Superconductivity in Low-Dimensional and Interacting Systems

697. WE-Heraeus-Seminar

03 - 06 June 2019
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 697. WE-Heraeus-Seminar:

The field of mesoscopic superconductivity has seen several important developments in the recent years. The Seminar aims at gathering leading experts and young researchers on highly topical activities in the field of mesoscopic superconductors, including among others

- Spin-polarized superconductors
- One-dimensional and two-dimensional superconductors
- Systems with spin-orbit interaction
- Superconductor semiconductor hybrids
- Granular superconductors
- Artificial topological systems
- Thermal transport in superconducting systems
- Thermoelectric effects
- Superconductor-insulator transitions

The organizers encourage in particular young researchers to present their results in short talks and posters and to take advantage of the ample of time to get deeper into the field and to discuss their findings among each other and with the more senior speakers and participants.

The three best poster presentations of the seminar will be awarded a prize. All speakers and participants will be members of the jury and are highly encouraged to vote for the poster prize.

Scientific Organizers:

Prof. Dr. Elke Scheer	Universität Konstanz, Germany E-mail: elke.scheer@uni-konstanz.de
Prof. Wolfgang Belzig	Universität Konstanz, Germany E-mail: wolfgang.belzig@uni-konstanz.de
Prof. Christoph Strunk	Universität Regensburg E-mail: christoph.strunk@physik.uni-regensburg.de

Program

Program

Sunday, 02 June 2019

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

Monday, 03 June 2019

08:00	*BREAKFAST*	
09:15 – 09:20	Scientific organizers	**Opening**
09:20 – 09:55	Yoichi Ando	**Quest for topological superconductivity**
09:55 – 10:30	Hervé Aubin	**Spin-orbit induced phase-shift in Bi_2Se_3 Josephson junctions**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:35	Yuli Nazarov	**Topological properties of multi-terminal superconducting nanostructures: effect of a continuous spectrum**
11:35 – 12:10	Fabrizio Nichele	**Evidence of topological superconductivity in planar Josephson junctions**
12:10 – 12:15	**Conference Photo** (in the front of the lecture hall)	
12:15 – 12:30	Break	
12:30	*LUNCH*	

Program

Monday, 03 June 2019

14:30 – 15:05	Laurens Molenkamp	**Topological superconductivity in HgTe-based devices**
15:05 – 15:30	William Mayer	**Anomalous phase shift in Al-InAs Josephson junctions**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:35	Tristan Cren	**Two-dimensional topological superconductivity in Pb/Co/Si(111)**
16:35 – 17:00	Simon Diesch	**Creation of equal-spin triplet superconductivity at the Al/EuS interface**
17:00 - 19:00	**Poster I**	*(Presenters of posters with ODD ordering numbers are asked to stay at their posters)*
19:15	*HERAEUS DINNER (social event with cold & warm buffet with complimentary drinks)*	

Tuesday, 04 June 2019

08:00	*BREAKFAST*	
09:15 – 09:50	Jukka Pekola	**Thermometry based on proximity superconductivity for ultra-sensitive calorimetry**
09:50 – 10:25	Detlef Beckmann	**Spin-dependent thermoelectric effects in superconductor/ferromagnet hybrid structures**
10:25– 11:00	*COFFEE BREAK*	
11:00 – 11:35	Francesco Giazotto	**Josephson field-effect transistors go metal: A groundbreaking route towards concrete superconducting electronics**
11:35 – 12:10	Natascha Pugach	**Spin amplification of electrons cooling in cold electron bolometers**
12:10 – 12:30	Break	
12:30	*LUNCH*	

Program

Tuesday, 04 June 2019

14:30 – 15:05	Angelo Di Bernardo	**Nodal superconducting exchange coupling**
15:05 – 15:30	Julien Basset	**Dynamics of strongly driven diffusive Josephson junctions**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:35	Hélène Bouchiat	**Microwave signature of topological Andreev level crossings in a Bismuth-based Josephson junction**
16:35 – 17:10	Christian Ast	**Yu-Shiba-Rusinov states from impurities with a quantum spin**
17:10 – 17:35	Akashdeep Kamra	**Superconductivity from squeezed magnons on normal metals and topological insulators**
18:30	*DINNER*	
20:00 – 21:00	Philipp Moll	**Exploring topology on the micron-scale**

Program

Wednesday, 05 June 2019

08:00	*BREAKFAST*	
09:15 – 09:50	Teun Klapwijk	**Absorption of low-frequency photons by a superconductor**
09:50 – 10:25	Attila Geresdi	**Andreev and Majorana bound states in semiconductor nanowire Josephson junctions**
10:25 – 11:00	*COFFEE BREAK*	
11:00 – 11:35	Leandro Tosi	**Spin-orbit splitting of Andreev states revealed by microwave spectroscopy**
11:35 – 12:10	Milena Grifoni	**The ac-Josephson effect in interacting nanostructures: diagrammatic theory in the particle-conserving framework**
12:10 – 12:30	Break	
12:30	*LUNCH*	
14:30 – 15:05	Ioan Pop	**Granular aluminum: A superconducting material for high impedance quantum circuits**
15:05 – 15:30	Çağlar Girit	**Non-local Josephson effect in Andreev molecules**
15:30 – 16:00	*COFFEE BREAK*	

Wednesday, 05 June 2019

16:00 – 16:35	JianTing Ye	**Field-induced superconductivity in transition metal dichalcogenides**
16:35 – 17:00	Nicola Paradiso	**Phase slip lines in few-layer $NbSe_2$ devices**
17:00 –19:00	**Poster II**	*(Presenters of posters with EVEN ordering numbers are asked to stay at their posters)*
19:15	*DINNER*	

Posters

Thursday, 06 June 2019

08:00	*BREAKFAST*	
09:15 – 09:50	Irina Bobkova	**Magnetoelectric effects in S/F and S/AF hybrids and Josephson detection of magnetization dynamics**
09:50 – 10:25	Clemens Winkelmann	**Tuning the singlet-doublet ground state transition in a superconductor-quantum dot hybrid**
10:25 – 11:00	*COFFEE BREAK*	
11:00 – 11:35	Aviad Frydman	**Specific heat measurements through the superconductor-insulator quantum phase transition**
11:35– 12:00	Raphaëlle Delagrange	**Non-linearity and quasi-particle dynamics in superconducting silicon resonator**
12:00 – 12:20	Scientific organizers	**Closing and Poster Award Ceremony**
12:30	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Friday morning

Posters

Posters

01	Daniel Arnold	**Light-induced transport changes of the superconducting two-dimensional LAO/STO interface**
02	Christian Baumgartner	**Gate-tunable supercurrent in epitaxial Al-InAs-based Josephson junctions**
03	Andreas Bloch	**Dynamic triplet pairing in long ferromagnetic Josephson junctions induced by FMR**
04	Alexander Bobkov	**Thermally induced torques and magnetization dynamics in S/F bilayers**
05	Francesca Chiodi	**Strongly non-linear superconducting silicon resonators**
06	Konrad Dapper	**Dispersive readout of flux vortex dynamics in quantum Josephson parallel arrays**
07	Asbjørn Drachmann	**High critical field superconducting heterostructures using anodic oxidation**
08	Juan C. Estrada Saldaña	**Subgap-state replicas in double quantum dot Josephson junctions**
09	Lorenz Fuchs	**RLC-resonators as kinetic inductance detectors**
10	Ali G. Moghaddam	**Impurity-induced subgap states in time-reversal-invariant topological superconductors**
11	Alexander Gabovich	**Josephson and quasiparticle currents between *d*-wave superconductors with charge-density waves**

Posters

12	Franzisca Gorniaczyk	**Electronic thermal conductivity in the insulating phase of amorphous indium oxide thin films**
13	Roy Haller	**Current-phase relation of a graphene rf SQUID inductively coupled to a superconducting resonator**
14	Robert Hussein	**Oscillator induced phase transition in a quantum dot Josephson junction**
15	David Indolese	**Superconducting proximity effect in hBN-graphene moiré superlattice**
16	Alzbeta Kadlecova	**Quantum phase transitions in superconducting quantum dots**
17	Ning Kang	**Grain boundaries and tilt-angle-dependent transport properties of 2D Mo_2C superconductor**
18	Joachim Kerner	**On a condensation phenomenon of electron pairs in a quantum wire**
19	Raffael Klees	**Microwave spectroscopy reveals the quantum geometric tensor of topological Josephson matter**
20	Preeti Pandey	**Electronic transport properties of multiterminal graphene based Josephson junctions**
21	David Perkins	**Fluctuation spectroscopy in superconducting granular boron-doped diamond films**
22	Jordi Picó Cortés	**A diagrammatic approach for transport through quantum dot-based Josephson junctions**

Posters

23	Krzysztof Pomorski	**Unified description of single electron semiconductor devices and Josephson junction devices in the direction of implementation hybrid semiconductor-superconductor quantum computer**
24	Lukas Powalla	**Fabrication and measurement of high impedance Josephson junctions**
25	Martin Prestel	**Channel analysis of atomic Palladium contacts by Andreev reflections**
26	Xianggang Qiu	**Dynamic vortex insulator to metal transition in superconducting Nb films with antidote lattices**
27	Daniil Rabinovich	**1. φ_0-contact in S/AF/S junction**
28	Daniil Rabinovich	**2. Resistive state of SFS Josephson junctions in the presence of moving domain walls**
29	Ali Rezaei	**1. Phase- and voltage-controlled triplet correlations in a hybrid superconductor-ferromagnet device**
30	Ali Rezaei	**2. Spin effects in a superconductor in proximity to an antiferromagnetic insulator**
31	Yannick Schön	**Rabi oscillations in disordered superconducting nanowire circuits**
32	Laura Sobral Rey	**Coulomb blockade experiments beyond orthodox theory**
33	Björn Sothmann	**Phase-dependent heat and charge transport through superconductor–quantum dot hybrids**
34	Susanne Sprenger	**Interplay of mesoscopic superconductivity and Coulomb blockade**

Posters

35	Annika Stellhorn	**Domain-superconductivity in Nb/FePd thin layers with lateral inhomogeneous magnetization**
36	Francesco Valenti	**Phonon traps to reduce the quasiparticle density in superconducting circuits**
37	Jan Nicolas Voss	**Metallic, superconducting and insulating low-temperature electrical transport response of disordered nanowires**
38	Stephan Weiß	**Dephasing of Andreev bound states revealed by iterative summation of path-integrals**
39	Micha Wildermuth	**Fluxoid dynamics in high impedance long Josephson junctions**
40	Kacper Wrześniewski	**Waiting time distribution and current cross-correlations in triple quantum dot-based Cooper pair splitter**
41	Ulrich Zuelicke	**Chiral *p*-wave superfluid from *s*-wave pairing in the BEC limit**

Abstracts of Talks

(in chronological order)

Quest for Topological Superconductivity

Y. Ando[1]

[1]*Physics Institute II, University of Cologne, Cologne 50937, Germany*

In this talk, I will start with a general introduction to topological superconductivity and Majorana fermions [1], and explain why spin-orbit coupling is useful for generating such novel states of matter. I will then elaborate on the nematic topological superconductivity recently found in electron-doped topological insulators such as $Cu_xBi_2Se_3$ [2, 3], and show some new results on $Cu_x(PbSe)_5(Bi_2Se_3)_6$, which is different from $Cu_xBi_2Se_3$ in that it has symmetry-protected gap nodes [4]. In the second part, I will present our efforts to address proximity-induced topological superconductivity on the surface of topological superconductors [5], and explain why such a platform is promising for topological quantum computing. Lastly, I will show some preliminary tunneling spectroscopy data on the qasi-1D superconductor $Tl_2Mo_6Se_6$, which is a topological superconductor candidate to host Kramers pairs of Majorana fermions at the ends [6].

References

[1] M. Sato and Y. Ando, Rep. Prog. Phys. **80**, 076501 (2017).
[2] K. Matano, M. Kriener, K. Segawa, Y. Ando, and G.-q. Zheng, Nature Phys. **12**, 852 (2016).
[3] S. Yonezawa, K. Tajiri, S. Nakata, Y. Nagai, Z. Wang, K. Segawa, Y. Ando, and Y. Maeno, Nature Phys. **13**, 123 (2017).
[4] L. Andersen, Z. Wang, T. Lorenz, and Y. Ando, Phys. Rev. B **98**, 220512 (2018).
[5] S. Ghatak, O. Breunig, F. Yang, Z. Wang, A. A. Taskin, and Y. Ando, Nano Lett. **18**, 5124 (2018).
[6] S.-M. Huang, C.-H. Hsu, S.-Y. Xu, C.-C. Lee, S.-Y. Shiau, H. Lin, and A. Bansil, Phys. Rev. B **97**, 014510 (2018).

Spin-Orbit induced phase-shift in Bi_2Se_3 Josephson junctions

A. Assouline[1], C. Feuillet-Palma[1], N. Bergeal[1], T. Zhang[1], A. Mottaghizadeh[1], A. Zimmers[1], E. Lhuillier[2], M. Eddrief[2], P. Atkinson[2], M. Aprili[3], H. Aubin[1,4]

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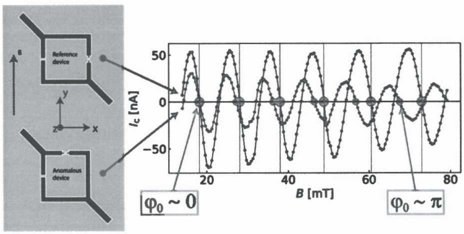

For Josephson junctions in open circuit, with both time-reversal and inversion symmetries, the phase difference between the two superconducting electrodes can only be a multiple number of π. However, when both symmetries are broken, a non-zero anomalous phase shift is expected in response to the spin-orbit coupling. In this talk, I will present our recent study of hybrid SNS Josephson junctions and Josephson interferometers fabricated with Bi_2Se_3, a topological material with strong spin-orbit coupling. Simultaneous measurements of two interferometers oriented differently with an in-plane magnetic field, see figure, enabled the observation of an anomalous phase shift. A careful analysis of the symmetry conditions under which this anomalous phase-shift is allowed leads to the conclusion that no other effect than the spin-orbit coupling can be responsible for the observed phenomena. From the amplitude of the anomalous phase shift, one can conclude that the major contribution to the superfluid current in the Josephson junction arises from the bulk electrons in the conduction band, spin-splitted by the Rashba effect. We extract a value α=0.38 eVA for the spin-orbit coefficient[1], in agreement with photoemission results.

References

[1] Assouline, A. *et al.* Spin-Orbit induced phase-shift in Bi2Se3 Josephson junctions. *Nat. Commun.* **10**, 126 (2019).

Topological properties of multi-terminal superconducting nanostructures: effect of a continuous spectrum

Evgeny Repin[1], Yuguang Chen[1], Yuli V. Nazarov[1]

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Recently, it has been shown that multi-terminal superconducting nanostructures may possess topological properties that involve Berry curvatures in the parametric space of the superconducting phases of the terminals, and associated Chern numbers that are manifested in quantized transconductances of the nanostructure. In this Article, we investigate how the continuous spectrum that is intrinsically present in superconductors, affects these properties. We model the nanostructure within scattering formalism deriving the action and the response function that permits a re-definition of Berry curvature for continuous spectrum.
We have found that the re-defined Berry curvature may have a non-topological phase-independent contribution that adds a non-quantized part to the transconductances. This contribution vanishes for a time-reversible scattering matrix.

References

[1] https://arxiv.org/abs/1812.09102

Evidence of Topological Superconductivity in Planar Josephson Junctions

Fabrizio Nichele[1], Antonio Fornieri[1], Alexander M. Whiticar[1], F. Setiawan[2], Elias Portoles Marin[1], Asbjørn C. C. Drachmann[1], Anna Keselman[3], Sergei Gronin[4,5], Candice Thomas[4,5], Tian Wang[4,5], Ray Kallaher[4,5], Geoffrey C. Gardner[4,5], Erez Berg[2,6], Michael J. Manfra[4,5,7,8], Ady Stern[6], Charles M. Marcus[1]

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There is growing interest in material systems that both support Majorana zero modes (MZMs), relevant for quantum computing, and can be fabricated into complex and scalable geometries. So far, MZMs have been tentatively identified in individual InSb or InAs nanowires with induced superconductivity. Future tests of non-Abelian statistics will likely involve braiding or interferometric measurement, requiring branched or looped geometries, challenging to realize using individual nanowires.
I will present investigations of hybrid superconductor/semiconductor devices performed at the University of Copenhagen. Devices are based on a planar InAs heterostructure strongly coupled to a thin layer of epitaxial Al. By top-down lithography, we defined one-dimensional wires characterized by a hard superconducting gap, ballistic tunneling probes and in-plane critical fields up to 3 T. In the presence of an in-plane magnetic field, zero energy states robust in field emerge and show a behavior consistent with theory for MZMs, including low temperature saturation at the conductance quantum. Finally, I will show how a new generation of Majorana devices could be realized by taking advantage of phase control in planar Josephson junction geometries.

Topological Superconductivity in HgTe-based Devices

L. Molenkamp

Physics Institute (EP3) Wuerzburg University, Wuerzburg, Germany

Suitably structured HgTe has been shown to be a topological insulator in both 2- (a quantum well wider than some 6.3 nm) and 3 (an epilayer grown under tensile strain) dimensions with favorable properties for quantum transport studies, i.e. a good mobility and a complete absence of bulk carriers.

In this talk I will summarize the results of our efforts (in collaboration with colleagues all over the globe) to induce superconductivity in the topological surface states of these materials. Special emphasis will be given to recent results on the ac Josephson effect. We will present data on Shapiro step behavior that is a very strong indication for the presence of a gapless Andreev mode in our Josephson junctions.

Anomalous Phase Shift in Al-InAs Josephson Junctions

William Mayer[1], Matthieu Dartiailh[1], Joseph Yuan[1], Kaushini S. Wickramasinghe[1], and Javad Shabani[1]
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The study of systems with both superconductivity and spin-orbit coupling has become an important topic in condensed matter with implications ranging from superconducting spintronics to the search for topological superconductivity. Developments in epitaxial growth of aluminum thin films on indium-arsenide quantum wells has opened new avenues to study mesoscopic superconductivity [1]. Building on earlier works we realize both gate-tunable spin-orbit coupling [2] and transparent superconductor-semiconductor interfaces [3]. In Josephson junctions where a proximitized normal region with spin-orbit coupling forms the weak link, theory predicts the interplay of these two properties will lead to an anomalous phase shift with the application of in-plane magnetic field due to an equilibrium spin current in the system. We measure the anomalous phase shift in Al-InAs Josephson junctions in a SQUID geometry as a function of in-plane magnetic field. Gate control over the magnitude of the anomalous phase shift is demonstrated. Rashba spin-orbit coupling is established as the dominant mechanism leading to the anomalous phase shift. Finally, we demonstrate that this system realizes larger anomalous phase shifts then predicted by existing theories due to the large proximitized gap in the system.

References:

1. M. T. Deng, S. Vaitiekenas, E. B. Hansen, J. Danon, M. Leijnse, K. Flensberg, J. Nygard, P. Krogstrup, C. M. Marcus, Science, **354**, 1557–1562 (2016)

2. K.Wickramasinghe, W. Mayer, J. Yuan, T. Nguyen, V. Manucharyan, J. Shabani, Appl. Phys. Lett. **113** (26), 262104 (2018)

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Two-dimensional topological superconductivity in Pb/Co/Si(111)

Gerbold C. Ménard[1], Sébastien Guissart[2], Christophe Brun[1], Mircea Trif[2], François Debontridder[1], Raphaël T. Leriche[1], Dominique Demaille[1], Dimitri Roditchev[3], Pascal Simon[2] and Tristan Cren[1]

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The examination of supposedly well-known condensed matter systems through the prism of topology has led to the discovery of new quantum phenomena that were previously overlooked. Just like insulators can present topological phases characterized by Dirac edge states, superconductors can exhibit topological phases characterized by Majorana edge states. Two-dimensional (2D) superconductors are expected to exhibit propagating Majorana edge states characterized by a Dirac-like dispersion. We have recently observed some hint of dispersive Majorana edge states in a single atomic layer Pb superconductor coupled to a buried Co-Si nano-magnet [1]. In addition to their dispersive edge states, 2D topological superconductors are also supposed to support Majorana bound states localized on topological defects, our recent measurements seem to support this theoretical prediction [2].

[1] G. C. Ménard et al., Nature Comm, **8**, 2040 (2017)
[2] G. C. Ménard et al., arXiv:1810.09541, Nature Comm (2019)

Creation of equal-spin triplet superconductivity at the Al/EuS interface

S. Diesch[1], P. Machon[1], M. Wolz[1], C. Sürgers[2], D. Beckmann[3], W. Belzig[1], and E. Scheer[1]

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In conventional superconductors, electrons are bound in singlet Cooper pairs, i.e. with opposite spin. More recently, experiments on superconductor-ferromagnet systems have shown supercurrents tunneling through ferromagnetic layers, indicating Cooper pairs of equal spin, thus corresponding to a long-range triplet proximity effect [1]. Most experimental evidence for triplet superconductivity comes from observations of the thickness dependence of the Josephson current through a ferromagnetic barrier, and there is now an increasing amount of direct spectroscopic evidence [2] to test the existing theoretical models.
In this contribution we present scanning tunneling spectra of thin films of the ferromagnetic insulator europium sulfide on superconducting aluminum measured at 280 mK and in varying magnetic fields [4]. We observe significant broadening of the superconducting energy gap and a variety of sub-gap structures induced by the presence of the ferromagnet. We interpret our findings based on an advanced circuit theory model [3].

References

[1] F. S. Bergeret, A. F. Volkov & K. B. Efetov, Phys. Rev. Lett. **86**, 4096 (2001)

[2] A. Di Bernardo, S. Diesch, Y. Gu, J. Linder, G. Divitini, C. Ducati, E. Scheer, M.G. Blamire & J.W.A. Robinson, Nat. Comm. **6**:8053 (2015)

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Thermometry based on proximity superconductivity for ultra-sensitive calorimetry

Jukka Pekola

Aalto University, School of Science, Helsinki/Finland

We present a radio-frequency thermometer based on a zero-bias anomaly of a tunnel junction between a superconductor and proximitized normal metal [1]. It features non-invasive detection and essentially uncompromised sensitivity down to the lowest temperatures of below 20 mK in contrast to commonly used finite bias thermometers that dissipate orders of magnitude more power and lose their sensitivity at low temperatures. Using this thermometer we demonstrate detection of equilibrium fluctuations of temperature in a system of about 10^8 electrons exchanging energy with phonon bath at a fixed temperature [2]. Moreover, temperature fluctuations under nonequilibrium conditions present a nontrivial dependence on the chemical potential bias of a hot electron source. These fundamental fluctuations of T set the ultimate lower bound of the energy resolution of a calorimeter.

[1] B. Karimi and J. P. Pekola, Phys. Rev. Applied 10, 054048 (2018).
[2] B. Karimi et al., arXiv:1904.05041

Spin-dependent thermoelectric effects in superconductor/ferromagnet hybrid structures

S. Kolenda[1], J. Heidrich[1], M. J. Wolf[1], C. Sürgers[2], D. Beckmann[1]

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We report on the experimental observation of spin-dependent thermoelectric effects in superconductor-ferromagnet tunnel junctions in high magnetic fields. The thermoelectric signals are due to a spin-dependent lifting of particle-hole symmetry on the energy scale of the superconducting gap. Due to the small energy scale, the thermoelectric effects can be quite large, and we infer a maximum Seebeck coefficient of about 100 µV/K from our data. The thermoelectric signals can be further enhanced by an exchange splitting induced by the proximity effect with a ferromagnetic insulator. Nonlocal thermoelectric effects elucidate the coupling of spin and heat transport in high-field superconductors.

References

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[2] S. Kolenda, P. Machon, D. Beckmann, and W. Belzig, Beilstein J. Nanotechnol. **7**, 1579 (2016)

[3] S. Kolenda, C. Sürgers, G. Fischer, and D. Beckmann, Phys. Rev. B **95**, 224505 (2017)

Josephson field-effect transistors go metal: A groundbreaking route towards concrete superconducting electronics

F. Giazotto

NEST Istituto Nanoscienze-CNR and Scuola Normale Superiore, I-56127 Pisa, Italy

In their original formulation of superconductivity, the London brothers predicted more than eighty years ago the exponential suppression of an electrostatic field inside a superconductor over the so-called London penetration depth, λ_L, in analogy to the Meissner-Ochsenfeld effect. Despite a few experiments indicating hints of perturbation induced by electrostatic fields, no clue has been provided so far on the possibility to manipulate conventional superconductors via field-effect. In this talk, I will report the evidence of full field-effect control of the supercurrent in all-metallic transistors made of different BCS superconducting thin films [1]. At low temperature, our field-effect transistors (FETs) show a monotonic decay of the critical current under increasing electrostatic field up to total quenching for gate voltage values as large as ±40V in titanium-based devices. This bipolar field effect persists up to ~ 85% of the critical temperature (~ 0.41K), and in the presence of sizable magnetic fields. A similar behavior, though less pronounced, was observed in aluminum thin film FETs [1]. Moreover, I will show the experimental realization of Ti-based Dayem bridge field-effect transistors (DB − FETs) [2, 3] able to control the Josephson critical current (I_C) of the superconducting channel. Our easy fabrication process DB − FETs show symmetric full suppression of I_C for an applied critical gate voltage as low as V_G^C ~ ±8V at temperatures reaching about the 85% of the record critical temperature 550mK for titanium. Our devices show extremely high values of transconductance (up to 15µA/V) and variations of Josephson kinetic inductance with gate voltage of two orders of magnitude. Finally, I will show the behavior of mesoscopic superconductor-normal metal-superconductor (SNS) Josephson field-effect transistors [4] which will reveal as well the impact of intense electrostatic fields even on proximity metals. All this seems to suggest that the field effect is *universal*, i.e., it can affect either genuine or proximity *fully-metallic* superconductors. Besides shedding light on a key issue in physics, these results represent a groundbreaking asset for the realization of an all-metallic superconducting field-effect electronics and leading edge quantum information architectures based on Josephson FETs. Possible electronic and circuital schemes based on this all-metallic technology will be furthermore discussed [3].

References

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Spin amplification of electrons cooling in cold-electron bolometers

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The method of electron cooling via current flow through a superconductor-insulator-normal metal junction is used in cold-electron bolometers (CEB) [1]. Andreev current limits the cooling effect at low temperatures, being a parasitic to the cooling quasiparticle current.

We have theoretically explained the obtained data on the electron cooling effect in CEB using Al absorber with a thin ferromagnetic (Fe) layer. A maximal electron cooling in CEB at phonon temperature 300 mK and below was reached experimentally. Several reasons allowing this achievement, are the optimization of geometry, the effective withdrawing of hot quasiparticles from the tunnel barrier using electron traps, and the suppression of Andreev current in hybrid N-island, composed by Fe and Al.

We show that the ferromagnetic presence provides the spin scattering, that suppresses the Andreev reflection in the normal absorber, and therefore, suppresses the Andreev current. The theory is based on the Keldysh technique for the Usadel equations.

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Nodal superconducting exchange coupling

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Predating the discovery of giant magnetoresistance [1-2], in 1966 Pierre de Gennes [3] predicted the superconducting equivalent of a ferromagnet/normal metal/ferromagnet (F/N/F) spin valve (SV). In de Gennes system, the N layer is replaced by a conventional (*s*-wave) S and, by changing the alignment of the magnetizations of the Fs from parallel (P) to antiparallel (AP), it is possible to modulate the S critical temperature (T_c). The T_c modulation is due to the additive nature of the pair-breaking magnetic exchange (h_{ex}) fields at the two S/F interfaces, meaning that in the P state they sum up hence resulting in a lower T_c compared to the AP configuration. Such effect has been experimentally observed in a variety FI/S/FI (FI being a ferromagnetic insulator) and F/S/F systems [4-9], which have showed that the changed in T_c between P and AP state, ΔT_c, occurs for a S thickness (d_S) of the order of its superconducting coherence length (ξ). In particular, for FI/S/FI trilayers with d_S smaller than ξ, a S-mediated exchange coupling between the FIs is observed [5] with a full suppression of T_c in the P state [4-5], in agreement with de Gennes prediction.

More recently, I have designed and investigated a full-oxide FI/S/FI system, where S is the nodal (*d*-wave) S $YBa_2Cu_3O_{7-\delta}$ (YBCO) and FI is the manganite $Pr_{0.8}Ca_{0.2}MnO_3$ (PCMO). In this talk, I will show the results that I have recently obtained for this trilayer system [10], which demonstrate evidence for an unconventional S-mediated exchange coupling between the PCMO layers. This novel form of coupling goes beyond that predicted by the Gennes in the sense that it is mediated by nodal quasiparticle states near the YBCO Fermi surface. ΔT_c values as large as 2K and oscillating in sign with d_S up to length scales of the order of 100 ξ are observed as result of this coupling mechanism.

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Dynamics of Strongly Driven Diffusive Josephson Junctions

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By measuring the Josephson emission of a diffusive Superconductor-Normal metal-Superconductor (SNS) junction at a finite temperature we reveal a non-trivial sensitivity of the supercurrent to microwave irradiation. We demonstrate that the harmonic content of the current-phase relation is modified due to the energy redistribution of quasiparticles in the normal wire induced by the electromagnetic field. The distortion originates from the phase-dependent out-of-equilibrium distribution function which is strongly affected by the ac-response of the spectral supercurrent. For phases close to π, transitions accross the Andreev gap are dynamically favored leading to a supercurrent reduction. This finding is supported by a comparison with the quasiclassical Green's function theory of superconductivity in diffusive SNS junctions under microwave irradiation [1].

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Microwave Signature of Topological Andreev level Crossings in a Bismuth-based Josephson Junction

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Demonstrating the topological protection of Andreev states in Josephson junctions is an experimental challenge. In particular the telltale 4 pi periodicity expected for the current phase relation has remained elusive, because of fast parity breaking processes. It was predicted that low temperature ac susceptibility measurements could reveal the topological protection of quantum Spin Hall edge states by probing their low energy Andreev spectrum at finite frequency. We have performed such a microwave probing of a phase-biased Josephson junction built around a bismuth nanowire, a predicted second order topological insulator, and which was shown to host one-dimensional ballistic edge states. We find absorption peaks at the Andreev level crossings, whose temperature and frequency dependencies point to protected topological crossings with an accuracy limited by the electronic temperature of our experiment.

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Yu-Shiba-Rusinov States from Impurities with a Quantum Spin

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Magnetic impurities in a superconductor give rise to pairs of quasiparticle levels inside the superconducting gap called Yu-Shiba-Rusinov (YSR) states. On or near surfaces, these impurities can be well studied locally by scanning tunneling microscopy (STM). We have studied intrinsic impurities in Vanadium showing a single pair of YSR states at the surface. Several indicators point towards a quantum spin-1/2 impurity, which will be discussed. In addition, we have observed a non-trivial energy dependence of the YSR state as a function of tip-sample distance, similar to findings that have been reported before. We find that the impurity-substrate coupling plays a decisive role in the behaviour of the YSR states at surfaces. We discuss this in the context of a model that extends the existing Green's function description of YSR states and also bridges a gap to related models. Further, picking up a magnetic impurity with the tip allows for tunnelling between single YSR states. This opens up an entirely new perspective for understanding tunnelling between single quasiparticle states, such as lifetime and spin polarization of YSR states as well as interaction with the environment during the tunnelling process.

Superconductivity from squeezed magnons on normal metals and topological insulators

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We study magnon-mediated superconductivity in a heterostructure consisting of a topological insulator and an antiferromagnetic insulator on a bipartite lattice. Our main finding is that one may significantly enhance magnon-mediated superconductivity on the surface of the topological insulator by coupling to only one of the two antiferromagnetic sublattices. Such a sublattice symmetry-breaking coupling considerably strengthens the effective attractive interaction between gapless helical fermions, living on the surface of the topological insulator, compared to the case where the topological insulator couples symmetrically to both sublattices. We provide a general physical picture of this mechanism based on the notion of squeezed bosonic eigenmodes. We also contrast our results to the analogous case of an antiferromagnetic insulator coupled to a normal metal.

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Exploring topology on the micron-scale

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The description of condensed matter traditionally focused on local quantum properties. The arrangement of orbitals within the unit cell, and the translational invariance of a crystalline environment, form the basis of our understanding of electrons in solids and lead to their band-structure classification into metals and insulators. In the past decade, we have seen new ideas expanding this local picture as the band structure can be twisted into topologically non-trivial states, leading to global electronic properties. While unobservable in the strictly infinite system, conductive edge modes are expected to appear at the surface, where the topologically non-trivial crystal and the trivial vacuum meet.

This has been most prominently shown in topological insulators, yet recently the attention has shifted to semi-metallic systems, the 3D Dirac- and Weyl-semimetals. Unlike insulators, these possess free electrons and their bulk conductivity renders the experimental observation of additional conductive surface modes challenging. I will present one possible route to address this challenge: By using Focused Ion Beam machining, the volume of a studied crystal can be reduced onto the sub-micron scale, thereby greatly enhancing the surface-to-volume ratio. On these length scales, novel processes are expected to occur that weave the topological surface states and the chiral bulk states together into new quantum objects. I will show the status of the field, as well as paint a roadmap of the current open questions.

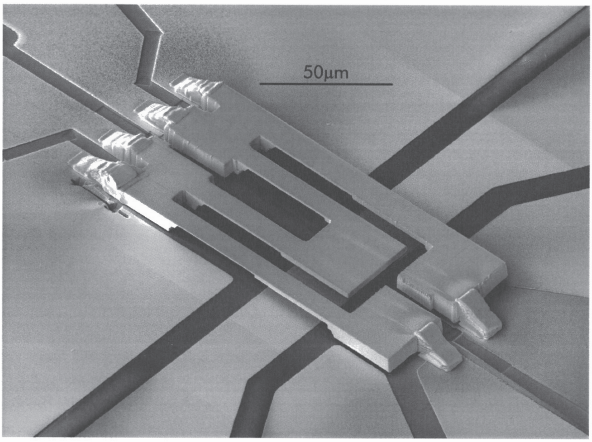

Figure: Single crystal Cd_3As_2 electromechanical topological device.

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Absorption of low-frequency photons by a superconductor

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A common viewpoint is that at low temperatures superconductors absorb photons only when the photon-energy exceeds the superconducting energy gap, $\hbar\omega > 2\Delta$, i.e. by creating quasi-particles out of the ground state of Cooper-pairs As a consequence, superconductors exposed to a microwave field with $\hbar\omega < 2\Delta$ are assumed to be lossless, which is an important parameter for superconductors in various applications such as parametric amplification and microwave kinetic inductance detectors. Stimulated by some recent experiments[1] we have revisited this problem[2] showing how the superconducting ground state gets modified by the microwave photons, leading, at a fixed temperature, to an increase in the density of quasiparticles. We discuss routes to evaluate experimentally the predicted properties[3].

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Andreev and Majorana bound states in semiconductor nanowire Josephson junctions

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The mesoscopic description of the Josephson effect is based on Andreev bound states pinned to the weak link between the superconducting leads. In this talk, I will summarize our measurements on Andreev levels in semiconductor InAs nanowires with in-situ grown epitaxial aluminium leads. We utilize a superconducting tunnel junction as an *on-chip* microwave generator to investigate the essential building blocks of prospective topological quantum bits. By exploiting the AC Josephson effect, we map the excitations of nanowire Josephson junctions up to 200 μeV ~ 90 GHz, bounded by the superconducting gap of the generator. With this technique, we show the presence of gate-tunable Andreev bound states in a ballistic semiconductor channel for the first time, and demonstrate how an external magnetic field influences the spectrum in the presence of strong spin-orbit coupling [1].
Next, I discuss our measurements of the AC Josephson effect in voltage-biased nanowire junctions. Utilizing the photon-assisted tunneling current in a superconducting tunnel junction as a broadband, *on-chip* frequency-sensitive probe, we observe the 4π-periodic Josephson effect above a threshold magnetic field approximately 200 mT, in agreement with the expected topological phase transition giving rise to Majorana bound states [2].

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Spin-orbit splitting of Andreev States revealed by microwave spectroscopy

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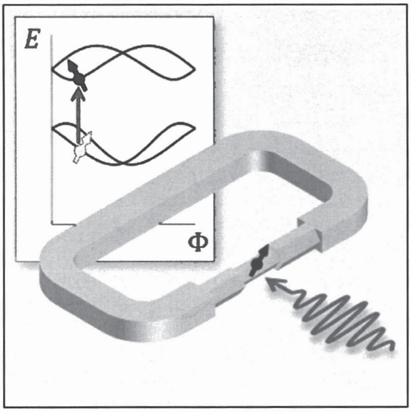
I will present our results on the microwave absorption spectroscopy of Andreev states in superconducting weak links tailored in an InAs-Al (core-full shell) epitaxially-grown nanowire. The spectra present distinctive features that arise from transitions between spin-split Andreev states. A simple empirical model, with Rashba spin-orbit interaction and two transverse modes as main ingredients, explains these features and their evolution with magnetic field. I will also present preliminary results on the coherent manipulation of localized excitations in this weak link.



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The ac-Josephson effect in interacting nanostructures: diagrammatic theory in the particle-conserving framework

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The ac-Josephson effect is a fundamental feature of driven superconducting systems, reflecting the intrinsic quantum-mechanical relationship between the phase of the wave function and particle number. Most studies of Josephson junctions are carried out in the mean-field BCS theory, in which particle number is not conserved and the collective wave function has a definite phase. This is clearly unsuited to treat many-body effects in which the conservation of particle number plays a key role. Instead a particle-conserving theory of superconductivity could be more appropriate [1]. To investigate new phenomena that may appear in strongly interacting nanostructures, we study the ac-Josephson effect in a junction composed of two superconductors and an interacting quantum dot. We show that crucial for the appearance of the ac-Josephson current in the particle conserving framework is to account for correlations bewtween the superconductors, which are no longer two independent particle reservoirs. Exemplarily, the ac- and dc- Josephson current are calculated in a diagrammatic approach [2,3] generalized to include cotunneling processes [4].

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Granular aluminum: A superconducting material for high impedance quantum circuits

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Superconducting quantum information processing machines are predominantly based on microwave circuits with relatively low characteristic impedance, of about 100 Ohm, and small anharmonicity, which can limit their coherence and logic gate fidelity. A promising alternative are circuits based on so-called superinductors, with characteristic impedances exceeding the resistance quantum R_Q = 6.4 kOhm. However, previous implementations of superinductors, consisting of mesoscopic Josephson junction arrays, can introduce unintended nonlinearity or parasitic resonant modes in the qubit vicinity, degrading its coherence. I will present a fluxonium qubit design using a granular aluminum (grAl) superinductor strip. Granular aluminum is a particularly attractive material because it self-assembles into an effective junction array with a remarkably high kinetic inductance [1] and low losses [2]. Moreover, its fabrication can be in-situ integrated with standard aluminum circuit processing. The measured Ramsey coherence time, up to 30 μs [3], illustrates the potential of grAl for applications ranging from protected qubit designs to quantum limited amplifiers and detectors.

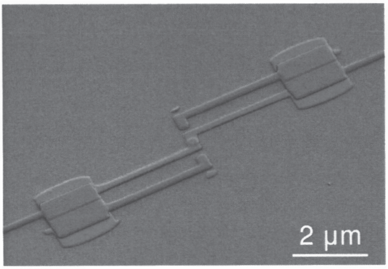

Figure 1: Scanning electron microscope image (in false color) of a small section of a granular Aluminum superinductor (in red) connected to a Josephson junction (extracted from Ref. [3]).

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Non-local Josephson effect in Andreev molecules

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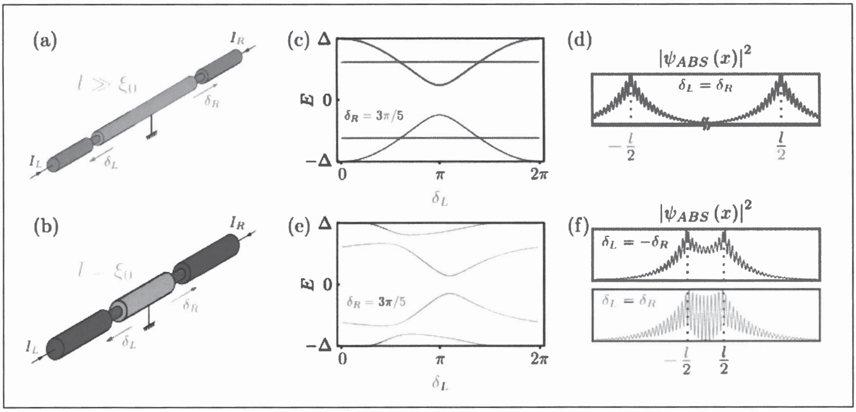
We propose the “Andreev molecule”, an artificial quantum system composed of two closely spaced Josephson junctions. The coupling between Josephson junctions in an Andreev molecule occurs through the overlap and hybridization of the junction’s “atomic” orbitals, Andreev Bound States. A striking consequence is that the supercurrent flowing through one junction depends on the superconducting phase difference across the other junction. Using the Bogolubiov-de-Gennes formalism, we derive the energy spectrum and non-local current-phase relation for arbitrary separation. We demonstrate the possibility of creating a ϕ-junction and propose experiments to verify our predictions. Andreev molecules may have potential applications in quantum information, metrology, sensing, and molecular simulation.



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Field-Induced Superconductivity in Transition Metal Dichalcogenides

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Field effect was recently proved to be an effective way to dope various materials electrostatically. By introducing a electric double layer transistor, the electrochemical version of a conventional field effect transistor (FET), highly efficient FETs can be made with the capability of accumulating dense carriers (~10^{14} cm^{-2}) mediated by the movement of organic ions at transistor channel surface. In this talk, I will focus on the experimental efforts using ionic gating as an effective tool to induce and control superconductivity in semiconducting transition metal dichalcogenides down to one monolayer. The gate- induced carriers experiences both Rashba and Zeeman type spin-orbit interaction forming so-called Ising pairing. The spin configuration is strongly protected by the Zeeman type effective magnetic field, making this paring state highly resilient against the in-plane magnetic field.

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Phase slip lines in few-layer $NbSe_2$ devices

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Van der Waals superconductors made it possible to study the superconducting properties of individual 2D crystals in a low disorder regime. In the present work, we show that few-layer $NbSe_2$ flakes do not switch directly to the normal phase under large current bias. In all the samples measured, we observed that dissipation emerges via the sequential nucleation of phase slip lines (PSLs), the two dimensional analogue of phase slip centers. We study the dynamic of PSL nucleation in a NS point contact, where the temperature and current bias dependence of the PSL-induced conductance step is quantitatively described by an adaptation of the model of Skocpol, Beasley and Tinkham [1,2]. In extended crystals the nucleation of one artificial phase slip line can be induced by mechanical stressing a narrow region whose width is comparable to the charge imbalance equilibration length.

In plain devices, the PSL pattern is sample dependent. However, we demonstrate that it is possible to induce an artificial PSL nucleation site by mechanically stressing a flake across its whole width.

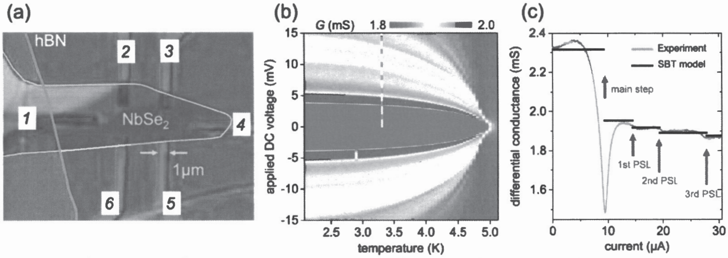

Fig. 1: (a) Optical microscope image of the device used to study the transport through a point contact. A $NbSe_2$ trilayer crystal is stamped on top of gold electrodes and then protected by a hBN flake. The point contact under study is at the interface between $NbSe_2$ and contact 5. (b) Color plot of the two-terminal differential conductance measured at the point contact, plotted as a function of voltage bias and temperature. (c) Differential conductance as a function of current for T=3.3 K. The current range corresponds to the bias range indicated by the orange dashed line in (b). The black curve shows the conductance calculated using the model of Skocpol *et al.*[1,2] with realistic parameters.

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Magnetoelectric effects in S/F and S/AF hybrids and Josephson detection of magnetization dynamics

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The inverse magnetoelectric effect in the hybrid structures consisting of superconductors and ferromagnets and antiferromagnets is discussed. It is demonstrated that in S/F/S Josephson junctions with spin-textured ferromagnets the magnetoelectric effect, which takes the form of the anomalous ground phase shift [1], is a manifestation of a generic supercurrent-mediated interaction between localized spins that breaks the global inversion symmetry of magnetic moments. The proposed interaction mechanism is capable of removing fundamental degeneracies between topologically distinct magnetic textures [2]. The prospects of using the effect for Josephson detection of magnetization dynamics and topology are discussed.
It is shown that the inverse magnetoelectric effect also exists in S/F hybrids with simply connected superconductors. In this case it manifests itself as inhomogeneous phase states, where the phase inhomogeneity can be localized in space or can take the form of a helical state [3].
We have also demonstrated that the inverse magnetoelectric effect in the form of the anomalous ground state phase shift exists in S/AF/S Josephson junctions with uncompensated antiferromagnets in the presence of SO-coupling. However, the physics of this phenomenon cannot be reduced to the effect of just one uncompensated layer and the AF order by itself is of crucial importance for current-carrying Andreev bound states spectra inside the interlayer. The prospects of exploiting this effect for Josephson detection of magnetization dynamics in antiferromagnets are discussed.

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Tuning the singlet-doublet ground state transition in a superconductor-quantum dot hybrid

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Gated superconductor - quantum dot - superconductor devices allow for studying the competition of a tunable single magnetic impurity and the superconducting ground state of the leads. We perform transport measurements on an electromigrated junction in the normal state of the leads, in which we characterize a strongly coupled quantum dot as a function of level depth, temperature and magnetic field. In particular, we extract the gate-dependent Kondo temperature scale of the device. In the superconducting state of the leads, we observe gate-dispersing sub-gap resonances in the transport data, pointing to Yu-Shiba-Rusinov states. A zero-energy crossing of these bound states is seen as the oddly occupied level is lowered, indicating that the transition from a screened to an unscreened local magnetic ground state takes place within the odd-charge diamond, and is due to the competition with the Kondo effect. Our sub-gap spectroscopies are reproduced by calculations that include interaction effects. Finally, we study the variation of the bound states' energies and spectral weights with temperature and magnetic field.

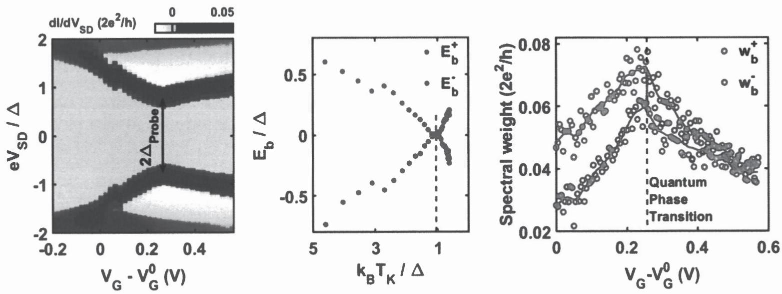

Figure 1. **Left**: differential conductance mapping of the sub-gap states versus gate voltage. The system formed by a S lead strongly coupled to the QD is probed spectroscopically by a second, weakly coupled, S lead. **Middle**: bound states' energy displaying the quantum phase transition for $k_B T_K / \Delta \approx 1$. **Right**: bound states' spectral weights showing an intensity inversion at the phase transition.

Specific Heat Measurements through the Superconductor-Insulator Quantum Phase Transition

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Bar Ilan University, Ramat Gan, Israel

The superconductor-insulator transition (SIT) is a prototype of a quantum phase transition which is very versatile experimentally: varying a non-thermal tuning parameter such as disorder, thickness, composition, magnetic field or gate-voltage causes the system to switch from a superconductor to an insulator. Though there has been increasing interest in this topic, the SIT has never been addressed from a thermodynamic point of view. So far, the experimental study of the SIT has mainly concentrated on resistivity based measurements such as transport and magnetoresistance and on global and local tunneling spectroscopy.

In my talk I will describe an experiment designed to go beyond conventional transport measurement. We use a unique highly sensitive setup to measure the specific heat of ultrathin Pb films through the SIT. The evolution of the specific heat through the quantum critical point in both granular and continuous films shows signatures for quantum criticality at the SIT and provides important information on electronic phenomena in the vicinity of the quantum phase transition.

Non-linearity and quasi-particle dynamics in superconducting silicon resonator

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We investigate the high frequency transport in silicon that has been made superconducting by ultra boron doping using laser annealing [1,2]. This Si:B is a disordered superconductor with a T_c of the order of 0.5K and a low charge carrier density ($10^{20} – 10^{21}$ cm^{-3}).

Using a microwave resonator made of Si:B, we show that this material has a kinetic inductance L_k>100pH/sq, yielding a ratio L_k/L_{tot} close to one. More surprisingly, this material is as well strongly non-linear, which makes it promising for detection of photons at sub-gap energies.

Quasiparticles are responsible for losses and decoherence in quantum circuits and their dynamics is crucial for the sensitivity of detectors based on the creation of quasiparticles by photon absorption. To understand their relaxation mechanisms in our material, we measure the response of the resonator to an excitation, either by a RF pulse at the resonant frequency (subgap) and by an infra-red LED pulse (above the gap). Both reveal a relaxation time of the order of 1ms, which is lowered as temperature increases.

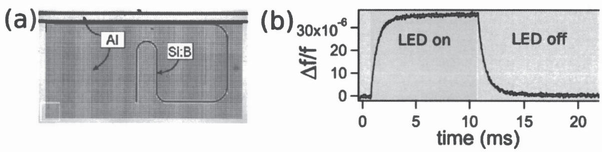

Fig. (a) Superconducting resonator inverstigated. The central line is made of doped silicon, the ground plane in aluminium. (b) Relative frequency shift of the resonance as a function of time when illuminated with an infra-red LED.

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Abstracts of Posters

(in alphabetical order)

Light-induced transport changes of the superconducting two-dimensional LAO/STO interface

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Illumination of the $LaAlO_3/SrTiO_3$ interface can change transport characteristics persistently [1,2]. We are able to tune the low temperature sheet resistance of a sample in Hall bar geometry by up to a factor of 5 by light at low temperatures in a controlled manner. Simultaneously the superconducting transition temperature shifts. The change in the transport characteristics persist even at low temperatures when the light is turned off. However, the initial state of the sample can be reestablished by increasing the temperature gradually to 11 K. We present temperature and magnetic field dependent transport measurements (Figure 1) and discuss the current voltage characteristics with respect to the inhomogeneous nature of the superconducting state. We compare the data with transport measurements performed recently on a high misscut sample, where we can produce superconducting terraces with a width smaller than the correlation length of the superconductor. This sample can give a hint on quasi 1D filamentary superconducting structures.

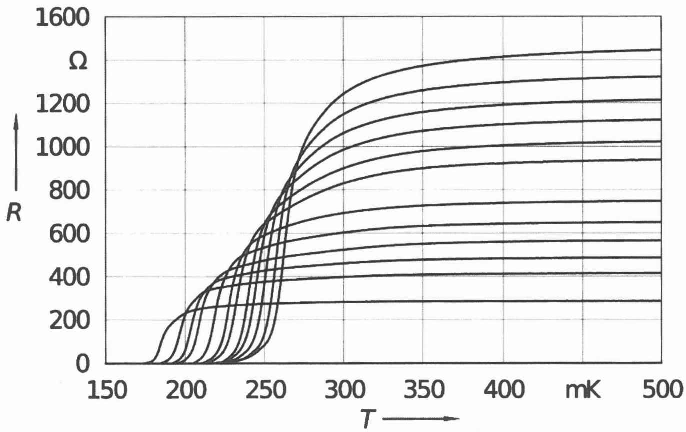

Figure 1: Sheet resistance R over temperature T for different illumination steps.

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Gate-tunable supercurrent in epitaxial Al-InAs-based Josephson junctions

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Coupling an s-wave superconductor to a two-dimensional semiconductor with strong spin-orbit interaction (SOI) offers new technological and research opportunities. Carriers in proximitized semiconductors acquire superconducting correlations while maintaining the charge tunability and the long mean free path typical of high mobility semiconductors. Several exotic phenomena are expected to emerge from the interplay of proximity effects, external magnetic field and SOI. We study SNS Josephson junctions where the SC is epitaxial Al and the weak link in between the banks is an InGaAs/InAs 2D electron gas. A challenge in the fabrication of such devices is the etching of the superconductor, which must preserve the high mobility of the 2DEG underneath. We demonstrate quantum point contacts with a clear crossover from tunneling to Andreev reflection regime and SNS junctions, whose supercurrent can be controlled by gating. A regular Fraunhofer pattern is observed, indicating a good homogeneity of the junction. These results constitute essential building block towards the implementation of more complex topological devices.

Dynamic triplet pairing in long ferromagnetic Josephson junctions induced by FMR

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Hybrid superconductor nanostructures have the potential to overcome the limitations of conventional, dissipative electronic devices. The practical realization of such nanostructures, however, requires a deep understanding of the transfer and the dynamics of spin and charge currents between superconducting and normal metal or ferromagnetic circuit elements.

In particular, we investigate novel spin and charge transport phenomena in superconductor (S) – ferromagnet (F) hybrid nanostructures under non equilibrium conditions. We focus on ferromagnetic Josephson junctions (fJJs), where two superconductors are separated by a ferromagnetic barrier.

It has been established that long range triplet cooper pairs can bridge a long ferromagnetic spacer. These triplet pairs are formed at a static spin active interfaces with a non collinear magnetization. Recently, theoretical predictions hint to the possibility to generate long range triplet pairing in SF hybrid systems via a dynamic coupling of the electron spin to the magnetization of the ferromagnet. This project aims to experimentally investigate this novel phenomenon. The objective is to show that superconducting pair correlations exist in fJJs with a long ferromagnetic spacer with spatially and temporally inhomogeneous magnetization induced by a ferromagnetic resonance. In this special situation, a pronounced supercurrent should be detected in transport experiments under microwave irradiation. Moreover, the experimental determination of the current phase relation of these fJJs provides direct access to their fundamental physical properties, which are studied to evaluate the role of the spin-polarization and the nature of the ferromagnetic spacer.

Thermally induced torques and magnetization dynamics in S/F bilayers

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We study the spin Seebek effect in S/F thin films in the presence of domain walls in the ferromagnet. Such a system can be effectively considered as a Zeeman-split superconductor with an inhomogeneous exchange field. It is demonstrated that in this case the thermally generated spin currents exert a torque on the domain wall. Thermally induced torques have already been reported for nonsuperconducting systems, but it is known that exploiting of superconducting elements can greatly enhance the spin Seebeck effect [1,2] in Zeeman-split superconductors. This also leads to enhancement of thermally induced torques in superconducting hybrids. We develop a microscopic theory of the thermally-induced torque in S/F hybrids. Our results indicate that the presence of superconducting elements influences not only the magnitude of the effect. It appears that the spin-transfer torque influences a domain wall in a qualitatively different way with respect to nonsuperconducting systems. The reason is the presence of superconducting condensate, which is sensitive to a gauge vector potential caused by a magnetic inhomogeneity even in equilibrium, while normal systems do not respond to a static vector potential.

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Strongly non-linear superconducting silicon resonators

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Silicon is one of the most well-known materials, and the main actor in today electronics.

Despite this, silicon superconductivity was only discovered in 2006 [1] in laser doped Si:B samples. Laser annealing is instrumental to cross the superconductivity threshold, as the required doping is above the solubility limit, and cannot be reached using conventional micro-electronic techniques. Laser doping allows the realisation of epitaxial, homogeneous, thin silicon layers (5-300 nm) with extreme active doping values as high as 11 at. %, and without the formation of B aggregates.

Silicon is a disordered superconductor, with a lower carrier density (10^{20} – 10^{21} cm^{-3}) than metallic superconductors, a critical temperature modulable with doping from 0 to 0.7 K, and a resistivity easily matched to the void impedance.

After demonstrating all-silicon SQUIDs and Josephson junctions [2,3], we have realised microwave silicon resonators, working in the 1-10 GHz range and with quality factors of the order of 4000. We have shown a strong non-linear response with power, observing a Kerr coefficient of the order of 300 Hz/photon where less than 1 Hz/photon was expected. This, coupled to Si high kinetic inductance, suggests that, once the losses sources identified and reduced, silicon resonators may be promising candidates for Kinetic Inductance Detectors.

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Dispersive readout of flux vortex dynamics in quantum Josephson parallel arrays

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We are investigating the dynamics of fluxoids in parallel arrays of discrete, nanoscale Josephson junctions (JJPA). The aim of our experiment is to identify different soliton states for a JJPA in the quantum regime, i.e. Ec, Ej > kB*T. We analyze the system both theoretically and by performing high frequency experiments in a dilution refrigerator. In particular, care has been taken to ensure a homogeneous current bias within the microwave readout scheme. We show detailed calculations of the system, preliminary fabrication and measurement results.

High critical field superconducting heterostructures using anodic oxidation

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In-situ growth of Al on top of shallow InAs 2DEG heterostructures gives close to perfect proximity effect between the super- and semiconductors [1-2].
The transparent super/semi interface combined with established customizable 2DEG lithography hold promise to many interesting applications, e.g. topological quantum computation [3-4].
Anodic oxidation (AO) can be used to controllably thin down aluminum, by transforming it to alumina from the top, thus increasing its superconducting properties [2,5-7]. We obtain in-plane critical field > 6 tesla and a perpendicular critical field > 3 tesla on mesocopic structures.
When Al is chemically etched on these heterostructures the underlying InAs is degraded by surface damage [2]. Instead of etching the aluminum, here we show that controllably oxidizing the Al all the way through using AO results in a Hall bar with up to a factor 2 increase in InAs peak mobility and the Hall bar has Quantum Hall effect emerging before 3 tesla.
Besides enhancing super- and semiconducting properties of established devices, this technique paves the way to new research topics, eg. Quantum Hall edge states proximitized by the surface Al with close to unity transparency.

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Induced spin-triplet pairing in the coexistence state of antiferromagnetism and singlet superconductivity: Collective modes and microscopic properties

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The close interplay between superconductivity and antiferromagnetism in several quantum materials can lead to the appearance of an unusual thermodynamic state in which both orders coexist microscopically, despite their competing nature. A hallmark of this coexistence state is the emergence of a spin-triplet superconducting gap component, called a π-triplet, which is spatially modulated by the antiferromagnetic wave vector, reminiscent of a pair density wave. In this paper, we investigate the impact of these π-triplet degrees of freedom on the phase diagram of a system with competing antiferromagnetic and superconducting orders. Although we focus on a microscopic two-band model that has been widely employed in studies of iron pnictides, most of our results follow from a Ginzburg-Landau analysis, and as such should be applicable to other systems of interest, such as cuprates and heavy fermion materials.

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Subgap-state replicas in double quantum dot Josephson junctions

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Recently, we reported for the first time a supercurrent in a double quantum dot (DQD) Josephson junction [1,2]. The junction was realized on an InAs nanowire with epitaxial aluminum leads. The supercurrent was revealed as a zero bias conductance peak due to thermal white noise of the finite resistance metal contacts to the nanowire heterostructure.

While the dependence of the supercurrent on dot occupation was well captured by the two-impurity Anderson model at various gate-tuned tunnel couplings, the behaviour of the subgap states is far more complex. These states exhibit crossings in agreement with the ground state transitions revealed by the supercurrent. However, each pair of states is seemingly replicated up to 10 times inside the gap. The behaviour cannot be understood in terms of a simple convolution of the Yu-Shiba-Rusinov subgap states arising from exchange of each quantum dot with quasiparticles in the closest superconductor. When an external magnetic field parallel to the nanowire is applied, the states cross at zero energy at a field B=0.16 T which is surprisingly independent of the charge on the quantum dots.

Our results suggest that Yu-Shiba-Rusinov states may hybridize with states in the hybrid nanowire-epitaxial Al leads, as previously suggested in single quantum dots [3]. This picture is further supported by the observation of small avoided crossings between replicas and states whose energy does not depend on dot occupation. The results advance our understanding of the spectroscopy of states in the leads via quantum dots [4].

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RLC-resonators as kinetic inductance detectors

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Direct measurement of the magnetic penetration depth on thin films with a thickness $d \ll \lambda$, λ being the magnetic penetration depth, have been challenging ever since. We use a resonant circuit to determine the kinetic inductance of a superconducting thin film meander in the few MHz regime [1]. The meander is patterned into a 5nm thick aluminum film that is grown epitaxially on an InAs substrate hosting a 2DEG and put into series with the rest of the circuit. A small change of the total inductance of the system due to the kinetic inductance $L_{kin} = \mu_0 \lambda^2/d$ of the superconductor below its critical temperature T_c leads to a significant decrease of f_0. The system is sensitive to changes of inductance smaller than 50 pH, which can compete with the accuracy of two-coil mutual inductance techniques [2]. In epitaxial aluminum we find a penetration depth of $\lambda(0) = (210 \pm 10)$ nm in good agreement with the dirty limit theory expectations from the normal state resistivity $R_\square = 9.3\ \Omega$ corresponding to $\lambda(0) \geq (180 \pm 20)$ nm. In strongly disordered aluminum we find $R_\square > 115\ \Omega$ and $\lambda(0) \approx 1.4\ \mu$m and a pronounced suppression of T_{BKT} with respect to the mean field T_{c0}. We analyze $L_{kin}(T)$ and $R(T)$ in the vicinity of the Berezinskii-Kosterlitz-Thouless transition.

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Impurity-induced subgap states in time-reversal-invariant topological superconductors

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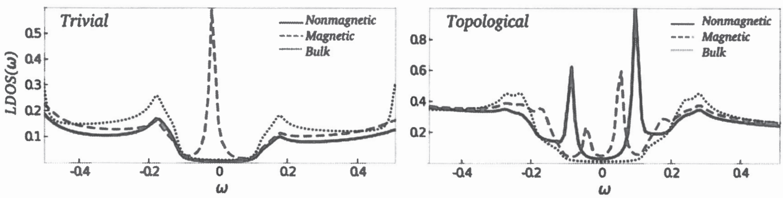
We investigate the role of nontrivial topology on the existence of impurity-induced subgap states in a time-reversal-invariant superconductor (TRIS) with an extended s-wave pairing and strong spin-orbit coupling. The model under study can host three different phases including (i) trivial s-wave, (ii) topological s_{+-}-wave, and (iii) nodal superconductivities [1]. While magnetic impurities give rise to the formation of Shiba state inside the superconducting gap for both trivial and topological phases, however, subgap states can emerge in the presence of nonmagnetic impurities in topological phase as well (see Fig. below). The formation of subgap states attributed to nonmagnetic impurities is a unique property of topological phase and they are absent in the trivial phase in agreement with Anderson's theorem. The underlying physics for the existence of subgap states in topological phase is related to the fact that an impurity can locally change the energy levels which can subsequently result in a transition to the trivial phase. So the bulk-edge correspondence guarantees the appearance of subgap states at the vicinity of the impurity. Based on our results, spectroscopy of nonmagnetic impurities can be used to probe the topological properties of TRIS [2].



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Josephson and quasiparticle currents between *d*-wave superconductors with charge-density waves

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Josephson and quasiparticle tunnel currents in junctions between d-wave superconductors partially gapped by charge-density waves (CDWs) were calculated. Both tunneling in *c*-axis and *ab*-plane directions were treated. Special emphasis was given to the break-junction technique. It was shown that CDWs can be found in measurements of applied voltage, temperature, and angular current dependences. The role of disorder was studied. It turned out that although the parameter spread may smear the CDW-driven peculiarities, the CDW influence could still be detected as the remnants of the strong features appropriate to the pure case and the clear-cut asymmetry of the current-voltage characteristics. The results were partly published in the articles listed below.

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Electronic thermal conductivity in the insulating phase of amorphous indium oxide thin films

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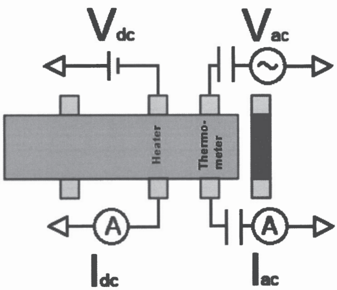
While the thermal properties of bulk superconductors were extensively studied during the last century, measurements on thin, quasi-2D, films and in the insulator were mostly neglected. In this work in progress I use a new method to extract the electronic thermal conductivity κ_{el} of amorphous indium oxide thin films. These films belong to the group of materials which, upon changing the magnetic field, transition from a superconductor to a highly insulating state. This insulator is of ambiguous physical origin and while there are clear indications relating it to the superconducting state it also bears similarities to a many-body localized state: for example the existence of discontinuous current-voltage characteristics (IVs) which manifest the transition from a very insulating state to a different, less resistive, state at a critical voltage V_c. In my measurements I use the quantitative electron-overheating model, fitting nearly perfectly to these IVs, to extract κ_{el}. While I find non-measurable values of the thermal conductivity below V_c, there is a strong increase at higher voltages marking the formation of the less thermally insulating state.



Measuring scheme to extract κ_{el}

Current-phase relation of a graphene rf SQUID inductively coupled to a superconducting resonator

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The interaction between Josephson junctions (JJs) and superconducting resonators is a popular research field in cavity quantum electrodynamics (cQED). For capacitive coupling, when the JJs form superconducting islands, the charge degree of freedom is detected, e.g. for a graphene transmon [1]. Whereas for inductive coupling, JJs embedded in superconducting loops form superconducting quantum interference devices (SQUIDs). In the latter the resonant circuit is sensitive to the current within the loop [2]. In addition, the phase across the JJ can be tuned via external magnetic field and therefore the current-phase relation (CPR) can be explored. There is a growing interest for measuring the CPR in different materials for characterization, since for topological JJs the CPR is predicted to be 4π-periodic whereas it is 2π-periodic for the trivial regime. However, a detailed understanding in terms of measurement parameters, material properties, circuit description and analysis is needed as e.g. relaxation processes or screening effects can mimic the opposite regime. We provide a detailed description of a reflection measurement from a NbTiN λ/4-resonator inductively coupled to a graphene JJ encapsulated in hexagonal boron nitride embedded in a MoRe loop. Via the dispersive frequency shift due to the phase-dependent load impedance, the CPR can by extracted self-consistently taking into account screening effects. Furthermore, we discuss hysteretic and power-broadened regimes and contrast the trivial regime findings with the predictions for the topological one.

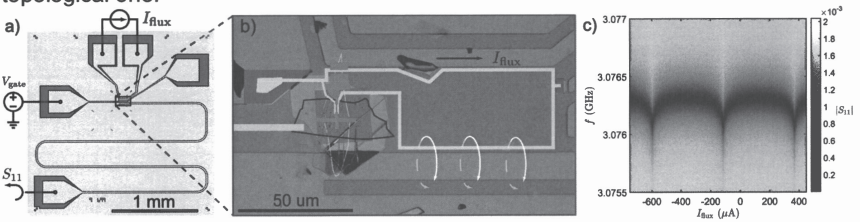

Fig. 1: a) Image of a NbTiN (85 nm) λ/4-resonator with sketched ports for measuring reflection, tuning the gate voltage and the external magnetic field. b) Microscope photograph of the resonator's current anti-node section where the graphene JJ is placed on top of a graphite bottom gate and embedded in a MoRe loop for inductive coupling and phase tunability. c) Typical resonance curve map (Q≈6000) as a function of external magnetic field (induced by the flux current I_{flux}) close to the charge neutrality point.

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Oscillator induced phase transition in a quantum dot Josephson junction

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We investigate the Josephson transport through a suspended carbon nanotube quantum dot–acting likewise as a mechanical resonator–in the presence of an external magnetic field. At sufficiently low temperatures, the transport properties are characterized by the ground state of the electronic subsystem being either in a singlet, doublet, or current suppressing triplet state. We show that the triplet blockade can be lifted by the coupling to the resonator and study the emergence of a triple point, where all three ground states coexist. Furthermore, we demonstrate that this oscillator induced phase transition also manifests in the critical current.

Superconducting proximity effect in hBN-graphene moiré superlattice

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By the alignment of the crystallographic axes of graphene and hexagonal boron-nitride (hBN) a new periodic potential is formed, which leads to a change in the bandstructure of graphene [1]. This change manifests in the appearance of so-called satellite Dirac points, van Hove singularities and a varying Fermi velocity. While such systems are widely studied with normal contacts and scanning-probe techniques, there are few experiments investigating proximity induced supercurrent in a Josephson junction (JJ) geometry. In our work [2], we study hBN-graphene superlattice Josephson junctions with MoRe contacts. In the long junction limit, where the transport channel length exceeds the coherence length, the product of the critical current and the normal state resistance is proportional to the Thouless energy. We show that the combined measurement of the critical current and the normal state resistance reveals signatures of the modified density of states (see Fig. 1) in a hBN-graphene superlattice. Further, we studied the dependence of the critical current on the normal state resistance in a ballistic superlattice by forming a p-n junction in the graphene transport channel.

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Quantum Phase Transitions in Superconducting Quantum Dots

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Quantum dots attached to BCS superconducting leads exhibit a 0-π impurity quantum phase transition, which can be experimentally controlled either by the gate voltage or by the superconducting phase difference. For the pertinent superconducting single-impurity Anderson model, we newly present two simple analytical formulae describing the position of the phase boundary in parameter space for the weakly correlated and Kondo regime, respectively. Furthermore, we show that the two-level approximation provides an excellent description of the low temperature physics of superconducting quantum dots near the phase transition. We discuss reliability and mutual agreement of available finite temperature numerical methods (Numerical Renormalization Group and Quantum Monte Carlo) and suggest a novel approach for efficient determination of the quantum phase boundary from measured finite temperature data. Our results enable fast and efficient, yet reliable characterization and design of such nanoscopic tunable Josephson junction devices.

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Grain Boundaries and Tilt-Angle-Dependent Transport Properties of 2D Mo_2C Superconductor

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The grain boundaries (GBs) of graphene and molybdenum disulfide have been extensively demonstrated to have a strong influence on electronic, thermal, optical, and mechanical properties. However, the GB structure of two dimensional (2D) transition-metal carbides (TMCs) and the influence of GB on their superconducting properties remain unknown.

Recently, we have obtained high-quality 2D ultrathin Mo_2C superconducting crystals by means of CVD method [1-3]. Here, we report on transmission electron microscopy combined with low temperature transport measurements to study the GB characteristic of ultrathin superconducting Mo_2C crystals. We found that 2D Mo_2C superconductor shows unique tilt angle-dependent GB structure and electronic transport properties. Electrical measurements on individual GBs show that GB structure strongly affects the transport properties. In the normal state, an increasingly stronger electron localization behavior is observed at the GB region with increasing tilt angle. In the superconducting state, the magnitude of the critical current across the GBs is dramatically reduced, associated with local suppression of superconductivity at GBs. These findings provide new understandings on the GB structure of TMCs and the influence of GB on 2D superconductivity.

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On a condensation phenomenon of electron pairs in a quantum wire

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In this talk we present recent mathematical results regarding pairs of (interacting) electrons moving in a simple quantum wire modelled by the half-line. More specifically, we start with a pair-Hamiltonian and investigate its spectral properties, showing that the discrete part of the spectrum is non-empty. We then show that the existence of a discrete spectral part implies Bose--Einstein condensation of a gas of free pairs given one treats each pair as a boson. We also present a scenario in which this condensate is destroyed by impurities in the quantum wire. Most importantly, we want to stress on the geometrical and quantum mechanical nature of this result.

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Microwave spectroscopy reveals the quantum geometric tensor of topological Josephson matter

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Concepts like Chern numbers and their relation to physical phenomena have become very familiar, but actually, key quantities like the quantum geometric tensor [1], which provides a much deeper information about quantum states, remain experimentally difficult to access. Recently it has been shown that multiterminal superconducting junctions constitute an ideal playground to mimic topological systems in a controlled manner [2]. We study the spectrum of Andreev bound states in topological Josephson matter and demonstrate that the quantum geometric tensor of the ground state manifold can be extracted with the help of microwave spectroscopy [3]. We develop the concept of artificially polarized microwaves, which can be used to obtain both the quantum metric tensor and the Berry curvature. The quantized integrated absorption provides a direct evidence of topological quantum properties of the Andreev states.

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Electronic transport properties of multiterminal graphene based Josephson junctions

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We present an experimental study of graphene based multierminal Josephson junctions where graphene acts as a weak link between two superconducting electrodes. In our devices, h-BN encapsulated graphene is connected to two superconducting electrodes on two parallel edges and to two normal metal electrodes on the other two edges. This geometry results in two orthogonal junctions, namely superconductor/graphene/superconductor (SGS) junction and normal metal/graphene/normal metal (NGN) junction. Properties of a Josephson weak link can be modified by applying a control current/voltage in the transverse direction to the Josephson junction [1]. In a recent theoretical investigation, multiterminal Josephson junctions have been studied and expected to be a testbed for nonlocal transport processes [2]. We study low temperature electronic transport across SGS junction as a function of control current/voltage across the NGN junction and vice versa. Since charge transport in graphene can be tuned from electron to hole doped regime with an applied gate voltage, it gives us an additional experimental parameter to tune. In our devices, we observe tuning of supercurrent as a function of applied control current/voltage as well as signatures of nonlocal transport processes. We tentatively attribute the observed nonlocal transport features to crossed Andreev reflections. The presumed crossed Andreev reflections are most prominent near the charge neutrality point of graphene weak link, becoming less pronounced at higher charge carrier densities due to the presence of supercurrent.

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Fluctuation Spectroscopy in Superconducting Granular Boron-doped Diamond Films

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Recent experiments on boron-doped nanocrystalline diamond (BNCD) films have explored the superconducting fluctuation contribution, σ_{fl}, to the electrical conductivity of a granular film [1]. Three distinct temperature regimes were observed in the vicinity of the transition temperature, T_c, with sharp crossovers between them. Each region exhibited clear power law dependences upon the reduced temperature $\varepsilon = (T - T_c)/T_c$, namely $\sigma_{fl} \sim \varepsilon^{-1/2}$ in the regions closest to and furthest from T_c, whilst $\sigma_{fl} \sim \varepsilon^{-3}$ for the intermediate region. A natural interpretation of this result involves comparing the size of a Cooper pair, ξ, to the typical grain size, a. Far from T_c, $\xi << a$, and close to T_c, $\xi >> a$, so we expect 3D intragrain and intergrain behaviour, respectively. In the intermediate regime, where $\xi \sim a$, quasi-0D behaviour has been predicted [2].

Using standard diagrammatic techniques for disordered granular materials [3], we consider the effects of superconducting fluctuations in detail. We include both intragrain and intergrain degrees of freedom to investigate both crossovers within a single framework. Our work shows that the simple interpretation described above is not correct, and the situation is rather more complicated:

(1) The Aslamazov-Larkin (AL) term, which is usually dominant in bulk materials, and has the temperature dependence detailed above, is no longer dominant in the quasi-0D and far-from-T_c regions.

(2) The Maki-Thompson (MT) and density of states (DOS) terms determine the dependence of the fluctuation conductivity, σ_{fl}, on reduced temperature, ε.

(3) The detailed behaviour is very sensitive to the temperature dependence of the phase-breaking mechanisms present in the system.

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A diagrammatic approach for transport through quantum dot-based Josephson junctions.

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Studying transport through interacting nanostructures is challenging due to the interplay between strong interactions and the coupling to large thermalized leads. In the case of quantum-dot based Josephson junctions, this is complicated by a number of features particular to superconductors. In the case of strong interactions, the usual mean-field (BCS) theory is unsuited and a particle-conserving framework [1] is preferrable. Furthermore, one has to consider coherent effects between the different leads, which are often neglected when dealing with normal contacts, the non-flat (and non-analytic) density of states of superconductors and the emergence of the time-periodic Ac Josephson effect from a time-independent theory. In this work, we develop a diagrammatic theory [2,3] which captures the features of weakly coupled Josephson junctions and show how these problems are overcome explicitly.

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Unified description of single electron semiconductor devices and Josephson junction devices in the direction of implementation hybrid semiconductor-superconductor quantum computer

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Unified tight-binding and Hubbard formalism with Quantum Field approach on the lattice is employed to study various physical properties of electrostatic position dependent qubits [3] in semiconductor, quantum circuits built from them and study the interface between CMOS quantum semiconductor electrostatic computer and superconducting Josephson junction quantum chips [2]. We are providing the methodology in studying quantum phase transitions and in the performance of quantum algorithms that are to be traced from the point of view physical processes occurring during the computation stages. Particular attention is also paid to quantum neural networks and hybrid classical-quantum neural networks. The concept of programmable quantum matter is illustrated with simulation results. The analogies between single Electron Devices and Josephson junction devices are given [1].

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Fabrication and measurement of high impedance Josephson junctions

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Josephson junctions are key components of superconducting circuits. They exist in a rich variety of shapes, regimes and applications. We have developed a new type of tunnel junctions, where the leads are made from a material with a high kinetic inductance fraction. This additional degree of freedom is especially interesting for long Josephson junctions, but not only, since it allows for tailored properties like for instance a high junction impedance.

We present fabrication results and transport measurements on long Josephson junctions with high kinetic inductance junction electrodes made from disordered oxidized aluminum, which we control with a high precision over a wide range of sheet inductance. Furthermore, we study the system with a focus on highly nonlinear mesoscopic effects such as fluxoid dynamics. Here, also ultra narrow junctions with a large charging energy are of interest, as a possibility to enter the quantum regime.

Channel Analysis of Atomic Palladium Contacts by Andreev Reflections

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For the strong paramagnetic material palladium (Pd) theoretical calculations predicted a local magnetic ordering [1]. In transport measurements a strong non-monotonic magneto-transport behavior as well as indications for Kondo resonances have been reported for atomic contacts in Pd [2]. To get a more detailed view of the nature of this magnetic ordering we want to investigate the transport channel distribution and their spin polarization in such contacts. Therefore we add superconducting leads to apply the method of multiple Andreev reflections [3, 4, 5]. In this contribution I will present first experimental superconducting current-voltage characteristics, revealing superconducting proximity effect into Pd, depending on the exact atomic configuration.

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Dynamic vortex insulator to metal transition in superconducting Nb films with antidote lattices

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We have studied the vortex dynamics and matching effect in superconducting Nb films with antidote lattices with different periods and antidote diameter. It is found that the vortex state can be distinguished into three characteristic regions, i.e., matching region, interstitial region, and surface superconductivity region. In the matching region, a vortex insulator-vortex metal transition driven by the applied electric current has been observed similar to those observed in superconducting island lattice on metal[1]. The effect of applied driven current and temperature on the insulator to metal transition has been studied in detail, and the underlying physics with the insulator to metal transition has been discussed.

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φ_0-contact in S/AF/S junction

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We investigate a Josephson junction through an antiferromagnet in the presence of Rashba SO-coupling. The similar problem has been intensively studied for ferromagnetic interlayers. In particular, the existence of the anomalous phase shift in the ground state was demonstrated. Furthermore, it was realized that the anomalous phase shift is of great interest for superconducting spintronics because provides a possibility for supercurrent control of magnetization and electrical detection of magnetization dynamics.

Josephson current through antiferromagnetic interlayers has already been investigated [1] and it was found that it is highly sensitive to the junction length revealing 0-π transitions depending on the number of atomic layers. However, to the best of our knowledge, the anomalous ground state phase shift in Josephson junction through antiferromagnets has not been reported. In our work a 2D antiferromagnet in (110) orientation is considered as an interlayer. In the framework of two-sublattice BdG formalism we calculate the current phase relation and demonstrate the existence of the anomalous phase shift in the ground state [2]. We find a wide range of parameters where anomalous phase difference $\varphi_0 \sim 1$.

It is found that this effect only exists if the antiferromagnet consists of odd number of layers, i.e. it is uncompensated. The presence of surface magnetization, stemming from broken translational symmetry at interfaces has already been observed experimentally and exploited for applications. However, in our work it is demonstrated that the effect cannot be explained by an influence of just one uncompensated layer and the AF order by itself is of crucial importance for current-carrying Andreev bound states spectra inside the interlayer.

In principle, our findings open a way to Josephson detection of antiferromagnetic inhomogeneities dynamics and investigation of their structure by electrical means.

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Resistive state of SFS Josephson junctions in the presence of moving domain walls

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It has been demonstrated [1] that the domain walls (DWs) can move under the action of the Josephson current in SFS junctions. In particular, in the presence of the spin-orbit coupling in the ferromagnetic interlayer even very small electric currents lower than the critical current jc of the Josephson junction are able to move the walls unless we do not take into account pinning effects. However, the DW motion is a dissipative process. The dissipation occurs via the Gilbert damping term in the Landau-Lifshitz-Gilbert equation. In order to maintain the DW motion a voltage should be generated at the junction even at $j < jc$. Therefore, in the presence of a moving DW the Josephson junction has no dissipationless regime and is in the resistive state starting from the smallest applied currents, which are able to move the wall. In the present work [2] we investigate how anomalous phase difference $\varphi_0(t)$, which depends on time via magnetization, enters current-phase relation as a time dependent generator. We show that via the relation $V = \hbar/2e\, \dot{\varphi}$ it leads to voltage generation that allows for Josephson detection of DWs and other magnetic defects.

We calculate effective resistance of the SFS junction with Rashba SO-coupling and with Neel or Bloch domain wall inside a ferromagnet in the regime $j = const < jc$, and show that this resistance depends only on characteristics of magnetic subsystem. For finite current impulses we analytically obtain time dependence of the voltage at the junction and demonstrate, that it consists of two terms of different origin: the first one is the purely Josephson response to the applied current, while the second term is of magnetic origin and exists only if there is a moving magnetic inhomogeneity inside the junction.

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Phase- and voltage-controlled triplet correlations in a hybrid superconductor-ferromagnet device

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We study charge and heat transport in superconductor-ferromagnet (S/FM) hybrid structures. Firstly, we analyse a bilayer tunnel junction consisting of a spin-split superconductor connected to a spin-polarized ferromagnet and find that spin-flip scattering strongly enhances the thermoelectric response of the system at low temperature and spin-splitting [1]. A large spin-splitting is also obtainable by employing an antiferromagnetic insulator (AFMI) adjacent to a superconductor in an S|AFMI device [2]. The advantage of using AFMs is the minimization of stray magnetic fields which normally accompany ferromagnets. Finally, we investigate the effects of spin-polarized quasiparticles and spin-mixing on the transport properties of a four-terminal hybrid device incorporating two superconductors which are connected to two ferromagnetic leads via a common central normal node. This geometry allows us to induce phase- and voltage-controlled triplet correlations and spin-currents in the system.

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Spin effects in a superconductor in proximity to an antiferromagnetic insulator

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Inspired by recent feats in exchange coupling antiferromagnets to an adjacent material, we demonstrate the possibility of employing them for inducing spin-splitting in a superconductor, thereby avoiding the parasitic effects of ferromagnets employed to this end. We derive the Gor'kov equation for the matrix Green's function in the superconducting layer, considering a microscopic model for its disordered interface with a two-sublattice magnetic insulator. We find that an antiferromagnetic insulator with effectively uncompensated interface induces a large, disorder-resistant spin-splitting in the adjacent superconductor, thereby addressing the feasibility of a wide range of devices involving spin-split superconductors. In addition, we find contributions to the self-energy stemming from the interfacial disorder. Within our model, these mimic impurity and spin-flip scattering, while another breaks the symmetries in particle-hole and spin spaces. The latter contribution, however, vanishes in the quasi-classical approximation and thus, does not significantly affect the superconducting state. Our results illustrate the potential of antiferromagnets for superconducting spintronics avoiding stray fields usually accompanying ferromagnets.

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Rabi oscillations in disordered superconducting nanowire circuits

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At feature sizes of nanometer scale, superconducting wires made from a material with high normal state resistance show a pronounced nonlinear microwave response.

Our material of choice, disordered oxidized (granular) aluminum, is a new material for superconducting quantum circuits which features not only a very high kinetic inductance but also microwave resonators with high quality factors. Microscopically, it can be described as a disordered network of nano-scale aluminum grains, coupled via the Josephson effect.

We demonstrate a new type of superconducting quantum circuit, using capacitively shunted granular aluminum nanowires embedded as nonlinear circuit element. We present circuit characterization in microwave response measurements featuring Rabi-oscillations and measure state life times in the µs range.

Coulomb blockade experiments beyond orthodox theory

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A single electron transistor (SET) can be built by connecting an island with two tunnel junctions to their respective leads and a gate electrode. Previous works were focused on studying all-superconducting (SSS) SET [1] or on a normal island with superconducting leads (SNS) [2]. The contributions to the current through these devices (related to Coulomb blockade (CB)) are quantitatively covered by the orthodox theory in this weak-coupling regime. The strong-coupling regime can be studied by replacing one tunnel junction by a mechanically controlled break junction (MCBJ) [3]. All the coupling regimes can be addressed by opening or closing the MCBJ. In this case, in a SSS SET, new effects not covered by the orthodox theory appear, like for instance multiple Andreev reflection (MAR).

To further investigate the non-orthodox Josephson quasiparticle cycle we design a SSN SET to suppress the Josephson coupling of the island to one of the leads. This should be done by using a Cu lead connected to the island by a Cu oxide barrier. MAR is expected when it's closed and tunneling transport when it's broken.

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Phase-dependent heat and charge transport through superconductor–quantum dot hybrids

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Phase-dependent caloritronics with superconducting circuits has recently received a lot of attention [1,2]. So far, the focus has been on superconducting tunnel junctions that can be described theoretically in terms of noninteracting electrons. Here, we analyze heat and charge transport through a strongly interacting single-level quantum dot coupled to two BCS superconductors at different temperatures to first order in the tunnel coupling [3]. In order to describe the system theoretically, we extend a real-time diagrammatic technique that allows us to capture the interplay between superconducting correlations, strong Coulomb interactions, and nonequilibrium physics. We find that a thermoelectric effect can arise due to the superconducting proximity effect on the dot. In the nonlinear regime, the thermoelectric current can also flow at the particle-hole symmetric point due to a level renormalization caused by virtual tunneling between the dot and the leads. The heat current through the quantum dot is sensitive to the superconducting phase difference. In the nonlinear regime, the system can act as a thermal diode.

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Interplay of Mesoscopic Superconductivity and Coulomb Blockade

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Electrical transport through superconducting quantum point contacts shows a variety of different current contributions depending on the applied voltage. In the subgap regime ($eV \leq 2\Delta$), Cooperpair transport and multiple Andreev reflection (MAR) carry the current, whereas for higher voltages ($eV \geq 2\Delta$) quasiparticles dominate the transport properties.

MAR describes the coherent transport of $m \geq 2$ quasiparticles each carrying an electron charge and sets in at voltage thresholds of $eV = 2\Delta/m$.

Combining this with a single electron transistor (SET), which is due to Coulomb blockade sensitive to single charges, leads to new observations. A SET consists of a small metallic island, contacted via two tunnel barriers. An additional Gate electrode is needed to influence the Coulomb blockade.

We present the fabrication as well as measurements on an all-superconducting single electron transistor, where a mechanically controlled break junction (MCBJ) made of aluminum replaces one of the tunnel barriers. An Al-AlO_x barrier forms the other tunnel contact. Using the MCBJ technique, we can tune the transmission channels and thereby the MAR contributions of the break junction. We address all regimes from weak to strong coupling.

We use orthodox theory [1] to qualitatively describe the weak coupling regime. Extending the theory by incorporating MARs we can identify some of the current signatures in the mesoscopic regime, while the nature of others is still unclear at present [2]. In the strong coupling regime orthodox theory breaks down.

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Domain-Superconductivity in Nb/FePd thin layers with lateral inhomogeneous magnetization

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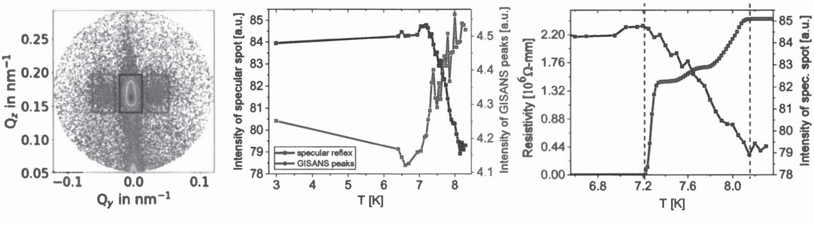
Ferromagnetism (F) and superconductivity (S) have long been considered as antagonist phenomena. When the magnetic state of the F-layer is inhomogeneous, magnetic domains can spatially confine the superconductivity in an adjacent thin S-layer [1]. The lateral magnetic depth profile near the S/F-interface still needs to be investigated further. As a prototype system we use thin film heterostructures of ferromagnetic FePd with a superconducting Nb toplayer. The heterostructures are grown using molecular beam epitaxy on a MgO(001) substrate. FePd is grown in the $L1_0$-ordered phase with a magnetic anisotropy perpendicular to the surface plane [2]. This ensures a lateral magnetic domain pattern. Resistivity measurements as a function of external magnetic field reveal the impact of the magnetic stray fields on the superconducting state, which leads to 2D superconducting effects even in an out of plane applied magnetic field near T_c. To investigate the depth profile of the magnetization in both the Nb and FePd layers we use neutron scattering techniques. Grazing Incidence Small Angle Neutron Scattering (GISANS) gives insight into the lateral magnetic fluctuations, in this case caused by the domain pattern. Zero field cooled measurements show a decrease of intensity in the GISANS peaks in the range of temperature where the resistivity decreases to zero with temperature. This is a strong sign for a change of magnetization in the periodic domain pattern and correlates with an increase in intensity of the specular spot (see Figure 1).



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Phonon traps to reduce the quasiparticle density in superconducting circuits

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Out of equilibrium quasiparticles (QPs) are a main source of dissipation and noise in superconducting circuits, and pinpointing their origin and decreasing their density remain outstanding tasks. The generation-recombination processes of QPs link their dynamics to the phonon dynamics of the circuit + substrate ensemble. We demonstrate that surrounding granular aluminum resonators with lower gapped aluminum islands increases the internal quality factors of the resonators in the single photon regime, suppresses the noise, and reduces the rate of observed QP generation events. The aluminum islands are positioned far enough from the resonators to be electromagnetically decoupled, and we attribute the decrease in dissipation and noise to phonon trapping.

Metallic, superconducting and insulating low-temperature electrical transport response of disordered nanowires

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We test the quantum phase slip model for a superconducting nanowire with a novel method to change the wire resistance in situ. This allows for a stepwise transition from insulating (QPS) over metallic to a superconducting response in about a hundred individual resistance steps. We observe that the critical Coulomb voltage for each resistance value is in good agreement with the QPS model prediction. Furthermore, using this method, we can adjust the critical current for the nanowire up to several hundred nAs.
We will present our experimental results for different wires, with a length ranging from 250 nm up to 1000 nm and a width of about 20 nm.

Dephasing of Andreev bound states revealed by iterative summation of path-integrals

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Multiple coherent reflections of electrons at superconductor/normal conductor interfaces lead to Andreev bound states (ABS), which have an energy that is smaller than the superconducting gap. As Andreev bound states are current-carrying, they may be probed within quantum-transport measurements. Coupling to a normal metal induces dephasing. We investigate a minimal model, which exhibit a tuneable ABS spectrum, i.e. an interacting quantum dot with a single spin-degenerate level that is brought into proximity to a superconductor. Iterative path-integral summations [1-4] are carried out to obtain the tunnelling current. Our method is numerically exact and treats spin-dependent resonant-tunnelling processes in a natural manner [3,4]. We take into account small to intermediate Coulomb interactions. A tunnel-coupled normal metal is used to monitor the spectrum of the quantum dot together with the induced dephasing of the Andreev bound states over a wide range of gate- and bias voltages at finite temperatures [4].

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Fluxoid dynamics in high impedance long Josephson junctions

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The dynamics of Josephson vortices in long Josephson junctions is a well-known example of soliton physics and allows to study highly nonlinear effects on a mesoscopic scale.
We experimentally study the characteristics of a Josephson junction with electrodes having a large kinetic inductance fraction. Here, the London penetration depth exceeds the stack thickness which results in an incomplete screening of magnetic fields, however fluxoid vortices can still exist in the system.
We present transport measurements of long Josephson junctions with electrodes made from disordered oxidized aluminum showing current step with and without external magnetic fields. These resemble the Fiske and zero-field steps of conventional long Josephson junctions.
A possible application has its origin in the large inductance of the electrodes. Here, the junction impedance can be increased to values close to 50 Ohm and therefore allows a matched coupling to waveguides.

Waiting time distribution and current cross-correlations in triple quantum dot-based Cooper pair splitter

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We study the spin-resolved subgap transport in a triple quantum dot system coupled to one superconducting and two ferromagnetic leads. We examine the Andreev processes in the parallel and antiparallel alignments of ferromagnets' magnetic moments in both the linear and nonlinear response regimes. The emphasis is put on the analysis of the electron waiting time and cross-correlations between the currents flowing through the left and right arms of the device. We show that both quantities can give an important insight into subgap transport processes and their analysis can help optimizing the setup parameters for the efficient Cooper pair splitting. Short waiting times for electrons tunneling through the distinct ferromagnetic contacts indicate fast splitting of emitted Cooper pairs, while strong positive values of cross-correlations are associated with the presence of tunneling processes enhancing the Cooper pair splitting efficiency.

Chiral *p*-wave superfluid from *s*-wave pairing in the BEC limit

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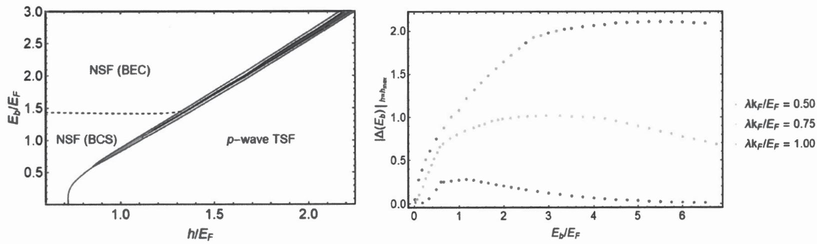
Two-dimensional (2D) spin-orbit-coupled Fermi gases subject to *s*-wave pairing can be driven into a topological phase by increasing the Zeeman spin splitting beyond a critical value [1]. In the topological regime, the system then exhibits the hallmarks of chiral *p*-wave superfluidity [2], including exotic Majorana excitations that are currently attracting great interest [3].

Previous theoretical studies of this realization of the 2D topological Fermi superfluid have focused on the BCS limit where the *s*-wave Cooper pairs are only weakly bound and, hence, the chiral-*p*-wave order parameter has a small magnitude. Motivated by the desire to explore potential new ways for the experimental realization of robust topological superfluids in ultra-cold atom gases, we studied the BCS-to-BEC crossover for this system. We obtain the phase diagram in the parameter space of two-particle bound-state energy E_b and Zeeman-splitting energy h (left figure panel below). Ordinary characteristics of the BEC limit are exhibited in the non-topological regime. In contrast, the topological phase retains all features of chiral-*p*-wave superfluidity even for large E_b. The concomitantly large *s*-wave pair potential Δ results in a significantly more robust *p*-wave order parameter than could be achieved in the BCS limit [4], even for moderate magnitudes of spin-orbit coupling. We identify optimal parameter ranges that can aid further experimental investigations (right figure panel below) and elucidate the underlying physical reason for the persistence of the chiral *p*-wave superfluid.



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