Superconducting Quantum Circuits Meet Quantum Materials

834. WE-Heraeus-Seminar

18 May - 22 May 2025

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 834. WE-Heraeus-Seminar:

This seminar is devoted to discuss recent developments in the field of mesoscopic superconductivity with a focus on superconducting hybrid devices realized with quantum materials. These systems often consist of hybrids of superconducting and nonsuperconducting materials. In these systems unexpected phenomena such as gate controllability of the supercurrents, the superconducting diode effect or the presence of peculiar superconducting phases (e.g. in twisted bilayer graphene) among other have been observed. At variance to earlier studies the constituents now include superconductors which are unconventional themselves, magnetic systems, semiconducting systems, and these are hybridized with electronically complex nonsuperconducting counterparts to tailor the properties of the resulting quantum circuits. A second aspect is the enormous recent progress in the measurement techniques that now give access to superconducting properties that before were only conceptually known. These include the measurement of the superconducting stiffness, or the heat released by a single phase slip event. The field of mesoscopic superconductivity is marked by a tight exchange between experimental and theoretical progress. In this seminar the experimental results are discussed in combination with theoretical studies and predictions using the most modern methods of non-equilibrium quantum field theory.

Introduction

Scientific Organizers:

Prof. Dr. Elke Scheer	Universität Konstanz Fachbereich Physik Konstanz, Germany E-Mail: elke.scheer@uni-konstanz.de
Prof. Dr. Christoph Strunk	Universität Regensburg Institut für Experimentelle und Angewandte Physik Regensburg, Germany E-Mail: christoph.strunk@physik.uni-regensburg.de
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Administrative Organization:

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Introduction

Venue:

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Registration:

Marion Reisinger (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday morning

Program

Program

Sunday, 18 May 2025

17:00 – 21:00	Registration	
18:30	*BUFFET SUPPER and informal get-together*	

Monday, 19 May 2025

08:00	*BREAKFAST*	
09:00 – 09:10	Elke Scheer Christoph Strunk Wolfgang Belzig	**Opening & Welcome words**
09:10 – 09:50	Jeong Min Park	**Simultaneous transport and spectroscopy of moiré graphene**
09:50 – 10:30	Deividas Sabonis	**Continuous monitoring of parity-flips in a planar superconducting island**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:40	Benjamin Sacépé	**Superfluid density near the superconductor-insulator transition**
11:40 – 12:20	Beena Kalisky	**Imaging Quantum Materials**
12:20 – 12:25	***Conference Photo***	
12:25 – 14:30	*LUNCH*	

Program

Monday, 19 May 2025

14:30 – 15:10	Leonid Glazman	**Microwave Spectroscopy of Schmid Transition and Theory of Quantum-Limited Dual Shapiro Steps**
15:10 – 15:35	Philippe Joyez	**Why the Schmid transition does not exist**
15:35 – 16:00	*COFFEE BREAK*	
16:00 – 16:40	Sebastián Díaz	**Engineering the topological landscape in magnet- superconductor heterostructures**
16:40 – 18:30	***Poster Session I***	
18:30 – 20:00	*DINNER*	
20:00	Claudia Felser	**Superconductivity, flatbands, topology, and beyond**

Program

Tuesday, 20 May 2025

08:00	*BREAKFAST*	
09:00 – 09:40	Landry Bretheau	**Superconducting Quantum Devices with Ultraclean Carbon Nanotubes**
09:40 – 10:05	Maciej Zgirski	**A single superconducting vortex on a leash**
10:05 – 10:30	Lucia Vigliotti	**Nonequilibrium plasmon fluid in a Josephson junction chain**
10:30 – 10:45	Scientific Organizers	**Video "About the Wilhelm and Else Heraeus Foundation"**
10:45 – 11:10	*COFFEE BREAK*	
11:10 – 11:50	Ambroise Peugeot	**Two-tone Josephson Spectroscopy**
11:50 – 12:30	Uri Vool	**Hybrid circuits with van-der-Waals cuprate superconductors**
12:30 – 14:30	*LUNCH*	
14:30 – 15:10	Milena Grifoni	**Friedel oscillations and chiral superconductivity in monolayer $NbSe_2$**
15:10 – 15:35	Hadar Steinberg	**Thickness effects in superconducting TMDs**
15:35 – 16:00	*COFFEE BREAK*	
16:00 – 16:40	Audrey Cottet	**A hybrid cavity-magnon-quantum circuit platform for axion dark matter detection**
16:40 – 17:05	Julien Basset	**Photoelectric detection of single microwave photons in a granular aluminum high-impedance quantum circuit**
17:05 – 17:30	Aleksandr Svetogorov	**Theory of three-terminal Andreev spin qubits**
18:30	*HERAEUS DINNER (social event with cold & warm buffet with complimentary drinks)*	

Program

Wednesday, 21 May 2025

08:00	*BREAKFAST*	
09:00 – 09:40	Dmitri Efetov	**Strongly correlated topological flat bands in the novel class of moiré materials**
09:40 – 10:20	Tristan Cren	**Misfit compounds as a platform for engineering doping, charge density waves and Ising superconductivity**
10:20 – 10:45	Samy Annabi	**Non-local Josephson effect in ultraclean carbon nanotube-based junctions**
10:45 – 11:10	*COFFEE BREAK*	
11:10 – 11:50	Nicolas Roch	**Josephson meta-materials: a new platform for quantum optics**
11:50 – 12:30	Floriana Lombardi	**Nanostructured substrate control of Quantum Phases in Ultrathin YBCO films: Enhanced Superconductivity and novel Emergent Orders**
12:30 – 14:30	*LUNCH*	
14:30 – 15:10	Chuan Li	**Revealing Higher-order topological states in $Bi_{1-x}Sb_x$ (x=3%) revealed by Josephson current**
15:10 – 15:35	Ruben Seoane Souto	**Majorana states in quantum dot systems**
15:35 – 16:00	*COFFEE BREAK*	
16:00 – 16:25	Alexandre Buzdin	**Magnetoelectric and photogalvanic effects in the helical state of a superconductor/ferromagnet bilayer**
16:25 – 16:50	Lea Pfaffinger	**Finite-size effects in the vicinity of the BKT transition**
16:50 – 18:30	***Poster Session II***	
18:30	*DINNER AND GET-TOGETHER*	

Program

Thursday, 22 May 2025

08:00	*BREAKFAST*	
09:10 – 09:50	Rais Shaikhaidarov	**Current quantization in small Josephson junctions due to synchronization of Bloch oscillations with microwave**
09:50 – 10:15	Denis Kochan	**Magnetoelectric phenomena of non-centrosymmetric superconductors – supercurrent diode effect and anisotropic vortex squeezing**
10:15 – 10:40	Danilo Nikolić	**Spin-resolved Josephson diode effect in strongly spin-polarized magnetic materials**
10:40 – 11:10	*COFFEE BREAK*	
11:10 – 11:50	Szabolcs Csonka	**Realization of basic types of Andreev-molecules**
11:50 – 12:00	***Poster Award***	
12:15 – 13:30	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Friday however, a self-service breakfast will be provided on Friday morning

Posters

Poster Session I, Monday 19 May, 16:40

Masoud Bahari	**Helical topological superconducting pairing at finite excitation energies**
Benedikt Baumgartner	**Non-reciprocal superconductivity in cobalt disilicide**
Lorenz Bauriedl	**Coplanar on-chip resonator for simultaneous kinetic inductance and resistance measurements of TMDC-superconductors**
Lou Bernabeu	**Microwave response of voltage states in strongly driven Josephson junctions**
Cenk Beydeda	**Nb:$SrTiO_3$: GHz Vortex Dynamics at mK Temperatures in a Type II Two-Band Superconductor**
Tycho Blom	**Josephson Junctions with spin polarization without exchange interaction**
Frederik Bolle	**Cyclotron resonance probed by coplanar waveguide resonators**
Lucas Bugaud	**Probing the helical states in WTe_2 with superconductors**
Anas Chadli	**Controlling the photonic joule effect in high-impedance superconducting quantum circuits**
Andreas Costa	**Theory of the supercurrent diode effect in josephson junctions**
Soumya Datta	**Exploring superconducting and topological quantum materials using advanced surface characterization techniques**
Vjeko Dimic	**Gate and flux tunable λ/4 resonators in two-dimensional al/inas hybrid superconductor/semiconductor heterostructures**

Poster Session I, Monday 19 May, 16:40

Tosson Elalaily	**Probing phase slip noise in gate-controlled Al/InAs nanowires.**
Bat Chen Elshalem	**Scanning SQUID microscopy on t-$PtBi_2$**
Simon Feyrer	**Signatures of spin orbit interaction in the kinetic inductance of epitaxial Al/InAs heterostructures**
Ronja Fischer Süßlin	**Investigation of Josephson junctions with Weyl-Kondo semimetals**
Mikhail Fistul	**Collective quantum phases and excitations emerging in superconducting networks**
Felix Gabel	**Synchronization in focused He-ion-beam-induced Josephson junction arrays in Y $Ba_2Cu_3O_7$**
Çağlar Girit	**First-principles quantum model of the resistively shunted Josephson junction**
Joren Harms	**Non-uniform phases in Ising superconductors**
Michael Hein	**Yu Shiba Rusinov states in Ising superconductors**
Oliver Irtenkauf	**Superconducting atomic contacts under microwave irradiation**
Alexander Kirchner	**Microwave Characterization of Josephson Junction Arrays tailored in Al/InAs Heterostructures**
Jennifer Koch	**Gate-controlled switching in non-centrosymmetric superconducting devices**

Poster Session II, Wednesday 21 May, 16:50

Konstantinos Kontogeorgiou	**Proposal for realizing Feynman's Ratchet with a Josephson Diode**
Yejin Lee	**Van der Waals Superconductors integrated Hybrid Microwave Resonators**
Pankaj Mandal	**Magnetically tunable supercurrent in dilute magnetic topological insulator based Josephson junction**
Max Mangold	**Josephson diode effect in the presence of interfacial spin-orbit coupling in all-metallic planar junctions**
Andrei Mazanik	**Interfacial spin-orbit coupling in superconducting hybrid systems**
Lei Meng	**Fast thermometry with SNS junctions at cryogenic temperatures**
Danilo Nikolić	**Quantum-Geometric Spin- and Charge Josephson Diode Effects**
David Christian Ohnmacht	**Multiterminal Josephson junctions: non-hermiticity, topology and reflectionless modes**
Banabir Pal	**Josephson diode effect from Cooper pair momentum in a topological semimetal**
Vladislav Pokorný	**Engineering quantum states in radical molecules on superconducting surfaces**
Hannes Riechert	**Coherent control of a carbon nanotube-based gatemon qubit**
Matthijs Rog	**Probing strongly correlated quantum systems with hybrid SQUID-on-tip imaging**
Leon Ruf	**Superconducting non-volatile memory based on charge trapping and gate-controlled superconductivity**

Poster Session II, Wednesday 21 May, 16:50

Erik Samuelsen	**Andreev molecules at distance**
Anne Schmidt	**2D HgTe Topological Insulator Josephson Junction Integrated in Superconducting Charge Qubit Circuits Using Flip-Chip Technique**
Jay Schmidt	**Gate tunable superconductivity in Al/STO hybrid structures**
Linus Stahlberg	**$[(SnSe)_{1+\delta}]m[NbSe_2]_1$ superlattices in the 2D to 3D crossover regime of superconductivity**
Marcel Strohmeier	**Tunneling spectroscopy on superconducting thin films of non-centrosymmetric niobium rhenium**
Leandro Tosi	**Quantum circuits with multiterminal Josephson-Andeev junctions**
Alexander Wagner	**Resistively shunted Josephson junction in the quantum regime**
Christian Wiedemann	**Superconductor-altermagnet heterostructures with nonmagnetic impurities**
Yuxiao Wu	**Nontrivial critical phenomena in the single layer graphene proximitized by a disordered superconductor InO**
Junting Zhao	**Superconducting proximity effect in semiconducting nanowires with ferromagnetic-insulator barriers**

Abstracts of Lectures

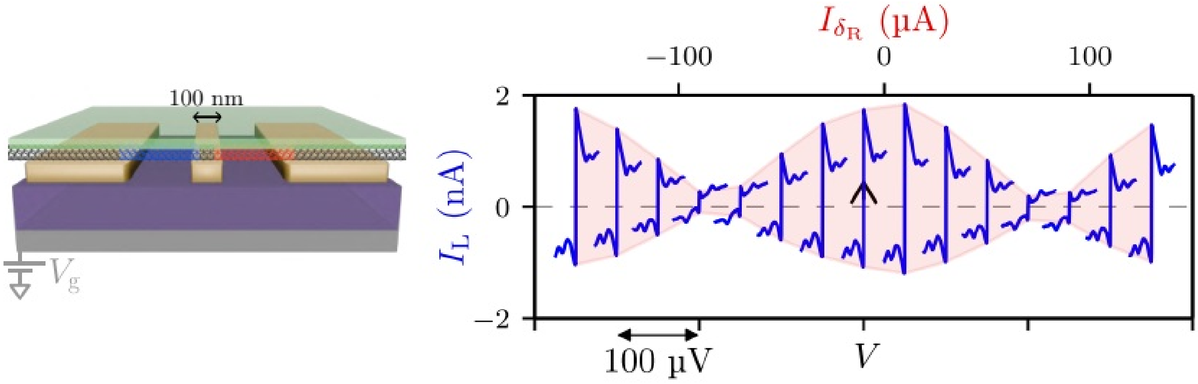
(in alphabetical order)

Non-local Josephson effect in ultraclean carbon nanotube-based junctions

S. Annabi[1], **E. Arrighi**[1], **A. Peugeot**[1], **H. Riechert**[1], **J. Griesmar**[1], **K. Watanabe**[2], **T. Taniguchi**[3], **L. Bretheau**[1] **and J.-D. Pillet**[1]

[1] *Laboratoire PMC, Institut Polytechnique de Paris, Palaiseau, France*
[2] *Research Center for Electronic and Optical Materials, NIMS, Namiki, Japan*
[3] *Research Center for Materials Nanoarchitectonics, NIMS, Namiki, Japan*

Andreev bound states (ABS) are fermionic states localized at the weak link of a Josephson junction. They carry a supercurrent that flows coherently through the device with an amplitude depending on the superconducting phase difference across the junction: it's the Josephson effect. When two Josephson junctions are sufficiently close to each other compared to the superconducting coherence length, the ABS wavefunctions hybridize forming an Andreev molecule and the Josephson effect becomes non-local: the supercurrent flowing through one junction not only depends on the phase difference across this junction, but also on the phase difference across the other junction [1]. We present here the experimental observation of such an effect in carbon nanotube-based Josephson junctions. This double quantum dot system based on an elementary quantum wire allows us to probe the microscopic mechanisms underlying ABS hybridization by revealing signatures of strong interdot coupling, as well as hints of non-local Cooper pair splitting.



Left : 3D representation of a CNT-based Andreev molecule device, where an individual CNT is used to form two closely-spaced Josephson junctions. Right : Modulation of the current-voltage $I_L(V)$ characteristic of the left junction as the superconducting phase difference δ_R across the right junction is varied by applying a current $I_{\delta R}$ to a flux line. The non-local Josephson effect manifests as the periodic modulation of the supercurrent branch.

References

[1] J.-D. Pillet et al., Nano Lett. **19**, 7138-7143 (2019)

Photoelectric detection of single microwave photons in a granular aluminum high-impedance quantum circuit

J. Basset, O. Stanisavljevic, M. Aprili, and J. Estève

Université Paris-Saclay, CNRS, Laboratoire de Physique des Solides, 91405 Orsay, France

In this talk I will present our recent efforts towards realizing the efficient photoelectric detection of single microwave photons, a key missing element in microwave quantum optics. I will start first by explaining our approach to realize an efficient and continuous microwave photon-to-electron converter with large quantum efficiency and low dark current. I will insist on the fact that these unique properties were enabled by the use of a high kinetic inductance disordered superconductor, granular aluminium, to enhance light-matter interaction and the coupling of microwave photons to electron tunnelling processes. As a consequence of strong coupling, we could observe both linear and nonlinear photon-assisted processes where two, three, and four photons are converted into a single electron at unprecedentedly low light intensities. I will then proceed by explaining the implementation of a charge-based detection technique that allows to sense individual microwave photons as a result of photoelectron conversion.

Superconducting Quantum Devices with Ultraclean Carbon Nanotubes

L. Bretheau

PMC, Ecole Polytechnique, CNRS, IPP, Palaiseau, France

The Josephson effect, which describes the coupling between two superconductors through a weak link, is the basis of several quantum devices. While it was mainly harnessed in tunnel junctions, hybrid Josephson junctions – in which quantum conductors are used as weak links – offer a rich physics to explore. Among them, carbon nanotubes (CNT) are particularly promising owing to their one-dimensional nature. These elementary quantum conductors combine structural simplicity with potential coherence enhancement. In this talk, I will review a series of experiments performed on CNT-based Josephson junctions. They are based on our ultraclean nanofabrication technique that exploits hexagonal boron nitride both as a pickup substrate and a pristine dielectric environment, which enables integration in superconducting circuits.

In a first experiment, we measured the supercurrent of a CNT Josephson junction via low-frequency quantum transport. The gate-dependence of the critical current exhibits sharp variations associated with quantum phase transitions of the fermionic Andreev ground state of different parities, owing to the competition between superconducting pairing and Coulomb repulsion. Going further, these measurements reveal a distinctive fourfold periodic modulation linked to the combined spin and orbital degeneracy of CNTs. In a second experiment, we implemented a CNT-based gatemon qubit, which is integrated into a circuit quantum electrodynamics architecture. The measured qubit spectrum can be tuned with a gate voltage over more than 4GHz and reflects the underlying Andreev physics. Going further, we demonstrate coherent control of this gatemon qubit through Rabi and Ramsey protocols, with T2* coherence times up to 200 ns, marking a significant milestone for carbon nanotube-based quantum devices.

References

[1] S. Annabi, E. Arrighi, A. Peugeot, H. Riechert, J. Griesmar, K. Watanabe, T. Taniguchi, L. Bretheau, and J.-D. Pillet, Phys. Rev. Applied **22**, 064035 (2024). https://doi.org/10.1103/PhysRevApplied.22.064035

[2] H. Riechert, S. Annabi, A. Peugeot, H. Duprez, M. Hantute, K. Watanabe, T. Taniguchi, E. Arrighi, J. Griesmar, J.-D. Pillet, and L. Bretheau, arXiv:2503.01978 (2025). https://doi.org/10.48550/arXiv.2503.01978

Magnetoelectric and photogalvanic effects in the helical state of a superconductor/ferromagnet bilayer

A. Buzdin[1], V. Plastovets[1], S. Mironov[2], A. Melnikov[2]

[1] University of Bordeaux, LOMA UMR-CNRS 5798, Talence Cedex, France
[2] Institute for Physics of Microstructures, Nizhny Novgorod, Russia

We investigate the nucleation of the helical superconducting state in a 2D superconductor/ferromagnet system with a spin-splitting field and weak Rashba spin-orbit coupling. By solving the Gorkov equations exactly, we describe the system's thermodynamic properties and derive the Ginzburg-Landau expansion. This enables analysis of magnetization control via transport supercurrent in dc and quasistatic ac regimes, linking these effects to the superconducting diode effect.
Moreover, superconducting materials and structures exhibiting the diode effect may reveal interesting photogalvanic phenomena. Using a generalized London model that incorporates quadratic nonlinearity in the relationship between supercurrent and superfluid velocity, we demonstrate that an incident electromagnetic wave can induce a nontrivial superconducting phase difference across the sample. When enclosed within a superconducting loop, this phase battery is expected to generate a circulating dc supercurrent. By increasing the intensity of the electromagnetic wave, one can trigger transitions between loop states with different vorticities.

A hybrid cavity-magnon-quantum circuit platform for axion dark matter detection

A. Cottet [1,2]

[1] LPENS, Ecole Normale Supérieure, Paris, France

[2] LPEM, ESPCI, Paris, France

Axions are hypothetical particles which do not belong to the standard model and are considered as good candidates to explain the dark matter in the Universe. As first proposed by P. Sikivie in 1983, it may be possible to detect them using a microwave cavity under a large magnetic field. Such a device is called a haloscope. I will describe a new type of haloscope which we have recently developed. It combines a superconducting quantum circuit and a magnetic crystal in addition to the microwave cavity. It aims to detect the axion signal by measuring a phase shift of the microwave signal. Furthermore, the magnetic crystal provides a frequency tunability, enabling in principle a large mass scanning range. This setup is expected to have an unprecedented figure of merit and mass scanning range. I will present both the concept and the first experimental results of our haloscope.

Misfit compounds as a platform for engineering doping, charge density waves and Ising superconductivity

Tristan Cren
Institut des NanoSciences de Paris, CNRS - Sorbonne University, 4 Place Jussieu, Paris

In the current quest of innovative materials which combine two-dimensionality, strong spin-orbit, valley physics, superconductivity, charge density wave, quantum-spin Hall effect, the transition metal dichalcogenides (TMD) misfit materials appear as extremely promising. They are constituted by sandwiching rocksalt layers, such as LaSe, and TMD layers such as $NbSe_2$. A very large combination of materials is achievable by playing on the stacking. TMD misfits are a new platform that allows achieving unprecedented high doping levels in TMD materials[1-2]. We will show how we have succeeded adjusting finely the chemical potential over a very wide range in $NbSe_2$ using a Pb_xLa_{1-x} rocksalt, and how this can used for stabilizing several charge density wave orders ($2 \times 2, 3 \times 3, \sqrt{3} \times \sqrt{3}$) and tuning the superconducting transition temperature over a wide range[2]. Superconductivity in these compounds exhibits a huge in-plane critical field which is much higher than the paramagnetic limit[3-4] due to a very strong Ising spin-orbit coupling. We will show some hint of non-conventional pairing in misfit compounds.

References:

[1] Misfit Layer Compounds: A Platform for Heavily Doped 2D Transition Metal Dichalcogenides, Raphaël T. Leriche et al., Advanced Functional Materials 31, 2007706 (2021)
[2] Layer Compounds as Ultratunable Field Effect Transistors: From Charge Transfer Control to Emergent Superconductivity, L Zullo, G Marini, T Cren, M Calandra, Nano Letters 23, 6658 (2023)
[3] Extreme in-plane upper critical magnetic fields of heavily doped quasi-two-dimensional transition metal dichalcogenides, P. Samuely et al., Phys. Rev. B 104, 224507 (2021)
[4] Protection of Ising spin-orbit coupling in bulk misfit superconductors, T. Samuely et al., Physical Review B 108, L220501 (2023)

Realization of basic types of Andreev-molecules

O. Kürtössy[1], M. Bodócs[1], C. P. Moca[2,5], Z. Scherübl[1], E. Nikodem[3], T. Kanne[4], J. Nygård[4], G. Zaránd[5], P. Makk[1], S. Csonka[1]

[1]Department of Physics, Institute of Physics, Budapest University of Technology and Economics, Hungary
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[4]Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark
[5]Department of Theoretical Physics, Budapest University of Technology and Economics, Hungary

Topological superconductivity provides a promising platform to realize fault tolerant quantum hardware. The simplest topological superconducting system is the Kitaev-model, which is a chain of localized sites where neighboring ones are coupled by superconducting pairing and direct tunneling. Since state-of-the-art semiconducting nanostructures allows to create artificial atoms and tunnel couple them or interconnect by superconductors, the basic ingredients are available to build up artificial chains, which we call superconducting artificial molecule, or Andreev-molecule. Very recently various realizations of such chains have been reported where the sites are coupled in different ways, e.g. via superconducting vacuum, superconducting bound state, or superconducting artificial atom.

We will present experimental realization of two types of Andreev-molecule: i) the analog of H_2 molecule, where two artificial atoms are tunnel coupled via a superconducting vacuum [1] and ii) the analog of H_2O molecule, where two artificial atoms are coupled via a 3rd superconducting atom [2].

References

[1] O. Kürtössy et al., Nano Letters, 21, 7929 (2021).
[2] O. Kürtössy et al., *arXiv:2407.00825.* (2024).

Engineering the topological landscape in magnet-superconductor heterostructures

S. A. Díaz[1]

[1]*University of Konstanz, Konstanz, Germany*

Magnet-superconductor heterostructures, due to the rich interplay between their adjacent order parameters, are fertile grounds for novel topological phenomena. Our theoretical studies demonstrate that topological defects in the magnetic order parameter lend themselves as versatile tools to engineer the superconducting order and its topological excitations. Magnetic domain walls manipulate superconducting vortices[1]. A chain of antiferromagnetic skyrmions induces topological superconductivity and supports Majorana bound states—the building blocks of topological quantum computing[2]. Ferromagnetic skyrmions coupled to superconducting vortices form bound pairs that can be used to braid Majorana bound states[3]. These findings strongly suggest that magnet-superconductor heterostructures are ideal arenas to further explore the mutual influence of magnetism and superconductivity to engineer and manipulate their order parameters and topological excitations.

References

1. S. A. Díaz *et al*., Phys. Rev. B **109**, L201110 (2024)
2. S. A. Díaz *et al*., Phys. Rev. B **104**, 214501 (2021)
3. J. Nothhelfer, S. A. Díaz, *et al*., Phys. Rev. B **105**, 224509 (2022)

Title: Strongly correlated topological flat bands in the novel class of moiré materials

Abstract: Twist-angle engineering of 2D materials has led to the recent discoveries of novel many-body ground states in moiré systems such as correlated insulators, unconventional superconductivity, strange metals, orbital magnetism and topologically nontrivial phases. These systems are clean and tuneable, where all phases can coexist in a single device, which opens up enormous possibilities to address key questions about the nature of correlation induced superconductivity and topology, and allows to create entirely novel quantum phases with enhanced interactions. In this talk we will introduce some of the main concepts underlying these systems, concentrating on magic angle twisted bilayer graphene (MATBG) and show how we can engineer strongly interacting, topological and superconducting states. We will further discuss our recent effort to explore the vast library of novel bilayer moiré materials (TMDs etc.) using a novel high-throughput quantum twisted microscope (QTM) technique, which will allow us to search for novel exotic ground states with ever higher interactions energy and temperatures. Last but not least we will show some recent quantum technology developments that were enabled by the ultra-low carrier density superconducting states in MATBG, culminating in the demonstration of highly tuneable single photon detectors.

Summary of achievements and track-record

Prof. Dr. Dmitri K. Efetov (M) received a Diploma (M.Sc.) in Physics from ETH Zurich (CH) in 2007. Subsequently Dmitri earned a M.A., M. Ph. and Ph.D. in Physics from Columbia University (USA) in 2014, under the supervision of one of the pioneers of graphene Prof. Dr. Philip Kim, with a thesis titled “Towards inducing superconductivity into graphene”. Dmitri then worked as a Postdoctoral Researcher at the Massachusetts Institute of Technology (MIT, USA) in the group of Prof. Dr. Dirk Englund, developing ultra-fast microwave thermometry and single photon detectors based on graphene. Since 2017 Dmitri was an Assistant Professor and Group Leader at ICFO (SP), and since 2021 is a Full Professor (W3) and Chair of Solid State Physics at LMU Munich (GER), with a research program that concentrates on the investigation of novel “moiré materials” at the intersection of condensed matter physics, optics and quantum science. Prof. Efetov received the Charles H. Towns Award for his outstanding research achievements during his PhD, the Obra Social ”laCaixa” Junior Leader Fellowship, an ERC Starting Grant, was a finalist of the LaVanguardia Science Prize, received the 2022 IUPAP Early Career Scientist Prize in Semiconductor Physics, and won the DFG Leibniz prize 2024 for his improvement of the device quality and the ground-breaking fundamental investigations of novel insulating, superconducting and topological phases in magic angle twisted bilayer graphene. He was the leader of the 2D-SIPC project in the EUs Quantum Technology Flagship, as well as a member of its Science and Engineering board. He is now a core-member of the Munich Center of Quantum Science and Technology (MCQST) and is member of the advisory board of the Center of Nano Science (CeNS).

Superconductivity, flatbands, topology, and beyond

C. Felser[1]

[1]*Max Planck Institute of Chemical Physics of Solids, Dresden, Germany*

While the exact pathway to high-temperature superconductors remains unknown, there are insights into the direction we should pursue. It is well-established that superconductors with higher transition temperatures are typically found near the boundaries of semiconductors, Mott insulators, and magnetism. By studying the properties of elements and compounds under pressure, it becomes clear that the highest transition temperatures tend to occur in elements located on the right side of the periodic table (such as semiconductors or insulators) and on the left side (including hydrogen, hydrides alkali and alkaline earth metals). Certain crystal structures, such as perovskites and the $ThCr_2Si_2$ structure, are generally associated with higher transition temperatures. These structures are favourable for both phonon-driven superconductors (e.g., $Ba_{1-x}K_xBiO_3$, $LuNi_2B_2C$) and unconventional superconductors (e.g., $YBa_2Cu_3O_{7-x}$, $Ba_{1-x}K_xFe_2As_2$). In addition to these structural insights, the role of flatbands in Kagome lattices such as CsV_3Sb_5 and twisted graphene and van Hove singularities has gained attention. Kagome lattices, characterized by their geometric frustration and flatbands, can enhance electronic correlation effects and contribute to unconventional superconductivity. These features, along with valence and electronic instabilities, act as key indicators for Fermi surface nesting, which is linked to the onset of superconductivity at higher temperatures.

This research was supported by the Klaus Tschira Stiftung as part of the SuperC collaboration.

Microwave Spectroscopy of Schmid Transition and Theory of Quantum-Limited Dual Shapiro Steps

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The Schmid transition was first introduced as a superconductor-insulator transition in the zero-frequency response of a shunted Josephson junction in equilibrium at zero temperature. As is typical for a quantum impurity problem, the transition is broadened to a crossover at finite frequencies. Modern attempts to observe the Schmid transition rely on microwave measurements of quantum circuits. The most controllable and thus promising such circuit is a high-impedance one-dimensional Josephson junctions array, containing a single ``weak'' junction. The weak junction allows for the superconducting phase slips and facilitates interaction between plasmon waves propagating along the array.

We predict the frequency dependence of the microwave reflection from such arrays and identify circuit parameters that allow for the universal scaling of the responses with frequency [1]. These predictions can help in identifying the Schmid transition from the finite-frequency measurements. Furthermore, we fully characterize the spectrum of radiation caused by the Bloch oscillations of charge passing through the weak junction in a DC-biased circuit. The character of Bloch oscillations and the associated shape of the dual Shapiro steps are closely linked to the physics of the Schmid transition [2]. In addition to predicting the results of future experiments, our theory offers a consistent interpretation of the existing experimental data.

[1] Manuel Houzet, Tsuyoshi Yamamoto, and Leonid I. Glazman, *“Microwave spectroscopy of Schmid transition”*, Phys. Rev. B **109**, 155431 (2024) https://doi.org/10.1103/PhysRevB.109.155431

[2] Vladislav D. Kurilovich, Benjamin Remez, and Leonid I. Glazman, *“Quantum theory of Bloch oscillations in a resistively shunted transmon”*, arXiv:2403.04624 (2024) https://arxiv.org/abs/2403.04624

Friedel oscillations and chiral superconductivity in monolayer $NbSe_2$

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In 1965 Kohn and Luttinger proposed a genuine electronic mechanism for superconductivity. Despite the bare electrostatic interaction between two electrons being repulsive, in a metal electron-hole fluctuations can give rise to Friedel oscillations of the screened Coulomb potential. Cooper pairing among the electrons then emerges when taking advantage of the attractive regions. The nature of the leading pairing mechanism in some two-dimensional transition metal dichalcogenides is still debated. Focusing on $NbSe_2$, we show that superconductivity can be induced by the Coulomb interaction when accounting for screening effects on the trigonal lattice with multiple orbitals.

Using ab initio-based tight-binding parametrizations for the relevant low-energy d-bands, we evaluate the screened interaction microscopically, in a scheme that includes Bloch overlaps and Umklapp processes. In the direct space, we find long-range Friedel oscillations which alternate in sign. The momentum-resolved gap equations predict two degenerate solutions at the critical temperature T_c, signaling the unconventional nature of the pairing. Their complex linear combination, i.e., a chiral gap with p-like symmetry, provides the ground state of the system. Our prediction of a fully gapped chiral phase well below T_c agrees with the spectral function extracted from tunneling spectroscopy measurements of single-layer $NbSe_2$.

[1] J. Siegl et al., arXiv:2412.00273v2

Why the Schmid transition does not exist

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We revisit the theory of the resistively shunted Josephson junction (RSJ) at equilibrium, using linear response, an exact path integral technique and symmetry considerations [1]. All three approaches independently lead to conclude that the superconducting-insulating quantum phase transition long believed to occur in the RSJ, cannot exist. This confirms the experimental invalidation published in 2020 [2] and qualitatively reproduces its data. We reveal and explain the subtle issues that lead to the incorrect prediction and to believe in it.

References

[1] C. Altimiras, D. Esteve, Ç. Girit, H. le Sueur, and P. Joyez, arXiv:2312.14754

[2] A.Murani, N. Bourlet, H. le Sueur, F. Portier, C. Altimiras, D. Esteve, H. Grabert, J. Stockburger, J. Ankerhold, and P. Joyez, Phys. Rev. X **10**, 021003 (2020).

Imaging Quantum Materials

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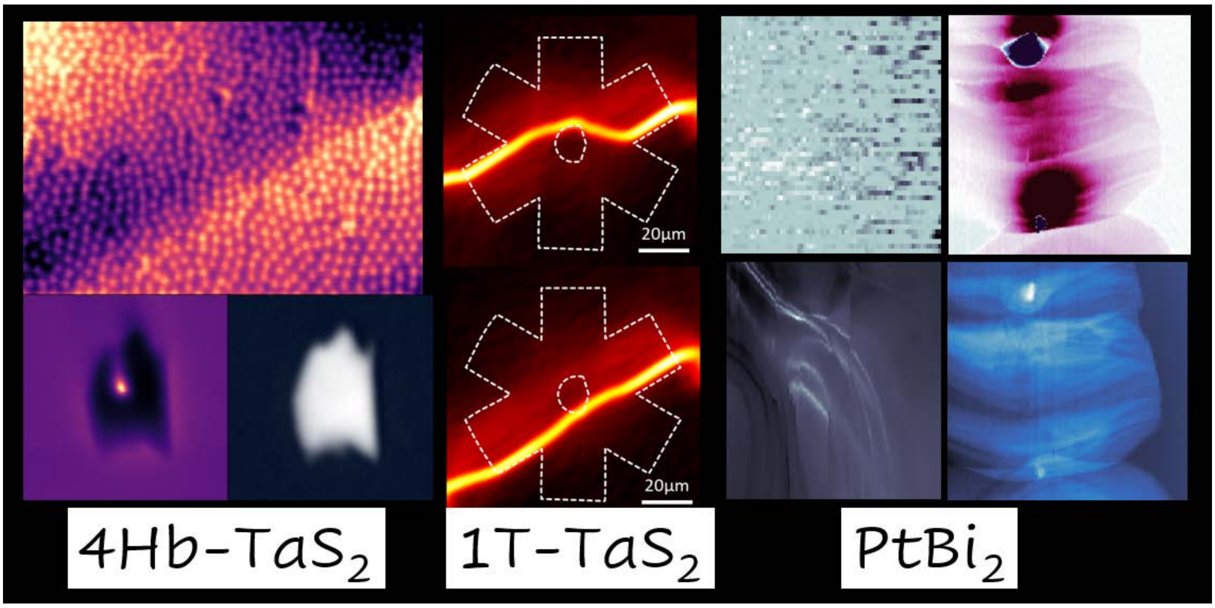
Competition between electronic orders with similar energy scales can give rise to complex emergent behaviors. Detecting traces of such orders requires versatile probes, which access different aspects of the system, such as conductivity, superconductivity and magnetism. I will describe few material systems where our local scanning SQUID view uncovered surprising mesoscopic effects. Two polymorphs of Tantalum disulfide: a van-der Waals material, 4Hb-TaS_2, in which we found a hidden magnetic phase and a 1T polymorph, in which we probed a hidden metallic state buried in an insulator. I will also show intriguing new findings in the superconducting state of the Weyl semimetal $PtBi_2$. These results demonstrate the power of a local phase-sensitive view in probing quantum materials.



Magnetoelectric phenomena of non-centrosymmetric superconductors – supercurrent diode effect and anisotropic vortex squeezing

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Superconductivity in materials with broken inversion symmetry has been a subject of theoretical and experimental studies from the early 90's. It was understood that unlike symmetric spin-orbit coupling found in centrosymmetric metals, spin-orbit coupling in non-centrosymmetric materials has a spectacular influence on the electronic bands through a specific spin splitting of the quasiparticle states. Superconductivity as a Fermi-surface instability towards pairing of electrons with opposite momenta and spins is naturally influenced by such a modification of the electronic states. The removal of inversion symmetry and also of time-reversal, e.g. by an applied external magnetic field, promotes a novel form of electron pairing–the so-called helical phase, in which Cooper pairs acquire a finite center of mass momentum. The latter gives rise to several interesting magneto-electric or magneto-chiral effects, like the enhancement of Tc in the presence of magnetic fields, the supercurrent diode effect, magneto-chiral inductance anisotropy, zero-pi-like transitions, the anomalous Josephson effect, as well as, unusual vortex squeezing and engendered London physics in the Meissner state. The last decade witnessed a renewed interest in superconductors with broken inversion symmetry by using the so called synthetic Rashba superconductors in a pursuit to find or engineer topologically non-trivial superconducting states with non-Abelian (Majorana) excitations.

In the talk I will discuss general properties of the non-centrosymmetric superconductors summarizing the main theoretical and phenomenological concepts standing behind. Apart of that, I will present exciting experimental evidences showing the emergence of A) supercurrent diode effect and Josephson inductance anisotropy in the synthetic Rashba-based Josephson junctions [1], and B) an unexpected enhancement of pinning and squeezing of Abrikosov vortices when probed in such non-centrosymmetric superconductors in a Meissner phase by applying an additional in-plane field [2]. I will elucidate these phenomena from the microscopic point of view, but as well as, phenomenologically as a direct manifestation of the Lifshitz invariant that is allowed in the Ginzburg-Landau free energy when the underlying Cooper pairs acquire a finite center of mass momentum.

[1] C. Baumgartner *et al.*, Nature Nanotech. **17**, 39 (2022).

[2] L. Fuchs *et al.*, Phys. Rev. X **12**, 041020 (2022).

Abstract Li Chuan

Title: Higher-order topological states in $Bi_{1-x}Sb_x$(x=3%) revealed by Josephson current

Higher-order topological insulators (HOTIs) represent a groundbreaking class of quantum materials, characterized by unconventional boundary states localized at corners or hinges, extending beyond the traditional bulk-edge correspondence. In this work, we investigate the higher-order topological states in the bismuth-antimony alloy $Bi_{1-x}Sb_x(x = 3\%)$ through Josephson current measurements. High-quality Josephson junctions were fabricated to probe supercurrent transport mediated by topologically protected hinge states in flakes of varying thicknesses. The experimental results consistently exhibit persistent signatures of hinge modes, including SQUID-like field-dependent critical currents, $I_c(B)$, indicative of enhanced edge currents. Temperature dependence, length dependence, and current-phase relation measurements confirm the ballistic nature of these junctions. Numerical simulations demonstrate that the hinge states are robust against defects and persist across projections onto different facets. Furthermore, thickness-dependent measurements reveal a distinct transition at a critical thickness, offering deeper insights into the interplay between bulk topology and hinge-bound edge states in HOTIs.

Nanostructured substrate control of Quantum Phases in Ultrathin YBCO films: Enhanced Superconductivity and novel Emergent Orders

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In cuprate high-temperature superconductors, the doping level is typically fixed during synthesis, limiting the ability to tune carrier density—unlike in many other two-dimensional materials. This has posed challenges in exploring their complex electronic phase diagram. Strain engineering has recently emerged as a powerful way to overcome this limitation. By altering lattice parameters, strain can modulate the competition between charge, spin, and superconducting orders—especially in thin films where substrate choice provides added control.

We have recently introduced a novel approach that involves using substrate surface nanofacets morphology to introduce an additional tunability knob to local strain and anisotropy. Nanofacets, formed during high-temperature substrate reconstruction, can strongly influence thin-film growth and electronic properties. In our previous work, we showed that ultrathin (YBCO) films grown on nanofaceted substrates exhibit electronic nematicity, unidirectional charge density wave (CDW) order and a strong modification of the strange metal phase, features not observed in bulk samples.

Building on this, we now show that such substrates not only induce new electronic phases but also enhance superconductivity. Specifically, we observe increases in both the onset temperature, and upper critical magnetic field in nanometer-thick YBCO films, signalling a robust modification of the superconducting ground state. We attribute this enhancement to an interface potential arising from the nanofacet-induced superstructure, which tunes the interplay between nematicity and CDW. These results highlight substrate morphology as a powerful tool for tuning and enhancing superconductivity in cuprates, paving the way for engineered, high-performance superconducting materials.

[1] E. Walhberg,…. and F. Lombardi Science 373, 1506 (2021)
[2] E. Walhberg,….A. Black Schaffer, G. Seibold T. Bauch and F. Lombardi arXiv:2502.03986
[3] G. Mirarchi,… F. Lombardi and G. Seibold Commun Mat. 5, 146 (2024)

Spin-resolved Josephson diode effect in strongly spin-polarized magnetic materials

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In this talk, we shall discuss the appearance of the spin-resolved Josephson diode effect in junctions comprising strongly spin-polarized magnetic materials (FM) with noncoplanar spin textures coupled to singlet superconductors (SC). The system is treated using the Gor'kov and quasiclassical Green's function techniques. Modeling the interfaces as spin-splitting δ-potentials, we account for the nontrivial coupling between the spin bands in the FM, allowing us to account for the Josephson current-phase relation (CPR). We apply this model to an SC/FM/SC junction, considering a conical state in the FM. Remarkably, the CPR displays an anomalous and significant Josephson diode effect with an efficiency greater than 40%. Our theory reveals an essential role of the quantum spin-geometric phase, which is determined by a noncoplanar spin texture of the material and which enters the Josephson CPR in a very similar manner to the superconducting phase difference. In our model, it is created by the intrinsically noncoplanar spin arrangement of the conical state, which breaks the time-reversal and inversion symmetries. However, a similar effect can be realized in a homogeneous ferromagnetic state if its magnetization, together with the magnetic moments of the SC/FM interfaces forms a noncoplanar spin profile. To get a better insight into the role of the spin-geometric phase, we perform the harmonic analysis of the spin-resolved Josephson CPRs, which allows interpreting the effect in terms of coherent transport of multiple equal-spin Cooper pairs.

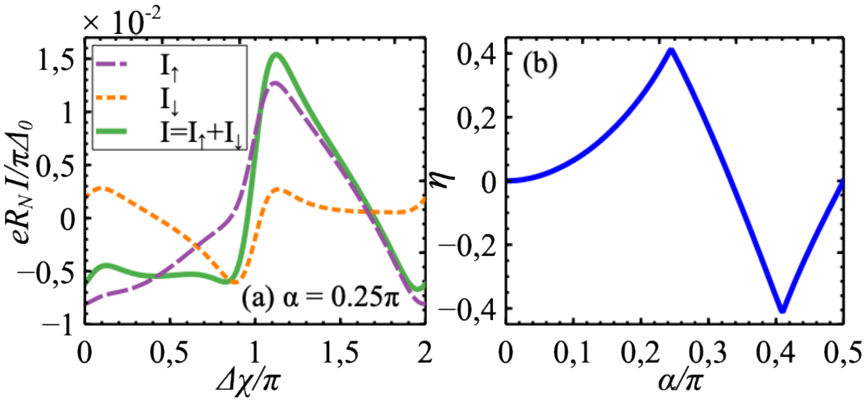

Fig. 1: Panel (a): Spin-resolved CPRs in an SC/FM/SC junction featuring the conical state in FM characterized by the conical angle $\alpha = \pi/4$. Panel (b): Charge diode efficiency η as a function α exceeding the maximum value of 41%.

References

[1] N. L. Schulz, D. Nikolić, and Matthias Eschrig, arXiv:2501.11751; arXiv:2501.12232 (2025)

Simultaneous transport and spectroscopy of moiré graphene: Distinct observation of the superconducting gap and signatures of nodal superconductivity

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Magic-angle twisted graphene superlattices have enabled the discovery of a plethora of correlated and topological phenomena, particularly superconductivity with unusual characteristics [1-5]. However, understanding the nature of superconductivity in magic-angle graphene remains a significant challenge. A key difficulty lies in resolving the various energy scales in this strongly interacting system, especially the superconducting gap. Here, we report the first simultaneous tunneling spectroscopy and transport measurements of magic-angle graphene, introducing a novel approach to probing the superconducting state. This method reveals two coexisting V-shaped tunneling gaps with different energy scales: a distinct low-energy superconducting gap that disappears at the superconducting critical temperature and magnetic field, and a higher-energy pseudogap. The superconducting tunneling spectra exhibit a gap-filling behavior with temperature and magnetic field and display the Volovik effect, consistent with a nodal order parameter. Our findings highlight the unconventional nature of the superconducting gap in magic-angle graphene and establish an experimental framework for multidimensional investigations of tunable quantum materials.

References

[1] Cao et al, Nature **556**, 43-50 (2018)
[2] Park et al, Nature **590**, 249-255 (2021)
[3] Hao et al, Science **371**, 1133-1138 (2021)
[4] Park et al, Nature Materials **21**, 877-883 (2022)
[5] Zhang et al, Science **377**, 1538-1543 (2022).

Two-tone Josephson Spectroscopy

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We introduce a novel two-tone spectroscopy technique for high-frequency quantum circuits [1], utilizing a voltage-biased superconductor-normal-superconductor (SNS) Josephson junction as an on-chip microwave source. This method enables the generation of radiation exceeding 80 GHz, well into the millimeter-wave band, facilitating the probing of highly coherent quantum systems. We demonstrate the efficacy of this approach by investigating two distinct systems: a transmon qubit and a multimode non-linear resonator. Our findings indicate that the SNS Josephson emitter provides a stable and tunable high-frequency signal, effectively exciting the quantum states of these systems. This advancement offers a robust platform for exploring high-frequency phenomena in hybrid superconducting circuits [2], potentially leading to new insights in quantum information processing [3] and condensed matter physics.

References

[1] A. Peugeot, *et al.*, Physical Review Applied **22.6**, 064027 (2024)
[2] G. Burkard, *et al.*, Nature Review Physics **2.3**, 129-140 (2020)
[3] J. I.-J. Wang, *et al.*, Nature Nanotechnology **14**, 120-125 (2019)

Finite-size effects in the vicinity of the BKT transition

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For 2D superconducting thin films Halperin and Nelson predict a finite resistance between the Berezinskii-Kosterlitz-Thouless temperature T_{BKT} and the mean-field critical temperature T_{c0} due to the unbinding of thermally excited vortex-antivortex pairs [1]. Recently, we observed a sharp BKT-transition in homogeneously disordered 3nm NbN films grown by ALD, which is in very good agreement with these theoretical predictions [2]. Although the sample width was much smaller the Pearl length $\Lambda_p \simeq 2\mathrm{mm} \gg \mathrm{w} = 10\mu\mathrm{m}$, we did not observe a size induced smearing of the transition. When further reducing the width to $w \leq 1\mu\mathrm{m}$, we eventually observe a finite resistance also for $T < T_{BKT}$ as expected from the cut-off of the divergence of the correlation length by the finite size [3]. We present a systematic study of this finite resistance regime vs. sample width combined with a detailed theoretical analysis in the limit of finite size based on the work of [1] and [3].

[1] B.I. Halperin, D.R. Nelson, J. Low Temp. Phys. 3**6**, 599 (1979).
[2] A. Weitzel *et al.*, Phys. Rev. Lett. **131**, 186002 (2023).
[3] L. Benfatto *et al.*, Phys. Rev. B **80**, 214506 (2009).

Josephson meta-materials: a new platform for quantum optics

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Josephson meta-materials have recently emerged as a highly promising platform for superconducting quantum science and technology. Their unique potential lies in the ability to engineer these materials at sub-wavelength scales, allowing for complete control over wave dispersion and nonlinear interaction.

In this talk, I will demonstrate how Josephson meta-materials can be utilized as microwave amplifiers with added noise that approaches the quantum limit. These materials are already widely used in experiments ranging from quantum information processing with superconducting qubits to dark matter detection.

Beyond these applications in quantum science, Josephson meta-materials also offer opportunities to explore new quantum optical phenomena. I will present a recent experiment in which we observed entangled counter-propagating photons generated by a left-handed (or negative index) Josephson meta-material.

This research is conducted in collaboration with the company Silent Waves.

Continuous monitoring of parity-flips in a planar superconducting island

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Understanding the complexity of coherence-limiting mechanisms is of paramount applied and fundamental importance in various hybrid device realizations. One of such limiting mechanisms, termed parity switching is responsible for an uncontrollable change in the number of quasiparticles in an otherwise stable electrostatic configuration. Protection against these errors requires access to high-fidelity parity measurements on a fast time scale. Here we report on real-time measurement and control of parity effect in a hybrid planar island by monitoring the response of the resonator that is inductively coupled to the device incorporated in a flux-biased loop. The strength of the parity effect could be tuned electrostatically by modulating the energy of a single, isolated bound state co-localized on the island without the need of an external magnetic field. Using our detection circuit we were able to resolve parity states with signal-to-noise ratio (SNR) exceeding 2 for integration time below 20 μs with detection fidelity above 98%. Time-resolved detection of parity-flips allowed to estimate the parity lifetime.

References

[1] M Hinderling, *et al.*, Phys. Rev. Appl. 19 (5), 054026 (2023).
[2] M Hinderling, *et al.*, PRX Quantum 5 (3), 030337 (2024).
[3] M Hinderling*, SC Ten Kate*, *et al.*, PRX Quantum 5 (3), 030357 (2024).

Superfluid density near the superconductor-insulator transition

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Superconducting films of amorphous Indium Oxide (a:InO) undergo a transition to an insulating state with increasing disorder, primarily due to the localization of pre-formed Cooper pairs. The continuous decrease in critical temperature as the critical disorder is approached suggests an equally continuous suppression of superfluid density. In this talk, I will discuss a systematic study of the superfluid density, measured via plasmon dispersion spectroscopy of microwave resonators made from a:InO, combined with DC resistivity measurements, as a function of disorder. We observed that the superfluid stiffness dictates the superconducting critical temperature over a wide range of disorder, underscoring the dominant role of phase fluctuations. Furthermore, we found that the superfluid density remains surprisingly finite at the critical disorder, indicating an unexpected first-order nature of the disorder-driven quantum phase transition to an insulating state.

Th. Charpentier et al. Nature Physics 21, 104 (2025)

Majorana states in quantum dot systems

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Majorana bound states (MBS) are quasiparticles with non-Abelian statistics, making them highly attractive for both fundamental research and applications in quantum computing. The Kitaev model predicts the emergence of these states at the ends of a chain under specific parameter conditions [1]. In experimental realizations, artificial Kitaev chains can be engineered using quantum dot (QD) –superconductor arrays [2,3]. Recently, a minimal two-site version of such a chain has been demonstrated, revealing the possibility of non-topological MBSs appearing at specific points [4].

Characterizing the emergent MBSs is a key challenge in the field, crucial for advancing towards robust quantum applications. In this presentation, I will introduce various methods for qualitatively and quantitatively identifying Majorana sweet spots through local current and conductance measurements [4]. These measurements enable the identification of parameter regimes with high MBS localization, an essential step toward fault-tolerant devices [6,7].

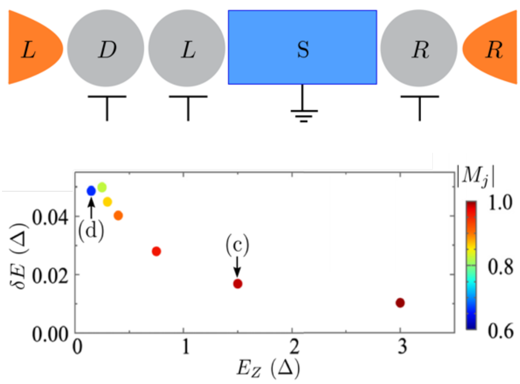

Figure 1: Top. Minimal Kitaev chain, formed by two QDs (L, R) coupled via a superconductor (blue). The chain couples to a measurement dot (D), used to infer the Majorana localization. Bottom: Splitting of the ground state energy as a function of the Zeeman field. Color indicates the Majorana localization, through the Majorana polarization, |M|. Reproduced from [8].

References

[1] A. Kitaev Phys. Usp. **44**, 131 (2001).
[2] J. Say and S. das Sarma, Nat. Commun. **3**, 964 (2012).
[3] M. Leijnse and K. Flensberg, Phys. Rev. B **86**, 134528 (2012).
[4] T. Dvir, et al., Nature **614**, 7948 (2023); S. ten Haaf et al., Nature **630**, 329 (2024).
[5] R. Seoane Souto, et al., Phys. Rev. Research **5**, 043182 (2023); A. Bordin et al., In preparison; R. Dourado, M. Leijnse, R. Seoane Souto, in preparison.
[6] D. M. Pino, R. Seoane Souto, R. Aguado, Phys. Rev. B **109**, 075101(2024).
[7] R. Seoane Souto, A. Tsintzis, et al., PRX Quantum **5**, 010323 (2024)

Current quantization in small Josephson junctions due to synchronization of Bloch oscillations with microwave.

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The supercurrent quantization due to Coherent Quantum Phase Sleep (CQPS) was recently demonstrated in highly disordered superconducting nanowire [1]. The synchronization of the Bloch oscillations with microwaves in small Josephson junction revealed similar current quantization [2]. The current steps are equal to *2efn*, where *2e* is cooper pair charge *f* is microwave frequency and *n* is step number. The effect is dual to voltage quantization with steps equal to $\Phi_0 f$ - the well-known Shapiro steps, where Φ_0 is flux quanta. These phenomena can be utilized to develop new electronic devices.

We demonstrate new electronic device, Bloch Transistor. Its purpose is to deliver quantized current to the quantum circuit. The current can be controlled with bias and gate voltage as well as microwave frequency and amplitude.

We probe feasibility of the Josephson voltage and current standard on a single chip.

References

[1] Shaikhaidarov et al, Nature, **608**, 45-49 (2022)
[2] Shaikhaidarov et al, Nature Comm., **15**, 9326 (2024)

Universality of Upper Critical Field in the TMD Superconductor Family

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In transition metal dichalcogenides (TMDs) such as H-$NbSe_2$ an H-TaS_2, superconducting properties are retained down to a single layer, making them useful platforms for studying thickness-dependent effects. Specifically, $NbSe_2$ exhibits a reduction in its T_C from 7.2 K in the bulk to approximately 3 K in the single-layer limit. In TaS_2, conversely, T_C increases from 0.8 K in the bulk to approximately 3 K in the single layer limit. This contradicting behavior, which long puzzled researchers, could be related to a thickness-dependent suppression of superconductivity by the competing charge density wave (CDW) phase.

I will present measurements of device-based high-resolution tunneling spectra in TaS_2, where we track the gap structure from the bulk all the way to a single layer. Our devices allow for simultaneous evaluation of the gap Δ, T_C, and the upper critical field H_{C2}. Although TaS_2 is considered as a dirty superconductor, we find that H_{C2} is proportional to Δ^2, a relation expected for clean superconductors. Even more curiously, we find that the same ratio between H_{C2} and Δ^2 holds for other TMDs: $NbSe_2$ of all thicknesses, and bulk $TaSe_2$, covering 4 orders of magnitude in H_{C2} and covering both clean and dirty limits.

Theory of three-terminal Andreev spin qubits

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We propose a next generation of Andreev spin qubits — three terminal Andreev spin qubits (TASQs). These new qubits outperform two-terminal devices in the speed of two-qubit gates, benefiting from enhanced spin splitting [1]. Our theoretical analysis reveals increased tunability and inter-qubit coupling mediated by the supercurrent. Furthermore, it provides a comprehensive explanation for the results of a recent experiment on a three-terminal device [2]. We identify the optimal operational regime for single- and two-qubit gates. Moreover, our concise theoretical framework for the equilibrium multi-terminal Josephson effect offers significant potential for exploring non-trivial physics in the artificial dimensions of superconducting phase differences

References

[1] B. van Heck, S. Mi, and A. R. Akhmerov, *PRB*, **90**, 155450 (2014)
[2] M. Coraiola, D. Z. Haxell, D. Sabonis, M. Hinderling, S. C. ten Kate, E. Cheah, F. Krizek, R. Schott, W. Wegscheider, F. Nichele, Phys. Rev. X **14**, 031024 (2024).

Nonequilibrium plasmon fluid in a Josephson junction chain

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With the recent push towards the development of quantum technologies, multimode quantum systems, such as superconducting resonators, have drawn considerable attention. These systems can be generally described as a set of weakly nonlinear bosonic modes, coupled to a thermal bath and subject to a coherent driving. As the number of modes grows and extrinsic decoherence is reduced, it becomes more relevant to understand the mode-to-mode interaction, which is a potential source of internal decoherence, and can be significantly enhanced when the system is brought far from equilibrium. In this work, we consider the interacting plasmonic modes emerging in a long chain of Josephson junctions, which can be probed via multitone microwave spectroscopy. We investigate the nonequilibrium kinetics of the resulting one-dimensional quantum fluid both theoretically and experimentally, focusing on four-wave mixing processes. We first assess the framework in the absence of driving, and then move to the out-of-equilibrium regime. Under two coherent drives, we observe cascaded coupling between plasmonic modes, which is reproduced theoretically by applying the input-output theory to multiplets of modes coupled by the nonlinear Hamiltonian. Under incoherent broadband drive, we explore the kinetics of weakly populated modes. We implement numerically a kinetic equation to predict the non-equilibrium steady state of the system, and match the observed excess linewidth of the non-driven modes due to internal dynamics. Our work establishes the key role of four-wave mixing nonlinearities in the non-equilibrium response of Josephson junction chains, and paves a way for studying far from equilibrium multimode quantum systems.

References

[1] A.V. Bubis *et al.*, paper in preparation

Hybrid circuits with van-der-Waals cuprate superconductors

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Superconducting circuits (SCs) are quantum devices that mimic the behavior of atomic systems even though they are made up of macroscopic microwave circuit elements. Their tunability, high coherence, and strong coupling has led to their rapid development as a leading implementation of quantum hardware. Traditional SCs are made using known superconductors such as aluminium or niobium, but the integration of novel superconductors as part of the circuit can lead to new scientific insights and new capabilities. Such hybrid circuits are ideal sensors, capable of measuring the superconducting gap structures of novel materials using micron-sized samples, which is especially useful for interface superconductors [1] or van-der-Waals flakes [2] which cannot be probed with bulk techniques. Furthermore, the unique quantum properties of unconventional superconductors can be utilized to make a new class of quantum devices [3]. This talk will present recent results where we explore van-der-Waals cuprate superconductors with hybrid circuits, and a path towards utilizing them in new hybrid devices for quantum technology.

References

[1] Bøttcher et al. Nature Physics (2024)
[2] Jin et al. Nano Letters (2025)
[3] Brosco et al. Phys. Rev. Lett (2024)

A single superconducting vortex on a leash

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We introduce the Single Vortex Box (SVB) (Fig.1) – a nanodevice that allows to treat a single superconducting vortex as a macroscopic, albeit quantized “particle”, which can be created and annihilated on demand with pulses of electrical current [1]. Using the method of fast nanosecond-resolving switching thermometry [2], we measure the temperature rise and the subsequent thermal relaxation resulting from the expulsion of just a single magnetic field vortex out of the aluminum SVB. Our experiment provides a calorimetric estimation of the dissipation in a superconductor due to a single moving vortex. This is a feat of the fundamental importance that has never been accomplished before for the lack of appropriate tools. Our pioneering demonstration is also a pivotal step towards the development of the vortex electronics i.e. memory cells, superconducting diodes, logical elements and heat valves.

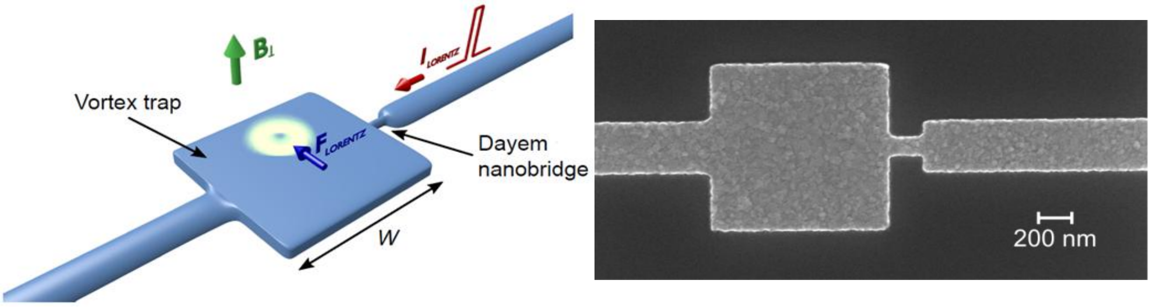

Fig.1: Left: Layout of the studied nanostructure consisting of a vortex trap (SVB), a Dayem nanobridge, and connecting leads. The vortex is expelled with the Lorentz force exerted by a current pulse. The state of the trap is probed via measurements of the critical current of the bridge. **Right:** A physical realization of the full-aluminum 30nm thick device.

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[1] M. Foltyn, K. Norowski, A. Savin, M. Zgirski,
Quantum thermodynamics with a single superconducting vortex,
Science Advances 10, eado4032 (2024).

[2] M. Zgirski, M. Foltyn, A. Savin, A. Naumov, K. Norowski, *Heat Hunting in a Freezer: Direct Measurement of Quasiparticle Diffusion in Superconducting Nanowire*,
Phys. Rev. Applied 14, 044024 (2020).

Abstracts of Posters

(in alphabetical order)

Helical Topological Superconducting Pairing at Finite Excitation Energies

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We propose helical topological superconductivity away from the Fermi surface in three-dimensional time-reversal-symmetric odd-parity multiband superconductors [1]. In these systems, pairing between electrons originating from different bands is responsible for the corresponding topological phase transition. Consequently, a pair of helical topological Dirac surface states emerges at finite excitation energies. These helical Dirac surface states are tunable in energy by chemical potential and strength of band splitting. They are protected by time-reversal symmetry combined with crystalline twofold rotation symmetry. We suggest concrete materials in which this phenomenon could be observed.

References

[1] Bahari, Masoud, Song-Bo Zhang, Chang-An Li, Sang-Jun Choi, Philipp Rüßmann, Carsten Timm, and Björn Trauzettel. Phys. Rev. Lett. 132.26 (2024)

Non-reciprocal superconductivity in cobalt disilicide

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Measurements of transport in S/N junctions containing $CoSi_2$ indicate that $CoSi_2$ might be a triplet superconductor [1]. In order to learn more about potential triplet superconductivity and effects of spin-orbit interaction in the superconducting phase of $CoSi_2$, we study DC and AC transport. To access the kinetic inductance, we integrate a $CoSi_2$-meander into an LC-circuit. The results show that the pinning potential of the vortices forming inside the material characteristically depends on the direction of an in-plane magnetic field. This observation is a clear signature of Rashba spin-orbit interaction [2]. When exposed to an in-plane field orthogonal to the current, the inductance $L(I_{DC})$ depends on the polarity of the DC bias. We attribute this observation to an intrinsic magnetochiral anisotropy that is a second signature of Rashba SOI.

References

[1] S.-P. Chiu et al. , Sci. Adv. **7**, eabg6569 (2021)
[2] L. Fuchs et al. Phys. Rev. X **12**, 041020 (2022)

Coplanar on-chip resonator for simultaneous kinetic inductance and resistance measurements of TMDC-superconductors

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Kinetic inductance is an observable which has the potential to unveil signatures of unconventional pairing states in TMDC-superconductors [1, 2, 3]. The small size of exfoliated flakes has so far limited experimental access to their kinetic inductance. We integrate a $NbSe_2$ flake into a robust, high-Q on-chip Nb resonator. Spiral inductors, fabricated alongside the resonator, act as low-pass filters for DC ports. They ensure the high-impedance environment needed to detect subtle changes in resonance frequency and enable simultaneous DC measurements. We demonstrate the change in kinetic inductance of a 2nm thick $NbSe_2$ flake when biased with DC currents and use this to isolate the effects of the magnetic field and temperature on the kinetic inductance of $NbSe_2$.

References

[1] J. Siegl *et al*, arXiv:2412.00273v2 [cond-mat.supr-con] (2025)
[2] S. Roy *et al*, *2D Mater.* **12** 015004 (2025)
[3] N.F.Q. Yuan & L. Fu, Proc. Natl. Acad. Sci. U.S.A. **119** e2119548119 (2022)

Microwave response of voltage states in strongly driven Josephson junctions

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Josephson junctions realize a superconducting version of the quantum pendulum. Under sufficiently strong drive, a classical pendulum will enter rotating states, which formally correspond to finite-voltage states when translated to the Josephson junction. The corresponding Shapiro steps [1] are well understood in DC circuits containing Josephson junctions, leading to e.g. metrological Josephson voltage standards and adjustable , but the inherent dissipation in these circuits makes the DC voltage states extremely short-lived when DC bias is removed. However, in microwave circuits, such voltage states may still be reachable under the right conditions for junctions without a DC shunting circuit and might be longer-lived. We try to reach and measure such ”zero-bias steps” by dispersively coupling the driven Josephson element to a resonator, expecting clear transitions in the system’s microwave response, aiming for detection without any DC connections and checking against weak DC measurements of the voltage. This could open the way to manipulating the dynamical voltage states V of junctions in the quantum regime, as coherent quantum objects.

References

[1] Shapiro, Sidney. « Josephson Currents in Superconducting Tunneling: The Effect of Microwaves and Other Observations ». Physical Review Letters 11, nº 2 (15 juillet 1963): 80-82. https://doi.org/10.1103/PhysRevLett.11.80.

$Nb:SrTiO_3$: GHz Vortex Dynamics at mK Temperatures in a Type II Two-Band Superconductor

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Superconducting doped $SrTiO_3$ exhibits a dome of critical temperatures T_c as a function of doping with a maximum T_c around 300 mK while the Fermi energy remains in the order of the superconducting energy gap [1]. Despite these unconventional features, the optical conductivity of $Nb:SrTiO_3$ in the superconducting state and in the absence of magnetic field is found to be well described by the Zimmermann formula [2]. In our stripline-resonator experiment, the optical conductivity of $Nb:SrTiO_3$ is measured between 2 and 40 GHz (below and above the energy gap) in magnetic field up to the critical field. We measure an additional contribution to the real part of the optical conductivity σ_1, which can result in σ_1 exceeding 4 times the normal conductivity at 2 GHz, such a strong increase with magnetic field is to our best knowledge not described in literature. We attribute this feature to the flux-flow conductivity introduced by the vortex motion. In the framework of the Coffey-Clem model, we find that the strong increase in σ_1 is only observed in a certain bandwidth where the lower frequency limit is set by the transition from the flux-pinning regime to the flux-flow regime and the upper frequency limit is set where the flux-flow skin depth equals the London penetration depth. We further find two upper critical magnetic fields, which we attribute to the two superconducting bands. We plot the dome of critical magnetic fields together with the critical temperatures and compare their dependencies on doping.

[1] C. S. Koonce et al. Phys. Rev. **163**, 380 (1967)
[2] M. Thiemann et al. Phys. Rev. Lett. **120**, 237002 (2018)

Josephson Junctions with Spin Polarization without Exchange Interaction

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The interplay of superconductivity and ferromagnetism, the subject of extensive research over the past few decades, is typically dominated by the exchange energy of the ferromagnet, which puts stringent limits on the existence of Cooper pairs in systems that include ferromagnets[1]. Spin polarization, also plays a role in the dynamics of superconductor-ferromagnet hybrid systems, reducing effectively Andreev reflection at the boundary, as the minority spin band limits this mechanism[2]. It has been a long standing question what would happen if proximity-induced superconductivity is combined with spin polarization without exchange interaction.

We study such a system by constructing a Josephson junction where the weak link is a normal metal in which spins are injected. Using multi-step electron beam lithography, combined with Manhattan style shadow evaporation, we construct a heterostructure with ferromagnetic cobalt and aluminium or copper with pristine interfaces. This device is used as a spin injector to create a current-dependent spin-polarization in the normal metal, which is then used as a weak link in a lateral junction with niobium leads. We characterize the resulting device using transport measurements, as well as SQUID-on-tip microscopy. We thus study the role of the exchange interaction in traditional superconducting-ferromagnetic hybrid junctions and investigate possible novel applications for superconducting spin transport without exchange.

References

[1] A. I. Buzdin, Rev. Mod. Phys. **77**, 935 (2005)
[2] M. J. M. de Jong and C. W. J. Beenakker, Phys. Rev. Lett. **74**, 1657 (1995)

Cyclotron Resonance Probed by Coplanar Waveguide Resonators

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Cyclotron resonance is a powerful tool to study the energy landscape of solids directly and non-destructively. We utilize microwave resonators in coplanar geometry to generate an alternating electric field in the GHz range to probe the intrinsic carrier dynamics of quasiparticles, when subjected to a perpendicular static magnetic field. These resonators allow us to study a wide range of temperatures down to the mK regime, as well as multiple frequencies given by higher harmonics.

We studied doped Germanium samples obtaining the temperature-dependent effective mass and scattering rate for different bands. Furthermore, we find signatures of magnetic field dependent avalanche ionization when increasing the power of the microwave field.

Probing the helical states in WTe_2 with superconductors

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WTe_2, a transition metal dichalcogenide with large spin-orbit interactions, is predicted to have striking topological properties that combine type II Weyl semimetal character with second-order 3D topological insulator (SOTI) character.[1][2] SOTIs are characterized by topologically protected (insensitive to disorder) helical 1D states at their hinges. 1D states located at certain edges of multilayer WTe_2 have indeed been demonstrated in Josephson interferometry experiments. However, their ballistic nature was not tested.

We have designed WTe_2-based Superconducting Quantum Interference Devices (SQUIDs) in which the supercurrent through the junction close to one edge of the crystal interferes with the supercurrent far from the edge.. Depending on the geometry of the junction along the edge, the SQUID oscillations are dominated by the contributions of either the bulk states or the edge states. In the case where a large number of bulk states are contacted by superconducting electrodes in both junctions, we observe sinusoidal SQUID-like oscillations whose amplitude is modulated by orbital interferences between diffusive trajectories delocalised in the whole bulk of the junctions. This interference pattern has been investigated in the three magnetic field directions. On the special case where only few edge states are contacted in the junction along the edge, the strongly asymmetric SQUID pattern is dominated by the contribution of the current-phase relation of those edge states and exhibits a sawtooth shape. This shape is a tell-tale sign that the supercurrent through the edge flows ballistically over 600 nm (which is ten times the estimated normal state mean free path) and is due to the SOTI character of WTe_2.

References

[1] YB. Choi and et al. "Evidence of higher-order topology in multilayer WTe_2 from Josephson coupling through anisotropic hinge states." In: *Nat. Mater.* 19 (2020).

[2] A. Kononov and et al. "One-Dimensional Edge Transport in Few-Layer WTe_2". In: *Nano Letters* 20.6 (2020).

Controlling the Photonic Joule Effect in High-Impedance Superconducting Quantum Circuits

Anas Chadli [1], **Samuel Cailleaux** [1], **Wiebke Guichard** [1], **Quentin Ficheux** [1], **Denis M.Basko** [2], **Nicolas Roch** [1]

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High-impedance superconducting quantum circuits integrate one or more Josephson junctions with high-impedance resonators or transmission lines. These circuits can be engineered for high coherence and utilized as novel qubits. Additionally, they provide a promising platform for Josephson photonics and quantum metrology when biased by a DC voltage, as demonstrated in various recent experiments. However, under DC bias, a Josephson junction can act as a potent microwave source, populating the high-impedance resonators and transmission lines in the circuit. This microwave radiation leads to a significant buildup of photonic populations, resulting in effects akin to the Joule effect **[1]** and even lasing phenomena. In this presentation, I will introduce a new architecture designed to address this significant limitation of high-impedance superconducting quantum circuits. It features a small Josephson junction coupled to high-impedance superconducting transmission lines (Z_c~10 kΩ). By employing a technique known as tapering in microwave engineering **[2]**, we can effectively match these high-impedance transmission lines to our low-impedance measurement circuitry (Z_c~50 Ω), thus reducing the buildup of photonic populations by several orders of magnitude. I will outline our recent experiments with these circuits and explain how they can enhance our understanding of Bloch oscillations and dissipative quantum phase transitions, such as the Schmid transition **[3]**, within high-impedance superconducting quantum circuits.

References:

[1] S. Cailleaux, Q. Ficheux, N. Roch, and D. M. Basko, "Theory of the Photonic Joule Effect in Superconducting Circuits," *arXiv preprint arXiv:2411.19912*, Nov. 2024

[2] D. M. Pozar, *Microwave Engineering*, 4th ed. Hoboken, NJ, USA: Wiley, 2011

[3] A. Schmid, “Diffusion and Localization in a Dissipative Quantum System,” *Phys. Rev. Lett.*, vol. 51, no. 17, pp. 1506–1509, 1983

Theory of the Supercurrent Diode Effect in Josephson Junctions

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Simultaneously breaking space-inversion and time-reversal symmetries in superconducting systems may imprint a polarity dependence (nonreciprocity) on the supercurrent [1], allowing to rectify supercurrents and engineer supercurrent diodes. The supercurrent diode effect (SDE) has been intensively investigated on various material platforms in recent years, including Josephson-junction arrays realized inside a narrow InAs quantum well [2–5].

This poster will summarize our theoretical efforts to understand the experimental data obtained from measurements on the Josephson-junction arrays by the Strunk group in Regensburg. We will provide a minimal theoretical model to explore the impact of spin-orbit coupling and magnetic exchange inside the quantum well on the spectroscopic (spin-split Andreev bound states) and transport (Josephson current–phase relations) characteristics [5]. From the latter, we will evaluate the polarity-dependent critical Josephson currents to quantify the SDE.

We will demonstrate that the Josephson junctions can undergo current-reversing 0–π-like phase transitions at large enough magnetic exchange, evident as sharp peaks followed by a sudden suppression in the SDE features [4,5]. Furthermore, we will also compute the Josephson inductance of the array—a measure that has been established as a sensitive probe of (nonreciprocal) Josephson transport [2,3]—and show that the aforementioned 0–π-like transitions simultaneously reverse the sign of the supercurrent magnetochiral anisotropy [4,5], offering another way to experimentally detect 0–π-like transitions without having access to the full current–phase relations.

This work was supported by DFG—project-IDs 314695032 and 454646522.

References

[1] F. Ando *et al.*, Nature **584**, 373 (2020)
[2] C. Baumgartner *et al.*, Phys. Rev. Lett. **126**, 037001 (2021)
[3] C. Baumgartner *et al.*, Nat. Nanotechnol. **17**, 39 (2022)
[4] A. Costa *et al.*, Nat. Nanotechnol. **18**, 1266 (2023)
[5] A. Costa, J. Fabian, and D. Kochan, Phys. Rev. B **108**, 054522 (2023)

Exploring Superconducting and Topological Quantum Materials Using Advanced Surface Characterization Techniques

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Surfaces and interfaces in quantum materials host fascinating phenomena, from topological surface states to unconventional superconductivity. To explore these properties, we have installed a state-of-the-art Surface Characterization Station at the Institute for Topological Insulators (ITI). This setup integrates NanoESCA (Energy-Filtered PEEM & k-space Imaging) and Low-Temperature Scanning Tunnelling Microscopy (LT-STM), allowing in-situ, high-resolution electronic and structural studies at the atomic scale. The system will be directly linked to a (soon to be relocated) Molecular Beam Epitaxy (MBE) cluster for contamination-free sample transfer, enabling precise correlation between growth conditions and quantum properties. In this work, we outline our research plans focusing on unconventional superconductivity and topological phases in materials such as HgTe, FeSe and YPtBi. Our goal is to leverage these cutting-edge tools to probe superconducting gap structures, quasiparticle interference, and Majorana bound states, shedding light on the interplay between superconductivity and topology.

Gate and Flux Tunable $\lambda/4$ Resonators in two-dimensional Al/InAs Hybrid Superconductor/Semiconductor Heterostructures

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We present the design and measurement of two tunable $\lambda/4$ microwave resonators fabricated out of a hybrid Al/InAs heterostructure. The heterostructure hosts a 2DEG which is proximitized by the Al and allows tailoring Josephson junctions. In one of the devices, the resonator is terminated by a single Josephson junction, while the other is terminated with a SQUID. We characterize the microwave response of the $\lambda/4$ resonators and show how the junction and the SQUID act as inductive loads that can be tuned via gate voltage and magnetic flux. We have observed the onset of a bifurcation regime for a large number of photons in the resonator, enhanced by the nonlinearity inherited from the Josephson elements. We discuss potential implementation of Josephson parametric amplifiers using these tunable resonators.

Probing phase slip noise in gate-controlled Al/InAs nanowires.

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Abstract

Gate-controlled supercurrent (GCS) in superconducting nanobridges has recently attracted attention as a means to create the superconducting equivalent of the semiconductor CMOS transistors. The earlier works attributed this effect to the electric field applied by the gate [1,2]. However, recent works have attributed the origin of this effect to the leakage current between the gate and the superconducting nanowires through the so-called stress-induced leakage current (SILC) [3,4]. Understanding the microscopic process behind the GCS effect and the switching dynamics of the superconducting nanowire under the influence of the gate would be crucial for assessing the reliability of the GCS-based devices for various electronic applications. Our recent results show fluctuations in the superconducting state under the influence of the gate [3]. In this work, we probed the high-frequency noise associated with with gate-induced phase slips in the superconducting nanowire. Furthermore, we compared the results with phase slips noise induced by heating the superconducting nanowire at elevated temperatures. The analysis of the noise Fano factor provides crucial insights into single phase-slip events and multiple phase slips near critical current occurring in both scenarios.

References

[1] De Simoni, G., Paolucci, F., Solinas, P., Strambini, E. & Giazotto, F. Metallic supercurrent field-effect transistor. *Nat. Nanotechnol.* **13**, 802–805 (2018)

[2] Rocci, M. et al. Gate-controlled suspended titanium nanobridge supercurrent transistor. *ACS Nano* **14**, 12621–12628 (2020).

[3] Elalaily, T., Berke, M., Lilja, I. *et al.* Switching dynamics in Al/InAs nanowire-based gate-controlled superconducting switch. *Nat Commun* **15**, 9157 (2024).

[4] Ruf, Leon, Elke Scheer, and Angelo Di Bernardo. "High-performance gate-controlled superconducting switches: Large output voltage and reproducibility." *ACS nano* **18**, 31 ,20600-20610 (2024).

Scanning SQUID microscopy on t-$PtBi_2$

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The type-I Weyl semimetal t-$PtBi_2$, has drawn much attention in recent years due to indications of surface superconductivity at approximately 5K [1] and a Berezinskii-Kosterlitz-Thoules (BKT) transition at the mK regime [2], suggesting a unique interplay between superconductivity and topologically protected surface states. Using scanning SQUID microscopy, we reveal superconducting fluctuations in the millikelvin regime and identify a diamagnetic phase transition at higher temperatures. These findings highlight the complex physics of t-$PtBi_2$ and suggest the need for new theoretical perspectives on its behavior.

References

[1] A. Kuibarov, *Nature* **626**, 294 (2024).
[2] A. Veyrat, *Nano Letters* **23**, 1229 (2023).

Signatures of spin orbit interaction in the kinetic inductance of epitaxial Al/InAs heterostructures

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We present microwave measurements of lumped element resonators taylored in a two-dimensional epitaxial Al/InAs heterostructure, which exhibits strong spin-orbit coupling and induced superconductivity. The resonators consist of narrow wires oriented along different crystal axes acting as inductors, in parallel with large interdigitated capacitors. The kinetic inductance of the wires dominates the microwave response of the resonators, which can be precisely oriented with respect to an applied in-plane magnetic field. We observe an anisotropic frequency shift and a dependence on magnetic field strength that deviates from the behavior expected by considering orbital pair-breaking alone. According to our theoretical model, these observations are consistent with the presence of disorder, spin-orbit interaction and with the emergence of Bogoliubov Fermi surfaces [1,2].

[1] Detecting induced p +ip pairing at the Al-InAs interface with a quantum microwave circuit, D. Phan, J. Senior, A. Ghazaryan, M. Hatefipour, W. M. Strickland, J. Shabani, M. Serbyn, and A. P. Higginbotham, arXiv:2107.03695

[2] Proximity-induced gapless superconductivity in two-dimensional Rashba semiconductor in magnetic field, Serafim S. Babkin, Andrew P. Higginbotham, and Maksym Serbyn, arXiv:2311.09347

Investigation of Josephson junctions with Weyl-Kondo semimetals

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A superconducting diode, i.e., a device with a polarity dependent supercurrent amplitude, would provide new functionalities for superconducting circuits. The superconducting diode effect (SDE) was observed in 2020 [1] in an artificial superlattice with inversion symmetry breaking and is now investigated in both Josephson junctions and junction-free superconductors.

We have fabricated and investigated Josephson junctions composed of superconducting electrodes and the Ce-based Weyl-Kondo semimetals $Ce_3Bi_4Pd_3$ [2] and $CeRu_4Sn_6$ [3] as weak links. These topologically nontrivial materials are promising candidates to investigate the SDE due to their intrinsic broken inversion symmetry and strong spin-orbit coupling, which are also responsible for the purely electric-field-driven nonlinear spontaneous Hall response [2,3].

References

[1] F. Ando, Nature **584**, 474-476 (2020)
[2] S. Dzsaber, PNAS **118**, e2013386118 (2021)
[3] D. Kirschbaum, arXiv: 2404.15924 (2024)

Collective quantum phases and excitations emerging in superconducting networks

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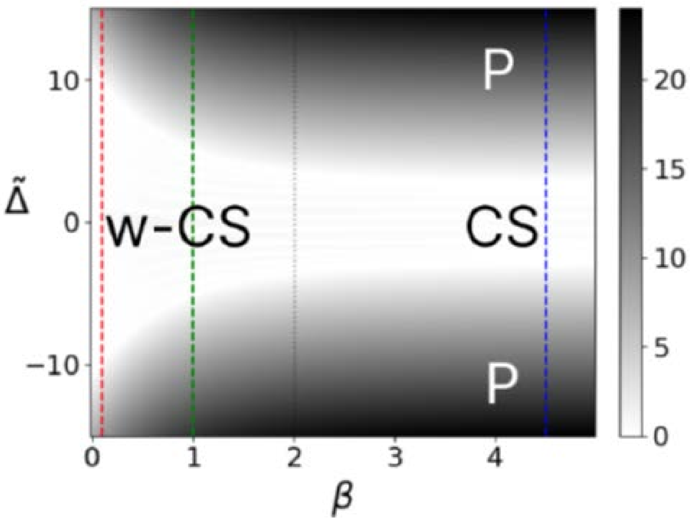
Geometrical frustration in correlated systems can give rise to a plethora of ordered/disordered states and intriguing quantum phases [1]. The networks of interacting superconducting qubits are a promising experimental platform to realize analogue quantum simulations for such systems, to identify novel collective quantum phases and excitations.

Here, we present a theoretical study of collective quantum phases and low energy excitations occurring in exemplary vertex-sharing frustrated superconducting qubits networks, i.e., sawtooth chains of 0- and π-Josephson junctions directly embedded in a dissipationless transmission line. Employing a variational approach the quantum dynamics of such qubits networks is mapped on various effective long/short interacting spin ½ models with local terms representing the coherent quantum superposition of persistent currents. The exchange interaction between well separated Josephson junctions (spins) decays with distance as $x^{-\beta}$, where the parameter β can be tuned in a wide region [2]. Combining exact numerical diagonalization for small networks, DMRG analysis, and quasi-classical mean field approach the collective quantum phases and low-lying excitations such as the paramagnetic (*P*), compressible superfluid (CS) and weakly compressible superfluid



(w-CS) were obtained.

References

[1] V. R. Shaginyan et al., Journal of Materials Science **55**, 2257 (2020).
[2] B. J. P. Pernack, M.V. Fistul, I. M. Eremin, Phys. Rev. B **110**, 184502 (2024).

Synchronization in focused He-ion-beam-induced Josephson junction arrays in $YBa_2Cu_3O_7$

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Utilizing focused helium ion beam (He-FIB) irradiation, we can modify the electrical properties of the high T_c superconductor $YBa_2Cu_3O_7$ (YBCO) at the nanoscale. Irradiation of a single line across a microbridge can create a barrier that forms a Josephson junction (JJ) [1]. By varying the irradiation dose, the creation of both JJs and insulating walls is possible. Applying area irradiation on a microbridge can provide YBCO resistors with ohmic behavior. Combining these entities, we realized Josephson junction arrays (JJAs), comprised of two JJs in series. To characterize the individual JJs in transport measurements, we structured an intermediate electrode between the JJs using He-FIB-induced insulating walls. To stimulate the synchronization, we He-FIB-structured a YBCO resistor in parallel to both JJs, working as an LR-shunt. The current-voltage characteristics (IVC) of the JJAs investigated at 4.2 K reveal features related to the coupling of JJs. First, the IVC of the first JJ with smaller I_c shows a back-bending and somewhat irregular behavior near the currents where the second JJ is switching to the voltage state. Second, at larger bias current, the JJs synchronize and the IVC branches stick together, exhibiting an identical voltage drop over a bias current range of 150 µA, indicating identical frequencies of the charge carrier oscillation. These oscillations have a tunable frequency range of 1.14 THz, with frequencies up to 1.40 THz, allowing the potential utilization of JJAs as tunable THz emitters. Our numerical simulations of a two-junction array with a parallel LR-shunt, based on the resistively shunted junction model, reproduced the characteristic back-bending and coupling regions observed experimentally. The simulations revealed a series of 1:n (n=4, 3, 2) synchronization steps, starting in the back-bending region intermixed with regions of incommensurate dynamics, ending in 1:1 synchronization.

References

[1] B. Müller, et al., Phys. Rev. Applied **11**, 044082 (2019).

First-principles quantum model of the resistively shunted Josephson junction

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The classical dynamics of a resistively and capacitively shunted Josephson junction is described by the RCSJ model, a second-order non-linear differential equation.
A straightforward way to include quantum fluctuations is to replace the resistor with an infinite collection of harmonic oscillators, the Caldeira-Leggett Hamiltonian.
Transforming the classical, dissipative RCSJ model with a single degree-of-freedom into a Hamiltonian formulation comes at the cost of introducing infinite degrees of freedom. We show how to reduce the resistor degrees of freedom to obtain an effective single-particle Hamiltonian.
Our quantum RCSJ Hamiltonian corresponds to a fluxonium, a Josephson junction shunted with an inductance $L \approx R^2C$.In the classical limit we recover the role played by the Stewart-McCumber parameter $\beta_c = R^2C/L_J = L/L_J$ in characterizing damping. We use our model to calculate the dispersive shift of a resonator coupled to a resistively shunted Josephson junction.Finally we consider the connection between our model, the Schmid-Bulgadaev transition, and Bloch oscillations.

Non-uniform phases in Ising superconductors

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Ising superconductors are transi0on metal dichalgogenides which can withstand large in-plane external magne0c fields. To a large extent the protec0on of the superconduc0ng state from the external magne0c field comes from the presence of Ising spin-orbit coupling (ISOC). Since ISOC breaks inversion symmetry and not 0me- reversal symmetry (TR) it could protect against an external magne0c field which breaks TR. In this work we study the influence of Rashba SOC on the magne0c field dependence of Ising superconductors and specifically focus on the forma0on of non-uniform phases—such as helical and Fulde–Ferrell–Larkin–Ovchinnikov phases.

Yu Shiba Rusinov states in Ising superconductors

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Magnetic impurities on superconducting surfaces induce so called *"Yu-Shiba-Rusinov"* (YSR) bound states. They have been widely studied using scanning tunnelling microscopy (STM) with substrates made of conventional BCS like superconductors [1].
In this work, we use the emergence of Yu-Shiba-Rusinov (YSR) states from the coupling of single magnetic impurities to so-called *Ising superconductors* [2] to investigate the nature of the superconducting state in two-dimensional transition metal dichalcogenides. We analyze characteristic signatures in the local density of states projected onto the impurity, the spin-resolved density of states, and the Andreev bound state spectrum induced by coupling YSR states to a BCS STM tip. Our results provide new insights into quasiparticle excitations and pairing mechanisms in these unconventional superconductors.

References

1. B. W. Heinrich, J. I. Pascual, and K. J. Franke, *Prog. Surf. Sci.* **93**, 1 (2018).
2. G. Tang et al.: Phys. Rev. Lett. **126**, 237001 (2021)

Electronic Transport in an Atomic Contact under Microwave Irradiation

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We form an atomic contact from a mechanically controlled aluminum break junction and irradiate it with microwaves in its superconducting state [1].
In the $\mathrm{d}I/\mathrm{d}V$-spectra, we observe the well-known structures caused by photon-assisted tunneling, which, in the case of tunnel contacts, are fully explained by the Tien-Gordon (TG) model [2]. However, for higher-order transport processes, the model requires extensions, as shown in simulations based on the TG model [3,4]. Shapiro steps, i.e., replicas of the supercurrent, reveal deviations from the theoretical predictions described in references [5,6]. However, both effects can be observed in Figure 1.
Fractional Shapiro steps, which we observe in atomic contacts with high-transmission channels at high frequencies, differ from traditional Shapiro steps and represent a new phenomenon.

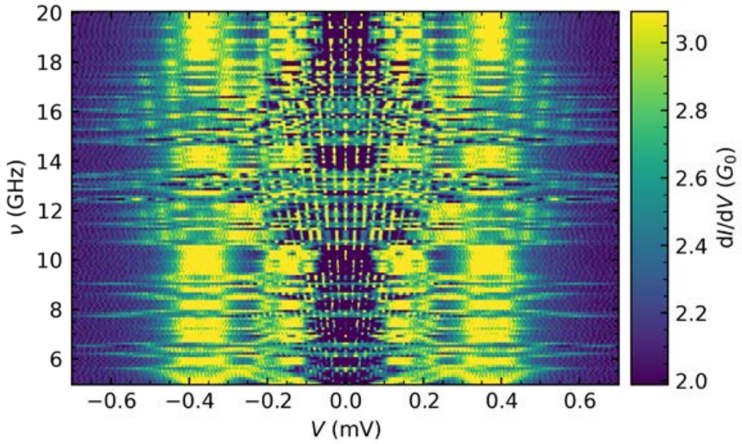

Figure 1: Differential Conductance ($\mathrm{d}I/\mathrm{d}V$) as a function of bias voltage (V) and microwave frequency (ν). The color scale represents the conductance in units of conductance quanta (G_0), with dark blue indicates lower conductance ($\sim 2G_0$) and bright yellow indicated higher conductance ($\sim 3G_0$). The pincode of the contact is given by $\tau = \{0.80,\ 0.63,\ 0.33, 0.25, 0.01\}$. Horizontal irregularities are due to experimental reasons, such as variing temperature ($100 - 200\mathrm{mK}$) and fluctuations in irradiation power.
Vertical features at $\pm 380\mu\mathrm{V}$ correspond to quasi-particle tunneling at 2Δ, while those at $\pm 190\mu\mathrm{V}$ are attributed to Andreev reflection at $2\Delta/2$. At zero bias, the presence of a Josephson current is observed. Inclined features following $eV_n = 2\Delta \pm n\nu h$ indicate to photon-assisted tunnelling, while those at $eV_n = \pm n\nu h$ correspond to Shapiro steps.

References

[1] P. Raif, Master Thesis, *Uni. Konstanz* (2024),
[2] P. K. Tien & J. P. Gordon, PR **129**, 647 (1963),
[3] P. E. Gregers-Hansen et al., PRL **31** 524 (1973),
[4] J.C. Cuevas et al., PRL **88**, 157001 (2002),
[5] G. Falci, V. Bubanja & G. Schön, Z. Phys. **85**, 451 (1991),
[6] P. Kot et al., PRB **101**, 134507 (2020).

Microwave Characterization of Josephson Junction Arrays Tailored in Al/InAs Heterostructures

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We present microwave characterization measurements of Josephson junction arrays (JJAs) fabricated on epitaxial Al/InAs heterostructures. By probing the low-energy plasmon modes of the arrays, we have direct access to the inductive contribution of the junctions and are able to determine useful parameters like the induced gap in the 2DEG hosted in the heterostructure. Due to the width of the junctions, the Josephson inductance is modulated in out-of-plane magnetic field. This gives rise to a Fraunhofer-like interference pattern observed in the single tone spectrum, the shape of which can be used to probe the effective current-phase relation. We were able to fit the Fraunhofer pattern of the plasmonic modes with an effective transparency $\tau=0.94$, which is in agreement with the high transparency Andreev-bound-states (ABS) reported in similar SNS junctions. JJAs can be used to achieve high inductances, suitable for the implementation of quantum circuits. They also provide an excellent test-bed for studying the interplay between the microscopic fermionic excitations of the Andreev spectrum and the plasmonic modes.

Gate-controlled switching in non-centrosymmetric superconducting devices

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Gate-controlled superconducting devices have become of great interest for the development of energy-efficient hybrid superconductor/semiconductor computing architectures. The idea behind this technology stems from the recent discovery that superconducting devices can be controlled electrically by applying a gate voltage [1, 2].

We investigate gate-controlled supercurrent (GCS) devices made of the non-centrosymmetric superconductor $Nb_{0.18}Re_{0.82}$ [3] and compare their performance with Nb-based devices, which are well-documented in the literature [4], to study the material dependence of the GCS effect. Our findings indicate that $Nb_{0.18}Re_{0.82}$-based devices perform better due to two key factors: they require lower switching power, and they achieve a higher output voltage due to their increased normal-state resistance, enhancing compatibility with existing CMOS technology.

References

[1] G. De Simoni et al., Metallic supercurrent field-effect transistor. *Nature Nanotech* **13**, 802-805 (2018)

[2] L. Ruf et al., Gate control of superconducting current: Mechanisms, parameters, and technological potential. *Appl. Phys. Rev.* **11**, 041314 (2024)

[3] J. Koch et al., Gate-controlled supercurrent effect in dry-etched Dayem bridges of non-centrosymmetric niobium rhenium. *Nano Res.* **17**, 6575–6581 (2024)

[4] L. Ruf et al., High-Performance Gate-Controlled Superconducting Switches: Large Output Voltage and Reproducibility. *ACS Nano* **18**, 31, 20600–20610 (2024)

Proposal for Realizing Feynman's Ratchet with a Josephson Diode

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(Dated: April 2025)

Nonreciprocity has attracted significant attention in recent years. Notably, a nonreciprocal version of the Josephson effect, known as a superconducting diode, has been experimentally demonstrated. In this work, we propose that a superconducting diode, when inductively coupled to a secondary circuit at a different temperature, naturally realizes Feynman's ratchet. Specifically, we show that this system can function as a heat engine by forming a specific current phase relation in the superconducting diode using some recent advances [1]. We compute the efficiency and Seebeck coefficient of this thermoelectric device, and we further investigate the conditions under which the system operates in reverse, acting as a Peltier cooler.

[1] A. M. Bozkurt, J. Brookman, V. Fatemi, and A. R. Akhmerov, SciPost Physics **15**, 204 (2023).

Van der Waals Superconductors integrated Hybrid microwave resonators

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Superconducting microwave resonators are highly coherent devices that are extensively used in quantum circuits. Their robustness and sensitivity also make them excellent probes for exploring novel materials, which are coupled to them in a hybrid system. Particularly good candidates are van der Waals materials, whose microscopic size makes them incompatible with conventional bulk measurement methods. However, such hybrid platforms require the development of a new process to maintain the high quality of the circuit. We present a technique to integrate a microwave resonator with a superconducting thin van der Waals flake with a crystalline-preserved pristine interface. We utilize a cryogenic dry transfer method for preserving structural integrity of the vdW flake. We investigate their microwave response as a function of temperature under various microwave powers. The hybrid resonator exhibits a significant modification in its resonant mode with the presence of the flake while maintaining a high-quality factor. Hybrid superconducting circuits integrated with vdW crystals offer an extensive potential in probing materials' unique properties and for developing high-quality devices for quantum technology.

References

[1] H. Jin, et al., Nano Letter **25**, 8, 3191-3198 (2025)

Magnetically tunable supercurrent in dilute magnetic topological insulator based Josephson junction

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In the ground state of a Bardeen-Cooper-Schrieffer superconductor, current is carried by Cooper pairs with zero total spin and momentum. Through magnetic influence on spins in a superconductor, a new ground state called Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) [1,2] with finite pair-momentum may appear. This state is characterized by a spatially oscillating order parameter. In this work we show for the first time that such a state can be induced by proximity effect when coupling a conventional superconductor to a two-dimensional dilute magnetic topological insulator [3]. In our experiment, the existence of the state is confirmed by the observation of supercurrent reentrance effects as a function of both magnetic field and temperature.

The device comprises of superconducting MoRe leads side-contacting a Mn doped HgTe quantum well with device size below electron mean free path. The incorporation of Mn atoms creates a giant Zeeman effect allowing enhanced tunability of the magnetic state [4]. Mn substitute Hg atoms isoelectrically, thus retaining high carrier mobility. Dilute magnetic topological insulators combined with superconductors are thus a promising platform to explore emergent spin-correlated supercurrent transport in two dimensions and edge modes. The experimental parameter space is carefully explored using a 3D vector magnet with negligible remnant field. Our architecture, with a semiconductor weak link, allows access to the mesoscopic transport regime and easy external tunability of the effect. This provides the experimenter tools to control the phase difference across the superconductors.

References

[1] P. Fulde and R. A. Ferrell, *Physical Review* **135**, A550 (1964).
[2] A. Larkin and Y. N. Ovchinnikov, *Soviet Physics-JETP* **20**, 762 (1965). [Zh.Eksp.Teor.Fiz. 47, 1136 (1964)].
[3] P. Mandal, S. Mondal, M. P. Stehno, S. Ilić, F. S. Bergeret, T. M. Klapwijk, C. Gould, L. W. Molenkamp, *Nature Physics*, **20**, 984-990 (2024).
[4] K. Furdyna, *Journal of Applied Physics* **64**, R29 (1988).

Josephson Diode Effect in the Presence of Interfacial Spin-Orbit Coupling in All-Metallic Planar Junctions

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In recent years, an interest in Josephson junction devices on weak links featuring strong spin-orbit coupling has emerged due to potential insights into the interaction between dissipationless charge transport by Cooper pairs and spin-orbit coupling.

Previous experimental studies of such systems have, among others, indicated that the zero-flux state of a junction may be reached at finite magnetic fields before sweeping across the zero-field point. These findings point towards an interplay of the Cooper pairs and the spin accumulation caused by the Rashba Edelstein effect inside the junction. [1,2,3]

Here we present the observation of a similar inverted hysteresis in the Fraunhofer patterns of a non-magnetic Josephson junction under the application of a magnetic field. When changing to an in-plane field, a Josephson Diode Effect is observed that depends on the angle between the current across the junction and the magnetic field. Control experiments suggest that the presence of a Rashba interface is necessary for the effects to occur, underlining the importance of spin-orbit coupling in the junction.

References

[1] Senapati *et al., nat. comm.* **14**, 7415 (2023)

[2] Nakamura *et al., PRL* **122**, 107001 (2019)

[3] Jeon *et al., nat. mater.* **21**, 1008-1013 (2022)

Interfacial spin-orbit coupling in superconducting hybrid systems

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We investigate the effects of interfacial spin-orbit coupling (ISOC) [1,2] on superconductors, focusing on its impact on electronic transport and spin-charge conversion. Using a symmetry-based nonlinear sigma model [3], we derive effective boundary conditions for the Usadel and Maxwell equations that account for spin-galvanic effect, spin relaxation, and spin precession. This approach allows for the analysis of various interfaces without relying on specific microscopic models. We apply these boundary conditions to derive ISOC-induced terms in the Ginzburg-Landau functional, which is then used to compute the critical temperature of superconducting films with ISOC subjected to an external magnetic field. Our findings show that, contrary to a recent prediction, the critical temperature of a film cannot be enhanced by an external magnetic field. Additionally, we demonstrate that the combination of ISOC and an external magnetic field leads to a superconducting diode effect. Its efficiency strongly depends on the interplay between the spin-galvanic and the spin relaxation terms. Our results provide a framework for understanding ISOC in superconducting systems and highlight the potential for optimizing diode efficiency through careful interface engineering. This talk is based on the article [4].

[1] Sanz-Fernández, C., Pham, V. T., Sagasta, E., Hueso, L. E., Tokatly, I. V., Casanova, F., & Bergeret, F. S. (2020). Quantification of interfacial spin-charge conversion in hybrid devices with a metal/insulator interface. *Applied Physics Letters*, *117*(14).
[2] Groen, I., Pham, V. T., Ilić, S., Chuvilin, A., Choi, W. Y., Sagasta, E., ... & Casanova, F. (2023). Emergence of large spin-charge interconversion at an oxidized Cu/W interface. *Physical Review B*, *107*(18), 184438.
[3] Kokkeler, T., Tokatly, I., & Bergeret, F. S. (2024). Nonreciprocal superconducting transport and the spin Hall effect in gyrotropic structures. *SciPost Physics*, *16*(2), 055.
[4] Mazanik, A. A., Kokkeler, T., Tokatly, I. V., & Bergeret, F. S. (2025). Interfacial spin-orbit coupling in superconducting hybrid systems. *arXiv preprint arXiv:2502.10911*.

Fast thermometry with SNS junctions at cryogenic temperatures

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Understanding nanoscale heat transport is essential for quantum device optimization and the study of hybrid quantum materials. Conventional temperature measurement methods are often limited by long thermal equilibration times, restricting access to transient thermal effects. To overcome this, we employ a Superconducting-Normal-Superconducting (SNS) junction-based fast thermometry technique, enabling nanosecond-scale temperature sensing.

The SNS junction relies on proximity-induced superconductivity, where the switching current (ISW) depends strongly on temperature. Instead of relying on a single-shot critical current measurement, which suffers from stochastic fluctuations, we employ a pulse-based probabilistic switching detection method. A probe current pulse near ISW determines whether superconducting to normal state phase transition occurs, with a readout current detects the voltage state. By repeating this process, we achieve A) nanosecond pulse resolution, which greatly improving time precision, and B) the switching probability vs. current that provides statistically robust temperature measurements.

Fabrication involves electron beam lithography and sputtering, forming MoRe/Au/MoRe junctions with well-defined superconducting leads. By applying controlled nanosecond-scale current pulses, we achieve precise thermometry at 10-300 mK under a 20 mT magnetic field, reducing the typical millisecond response time of conventional techniques to the nanosecond regime.

This method provides a powerful tool for investigating quasiparticle relaxation, electron-phonon interactions, and heat diffusion in superconducting quantum circuits. Its ability to capture transient thermal effects with high precision makes it particularly suited for probing non-equilibrium thermal dynamics in hybrid quantum materials.

References

[1] M. Zgirski et al. Phys. Rev. Applied 10, 044068 (2018)
[2] S. Volosheniuk et al. Appl. Phys. Lett. 122, 10. (2023)
[3] M. Zgirski et al. Phys. Rev. B. 104, 014506 (2021)

Quantum-Geometric Spin- and Charge Josephson Diode Effects

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Long-range equal-spin triplet supercurrents induced by nontrivial spin textures are of fundamental importance both for the understanding and the applications of superconducting spintronics. In this work [1], we investigate the effect of the noncoplanarity of the magnetizations in a Josephson junction consisting of a strongly spin-polarized ferromagnet (sFM) connected to two BCS superconductors by ferromagnetic insulating barriers [see Fig.1(a)].

A noncoplanar spin texture together with spin filtering effects create a quantum-geometric phase $\Delta\varphi = \varphi_2 - \varphi_1$, which enters the current-phase relation in a very similar manner to the superconducting phase difference, consequently modifying it.

Our theory predicts a large charge Josephson diode effect with an efficiency of 33% [see Fig.1(b)] and a perfect spin diode effect with 100% efficiency [see Fig. 1(c)]. The appearance of these effects crucially depends on two conditions: (i) a noncoplanar profile of the three magnetization vectors in the system and (ii) different densities of states of the spin-up and spin-down bands in the sFM. Further insights are obtained by a harmonic decomposition of the Josephson current in both the superconducting and the quantum-geometric phase difference.

Finally, we show that a SQUID geometry of the mentioned junction allows for a switch of almost completely spin-polarized supercurrents across the ferromagnet by reverting the applied magnetic flux.

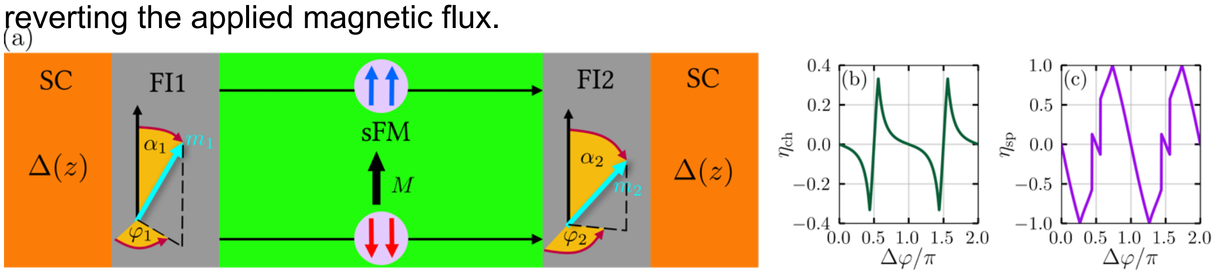

Figure 1: (a) A scheme of the junction under study consisting of a strongly spin-polarized ferromagnet (sFM) connected to two BCS superconductors (SC) via two ferromagnetic insulating interfaces (FI1/2). The interface magnetic moments $(m_{1,2})$ point in arbitrary directions with respect to the magnetization in the sFM characterized by spherical angles (α_i, φ_i). The charge (b) and the spin diode efficiency (c) as a function of the quantum-geometric phase difference $\Delta\varphi = \varphi_2 - \varphi_1$ [1].

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References

[1] N. L. Schulz, D. Nikolić, and M. Eschrig, arXiv:2501.11751; arXiv:2501.12232 (2025).

Multiterminal Josephson Junctions: non-hermiticity, topology and reflectionless modes

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In multiterminal Josephson junctions (MTJJs), the Andreev bound state energies depend on multiple phase differences, enabling band structure engineering with external flux control. This tuneability offers unique controllability of the momentum-like phases, which grants insight into unique transport processes as well as phase transitions. MTJJs are predicted to host non-trivial topological phases and associated Weyl nodes in the synthetic Brioullin zone spanned by these superconducting phases [1].

We predict that such MTJJs, in the presence of additional normal leads, host non-trivial non-Hermitian topology, leading to spectral topology in the form of point gaps and Weyl disks [2].

Additionally, we predict that reflectionless scattering modes in MTJJs are a source of topological phase boundaries [3]. Our work provides an effective bulk boundary correspondence by demonstrating a relationship between unity transmission modes and boundaries between topologically trivial and non-trivial regions, like in quantum Hall systems.

References

[1] R.-P. Riwar, et. al., Nature Commun. 7, 1 (2016)
[2] D. C. Ohnmacht, et. al., arXiv:2408.01289 (2024) (accepted in PRL)
[3] D. C. Ohnmacht, et. al., arXiv:2503.10874 (2025)

Josephson diode effect from Cooper pair momentum in a topological semimetal

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The absence of time reversal and inversion symmetries can impart a finite non-zero momentum to Cooper pairs in a superconductor [1]. Such unconventional pairing is predicted to give rise to a plethora of intriguing ground states such as spin triplet and topological superconductivity, gapless superconductivity with segmented Fermi surface, and Majorana bound states [1-3]. Recent calculations predict that such mechanism can stabilize yet another exotic non-reciprocal superconducting ground state where a unidirectional flow of supercurrent can be realized making them technologically relevant. Here we demonstrate a polarity dependent large asymmetry in critical currents in the presence of a small field in a Josephson junction fabricated using a type-II Dirac semimetal $NiTe_2$. We provide strong experimental evidence in conjunction with a phenomenological model that the observed 'Josephson diode effect' (JDE) is enabled by finite momentum Cooper pairing in the spin-split topological surface states, in an otherwise centrosymmetric system [4]. The observation of such a giant JDE and the proposed underlying mechanism to understand the physics behind brings us closer to a long-standing goal of building nonreciprocal superconducting electronics.

References

[1] M. Eschrig, Rep. Prog. Phys. **78**, 104501 (2015)
[2] Z. Zhu et al. Science **374**, 1381 (2021)
[3] C. Qu et al. Nat. Commun. **4**, 2710 (2013)
[4] B. Pal et al. Nat. Phys. **18**, 1228 (2022)

Engineering quantum states in radical molecules on superconducting surfaces

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We present a study of molecular assemblies formed by tetrabromo-tetraazapyrene radicals on a Pb(111) superconducting substrate [1]. Employing scanning tunneling spectroscopy and advanced theoretical modeling based on the superconducting Anderson impurity model, we explore the emergence and manipulation of Yu-Shiba-Rusinov (YSR) states. We demonstrate tip-induced quantum phase transitions in isolated molecules, switching between singlet and doublet ground states. Furthermore, we reveal the tunability of YSR states in molecular dimers through controlled variations in intermolecular distance and orientation. Finally, we showcase the formation of molecular chains exhibiting alternating charge states, which can be manipulated by external electric fields, suggesting potential for information storage. Our findings establish these molecular assemblies as versatile building blocks for future superconducting molecular quantum technologies, highlighting their potential for tailored quantum functionalities.

References

[1] C. Li, V. Pokorný, M. Žonda, J.-C. Liu, P. Zhou, O. Chahib, T. Glatzel, R. Häner, S. Decurtins, S.-X. Liu, R. Pawlak, and E. Meyer, ACS Nano **19**, 3403 (2025).

Coherent control of a carbon nanotube-based gatemon qubit

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The standard transmon qubit may be modified by using a Josephson junction based on a quantum conductor with few well-transmitted channels instead of a tunnel junction. Via a gate the electronic properties and thus qubit frequency become tunable. Previous works have shown coherent measurements in such gatemon qubits with nanowire or graphene-based junctions. We present a qubit design using as junction material an ultraclean single carbon nanotube, an intrinsically one-dimensional conductor, within a hybrid cQED architecture. The measured gate-dependent qubit spectrum exhibits clear features associated with charge parity change of the fermionic Andreev bound states that are at the heart of the Josephson effect in the carbon nanotube. Going further, we demonstrate coherent control of this gatemon qubit through Rabi and Ramsey protocols, with coherence times up to 200 ns. Our investigation shows a strong gate dependence of the coherence time and we identify charge noise as a limiting factor. This work paves the path towards coherent manipulation of superconducting fermionic qubits in carbon nanotubes.

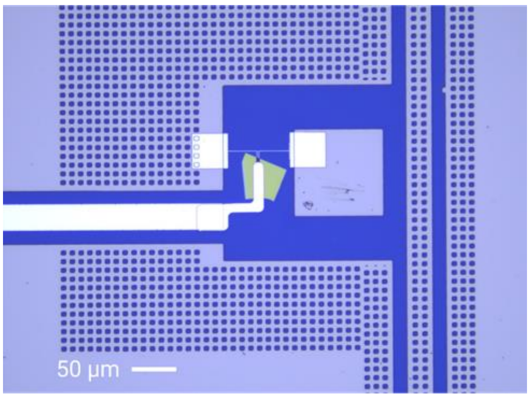

Figure 1: Optical micrograph of carbon nanotube transmon qubit coupled to a coplanar waveguide (on the right) and a gate (towards the left).

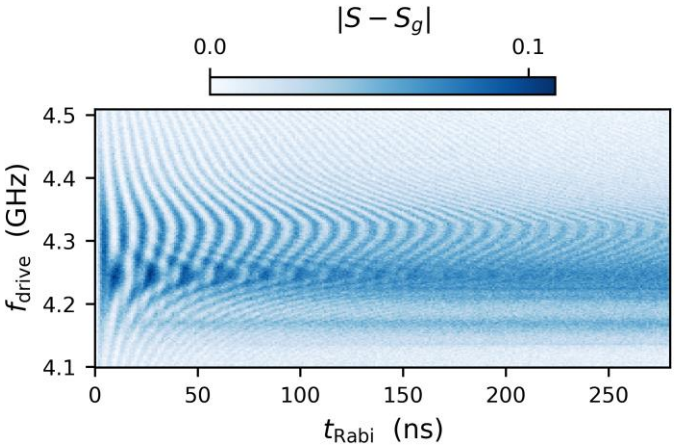

Figure 2: Rabi oscillations around qubit frequency at 4.32GHz and Rabi oscillations to the second excited state in two-photon process at 4.25GHz.

Probing strongly correlated quantum systems with hybrid SQUID-on-tip imaging

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Describing the physics of strongly correlated quantum systems requires investigating the interplay between dissipation, magnetism and electronic structure. Probing their correlations is a major challenge, as most microscopes measure only one parameter at a time. Our lab develops hybrid microscopy techniques that simultaneously visualize multiple critical variables; by combining SQUID-on-tip (SOT) with atomic force microscopy (AFM) we can simultaneously image magnetic flux, electrical currents and dissipation.

SQUID-on-tip microscopy is a powerful scanning probe technique where a nanostructured superconducting sensor is directly scanned over the surface of a sample. This microscopy technique acquires both magnetic and thermal images at the same time. [1] This enables the study of charge transport, dissipation and magnetism. SQUID-based microscopy has already been successfully applied to imaging vortex matter, quantum phase fluctuations and electron hydrodynamics. However, its traditionally poor height control strongly limits both sensitivity and usefulness for the study of nanostructured devices. In our lab, we solve these problems by combining SQUID-on-tip with atomic force microscopy (AFM). This allows us to fully explore quantum devices, while the accurate height-control of AFM increases our sensitivity.

Here I will present the first results of our SQUID-on-tip microscope. After demonstrating the technique, I will show the first applications to strongly correlated electron systems, where our microscope offers immediate new insight into their underlying physics. Our approach to SQUID-on-tip will allow for versatile studies of quantum phase transitions, time-reversal symmetry breaking, and novel transport phenomena.

References

[1] Halbertal, D., Cuppens, J., Shalom, M. *et al.* Nanoscale thermal imaging of dissipation in quantum systems. *Nature* **539**, 407–410 (2016).

Superconducting non-volatile memory based on charge trapping and gate-controlled superconductivity

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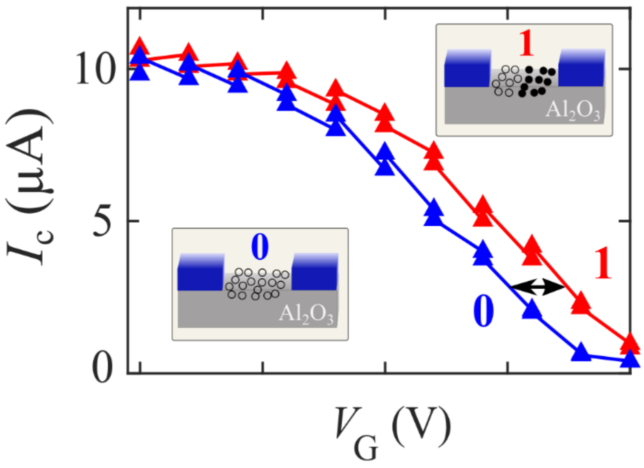
Gate-controlled supercurrent (GCS) is an emerging and highly debated research field. In gated three-terminal Ti and Al devices, it was found that supercurrents can be modulated by the application of a gate voltage. The authors attributed their findings to a direct electric field effect [1]. However, other studies suggest a leakage-related effect, such as high-energy electron emission [2], phonon-induced heating [3], and out-of-equilibrium states from phonons or high-energy electrons [4]. Here, we study the GCS in Dayem bridges on industrial-grade SiO_2 and Al_2O_3 substrates. Our results demonstrate a strong correlation between the substrate material and the GCS parameters. Notably, we observe that charge trapping in the gate dielectric, Al_2O_3, affects the voltage threshold required to suppress the supercurrent in our device [5]. In a proof of concept, we demonstrate how we can switch reversibly between two defined charge-trapping states, associated to two critical currents. Further, we discuss the advantages of our memory prototype in NOT AND (NAND) layouts.



References

[1] D. Simoni et al., Nat. Nanotechn.13, 802 (2018)
[2] L. Alegria et al., Nat. Nanotechn.16, 404 (2021)
[3] M. Ritter et al., Nat. Electron. 5, 71 (2022)
[4] J. Basset et al., Phys. Rev. Res. 3, 043169 (2021)
[5] L. Ruf et al., arXiv:2503.17241(2025)

Andreev Molecules at distance

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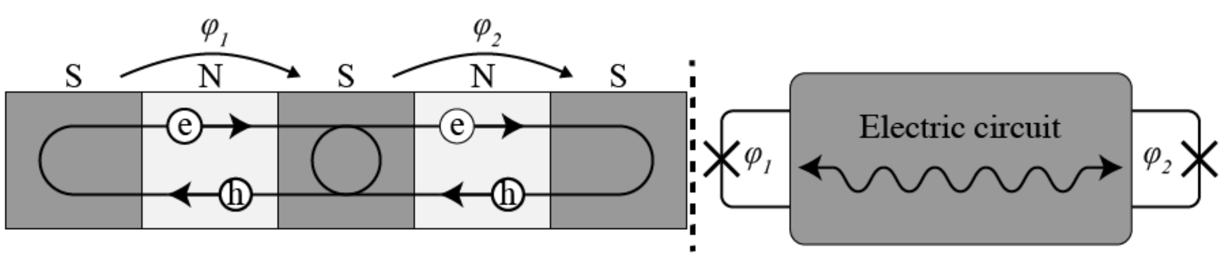
Andreev molecule states arise in systems where Andreev Bound states in different Josephson Junctions hybridize, hosting exotic physics such as the non-local Josephson effect [1]. The hybridization is commonly induced by coupling two Josephson Junctions in proximity by a shared superconducting lead that facilitates coherent cooper pair tunneling between the junctions (see left figure). A recent experiment has demonstrated the possibility of coupling Andreev level qubits over longer distances through a superconducting resonator [2]. We propose to realize more general Andreev molecule physics in a similar setup, where Josephson junction loops, hosting Andreev level qubits, are hybridized through photon exchange via a general electric circuit (see right figure). Solving the associated Lindblad equation that generates the dissipative real time dynamics of the system we identify relevant regimes where the Andreev level qubits hybridize and show that this is accompanied by a mutual inductance between the junctions, demonstrating the non-local Josephson effect.



References

[1] D. Z. Haxell et al., Nano Letters **23**, 7532 (2023)
[2] L. Y. Cheung et al., Nature Physics **20,** 1793 (2024)

2D HgTe Topological Insulator Josephson Junction Integrated in Superconducting Charge Qubit Circuits Using Flip-Chip Technique

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One of the most fascinating predictions when combining a topological insulator (TI) with a superconductor (S) is the emergence of Majorana zero modes at their interface - an essential ingredient for realizing topologically protected quantum computation.[1] However, clear experimental evidence for these Majorana modes remains elusive, and researchers worldwide are exploring different approaches to detect their signatures.

A promising route involves integrating S-TI-S junctions into superconducting charge qubit circuits and employing circuit quantum electrodynamics (cQED) techniques for readout. These qubits, known as Majorana transmons, are expected to exhibit distinct signatures of Majorana quasiparticles. One notable prediction is the appearance of additional qubit transitions resulting from parity state hybridization.[2,3] Additionally, the critical current of a TI-based junction is gate-tunable, enabling frequency control of these qubits via electrostatic gating.

Motivated by these prospects, we focus on utilizing hybrid S-TI Josephson junctions to realize superconducting charge qubits. Here, I will present the use of the 2D TI HgTe as junction material, which offers gate-tunable critical current and eliminates the need for an external magnetic field to reach the topological phase – different than in 3D TI nanowires. This transition to HgTe is accompanied by a shift in our standard qubit fabrication process to a flip-chip approach, which decouples the fabrication of the cQED resonator structure from that of the S-TI junction. This method enables the independent fabrication of high-Q resonators for enhanced readout, as well as high-quality S-TI junctions, thereby advancing the development of TI-based superconducting qubits.

References

[1] A. Cook and M. Franz, Phys. Rev. B, **84**, 201105 (2011).
[2] E. Ginossar and E. Grosfeld, Nat. Commun. **5**, 4772 (2014).
[3] K. Yavilberg, E. Ginossar, and E. Grosfeld, Phys. Rev. B, **92**, 7 (2015).

Gate tunable superconductivity in Al/STO hybrid structures

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We present a systematic study of the gate-tunable superconducting properties of aluminum (Al) thin films epitaxially grown on strontium titanite (STO) substrates. As a quantum paraelectric, STO exhibits an exceptionally high dielectric constant ($\varepsilon \approx 7000$), enabling significant charge modulation at the Al/STO interface. By applying a back-gate voltage, the superconducting critical temperature T_C and the critical magnetic field B_C of Al can be significantly changed, with observed variations of up to ±15% and ±50%, respectively. Notably, the observed T_C values (approx. 0.92 – 1.06 K) are lower than those of pristine Al thin films (≈1.4 K) but exceed those of STO.

We also investigated the superfluid stiffness and find a substantial bipolar gate dependence with variations of up to ±15%. Additionally, measurements of the vortex inductance reveal anisotropic behavior in nearly in-plane magnetic field. Furthermore, when a DC current is superimposed on the AC signal, we observe signatures suggesting an intrinsic supercurrent diode effect in the non-linear inductance.

These results underline the potential of the Al/STO heterostructure as a versatile platform for exploring the gate-tuning of superconducting properties.

$[(SnSe)_{1+\delta}]_m[NbSe_2]_1$ superlattices in the 2D to 3D crossover regime of superconductivity

Linus P. Stahlberg[1], Wieland G. Stoffel[1], Tom Herter-Lehmann[1], Willi Vallant[1], Alina Dietrich[1], Olivio Chiatti[1], Danielle Hamann[2], David C. Johnson[2], and Saskia F. Fischer[1,3]

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Understanding and controlling the coupling between superconducting layers in van der Waals superlattices is key to engineering their electronic properties [1]. We investigate designed superlattices where superconducting $NbSe_2$ monolayers are embedded in semiconducting SnSe spacer layers. In these structures, turbostratic disorder allows for atomically precise stacking and fine-tuned interlayer coupling [2]. This enables scanning through a large region in the 2D to 3D crossover between characteristics of monolayer and bulk superconductors. Hence, we can systematically determine key parameters for the interlayer coupling in these systems, like the Ginzburg-Landau coherence lengths. By comparing these to the sample dimensions we explain the vortex dynamics leading to the occurance of low-dimensional effects, like phase slips and BKT transtions. Furthermore, a large magnetoresistance hysteresis and a significant increase of the sample capacitance motivates the interpretation as a superconductor-insulator transition with increasing $NbSe_2$ interlayer spacing. These findings provide new insights into the interlayer coupling mechanisms in van der Waals superconductors and their impact on low-dimensional effects in superconductivity.

References

[1] Chiatti *et al.*, J. Phys.: Condens. Matter **35**, 215701 (2023)
[2] Grosse *et al.*, Sci. Rep. **6**, 33457 (2016)

Tunneling spectroscopy on superconducting thin films of non-centrosymmetric niobium rhenium

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In recent years, non-centrosymmetric superconductors have attracted increasing attention as they reveal various properties of unconventional superconductivity. With the absence of inversion symmetry and an asymmetric Rashba-type spin-orbit coupling (SOC) a mixed spin-singlet and spin-triplet pairing state is predicted in these materials. In our study, we focus on the non-centrosymmetric compound $Nb_{0.18}Re_{0.82}$, whose superconducting order parameter remains under debate [1,2,3]. Its favorable combination of material properties such as structural disorder, strong SOC and relatively high critical current densities makes NbRe an promising candidate for applications in superconducting single-photon detection (SSPD) and gate-controlled supercurrent (GCS) devices [4,5]. We present low-temperature scanning tunneling microscopy measurements (STM) on polycrystalline NbRe fabricated by DC magnetron sputtering. Using high-energy resolution N-I-S spectroscopy, we probe the local density of states in thin films of varying thickness and crystallinity to gain insights into the intrinsic pairing symmetry of the superconductor.

References

[1] Z. M. Kakhaki et al., Beilstein J. Nanotechnol. 14, 45 (2023)
[2] C. Cirillo et al., Supercond. Sci. Technol. 36, 074001 (2023)
[3] C. Cirillo et al., PRB 94, 104512 (2016)
[4] C. Cirillo et al., Sci. Rep. 14, 20345 (2024)
[5] J. Koch et al., Nano Res. 17, 6575 (2024)

Quantum circuits with Multiterminal Josephson-Andeev junctions

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We explore superconducting quantum circuits where several leads are simultaneously connected beyond the tunneling regime, such that the fermionic structure of Andreev bound states in the resulting multiterminal Josephson junction influences the states of the full circuit. Using a simple model of single channel contacts and a single level in the middle region, we discuss different circuit configurations where the leads are islands with finite capacitance and/or form loops with finite inductance. We find situations of practical interest where the circuits can be used to define noise protected qubits, which map to the bifluxon and 0-pi qubits in the tunneling regime. We also point out the subtleties of the gauge choice for a proper description of these quantum circuits dynamics.

References

[1] F.J. Matute-Cañadas, L. Tosi, and A. Levy Yeyati, PRX Quantum 5, 020340 (2024)

Resistively shunted Josephson junction in the quantum regime

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We perform spectroscopy of resistively shunted Josephson junctions in a superconducting circuit QED experiment. We investigate a range of parameters for the junction impedance EJ/EC ≈ 0.1-10, covering the Cooper-pair box to the light transmon. The galvanically connected resistive shunt R is varied over several orders of magnitude, R ≈ 0.01-100 RQ, where RQ = h/(2e)2 ≈ 6.5 kΩ. Our setup avoids issues of previous experiments including Joule heating, DC noise, and implementation of a resistor as a finite transmission line. The data hints at a new phase diagram for the damped Josephson junction and disagrees with the prediction by Schmid-Bulgadaev of an insulating state for R >> RQ. Our phase diagram approaches that of the damped harmonic oscillator for EJ >> EC and deviates from it for EJ ≤ EC. We clarify the role of a dissipative high impedance element on the dynamics of a Josephson junction in the quantum regime and set the stage for a better understanding of phenomena such as dual Shapiro steps, also known as Bloch oscillations.

Superconductor-altermagnet heterostructures with nonmagnetic impurities

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Altermagnetism is an ordered magnetic phase with zero net magnetization and momentum-dependent spin-split Fermi surface that has only recently been discovered [1]. Proximity effects between superconductors (S) and altermagnets (AM) occur similarly to ferromagnets [2], but include this momentum dependence. In most cases when studying such effects, impurities are assumed to be negligible (clean limit) [3,4], which is not necessarily the case in experimental settings. The goal of this work is to study this proximity effect of the altermagnetic spin-split and resulting modification of the properties of singlet superconductors in an S/AM bilayer. The focus lies on the effect of non-magnetic impurities on the order parameter and the density of states, both of which are self-consistently calculated using the quasiclassical Green's function theory. A range of effects are observed, including gapless superconductivity and an impurity-enhanced critical temperature.

References

[1] L. Šmejkal et al, Phys. Rev. X **12,** 040501 (2022).
[2] A. I. Buzidn, Rev. Mod. Phys. **77**, 935 (2005); M. Eschrig, Rep. Prog. Phys. **78**, 104501 (2015).
[3] S. Chourasia et al, arXiv:2403.10456
[4] M. Wei et al, Phys. Rev. B **109**, L201404 (2024).

Nontrivial critical phenomena in the single layer graphene proximitized by a disordered superconductor InO

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Unlike in real granular superconducting systems, emergent superconducting grains have been observed within a morphologically uniform film of Indium Oxide (InO), embedded in an insulating matrix. Tuning the grain sizes and the internal Josephson coupling drive the thin film to achieve a superconductor to insulator transition (SIT). Granular superconductivity is induced from InO into graphene, a two-dimensional diffusive metal, through the superconducting proximity effect. This could enable a superconducting transition and its critical temperature and current in the heterostructure controlled by a gate voltage manipulation. In this talk, I will present the intriguing experimental results obtained from the electronic transport and differential resistance measurements with a back gate control were performed on the graphene/InO heterostructure. Additionally, I will discuss the connection between charge carrier density and superconductivity, then explore possible mechanisms for nontrivial phenomena in superconducting critical properties.

Superconducting proximity effect in semiconducting nanowires with ferromagnetic-insulator barriers

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(Dated: March 28, 2025)

We report transport studies of triple-hybrid Josephson junctions based on semiconducting InAs nanowires grown with fully overlapping epitaxial ferromagnetic-insulator EuS and superconductor Al shells. Current transport measurements display a hysteretic superconducting window around the coercive field of the ferromagnet with a sizable supercurrent, accompanied by multiple Andreev reflections. Tunneling spectroscopy reveals a superconducting gap characterized by three coherence peaks. We attribute these findings to exchanged-induced spin splitting combined with spin mixing due to spin-orbit coupling. The realization of proximity-induced superconductivity in a semiconductor through a ferromagnetic insulator opens new avenues for exploring synthetic spin-triplet pairing.

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