of the Higgs mode in transport through a normal-metal–superconductor junction

Gaomin Tang,[1] Wolfgang Belzig,[2] Ulrich Zülicke,[3] and Christoph Bruder[1]

[1]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*

[2]*Fachbereich Physik, Universität Konstanz, D-78457 Konstanz, Germany*

[3]*School of Chemical and Physical Sciences and MacDiarmid Institute for Advanced Materials and Nanotechnology, Victoria University of Wellington, P.O. Box 600, Wellington 6140, New Zealand*

(Received 21 February 2020; revised manuscript received 5 June 2020; accepted 8 June 2020; published 29 June 2020)

A superconductor subject to electromagnetic irradiation in the terahertz range can show amplitude oscillations of its order parameter. However, coupling this so-called Higgs mode to the charge current is notoriously difficult. We propose to achieve such a coupling in a particle-hole-asymmetric configuration using a DC-voltage-biased normal-metal–superconductor tunnel junction. Using the quasiclassical Green's function formalism, we demonstrate three characteristic signatures of the Higgs mode: (i) The AC charge current exhibits a pronounced resonant behavior and is maximal when the radiation frequency coincides with the order parameter. (ii) The AC charge current amplitude exhibits a characteristic nonmonotonic behavior with increasing voltage bias. (iii) At resonance for large voltage bias, the AC current vanishes inversely proportional to the bias. These signatures provide an electric detection scheme for the Higgs mode.

Possibility to observe the collective amplitude (Higgs-type) mode of the order parameter in presence of ultrafast ac field.

SIMILAR IDEAS: #4 HIGGS & GOLDSTONE MODES

PHYSICAL REVIEW B **103**, 045414 (2021)

Higgs-like pair amplitude dynamics in superconductor–quantum-dot hybrids

Mathias Kamp and Björn Sothmann
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(Received 2 October 2020; revised 11 December 2020; accepted 11 December 2020; published 14 January 2021)

We consider a quantum dot weakly tunnel coupled to superconducting reservoirs. A finite superconducting pair amplitude can be induced on the dot via the proximity effect. We investigate the dynamics of the induced pair amplitude after a quench and under periodic driving of the system by means of a real-time diagrammatic approach. We find that the quench dynamics is dominated by an exponential decay towards equilibrium. In contrast, the periodically driven system can sustain coherent oscillations of both the amplitude and the phase of the induced pair amplitude in analogy to Higgs and Nambu-Goldstone modes in driven bulk superconductors.

Possibility to observe the collective amplitude (Higgs-type) and phasal (Goldstone-type) modes of the order parameter.

FINAL CONCLUSIONS

Quench imposed on quantum dot attached to superconductor:

- **induces the Rabi-type oscillations** **(due to particle-hole mixing)**

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FINAL CONCLUSIONS

Quench imposed on quantum dot attached to superconductor:

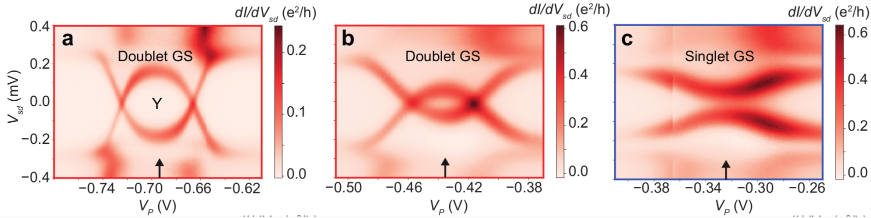
- **induces the Rabi-type oscillations** **(due to particle-hole mixing)**
- **leads to emergence/rearrangement of the in-gap states**
- **can drive dynamical transitions** **(changeover of ground states)**

These phenomena are empirically detectable by the charge transport measurements (Andreev spectroscopy).

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

$U \gg \Gamma_s$ $\qquad$ $U \geq \Gamma_s$ $\qquad$ $U < \Gamma_s$



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

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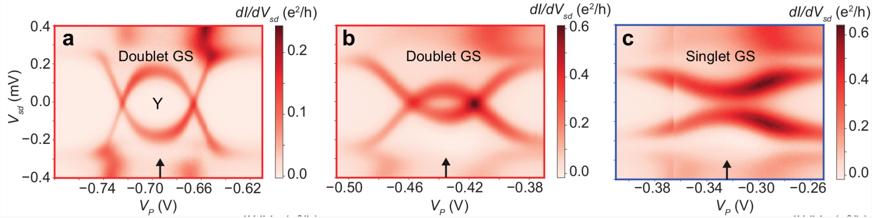

J. Estrada Saldaña, A. Vekris, V. Sosnovtseva, T. Kanne, P. Krogstrup, K. Grove-Rasmussen and J. Nygård, Commun. Phys. 3, 125 (2020).

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