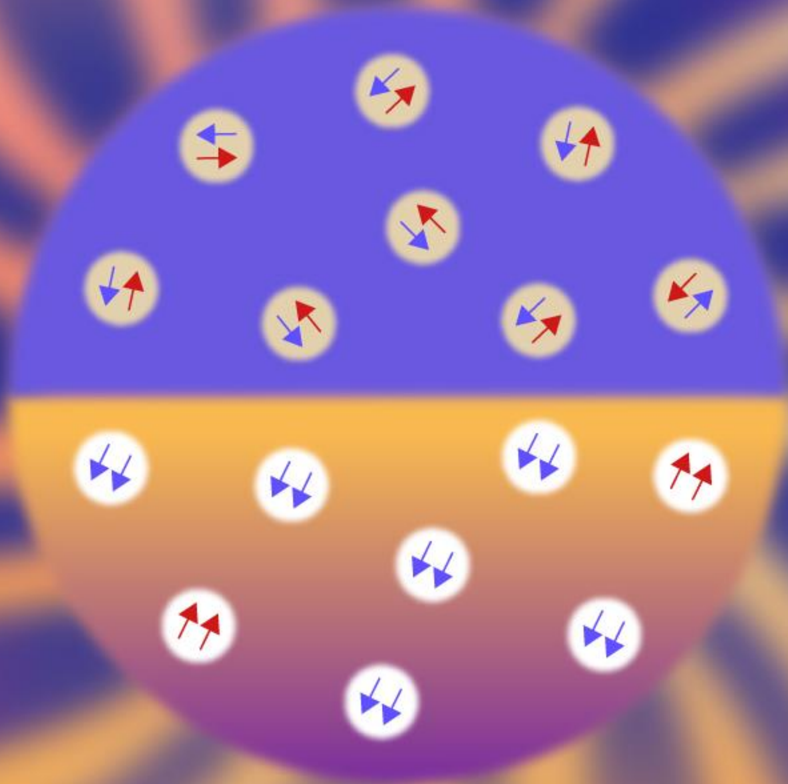
NISE
NANO-SYSTEMS FROM IONS, SPINS AND ELECTRONS



UNCONVENTIONAL SUPERCONDUCTING PHENOMENA

Schloss Ringberg

May 30 – June 2, 2023

Aim of the Workshop

The workshop concerns recent developments in unconventional superconducting phenomena including novel pairing mechanisms, non-reciprocal effects, proximity-induced superconductivity and superconducting spintronics. The workshop includes a discussion of these recent topics from both a theoretical and experimental perspective. Whilst the main focus of the workshop is on the fundamental understanding of these phenomena, there is also great potential for the application of these unconventional phenomena and the materials that support them for potential applications in both classical and quantum technologies at low temperatures.

Start | End Time

We invite you to arrive on Tuesday, May 30th at Ringberg from noon onwards. At that time rooms will be available for check-in.
On Thursday afternoon you are invited to join an excursion to a nearby distillery (registration required). The price for the distillery tour including the tasting is 20 € per person which participants are requested to pay in cash.
The workshop will end on Friday, June 2nd around 1 p.m. (lunch boxes will be provided). Check-out is foreseen after breakfast.

Address | Info on Accommodation

Schloss Ringberg - Schlossstraße 20 - 83708 Kreuth | Phone: +49 (0)8022 27 90 | https://www.schloss-ringberg.de/convention-site/contact

The access code for internet access is available in the reception hall.
Breakfast is served from 8:00 a.m. to 9 a.m.

Munich Airport / Central Station ←→ Tegernsee

For your arrival / departure by public transportation, please check the website of "Deutsche Bahn" at https://www.bahn.com/en. At Munich Central Station, make sure that you board the part of the train going to Tegernsee. Train will be split!

You can buy your ticket online. Your destination is "Tegernsee".

Please take a taxi from the train station "Tegernsee" to the castle.
Taxi Jasinski – tel. +49 (0)8022 / 95 0 99
Taxi Pektas – tel. +49 (0)8022 / 507 14 38

We look forward to welcoming you at Ringberg. Have a save trip and see you soon!

Stuart Parkin

Director, NISE, Max Planck Institute of Microstructure Physics, Halle (Saale)

Tuesday, May 30

Time	Speaker	Topic
		Arrival / Lunch
15:00	Matthew Gilbert	Expanding the Theory of Josephson Diodes: From Classical to Topological
15:45	Marco Aprili	Spin Physics in Superconductors at Nanoscale
16:30		*Coffee*
17:00	Annica Black-Schaffer	New mechanisms and materials for odd-frequency superconductivity
17:45	Christian Schönenberger	Search for topological signatures in superconducting junctions realized with supposably topological materials
18:30		*Dinner*

Wednesday, May 31

Time	Speaker	Topic
08:00		*Breakfast*
09:00	Norman Birge	Games with spin-triplet supercurrent in ferromagnetic Josephson junctions
09:45	Jan Aarts	Supercurrents in a halfmetallic manganite
10:30		*Coffee*
11:00	Takis Kontos	Superconducting proximity effect in the presence of a magnetic texture
11:45	Francesco Giazotto	A Josephson Bipolar Quantum Heat Engine
12:30		*Lunch*
14:00	Julia Meyer	Topological classification for multiterminal Josephson junctions

Time	Speaker	Topic
14:45	Christoph Strunk	Supercurrent diodes and squeezed vortices: insights from inductance measurements
15:30		*Coffee*
16:00		Poster Session
18:30		*Dinner*

Thursday, June 1

Time	Speaker	Topic
08:00		*Breakfast*
09:00	Sebastián Bergeret	Magnetoelectric effects and non-reciprocal transport in superconducting systems
09:45	Piet Brouwer	Non-Abelian holonomy of Majorana zero modes coupled to a chaotic quantum dot
10:30		*Coffee*
11:00	Uri Vool	Hybrid superconducting circuits as probes for unconventional superconductivity
11:45	Angelo di Bernardo	Gate-controlled superconducting currents
12:30		*Lunch*
14:00		**Excursion** to distillery (*registration required*) Edelbrand Destillerie Liedschreiber | Schafstatt 1 | 83703 Gmund am Tegernsee Entrance fee: **20 € per person** (please bring in cash!) Guided tour + tasting of selected products accompanied by local cheese.
18:30		*Dinner*

Friday, June 2

Time	Speaker	Topic
08:00		*Breakfast*
09:00	Sophie Guéron	Long-lived Andreev states in a bismuth nanoring Josephson junction: Evidence for topological hinge modes
09:45	Mathias Eschrig	Geometric Phases and Spin Pumping in Superconducting Spintronics Devices
10:30		*Coffee*
11:00	Daniel Loss	Superconducting Spin Qubits
11:45	Wolfgang Belzig	Magnetic field-induced mirage gap and singlet-triplet mixing in Ising superconductors
		Lunch boxes / Departure

Abstracts

TUESDAY

Expanding the Theory of Josephson Diodes: From Classical to Topological

| Matthew Gilbert

University of Illinois Urbana-Champaign, USA | matthewg@illinois.edu

The resurgence of the Josephson junction as a means of generating chiral or unidirectional current flows has produced a veritable plethora of experimental results covering a broad range of materials. The materials under consideration range from classic spin-orbit coupled metals, like platinum, to complex Dirac semimetals, such as $PtTe_2$, and beyond. Furthermore, one need not be limited to the use of a single Josephson junction as there have been interesting unidirectional currents generated using multiple Josephson junctions coupled through a common material. In this talk, we use a combination of numerical calculations and analytic analysis of these disparate Josephson junctions to elucidate the underlying physics that pervades their diode effects and discuss the limitations on their performance.

Biographical sketch

Matthew J. Gilbert is an Associate Professor in the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign (UIUC). He is affiliated with the Micro and Nanotechnology Laboratory, the Department of Physics and the Institute for Condensed Matter Theory, and the Institute for Quantum Information Science and Technology at UIUC. He is a member of the Technical Advisory Group (TAG) for topological science with the Department of Defense advising on future directions in DoD related research in topology and reviewing ongoing programs. Professor Gilbert has won the Young Investigator Prize from the Army Research Office, the CAREER award from the NSF, and the Bando International Prize Fellowship from the University of Pisa. His current research broadly focuses on theoretically elucidating new phenomena in emergent materials with the goal of developing new types of next-generation quantum information processing and quantum computing systems. Professor Gilbert has published papers in many different areas of physics, engineering, and materials science. His current work reflects diverse interests within engineering and physics that include: understanding the properties of topological materials, including insulators, semimetals, photonic materials, circuits and superconductors, topological electronic and magnetic devices, the strain engineering of 2D materials, designer imprinted topological heterostructures, and the connection between gravitational physics and topology in heavy fermion magnetic materials.

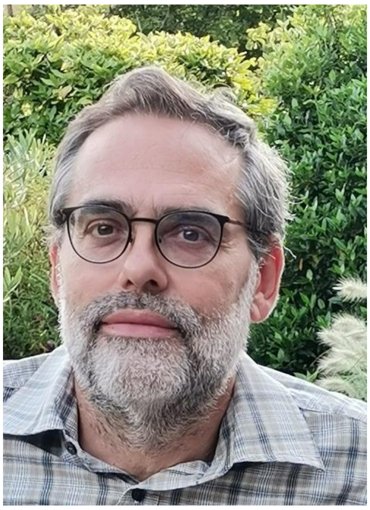
TUESDAY

Spin Physics in Superconductors at Nanoscale

| Marco Aprili

Université Paris-Saclay, France | marco.aprili@universite-paris-saclay.fr

One key aspect in search for topological superconductivity and dissipation-less spin transport is the capability to act directly on the spin degree of freedom of the electrons forming the condensate. In conventional singlet superconductors this can be done through the exchange interaction with an external or an internal magnetic field and through the spin-orbit coupling. For instance, the spin-orbit coupling which is present in 2D materials because of inversion breaking symmetry allows a triplet component of the order parameter to appear. Similarly, the exchange coupling between a magnetic atom and the electrons of a superconductor originate locally spin resolved bound states. Therefore, manipulation of magnetic adatoms on a superconducting surface sounds as an interesting route for non-trivial band structure as theoretically proposed. In this talk I'll present a series of quantum transport and tunneling spectroscopy experiments at nanoscale that address these issues.



Biographical Sketch

Marco Aprili serves as a CNRS Senior Researcher at the Laboratoire de Physique des Solides at the Université Paris-Saclay.

He has been working on experimental condensed matter physics focusing on correlated electron systems, unconventional superconductivity and quantum coherent effects in nano-sized systems. He performed pioneer researches on hybrid devices with competing ground-states. Recently he has been investigating the dynamics of spins, electrons and photons in quantum materials, conductors and circuits.

Manipulating the spin part of the superconducting wave function remains an open question. To address the dynamics of new phases of matter, he proposed a unique set-up based on a scanning tunneling microscope to address quantum electrodynamics at atomic scale. In parallel, he has been studying equilibrium and non-equilibrium spin physics in mesoscopic superconducting devices using quantum transport measurements.

Advances in nanotechnology and quantum electronics are now opening new paths towards artificial quantum materials realized by coupling a large number of circuits to study many-body physics. In these circuits, he has been interested on the strong coupling between microwave photons and quantum transport.

His biometrics include 76 articles in peer-reviewed international journals, 51 invited talks at International Conferences and Workshops, one patent, 7 Lectures at International Summer Schools, and Supervision of 14 PhD students and post-docs.

New mechanisms and materials for odd-frequency superconductivity

| Annica Black-Schaffer

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Odd-frequency superconductivity is a remarkable superconducting phase appearing when electrons pair at unequal times, with the pair amplitude being odd under the exchange of the time coordinates, or equivalently, odd in frequency. Since odd-frequency pairing vanish at equal times it is, in contrast to conventional superconductivity, intrinsically non-local in time and represent a truly dynamical effect. Odd-frequency superconductivity has been realized to be the key to understand the surprising physics of superconductor-ferromagnet (SF) hybrid structures and has also enabled the emerging field of superconducting spintronics. We have identified odd-frequency superconductivity also in many other systems, ranging from doped topological insulators and multiband superconductors, such as Sr_2RuO_4 and UPt_3, to light-driven conventional superconductors as well as due to non-Hermitian effects in superconductor hybrid structures.

Biographical sketch

Annica Black-Schaffer received her M.Sc. from Linköping University and Ph.D. from Stanford University in 2009. After 1.5 years as a Nordita fellow at the Nordic Institute for Theoretical Physics in Stockholm, she secured an assistant professor fellowship from the Swedish Research Council and joined Uppsala University, where she was promoted to Full Professor in 2017. Beyond leading her own research group she is also the chair of the Quantum Matter Theory research program since 2020 and assistant chair of the Department of Physics and Astronomy at Uppsala.

The work in her research group is mainly focused on the mechanisms and properties of unconventional and topological superconductivity, using detailed models to study superconductivity in many different novel materials and superconducting hybrid structures. Her research is funded by the European Research Council (ERC Starting grant, ERC Consolidator Grant), the Swedish Research Council (VR Consolidator Grant 2022), the Wallenberg Academy Fellows program, and the Knut and Alice Wallenberg Foundation. She was also the recipient of the L'Oréal-UNESCO For Women in Science Prize Sweden in 2016 and the Göran Gustafsson prize for your researchers in 2014. More information is available at http://materials-theory.physics.uu.se/blackschaffer.

Search for topological signatures in superconducting junctions realized with supposably topological materials

| Christian Schönenberger

University of Basel, Switzerland | christian.schoenenberger@unibas.ch

We have fabricated superconducting junctions in a range of topological and non-topological materials and measured (a) the current-phase relation in a range of samples and (b) the AC Josephson effect, i. e. the emitted microwave radiation when the junction is DC biased with a voltage V. In this talk, we will emphasize critical parameters that may lead to wrong claims regarding topological superconductivity. For example, we will show measurements of a 4pi-periodic switching current-phase relation (CPR) through an asymmetric SQUID, formed by the higher-order topological insulator WTe_2. Contrary to established wisdom, we show that a high asymmetry in critical current and negligible loop inductance are not sufficient by themselves to reliably measure the CPR. Instead, we find that this system is heavily influenced by additional inductances originating from the self-formed $PdTe_x$ inside the junction.

While there are multiple claims of evidence for the fractional Josephson effect in contemporary literature based on missing odd Shapiro steps, we will show that missing Shapiros steps can be generated even in the most basics non-topological Al-Al-oxide-Al junctions. Further on, we report on our search for AC radiation due to the existence of a 4pi-periodic CPR, which should give rise to a signal at frequency eV/h, instead at the Josephson frequency $2e/h$. The strongest evidence for this effect, the so-called fractional Josephson effect, has been reported in a 2017 publication [1]. However, this experiment has not been reproduced by any group until today. We have tried to do so using different materials: Al proximitized InAs quantum wells, the Dirac semimetal cadmium arsenide, the Weyl semimetal tungsten telluride WTe_2, the 3D topological insulator HgTe, InAs nanowires and carbon nanotubes, as well as conventional Al-based reference Josephson junctions. We have not observed any evidence in these experiments for an emission at half the Josephson frequency! However, we often find signals at similar frequencies due to spurious resonances that form in the environment.

References

[1] *Josephson Radiation from Gapless Andreev Bound States in HgTe-Based Topological Junctions* R. S. Deacon et al. Phys. Rev. X 7, 021011 (2017).

Biographical sketch

Christian Schönenberger is an electrical engineer and experimental physicist by training. He was awarded a Ph.D degree in physics from ETH-Zürich in 1990 for his work conducted at the IBM research laboratory in Switzerland. He then stayed as a postdoctoral fellow and staff researcher at Philips research Eindhoven for 5 years and was then appointed full professor in experimental condensed matter physics at the University of Basel in 1995. At the University of Basel, he leads the quantum- and nanoelectronics group, see *www.nanoelectronics.ch* His research interest is in unravelling fundamental aspects of charge transport in nanodevices by conducting low-temperature quantum transport experiments., both at DC and microwave frequencies. He early on explored hybrid devices by combining superconducting, magnetic and semiconducting materials in nano scaled systems, such as carbon nanotubes, 2D van der Waal's materials and semiconducting nanowires. He is advisor for many public organizations, an elected life-time member of the Swiss Academy of Technical Sciences (SATW) and a fellow of the American Physical Society (APS). He was the director of the NCCR on Nanoscale Science, funded by the Swiss National Science Foundation. He is a co-founder of the Swiss Nanoscience Institute and since its start in 2006 its acting director until summer 2023. He has been awarded two ERC advanced research grants. He has been coordinating many research projects, among them a large Swiss-wide project on bio-chemical sensing using ion-sensitive field-effect transistors which led to two start-up companies.

Games with spin-triplet supercurrent in ferromagnetic Josephson junctions

| Norman Birge

Michigan State University, USA | birge@msu.edu

The theoretical prediction of spin-triplet pair correlations in hybrid systems containing only conventional superconducting (S) and ferromagnet (F) materials [1] launched a new field of condensed matter physics called “superconducting spintronics.” Whereas spin-singlet pair correlations oscillate and decay quickly in ferromagnets, spin-triplet pair correlations extend over much longer distances. Our group was one of several that confirmed the predictions by demonstrating long-range supercurrents in Josephson junctions containing a trio of strong F materials [2,3]. We then showed how to turn the spin-triplet supercurrent on and off by rotating one of the F layers by 90°[4], and how to toggle the ground-state phase across the junction between 0 and π by rotating one of the F layers by 180°[5]. There are still more games to play. If the magnetizations of the three F layers in the junction are non-coplanar, then one should be able to create a so-called “φ_0-junction” with an arbitrary ground-state phase difference [6]. Due to the coupling between the magnetizations and the supercurrent, it should be possible to induce magnetization switching by applying a supercurrent through the junction or by applying a static phase difference across the junction, although this has not yet been achieved in experiments. I will discuss our progress toward making a φ_0-junction [7] and discuss some of the difficulties associated with induced magnetization switching. Finally, if there is time, I may mention our work on simpler junctions containing only two F layers, which also exhibit a controllable ground-state phase difference of 0 or π but cannot produce arbitrary phase states [8].

Work supported by the US DOE under grant DE-FG02-06ER46341, by Northrop Grumman Corporation, and by IARPA via U.S. Army Research Office contract W911NF-14-C-0115.

References

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[2] T.S. Khaire, M.A. Khasawneh, W.P. Pratt, Jr., and N.O. Birge, Phys. Rev. Lett. 104, 137002 (2010); C. Klose et al, Phys. Rev. Lett. 108, 127002 (2012).
[3] M. Houzet and A.I. Buzdin, Phys. Rev. B 76, 060504(R) (2007).
[4] W. Martinez, W.P. Pratt, Jr., and N.O. Birge, Phys. Rev. Lett. 116, 077001 (2016).

[5] J.A. Glick, V. Aguilar, A. Gougam, B.M. Niedzielski, E.C. Gingrich, R. Loloee, W.P. Pratt, Jr. and N.O. Birge, Science Advances 4, eaat9457 (2018).
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Biographical Sketch

Norman Birge received his Ph.D. in 1986 from the University of Chicago, studying the glass transition in supercooled liquids. He changed his focus to electronic transport during his post-doctoral work at AT&T Bell Laboratories. He came to Michigan State University in 1988 and has been there ever since, aside from two sabbatical years with the Groupe Quantronique at the CEA Saclay in France and a COVID-shortened visit with Geoffrey Beach's group at MIT in 2020. His research has spanned several topics in quantum transport and mesoscopic physics, including 1/f noise and universal conductance fluctuations, dissipative quantum tunneling of defects in metals, electron phase coherence at very low temperatures, the superconducting proximity effect, and nonequilibrium phenomena in mesoscopic metallic systems. His current research focuses on the interplay between superconductivity and ferromagnetism in hybrid structures, with an emphasis on the generation and control of spin-triplet supercurrent in ferromagnetic Josephson junctions.

Supercurrents in a halfmetallic manganite

| Jan Aarts

Universiteit Leiden, The Netherlands | *director@physics.leidenuniv.nl*

Fully spin-polarized supercurrents would be a valuable addition to the toolbox of superspintronics. A candidate halfmetallic ferromagnet for this purpose is the perovskite manganite $La_{0.7}Sr_{0.3}MnO_3$ (LSMO), which has mostly been studied in all-oxide combination with perovskite superconductors, in particular $YBa_2Cu_3O_7$. Here we report on various experiments we performed with junctions fabricated from LSMO and superconducting NbTi. Without purposely engineering magnetic inhomogeneity to generate triplet correlations, we still find (strong) supercurrents in junctions with both bar- and disk-shaped geometries with small lengths (of the order of 20 nm, made by Focused Ion Beam), but also in long junctions (up to 1.3 µm) fabricated with e-beam lithography and a hard mask process. Combining oxide magnets with (s-wave) alloy superconductors appears a promising new route to realizing superconducting spintronics.

Biographical Sketch

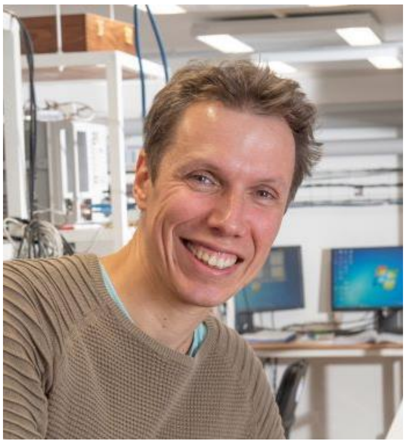
Jan Aarts has been a Full Professor in Experimental Condensed Matter Physics in Leiden since 2004, at present he is Scientific Director at the Leiden Institute of Physics. He has been working in the field of magnetism and superconductivity for a number of years, involving both conventional metals and perovskite oxides.

Superconducting proximity effect in the presence of a magnetic texture

| Takis Kontos

CNRS Paris, France | *takis.kontos@ens.fr*

In this talk, I will describe how one can shape unconventional superconductivity using magnetically textured materials and the proximity effect. I will discuss in particular how superconducting correlations are modified when they are induced in a 1D system - a carbon nanotube - with a magnetic texture or in a chiral antiferromagnet such as Mn_3Ge. The connections with topologically protected quantum computation will also be discussed.



Biographical sketch

Takis Kontos has been a CNRS research director since 2013 and the head of the Hybrid Quantum Circuits group at the physics department of Ecole Normale Supérieure, Paris, France. Dr. Kontos is an expert in hybrid quantum systems in condensed matter, ranging from superconducting/ ferromagnetic heterostructures to electron-photon system in circuit quantum electrodynamics with carbon nanotubes. During the last decade, Dr. Kontos has focused on the implementation of a mesoscopic quantum electrodynamics architecture with mesoscopic circuits, and in particular quantum dot circuits made out of carbon nanotubes. He is also the co-founder and member of the scientific board of the «quantum» start-up C12 quantum electronics which aims to develop spin quantum bits based quantum processors.

A Josephson Bipolar Quantum Heat Engine

| Francesco Giazotto

Superconducting Quantum Electronics Lab, Pisa, Italy
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Thermoelectric effects in metals are typically small due to the nearly perfect particle–hole symmetry around their Fermi surface. Furthermore, thermo-phase effects and linear thermoelectricity in superconducting systems have been identified only when particle–hole symmetry is explicitly broken, since thermoelectric effects were considered impossible in pristine superconductors.

Here, we experimentally demonstrate that superconducting tunnel junctions develop a very large bipolar thermoelectricity in the presence of a sizable thermal gradient thanks to spontaneous particle–hole symmetry breaking [1]. Our junctions show Seebeck coefficients of up to ±300 μV K^{-1}, which is comparable with quantum dots and roughly 10^5 times larger than the value expected for normal metals at subkelvin temperatures [2]. Moreover, by integrating our junctions into a Josephson interferometer, we realize a bipolar thermoelectric Josephson engine generating phase-tunable electric powers of up to ~140 nW mm^{-2} [2,3]. Notably, our device implements also the prototype for a persistent thermoelectric memory cell, written or erased by current injection.

We expect that our findings will lead to applications in the field of superconducting quantum technologies.

We acknowledge funding from EU's Horizon 2020 Research and Innovation Framework Programme under Grant No. 101057977 - SPECTRUM.

References

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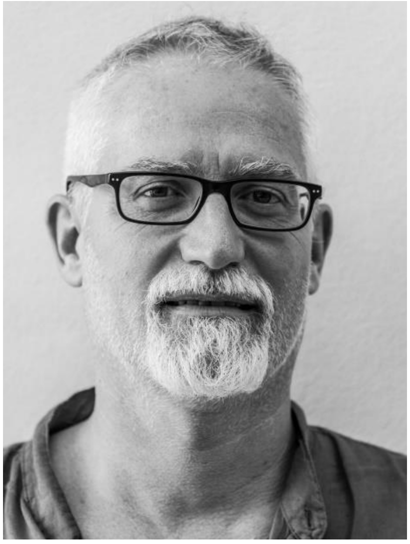

Biographical sketch

Francesco Giazotto graduated in Physics, and got a PhD in Physics (cum laude) in 2002 at Scuola Normale Superiore in Pisa. He is a research director at Istituto Nanoscienze of CNR in Pisa. He was a visiting scientist for various periods from 2003 to 2008 at Aalto University in Helsinki (FI), and in 2011 at University Joseph Fourier in Grenoble (FR). Dr. Giazotto coordinates as Principal Investigator (PI) the activities of mesoscopic superconductivity, coherent caloritronics, electronic refrigeration, ultrasensitive quantum magnetometry, superconducting spintronics, and quantum transport in hybrid systems at ultralow temperatures at NEST laboratory. He has co-authored more than 220 articles in international journals, holds 13 patents on superconducting nanodevices, and has given more than 120 invited talks at national and international conferences. His papers have attracted more than 7650 citations and a 5-years h-index of 44 (Google Scholar). He is also referee of European projects and major international scientific journals. Since 2007 Francesco Giazotto has been PI in 18 projects (▪ 6.5 M€), both European and national. For his research activities in the field of thermal transport at the nanoscale he has achieved an ERC Consolidator Grant in 2013, and an ERC PoC Grant in 2020.

Topological classification for multiterminal Josephson junctions

| Julia Meyer

Université Grenoble-Alpes, France | julia.meyer@univ-grenoble-alpes.fr

Topological phases of matter have been a subject of intense studies in recent years. In many instances, topological properties are encoded in the band structure and one has to find the right material or combination of materials in order to realize them. More recently, an alternative approach to finding and exploring topological states of matter has emerged: namely, one can "imitate" necessary physical ingredients by using other degrees of freedom. Multiterminal Josephson junctions are of interest both as probes of the topological properties of the superconducting leads and as synthetic topological matter. Using the superconducting phases of the terminals in n-terminal Josephson junctions as variables, one may realize topological band structures in d=n-1 dimensions. In particular, we have shown that a 4-terminal junction may realize the analog of a Weyl semimetal, whereas a 3-terminal junction may realize the analog of a Chern insulator. Extending the analogy to more terminals opens the possibility of realizing topological phases in arbitrary dimensions, not accessible in real materials. We classify possible gapped phases and provide an example for a 3-dimensional topological phase characterized by a Z2-invariant in symmetry class C using 5-terminal junctions.

Biographical sketch

Julia Meyer is Professor of Theoretical Condensed Matter Physics at the Université Grenoble Alpes in France since 2009. Before moving to France, she obtained her Ph.D. in Germany at the Universität zu Köln and worked in the United States at the Ohio State University as an Assistant Professor for several years. Her recent research activities focus mainly on hybrid superconducting systems and topological phases of matter.

Supercurrent diodes and squeezed vortices: insights from inductance measurements

| Christoph Strunk

University of Regensburg, Germany | christoph.strunk@ur.de

The recent discovery of intrinsic supercurrent diode effect [1], and its prompt observation in a rich variety of systems, has shown that nonreciprocal supercurrents naturally emerge when both space- and time-inversion symmetries are broken. I will report on ac-manifestations of the diode effect in the non-linear inductance in planar Josephson junctions, based on a ballistic Al/InAs heterostructure that is exposed to an in-plane magnetic field B_{ip} [2]. At low B_{ip} a non-reciprocal term is found in the inductance that is linear in B_{ip}. At higher B_{ip} a sign reversal of the magnetochiral term is observed that can be traced back to a 0-p-like transition in the current-phase relation.

In a small perpendicular magnetic field, also the unpatterned heterostructure features a large inductance which results from the oscillations of pinned vortices around pinning centers. The vortex inductance is inversely proportional to the pinning potential. If a parallel field is applied in addition, the vortex inductance unexpectedly *decreases* in an anisotropic fashion. This observation can be understood as an anisotropic squeezing of the vortex cores, which is consequence of Lifschitz invariants in the free energy of our non-centrosymmetric heterostructure [3].

References

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Biographical sketch

Christoph Strunk graduated on the interplay of superconductivity and magnetism in superconductor-ferromagnet multilayers. During postdoctorals stays in Belgium and Switzerland, he came in contact with mesoscopic physics with a focus on heterostructures of metals, semiconductors and carbon nanotubes. Since 2000, he is a professor of physics at Regensburg University, where he concentrates on mesoscopic superconductivity and the superconductor-insulator transition in recent years. At present, the formation of Cooper-pairs in materials with strong spin-orbit interactions forms a central topic in his group.

Magnetoelectric effects and non-reciprocal transport in superconducting systems

| Sebastián Bergeret

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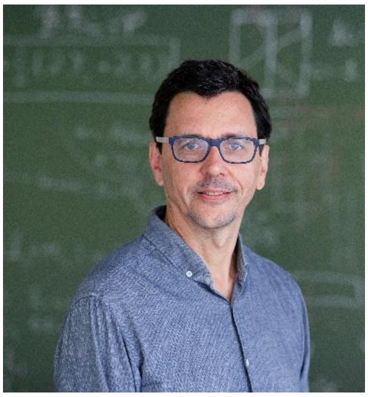
Much attention is being paid to the study of superconducting systems whose transport properties depend on the direction of the supercurrents. Non-reciprocal transport effects have been proposed and observed in various structures, motivated by the creation of a perfect superconducting diode. These systems exhibit a critical superconducting current that depends on the direction of the applied current. Besides potential applications, the physics of non-reciprocal effects is very rich, especially in systems where superconductivity coexists with spin-dependent fields. In this talk, I will discuss the superconducting diode effect and its connection to other closely related phenomena. These include the anomalous current and ϕ-Josephson junctions, the helical phase of Rashba superconductors, and magnetoelectric effects induced by spin-orbit coupling.



Biographical Sketch

Sebastián Bergeret is a Research Professor at the Materials Physics Center in San Sebastian, Spain, specializing in theoretical quantum transport and mesoscopic superconductivity. His seminal studies include predicting the odd triplet superconductivity and anomalous supercurrents in diffusive systems. In recent years, he has focused on electronic charge, spin, and heat transport in hybrid nanostructures that combine superconductors with normal metal, ferromagnets, and semiconductors. In 2021 he was awarded the Frederich-Wilhelm Bessel Prize by the Humboldt Foundation.

Non-Abelian holonomy of Majorana zero modes coupled to a chaotic quantum dot

| Piet Brouwer

Freie Universität Berlin, Germany | brouwer@physik.fu-berlin.de

If a quantum dot is coupled to a topological superconductor via tunneling contacts, each contact hosts a Majorana zero mode in the limit of zero transmission. Close to a resonance and at a finite contact transparency, the resonant level in the quantum dot couples the Majorana modes, but a ground state degeneracy remains if the number of Majorana modes coupled to the dot is five or larger. Upon varying shape-defining gate voltages while remaining close to resonance, a nontrivial evolution within the degenerate ground-state manifold can be achieved.

Biographical sketch

Piet Brouwer is a professor at Freie Universität Berlin and the founding director of the Dahlem Center for Complex Quantum Systems. He is a theoretical physicist, interested in mesoscopic quantum transport, quantum chaos, random matrix theory, the superconductor proximity effect, spintronics and magnetization dynamics, and topological insulators, superconductors and semimetals. In 2009 he received an Alexander von Humboldt Professorship at Freie Universität.

Hybrid superconducting circuits as probes for unconventional superconductivity

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Superconducting circuits are quantum devices that display many of the effects of atomic systems but are made up of macroscopic microwave circuit elements. Their tunability, high coherence, and strong coupling has led to their rapid development as a leading implementation of quantum hardware. Traditional circuits are made using known superconductors such as aluminium or niobium, but the integration of novel superconductors as part of the circuit can lead to new scientific insights and new capabilities. Such hybrid circuits are ideal sensors, capable of measuring the superconducting gap structure of new unconventional superconductors using -sized samples, which have thus far been inaccessible. Once we have good control of the hybrid devices, the unique properties of unconventional superconductors can also be used to make new devices for quantum technology applications. This talk will introduce superconducting circuits and how they can be used as probes of unconventional superconductivity. We will then discuss challenges in combining such materials into devices and fabricating high quality hybrid SCs and how they can be overcome, and present preliminary measurements of hybrid devices.

Biographical sketch

Uri Vool was born in Donetsk, Ukraine and grew up in Jerusalem, Israel. He completed his Ph.D. at Yale University, working in the lab of Professor Michel Devoret and conducting theoretical research with Professor Steven Girvin. Uri's graduate work explored the different kinds of artificial atoms accessible using superconducting circuits. As a John Harvard distinguished science fellow at Harvard University, Uri worked with Professor Amir Yacoby on quantum scanning magnetometry with nitrogen-vacancy centers and the use of quantum information techniques to study condensed matter properties. Uri is currently a Max Planck Research Group (MPRG) leader at the MPI-CPfS in Dresden, leading the Quantum Information for Quantum Materials (QIQM) group.

Gate-controlled superconducting currents

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In conventional metal-oxide semiconductor (CMOS) electronics, the logic state of a device is set by a gate voltage (V_G). The superconducting equivalent of such effect had remained unknown until it was recently shown that a V_G can tune the superconducting current (supercurrent) flowing through a nanoconstriction in a superconductor [1-5]. This so-called gate-controlled supercurrent (GCS) effect has raised great interest because it can lead to superconducting logics like CMOS logics, but with lower energy dissipation.

In this talk, I will review the different mechanisms that have been proposed to explain the GCS effect, and present results obtained from our group which demonstrate evidence for the same effect. I will discuss the importance of physical parameters like spin-orbit coupling, disorder, and surface states for the observation of the GCS effect, starting from a series of experiments that we have systematically carried out on a variety of gate-controlled devices based on elemental metallic superconductors (e.g., Nb), non-centrosymmetric superconductors (e.g., $Nb_{0.18}Re_{0.82}$) and unconventional oxide superconductors (Sr_2RuO_4) and fabricated via different approaches [6].

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Biographical sketch

Angelo Di Bernardo is currently an Associate Professor at the University of Salerno in Italy with a joint affiliation with the University of Konstanz in Germany. Di Bernardo got his Ph.D. from the University of Cambridge in 2016 with a thesis on the investigation of unconventional superconducting states at the interfaces between superconductors and ferromagnets. After his Ph.D., he was awarded a very competitive Research Fellowship by St John's College in Cambridge which allowed him to pursue an independent scientific project for 3 years. In 2019, he was the recipient of one of the six Sofja Kovalevskaja grants from the Humboldt Foundation, which allowsd him to move to Germany and establish an independent research group in Konstanz. His group at the University of Konstanz progressively expanded thanks to the support of other grants from the DFG and the European Union via the FET-Open project SuperGate. Di Bernardo has then become Associate Professor in Konstanz in August 2020, and he has recently been appointed as Associate Professor in Italy with a tenured position starting from May 2023. For his research in the fields of superconducting spintronics and materials systems for superconducting applications, Di Bernardo has been awarded several international prizes including the IEEE Graduate Study Fellowship, the ESAS Prize for Young Researchers, the IOP Brian Pippard Award and the Nicholas Kurti Prize for Europe.

Long-lived Andreev states in a bismuth nanoring Josephson junction: Evidence for topological hinge modes

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A three-dimensional Second-Order Topological Insulator is a 3D material with insulating bulk and surfaces, but topologically protected 1D states which conduct current along the hinges between the crystal surfaces. Those hinge states are counter-propagating helical states in which the spin orientation is locked to the propagation direction. Such states open many possibilities, from dissipationless charge and spin transport to new avenues for quantum computing. Bismuth has been shown to belong to this class of materials [1,2,3]. Adding superconducting contacts to bismuth nanowires has allowed us to reveal the ballistic character of the Andreev states at the hinges, via the sawtooth-shaped supercurrent-versus-phase relation [1,2]. We also recently demonstrated the topological nature of those states in an ac-squid configuration, thanks to the tell-tale high frequency signature of protected Andreev level crossings, a peaked absorption at phase pi [3].

In this talk, I will present our investigation of how helical Andreev edge states differ from spin-degenerate Andreev states of a non-topological ballistic wire [4]. In particular, I will present our use of the statistical distribution of the switching current of a bismuth nanoring Josephson junction to probe the relative occupation probability of different possible states (ground or excited) of the hinge Andreev modes. Using a phenomenological model, we determine the relative relaxation times of pairs and quasiparticles. In striking contrast with non-topological systems for which the pair relaxation is orders of magnitude faster, we find a relatively slow pair relaxation, which we attribute to the spatial separation of the helical hinges, and hence the SOTI character of bismuth. This experiment provides insight into how Cooper pairs must distribute into spatially separate helical Andreev modes to travel through a SOTI.

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Biographical sketch

Sophie Guéron's research focuses on quantum coherent phenomena in mesoscopic conductors, from metals to molecules. Most recently, this includes probing the superconducting proximity effect in graphene-based 2D materials, higher-order topological insulators, as well as detecting orbital magnetism in isolated samples. This research is conducted in collaboration of the members of the Mesoscopic Physics group in Orsay, Université Paris Saclay.

Geometric Phases and Spin Pumping in Superconducting Spintronics Devices

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Superconducting spintronics combines superconducting quantum coherence and lossless transport with spin selectivity and spin magnetism. In contrast to conventional superconducting devices, superconducting spintronics deals with electronic pairs that carry a spin. When a ferromagnet is sandwiched between two superconductors, the spin texture of the interface layers (natural or artificial) can lead to non-coplanar spin arrangement with the ferromagnet magnetization vector. The corresponding geometric solid angle defines a spin-geometric phase that spin-selectively modifies the coupling of superconducting condensate phases across a ferromagnet. This property of spin-geometric phases has the potential to lead to an entirely new branch in superconducting spintronics, introducing new types of control of superconducting devices. In a number of recent experiments unusual behaviour was observed in superconducting spintronics devices when a precession of the magnetisation was induced by ferromagnetic resonance. By using a non-equilibrium Usadel Green's function formalism, we solve for spin-resolved distribution functions and demonstrate that the spin injection process in superconductors is governed by the inverse proximity effect in the superconducting layer. We find that equal-spin Cooper pairs, which are produced by the two misaligned ferromagnetic layers, transport spin inside the S layer. This then results in an increase of the injected spin current below the superconducting critical temperature. Our calculations provide the first evidence of the essential role of equal- spin Cooper pairs on spin-transport properties of S/F devices and pave new ways for the design of superconducting spintronics devices.

Biographical Sketch

Matthias Eschrig completed his Ph.D. at the University of Bayreuth, Germany, in 1997. After postdoctoral research in the U. S. at Northwestern University and at Argonne National Laboratory, he moved in 2001 to University of Karlsruhe (Karlsruhe Institute of Technology) in Germany, where he completed his Habilitation Degree in 2005. After guest professorships at University of Konstanz, he joined in November 2010 the faculty at Royal Holloway, University of London, where he became Full Professor in January 2012. In 2019 he accepted the offer of a Chair in Condensed Matter Physics at University of Greifswald. He acted as founding member and co-director of the Hubbard Theory Consortium, as founding member of the Baltic Consortium of Theoretical Physics, as Fellow of the South East Physics Network in UK, and as member of the Board of Governors of the International Institute for Complex Adaptive Matter. He is presently Deputy Executive Director of the Institute of Physics at the University of Greifswald. In 2015 he was awarded the Lars Onsager Guest Professorship and Lars Onsager Medal of the Norwegian University of Technology.

Superconducting Spin Qubits

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Hybrid systems comprising superconductors and semiconductors are the workhorse of modern quantum technology, with applications in low-power electronics and in neuromorphic and quantum computing. Front-runner quantum bits (qubits) are encoded in the spin of particles confined in semiconducting quantum dots or in collective modes of superconducting devices. Spin qubits are compact but challenging to address, while superconducting qubits are bulky but easy to couple. By combining the best properties of each architecture, hybrid qubits could outperform the state-of-the-art and pave the way toward large-scale quantum processors. In this talk I will present some recent results on superconducting (Andreev) spin qubits in hybrid superconducting-semiconducting systems, in particular, on singlet-triplet spin qubits in double quantum dots coupled by superconductors and in the presence of strong spin orbit interaction[1].

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Biographical sketch

Daniel Loss received his Diploma (1983) and Ph.D. (1985) in theoretical physics at the University of Zürich. From 1989 to 1991 he worked as a postdoc at with Nobel Laureate A. J. Leggett in Urbana, and from 1991 to 1993 at the IBM T.J. Watson Research Center, NY. In 1993 he joined the faculty of SFU in Vancouver, and then returned to Switzerland in 1996 to become Professor of Theoretical Physics (Ordinarius) at the University of Basel where he founded the Basel Center for Quantum Computing and Quantum Coherence (QC2) in 2005. His research interests include spin physics, quantum coherence, and topological effects in semiconducting and magnetic nanostructures, and quantum computing. Loss has an extensive publication record with over 59’000 citations and an h-index of 109. In 2000 he became an APS Fellow, in 2013 Member of the European Academy of Sciences, in 2014 Member of the German National Academy of Sciences Leopoldina, and in 2021 External Scientific Member of the Max Planck Society at MPI Halle. In 2005 he received the Humboldt Research Prize, in 2010 the Marcel Benoist Prize by the Swiss government, in 2014 the Blaise Pascal Medal in Physics from the European Academy of Sciences, and in 2017 the King Faisal International Prize in Science. Since 2012 he holds an honorary position at RIKEN near Tokyo. He is currently co-director of the
Swiss national center on spin-based quantum computing in semiconductors, a field he pioneered in a series of publications starting in 1998 with his work on spin qubits in quantum dots (with DiVincenzo). Their visionary paper led to a new field and is one of the highest cited research papers in quantum computing.

Magnetic field-induced mirage gap and singlet-triplet mixing in Ising superconductors

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Superconductivity is commonly destroyed by a magnetic field due to orbital or Zeeman-induced pair breaking. Surprisingly, the spin-valley locking in a two-dimensional superconductor with spin-orbit interaction makes the superconducting state resilient to much stronger magnetic fields. We investigate the spectral properties of such an Ising superconductor in a magnetic field taking into account disorder [1]. The interplay of the in-plane magnetic field and the Ising spin-orbit coupling leads to noncollinear effective fields. We find that the emerging singlet and triplet pairing correlations manifest themselves in the occurrence of “mirage” gaps: at (high) energies of the order of the spin-orbit coupling strength, a gaplike structure in the spectrum emerges that mirrors the main superconducting gap. We show that these mirage gaps are signatures of the equal-spin triplet finite-energy pairing correlations and due to their odd parity are sensitive to intervalley scattering.

Furthermore, we study a Josephson junction formed by two Ising superconductors that are in proximity to ferromagnetic layer [2]. This leads to highly tunable spin-triplet pairing correlations which allow to modulate the charge and spin supercurrents through the in-plane magnetic exchange fields. For a junction with a nonmagnetic barrier, the charge current is switchable by changing the relative alignment of the in-plane exchange fields, and a pi-state can be realized. Furthermore, the phases of both the charge and spin currents are tunable for a junction with a strongly spin-polarized ferromagnetic barrier.

Finally, we investigate the influence of a triplet-pairing interaction on the Mirage gap and the Josephson effect in layered and planar heterostructures.

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Biographical sketch

Wolfgang Belzig studied physics at TU Karlsruhe (now KIT) and finished with a diploma thesis in the group of Gerd Schön on superconducting proximity effects in 1995. He obtained his PhD on the topic of unconventional superconducting heterostructures at the same institution in 1999. After that he spent two years as Feodor-Lynen-Fellow and FOM postdoc at TU Delft working with G.E.W. Bauer and Yu. V. Nazarov. In 2001 he joined the group of Christoph Bruder at University of Basel, where he obtained his Habilitation on superconductor-ferromagnet heterostructures in 2003. In 2005 he was awarded an SNF Assistant professorship at the University of Basel, received the Walter-Schottky prize of the German physical Society and accepted an offer for a tenured W3 professor position at the University of Konstanz. From 2012 until 2019 he was spokesperson of the DFG-funded collaborative research center SFB 767 Controlled Nanosystems and since 2021 is the spokesperson of SFB 1432 Fluctuations and Nonlinearities in Classical and Quantum Matter beyond Equilibrium. In 2012 he received the APS Outstanding Referee Award of the American Physical Society. From 2015-2021 he served on the Walter-Schottky-Award committee and as Member of the Council of the German Physical Society.

Poster abstracts

Josephson Diode effect and Bilinear Magnetoelectric resistance in Bismuth nanowires

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We have measured the field dependence of the critical current of a bismuth nanowires under superconducting proximity effect for different field orientations. This field dependence exhibits a large asymmetry in magnetic field depending on the sign of the current (so called Josephson Diode effect). The shift in the Josephson interference pattern of critical current can be interpreted in terms of an effective magnetic field superimposed to the applied one.

In order to investigate the influence on this effect of the large spin orbit coupling present in the material, we also, performed magneto-electric experiments on the same nanowires in the normal state. This was does by measuring the linear field dependence of the second harmonic response in V(I) with an ac current excitation. This quantity is directly related to the bilinear magnetoresistance expected in large SO non-centro symmetric materials giving rise to current spin polarization (Edelstein effect) and can be interpreted as the existence of an effective field acting on the spins and proportional to the current like in the S state.

We analyze this effective magnetic field for different orientations of the applied magnetic field. These experiments reveal a similar behavior in the N state compared to the S state whereas the amplitude of this effective magnetic field is different for both experiments.

The combination of these experiments in the suggest that Bismuth nanowires present an Edelstein effect both in the normal state and the superconducting state.

Supercurrent diode effect in a 1d array of three-terminal Josephson junctions

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We present DC transport measurements of an 1d array of three-terminal Josephson junctions based upon an epitaxial Al-InAs heterostructure. Two terminals are connected via a superconducting loop. Under the influence of perpendicular magnetic fields the critical current displays a complex diffraction pattern resembling the superposition of a Fraunhofer pattern-like envelope and SQUID oscillations. In the presence of an additional in-plane magnetic field this pattern develops asymmetries: The main lobe shows clear supercurrent diode behavior, which results in different critical currents depending on the applied current direction. At higher magnetic fields we observe a pronounced sign change of the supercurrent diode effect, as well as a markedly asym-metry of the side maxima of the envelope. The latter means, that with increasing in-plane magnetic field the critical current is enhanced for one polarity of the perpendicu-lar magnetic field.

Josephson diode effect in 2D materials

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Ever since the isolation of graphene using the famous scotch tape technique, 2D materials have attracted a lot of attention from the scientific community. 2D materials like metal, semimetals and insulators with respect to the different band dispersion in the momentum space and the ferromagnetic, antiferromagnetic and diamagnetic van der waals crystals depending on the magnetic properties, make the 2D materials space a very interesting and exciting landscape to work with. Breaking of symmetries at the interfaces or in the bulk and proximity effects have become one of the most sought-after avenues for research in the 2D materials space. In my poster, I shall discuss the discovery of a giant Josephson diode effect (JDE) in $NiTe_2$, a type-II Dirac semimetal. The field and angular dependence of the JDE are accounted for by a model based on finite-momentum Cooper pairing that largely originates from the Zeeman shift of spin-helical topological surface states.

Nonreciprocal Hall Effect in the superconductor/ferromagnet Heterostructure

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Heterostructures constructed between superconductors (SCs) and ferromagnets (FMs) display exotic physical phenomena, including Bogoliubov quasiparticles, superconducting vortex, FFLO states, spin-triplet superconductivity, and Majorana states. Nonreciprocal transport mediated by spin polarized supercurrents in SC/FM heterostructures could be realized in the nonlinear regime by AC transport measurements. Here we present a heterostructure between multiferroic and superconducting materials, which could realize a nonreciprocal Hall effect in DC transport measurements.

1D boundary modes in van der Waals heterostructure

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Engineering atomically flat interfaces by stacking different materials presents a promising route to create exotic states of matter such as topological superconductivity [1,2,6,7], quantum spin liquids [3], unconventional superconductivity [4], vortex-oriented ferroelectricity [5], etc. Here, we use molecular beam epitaxy to create a van der Waals heterostructure comprising of monolayer 2D ferromagnet $CrCl_3$, coupled to a 2D superconductor $NbSe_2$. The structural and electronic properties of the heterostructure are investigated by low-temperature scanning tunneling microscopy and spectroscopy. Our measurements reveal an enhancement of the zero-bias conductance (ZBC) at the edge of monolayer $CrCl_3$ islands as compared to that of the bulk $CrCl_3$ and the $NbSe_2$ substrate. We study the magnetic-field dependence of this ZBC as a function of the magnetic field. We observe that the edge mode tends to fade away by progressively increasing the strength of the magnetic field, and completely disappears once the superconducting state is quenched. Overall our results reveal an intimate link between the emergence of zero energy edge modes and proximity-induced superconductivity in $CrCl_3$ and are consistent with previous reports of Majorana zero energy modes in 2D which are localized near the edge of the magnetic islands and features dispersing 1D mode along the edge that traverses the superconducting gap [6,7].

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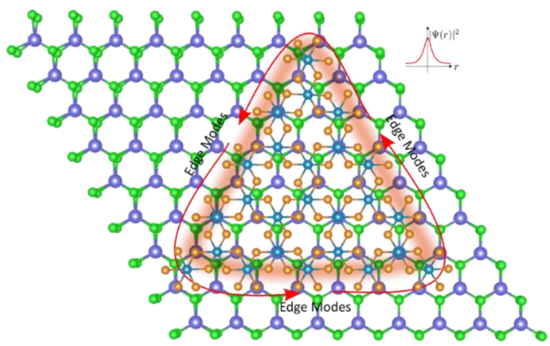

Phase coherent transport in chiral topological metals

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The recent discoveries of topological phases, such as topological insulators and (semi)metals, have opened up new possibilities for the next generation of electronics. The wave-like nature and collective interacting behavior of electrons at the mesoscopic scale in these phases provide us with new degrees of freedom (DOF) in-addition to charge and spin. Understanding these DOF and developing strategies to manipulate them is essential to create efficient and low-noise electrical devices. In this poster, I will introduce a new class of material called chiral topological metals (CTM) and their fascinating electromagnetic responses. Its topological nature arises from multifold band crossing near the Fermi level at high symmetry points in the Brillouin zone. The collective behavior of the electrons near these crossings gives rise to chiral fermions. These metals can generate spin currents under longitudinal electric and magnetic fields due to the phenomenon known as the chiral anomaly. However, these spin currents are localized, short-lived, and often masked by electrical transport in the trivial bulk bands. My poster aims to identify the charge transport in these topological states and understand the phenomenon of the chiral anomaly in CTM. It presents experimental strategies based on focused-ion beam crystal micro-sculpting to study the symbiosis of crystallographic chirality and band topology in CTM during electrical transport measurements.

Magnetic topological structures in a room temperature ferromagnetic 2D material

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Magnetic textures such as Skyrmions are known for being topologically protected and can be utilized in memory devices such as racetracks. This has resulted in substantial research and development of the field. The investigation of 2D van der Waals magnets gives the added benefit of flexibility and possibility to stack any combination of materials. The recent finding of Skyrmions in the itinerant ferromagnet Fe_3GeTe_2 (FGT3) raises questions regarding its sibling materials with varying iron concentration. Fe_5GeTe_2 (FGT5) is a strong candidate for usage in practical applications since it is ferromagnetic at room temperature. To study the properties of this material we have done transport measurements, extensive XRD structural analysis, HRTEM study and deployed Magnetic imaging techniques like LTEM, MFM and STXM. We report the existence of magnetic bubbles of types I and II in the material. In addition, we have conducted an extensive thickness-dependent analysis of FGT5 flakes, demonstrating the presence of intriguingly different states. We have in total observed three distinct states in the room temperature ferromagnetic 2D Van der Waals magnet Fe_5GeTe_2. At low thickness it has a very large domain state. As Fe_5GeTe_2 flake thickness crosses around 30 nm it becomes a stripe domain. Further increasing thickness results in the increment of stripe domain size. At the bulk limit it achieves a fractal magnetic state.

Temperature dependent dynamics of chiral magnetic textures

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The effective control on dynamics of magnetic structures are the cornerstone of next generation magnetic random-access memory devices, e.g. racetrack memory. Through electrical current injection, the chiral magnetic structures such as magnetic domain walls and skyrmions, which serve as data bits, can be well motivated in the racetrack memory and thus realizing the writing and reading of information. Recently, proposal for cryogenic racetrack device, which incorporate the dissipationless spin supercurrent to motivate the magnetic structures, has attracted much attention since it combines the advantage of superconducting and spintronic devices, such as ultra-low energy consumption and non-volatility. It will be of great importance to look into the temperature dependence of current-induced magnetic dynamics since it will be instructive for future design of cryogenic racetrack memory device. In this work, the temperature dependent magnetic dynamics of chiral domain walls in ferromagnetic and ferrimagnetic systems are investigated.

Chiral domain-wall logic and memory technologies II – Summary of recent progresses in racetrack memory development projects

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Due to the soaring demands of data process and storage in the era of information, we need radical solutions to go beyond complementary metal-oxide semiconductor (CMOS) based binary memory and computing technologies. More than a decade ago, the innovative concept of racetrack memory was proposed [1], and it has led to the unveiling of domain-wall-dynamics related physics, as well as the development of novel electronic devices in the field of spintronics – for example, spin-torque-driven domain wall motion. In spite of the great number of scientific and technological publications about racetracks, there lack realistic approaches to bring this technology into the landscape of microelectronic applications. Here, we provide solutions to long-lasting technical challenges on racetracks. Within our collaborations with Samsung electronics and Fraunhofer institute, we have invested considerable efforts to overcome critical aspects regarding racetrack memory technology. In particular, we focus on (1) lowering operation energy while increasing thermal stability, (2) device integration process and smart designing, (3) understanding domain wall dynamics at nm-scale, (4) controlling and understanding the stability of information bits, (5) developing new materials and interfaces for more efficient device operation, and (6) large scale (300 mm wafer technology) device integration. We summarize our very recent progress within these projects and discuss how racetrack technology can be functional beyond current binary computing technologies.

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Magnetization dynamics and spin-triplet Cooper pairs in ferromagnetic Josephson junctions

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Recent breakthroughs in superconducting hybrid structures have demonstrated the possibility of bridging the gap between the conventionally opposing magnetic and superconducting orders. Interfaces between s-wave superconductors and magnetic materials facilitate the conversion of singlet Cooper pairs into triplet Cooper pairs [1,2]. The interaction between spin-polarized triplet pairs and magnetic spins can lead to exciting applications and the emergence of super-spintronics [3,4]. Although previous studies have shown that magnetic order can affect spin-polarized supercurrent [5, 6], the inverse relationship remains largely under-explored experimentally. Furthermore, investigations at cryogenic temperatures present challenges due to the emergence of new types of electromagnetic coupling [7]. In this experimental study, we aim to combine established devices, such as magnetic racetracks and ferromagnetic Josephson junctions to further examine the interplay between magnetic states and superconducting condensates. We explore the potential applications of these devices in sensing and manipulation of magnetic structures at low temperatures.

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Proximity-Induced Odd-Frequency Superconductivity in Bi_2Se_3

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Inversion symmetry breaking at an interface with a superconductor can allow superconductivity to change dramatically and exhibit novel correlations. One of these is the formation of odd-frequency pairing, exhibiting a paramagnetic Meissner effect. Experimentally, we can probe this effect directly by using low energy muon spin spectroscopy to measure the Meissner screening profile. I will illustrate this on the example of a proximity-induced superconducting state in a thin layer of the prototypical topological insulator, Bi_2Se_3 proximity coupled to an adjacent Nb layer. From depth-resolved magnetic field measurements below the superconducting transition temperature of Nb, we observe a local enhancement of the magnetic field in Bi_2Se_3 that exceeds the externally applied field, thus supporting the existence of an intrinsic paramagnetic Meissner effect arising from an odd-frequency superconducting state. Our experimental results are complemented by theoretical calculations supporting the appearance of such a component at the interface which extends into the topological insulator.

Engineered Heterostructures of Oxide Interfaces for Superconducting Applications

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Utilizing the power of molecular beam epitaxy (MBE) and the in-situ characterization facilities, we grew high -quality oxide interfaces of very smooth surface. The proximity effect of such interfaces coupled with various superconducting candidates is studied. Despite a reduction of the superconducting transition temperature (T_c) is observed, however various interesting properties may evolute at the interface. The main purpose of this work is to prop the interface dynamics and to search for potential oxides candidates valid for generating spin-triplet superconductors.

Influence of van Hove singularities on superconductivity in type-II Dirac semimetallic transition metal dichalcogenides

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Presented here are experimental ARPES results on the type II Dirac semimetals $NiTe_2$ and $PdTe_2$ showing the 3D dispersion of van Hove singularities (vHS) close to the Fermi level (EF). A vHS corresponds to a singularity in the density of states, and the position of this relative to EF is known to increase the stability of superconductivity. Shifting this anomaly closer to EF through Cu intercalation of $PdTe_2$ has been shown to result in an enhanced Tc [1]. However, we find that the position of the vHS in non-superconducting $NiTe_2$ is much closer to EF than in pure or doped $PdTe_2$, suggesting that the vHS is not the key factor determining superconductivity in these compounds. Finally, we show that the position of the vHS in $NiTe_2$ remains unchanged upon deposition of an Al layer, making it a promising candidate for studying proximity-induced superconductivity.

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Chiral domain-wall logic and memory technologies I – Fundamentals of domain wall motion and the role of interface engineering

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The manipulation of magnetic domain walls by electric currents has led to the development of domain-wall-based racetrack memory and logic technology [1], that has the potential to introduce advanced functionalities while reducing the energy consumption of conventional microelectronic applications. Increasingly sophisticated interface engineering of thin films has allowed the rapid evolution from the initial racetrack systems based on in-plane magnetized materials, to advanced multi-layered films with perpendicular magnetic anisotropy, and eventually to synthetic antiferromagnets [2]. Despite the extended scientific investigation of domain wall motion in different systems – including ferrimagnets, 2D materials, antiferromagnets – a device which fulfils the requirements for the technological implementation of racetracks is not realized yet. In order to step forward to successful implementation, we review the principles of current-induced motion of chiral domain walls in multi-layered racetrack devices, which show enhanced efficiency due to the simultaneous occurrence of spin-orbit torque, Dzyaloshinskii-Moria interaction and exchange coupling torque. In particular we focus on the role of interfacial interactions, which is critical for the magnetic properties and domain wall motion of racetrack devices. In addition, we show that careful interface engineering of synthetic antiferromagnets is of paramount importance to increase the efficiency of current-induced domain wall motion, as well as allow the integration of racetrack devices with magnetic reading sensors.

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

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Describing the physics of strongly correlated quantum systems requires a deep understanding of the interplay between dissipation, magnetism and electronic structure. Probing their correlations is a major challenge, as most forms of microscopy image only one parameter at a time. We are developing hybrid microscopes that combine SQUID-on-tip with STM and AFM, to simultaneously image magnetic field, temperature and density of states.

SQUID-on-tip microscopy is a powerful type of scanning probe imaging where a nanostructured superconducting magnetometer is directly scanned over the surface of a sample. Both magnetic and thermal images can be extracted from the acquired data. This enables the study of transport, dissipation and magnetism. SQUID-based microscopy has been successfully applied to imaging vortex matter, quantum phase fluctuations and electron hydrodynamics. In our lab, we are constructing two setups to respectively combine SQUID-on-tip with scanning tunneling spectroscopy (STS) and atomic force microscopy (AFM). These are well-established techniques for measuring topography and carefully controlling the tip-sample distance. The approaches are complementary: while STS allows for mapping the local density of states, AFM can explore nanostructured quantum devices. These hybrid approaches to SQUID-on-tip will allow for versatile studies of quantum phase transitions, time-reversal symmetry breaking, and exotic transport phenomena.

We have succeeded in fabricating SQUIDs at the apex of a silicon tip using focused-ion-beam milling. Our probes show excellent magnetic and thermal sensitivity, and a 120 nm device diameter. As the device diameter is the limiting factor in the spatial resolution, these probes are promising for high-resolution hybrid imaging.

Anisotropic vortex squeezing in synthetic Rashba superconductors

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In this work, we demonstrate the interplay of spin-orbit-interaction and in-plane magnetic field in synthetic Rashba superconductors. We investigate the vortex inductance of epitaxially grown Al/InAs heterostructures containing an high-mobility surface-near InAs quantum well covered with a epitaxial layer of aluminum. An ac-current drives vortex oscillations around pinning centers which can be probed via inductance. The vortex inductance was found to be orders of magnitude larger than the kinetic inductance. When applying an in-plane field, the vortex inductance drops in particular for fields applied perpendicular to the AC current, signaling an increase of the pinning force. With respect to the angle between magnetic field and ac-current, a prominent two-fold anisotropy is observed. The unusual behavior of the vortex inductance signals a deformation of the vortex cores and can be theoretically explained by introducing an additional term in the Ginzburg-Landau free energy of a superconductor, resulting from the Rashba spin-orbit interaction [1].

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Search for Majorana flat bands on the side surface of nodal superconductors

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The search for Majorana bound states in topological superconductors has been challenging because energy-dependent signatures, such as zero-bias anomalies, can also have alternative trivial origins. However, in nodal superconductors, topological edge modes are predicted to have a characteristic momentum dispersion that could in principle be resolved with angle-resolved photoelectron spectroscopy (ARPES): They only exist in-between the projection of two spectral nodes with opposite topological charge, but not between nodes of the same topological charge. As a result, there is a characteristic presence and absence of Majorana states in subsequent projections of the spectral gap. Due to their large energy degeneracy, these flat-bands could also act as a sensitive probe for the correlations in the bulk.

However, preparing clean side surfaces of nodal superconductors where these Majorana states could be observed has been a great technical challenge. Using a new sample preparation technique, we have recently obtained the first Fermi-surface spectrum on the [110]-side surface of a high-Tc superconductor, which sets the stage for the search for its predicted topological surface states.

Rashba spin-momentum locking and non-reciprocal 0-π Josephson junctions in 1T-$PtTe_2$

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In recent years, there has been a renewed interest in using supercurrent diodes as building blocks for superconducting classical computers that can be much more energy-efficient. While there have been a lot of reports on the observation of a superconducting or Josephson diode effect in different material systems, which claim to be based on the inversion and time-reversal symmetry breaking of the system, there could also be extrinsic factors at play that can simulate these effects and lead to non-reciprocal supercurrents based on device architecture. In this work, we study the current-phase relationship in Josephson junctions of a two-dimensional Van der Waals material 1T-$PtTe_2$ that has helical spin-momentum locking. The presence of Rashba spin-momentum locking in the system is revealed by probing the Josephson diode effect in $PtTe_2$ in various configurations. We also show that it is possible to obtain a non-zero Josephson diode effect due to the measurement geometry, which is purely extrinsic in origin and that it has nothing to do with electronic structure of the junction material itself. Hence, a careful examination of the origin is necessary before using the Josephson diode effect as an effective tool to assert material properties. Further, we also show that there is a non-reciprocal phase accumulation in the system that leads to the Josephson diode effect and that the supercurrent distribution is different along opposite directions.

Near field light matter interaction of strongly correlated materials

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Strongly correlated materials exhibit remarkable physical properties such as high-temperature superconductivity and metal-insulator transitions, which are of great interest in the scientific community. Our research focuses on the investigation of these materials using near-field optical microscopy, which allows for the exploration of light-matter interactions with high spatial resolution. Using a scattering-Scanning Near-Field Optical Microscope (s-SNOM), we can measure the near-field optical interactions between a sharp probe and the sample to obtain information about the electronic structure, conductivity, optical absorption, and scattering properties of the sample. Our aim is to gain valuable insights into the local electronic properties of the materials, which can help in understanding the local interactions that lead to global phenomena. In this study, we are using s-SNOM to visualize and investigate the low-temperature electronic phases and superconducting transition of the high-Tc superconductor YBCO. Through our research, we aim to provide novel approaches for manipulating the electronic properties of strongly correlated materials.

Controlled and Quantified Mechanical Exfoliation of 2D Materials

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Two-dimensional (2D) materials are a highly researched topic in physics and materials science due to their unique properties. These materials can be mechanically exfoliated and stacked with other layered materials to create artificial van der Waals (vdW) heterostructures with different physical properties, such as semiconducting, insulating, metallic, superconducting, and magnetic materials. However, not all 2D materials can be easily exfoliated or transferred by traditional methods, such as high-temperature superconducting materials, due to their strong interlayer interactions or reactive chemical properties. Moreover, manual exfoliation and transfer can be time-consuming and require skilled researchers. Therefore, there is a high demand for automatic techniques to prepare 2D materials and their heterostructures.

In our study, we aim to develop a nanoscale piezoelectric displacement stage to precisely observe and control the mechanical exfoliation process. Additionally, we plan to build an in-situ dry transfer setup that will allow us to perform material exfoliation, searching, transferring, and encapsulation continuously and controllably in unconventional operating environments, such as inert gas atmospheres. Our ultimate goal is to develop a controllable mechanical device for the preparation of unconventional 2D materials. This full-automatic method will significantly enhance the efficiency of our research and enable us to further explore unconventional phenomena, such as superconductivity in 2D systems.

Modified Coulomb interaction via carrier and dipole screening in both 2D and 3D case

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With the shrink of dimensionality, Coulomb interaction is greatly enhanced owing to reduced dielectric screening and spatial confinement. As a basic interaction, the enhanced Coulomb interaction plays a more significant role in electronic properties of the 2D materials than their 3D counterparts, usually determining many fantastic optical and electric properties in 2D case, such as giant band gap renormalization, superconducting related properties. In contrast to three-dimensional (3D) cases where the macroscopic Coulomb screening is well described by a single macroscopic dielectric constant ε_r, more accurately a permittivity tensor in the modified Coulomb potential, the macroscopic screening in 2D dielectric cases is highly nonlocal and the induced polarization is confined to the 2D plane, resulting in a suppression of dielectric screening in the out-of-plane direction. This contrasting polarization in 2D is widely described in the form of Rytova-Keldysh potential, $(V_{2D}(r, z=0) = -\frac{e^2}{8\varepsilon_0 r_0}\left[H_0\left(\frac{\varepsilon_r r}{r_0}\right) - Y_0\left(\frac{\varepsilon_r r}{r_0}\right)\right])$. When free charged carriers exist, the screened Coulomb potential is further modified. In a 3D system this is well described by the Thomas-Fermi model or Lindhard theory. Here, we successfully extend the screened Coulomb potential in 2D case, taking both free carriers and excitons/dipoles into account, obtaining the specific quantitative description of the screened Coulomb potential in reciprocal space $(\varphi(\boldsymbol{q}) = \frac{e}{q(2\varepsilon + q\alpha_{total}^{2D}) - e^2\chi_{carrier}(q) - 2e^2\chi_{dipole}(q)(1 - J_0(qd))})$. The result offers a simple and direct way to evaluate the strength of the Coulomb interaction and a design tool for Coulomb potential engineering in 2D systems.

Current-induced domain wall motion in van der Waals material Fe_3GeTe_2

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Magnetism in van der Waals has attracted wide attention due to its novel physical phenomena and application in spintronics devices. Among them, Fe_3GeTe_2, as a relatively high Curie temperature van der Waals ferromagnetic material, is a good candidate for researching dynamics of spin texture. Here, the current-induced domain wall motion in a few-layer Fe_3GeTe_2 films has been thoroughly investigated through magneto-optical Kerr effect. Single domain wall in racetrack-shape Fe_3GeTe_2 micro-devices can be smoothly driven by nanosecond current pulses based on either spin transfer torque effect in itself or spin orbital torque effect with an attached heavy metal layer. These achievements explore the dynamic of domain wall motion in van der Waals materials and provide the possibility for practical racetrack memory.

Notes