Abstract book of the International meeting on superconducting quantum materials and nanodevices

17 to 21 April 2023

Contents

AIMS AND SCOPE

Rapid recent developments in the physics of superconducting quantum materials pose the grand challenge to integrate the acquired fundamental insights into the quantum devices with radically new functionalities. To promptly address such challenges requires facilitated interactions and collaboration between the key research stakeholders, junior and senior, towards the jointly made advances in modern quantum technology.

Therefore, this meeting is conceptualized as a school in conference format, and intends to promote the collaboration and exchanges of ideas among expert and early-stage scientists active in nanoscale quantum physics, synthesis and characterization of novel superconducting materials and heterostructures, device fabrication, and theoretical modeling. The meeting will be fully in-person, in a confined and relaxed atmosphere, optimally promoting the discussions and meetings among all participants. Additionally, this meeting serves an important purpose to promote and disseminate the activities of the COST Action SUPERQUMAP in ITC and Eastern European countries. Topics include (and are not limited to):

- Topological superconductivity.
- Novel Josephson effects in bulk and artificial layered materials.
- Interplay between magnetism and superconductivity, including magnonics and fluxonics.
- New high-temperature superconductors – in silico design and synthesis.
- Emergent physics in new (unconventional) superconductors and superconductivity vs charge-density wave orders.
- Superconducting Quantum bits and quantum circuits.
- Three-dimensional superconducting nanostructures.
- Superconducting devices for quantum technology.
- Superconductivity vs. charge-density wave orders.
- Imaging of superconducting vortices, Shiba and Majorana states.
- Confinement effects at the nanoscale and three-dimensional superconducting nanostructures.
- Advanced theoretical modeling and multiscale simulations.

The COST Action superqumap

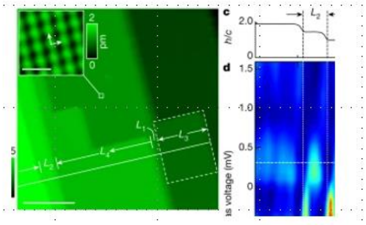
The COST Action SUPERQUMAP is organized by researchers from all European countries and includes collaborators all over the world. Superqumap started in October 2021 and will continue until October 2026. Superqumap will significantly shape research in superconductivity by a series of instruments provided by the well proven COST Action system. These includes two meetings a year, short term scientific missions and support to attend meetings organized by other entities in the same field. The management committee includes researchers from 29 countries, which share the common goal of advancing in the objectives of the Action. The approach is completely open to any researcher that can contribute to the objectives of the Action in any country.

The Action superqumap aims to harness the results obtained recently in superconductivity and build a collaborative effort to provide radically new approaches to superconducting based quantum devices. Research has three main objectives:

- To synthesize, characterize, model and understand superconducting materials and devices using a collaborative approach including techniques and capabilities available all over Europe.
- To improve our understanding of superconductors at interfaces and in combination with other systems such as magnets and insulators.
- To achieve a disruptive advance in superconducting devices for quantum technologies.

The work is organized in three work packages, which aid to shape the meetings and networking activities in which researchers mutually benefit from complementary knowledge to advance in the objectives of the Action.

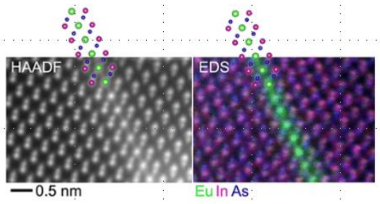
Quantum well states at the surface of a heavy-fermion superconductor, Nature (2023), https://doi.org/10.1038/s41586-023-05830-1



- Work package 1: Quantum materials
    - Obtain topological and triplet superconductivity by tuning correlations and the properties at interfaces.
    - Understand the relationship between electronic correlations, magnetism and unconventional superconducting properties.

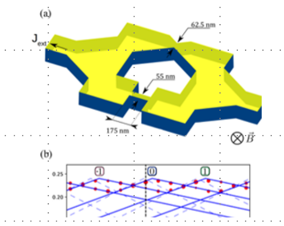
- Work package 2: New functionalities for sensors and devices
    - Control the degree of disorder in low dimensional and low carrier density superconductors.
    - Achieve a better understanding of electronic behavior between the extreme limits of infinity and zero resistance.
    - Understand transport in hybrid magnetic-superconducting devices and explore the behavior of junctions made of hybrid heterostructures.

Intrinsic magnetic (EuIn)As nanowire shells with a unique crystal structure, Nano Lett (2022), 22, 8925



- Work package 3: Building Quantum Systems.
    - Create and characterize novel two-level systems in superconducting junctions and devices suitable for quantum computation.
    - Design and test methods for their coherent manipulation in quantum devices.

Metastable states and hidden phase slips in nanobridge SQUIDs, Phys Rev B (2022), 106, 134518



Everyone interested in contributing to the objectives of the Action is cordially invited to join us. Participation is very easy. First by joining a working group, which will allow us to keep you updated. Then, by attending one of our workshops, schools or conferences, by organizing a short term visit or by disseminating the results obtained in the field of the Action. Other, equally important, initiatives include dissemination activities, such as the promotion of books, both scientific and for the general public and the dissemination of our results.

The meeting in Budva, Montenegro, is our first in-person meeting. We purposely chose a location in an ITC country, with the aim to motivate activities within our field in these important European countries. The interest has been overwhelming and it was even difficult to make choices both in the program and in the available funds. The final result is an outstanding program, with about half of the participants from ITC countries, and where senior and young researchers openly meet around posters, talks and other collaborative activities.

Stay tuned to further activities of superqumap and we hope to see you very often.

ORGANIZERS

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Pop, Ioan (Germany)
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And the Cost Action SUPERQUMAP committee (https://www.cost.eu/actions/CA21144/#tabs+Name:Management%20Committee)

Grant Manager:

Irene González Martín

LOCATION

International meeting on superconducting quantum materials and nanodevice, organized by COST action CA21144 *Superqumap*, will be held in Budva, Montenegro. Budva is situated along the central part of the Montenegrin coast soaked in sunshine and surrounded by the beauty of nature.

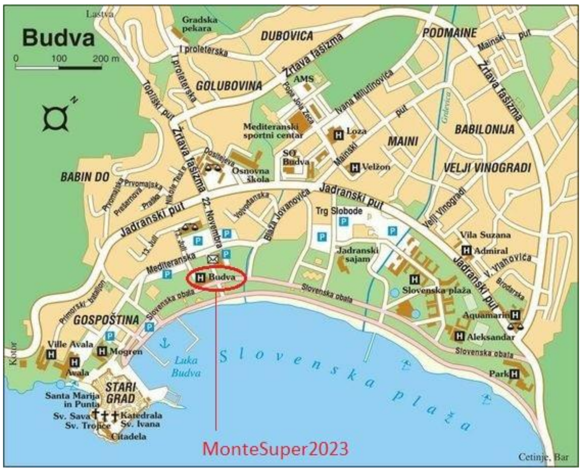
An adventageous geographical location and mild climate created hospitable conditions for the early settlement in the Budva region. Budva riviera covers an area of 122 sq.km.

Along its 25km of coastline lie some 17 sandy and pebble beaches, stretching from Trsteno and Jaz in the north all the way to Buljarica at the very south. Surrounded by a massive and spectacular mountain range, Budva is protected from the strong northern winds.

The region of Budva enjoys typical Mediterranean climate. The winters are mild with plentiful rain, while spring, summer and most of autumn are dry. Budva is placed at the very top of the most desired tourist destinations in the Mediterranean.

Today, Budva is a castle-cum-theatre, and the stage for many theatrical events. During the summer time number of visitors increases one hundred-fold. This is also a place which adopts to visitors, and more then that – it liberates them. Budva helps us find out who we are, to whom we belong and where we are from.

The venue of the conference is the "Budva" hotel.



INVITED SPEAKERS

NAME	ORGANISATION
Adrian Crisan	*National Institute of Materials Physics*
Alberto M Ruiz	*Instituto de Ciencia Molecular (ICMol), Universidad de Valencia*
Alexander Buzdin	*University of Bordeaux*
Angelo Di Bernardo	*University of Konstanz*
Balazs Ujfalussy	*Wigner Research Centre for Physics*
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Brigitte Leridon	*CNRS/ ESPCI*
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Daniele Torsello	*Politecnico di Torino, Department of Applied Science and Technology*
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Dimitri Roditchev	*LPEM ESPCI*
Elena Gati	*Max-Planck-Institute for Chemical Physics of Solids*
Elisabetta Paladino	*Dipartimento di Fisica e Astronomia Ettore Majorana*
Estefani Marchiori	*University of Basel*
Filippo Gaggioli	*ETH Zürich*
Floriana Lombardi	*Chalmers University of Technology*
Francesco Giazotto	*NEST, Instituto Nanoscienze – CNR & Scuola Normale Superiore*
Hadar Steinberg	*Hebrew University of Jerusalem*
Halima Giovanna Ahmad	*Department of Physics Ettore Pancini, University of Napoli Federico II*
Hugo Dil	*Ecole Polytechnique Fédérale de Lausanne (EPFL)*
Ipsita Das	*Ludwig-Maximilians-Universität München*
Jan Aarts	*Leiden Institute of Physics*
Javier Villegas	*Unité Mixte de Physique CNRS/Thales*
Jelena Pešić	*Institute of Physics Belgrade*

Jianting Ye	*University of Groningen*
Jonas Bekaert	*University of Antwerp*
Julia S Meyer	*Université Grenoble Alpes*
Kazuo Kadowwaki	*Institute for Quantum Materials Research*
Klaus Hasselbach	*Institut Néel Université Grenoble Alpes CNRS*
Levente Rózsa	*Wigner Research Centre for Physics*
Maciej Zgirski	*Institute of Physics, Polish Academy of Sciences*
Malcolm Connolly	*Imperial College London*
Manuel Houzet	*CEA Grenoble*
Marta Fernández-Lomana	*Universidad Autónoma de Madrid*
Mazhar Ali	*Delft University of Technology*
Michal Šindler	*Institute of Physics of the Academy of Science*
Mikko Mottonen	*Aalto University*
Nenad Lazarević	*Institute of Pđhysics Belgrade*
Nicolas Bergeal	*LPEM ESPCI Paris*
Oleksandr Dobrovolskiy	*University of Vienna*
Pablo Burset	*Autonomous University of Madrid*
Pascal Simon	*Laboratoire de Physique des Solides, University Paris Saclay*
Pasquale Mastrovito	*University of Naples Federico II*
Peter Makk	*Budapest University of Technology and Economics*
Peter Wahl	*University of St Andrews*
Riccardo Arpaia	*Chalmers University of Technology*
Rubén Seoane Souto	*Autonomous University of Madrid*
Simon Reinhardt	*Institute of Experimental and Applied Physics, University of Regensburg*
Somesh Chandra Ganguli	*Aalto University*
Stefan Marinković	*Experimental Physics of Nanostructured Materials, Q-MAT, CESAM, Université de Liège*
Tania Paul	*MagTop, Institute of Physics, Polish Academy of Sciences*
Tristan Cren	*CNRS & Sorbonne University*
Vladimir Fomin	*Faculty of Physics and Engineering, Moldova State University*
Vladimir Krasnov	*Department of Physics, Stockholm University*
Zoe Velluire	*LPEM ESPCI*
Zorica Popović	*University of Belgrade, Faculty of Physics*

PROGRAM

MONTESUPER 2023									
17.04.		**18.04.**		**19.04.**		**20.04.**		**21.04.**	
		8.15	**Opening**						
		Sensing advances		Devices		Quantum tech		Iron-based SCs	
		8.30	Kadowaki	8.30	Giazotto	8.30	Möttönen	8.30	Gati
		8.55	Koelle	8.55	Di Bernardo	8.55	Mastrovito	8.55	Pešić
		9.20	Marchiori	9.20	Villegas	9.20	Seoane Souto	9.20	Crisan
		9.45	Šindler	9.45	Aarts	9.45	Burset	9.45	Coffee break
		10.10	Coffee break	10.10	Coffee break	10.10	Coffee break	Vortex devices	
		Cuprates		SC diodes		Majoranas in S-F hybrids		10.15	Dobrovolskiy
		10.40	Lombardi	10.40	Ali	10.40	Cren	10.40	Zgirski
		11.05	Marinković	11.05	Krasnov	11.05	Rózsa	11.05	Fomin
		11.30	Arpaia	11.30	Reinhardt	11.30	Simon	11.30	Buzdin
		11.55	Velluire	11.55	Makk	11.55	Ujfalussy	**11.55**	**Closing remarks**
		12.20	Lunch	12.20	Lunch	12.20	Lunch		
		2D SCs and devices		Unconventional SCs		CDW vs SC		**Lunch and departure**	
		14	Roditchev	14	Meyer	14	Dil		
		14.25	Ye	14.25	Wahl	14.25	Bekaert		
		14.50	Das	14.50	Hasselbach	14.50	Lazarević		
		15.15	Quay	Rising stars II		15.15	Leridon		
Arrival and registration		15.40	Coffee break	15.15	Torsello	15.40	Coffee break		
		2D heterostructures		15.35	Fernández-Lomana	Novel Josephson devices			
		16.10	Steinberg	15.55	Chandra Ganguli	16.10	Paladino		
		16.35	Bergeal	**Discussion and collaborative planning per workgroup of the Action**		16.35	Houzet		
		Rising stars I				17	Connolly		
		17	Ruiz			17.25	Popović		
		17.20	Šoškić			17.50	Ahmad		
		17.40	Gaggioli			18.15-20.15	**Poster session II**		
		18	Paul						
		18.20-20.20	**Poster session I**						
19-21	Dinner	20.30-22	Dinner	20.30-22	Dinner	20.30-23	**Conference dinner**		
21-22	**Evening reception**								

ABSTRACTS

TUESDAY 18 APRIL

Sensing advances

08:30-08:55 Kazuo Kadowaki

HIGH PERFORMANCE THz EMITTING DEVICES FROM HIGH-Tc SUPERCONDUCTING IJJ MESA STRUCTURES

K. Kadowaki[1*], N. Subotic[2], T. Kashiwagi[2], H. Minami[2], H. Shigekawa[2] O. Takeuchi[2] and J. Mirkovic[3]

[1]IQMR(The Institute for Quantum Materials Research), 3441 Kamihara, Tsukuba, Ibaraki 305-0001, Japan
[2]Faculty of Pure & Applied Sciences, University of Tsukuba, 1-1-1, Tennodai, Tsukuba, Ibaraki 305-8573, Japan
[3]Faculty of Sciences, University of Montenegro, P.O. Box 211, 81000 Podgorica, Montenegro

**Presenting author: dr.kazuo.kadowaki@gmail.com*

Electromagnetic waves (EMWs) in terahertz (THz) frequencies are a superseding target not only with the next generation communication medium of 6G, 7G or higher, but also with the emerging novel quantum technologies. In particular, the development of both continuous coherent THz sources with sufficient power and fast, sensitive and low noise detectors in THz frequencies are urgent and hot technological issues. In 2007, we discovered a novel phenomenon which can generate tunable, continuous and coherent THz EMWs using high-T_c superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ intrinsic Josephson junctions (IJJs). So far, our effort has been made towards two directions: one is to establish emitters with higher efficiency, and the other is to enhance the power by external(internal) power amplifier by using parametric as well as plasmonic techniques. These experimental aspects will be presented.

Tuesday 18 April
08:55-09:20 Dieter Koelle

NANOSQUIDS FOR SQUID-ON-LEVER SCANNING PROBE MICROSCOPY

T. Griener[1], S. Koch[1], S. Pfander[1], C. Bureau-Oxton[2], D. Jetter[3], A. Vervelaki[3], K. Bagani[3], U. Drechsler[2], R. Kleiner[1], A. Knoll[2], M. Poggio[3] and D. Koelle[1*]

[1]*Physikalisches Institut, Center for Quantum Science (CQ) and LISA⁺, Universität Tübingen, Germany*
[2]*IBM Research Center Europe – Zürich, Rüschlikon, Switzerland*
[3]*Department of Physics and Swiss Nanoscience Institute, University of Basel, Switzerland*

**Presenting author: koelle@uni-tuebingen.de*

Strongly miniaturized nanoscale superconducting quantum interference devices (nanoSQUIDs) can reach ultra-low levels of magnetic flux noise. Together with their small size, this makes them promising candidates for detectors of local sources of magnetic field with high spin sensitivity in scanning probe microscopy. We describe here our attempts to integrate nanoSQUIDs on atomic force microscopy (AFM) Si cantilevers. This approach shall provide ultrahigh-resolution scanning SQUID microscopy (SSM), combined with simultaneous topographic imaging in conventional AFM mode [1]. We will focus on nanoSQUIDs fabricated from single layer Nb thin films, that are patterned by focused ion beams, using Ga, Ne and He. We will discuss the status of the project and challenges that have to be met on the way to combined SSM and AFM imaging.

Financial supported by the European Commission under H2020 FET Open grant “FIBsuperProbes” (Grant No. 892427) is gratefully acknowledged.

[1] M. Wyss, K. Bagani, D. Jetter, E. Marchiori, A. Vervelaki, B. Gross, J. Ridderbos, S. Gliga, C. Schöneberger, and M. Poggio, *Magnetic, Thermal, and Topographic Imaging with a Nanometer-Scale SQUID-On-Lever Scanning Probe*, Phys. Rev. Applied **17** (2022) 034002.

Tuesday 18 April
09:20-09:45 Estefani Marchiori

REAL-SPACE IMAGING OF MAGNETIC PHASES IN THE CHIRAL MAGNET Cu_2OSeO_3

E. Marchiori[1*], G. Romagnoli[1], P. Baral[2], A. Magrez[2] and M. Poggio[1,3]

[1]*Department of Physics, University of Basel, 4056 Basel, Switzerland*
[2]*Institute of Physics, École Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland*
[3]*Swiss Nanoscience Institute, University of Basel, 4056 Basel, Switzerland*

**Presenting author: estefani.marchiori@unibas.ch*

The chiral magnet Cu_2OSeO_3 is a ferroelectric material that exhibits a variety of interesting magnetic phases, including two distinct topological skyrmion spin textures. Skyrmion phases exist at relatively high temperatures of tens of Kelvin because they require thermal fluctuations to become thermodynamically stable in bulk materials. Recently, small-angle neutron scattering measurements (SANS) revealed a second low-temperature skyrmion phase in Cu_2OSeO_3 [1,2]. Distinct from the well-known high-temperature phase, this low-temperature phase is highly hysteretic and believed to be stabilized by cubic anisotropy. To understand the mixed magnetic phases and the new skyrmion phase in Cu_2OSeO_3, we performed magnetic imaging of a bulk single crystal using scanning SQUID-on-tip microscopy with sub-100-nm spatial resolution [3]. I shall discuss the disordered low-temperature skyrmion phase, domain formation, and helimagnetic phases observed.

[1] A. Chacon, *et al.* Nat. Phys. 14 (2018) 936.
[2] F. Qian, *et al.* Sci. Adv. 4 (2018) eaat7323.
[3] E. Marchiori, *et al.* Nat. Rev. Phys. 4 (2022) 49.

Tuesday 18 April
09:45-10:10 Michal Šindler

Terahertz spectroscopy of thin NbN films

M. Šindler[1*], F. Kadlec[1] and C. Kadlec[1]

[1] *Institute of Physics of the Czech Academy of Sciences, Na Slovance 1999/2,Prague, Czech Republic*

**Presenting author: sindler@fzu.cz*

Terahertz (THz) spectroscopy enables an in-depth understanding of superconducting properties, namely, superconducting gap, penetration depth, quasiparticle behaviour, vortex dynamics and non-equilibrium relaxation. The advantages and limitations of the THz method will be briefly demonstrated in our previous measurements of high-quality thin NbN films. We will then focus in more detail on the case of superconductor-insulator transition in a 5 nm thick NbN sample under an in-plane magnetic field [1]. The superconducting properties are diminished at 7 tesla: the dissipation below the optical gap is increased while the imaginary part of the conductivity or the optical gap are changed only slightly. We believe that we observe the onset of a superconductor-insulator transition in which nanoscale inhomogeneity is induced by the field.

[1] M. Šindler, F. Kadlec, and C. Kadlec, Phys. Rev. B, 105 (2022) 014506 .

Cuprates

Tuesday 18 April
10:40-11:05 Floriana Lombardi

INTERTWINING BETWEEN SUPERCONDUCTIVITY, STRANGE METAL PHASE AND CHARGE DENSITY WAVE IN UNDERDOPED CUPRATES

E. Wahlberg [1], R. Arpaia [1,2], G. Seibold[3], E. Trabaldo[1], S. Caprara [4], U. Gran[5], L. Braichovich[2], G. Ghiringhelli[2], T. Bauch[1] and F. Lombardi[1*]

[1]*Quantum Device Physics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-41296, Göteborg, Sweden*
[2]*Dipartimento di Fisica, Politecnico di Milano, I-20133 Milano, Italy*
[3]*Institut für Physik, BTU Cottbus-Senftenberg - PBox 101344, D-03013, Cottbus, Germany*
[4]*Dipartimento di Fisica, Università di Roma "La Sapienza", P.le Aldo Moro 5, I-00185 Roma, Italy*
[5]*Division of Subatomic, High-Energy and Plasma Physics, Chalmers University of Technology, SE-41296, Göteborg, Sweden*

**Presenting author: floriana.lombardi@chalmers.se*

The "strange metal" phase of High Critical Temperature Superconductors (HTS) is one of the most striking manifestations of the strong electron-electron correlation correlations in these materials. At optimal doping the strange metal manifests as a linear temperature dependence of the resistivity that persists to the lowest *T* when superconductivity is suppressed. This behavior is fundamentally different from that observed in more conventional metals, where a *T*-linear dependence of the resistivity is found, only at high temperatures, where phonon scattering dominates the transport. For underdoped cuprates this behavior is lost below the pseudogap temperature *T**, where Charge Density Waves (CDW) together with other intertwined local orders characterize the ground state. The association between the departure from the *T*-linear resistivity and the occurrence of the pseudogap phenomenon has long been speculated without a general consensus. To address this issue we have tuned the ground state of underdoped HTS by using the geometric modification of the unit cell under the strong strain induced by the substrate. We show that the *T*-linear resistivity of highly strained, ultrathin and underdoped $YBa_2Cu_3O_{7-\delta}$ (YBCO) films is restored when the CDW amplitude, detected by Resonant Inelastic X-ray scattering, is suppressed [1]. This observation points towards an intimate connection between the onset of CDW and the departure from the strange metal behavior in underdoped cuprates. In addition we find that in ultrathin thin films the superconducting critical temperature onset and the upper critical field Hc2 are strongly enhanced compared to single crystals which point towards a competition between CDW and superconductivity [2]. Our results also illustrate the potential of using strain control to manipulate the ground state of quantum materials.

[1] E. Wahlberg,R. Arpaia, G. Seibold, E. Trabaldo, S. Caprara , U. Gran, L. Braichovich, G. Ghiringhelli , T. Bauch and F. Lombardi, Science **373,** 1506 (2021)
[2] E. Wahlberg, R. Arpaia, G. Seibold, E. Trabaldo, S. Caprara , U. Gran, L. Braichovich, G. Ghiringhelli , T. Bauch and F. Lombardi, Supercond. Sci. Technol. **36** 024001 (2022)

Tuesday 18 April
11:05-11:30 Stefan Marinković

Oxygen ordering in untwinned $YBa_2Cu_3O_{7-\delta}$ films driven by electrothermal stress

Stefan Marinković ,[1,*] Edoardo Trabaldo,[2] Simon Collienne ,[1] Floriana Lombardi,[2] Thilo Bauch,[2] and Alejandro V. Silhanek [1]

[1]*Experimental Physics of Nanostructured Materials, Q-MAT, CESAM, Université de Liège, B-4000 Sart Tilman, Belgium*
[2]*Department of Microtechnology and Nanoscience, Quantum Device Physics Laboratory, Chalmers University of Technology, SE-41296 Göteborg, Sweden*

**Presenting author: smarinkovic@uliege.be*

We experimentally investigate the displacement of oxygen vacancies at high current densities in highly untwinned $YBa_2Cu_3O_{7-\delta}$ films grown on top of MgO substrates.[1] Transport bridges oriented along the $YBa_2Cu_3O_{7-\delta}$ crystallographic directions [100] (a axis), [010] (b axis), and [110] (45° from principal axes) reveal that the onset of vacancy migration is mainly determined by the local temperature (or equivalently by the dissipated power) rather than the associated activation energy. Exceeding this threshold value, a clear directional migration proceeds as evidenced by optical microscopy. Concomitant electrotransport measurements, previously having been applied in similar manner in twinned $YBa_2Cu_3O_{7-\delta}$ films[2], and related perovskite systems[3], show that an intermediate phase, characterized by a decrease in resistivity, precedes long-range migration of vacancies. We numerically demonstrate that this intermediate phase consists of a homogenization of the oxygen distribution along the transport bridge, a phenomenon strongly dependent on the activation energy and the initial degree of disorder. These findings provide some important clues to determine the level of order/disorder in $YBa_2Cu_3O_{7-\delta}$ films based on electric transport measurements.

[1] S. Marinković, E. Trabaldo, S. Collienne, F. Lombardi, T. Bauch and A. V. Silhanek, Oxygen ordering in untwinned $YBa_2Cu_3O_{7-\delta}$ films driven by electrothermal stress, Phys. Rev. B **107**, 014208 (2023).
[2] S. Collienne, S. Marinković, A. Fernández'Rodríguez, N. Mestres, A. Palau, and A. V. Silhanek, Electrically'driven oxygen vacancy aggregation and displacement in YBa2 Cu3 O7−δ films, Adv. Electron. Mater. **8**, 2101290 (2022).
[3] Marinković, S., Fernández-Rodríguez, A., Fourneau, E., Cabero, M., Wang, H., Nguyen, N. D., Gazquez, J., Mestres, N., Palau, A., Silhanek, A. V. (2022). Advanced Materials Interfaces

Tuesday 18 April
11:30-11:55 Riccardo Arpaia

Signature of quantum criticality in cuprates by charge density fluctuations

R. Arpaia[1*], L. Martinelli[2], M. Moretti[2], S. Caprara[3], N. B. Brookes[4], K.-J. Zhou[5], T. Bauch[1], C. Di Castro[3], M. Grilli[3], F. Lombardi[1], L. Braicovich[2,6] and G. Ghiringhelli[2]

[1]*Department of Microtechnology and Nanoscience, Chalmers University, SE-41296 Göteborg, Sweden*
[2]*Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, I-20133 Milano, Italy*
[3]*Dipartimento di Fisica, Università di Roma "La Sapienza," P.le Aldo Moro 5, I-00185 Roma, Italy*
[4]*ESRF, The European Synchrotron, 71 Avenue des Martyrs, F-38000 Grenoble, France*
[5]*Diamond Light Source, Harwell Campus, Didcot OX11 0DE, United Kingdom*

**Presenting author: riccardo.arpaia@chalmers.se*

The strange metal phase, which dominates large part of the phase diagram of the cuprates, has been found in many quantum materials, including pnictides, heavy fermions and magic angle double layer graphene. One suggested origin of this universality is that it stems from the presence of a quantum critical point (QCP), i.e., a phase transition at zero temperature ruled by quantum fluctuations, in contrast to ordinary phase transitions ruled by thermal fluctuations. Although in cuprates superconductivity hinders the direct observation of the QCP phenomenology at low temperatures, indirect evidence comes from the identification of fluctuations compatible with the strange metal phase at higher temperatures.
Here we show that the recently discovered charge density fluctuations (CDF) [1,2] possess the right properties to be associated to a quantum phase transition. By using resonant x-ray scattering (RIXS), we have studied CDF in two families of cuprate superconductors over a wide range of doping p, up to p = 0.22. We show that at $p^* \approx 0.19$, corresponding to the putative QCP, the CDF intensity is the strongest, and the characteristic energy Δ is the smallest, marking a wedge-shaped region in the phase diagram indicative of a quantum critical behavior, although with anomalous properties [3]. These results support the leading role of charge order in driving the unconventional phenomenology of the strange metal and add new elements for the understanding of high critical temperature superconductivity.

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Tuesday 18 April
11:55-12:20 Zoe Velluire

Hybrid Quantum Systems with High-Tc Superconducting Resonators

Z. Velluire[1]*, E. Maréchal[1], N. Moulonguet[1], G. Saïz[1], G. Ménard[1], S. Kozlov[1], F. Couëdo[1,2], P. Amari[1], C. Medous[3], J. Paris[4], R. Hostein[4], J. Lesueur[1], C. Feuillet-Palma[1], N. Bergeal[1]

[1] *Laboratoire de Physique et d'Etude des Matériaux, ESPCI Paris, PSL University, CNRS, Sorbonne Université, Paris, France.*
[2] *Laboratoire National de Métrologie et d'Essais (LNE)*
[3] *Université Grenoble Alpes, CNRS, Institut Fourier, 38000 Grenoble,France*
[4] *MyCryofirm*

**Presenting author: zoe.velluire@espci.fr*

Resonators are essential building blocks of microwave circuits and serve a wide variety of functions, from narrow-band filtering to enhancing the interactions between quantum systems and electromagnetic waves. Though fabrication techniques have improved considerably, the performance of resonators remain limited by materials losses. The use of superconductors as the conducting part of resonators significantly reduces dissipation, thus increasing quality factors. So far, most superconducting resonators have been made using low-Tc superconductors (Al, Nb, NbN) through well-established fabrication processes. Their properties have been well characterized and reported, with ultra-high quality factors achieved [1,2]. Still, using high temperature superconductors could be of great interest for the fabrication of resonators and would considerably increase operating ranges of resonators, both thermal and magnetic, while maintaining relatively high quality factors.

We have carried out a detailed study of coplanar waveguide resonators made of the high-Tc superconducting cuprate $YBa_2Cu_3O_{7-\delta}$ thin film by varying their coupling capacitors. We show that increasing the capacitive coupling to the external circuit leads to a continuous transition from an undercoupled dissipative regime to a lossless overcoupled one, characterized by a decrease in the resonator quality factor. Our experimental results (resonance frequency, coupling, quality factor, and insertion loss) are in good agreement with the predictions of circuit model theory and the reported results for low-Tc resonators [2]. To assess the potential of $YBa_2Cu_3O_{7-\delta}$ resonators, we used our highest quality factor resonator to perform electron spin resonance on a di(phenyl)-(2,4,6- trinitrophenyl)iminoazanium (DPPH) molecular spin ensemble [3]. The measured spectra reveal a double peak structure characteristic of a Rabi splitting arising from spin-cavity hybridization in a strong cooperative regime. The analysis of the spin-cavity coupling strength, the spin decay rate, and the Landé g- factor indicates an antiferromagnetic transition at low temperatures [4].

Our results show that $YBa_2Cu_3O_{7-\delta}$ resonators offer a promising technology, not only to perform ESR experiments, but also to realize hybrid quantum systems in which quantum information could be stored or processed.

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2D superconductors and devices

Tuesday 18 April
14:00-14:25 Dimitri Roditchev

Gold Atoms Promote Macroscopic Superconductivity in an Atomic Monolayer of Pb on Si(111)

Denis S. Baranov[1], Sergio Vlaic[1], Jonathan Baptista[1], Enrico Cofler[1], Vasily S. Stolyarov[2], Dimitri Roditchev[*1], Stéphane Pons[1]

[1] Laboratoire de Physique et d'Etude des Matériaux, ESPCI Paris, PSL University, CNRS, Sorbonne Université, Paris, France
[2] Center for Advanced Mesoscience and Nanotechnology, Moscow Institute of Physics and Technology, Dolgoprudny, Moscow 141700, Russia; Dukhov Research Institute of Automatics (VNIIA), Moscow 127055, Russia; National University of Science and Technology MISIS, 4 Leninsky Prosp., Moscow 119049, Russia

**Presenting author: dimitri.roditchev@espci.fr*

Atomically thin superconductivity in Pb monolayers grown on Si(111) is affected by adding a tiny amount of Au atoms [1]. In situ macroscopic electron transport measurements [2,3] reveal that superconductivity develops at higher temperatures and manifests a sharper superconducting transition to zero resistance [4] as compared to pristine Pb/Si(111). Scanning tunneling microscopy and spectroscopy show that Au atoms decorate atomic step edges of Pb/Si(111) and link the electronic reservoirs of neighboring atomic terraces [4]. The propagation of superconducting correlations across the edges is enhanced, facilitating the coherence between terraces and promoting macroscopic superconductivity at higher temperatures. This finding opens new ways to design and control Josephson junctions at the atomic scale.

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[2] Uchihashi, T.; Mishra, P.; Aono, M.; Nakayama, T. Macroscopic Superconducting Currentthrough a Silicon Surface Reconstruction with Indium Adatoms:Si(111)−($\sqrt{7}\times\sqrt{3}$)−In.Phys. Rev. Lett.2011,107, 207001
[3] Yamada, M.; Hirahara, T.; Hasegawa, S. Magnetoresistance Measurements of a Superconduct-ing Surface State of In-Induced and Pb-Induced Structures on Si(111).Phys. Rev. Lett.2013,110, 237001.
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Tuesday 18 April
14:25-14:50 Jianting Ye

Field-Effect Control of Clean Superconductivity and Unconventional FFLO States in 2D Materials

Jianting Ye[1*]

[1] *Device Physics of Complex Materials, Zernike Institute for Advanced Materials, University of Groningen*

**Presenting author: j.ye@rug.nl*

Many recent discoveries on novel electronic states were made on 2D materials. Especially by making artificial bilayer systems, new electronic states such as unconventional superconductivity and orbital ferromagnetism have been reported. This talk will discuss quantum phase transitions and Ising superconductivity induced in 2D transition metal dichalcogenides. Using ionic gating, quantum phases such as superconductivity can be induced electrostatically on many 2D materials. In this talk, we will discuss 1) how to improve the mobility of ion-gated carriers and enter the clean regime of Ising superconductivity [1]. And 2) how to couple two Ising superconducting states through Josephson coupling and form FFLO states [2].

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Tuesday 18 April
14:50-15:15 Ipsita Das

Magnetic Field Driven Quantum Phases in Magic Angle Twisted Bilayer Graphene

I. Das[1,2*], Xiaobo Lu[1], Cheng Shen[1], Alexandre Jaoui[2], Jonah Herzog-Arbeitman[3], Zhi-Da Song[3], Aaron Chew[3], Chang-Woo Cho[4], Kenji Watanabe[5], Takashi Taniguchi[5], Benjamin A Piot[4], B Andrei Bernevig[3] and D. K. Efetov[2]

[1]*ICFO - Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, Castelldefels, Barcelona, 08860, Spain*
[2]*Fakultät für Physik, Ludwig-Maximilians-Universität, 80799 München, Germany*
[3]*Department of Physics, Princeton University, Princeton, NJ, USA*
[4]*Laboratoire National des Champs Magnétiques Intenses, Université Grenoble Alpes, UPS-INSA-EMFL-CNRS-LNCMI, Grenoble, France*
[5]*National Institute for Materials Science, Tsukuba, Japan*
**Presenting author: Ipsita.das@lmu.de*

The recent discovery of magic angle twisted bilayer graphene (MATBG), in which two sheets of monolayer graphene are precisely stacked to a specific angle, has opened a plethora of grand new opportunities in the field of topology, superconductivity, and other strongly correlated effect. In twisted van der Waals materials, lattice mismatch can generate moiré patterns, which act as an additional periodicity that has a length scale order of magnitude larger than the underlying atomic lattice scale. For MATBG with a small twist angle close to $\theta = 1.1°$, the electronic bands are flattened by the periodic potential of the moiré bands and isolated from higher-energy dispersive bands. These flat electronic bands in magic-angle twisted bilayer graphene (MATBG) have recently emerged as a rich platform to explore strong correlations, superconductivity and magnetism. However, the phases of MATBG in a magnetic field and what they reveal about the zero-field phase diagram remain relatively uncharted. We report a rich sequence of wedge-like regions of quantized Hall conductance with Chern numbers $C = \pm1, \pm2, \pm3$ and ±4, which nucleate from integer fillings of the moiré unit cell $\boldsymbol{\nu} = \pm3, \pm2, \pm1$ and 0, respectively. The exact sequence and correspondence of the Chern numbers and filling factors suggest that these states are directly driven by electronic interactions, which specifically break the time-reversal symmetry in the system. The analysis of Landau-level crossings from higher energy bands enables a parameter-free comparison to a newly derived 'magic series' of level crossings in a magnetic field and provides constraints on the parameters of the Bistritzer–MacDonald MATBG Hamiltonian [1]. Additionally, we studied the detailed magnetotransport behaviour of the Hofstadter spectrum of MATBG. We observed the re-entrance of insulating states at $\boldsymbol{\nu} = +2, \pm3$ of the moiré unit cell of MATBG upon applying an external magnetic field close to the full flux quantum $\Phi/\Phi_0 = 1$ of the superlattice unit cell ($B = 25\theta^2$ T) and interaction-driven Fermi-surface reconstructions at other fillings, which are identified by new sets of Landau levels originating from these. These experimental observations are supplemented by theoretical work that predicts a new set of eight well-isolated flat bands at Φ_0, of comparable band width, but with different topology than in zero field [2].

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[2] I. Das et al, *Physical Review Letters*, 128 (21), 217701

Tuesday 18 April
15:15-15:40 Charis Quay

Tunnelling spectroscopy of few-monolayer $NbSe_2$ in high magnetic field: triplet superconductivity and Ising protection

M. Kuzmanović[1,2], T. Dvir[3,4], D. LeBoeuf[5], S. Ilić[6,7], M. Haim[3], D.Möckli[3,8], S. Kramer[5], M. Khodas[3], M. Houzet[6], J.S. Meyer[6], M. Aprili[1], H. Steinberg[3], and C. H. L. Quay[1]

[1]Laboratoire de Physique des Solides (CNRS UMR 8502), Bâtiment 510, Université Paris-Saclay 91405 Orsay, France
[2]QTF Centre of Excellence, Department of Applied Physics, Aalto University School of Science, P.O. Box 15100, 00076 Aalto, Finland
[3]Racah Institute of Physics, Hebrew University of Jerusalem, Givat Ram, Jerusalem 91904 Israel
[4]QuTech and Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, the Netherlands
[5]Laboratoire National des Champs Magnétiques Intenses (LNCMI-EMFL), CNRS, UGA, UPS, INSA, Grenoble/Toulouse, France
[6]Université Grenoble Alpes, CEA, Grenoble INP, IRIG, PHELIQS, 38000 Grenoble, France
[7]Centro de Física de Materiales (CFM-MPC), Centro Mixto CSIC-UPV/EHU, 20018 Donostia-San Sebastián, Spain
[8]Instituto de Física, Universidade Federal do Rio Grande do Sul, 91501-970 Porto Alegre, RS, Brazil

**Presenting author: charis.quay@universite-paris-saclay.fr*

In conventional Bardeen-Cooper-Schrieffer (BCS) superconductors, Cooper pairs of electrons of opposite spin (i.e. singlet structure) form the ground state. Equal spin triplet pairs (ESTPs), as in superfluid ^{3}He, are of great interest for superconducting spintronics and topological superconductivity, yet remain elusive. Recently, odd-parity ESTPs were predicted to arise in (few-)monolayer superconducting NbSe2, from the non-colinearity between the out-of-plane Ising spin-orbit field (due to the lack of inversion symmetry in monolayer $NbSe_2$) and an applied in-plane magnetic field. These ESTPs couple to the singlet order parameter at finite field. Using van der Waals tunnel junctions, we perform spectroscopy of superconducting NbSe2 flakes, of 2–25 monolayer thickness, measuring the quasiparticle density of states (DOS) as a function of applied in-plane magnetic field
up to 33T. In flakes $\lesssim$ 15 monolayers thick the DOS has a single superconducting gap. In these thin samples, the magnetic field acts primarily on the spin (vs orbital) degree of freedom of the electrons, and superconductivity is further protected by the Ising field. The superconducting energy gap, extracted from our tunnelling spectra, decreases as a function of the applied magnetic field. However, in bilayer $NbSe_2$, close to the critical field (up to 30T, much larger than the Pauli limit), superconductivity appears to be more robust than expected from Ising protection alone. Our data can be explained by the above-mentioned ESTPs.

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2D heterostructures

Tuesday 18 April
16:10-16:35 Hadar Steinberg

Tunable all van-der-Waals Superconducting Devices

Zalic[1], P. Ramachandran[1], E. Grynszpan[1], T. Taniguchi[2], K. Watanabe[2], A. Keselman[3], S. Gazit[1], and H. Steinberg[1*]

[1]Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel
[2] International Center for Materials Nanoarchitectonics, National Institute for Materials Science, 1-1 Namiki,Tsukuba 305-0044, Japan
[3]Physics Department, Technion, 32000 Haifa, Israel

**Presenting author: hadar@phys.huji.ac.il*

Stacking exfoliated two-dimensional materials enabled the creation of new types of devices and new ways to study superconductivity. I will describe a new type of superconducting two-dimensional devices, where graphene forms a weak link between two ultrathin flakes of the superconductor $NbSe_2$. Being entirely two-dimensional, these devices, which we name “two-dimensional Josephson device” (2DJJ), can retain their superconducting properties up to very high magnetic fields applied parallel to the plane of the sample. At this regime, two factors limit the supercurrent: First are minute deviations from the perfect planar geometry, making the 2DJJ extremely sensitive to sub-mili-radian deviations from perfect planarity. Second are the effects of the electron spin, which become accentuated at high magnetic field. The devices exhibit a re-orientation of supercurrent due to the in-plane field. I will discuss various possible mechanisms which limit supercurrent at high in-plane fields.

Tuesday 18 April
16:35-17:00 Nicolas Bergeal

Superconductivity and Rashba spin orbit coupling in KTaO3-based 2DEG

S. Mallik[1], G. C. Ménard[2], G. Saïz[2], H. Witt[1,2], J. Bréhin[1], L. M. Vicente-Arche[1], I. Boventer[1], A. Gloter[3]. J. Lesueur[2], L. Benfatto[4], M. Bibes[1] & N. Bergeal[2*]

[1] *Unité Mixte de Physique, CNRS, Thales, Université Paris-Saclay, 1 Avenue Augustin Fresnel, 91767 Palaiseau, France*
[2] *Laboratoire de Physique et d'Etude des Matériaux, ESPCI Paris, PSL University, CNRS, Sorbonne Université, Paris, France.*
[3] *Laboratoire de Physique des Solides, Université Paris-Saclay, CNRS UMR 8502, 91405 Orsay, France.*
[4] *Department of Physics and ISC-CNR, Sapienza University of Rome, Rome, Italy.*

**Presenting author: nicolas.bergeal@espci.fr*

The search for Majorana Zero Modes, driven by their potential application for quantum computing, continues to be a challenge. So far, most attempts have been focused on hybrid superconducting-semiconductors nanowires, but other platforms have been suggested. In particular, two-dimensional electron gases (2-DEGs) at oxide interfaces display a unique combination of superconductivity and Rashba spin-orbit coupling, which are the two main ingredients for the realization of topological superconducting states.

After fifteen years of intense work on the $LaAlO_3/SrTiO_3$ interface [1], the recent discovery of a superconducting 2-DEG) in (111)-oriented $KTaO^3$-based heterostructures injected new momentum to the field of oxides interface [2,3]. In this system, the superconducting T_c can be larger than 2K, which is almost one order of magnitude higher than in the $SrTiO_3$ based interfaces. Since Ta is much heavier than Ti, spin-orbit effects are also significantly enhanced as demonstrated recently [4,5]. $KTaO_3$ based 2-DEGs could therefore enable the realization of topological superconductivity, originally proposed for $SrTiO_3$ based 2-DEGs but non-achievable due to the weakness of the relevant energies. In this talk, I will present dc and microwave transport experiments on gate tunable superconducting 2-DEGs formed at the (111)-oriented $AlOx/KTaO_3$ interface. The temperature dependence of the superfluid stiffness of the 2-DEGs is found to be consistent with a node-less superconducting order parameter having a gap value larger than expected within a simple BCS weak-coupling limit model [6]. In addition, the superconducting transition follows the Berezinskii-Kosterlitz-Thouless scenario, which was not reported on $SrTiO_3$ -based interfaces. Finally, I'll also present bilinear magnetoresistance measurements in $KTaO_3$ 2-DEGs that directly probe the Rashba spin-orbit coupling, and discuss challenges and perspectives towards device applications [7].

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Rising stars I

Tuesday 18 April
17:00-17:20 Alberto M Ruiz

BAND STRUCTURE, SUPERCONDUCTIVITY AND POLYTYPISM IN $AuSn_4$

Alberto M. Ruiz[3,*], Edwin Herrera,[1] Beilun Wu,[1] Evan O'Leary,[2] Miguel Águeda,[1] Pablo García Talavera,[1] Víctor Barrena,[1] Jon Azpeitia,[4] Carmen Munuera,[4] Mar García-Hernández,[4] Lin-Lin Wang,[2] Adam Kaminski,[2] Paul C. Canfield,[2] José J. Baldoví,[3] Isabel Guillamón[1], and Hermann Suderow[1]

[1]*Laboratorio de Bajas Temperaturas y Altos Campos Magnéticos, Departamento de Física de la Materia Condensada, Instituto Nicolás Cabrera and Condensed Matter Physics Center (IFIMAC), Unidad Asociada UAM-CSIC, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
[2]*Ames Laboratory and Department of Physics & Astronomy, Iowa State University, Ames, Iowa 50011, USA*
[3]*Instituto de Ciencia Molecular (ICMol), Universitat de Valéncia, Catedrático José Beltrán 2, 46980 Paterna, Spain*
[4]*Instituto de Ciencia de Materiales de Madrid, Consejo Superior de Investigaciones Científicas (ICMM-CSIC), Sor Juana Inés de la Cruz 3, 28049 Madrid, Spain*

**Presenting author: alberto.montoya@uv.es*

The orthorhombic compound $AuSn_4$ is compositionally similar to the Dirac node arc semimetal $PtSn_4$. $AuSn_4$ is, contrary to $PtSn_4$, superconducting with a critical temperature of Tc = 2.35 K [1]. Recent measurements present indications for quasi-two-dimensional superconducting behaviour in $AuSn_4$. Here we present measurements of the superconducting density of states and the band structure of $AuSn_4$ through scanning tunneling microscopy and angular resolved photoemission spectroscopy (ARPES) [2]. The superconducting gap values in different portions of the Fermi surface are spread around $\Delta_0 = 0.4$ meV, which is close to but somewhat larger than $\Delta = 1.76 k_B T_c$ expected from BCS theory. We observe superconducting features in the tunneling conductance at the surface up to temperatures about 20% larger than bulk Tc. The band structure was calculated with density functional theory (DFT). The surface band structures were computed by constructing maximally localized Wannier functions in the Wannier90 code (by selecting Au s,d and Sn s,p orbitals as projectors) [3] and then using the surface Green's function method, as implemented in Wanniertools [4]. By applying this methodology, the surface band structures follow well the results of ARPES. The crystal structure presents two possible stackings of Sn layers (space groups No. 68 and No. 41), which are very close in energy and giving two nearly degenerate polytypes. This polytypism can be viewed as a natural sequence of stacking faults which do not produce any other structural change than a rotation or another symmetry operation on a layer. This makes $AuSn_4$ a rather unique case with a three-dimensional electronic band structure but properties ressembling those of low-dimensional layered compounds.

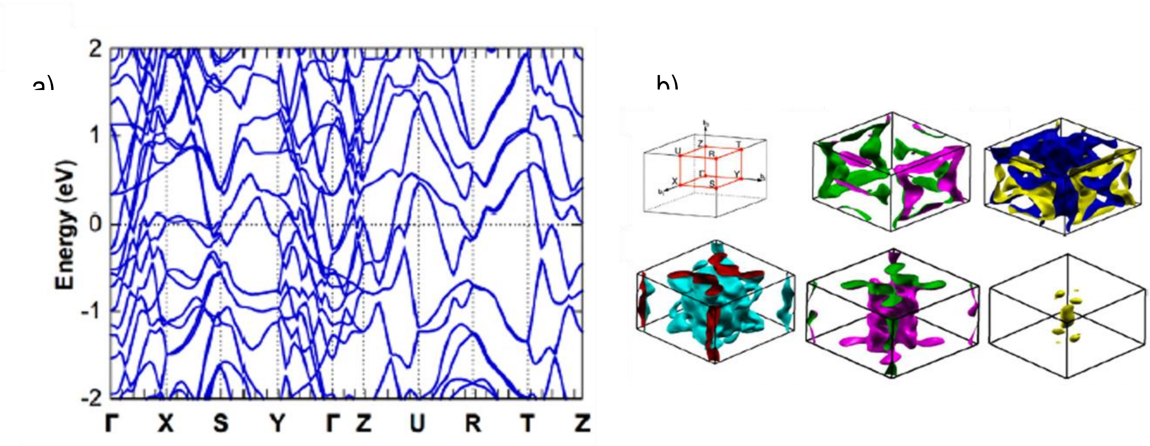

Figure 1. (a) Bulk band structure of $AuSn_4$ (space group No. 68), (b) Brillouin zone of orthorhombic lattice and the five Fermi surface sheets crossing the Fermi level.

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Tuesday 18 April
17:20-17:40 Božidar Šoškić

PHONON-MEDIATED SUPERCONDUCTIVITY IN DOPED MONO- AND BILAYER BOROPHENES

B. N. Šoškić[1*], Ž. Šljivančanin[2], and P. Miranović[1]

[1]*Faculty of Natural Sciences and Mathematics, University of Montenegro, Džordža Vašingtona bb, 81000 Podgorica, Montenegro*
[2]*Vinča Institute of Nuclear Sciences, National Institute of Republic of Serbia, University of Belgrade, P. O. Box 522, RS-11001 Belgrade, Serbia*

**Presenting author: bozidarsoskic@edu.ucg.ac.me*

Placed between nonmetallic carbon and metallic beryllium, boron is one of the most chemically flexible atoms forming at least sixteen bulk polymorphs, which is a consequence of boron's electron deficiency, resulting in the creation of multicentred B–B bonds, that are much more complicated than those of carbon **[1]**. Broad studies on small-scale planar boron clusters provided, in 2015, the first experimental evidence for the growth of two-dimensional (2D) boron structures, named borophenes **[2]**. Borophene possesses a metallic nature and is the lightest known 2D material, with high potential to revolutionize batteries, sensors, with high hydrogen storage capacity, already proven as a catalyst in oxygen reduction, and with theoretical predictions that it possesses superconducting properties **[3,4]**. However, the practical usage of borophene is lagging behind, mainly because borophene oxidizes immediately upon exposure to air, rendering it nonconductive and ruining other potentially useful functional properties. A big step in overcoming this problem was made by the synthesis of hydrogenated borophene (borophane) **[5]**, and different polymorphs of bilayer borophene **[6,7]**, since hydrogenation reduces the undesired reactivity of borophene, and bilayer structures are less prone to being oxidized than their monolayer counterparts. Inspired by the latest discoveries, I will present the beneficial effects of hydrogenation on the superconducting properties in monolayers, and the way how intercalation helps to stabilize and enhance phonon-mediated superconductivity in the bilayer borophenes. The main goal is to create and understand the superconducting properties of these structures, which are stable outside the vacuum chamber and not chemically active, making them therefore applicable for producing advanced nano-superconducting devices.

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Tuesday 18 April
17:40-18:00 Fillipo Gaggioli

Surface barrier and bulk pinning in narrow 2D superconductors

F. Gaggioli[*,1], G. Blatter[1] and V. Geshkenbein[1]

[1]*Institut für Theoretische Physik, ETH Zürich, CH-8093 Zürich, Switzerland*

**Presenting author: filippog@phys.ethz.ch*

Atomically thin systems constitute one of the most exciting research platforms in contemporary condensed matter physics. These materials host a variety of exotic phases of matter, e.g., super- conductivity, correlated-insulator, strange metal, and promise to unlock powerful and innovative technological applications. Magnetic and transport properties of atomically thin superconductors, in particular, have been the object of many experimental and theoretical studies, especially since the first experiments on magic angle twisted bilayer graphene[1]. In a perpendicular magnetic field H, the material response of these superconductors is characterized by the Pearl length $\lambda_\perp = 2\lambda^2/d$. For atomically thin films, this penetration depth greatly exceeds the London length λ as the latter is much larger than the thickness d. More over, $\lambda_\perp$ can easily exceed the sample width W , allowing the magnetic field to fully penetrate inside the system. For such thin films, the ratio $\lambda_\perp/\xi$ is typically much larger than unity, bringing these superconductors under the type-II paradigm. The critical current $I_c(H)$ in these materials is therefore determined by the motion of vortices inside the thin film. At low magnetic fields, this is hampered by a steep surface barrier, preventing vortices from penetrating inside the sample. The critical current then depends linearly on the magnetic field, and displays a peak at H = 0. At higher fields, vortices that penetrate are trapped inside the thin film, and pinning from material inhomogeneities plays an important role. The critical current then decays $\propto 1/H$ and saturates to a finite value determined by vortex pinning.

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Tuesday 18 April
18:00-18:20 Tania Paul

INTERPLAY OF QUANTUM SPIN HALL EFFECT AND SPONTANEOUS TIME-REVERSAL SYMMETRY BREAKING IN ELECTRON-HOLE BILAYERS

T. Paul[1*], V.F. Becerra[2] and T. Hyart[1,2,3]

[1]International Research Center, MagTop, Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, Warsaw, 02-668, Poland
[2]Department of Applied Physics, Aalto University, 00076, Aalto, Espoo, Finland
[3]AComputational Physics Laboratory, Physics Unit, Faculty of Engineering and Natural Sciences, Tampere University, FI-33014 Tampere, Finland

**Presenting author: tpaul@mgtop.ifpan.edu.pl*

It has been proposed that in band-inverted electron-hole bilayers the excitonic correlations arising due to Coulomb interactions lead to phase transitions from a trivial insulator phase to an insulating phase with spontaneously broken time-reversal symmetry and finally to a nontrivial quantum spin Hall insulator phase as a function of increasing electron and hole densities[1]. Importantly, in contrast to the standard paradigm of topological phase transitions, the trivial insulator phase is connected to a quantum spin Hall insulator without an energy gap closing appearing in the fermionic spectrum. We perform a quantum transport study on a Corbino disc which allows bulk and edge contributions to be observed separately. We observe that the edge becomes smoothly conducting while the bulk remains gapped, therefore confirming the presence of the spontaneously broken time-reversal phase[2]. Additionally, we show that it is possible to realize Majorana Zero modes at the interface of the bilayer in its time-reversal symmetry broken phase and an s-wave superconductor in the absence of magnetic field or a ferromagnetic insulator[3]. We develop an effective low-energy theory for the system in the presence of time-reversal symmetry breaking order parameter to obtain analytically the Majorana zero modes and we find a good agreement between the numerical and analytical results in the limit of weakly broken time-reversal symmetry. We show that the Majorana zero modes can be experimentally detected in superconductor/time-reversal symmetry broken insulator/superconductor Josephson junctions through the measurement of a 4π Josephson current, which is one of the signatures of the presence of Majorana Zero Modes.

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Poster session I

Tuesday 18 April
I-1 Abdou Hassanien

EXPOSING TOPOLOGICAL STATES AT ZIGZAG EDGES OF ARMCHAIR GRAPHENE NANORIBBON

S. Šćepanović[1,2], B. Zhou[3], A. Kobayashi[3], J. J. Mirkovic[2] and A. Hassanien[1*]

[1]*Jozef Stefan Institute, 39 Jamova, Ljubljana, Slovenia*
[2]*Faculty of Science, University of Montenegro, G. Washington str. bb, Podgorica*
[3] *Nihon University, Sakurajosui, Setagaya-ku, Tokyo 156-8550, Japan*

**Presenting author: Abdou.Hassanien@ijs.si*

The zigzag edges of arm-chair graphene nanoribbon (GNR) offer unique advantages such as selective site functionalization, quantum magnetism and to tune the bonding of ribbon to external electrical leads. In the pristine form, these edges are expected to be spin active thus naturally giving a nontrivial topological character to the ribbon without the need for elaborate chemical modifications. However, due to its high reactivity, the edges are passivated by atom abstraction and radical recombination reactions which in turn destroy their magnetic properties. To revive edge magnetism and explore the topological properties there is a need for a non-invasive bottom-up method that preserves the structural integrity and protect spin states from interacting with microenvironment. In this work we describe a facial method for addressing these issues in addition to decoupling the physiosorbed nanoribbon from the underlying substrate. Moreover, while it is impossible to covalently bond the ribbon to external electrodes, we demonstrate a procedure that makes it feasible to connect GNR to metal electrodes. Evidence of robust bonding to metal lead is manifested by using GNR as a STM tip for high resolution selective mapping of the structure and electronic properties of edge states on Au(111).

Poster session I

Tuesday 18 April
I-2 Albert Varonov

ELECTRONIC EQUIPMENT FOR OBSERVATION OF BERNOULLI EFFECT IN SUPERCONDUCTORS

A. Varonov[1*] and T. Mishonov[1]

[1]Georgi Nadjakov Institute of Solid State Physics, Bulgarian Academy of Sciences,
72 Tzarigradsko Chaussee Blvd., BG-1784 Sofia, Bulgaria

**Presenting author: varonov@issp.bas.bg*

The current induced contact potential difference (CPD) is known also as Bernoulli effect in superconductors; this is a well-forgotten practically new effect in condensed matter physics. The contact potential difference U is proportional to the square of the electric current density j^2 as lift force of the plane is proportional to the velocity. The proportionality coefficient is expressed by effective mass of Cooper pairs m^*, and this equipment is actually a tool for creation of Cooper pair mass spectroscopy. For measurement of CPD capacitive coupling is indispensable. Another complication is that CPD is in the nano-Volt range. We solve these tasks using low noise operational amplifiers and active resonance filters. We describe an universal amplifier with 120 db (in power) amplification and resonance filter by frequency dependent negative resistance. Our future task will be coupling of the device with a superconducting samples preferably thin films.

Poster session I

Tuesday 18 April
I-3 Alessia Garibaldi

Tuning transport properties of YBCO-based SQUID weak links with Thermomigration

A. Garibaldi[1*], E. Trabaldo[2], F. Lombardi[2] and T. Bauch[1,2]

Chalmers University of Technology,Departement of Microtechnology and Nanoscience, 412 96 Göteborg , Sweden

**Presenting author: alessiag@chalmers.se*

Superconducting Quantum Interference Devices (SQUIDs) are extremely sensitive flux-to-voltage transducers, and base components of systems in a wide variety of applications ranging from medical diagnostics to geophysical surveys. Tremendous efforts have been devoted to the development of high critical temperature superconductor (HTS) based Josephson junctions, the key ingredient of SQUIDs operational above liquid nitrogen temperatures, during the last few decades. However, this is a challenging task for cuprate HTS due to their chemical instability and small coherence length. Various JJ fabrication techniques have been successfully developed for HTS SQUIDs such as grain boundary-, nanowire-, or Grooved Dayem Bridge- (GDB) based JJs. Yet, the reproducibility of high quality JJs implementing such approaches is rather limited.
Here we present the possibility to perform an ex-situ optimization procedure on $YBa_2Cu_3O_{7-\delta}$ (YBCO) JJs (or weak links) implementing thermo-migration.

Thermo-migration consists of sending large AC electric currents through a weak link such as a nanowire or GDB. The concomitant localized Joule heating results in the formation of a large temperature gradient between the constriction and the wide electrodes. This gradient then leads to a displacement of the dopant oxygen atoms of YBCO from the center of the (hot) weak link towards the wide (and cooler) electrodes, resulting in a variation of the material's doping level at the center of the weak link and, therefore, the transport properties of the weak link.

As a proof of principle, we performed thermo-migration on nanowire-based YBCO SQUIDs [1]. Here improvements of the SQUID voltage modulation depth up to a factor 8 has been observed. Similar improvements have been also achieved for GDB-based SQUIDs.

Being able to tune and therefore control the transport properties of weak links ex-situ will be an important step forward in the optimization process of YBCO-based SQUIDs and their applications. The introduction of reliable ex-situ tuning of weak link properties might pave the way for reproducible, possibly even more sensitive, devices.

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Poster session I

Tuesday 18 April

I-4 Alfredo Spuri

Characterization and spectroscopy of a new non-centrosymmetric superconductor

A.Spuri*[1], S.Chakraborty[1], D.Nikolic[1], W.Belzig[1], E.Scheer[1], A. Di Bernardo[1], S.Singh[2], M.Klang[2], P.Ramachandran[2], H.Alpern[2], O.Millo[2], H.Steinberg[2], G. Tang[3], C.Bruder[3], R.Klees[4].

[1] *University of Konstanz, 78464 Konstanz, Germany*
[2] *The Hebrew University of Jerusalem,* 9190401, Jerusalem, *Israel*
[3] *University of Basel, 4001* , Basel, Switzerland
[4] *University of Wurzburg, 97070, Würzburg, Germany*

**Presenting author: alfredo.spuri@uni-konstanz.de*

Several studies [1][2] performed on three-dimensional (3D) superconductor/ferromagnet (S/F) structures have shown that a viable route to generate fully spin-polarized (i.e., spin-triplet) superconducting states consists in using F materials with an intrinsically inhomogeneous magnetization [3].

The metallic F $Cr_{1/3}NbS_2$ shows a magnetically inhomogeneous ground state, where the magnetization follows a helimagnetic pattern along the crystallographic *c*-axis. Previous reports on 2D flakes of $Cr_{1/3}NbS_2$ have also shown that the helimagnetic spin texture in this material can be modulated via soliton excitations [4] activated by an in-plane applied magnetic field *H*.

We have fabricated 2D S/F bilayers consisting of $Cr_{1/3}NbS_2$ stacked via van der Waals interactions onto NbS_2 (2D S) and we have characterized their low-temperature magnetotransport properties to find evidence for spin-triplet states. Our results demonstrate strong evidence for a superconducting proximity effect occurring in the $Cr_{1/3}NbS_2/NbS_2$ system which manifests through the emergence of *H*-tunable reentrant resistive states below the superconducting transition of the bilayers and through a non-monotonic variation of the superconducting critical temperature (T_c) with the applied *H*. The latter result is possibly consistent with the generation of long-ranged spin-triplet pairs at the NbS_2/ $Cr_{1/3}NbS_2$ interface.

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Poster session I

Tuesday 18 April
I-5 Ana Milosavljević

EVOLUTION OF LATTICE, SPIN, AND CHARGE PROPERTIES ACROSS $FeSe_{1-x}S_x$ PHASE DIAGRAM

A. Milosavljević[1*], N. Lazarević[1], A. Baum[2,3], L. Peis[2,3], R. Stumberger[2,3], J. Bekaert[4], A. Šolajić[1], J. Pešić[1], Aifeng Wang[5], M. Šćepanović[1], A. M. Milinda Abeykoon[6], M. V. Milošević[4], C. Petrovic[7], Z. V. Popović[8], and R. Hackl[2,3,9]

[1]*Center for Solid State Physics and New Materials, Institute of Physics Belgrade, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia*
[2]*Walther Meissner Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany*
[3]*Fakultät für Physik, Technische Universität München, 85478 Garching, Germany*
[4]*Department of Physics, University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerp, Belgium*
[5]*School of Physics, Chongqing University, Chongqing 400044, China*
[6]*National Synchrotron Light Source II, Brookhaven National Laboratory, Upton, New York 11973, USA*
[7]*Condensed Matter Physics and Materials Science Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*
[8]*Serbian Academy of Sciences and Arts, Kneza Mihaila 35, 11000 Belgrade, Serbia*
[9]*IFW Dresden, Helmholtzstr. 20, 01069 Dresden, Germany*

**Presenting author: anam@ipb.ac.rs*

Iron-based compounds are widely believed to host unconventional superconductivity. Among them in binary compound FeSe nematic and structural phase transition occurs simultaneously at 90 K and below 9 K superconductivity is observed. In isoelectronic FeS, structural phase transition is not detected down to the lowest temperatures. By substituting selenium with sulfur atoms by 20% a zero nematic phase transition temperature is reached suggesting the existence of quantum critical point (QCP). At this point T_c drops down to approximately 2 K [1]. In order to investigate in which extent the properties and other instabilities of FeSe and FeS are interrelated, the entire substitution range of the $FeSe_{1-x}S_x$ is studied by Raman scattering technique. Data were taken as a function of sulfur concentration x for $0 \leq x \leq 1$, of temperature and of scattering symmetry. All types of excitations including phonons, spins, and charges are analyzed. It is observed that the energy and linewidth of the Fe-related B_{1g} phonon mode vary continuously across the entire range. The A_{1g} mode disappears above $x = 0.23$ and reappears at much higher energy for $x = 0.69$. In a similar way the spectral features appearing at finite doping in A_{1g} symmetry vary discontinuously. The magnetic excitation at approximately 500 cm^{-1} disappears above $x = 0.23$ where the A_{1g} lattice excitations exhibit a discontinuous change in energy. The low-energy mode associated with fluctuations displays maximal intensity at the nematostructural transition and thus tracks the phase boundary [2].

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Poster session I

Tuesday 18 April
I-6 Celia González Sánchez

TOWARDS HYBRID VAN DER WAALS JOSEPHSON JUNCTIONS BASED ON NBSE$_2$

Celia González Sánchez[1]*, J. Cuadra[1], V. Barrena[1], A. Spuri[2], E. Scheer[2], H. Suderow[1], A. di Bernardo[2], E. J. H. Lee[1]

[1] *Condensed Matter Physics Department, Universidad Autónoma de Madrid, Ciudad Universitaria de Cantoblanco, 28049 Madrid, Spain.*
[2] *Department of Physics, Universität Konstanz, Universitätsstraße 10, 78464 Konstanz, Germany.*

**Presenting author: celia.gonzalezs@uam.es*

The emergence of van der Waals heterostructures has paved the way for a "designer" approach, in which novel devices and new physics can be obtained by combining the properties of distinct two-dimensional materials. Among the many possibilities in this context, heterostructures based on superconducting few-layer $NbSe_2$ attract great interest for studying Josephson effects and the superconducting proximity effect in 2D systems [1]. Interestingly, recent work has reported on signatures of a topological superconducting phase in heterostructures based on $NbSe_2$ and 2D ferromagnets [2]. Moreover, first demonstrations of magnetic vdW Josephson junctions have been recently reported using a similar material combination [3, 4, 5, 6]. Motivated by the above developments, we present here our first steps towards the fabrication of nanodevices based on $NbSe_2$, including our first attempts to fabricate Josephson junctions with and without ferromagnetic and antiferromagnetic tunnel barriers.

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[4] K. Kang et al., arXiv:2101.01327
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[6] K. Kang et al., Nano Lett., **22** (2022) 5510-5515

Poster session I

Tuesday 18 April
I-7 Cem Sevik

STRAIN AND GATE-MODULATED SUPERCONDUCTING PROPERTIES OF TWO-DIMENSIONAL MXENE MATERIALS

C. Sevik[1]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Eskisehir Technical University, 26555 Eskisehir, Turkey*

**Presenting author*: *csevik@eskisehir.edu.tr*

We have systematically studied layered and two-dimensional MXene crystals as potential novel superconductors using a combination of first-principles calculations and Eliashberg theory. Our high-throughput material selection approach showed excellent agreement with experimental results for the superconducting transition of bulk-layered MXenes and predicted highly promising superconducting MXene structures, demonstrating their potential for low-dimensional superconducting device applications [1]. Our findings indicate that surface hydrogen adatoms not only significantly increase the critical temperature values but also transform a MXene layer into a superconducting one [2]. Additionally, we demonstrate that gate- and strain-induced enhancements of critical temperatures are feasible for both bulk-layered and monolayer Nb_2CCl_2 crystals, reaching values up to 40 K. $Nb_3C_2S_2$ was also found to be superconducting in both bulk-layered and monolayer forms, with a critical temperature around 30 K [3]. Our results highlight MXene crystals as a new class of atomically thin superconductors with tunable properties through surface functionalization, strain, and gating, presenting a unique opportunity for superconducting materials engineering.

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Poster session I

Tuesday 18 April
I-8 Dominik Volavka

MISFIT LAYER COMPOUNDS AS HEAVILY DOPED 2D TRANSITION METAL DICHALCOGENIDES

D. Volavka[1]*, T. Samuely[1], O. Šofranko[1], M. Gmitra[1], J. Haniš[1], M. Kuzmiak[1], J. Kačmarčík[1], P. Szabó[1], P. Samuely[1], Tristan Cren[2], D. Volavka[1], S. Sasaki[3], L. Cario[3]

[1] *Centre of Low Temperature Physics, Faculty of Science, P. J. Šafárik University, 04001 Košice, Slovakia*
[2] *Institut des NanoSciences de Paris, Sorbonne Université and CNRS-UMR 7588, Paris 75005, France*
[3] *Institut des Matériaux Jean Rouxel, Université de Nantes and CNRS-UMR 6502, Nantes 44322, France*

**Presenting author: dominik.volavka@student.upjs.sk*

Transition metal dichalcogenides (TMDs) display a rich variety of instabilities such as spin and charge orders, Ising superconductivity, and topological properties. Their physical properties can be controlled by doping in electric double-layer field-effect transistors. However, for the case of single layer $NbSe_2$, the doping is limited to ca. 1×10^{14} cm^{-2}, while a somewhat larger effect can be obtained via deposition of K atoms. Our previous study has shown that a misfit compound $LaSe_{1.14}(NbSe_2)_2$ behaves as a $NbSe_2$ single layer with a rigid doping of ca. 6×10^{14} cm^{-2}[1]. Here we show, that a similar compound $LaSe_{1.14}(NbSe_2)$ exhibits an even higher doping of ca. 8×10^{14} cm^{-2}. Still, contrary to the former case, the charge transfer is smaller than expected from stoichiometry[2]. Our experiments show that this is due to the presence of La vacancies. By varying the number of vacancies and Pb substitution, we were able to further tune the amount of doping. This allows us to explore the properties of TMDs over an unprecedented wide range of doping.

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[2] Samuely et al., Phys. Rev. B 104 (2021) 7

Tuesday 18 April
I-9 Filip Košuth

Superconducting properties of medium entropy alloys TiZrNb studied by point-contact spectroscopy

F. Košuth[1,2,*], G. Pristáš[1], J. Bačkai[1,3] , M. Orendáč[1] , S. Gabáni[1] , M. Kuzmiak[1,3] , E. Gažo[1] , R. Franz[4] , S. Hirn[4] , G.C. Gruber[4] , C. Mitterer[4] , S. Vorobiov[2] , K. Flachbart[1], P. Samuely[1] and P. Szabó[1]

[1]Institute of Experimental Physics, Slovak Academy of Sciences, Watsonova 47, 040 01 Košice, Slovakia
[2]Institute of Physics, P. J. Šafárik University, Park Angelinum 9, 040 01 Košice Slovakia
[3]Faculty of Electrical Engineering and Informatics, Technical University, Letná 9, 04200 Košice, Slovakia
[4]Department of Materials Science, Montanuniversität Leoben, Franz-Josef-Straße 18, 8700 Leoben, Austria

**Presenting author: kosuth@saske.com*

Medium-entropy alloys (MEAs) represent a relatively new class of materials that have attracted research interest in materials science and engineering in the past two decades. They consist of several different constituting elements where the atoms arrange themselves on crystallographic positions of simple lattices with a high degree of disorder, i.e., with a high configurational entropy. Most of them involve elements from 3d, 4d and 5d series of metals. The studied TiZrNb samples were prepared by arc-melting and crystalize in bcc type structure. We performed point-contact spectroscopy measurements and our results point to coexistence of multiple phases with different critical temperatures, superconducting gaps and different superconducting coupling strengths. Our results indicate that in the superconducting properties of this this system the NbTi phase dominates.

Poster session I

Tuesday 18 April
I-10 František Herman

The Advanced approach of superconducting gap function extraction from tunneling experiments

František Herman[1*]

[1]*Department of Experimental Physics, Comenius University, Mlynská Dolina F2, 842 48 Bratislava, Slovakia*

**Presenting author: herman2@uniba.sk*

In the continuation of the previous project [1], I introduce and examine an advanced theoretical framework [2]. Its main idea is to extract properties of the superconducting pairing gap function $\Delta(\omega)$ in conventional, nearly localized superconductors. To test the approach, I present an experimentally relevant benchmark model with defined normal and superconducting sectors. The developed reverse engineering framework consists of two logic steps. First, dismantle the superconducting density of states into the effects coming from the superconducting pairing and effects inherited from the normal state. Second, extract and reconstruct properties of $\Delta(\omega)$ and compare it to the superconducting sector of the defined benchmark model. Applying this approach, I can (i) simulate extraction from the actual experimental low-temperature tunneling data and comment on their required properties, and (ii) maintain absolute control above the reconstructed Cooper-pair-influencing properties during ameliorating the individual steps of the method.

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[2] F. Herman, Phys. Rev. B **106**, 224521 (2022).

Poster session I

Tuesday 18 April
I-11 Gabriel Moraes Oliveira

Characterization of the superconductivity of the epitaxial Al shell in hybrid InAs-Al nanowires

Gabriel Moraes Oliveira1*, Ignacio Casal Iglesias1, Ángel Ibabe1, Mario Gómez1, Gorm O. Steffensen2, Thomas Kanne3, Jesper Nygård3, Alfredo Levy Yeyati2, and Eduardo Lee1

1. Condensed Matter Physics Department, Universidad Autónoma de Madrid, 28049 Madrid, Spain
2. Department of Theoretical Condensed Matter Physics, Universidad Autónoma de Madrid, 28049 Madrid, Spain
3. Center for Quantum Devices & Nano-science Center, Niels Bohr Institute, Univ. of Copenhagen, Copenhagen, Denmark

**Presenting author:* gabriel.moraes@uam.es

In the past decade, hybrid superconductor-semiconductor nanostructures have attracted great attention as a promising platform for the search of topological superconductivity [1, 2] and for the development of hybrid superconducting qubits [3]. Recent progress in this field has been enabled by the development of growth methods that warrant a clean interface between superconductor and semiconductor, such as the epitaxial growth of superconductors onto InAs and InSb nanowires [4-6]. Among these cleaner crystals, hybrid InAs-Al wires have been developed first and have been, by far, explored the most. Despite this, there are only very few experiments addressing the superconducting properties of the epitaxial Al shell [7-8], even though it is responsible for inducing superconductivity via the proximity effect onto the semiconductor core.

In this work, we perform a detailed characterization of the superconductivity of Al in full-shell hybrid InAs-Al nanowires. To this end, we employ DC transport measurements to probe the resistance of the shell as a function of the applied magnetic field, also in the Little-Parks regime, and of the temperature. Our observations point toward the formation of normal regions in the Al shell with increasing temperature or external magnetic field, consistent with the formation of phase slip centers [9-10]. This is further supported by the observation of Shapiro steps resulting from the irradiation of microwaves.

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Poster session I

Tuesday 18 April
I-12 Jaydean Schmidt

ANISOTROPIC VORTEX SQUEEZING IN SYNTHETIC RASHBA SUPERCONDUCTORS

J. Schmidt[1], L. Fuchs[1], D. Kochan[2], M. Ufer[1], S. Reinhardt[1], M. Prager[1], M. Kronseder[1], D. Bougeard[1], S. Gronin[3], G. C. Gardner[3], T. Lindemann[4;3], M. Manfra[3;4;5;6], N. Paradiso[1], and C. Strunk[1]

[1] *Dept. of Exp. and Appl. Phys., University of Regensburg, Germany*
[2] *Dept. of Theoretical Phys., University of Regensburg, Germany*
[3] *Birck Nanotechnology Center, Purdue University, West Lafayette, USA*
[4] *Dept. of Phys. and Astron., Purdue University, West Lafayette, USA*
[5] *School of Materials Eng., Purdue University, West Lafayette, USA*
[6] *School of Electr. and Comp. Eng., Purdue University, West Lafayette, USA*

**Presenting author Jaydean Schmidt: nancy.schmidt@ur.de*

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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Poster session I

Tuesday 18 April
I-13 José J. Baldoví

ENGINEERING SPIN EXCITATIONS IN 2D MAGNETIC MATERIALS

J. J. Baldoví[1*], A. M. Ruiz[1], A. Rybakov[1], D. L. Esteras[1], G. Rivero[1] and D. López-Alcalá[1]

[1]*Instituto de Ciencia Molecular, Universitat de València, 46980, Paterna, Spain*

**Presenting author: j.jaime.baldovi@uv.es*

The recent isolation of two-dimensional (2D) magnets offers tantalizing opportunities for spintronics and magnonics at the limit of miniaturization.[1] Among the key advantages of atomically-thin materials are their flexibility, which provides an exciting avenue to control their properties by strain engineering, and the more efficient tuning of their properties with respect to their bulk counterparts. In this presentation we will provide an overview of our recent results on this fascinating topic. First, we will focus on the magnetic properties, magnon dispersion and spin dynamics of the air-stable 2D magnetic semiconductor CrSBr (TC = 146 K)[2] and will investigate their evolution under mechanical strain and Coulomb screening using first-principles.[3] Our results provide a deep microscopic analysis of the competing interactions that stabilize the long-range ferromagnetic order and the orientation of the spin in the monolayer.[4]

Then, we will apply our approach to some of the derivatives of the family of transition-metal phosphorus trichalcogenides and we will show the possibility of tuning spin wave transport by atomic-layer substitution, building a so-called Janus single-layer.[5] Finally, we will introduce novel hybrid molecular/2D heterostructures using sublimable organic molecules to show, as a proof-of-concept, the potential of a chemical approach for magnon spintronics applications.

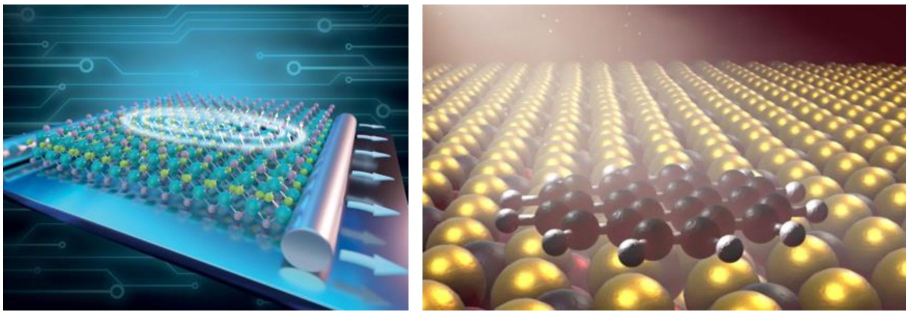

Fig. 1: *Artistic representation of (left) strain-engineering of spin waves in single-layer CrSBr and (right) a coronene molecule on the surface of a 2D magnetic material.*

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Poster session I

Tuesday 18 April
I-14 Július Bačkai

SUPERCONDUCTIVITY IN MEDIUM- AND HIGH-ENTROPY ALLOY THIN FILMS: IMPACT OF THICKNESS AND EXTERNAL PRESSURE

Július Bačkai[1,2*],Gabriel Pristáš[1], Matúš Orendáč[1], Slavomír Gabáni[1], Filip Košuth[1,3], Marek Kuzmiak[1,2], Pavol Szabó[1], Emil Gažo[1], Robert Franz[4], Sabrina Hirn[4], Georg C. Gruber[4], Christian Mitterer[4], Serhii Vorobiov[3], and Karol Flachbart[1]

[1]*Institute of Experimental Physics, Slovak Academy of Sciences, Watsonova 47, 040 01 Košice, Slovakia*

[2]*Faculty of Electrical Engineering and Informatics, Technical University, Letná 9, 04200 Košice, Slovakia*

[3]*Institute of Physics, P. J. Šafárik University, Park Angelinum 9, 040 01 Košice, Slovakia*

[4]*Department of Materials Science, Montanuniversität Leoben, Franz-Josef-Straße 18, 8700 Leoben, Austria*

**Presenting author: backai@saske.sk*

We have prepared and investigated superconducting $Nb_{67}Hf_{11}Ti_{11}Zr_{11}$ and $Nb_{35}Ta_{35}Hf_{10}Ti_{10}Zr_{10}$ medium and high-entropy alloys in form of thin films with thicknesses of 600, 100, and 30 nm, and compared their properties with bulk counterparts. We show that the superconducting transition temperature T_c as well as the upper critical magnetic field $B_{c2}(0)$ decrease with decreasing thickness. Application of hydrostatic pressure up to 33 kbar on the 600-nm $Nb_{35}Ta_{35}Hf_{10}Ti_{10}Zr_{10}$ film shows a decrease of T_c with pressure, which differs from that observed on bulk sample. However, no clear T_c dependence was observed if pressure was applied on the 100-nm film. This result is most likely related to increasing disorder (tendency to structure amorphization) in thinner films.

Poster session I

Tuesday 18 April
I-15 Konrad Norowski

THE FASTEST THERMOMETRY IN THE NANOWORLD

K. Norowski,[1*] M. Foltyn,[1] A. Savin,[2] M. Zgirski,[1]

[1] *Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, PL 02668 Warsaw, Poland*
[2] *Low Temperature Laboratory, Department of Applied Physics, Aalto University School of Science, P.O. Box 13500, 00076 Aalto, Finland*

**Presenting author: norowski@ifpan.edu.pl*

In the low temperature mesoscopic systems, thermal decoupling of electrons from lattice and small heat capacities make the dynamical measurements of thermal properties difficult. The former makes the observation of overheated electrons effects possible. The latter one, together with thermal conductivity, sets the characteristic timescales of energy relaxation processes, which at nanoscale may easily fall significantly below 1µs. These circumstances call for the development of a fast and reliable thermometer. We fulfill this need by demonstrating a time-resolved thermometry, which uses a superconducting junction in a form of a Dayem nanobridge as a temperature sensitive element. By probing the bridge with current pulses, we are able to monitor thermal transients induced in the tested structure [1]. Due to the fast intrinsic dynamics of a superconducting junction, the presented method has a superb temporal resolution, reaching single nanosecond with a perspecitvie of improving it even further. It allows to examine numerous nonequilibrium processes of energy transfer in nanoscale. Among them, we study thermal relaxation of superconducting nanowires [Fig. 1], quasiparticle transport from heater to the thermometer [2], overheating of phonons [3] and phonon propagation through the nonconducting substrate [Fig. 2]. These studies let us infer the mechanisms of electron-phonon coupling, electron thermal conductivity (diffusion) and the energy exchange between two nanostructures mediated by the phonon emission channel. The acquired knowledge about the mentioned processes is essential to optimize operation of many known nanoscale devices like low temperature calorimeters and bolometers, and can enhance performance of qubits, RSFQ logic and single electron boxes.

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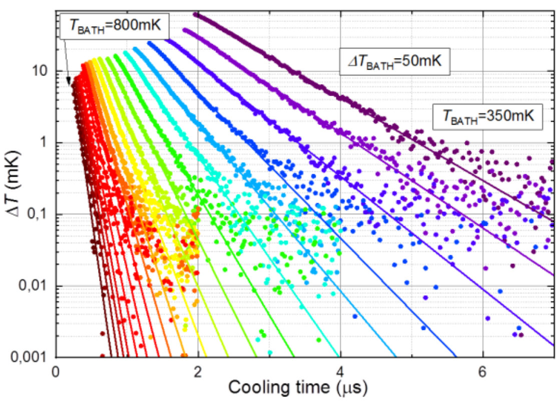

Fig. 1 The cooling curves of a superconducting nanowire, measured in various bath temperatures (the thermometer is embedded in the middle of the wire). Linear fits show the exponential cooling of the electron temperature to the equilibrium value , with corresponding temperature dependent relaxation times.

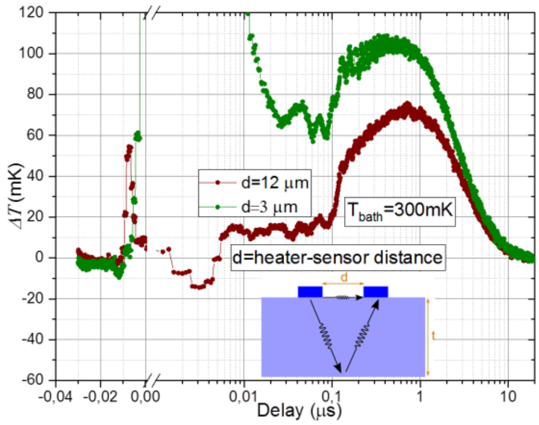

Fig. 2 The phonon propagation between heating line and the galvanically isolated detector. The testing signal sent on the detector is delayed with respect to the heating pulse. The abrupt rise of the signal at delay ~0.1 µs corresponds to the onset of ballistic phonon arrival.

Poster session I

Tuesday 18 April
I-16 Krzysztof Szulc

Spin-wave resonances in ferromagnet/insulator/superconductor disc heterostructures

K. Szulc[1*], J.W. Kłos[1] and O.V. Dobrovolskiy[2]

[1]*ISQI, Faculty of Physics, Adam Mickiewicz University, Poznań, Uniwersytetu Poznańskiego 2, 61-614 Poznań, Poland*
[2]*University of Vienna, Faculty of Physics, Nanomagnetism and Magnonics, Superconductivity and Spintronics Laboratory, Währinger Str. 17, 1090 Vienna, Austria*

**Presenting author: krzysztof.szulc@amu.edu.pl*

Cavity-enhanced light-matter interaction has become an efficient tool to control and explore the properties of quantum materials [1]. This approach is based on the formation of hybrid states consisting of matter and field components, resulting in various collective modes such as magnon-polaritons and hybrid superconducting modes [2-4]. In this regard, it is appealing to realize such modes in hybrid systems where magnons (quanta of spin waves) represent "matter", microwave cavity fields represent "light", and confinement is controlled by a superconductor [5]. Here, we realize such hybridization in ferromagnet/insulator/superconductor disc heterostructures. The spin-wave resonant spectra of the discs are studied numerically for the magnetization configurations of a single-domain and a magnetic vortex state. Because of the Meissner effect, the superconductor modifies the magnetic-field value and direction in its vicinity. The resulting non-uniform field induces a non-collinear magnetization configuration in the ferromagnetic disc, affecting its spin-wave resonant modes. The problem is treated relying upon the Landau-Lifshitz and London-like equations which are coupled through the magnetic vector potential. The presence of the superconductor leads to a confinement of the magnonic components of the low-frequency hybrid modes in the center of magnetic disc and strongly affects their intensities and frequencies. In the case of a smaller superconducting disc on top of a larger magnetic disc, the effect of partial magnetic field expulsion enforces a specific selection rule for the modes based on the system's geometry. The field-dependent measurements of the resonant modes reveal anomalous frequency changes.

KS and JWK acknowledge the grants of National Science Centre, Poland, No. UMO-2021/41/N/ST3/04478 and UMO-2021/43/I/ST3/00550. OVD acknowledges support by the Austrian Science Fund (FWF) under Grant I 6079-N (FluMag).

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Poster session I

Tuesday 18 April
I-17 Leonardo Cadorim

Vortical versus skyrmionic states in the topological phase of a twisted bilayer with d-wave superconducting pairing

Cadorim, L. R.[1,2*], Sardella, E[2] and Milosevic, M, V[2,3]

[1] *Departamento de Física, Faculdade de Ciências, Universidade Estadual Paulista (UNESP), Caixa Postal 473, 17033-360, Bauru-SP, Brazil*
[2] *Department of Physics, University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerp, Belgium*
[3] *Instituto de Física, Universidade Federal de Mato Grosso, 78060-900 Cuiabá, Mato Grosso, Brazil*

**Presenting author: leonardo.cadorim@unesp.br*

Chiral superconductivity has been a topic of tremendous interest in the recent literature due to its rich phenomenology, including appearance of non-trivial surface currents and half-quantum vortices, to name a few examples. Recently, it was shown [1] that a twisted bilayer composed of two monolayers of the high-temperature superconductor Bi-2212 can display a chiral topological phase which breaks time-reversal symmetry for twist angles near 45º. This occurs because, at a twist angle equal to 45º, the $d_{x^2-y^2}$ order parameter of each layer, characteristic of Bi-2212, induces a significant d_{xy} component in the order parameter of the other layer. This results in a superconducting state with $d + id'$ pairing symmetry. In this work, we show how such system behaves in the presence of an applied magnetic field, investigating the vortex matter of the sample for different values of the twist angle. As we show, due to the broken time-reversal symmetry, two different skyrmionic states emerge in the topological phase. These states have clearly distinct magnetic signatures. In the first one, the broken time-reversal symmetry manifests in the formation of vortex pairs between vortices of each layer, in each of these pairs, the phase difference between the layers is equal to π. In contrast, in the second skyrmionic state, vortices in each layer organize themselves in long vortex chains, which separate regions with interlayer phase difference equals to –π/2 or π/2. These chains can have lateral dimensions in the region of the micron scale. Giving that each skyrmionic state possess a well-defined magnetic signature, the detection of such states can be used as a smoking gun for the detection of topological superconductivity in such systems.

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WEDNESDAY 19 APRIL

Devices

08:30-08:55 Francesco Giazotto

Manipulation of Thermal Transport Via Proximity Effect: The Thermal Superconducting Quantum Interference Proximity Transistor

F. Giazotto[1]

[1]*NEST, Instituto Nanoscienze – CNR & Scuola Normale Superiore, Pisa, Italy*

**Presenting author: francesco.giazotto@sns.it*

Superconducting materials are known to be good thermal insulators at sufficiently low temperatures thanks to the presence of the energy gap in their density of states (DOS). Yet, the proximity effect allows to tune the local DOS of a metallic wire by controlling the phase biasing imposed across it. As a result, the wire thermal resistance can be largely tuned by phase manipulation. In this talk I will show the experimental implementation of efficient control of thermal current by phase tuning the superconducting proximity effect. This is achieved by using the magnetic flux-driven modulation of the DOS of a quasi one-dimensional aluminum nanowire forming a weak-link embedded in a superconducting loop [1]. Moreover, phase-slip events occurring in the nanowire are able to induce a hysteretic dependence of its local DOS on the direction of the applied magnetic field. Thus, we also demonstrate the operation of the nanovalve as a phase-tunable thermal memory [1, 2], thereby encoding information in the local temperature of a metallic electrode nearby connected. Besides quantum physics, our results are relevant for the design of innovative phase-coherent caloritronics devices such as thermal valves and temperature amplifiers, which are promising nanostructures for the realization of heat logic architectures.

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Acknowledgements
The EU's Horizon 2020 research and innovation program under Grant Agreement No. 964398 (SUPERGATE) is acknowledged for partial financial support.

Wednesday 19 April
08:55-09:20 Angelo Di Bernardo

Reversible tuning of a supercurrent in superconducting nanoconstrictions

Leon Ruf[1], Jennifer Koch[1], Priyana-Puliyappara Babu[1], R. Hartmann[1], Carla Cirillo[2], A. Vecchione[3], Carmine Attanasio[3], Elke Scheer[1], Angelo Di Bernardo[1*]

[1]Department of Physics, University of Konstanz, Universitätstraße 10, 78457 Konstanz, Germany
[2]Department of Physics, University of Salerno, via Giovanni Paolo II 132, 84084 Fisciano, Italy
[3]CNR-Spin c/o University of Salerno, via Giovanni Paolo II 132, 84084 Fisciano, Italy

**Presenting author: angelo.dibernardo@uni-konstanz.de*

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).

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Wednesday 19 April
09:20-09:45 Javier Villegas

Superconducting photomemristor based on a High-T_C superconducting cuprate

Ralph El Hage[1]. Vincent Humbert[1], Victor Rouco[1], Gabriel Sánchez-Santolino[2], Aurelien Lagarrigue[1], Kevin Seurre[1], S. Carreira[1], Anke Sander[1], Jérôme Charliac[3], Salvatore Mesoraca[1], Juan Trastoy[1], Javier Briatico[1], Jacobo Santamaría[1,2] & Javier E. Villegas[1,*]

[1]*Unité Mixte de Physique, CNRS, Thales, Université Paris Saclay, 91767 Palaiseau, France*
[2]*GFMC, Dpto. Física de Materiales. Universidad de Ciencias Físicas, Universidad Complutense de Madrid, 28040 Madrid, Spain*
[3]*Laboratoire de Physique des Interfaces et des Couches Minces (UMR7647), CNRS, Ecole Polytechnique, 91128 Palaiseau Cedex, France*

**Presenting author: javier.villegas@cnrs-thales.fr*

Memristors are a key element for novel neuromorphic computing architectures. By definition, a memristor is sensitive to the history of electrical stimuli, which change its electrical resistance across a continuum of nonvolatile states. Currently, there is much intereset in realizing devices that present an analogous response to optical stimuli-Here we realize a new class of device, a photo-memristor, whose behaviour is bimodal: both electrical and optical stimuli can trigger the switching across resistance states in a way determined by the dual optical-electrical history. This unique behaviour is obtained in a device of ultimate simplicity: an singly interface between a high-temperature superconductros and a transparent semiconductor. The microscopic mechanism at play is a reversible nanoscale redox reaction between both materials, whose oxygen content determines the electron tunnelling rate across their interface. Oxygen exchange is controlled here via illumination by exploiting a competition between electrochemistry, photovoltaic effects and photo-assisted ion migration. In addition to their fundamental interest, the unveiled electro-optic memory effects have considerable technological potential. Especially in combination with high-temperature superconductivity which, beyond facilitating the high connectivity required in neuromorphic circuits, brings photo-memristive effects to the field of superconducting electronics.

Work supported by ERC grant N° 647100 "SUSPINTRONICS", ERC grant Nº 966735 "SUPERMEM", French ANR grant ANR-17-CE30-0018-04 "OPTOFLUXONICS", COST Action CA 21144 superqumap, and Spanish AEI PID2020-118078RB-I00.

Wednesday 19 April
09:45-10:10 Jan Aarts

Supercurrents in a halfmetallic manganite

Yao Jungxiang, Remko Fermin, Kaveh Lahabi, and Jan Aarts*
Huygens-Kamerlingh Onnes Laboratory, PO Box 9504, 2300 RA Leiden, The Netherlands

** Presenting author: aarts@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 demonstrate clear supercurrents in lateral Josephson junctions fabricated from a bilayer of LSMO and superconducting NbTi. The weak link is formed by a trench in the NbTi layer, made by Focused Ion Beam milling, and FIB milling also defines the junction geometry. The trench width, and therefore the junction length, was of the order 20 nm. Finding (strong) supercurrents in such junctions is surprising, since no magnetic inhomogeneity was built into the system. In bar-shaped junctions, we find a Fraunhofer-type interference pattern when applying an out-of-plane magnetic field, indicating homogeneous current flow. Disk-shaped junctions show a different pattern, indicating stronger currents along the edge of the disk. We find Josephson couplings (I_cR_N products) around 50 μV, which is large compared to all-metal junctions. We surmise that sufficient magnetic inhomogeneity exists in the LSMO layer close to the interface with NbTi to work as triplet generator. Following up on these results, we used e-beam lithography and a hard mask process to fabricate long junctions, also starting from a bilayer. Again we find supercurrents, even up to a record junction length of 1.3 μm, and with high current densities, of the order of 10^9 A/m^2 at 2 K. Combining oxide magnets with (s-wave) alloy superconductors appears a promising new route to realizing superconducting spintronics

Superconducting diodes

Wednesday 19 April
10:40-11:05 Mazhar Ali

Non-reciprocal superconductivity and the field-free Josephson Diode

H. Wu[1,2], Y. Wang[1,2], M. N. Ali[1,2]*

[1]*TU Delft, Faculty of Applied Sciences, Department of Quantum Nanoscience, Loretnzweg 1, B22, 2628CJ, Delft, NL*
[2] *Kavli Institute of Nanoscience, Loretnzweg 1, 2628CJ, Delft, NL*

**Presenting author: m.n.ali@tudelft.nl*

Nonreciprocal transport is incredibly important in technology; asymmetry in the current-voltage response in semiconductor junctions has been the basis for diodes and transistors, basic demonstrations of nonreciprocity. Nonreciprocal superconductivity, however, proved elusive, and only in 2020 was the superconducting diode effect (superconducting in one direction while normal conducting in the other) discovered for the first time in an alloy of V/Nb/Ta, using a magnetic field. Recently, we demonstrated a Josephson diode (JD), created in a quantum material Josephson junction; a diodic effect was seen without an applied magnetic field; important for technological application as nanoscale field control remains a challenge. Using an inversion symmetry breaking heterostructure of NbSe2/Nb3Br8/NbSe2, half-wave rectification was achieved with low switching current density and high rectification ratio. Following that, a plethora of nonreciprocal QMJJ and other architectures have been investigated and future directions for optimizations and novel explorations will be discussed.

Wednesday 19 April
11:05-11:30 Vladimir Krasnov

A VORTEX-BASED JOSEPHSON DIODE

T. Golod and V. M. Krasnov*

Department of Physics, Stockholm University, AlbaNova University Center, SE-10691 Stockholm, Sweden.

**Presenting author: vladimir.krasnov@fysik.su.se*

Diode is one of the primary electronic components. Its nonreciprocal current–voltage (I–V) characteristics allow rectification of alternating currents, which is necessary for signal processing and ac–dc conversion. Diodes can be also used as building blocks for Boolean logics in digital computation. Superconducting diodes should have strongly asymmetric critical currents, $|I_c^+| \neq |I_c^-|$. It is well known that nonreciprocity may appear in spatially asymmetric superconducting devices. Diodes, based on spatially nonuniform Josephson junctions (JJs), were demonstrated long time ago [1]. Also SC ratchets, rectifying motion of either Josephson or Abrikosov vortices, were intensively studied. However, such spatially asymmetric devices operate only at finite magnetic fields, while electronic components should work at zero field. Nonreciprocity at $H = 0$ is prohibited by the time-reversal symmetry, which requires invariance of electromagnetic characteristics upon simultaneous flipping of current and magnetic field [1]. Therefore, zero-field SC diode requires breaking of both space and time-reversal symmetry.

In this talk I will describe our recent results on realization of a superconducting diode [2]. We demonstrate prototypes of SC diodes with a large and switchable nonreciprocity of supercurrent at zero magnetic field. They are made of a conventional Nb superconductor and contain cross-like planar Josephson junctions with additional electrodes and an artificial vortex trap. Nonreciprocity is induced by a combination of self-field effect from asymmetric bias and stray fields from trapped Abrikosov vortex. We demonstrate that the ratio, $|I_c^+/I_c^-|$, of such diodes can reach an order of magnitude and rectification efficiency can exceed 70%. Furthermore, we can switch nonreciprocity on and off, as well as change diode polarity in one and the same device. This is achieved by trapping/removing either a vortex, or an antivortex, and/or by changing the bias configuration. This facilitates memory functionality. We argue that such a diode-with-memory can be used for a new generation of superconducting in-memory computers.

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Wednesday 19 April
11:30-11:55 Simon Reinhardt

Sign reversal of the supercurrent diode effect and 0–π-like transitions in ballistic Josephson junctions

Christian Baumgartner[1], Andreas Costa[1], Simon Reinhardt[1*], Johanna Berger[1], Sergei Gronin[2], Geoffrey C. Gardner[2], Tyler Lindemann[2], Michael J. Manfra[2], Denis Kochan[1], Jaroslav Fabian[1], Nicola Paradiso[1], and Christoph Strunk[1]

[1]*University of Regensburg, 93040 Regensburg, Germany*
[2]*Purdue University, West Lafayette, Indiana 47907, USA*

**Presenting author: simon.reinhardt@ur.de*

Since the discovery of the supercurrent diode effect by Ando et al. [1] and its observation in a rich variety of systems, there is an increasing interest in the physics of non-reciprocal superconductivity.
We study Josephson junctions in hybrid aluminum/InGaAs/InAs structures. Using a cold resonator technique, we measure the Josephson inductance as well as DC transport properties [2-4]. We demonstrate a sign reversal of the supercurrent diode effect, in both its AC and DC manifestations. In particular, the AC diode effect − i.e., the asymmetry of the Josephson inductance as a function of the supercurrent − allows us to probe the current-phase relation near equilibrium. Using an analytical model, we can then link the sign reversal of the AC diode effect to the so-called $0-\pi$-like transition, a predicted, but still elusive feature of multi-channel junctions [5].

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Wednesday 19 April
11:55-12:20 Peter Makk

Strong non-local transport signatures of Andreev molecular state

P. Makk[1*], M. Kocsis [1], Z. Scherübl[1], G. Fülöp[1], O. Kürtössy[1], Sz. Csonka[1]

[1]*Dept. Of Physics, Budapest University of Technology and Economics, 3 Muegyetem Rakpart, Budapest, Hungary-1111*

**Presenting author:* *makk.peter@ttk.bme.hu*

Recent advances in hybrid superconducting – semiconducting structures allows for well-controlled fabrication of complex nanodevices. Placing two Josephson junctions next to each other, closer than the superconducting coherence length, the Andreev bound states hybridize into an Andreev molecular state. Here we investigate the scenario where the Josephson junctions are formed with a quantum dot as the channel. We have recently demonstrated the formation of Andreev molecule in double nanowires with bias spectroscopy measurements [1]. Here we will go beyond and investigate the possible signatures in supercurrent measurements.

Similar molecular state were theoretically investigated in ballistic channels, in the absence of electron-electron interactions, where the non-local tunability of the supercurrent was argued [2,3]. In quantum dots, the presence of the Coulomb interaction and the possibility of electrostatic gating allows for a more versatile tunability. First of all, doublet grounds are only possible with finite Coulomb interactions.

In this contribution we discuss how the molecular state is formed and how the supercurrent of a given junction is affected by the control parameters of the other junction, namely the level position and the superconducting phase difference. Beside the usual parity driven 0-pi transition we identified 0 and pi regions within the same ground state. We demonstrate a large, strongly tunable phi0 phase in the absence of spin-orbit interaction. Furthermore exotic current phase relations and superconducting diode effect are discussed. The non-local tunability of these effects are the smoking gun features of the Andreev molecular state.

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Unconventional superconductors

Wednesday 19 April
14:00-14:25 Julia Meyer

SPIN SUSCEPTIBILITY OF NONUNITARY SPIN-TRIPLET SUPERCONDUCTORS

J. S. Meyer

Univ. Grenoble Alpes, CEA, Grenoble INP, IRIG, PHELIQS, 38000 Grenoble, France

**Presenting author: julia.meyer@univ-grenoble-alpes.fr*

The spin susceptibility is an important probe to characterize the symmetry of the order parameter in unconventional superconductors. Among them, nonunitary triplet superconductors have attracted a lot of attention recently in the context of the search for topological superconductivity. Here [1], we derive a general formula for the spin susceptibility of nonunitary triplet superconductors within a single-band model of non-magnetic, centrosymmetric materials with strong spin-orbit coupling. We use it to critically assess experimental claims of nonunitary triplet superconductivity in some materials.

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Wednesday 19 April
14:25-14:50 Peter Wahl

Low energy electronic structure in strontium ruthenates: from surface distortions to magnetic-field control of the electronic structure

P. Wahl[1*]

[1] *School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, KY169SS, United Kingdom*

**Presenting author: wahl@st-andrews.ac.uk*

The phenomenology and radical changes seen in materials properties traversing a quantum phase transition has captivated condensed matter research over the past decades. Strong electronic correlations lead to novel ground states, including magnetic order, nematicity and unconventional superconductivity. To provide a microscopic model for these requires knowledge of the electronic structure in the vicinity of the Fermi energy. The strontium ruthenates provide a family of ideal model systems to explore this physics using spectroscopic techniques: they exhibit an anisotropic, quasi-two-dimensional electronic structure and occur as single-, double- and triple-layer compounds with similar crystal structure but disparate ground states ranging from unconventional superconductivity via metamagnetism to itinerant ferromagnetism. In the metamagnetic compounds, spectroscopic information about the low energy electronic structure would allow verification of different scenarios that have been proposed to explain their exotic properties. I will present spectroscopic imaging of the electronic structure performed at temperatures down to 100mK[1] and in vector-magnetic fields, and discuss the implications for the low energy electronic structure. Notably, for several of the strontium ruthenates the surface provides a platform to study the properties of the electronic structure under conditions not accessible in the bulk.[2,3]

This work was done in close collaboration with C.A. Marques, L.C. Rhodes, M. Naritsuka, I. Benedičič, as well as colleagues from the University of St Andrews, CNR SPIN, and the Max Planck Institute for the Chemical Physics of Solids.

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Wednesday 19 April
14:50-15:15 Klaus Hasselbach

Chiral Superconductivity in UPt3 observed by scanning SQUID Microscopy

Pablo García Campos[1], Dai Aoki[2,3], Klaus Hasselbach[1]

[1]*University. Grenoble Alpes, CNRS, Institut Néel, 38000 Grenoble, France*
[2]*IMR, Tohoku University Ibaraki Japan*
[3]*University Grenoble Alpes, CEA, IRIG-PHELIQS, 38000 Grenoble, France*

**Presenting author: klaus.hasselbach@neel.cnrs.fr*

Symmetry and topology are tools to describe states of quantum matter: A long sought after indication for unconventional pairing of superconducting electrons is the breaking of additional symmetries other than gauge symmetry.
UPt_3 undergoes at low temperatures a strong electron mass renormalization (more than 100 times the free electron mass). These heavy fermions form superconducting Cooper pairs below 0.55 K. Superconductivity is expected to be mediated by spin fluctuations.
UPt_3 presents at ambient pressure three different superconducting phases A,B,C each with an order-parameter of different symmetry. Upon cooling in zero applied magnetic field the frontier between the A and the chiral B phase (breaking time reversal symmetry) is crossed at 0.5 K. In the B phase, energetically degenerate chiral domains are expected to appear: Theory predicts the existence of fractional vortices and an unusual flux distribution at the domain wall separating chiral domains.
With our scanning SQUID microscope we could observe in the B phase of UPt_3 magnetic flux aligning with domain walls and detect half-Φ0 vortices. Half-Φ0 vortices are not observed in the A phase.

These direct observations are a strong indication for time reversal symmetry breaking and chiral superconductivity in UPt_3.

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Rising stars II

Wednesday 19 April
15:15-15:35 Daniele Torsello

INTERPLAY OF COEXISTING SUPERCONDUCTING AND FERROMAGNETIC ORDERS IN $EuFe_2(As_{1-x}P_x)_2$

D. Torsello[1,2*], R. Gerbaldo[1,2], L. Gozzelino[1,2], F. Laviano[1,2] and G. Ghigo[1,2]

[1]*Politecnico di Torino, Department of Applied Science and Technology, c.so Duca degli Abruzzi 24, 10129 Torino, Italy*
[2]*Istituto Nazionale di Fisica Nucleare, Sez. Torino, via P. Giuria 1, 10125 Torino, Italy*

**Presenting author: daniele.torsello@polito.it*

The coexistence down to the atomic level of superconductivity (SC) and ferromagnetism (FM) in iron-based superconductors containing magnetic rare-earth metal elements offers a unique opportunity to study the interplay of these two orders. Our study focuses on $EuFe_2(As_{1-x}P_x)_2$, a compound that, in a limited range of composition, displays a magnetic ordering temperature below the superconducting transition temperature. The samples were analyzed using a coplanar waveguide resonator technique, which allowed us to access the complex magnetic susceptibility and the London penetration depth [1]. Our results reveal complex dynamic processes visible from the imaginary component of the susceptibility [2]. To better understand this rich phenomenology, we compared our findings with those obtained from other techniques such as magnetic force microscopy, muon-spin spectroscopy, and ac susceptibility. The dynamics of superconducting vortices and antivortices, influenced by the complex magnetic Meissner domains, and the identification of intra and interdomain depinning processes were investigated over frequencies spanning several orders of magnitude [3]. Additionally, we observed a crossover from "ferromagnetic superconductivity" to "superconducting ferromagnetism" due to P-doping and disorder induced by 3.5-MeV proton irradiation [4]. Our findings suggest that SC and FM in $EuFe_2(As_{1-x}P_x)_2$ are two coexisting but independent and slightly competing phenomena: with increasing disorder SC is suppressed while FM starts to manifest at higher temperatures [5].

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Wednesday 19 April
15:35-15:55 Marta Fernández Lomana

TWO-DIMENSIONAL HIGH-TC SUPERCONDUCTIVITY IN THE IRON BASED SUPERCONDUCTOR KFe_2As_2

M. Fernández Lomana, [1*] B.Wu[1], E. Herrera[1], A. A. Haghighirad[2], R Valentí[3], Y-J. Song[3], H.Suderow[1,4] , A.E. Böhmer[2,4,] , and I.Guillamón[1,4]

[1] Laboratorio de Bajas Temperaturas, Departamento de Física de la Materia Condensada, Instituto de ciencia de Materiales Nicolás Cabrera, Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, E-28049.
[2] Institute for Quantum Materials and Technologies (IQMT), Karlsruhe Institute of Technology, 76021 Karlsruhe, Germany.
[3] Institut für Theoretische Physik, Goethe-Universität Frankfurt, Max-von-Laue-Strasse 1, 60438 Frankfurt am Main, Germany
[4] Unidad Asociada de Bajas Temperaturas y Altos Campos Magnéticos, UAM, CSIC, Cantoblanco, E-28049 Madrid, Spain 4Institut für Experimentalphysik IV, Ruhr-Universität Bochum, 44801 Bochum, Germany

**Presenting author: marta.fernandez-lomana@uam.es*

We have discovered a two-dimensional High-Tc superconducting phase on the surface of the iron-based superconductor KFe_2As_2. This system is at the end of the $Ba_{1-x}K_xFe_2As_2$ series and shows bulk superconductivity with Tc=3.4 K. It has been proposed to be a nodal superconductor with a strongly enhanced electronic effective mass due to the proximity to an orbital-selective Mott transition [1].

Here we present first STM measurements at very low temperatures and high magnetic fields [2]. We have measured the superconducting density of states at 100 mK and observed the opening of two superconducting gaps of 0.92 meV and 2.07 meV that disappear at 12 K, a temperature which is a factor of 4 higher than the Tc of the bulk. Under magnetic field, we have imaged the vortex lattice up to 12 T, well above the macroscopic upper critical field (H_{c2} ~1.4T). The two-dimensional character of the superconducting properties at the surface is confirmed by the spatial extension of the scattering signal around individual defects. Quasiparticle interference measurements at the superconducting (zero field) and normal (20 T) phases show the presence of modulations of the density of states that are associated to an interband scattering vector. In the superconducting phase, the scattering has a strong fourfold anisotropy showing the presence of very anisotropic superconducting gaps. In the normal phase at 20 T, we find a spectral function suggestive of strong electron correlations close to the Fermi level. Our data show that two-dimensionality and correlations can bring, together, robust superconductivity at high temperatures and magnetic fields.

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Wednesday 19 April
15:55-16:15 Somesh Chandra Ganguli

Evidence of strong correlations and unconventional superconductivity in monolayer transition metal dichalcogenides 1H-$NbSe_2$ and 1H-TaS_2

Somesh Chandra Ganguli[1*], Viliam Vaňo[1], Mohammad Amini[1], Linghao Yan[1], Maryam Khosravian[1], Guangze Chen[1], Shawulienu Kezilebieke[1], Jose L. Lado[1], and Peter Liljeroth[1]

[1] *Department of Applied Physics, Aalto University, FI-00076 Aalto, Finland*

**Presenting author: somesh.ganguli@aalto.fi*

Unconventional superconductors have been at the forefront of strongly correlated materials due to the existence of competing electronic interactions in these systems. Paradigmatic examples of these systems include high temperature superconductors, heavy fermion superconductors and topological superconductors. These systems have non-s wave pairing symmetry and possible pairing mechanism driven by magnetic excitations. Despite these advancements, unambiguous discovery of unconventional superconductivity in van der Waals (vdW) systems have remained elusive.

In our work, we investigated two monolayer vdW superconductors 1H-$NbSe_2$ and 1H-TaS_2 grown using MBE on graphite (HOPG) by low temperature STM and STS. In the first part of the work [1], we demonstrate that by controlling the 1H-$NbSe_2$ island sizes, we can drive a superconductor to correlated insulator transition. This transition is rationalized from enhanced repulsive Coulomb interactions, which dramatically change the nature of the ground state in $NbSe_2$. Furthermore, we showed that for correlated 1H-$NbSe_2$ islands close to the phase transition, superconducting proximity effect strongly impacts the ground state, pushing the system through the superconductor-correlated phase boundary. In the second part [2], we demonstrate that pristine monolayer 1H-TaS_2 realizes a nodal f-wave superconducting state, which is driven to a conventional gapped s-wave state by inclusion of non-magnetic disorder. We also observe the emergence of many-body excitations potentially associated to the unconventional pairing mechanism. Our results demonstrate the emergence of unconventional superconductivity in vdW monolayers and therefore opens possibilities to create designer unconventional superconductivity and strongly correlated material by artificial van der Waals heterostructures [3].

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[3] V. Vaňo, M. Amini, S. C. Ganguli et al. Nature 599 (2021) 582–586.

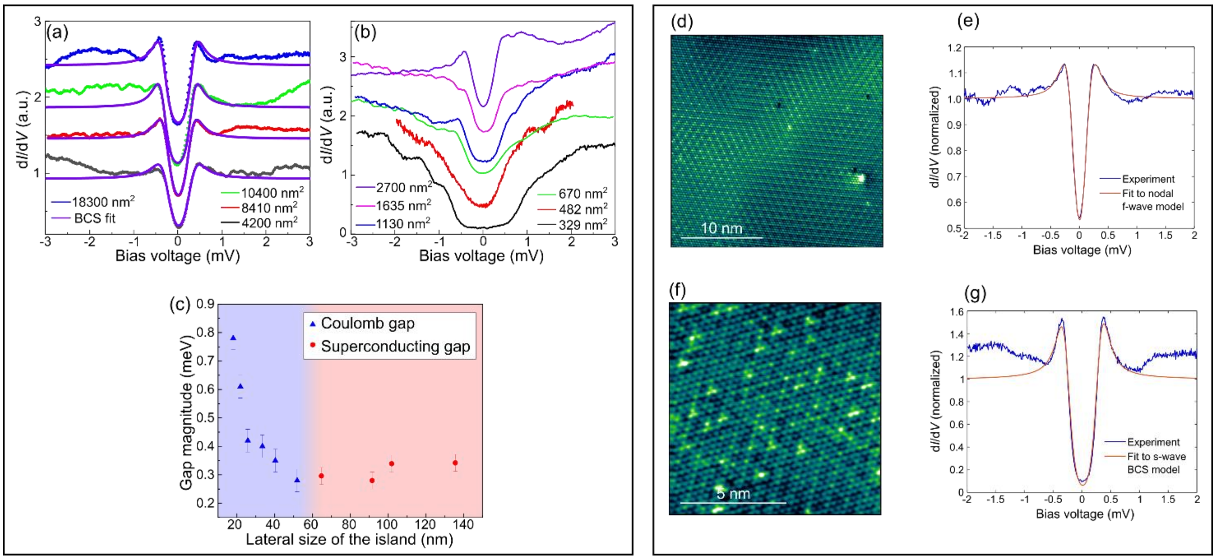

Fig 1. (a-c) Superconductor to correlated insulator transition in 1H-$NbSe_2$: (a) Spectra in SC islands with Dynes fit. (b) Spectra in Coulomb-gapped islands. All spectra have been vertically offset for clarity. (c) Island size dependence of the extracted gaps. (d-g) Nodal f-wave superconductivity in 1H-TaS_2: (d), (e) Atomic resolution and averaged dI/dV along with nodal f-wave fit in pristine 1H-TaS_2. (f), (g) Atomic resolution and averaged dI/dV along with BCS s-wave fit in dirty 1H-TaS_2.

THURSDAY 20 APRIL

Quantum technology

08:30-08:55 Mikko Möttönen

Unimon qubit and single-shot readout using a thermal detector

Mikko Möttönen*[1]

[1]Aalto University

Presenting author: mikko.mottonen@aalto.fi

Owing to low anharmonicity of the transmon qubit, it has limited speed for quantum logic gates and readout. We present the unimon qubit that has increased anharmonicity and bears several potential advantages such as complete insensitivity to off-set charges. We demonstrate 99.9% fidelity of single-qubit gates using the unimon. Then we integrate an ultrasensitive bolometer to the readout circuit of a transmon and demonstrate single-shot readout using a thermal detector for the first time. This readout technique is fundamentally different from usual voltage amplification methods and hence together with the unimon, it may provide a path to fast high-fidelity readout of superconducting qubits.

Thursday 20 April
08:55-09:20 Pasquale Mastrovito

Digital non-demolition read-out of superconducting qubits using a tunable phase detector

P. Mastrovito[1], L. Di Palma[5], A. Miano[2], D. Massarotti[3,4], D. Montemurro[1,4], M. Arzeo[5], F. Tafuri[1], O. Mukhanov[5]

[1] *Dipartimento di Fisica, Università di Napoli Federico II; Monte Sant'Angelo – via Cinthia; I-80126 Napoli-Italy*

[2] *Department of Applied Physics, Yale University, New Haven, Connecticut 06520, USA*

[3] *Dipartimento di Ingegneria Elettrica e delle Tecnologie dell'Informazione, Università di Napoli Federico II, Via Claudio, I-80125 Napoli, Italy*

[4] *CNR-SPIN, UOS, Napoli, Italy*

[5] *SeeQC: Elmsford, New York, USA*

**Presenting author: pasquale.mastrovito@unina.it*

In the last decade, the optimization and engineering of superconducting qubits brought significant technological breakthroughs in their performance. This led to the design of a variety of quantum processors containing a number of qubits that continues to grow year by year.

Given the increase in size and complexity, it becomes of central importance the exploration of alternative schemes able to enhance the efficiency of the whole architecture.

In this context, the phase dynamic of Josephson junctions [1] [2] can be exploited to develop tunable systems that serve multiple purposes. We propose a superconducting flux-tunable circuit named Josephson Digital Phase Detector (JDPD) [3]. We have characterized the dynamics of the system and its dependencies on external flux drives. We show that by dynamically changing the applied flux, the circuit is capable of evaluating the phase of a signal in the RF range. This behavior allows to perform non-destructive read-out of a superconducting qubit in situ and makes the JDPD suitable for digital cryogenic technologies such as the Single Flux Quantum (SFQ) [4].

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Thursday 20 April
09:20-09:45 Rubén Seoane Souto

Superconductor-semiconductor hybrid devices for quantum science and technology

R. Seoane Souto[1,2,3*]

[1]Division of Solid State Physics and NanoLund, Lund University, S-221 00 Lund, Sweden
[2]Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark
[3]Departamento de Física Teórica de la Materia Condensada, Condensed Matter Physics Center (IFIMAC) and Instituto Nicolás Cabrera, Universidad Autónoma de Madrid E-28049 Madrid, Spain

**Presenting author: ruben.seoane@uam.es*

When a semiconductor is brought into proximity with a superconductor, superconductivity can leak into the semiconductor (superconducting proximity effect). The resulting superconducting state can inherit several interesting properties from the semiconductor, such as large g-factors, strong spin-orbit coupling and the ability to tune the density of Cooper pairs with a gate voltage. In my presentation, I will discuss how to engineer these properties by choosing appropriate superconducting and semiconducting materials, and by controlling the geometry of the hybrid structures. I will also discuss how to exploit the properties of superconductor-semiconductor hybrid structures in new types of superconducting circuits and quantum devices, including qubits and supercurrent diodes [1]. A particular focus has been on reaching a topological superconducting phase, where Majorana bound states occur at edges and defects. I will discuss the prospect of reaching a topological superconducting phase in systems with proximity-induced magnetism [2-4], as well as in chains of strongly interacting quantum dots [5,6].

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Thursday 20 April
09:45-10:10 Pablo Burset

TUNABLE ANDREEV-CONVERSION OF SINGLE-ELECTRON CHARGE PULSES

P. Burset[1*], B. Roussel[2], M. Moskalets[3], and C. Flindt[2]

[1]*Department of Theoretical Condensed Matter Physics, Condensed Matter Physics Center (IFIMAC) and Instituto Nicolás Cabrera, Universidad Autónoma de Madrid, 28049 Madrid, Spain*
[2]*Department of Applied Physics, Aalto University, 00076 Aalto, Finland*
[3]*Department of Metal and Semiconductor Physics, NTU "Kharkiv Polytechnic Institute", 61002 Kharkiv, Ukraine*

**Presenting author: pablo.burset@uam.es*

Electron quantum optics explores the coherent propagation and interference of single-electron charge pulses in electronic nano-scale circuits that are similar to table-top setups with photons [1]. So far, experiments with dynamic single-electron emitters have focused on normal-state conductors, however, the inclusion of superconducting elements [2,3] would pave the way for a wide range of applications that exploit the electron-hole degree of freedom, for example, for quantum information processing or quantum sensing. Here, we propose and analyze a tunable mechanism for the on-demand conversion of single-electron pulses into holes through Andreev processes on a superconductor [4]. To this end, we develop a Floquet-Nambu scattering formalism that allows us to describe the conversion of charge pulses on a superconductor, and we show that it is possible to generate arbitrary superpositions of electrons and holes with the degree of mixing controlled by the magnetic flux in an interferometric setup. We provide a detailed discussion of the optimal operating conditions in realistic situations and demonstrate that our proposal is feasible based on current technology.

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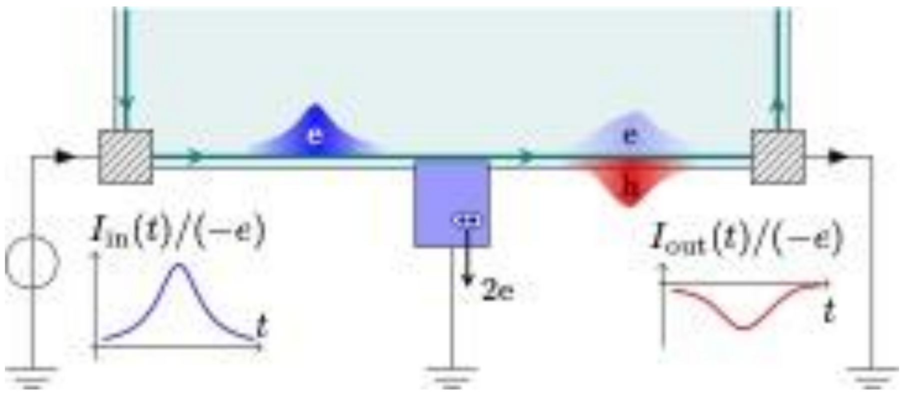

Majoranas in S-F hybrids

Thursday 20 April
10:40-11:05 Tristan Cren

STS investigation of odd-frequency pairing induced by a magnetic impurity

V. Perrin[1], F.L.N. Santos[1], G.C. Ménard[2], C. Brun[2], Tristan Cren[2], M. Civelli[1] and P. Simon[1]

[1]*Université Paris-Saclay, CNRS, Laboratoire de Physiques des Solides, Orsay, France* [2]*Sorbonne Université, CNRS, Institut des NanoSciences de Paris, Paris, France*

**Presenting author: tristan.cren@sorbonne-universite.fr*

Due to Fermi-Dirac statistics, the two-electron pairing correlation function at different times t_1 and t_2 has to be anti-symmetric under exchange of the two electrons or equivalently under the exchange of all their labels. These include time, spin, position and possibly other orbital degrees of freedom. In the conventional s-wave superconductor, the pairing function corresponds to an equal time, s-wave and spin-singlet pairing while the coveted p-wave superconductor corresponds to an equal time, p-wave, spin-triplet pairing function. In the former case the sign change of the pair amplitude is provided by the spin variable, while in the latter by the space one. However there is a possibility that the sign may change under exchange of the two different time coordinates $t_1 \neq t_2$. Berezinskii proposed this possibility, the odd-frequency pairing (thus odd under time exchange) in the s-wave triplet pairing of He^3. It was subsequently proposed by Bergeret et al. that odd-frequency pairing should appear in heterostructures made of a conventional s-wave superconductor and a ferromagnet [2]. The odd-frequency pairing in these hybrid structures is the result of a proximity effect where the ferromagnet induces a spin-singlet to spin-triplet conversion of Cooper pairs.. Subsequent studies demonstrated that odd-frequency pairing in fact appears in a wide variety of physical systems as a result of symmetry breaking. For example, odd-frequency pairing can be realized in non-magnetic junctions due to spatial parity breaking at the interface [5–7], which allows the conversion from s-wave to p-wave orbital symmetry. According to these predictions, odd-frequency pairing should be rather ubiquitous in hybrid systems.

Here we propose a direct way to measure odd-frequency pairing in the simplest hybrid system: a single magnetic impurity immersed in a conventional s-wave, spin singlet, even-frequency superconductor [8]. We show that on the magnetic impurity site a local s-wave, spin triplet and odd-frequency superconducting component arises from the breaking of the rotational symmetry. We establish an exact proportionality relation between the even-frequency component of the local-impurity electron density of states (LDOS) and the imaginary part of the odd-frequency superconducting function. We apply these results to account for the local density of states measured with scanning tunneling spectroscopy (STS) on top of magnetic impurities immersed in a superconducting monolayer of Pb/Si(111). This provides a direct evidence of the presence of the odd-frequency pairing component and we are able to extract and explicitly display the superconducting odd-frequency pairing function.

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Thursday 20 April
11:05-11:30 Levente Rózsa

DESIGN OF YU-SHIBA-RUSINOV STATES AT THE ATOMIC SCALE

L. Rózsa[1,2*], L. Schneider[3], P. Beck[3], J. Neuhaus-Steinmetz[3], K. Palotás[1,2,4], A. Lászlóffy[1], L. Szunyogh[2,5], T. Posske[6,7], J. Wiebe[3] and R. Wiesendanger[3]

[1]*Department of Theoretical Solid State Physics, Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, Konkoly-Thege Miklós út 29-33., H-1121 Budapest, Hungary*
[2]*Department of Theoretical Physics, Budapest University of Technology and Economics, Műegyetem rkp. 3, H-1111 Budapest, Hungary*
[3]*Department of Physics, University of Hamburg, Jungiusstrasse 9A, D-20355 Hamburg, Germany*
[4]*ELKH-SZTE Reaction Kinetics and Surface Chemistry Research Group, University of Szeged, H-6720 Szeged, Hungary*
[5]*ELKH-BME Condensed Matter Research Group, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary*
[6]*I. Institute for Theoretical Physics, University of Hamburg, Jungiusstrasse 9A, D-22607 Hamburg, Germany*
[7]*The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany*

**Presenting author: rozsa.levente@wigner.hu*

Magnetic impurities in conventional superconductors locally break Cooper pairs, leading to the emergence of Yu-Shiba-Rusinov (YSR) bound states. Chains of YSR impurities have been theoretically predicted to give rise to Majorana bound states, which hold promises for realizing topological quantum computers. A fundamental understanding of the formation of YSR states in small atomic clusters is essential for revealing the topological properties of the YSR band structure. The accurate theoretical modelling of YSR states represents a considerable challenge, since it requires a simultaneous description of the electronic structure, the magnetic ordering of the impurities and superconductivity on significantly different energy scales.

Here, first-principles simulations are combined with tight-binding model calculations to determine the influence of the electronic and magnetic structure on the interactions between the YSR states. It is explained how the spin-orbit coupling influences the hybridization of YSR bound states of dimers with ferromagnetic and antiferromagnetic spin alignments [1]. The calculations are extended to atomic chains, where extended and interacting precursors of Majorana bound states are found in ferromagnetic chains [2], while localized but topologically trivial end states are formed in antiferromagnetic chains [3]. The theoretical concepts are illustrated by experimental realizations in specific materials.

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Thursday 20 April
11:30-11:55 Pascal Simon

New insights from electronic transport in superconducting bound-states

U. Thupakula[1], V. Perrin[1], A. Palacio-Morales[1], L. Cario[2], M. Civelli[1] , M. Aprili[1], F. Massee[1] , **Pascal Simon**[1]

[1] *Laboratoire de Physique des Solides, University Paris-Saclay, CNRS, 91405 Orsay, France*
[2] *Institut des Matériaux Jean Rouxel, IMN, Université de Nantes, CNRS, F-44000 Nantes, France*

**Presenting author: pascal.simon@universite-paris-saclay.fr*

Majorana bound states are promising building blocks of forthcoming technology in quantum computing. Chains and islands of magnetic impurities in superconductors have attracted considerable attention recently as such systems may host Majorana bound states. However, their non-ambiguous identification has remained a difficult issue because of the concomitant competition with other topologically trivial fermionic states, which poison their detection in most spectroscopic probes. I will theoretically show that the Fano factor, which is the ratio between shot noise and the current, turns out to be a very interesting and distinctive tool in that respect. In particular, the Fano factor tomography displays a spatially constant Poissonian value equal to one for Majorana bound states while it is strongly spatially dependent and exceeds one as a direct consequence of the local particle-hole symmetry breaking for other trivial fermionic in-gap states such as Yu-Shiba-Rusinov or Andreev ones. I will also show how shot noise can be used to reveal coherent and incoherent dynamics of an in-gap bound state associated to the presence of a magnetic impurity in a superconductor which sets the stage for a comparison with experimental shot noise data [2].

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Thursday 20 April
11:55-12:20 Balazs Ujfalussy

Shiba bands and zero energy states of artificial spin chains from first principles

B. Ujfalussy[1*], B. Nyári[2] , A. Lászlóffy[1] , G. Csire[3], L. Szunyogh[2] , K. Park[4] and N. Kucska[1]

[1]*Wigner Research Centre for Physics, P.O. Box 49, H-1525 Budapest, Hungary*
[2]*Budapest University of Technology and Economics, Múegytem rkp. 3., H-1111 Budapest, Hungary*
[3]*Materials Center Leoben Forschung GmbH, Roseggerstraße 12, 8700 Leoben, Austria*
[4]*Department of Physics, Virginia Tech, Blacksburg, Virginia 24061, USA*

**Presenting author: ujfalussy.balazs@wigner.hu*

Majorana Zero Modes (MZM) at the ends of a chain of magnetic atoms on the surface of a superconductor has been of high interest over the past few years triggered by their possible applications as fault tolerant quantum bits. However, experimentally it is still very challenging to uniquely identify MZMs based solely on the spectral properties. At the same time, most theoretical models which claim to calculate Majoranas are forced to use unrealistic parameters. In such a situation, first-principles calculations are especially helpful, both in identifying and in designing such topological systems.
In this talk a first-principles computational approach is presented based on a microscopic relativistic theory of inhomogeneous superconductivity to scrutinize edge states of chains of magnetic atoms deposited on the surface of superconductors. After studying single impurities as an introduction to the method, we investigate an Fe chain on the top of Au-covered Nb(110) as a prototypical system, and we make quantitative predictions on various properties of the chain. We confirm that ferromagnetic chains do not support any MZM, however, a broad range of spin-spirals can be identified with a robust zero energy state displaying signatures of MZMs. For these spirals, we explore the structure of various superconducting order parameters, where we find a new tool to determine the topological nature of the induced gap in the Shiba bands. Furthermore, we also discover from first principles that the topological edge states form an exotic type of state: an internally antisymmetric triplet. Through additional computer experiments, we show that MZMs are localized to the boundaries of the topological region of the chain and their robustness is also demonstrated, representing a huge step toward potential applications.

Charge density waves vs. superconductivity

Thursday 20 April
14:00-14:25 Hugo Dil

Exploring superconductors and CDW materials with spin-resolved photoemission

Hugo Dil[1,2*]

[1]Institut de Physique, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland
[2]Photon Science Division, Paul Scherrer Institut, CH-5232 Villigen, Switzerland

**Presenting author: hugo.dil@epfl.ch*

The study of correlated states of matter, like high temperature superconductors and charge density wave compounds, has been one of the main driving forces in the development of angle-resolved photoemission spectroscopy (ARPES). The spin-resolved version (SARPES) has primarily gained fame for its use on topological materials [1] and low-dimensional systems with strong spin-orbit interaction [2] and its applications in the study of correlated materials is less known. Here it will be shown how SARPES can be used to distinguish between singlet and triplet spin order in cuprates and give general information about their contributions to the superconducting properties. With ongoing developments with regard to resolution, detection efficiency, and control of light polarisation and photon energy it will soon become possible to take these types of experiments to a next level. It should for example become possible to detect antiferromagnetic fluctuations and look for hidden order parameters.

A rather different application of SARPES, that also uses the measured spin-polarisation of spin degenerate states, is to determine the quantum mechanical time scale of the photoemission transition [3]. We have applied this technique to simple metals like Copper and Silver yielding time scales in the order of 25 attoseconds (as). For a cuprate superconductor the measured time scale increases to around 100 as, whereas for charge-density wave materials it becomes of the order of 300 as. Whether this indicates an additional sticking time due to electron interactions requires further experimental and theoretical investigantions. Here it primarily serves to show the possibilities that SARPES brings as an experimental technique going beyond the typical application.

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Thursday 20 April
14:25-14:50 Jonas Bekaert

Alternating superconducting and charge density wave monolayers in a TaS_2 heterostructure

Jonas Bekaert[1*]

[1] *Department of Physics & NANOlab Center of Excellence, University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerp, Belgium*

**Presenting author: jonas.bekaert@uantwerpen.be*

Van der Waals (vdW) heterostructures continue to attract intense interest as a route of designing materials with novel properties that cannot be found in nature. Recently, researchers from the National Graphene Institute of the University of Manchester have been able to create a vdW heterostructure consisting of 1H tantalum disulfide (TaS_2) monolayers, interlayered with 1T TaS_2 monolayers, by phase conversion of 1T TaS_2 at 800 °C in an inert atmosphere [1]. Subsequent electron microscopy measurements identified this bulk heterostructure as the 6R-phase of TaS_2 [1].

Among transition metal dichalcogenides (TMDs), TaS_2 has a unique place due to the exciting interplay between Charge Density Waves (CDWs) and superconductivity. Both 1T [2] and 2H [3] forms of TaS_2 show CDWs, which are in direct competition with the superconducting pairing. In the 6R TaS_2 sample, a superconducting transition (T_c) was found at 2.6 K, exceeding the T_c of the bulk 2H phase. In addition, satellite spots were observed in the measured electron diffraction patterns, indicative of the presence of a CDW state.

Using advanced first-principles calculations, I will demonstrate that the coexistence of superconductivity and CDWs within 6R-TaS_2 stems from the combined properties of adjacent 1H and 1T monolayers, where the former dominate the superconducting state and the latter the CDW behavior [1]. This alternating layered structure makes this material a unique 2D superconductor in bulk form, and opens a plethora of intriguing questions related to Josephson physics, THz radiation, and so forth.

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Thursday 20 April
14:50-15:15 Nenad Lazarević

Probing charge density wave phases and Mott transition in 1-TaS_2 by inelastic light scattering

S. Djurdji´c Mijin,[1] A. Baum,[2] J. Bekaert,[3] A. Šolajić,[1] J. Pešić,[1] Y. Liu,[4] Ge He,[2] M. V. Milošević,[3] C. Petrovic,[4] Z. V. Popović,[5] R. Hackl,[2] and N. Lazarević[1*]

[1]*Center for Solid State Physics and New Materials, Institute of Physics Belgrade, University of Belgrade, Pregrevica 118, RS-11080 Belgrade, Serbia*
[2]*Walther Meissner Institut, Bayerische Akademie der Wissenschaften, D-85748 Garching, Germany*
[3]*Department of Physics, University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerp, Belgium*
[4]*Condensed Matter Physics and Materials Science Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*
[5]*Serbian Academy of Sciences and Arts, Knez Mihailova 35, RS-11000 Belgrade, Serbia*

**Presenting author: nenad.lazarevic@ipb.ac.rs*

We present a polarization-resolved, high-resolution inelastic light scattering study consecutive CDW regimes in 1T-TaS_2 single crystals, supported by ab initio calculations. The analysis of the spectra within the low-temperature C-CDW regime suggests $P\bar{3}$ symmetry of the system. The spectra of the high-temperature IC-CDW phase directly project the phonon density of states due to the breaking of the translational invariance, supplemented by sizable electron-phonon coupling. Between 200 and 352 K, our Raman spectra show contributions from both the IC-CDW and the C-CDW phases, indicating their coexistence in the NC-CDW phase. The temperature dependence of the symmetry-resolved Raman conductivity indicates the stepwise reduction of the density of states in the CDW phases, followed by a Mott transition within the C-CDWphase. By means of inelastic light scattering, we were able to determine the size of the Mott gap at 170–190 meV, and to track its temperature dependence

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Thursday 20 April
15:15-15:40 Brigitte Leridon

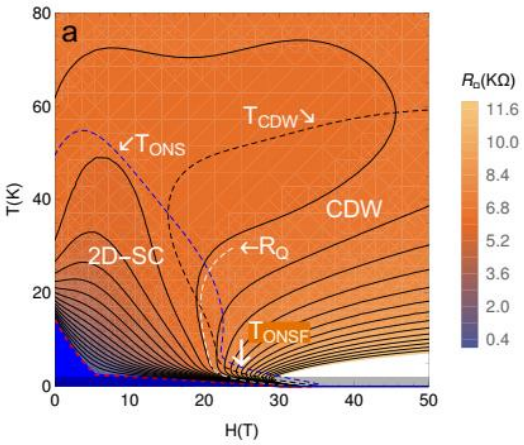
FILAMENTARY SUPERCONDUCTIVITY PROTECTED BY CHARGE-DENSITY WAVE DOMAINS AND MAGIC DOPING x=1/8 IN HIGH-TC SUPERCONDUCTORS

S. Caprara[1], J. Vanacken[2], V. Moshchalkov[2], B. Vignolle[3], R. Porwal[4], R.C. Budhani[4], A. Attanasi[1], M. Grilli[1], J. Lorenzana[1] and B. Leridon[5]

[1] ISC-CNR and Department of Physics, Sapienza University of Rome, Piazzale Aldo Moro 2, I-00185, Rome, Italy
[2] KULeuven, Celestijnenlaan 200 D, B-3001 Leuven, Belgium
[3] LNCMI (CNRS, EMFL, INSA, UJF, UPS), Toulouse 31400, France
[4] CSIR-National Physical Laboratory, New Delhi-110012, India
[5] LPEM, ESPCI Paris, CNRS, Université PSL, Sorbonne Universités, 10 rue Vauquelin, 75005 Paris, France

**Presenting author: brigitte.leridon@espci.fr*

$La_{2-x}Sr_xCuO_4$ thin film resistivity measured by pulsed high magnetic field reveals a complex phase diagram as function of Sr doping x, magnetic field and temperature. Two critical regimes are observed. The first one is at high temperature and low fields and is dominated by the clean-limit physics and the second one is at high field and low temperature and corresponds to the dirty-limit behavior. Using a careful interpolation of the resistivity, a generic phase diagram can be derived, which takes into account the full R(H,T) behaviour. By comparing this phase diagram to a theoretical calculation obtained by assuming a situation where a momentum-space-ordered state competes with a real-space-ordered state, we infer the existence of a low-temperature superconductivity filamentary phase surviving in the domain of stability for the charge density wave (CDW).
Interestingly enough, the magic doping corresponding to x= 1/8 in cuprates is precisely the doping for which CDW and superconductivity coexist at H=0.



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Thursday 20 April
16:10-16:35 Elisabetta Paladino

Supercurrent noise in short ballistic graphene Josephson junctions

Francesco M.D. Pellegrino[1,2*] , Giuseppe Falci[1,2,3] and Elisabetta Paladino

[1]*Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Via S. Sofia 64, I-95123 Catania, Italy.*
[2]*INFN, Sez. Catania, I-95123 Catania, Italy.*
[3]*CNR-IMM, Via S. Sofia 64, I-95123 Catania, Italy.*

**Presenting author: elisabetta.paladino@dfa.unict.it*

Short ballistic graphene Josephson junctions sustain superconducting current with a non-sinusoidal current-phase relation up to a critical current threshold. The current-phase relation, arising from proximitized superconductivity, is gate-voltage tunable and exhibits peculiar skewness observed in high quality graphene super-conductors heterostructures with clean interfaces. These properties make graphene Josephson junctions promising sensitive quantum probes of microscopic fluctuations underlying transport in two-dimensions. Understanding material-inherent microscopic noise sources possibly limiting the phase-coherent behavior of GJJ-based quantum circuits represents an essential, still unexplored, prerequisite. An especially relevant issue is understanding the impact on ballistic GJJs of fluctuations responsible for current noise with 1/f power spectrum [1], which is observed in a variety of graphene devices [2]

In this presentation we first demonstrate that fluctuations with 1/f power spectrum of the critical current of a short ballistic GJJ directly probe carrier density fluctuations of the graphene channel induced by the presence of charge traps in the nearby substrate, modeled by a spatially uniform distribution of independent generation–recombination centers [3]. Tunability with the Fermi level, close to and far from the charge neutrality point, and temperature dependence of the noise amplitude are clear fingerprints of the underlying material-inherent processes. Secondly, we study the effect of a dilute homogeneous spatial distribution of non-magnetic impurities on the equilibrium supercurrent within the Dirac-Bogoliubov-de Gennes approach and modeling impurities by the Anderson model. We find a modification of the current-phase relation with a reduction of the skewness induced by disorder, and a nonmonotonic temperature dependence of the critical current. The potentialities of the supercurrent power spectrum for accurate spectroscopy of the hybridized Andreev bound states-impurities spectrum are highlighted. In the low temperature limit, the supercurrent zero frequency thermal noise directly probes the spectral function at the Fermi energy [4]. Our results suggest a roadmap for the analysis of decoherence sources in the implementation of coherent devices by hybrid nanostructures.

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Thursday 20 April
16:35-17:00 Manuel Houzet

Topological properties of multiterminal Josephson junctions

Manuel Houzet

Univ. Grenoble Alpes, UGA, Grenoble INP, IRIG, PHELIQS, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France

**Presenting author: manuel.houzet@cea.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. Multi-terminal 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 show 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 phases and provide an example for a gapped 3-dimensional topological phase characterized by a Z_2-invariant in symmetry class C using 5-terminal junctions.

Thursday 20 April
17:00-17:25 Malcolm Connolly

Integration of semiconductor Josephson junctions in superconducting quantum circuits

M. R. Connolly[1*]

[1]*Blackett Laboratory, Imperial College London, London, SW7 2AZ, UK*

**Presenting author:* *m.connolly@imperial.ac.uk*

The integration of semiconductor Josephson junctions (JJs) in superconducting quantum circuits provides a versatile platform for realising hybrid qubits and probing exotic quasiparticle excitations. Recent proposals for using circuit quantum electrodynamics to detect topological superconductivity motivate the integration of novel topological materials in such circuits. In this talk I describe progress towards this goal using indium arsenide quantum wells [1] and topological insulator nanoribbons [2]

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Thursday 20 April
17:25-17:50 Zorica Popović

Interplay between d-wave superconducting electrodes orientation and misorientation of magnetization on Josephson current in DFFD junctions

Z. Popović[1*] and S. Djurdjević[2]

[1]*University of Belgrade, Faculty of Physics, Studentski trg 12, 11001 Belgrade, Serbia*
[2]*University of Montenegro, Faculty of Natural Sciences and Mathematics, Džordža Vašingtona bb, 81000 Podgorica, Montenegro*

**Presenting author: pzorica@ff.bg.ac.rs*

We study Josephson effect in a junction with arbitrarily oriented d-wave superconducting electrodes connected through two ferromagnets with noncollinear magnetizations. We solve the scattering problem based on the Bogoliubov-de Gennes formalism, extended to the case of anisotropic superconductors and presence of spin flip scattering due to ferromagnet interlayer. We investigate mutual influence of crystal orientation of superconducting electrodes and angle α between magnetizations in ferromagnetic bilayer of thickness d by calculating critical value of Josephson current I_C. For various orientation of superconducting electrodes, we calculate (d,α) phase diagram, and discuss the possibility to achieve except coexistence of two stable states 0 and π, also coexistence of three stable states 0, π and π/2, by varying the angle between magnetizations which can be much better for application compared to varying thickness of barrier or temperature. In the crossover point triply degenerate 0, π/2 and π equilibrium states occur, the fourth harmonic have dominant contribution and $I \sim \sin 4\varphi$, in the same way as in SFS junction where second harmonic have dominant contribution in 0-π crossover point. We observe also areas of coexistence of stable and metastable states.

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Thursday 20 April
17:50-18:15 Halima Giovanna Ahmad

Novel approaches for digital scalable superconducting quantum processors and magnetization-noise sensors: the ferromagnetic transmon qubit

H.G. Ahmad[1,2], V. Brosco[3,4], A. Miano[1], L. Di Palma[1], M. Arzeo[5], R. Satariano[1], R. Ferraiuolo[2,1], D. Montemurro[1], P. Lucignano[1,2], R. Fazio[6,1], G.P. Pepe[1,2], F.Tafuri[1,2], and D. Massarotti[7,2]

[1] *Dipartimento di Fisica "Ettore Pancini", Università degli Studi di Napoli Federico II, I-80125 Napoli, Italy*
[2] *CNR-SPIN, UOS-Napoli, c/o Monte Sant'Angelo, Via Cinthia I-80126 Napoli, Italy*
[3] *Dipartimento di Fisica, Università di Roma La Sapienza, Piazzale A. Moro, 2 00185 Roma, Italy*
[4] *ISC-CNR, Via dei Taurini, 19 00185 Roma, Italy*
[5] *Seeqc-EU, Strada Vicinale Cupa Cinthia, 21, I-80126, Napoli, Italy*
[6] *International School for Advanced Studies (SISSA), Via Beirut 2-4, I-34014 Trieste, Italy*
[7] *Dipartimento di Ingegneria Elettrica e Tecnologie dell'Informazione, Università degli Studi di Napoli Federico II, I-80125 Napoli, Italy*

**Presenting author: halimagiovanna.ahmad@unina.it*

In the last decades, the search for novel quantum platforms has increased due to the request for high-performing quantum computing [1]. Superconducting quantum processors have the advantage to be strongly engineerable, in terms of both integrated materials, circuital designs and easy-interface with commercially available readout/control electronics [1]. In spite of the enormous advancements in the field, and specifically the outstanding research on novel multi-qubit coupling paradigms and quantum gate implementation that use, as an example, flux-tunable transmon qubits [2-5], the research community is still facing several challenges in terms of scalability and coherence [6]. We here discuss about the possibility to implement novel tunability schemes for flux-tunable superconducting transmon qubits, by integrating unconventional low-dissipative tunnel ferromagnetic Josephson junctions (SFS JJs) [7-14] in the device. In this novel hybrid ferromagnetic transmon qubit, namely the ferrotransmon, the qubit frequency can be digitally tuned by means of in-plane magnetic field pulses, by exploiting the magnetic hysteretic behavior in the ferromagnetic barrier, rather than continuous magnetic flux fields [13]. This will possibly reduce the impact of flux-noise decoherence [13,15]. Finally, the integration of unconventional Josephson junctions in quantum coherent devices such as superconducting qubits allows for the investigation of the exotic physics that may occur in hybrid superconducting/ferromagnetic Josephson devices, such as spin-triplet superconductivity [16] and inverse-proximity effect [12,17], thus providing a useful platform for the study of condensed matter noise and fluctuations at the quantum level.

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Poster session II

Thursday 20 April
II-1 Lucia Gelenekyová
Idea of the density of state function deconvolution from tunneling conductance

L. Gelenekyová[1*] and F. Herman[1]

[1] *Department of Experimental Physics, Comenius University, Mlynská Dolina F2, 842 48 Bratislava, Slovakia*

**Presenting author: gelenekyova3@uniba.sk*

Recently, an effort to study detailed imprints of the superconducting state in the density of states (DOS) was formulated [1][2] for the conventional, low-temperature superconductors. Both of the formulated approaches are based on the knowledge of the DOS function. It shows, however, that the experimentally available information is available in the tunneling conductance data from the scanning tunneling measurements (STM). It is also very well known [3] that the tunneling conductance is a convolution of the DOS function together with the temperature smearing expressed by the derivative of the Fermi-Dirac distribution. Our approach of deconvolution, which leads to the elimination of the temperature broadening is based on the decomposition of the tunneling conductance into the orthonormal base of Hermit functions. We believe that this approach can allow us to reconstruct DOS even for a higher temperature than the standardly used Sommerfeld approach [4]. So far, we were able to test our approach on the benchmark theory model of the Dynes superconductor, where we have absolute control over the expected result. It shows, that the length of the interval of the measured conductance data matters and we want to present the details of our preliminary results, since this message can be valuable for the experimentalists doing the STM measurements.

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Poster session II

Thursday 20 April
II-2 Marek Kuzmiak

FROM SUPERCONDUCTING TO INSULATING STATE IN Mo_2N THIN FILMS. TRANSPORT AND STM STUDIES AT INCREASED DISORDER AND MAGNETIC FIELDS

M. Kuzmiak[1,2]*, M. Kopčík[1,2], F. Košuth[1,3], V. Vaňo[4], T. Samuely[1,3], V. Komanický[3], J. Kačmarčík[1], P. Szabó[1], and P. Samuely[1,3]

[1]*Centre of Low Temperature Physics, Institute of Experimental Physics, Slovak Academy of Sciences, SK-04001 Košice, Slovakia*
[2]*Department of Physics, Faculty of Electrical Engineering and Informatics, Technical University of Košice, SK-04001 Košice, Slovakia*
[3]*Centre of Low Temperature Physics, Faculty of Science, P. J. Šafárik University, SK-04001 Košice, Slovakia*
[4]*Department of Applied Physics, Aalto University, FI-00076 Aalto, Finland*

**Presenting author: kuzmiak@saske.sk*

The superconductor insulator transition (SIT) represents a very interesting phenomenon, when one material can change its properties only by tuning various physical parameters, such as disorder, voltage gating, or magnetic field. In this contribution, we present our recent results dealing with the experimental study of the mechanism of the SIT in strongly disordered γ-Mo_2N thin films with thicknesses from 30 nm to 1.5 nm. Based on our transport and low-temperature scanning tunnelling microscopy (STM) measurements we show that the SIT in γ-Mo_2N thin films tuned by both disorder or magnetic fields is realized by the Fermionic pathway. The spin-dependent Altshuler-Aronov effect, observed on insulating samples and in the field-induced normal state of strongly disordered superconducting samples, points to the dominance of Zeeman effects in γ-Mo_2N thin films, which are in the proximity of the critical disorder.

Poster session II

Thursday 20 April
II-3 Maryam Khosravian

Impurity-induced excitations in a topological two-dimensional ferromagnet/superconductor van der Waals moiré heterostructure

Maryam Khosravian[1*] and Jose L. Lado[1]

[1]*Department of Applied Physics, Aalto University, 02150 Espoo, Finland*

**Presenting author: maryam.khosravian@aalto.fi*

The emergence of a topological superconducting state in van der Waals heterostructures provides a new platform for exploring novel strategies to control topological superconductors. In particular, impurities in van der Waals heterostructures, generically featuring a moire pattern, can potentially lead to the unique interplay between atomic and moire length scales, a feature absent in generic topological superconductors. Here [1] we address the impact of non-magnetic impurities on a topological moire superconductor, both in the weak and strong regime, considering both periodic arrays and single impurities in otherwise pristine infinite moire systems. We demonstrate a fine interplay between impurity induced modes and the moire length, leading to radically different spectral and topological properties depending on the relative impurity location and moire lengths. Our results highlight the key role of impurities in van der Waals heterostructures featuring moire patterns, revealing the key interplay between length and energies scales in artificial moire systems.

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Poster session II

Thursday 20 April
II-4 Michal Wyszynski

RECENT ADVANCES IN GINZBURG-LANDAU SIMULATIONS OF NANOENGINEERED SUPERCONDUCTING CIRCUITRY

Michal J. Wyszyński* and Milorad V. Milošević

Department of Physics, University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerp, Belgium

**Presenting author: michal.wyszynski@uantwerpen.be*

The ongoing second quantum revolution offers unprecedented opportunities stemming from controlling individual quantum systems and taking advantages from their intrinsic quantum properties. Among the fields most relevant to that revolution are quantum computation, information, and communication, all yielding promise for a wave of novel technological applications. In that race, the approaches to quantum computing chosen by Google, Microsoft, and IBM all rely on superconducting quantum bits (qubits). Their distinguishing feature is the use of a Josephson junction in the quantum circuit – an element with no equivalent in conventional electronics.
The simulation approaches based on Ginzburg-Landau (GL) theory are to date the best-suited tool for studying the statics and dynamics of a superconducting condensate at the mesoscale. Although derived as a phenomenological expansion of the free energy in superconducting order parameter and its derivatives close to the critical temperature of superconductivity, the theory was proven remarkably efficient under far broader range of conditions, and can be strictly linked to microscopic properties of the material and details of the nanoengineered sample in question [1].
In this presentation, we exemplify the successful application of stationary and time-dependent Ginzburg-Landau simulations to different experimentally realized superconducting circuits containing Josephson junctions. These circuits include SQUID loops (both usual planar and 3D vectorial ones [2]), where superconducting arms in a loop are intercepted by two Josephson junctions (that may be delibarately made asymmetric, for additional functionality [3]), allowing for extremely precise measurements of magnetic fields penetrating the loop. The simulations offer insights into the dynamics of the condensate (phase slips) in the exact geometry of the experimentally realized device, as well as into the interplay between the applied magnetic field and the field of the supercurrent induced in response to the applied field. Further example details the properties of a Josephson junction connecting two square superconducting boxes. The simulations reveal subtle changes in the density of the superconducting condensate with every vortex entry in either trap, corroborating the experimental observation of unprecedented junction sensitivity to the vortex state realized in the trap [4]. Altogether, the presented analysis promotes the applicability of Ginzburg-Landau simulations to suitably nanoengineer the superconducting circuits of relevance to the 2nd quantum revolution.

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Poster session II

Thursday 20 April
II-5 Nikola Subotić

Topological Superconductivity from the Material Point of View

Nikola Subotic[1,2,4,*] Takanari Kashiwagi[1], Osamu Takeuchi[1], Hidemi Shigekawa[1], Takashi Mochiku[3], Yoshitaka Matsushita[3], Kazuo Kadowaki[2,4]

[1] *Faculty of Pure and Applied Sciences, University of Tsukuba, 1-1-1, Tennodai, Tsukuba, Ibaraki, 305-8537, Japan*
[2] *Nanoscience Center, Montenegrin Science Promotion Foundation PRONA, Marka Radovica 149, OBJ-M-20, 81000 Podgorica, Montenegro*
[3] *National Institute of Material Science (NIMS), 1-2-1, Sengen, Tsukuba, Ibaraki, 305-0047, Japan*
[4] *Institute of Quantum Material Research (IQMR), 3441-19, Kurihara, Tsukuba, 305-0001, Japan*

** Presenting author: nikolasubotic95@gmail.com*

The search for a material that could behave as a topological superconductor is a hot topic due to interesting phenomena such as the possible emergence of Majorana fermions due to the peculiar nature of superconducting quasiparticles. Majora zero modes, a bound state of Majorana fermions, are supposed to be immune to the decoherence effect, making them useful for the realization of qubits

Most studied topological superconductor candidates such as $Bi_2Se_3Cu_x$, $FeSe_{1-x}Te_x$, show that one of the main issues of topological superconductors is the **fabrication of high-quality crystals**, which could make the detection of topological states easier. Unfortunately, most of the topological materials are Pb, Sn, Bi, Se, Te, and Sb compounds, whose phase diagrams are not understood well, making crystal growth a perplexing endeavor.

Search for new superconductors that have topological properties that might contribute to the solution of the above-mentioned problem. Therefore, the ternary phase diagram Au-Pb-Rh has been explored for the first time. After detailed research of binary phase diagrams Au-Pb and Pb-Rh [1,2], two new compounds have been discovered $AuPb_4Rh_5$ and $AuPb_2Rh_2$ [3]. Moreover, two superconducting transitions were observed which are different from compounds found in binary phase diagrams Au-Pb and Pb-Rh. Surprisingly, further investigation of the ternary phase diagram Au-Pb-Rh showed that $RhPb_3$ Rh_2Pb_3 might be stable, which does not exist according to the known phase diagrams, stating the main problem mentioned above. A detailed investigation is underway to determine the nature of the discovered materials.

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Poster session II

Thursday 20 April
II-6 Raffaella Ferraiuolo

FERROMAGNETIC JOSEPHSON JUNCTION FOR HYBRID QUANTUM ARCHITECTURE

R. Ferraiuolo[1,2*], R. Satariano[2], G. H. Ahmad[2,3], G. Serpico[1], Carmine Granata[4,5], Antonio Vettoliere[4], L.Parlato[1,2], G.Ausanio[1,2], G.G.Pepe[1,2], F. Tafuri[1], D. Massarotti[1,3] and D. Montemurro[1]

[1]*Dipartimento di Fisica "E. Pancini", Università degli studi di Napoli "Federico II", Monte S'Angelo – Via Cinthia, I-80126 Napoli, Italy.*
[2] *Consiglio Nazionale delle Ricerche- SPIN, Monte S'Angelo – Via Cinthia, I-80126 Napoli, Italy.*
[3]*Dipartimento di Ingegneria elettrica e delle Tecnologie dell'Informazione, Università degli studi di Napoli "Federico II", Via Claudio, I-80125 Napoli, Italy.*
[4]*Consiglio Nazionale delle Ricerche – ISASI, Via Campi Flegrei 34, I.80078 Pozzuoli, Italy.*
[5]*Dipartimento di Matematica e Fisica, Università della Campania "L. Vanvitelli", Aversa, Italy.*

**Presenting author: raffaella.ferraiuolo@unina.it*

Recently, Magnetic Josephson Junctions (MJJs) because of the interplay between superconducting and magnetic order in a ferromagnet [1], give rise to a wide class of unconventional phenomena that open up to both fundamental investigation [2] and applications [3,4,5].

Due to the possibility of switching between different magnetic states, junctions that even employ a magnetic barrier pave the way to a wide range of applications such as cryogenic memories, spintronics and superconducting digital circuits [2][3]. A compelling perspective, that has been recently proposed, and we are intensively working on it, is represented by the integration of an MMJ in a hybrid Qubit architecture that have been elsewhere called FerroTransmon Qubit [6]. A strong requirement for the implementation of MMJ in a superconducting quantum circuit is the presence of a hysteretic nature of the entire barrier that has to have a dissipative-less behaviour.
In this talk, it will be first discussed the characterization of the transport properties of magnetic tunnel SIsFS junctions, based on niobium and aluminum technologies. Then, the comparative analysis of different geometries and materials will be shown. Finally, it will be highlighted how to embed the developed MMJ in a quantum circuit to build the FerroTransmon Qubit[6,7,8].

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Poster session II

Thursday 20 April
II-7 Rai Maciel de Menezes

SKYRMION-VORTEX COUPLING IN CHIRAL MAGNET-SUPERCONDUCTOR HETEROSTRUCTURES

A. P. Petrović[1], M. Raju[1], X. Y. Tee[1], A. Louat[2], I. Maggio-Aprile[3], R. M. Menezes[4*], M. J. Wyszyński[4], N. K. Duong[1], M. Reznikov[2], Ch. Renner[3], M. V. Milošević[4], and C. Panagopoulos[1]

[1]Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, 637371 Singapore
[2]Department of Physics, Technion, Haifa 32000, Israel
[3]Department of Quantum Matter Physics, Universit´e de Gen`eve, 24 Quai Ernest Ansermet, CH-1211 Geneva 4, Switzerland
[4]Department of Physics, University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerp, Belgium

**Presenting author: Rai.MacieldeMenezes@uantwerpen.be*

Heterostructures often present nontrivial phenomena enabled by the competition or hybridization of the physical properties of their parts. Particularly, magnet-superconductor heterostructures have received much attention in recent years, either for their possible applications in spintronics and Josephson devices or for the rich emergent physics in such systems. Recently, theoretical works on chiral magnet (CM)-superconductor (SC) heterostructures have demonstrated that the stray magnetic field of superconducting vortices may be able to create skyrmions in an adjacent magnetic layer, also to trap or repel the preexisting skyrmions, depending on vortex polarity. The ability to trap and manipulate magnetic skyrmions is of great importance for cutting-edge memory devices and information technology. In addition, the combination of the Zeeman field with spin-orbit coupling in hibrid systems is suggested for the creation of a topological superconductor hosting Majorana fermions at its boundaries and vortex cores, thus suggesting the applicability of such systems in quantum computation. Therefore, controlling the nucleation and dynamics of vortices in the presence of skyrmions is an important step towards unlocking the potential of SC-CM hybrids for topological and fluxonic quantum computation. In this work, we discuss experimental observations of the skyrmion-vortex interaction in SC-CM heterostructures, followed by a numerical study of the effects of skyrmion stray field on a superconducting film, where we demonstrate the nucleation of the skyrmion-vortex pair in engineered hybrid material. Next, we provide a detailed analysis and investigate the manipulation of an isolated skyrmion-vortex pair in a SC-CM hybrid by means of applied currents, in the case of independently biased films (current applied to either CM or SC part). We stress the possibility of compensating the skyrmion Hall effect in such systems by applying combined currents into both constituent materials of the heterostructure, which is of importance for the facilitated skyrmion/vortex guidance in racetrack applications.

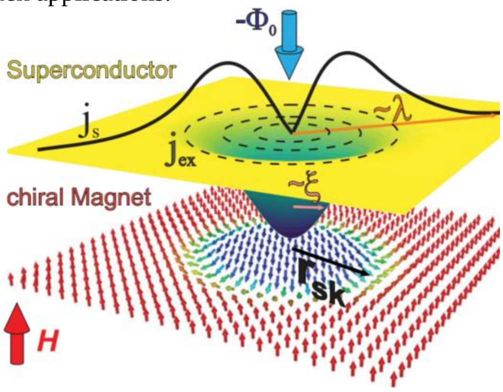

Figure 1: Schematic of skyrmion-vortex coupling in a CM-SC heterostructure.

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Poster session II

Thursday 20 April
II-8 Stefan Šćepanović

GRAPHENE NANORIBBON AS A TUNNELING TIP FOR SELECTIVE VISUALIZATION OF EDGE STATES

S. Šćepanović[1,2*], J. Mirković[1] and A. Hassanien[2]

[1]*University of Montenegro, Džordža Vašingtona bb, Podgorica, Montenegro*

[2]*''Jožef Stefan'' Institute, Jamova 39, Ljubljana, Slovenia*

**Presenting author: stefanscepanovic@gmail.com*

The precise positioning of scanning tunneling microscope tip gave the opportunity to manipulate atoms and molecules on clean surfaces, which can be used to engineer the micro-environmental conditions to test theories in a well-defined system. Of particular interest is the manipulation of Graphene Nanoribbons (GNRs) due to their interesting one-dimensional properties and the possibility of inducing topological states. Herein, we present a vertical manipulation methodology in which we utilize GNR as a tunneling tip for high-resolution imaging of edge states. Scanning tunneling spectroscopy shows that the suspended tip has a flat band gap of 2.85 eV which is in full agreement with earlier theoretical predication. The origin of high-resolution is related to the presence of Tamm states at suspended ribbon and therefore provide a pathway for selective tunneling from edge states. Implication on mapping spin states will also be discussed.

Poster session II

Thursday 20 April

II-9 Stevan Đurđević

JOSEPHSON CURRENT IN $d_{x^2-y^2}$/F/I/F/d_{xy} JUNCTIONS: ROLE OF SPIN-ACTIVE INTERFACES

S. Djurdjević[1,2] and Z. Popović[2]

[1]*University of Montenegro, Faculty of Natural Sciences and Mathematics, Džordža Vašingtona bb, 81000 Podgorica, Montenegro*
[2]*University of Belgrade, Faculty of Physics, Studentski trg 12, 11000 Belgrade, Serbia*

**Presenting author: stevandj@ucg.ac.me*

We study a quasi two-dimensional Josephson junction of d-wave superconductors through two ferromagnetic layers in between. Ferromagnets can be separated by insulator barrier. We investigate the influence of spin-active interfaces between layers. In the frame of Bogoliubov – de Gennes formalism we solve scattering problem to find current-phase relations in the case of $d_{x^2-y^2}$/ferromagnetic barrier/d_{xy}-wave superconductor junctions. We study the possibility of anomalous dc current-phase relation where I(φ=0)≠0, with I(φ)=−I(−φ+π), and has 2π periodicity. The net Josephson current can be separated in two series which are proportional to sin(2nφ), and cos((2n−1)φ), for n≥1. These two components of Josephson current exhibit phase transition from coexistence of 0 and π states to π/2 state of junction and vice versa with increasing of ferromagnetic layer thickness but for different values of thicknesses. We observed nonmonotonous temperature dependence of critical current through this junction with finite interface transparency between ferromagnets. This result gave a possibility of junction phase transition with changing a temperature.

Poster session II

Thursday 20 April
II-10 Tamás Papai

INVESTIGATION OF GRAPHENE-BASED MULTI-TERMINAL JOSEPHSON JUNCTIONS

M. Kedves[1,2*], T. Papai[1,2], G. Fulop[1,3], Sz. Csonka[1,3] and P. Makk[1,2]

[1]1Department of Physics, Institute of Physics, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111, Budapest, Hungary
[2]MTA-BME Correlated van der Waals Structures Momentum Research Group, Műegyetem rkp. 3., H-1111 Budapest, Hungary
[3]MTA-BME Superconducting Nanoelectronics Momentum Research Group, Műegyetem rkp.3., H-1111 Budapest, Hungary

**Presenting author: papait@edu.bme.hu*

The Andreev spectrum of an N-terminal Josephson junction is expected to host Weyl singularities in the (N-1)-dimensional space of the individual superconducting phases, thus mimicking the band structure of topological materials [1]. Graphene is an ideal platform to realize such multiterminal junctions, where high quality Josephson junctions can be formed in a planar geometry.

First, we will show the realization of high-quality graphene-based Josephson junctions and characterize their behavior using CPR measurements. Afterwards, we investigate a 3-terminal Josephson junction containing hBN-encapsulated graphene as the weak link connecting the terminals. We characterize the junction by DC transport measurements and apply RCSJ simulations to understand the multi-terminal behavior. By applying current bias to 2 different leads, we obtain a differential resistance map with several complex features and observe the coexistence of normal and superconducting current paths in the graphene region [2,3,4]. Furthermore, we perform switching current distribution measurements to probe the switching mechanism in this multiterminal system.

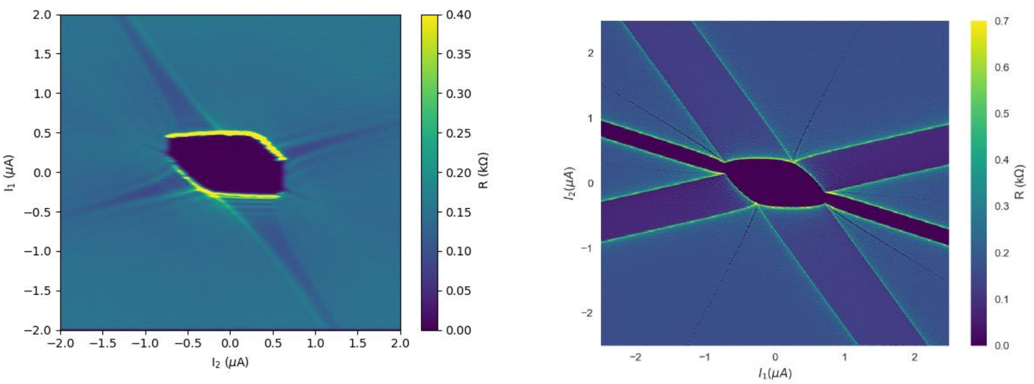

Figure 1: Differential resistance of a 3-terminal Josephson junction (measurement – left and simulation on the right).

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Poster session II

Thursday 20 April
II-11 Todor Mishonov

HOW CORRELATION BETWEEN THE CRITICAL TEMPERATURE T_C AND THE SHAPE OF THE FERMI CONTOUR IN P-DOPED CUPRATES REVEALS THE PAIRING MECHANISM

T. Mishonov[1*] and A. Varonov[1,2]

[1]*Georgi Nadjakov Institute of Solid State Physics, Bulgarian Academy of Sciences, 72 Tzarigradsko Chaussee Blvd., BG-1784 Sofia, Bulgaria*

**Presenting author: mishonov@gmail.com*

The rounded square shape of the Fermi contour is a property of electron band theory of independent electrons. However, superconductivity is created by interaction of electron charge carriers. More than 20 years ago Pavarini *et al.* [Phys. Rev. Lett. 87, 047003 (2001)] discovered a remarkable correlation between the shape and T_c, which is one of the most cited studies in the physics of high-T_c cuprates. This correlation is spread to all temperature intervals and definitely gives a hint for the pairing mechanism. The task is very simple which interaction can be responsible for this correlation. The solution is unique – only the well-known Zener *s*-*d* interaction with Kondo sign of the exchange amplitude can explain this correlation. As the critical temperature is much smaller than the Fermi energy or bandwidth in general it is possible to use the BCS theory for analysis. Strong electron correlations created by Coulomb repulsion (the Hubbard *U*) are concentrated in the *s*-*d* exchange: one 4*s* electron jumps to the 3*d* orbital and simultaneously another electron from the 3*d* orbital arrives in the 4*s* Cu orbital of the same ion. We explain this correlation and reveal that this is a correlation between the BCS coupling constant and T_c. We have simply calculated the matrix elements of the Zener-Kondo exchange in the framework of the LCAO approximation.

Poster session II

Thursday 20 April
II-12 Tomáš Novotný

Generalized atomic limit of a double quantum dot coupled to superconducting leads

Martin Žonda[1], Peter Zalom[2], Tomáš Novotný[1*], Georgios Loukeris[3], Jakob Bätge[3] and Vladislav Pokorný[2]

[1]*Department of Condensed Matter Physics, Faculty of Mathematics and Physics, Charles University, Ke Karlovu 5, CZ-12116 Praha 2, Czech Republic*
[2]*Institute of Physics, Czech Academy of Sciences, Na Slovance 2, CZ-18221 Praha 8, Czech Republic*
[3]*Institute of Physics, Albert Ludwig University of Freiburg, Hermann-Herder-Strasse 3, DE-79104 Freiburg, Germany*

**Presenting author: tno@karlov.mff.cuni.cz*

We present an exactly solvable effective model of a double quantum dot coupled to superconducting leads. This model is a generalization of the well-known superconducting atomic limit approximation of the paradigmatic superconducting impurity Anderson model. However, in contrast to the standard atomic limit, and other effective models, it gives quantitatively correct predictions for the quantum phase transition boundaries, subgap bound states as well as Josephson supercurrent in a broad range of parameters including experimentally relevant regimes. The model allows fast and reliable parameter scans important for preparation and analysis of experiments which are otherwise inaccessible by more precise but computational heavy methods such as quantum Monte Carlo or the numerical renormalization group. The scans also allowed us to identify and investigate new previously unnoticed phase diagram regimes. We provide a thorough analysis of the strengths and limitations of the effective model and benchmark its predictions against numerical renormalizationgroup results.

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Poster session II

Thursday 20 April
II-13 Tomáš Samuely

ISING SPIN-ORBIT COUPLING IN BULK SUPERCONDUCTORS

T. Samuely[1]*, O. Šofranko[1], M. Gmitra[1], J. Haniš[1], M. Kuzmiak[1], J. Kačmarčík[1], P. Szabó[1], P. Samuely[1], Tristan Cren[2], D. Volavka[1], S. Sasaki[3], L. Cario[3], D. Wickramaratne[4], I. I. Mazin[5]

[1] *Centre of Low Temperature Physics, Pavol Jozef Safarik University & Slovak Academy of Sciences, 04001 Košice, Slovakia*
[2]*Institut des NanoSciences de Paris, Sorbonne Université and CNRS-UMR 7588, Paris 75005, France*
[3]*Institut des Matériaux Jean Rouxel, Université de Nantes and CNRS-UMR 6502, Nantes 44322, France*
[4]*Center forComputational Materials Science, U.S. Naval Research Laboratory, Washington, DC 20375,USA*
[5]*Department of Physics and Astronomy, George Mason University, Fairfax, Virginia 22030, USA and Quantum Science and Engineering Center, George Mason University, Fairfax, Virginia 22030, USA*

**Presenting author: tomas.samuely@upjs.sk*

2D materials can have remarkable properties distinct from their bulk counterparts. In contrast to bulk, however, they are often unstable and impractical. $NbSe_2$ monolayer exhibits broken inversion symmetry that leads to Ising spin-orbit coupling confining the spins of the electrons in Cooper pairs to the out-of-plane direction. This protects the superconductivity against in-plane magnetic fields and enables the violation of the Pauli paramagnetic limit. Yet, no such behavior occurs in bulk $NbSe_2$[1]. Although layered materials have been reported to exceed the Pauli limit, the relevance of Ising spin-orbit coupling in bulk remains unclear. Here we show that Ising spin-orbit coupling is responsible for the Pauli limit violation in bulk monocrystals $(LaSe)_{1.14}(NbSe_2)$ and $(LaSe)_{1.14}(NbSe_2)_2$. These are misfit layered superconductors with a two-dimensional band structure equivalent to a highly doped $NbSe_2$ monolayer [2] and in-plane upper critical fields surpassing the Pauli limit by a factor of up to 10[3]. By employing a variety of experimental techniques, we show that both compounds exhibit a 2D band structure of a highly doped $NbSe_2$ monolayer. Moreover, our first-principles calculations corroborated by our experimental results provide quantitative details of their band structure. It enables us to elucidate the microscopic origin of the Ising spin-orbit coupling in bulk superconductors.

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Poster session II

Thursday 20 April
II-14 Vladislav Pokorný

LOW-ENERGY MODEL FOR SUPERCONDUCTING IMPURITY SYSTEMS

V. Pokorný[1*] and M. Žonda[2]

[1]*FZU - Institute of Physics, Czech Academy of Sciences, Na Slovance 2, 182 21 Prague, Czech Republic*
[2]*Faculty of Mathematics and Physics, Charles University, Ke Karlovu 5, 121 16 Prague, Czech Republic*

**Presenting author: pokornyv@fzu.cz*

We present a method to extract the Andreev bound state energies of a single-level quantum dot connected to superconducting leads from the imaginary-time quantum Monte-Carlo results without the use of analytic continuation techniques like the maximum entropy method. We describe the system using the superconducting impurity Anderson model and show that for low energies it maps on an interacting atomic-like model with renormalized parameters. The renormalization factor can be extracted from the interaction self-energy calculated in imaginary-frequency domain using the hybridization-expansion quantum Monte Carlo method. We compare the results to zero-temperature numerical renormalization group data to show the limits of usability of the low-energy model.

[1] V. Pokorný and M. Žonda, arXiv:2209.11868 (2022).

Poster session II

Thursday 20 April
II-15 Wolfgang Lang

ORDERED BOSE VORTEX GLASS IN YBCO: COMPETING PERIODIC AND RANDOM DEFECTS

W. Lang[1*], B. Aichner[1], L. Backmeister[1], M. Karrer[2], C. Schmid[2], K. Wurster[2], P. A. Korner[1], R. Kleiner[2], E. Goldobin[2], D. Koelle[2]

[1]Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Wien, Austria
[2]Physikalisches Institut, Center for Quantum Science (CQ) and LISA+, Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany

**Presenting author: wolfgang.lang@univie.ac.at*

The competition between intrinsic random disorder in superconducting $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films and an ultradense triangular lattice of cylindrical pinning centers with 30 nm spacings, leads to a novel topological phase, recently uncovered as the ordered Bose glass of vortices [1]. It can emerge from a vortex Mott insulator when thermal energy and disorder weaken the vortex correlations. The voltage-current isotherms reveal critical behavior and scale around the second-order glass transition. The latter shows a pronounced peak in melting temperature at the magnetic commensurability field, together with a sharp rise in the lifetime of glassy fluctuations. Angle-dependent magnetoresistance measurements in constant Lorentz force geometry unveil a strong increase of anisotropy compared to a pristine reference film when the density of vortices matches that of the columnar defects. Then, only the magnetic-field component parallel to the columnar defects dominates the pinning, revealing its one-dimensional nature. These findings affirm the concept of an ordered Bose glass phase.

The samples were fabricated by scanning the focused beam of a helium-ion microscope over the surface of epitaxially-grown thin YBCO films [2]. This process creates nanopillars of point defects to suppress superconductivity locally. The method overcomes the severe constraints of conventional lithographic techniques and leaves the material's crystallographic framework intact. Further applications of this method will be briefly discussed, e.g., the fabrication of ultradense pinning landscapes with magnetic commensurability fields up to 6 T that can be observed over a wide temperature range and down to 2 K.

Acknowledgments: This work is funded by a joint project of the Austrian Science Fund (FWF), grant I4865-N, and the German Research Foundation (DFG), grant KO 1303/16-1, and is based upon work from COST Actions CA21144 (SuperQuMap), CA19108 (Hi-SCALE), and CA19140 (FIT4NANO), supported by COST (European Cooperation in Science and Technology)

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Poster session II

Thursday 20 April
II-16 Zoe Velluire

Microwave conductivity of 2D superconducting BSCCO flakes

Zoe Velluire[1*], Jerome Lesueur[1], Nicolas Bergeal[1], Cheryl Feuillet-Palma[1]
Bergeal[1]

[1] *Laboratoire de Physique et d'Etude des Matériaux, ESPCI Paris, PSL University, CNRS, Sorbonne Université, Paris, France.*

**Presenting author: zoe.velluire@espci.fr*

Two-dimensional superconductors confront physicists with a variety of new challenges by exhibiting a large diversity of exotic electronic phases. The cuprate Bi2Sr2CaCu2O8+y (Bi2212) has a lamellar structure of CuO2 superconducting bilayers separated by Bi2O2+ySr2O2 layers. The unit cell exhibit a cleavage plane due to weak Van der Waals interactions between BiO layers, allowing for the exfoliation and isolation of single superconducting flakes. As the superconductivity of CuO2 planes is two dimensional, Bi2212 single flake makes for an ideal system to study 2D electronic interactions in the different electronic phases. The exploration of this phase diagram has already been performed using chemical doping of samples which also introduces structural changes and disorder, acting on the electronic interactions as well.

In this work we report electrostatic doping of Bi2212 flakes to tune the hole density [1]. We have measured the resistivity at different doping level to get more insight on the electronic interactions in the different region of the phase diagram. We will show our first results toward measuring the microwave properties of such a field effect tunable 2D superconducting material.

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FRIDAY 21 APRIL

Iron-based superconductors

08:30-08:55 Elena Gati

Anisotropic strain tuning of the iron-based superconductor $CaKFe_4As_4$

B. Zúñiga Céspedes[1], A. Valadkhani[2], S. Mandloi[1], M. Xu[3,4], J. Schmidt[3,4], S.L. Bud'ko[3,4], P.C. Canfield[3,4], A.P. Mackenzie[1,5], R. Valentí[2], E. Gati[1]*

[1] *Max-Planck-Institute for Chemical Physics of Solids, Nöthnitzer Str. 40, 01187 Dresden, Germany*
[2] *Institute for Theoretical Physics, Goethe University, Max-von-Laue-Str. 1, 60438 Frankfurt, Germany*
[3,4] *Ames National Laboratory/Iowa State University, 2323 Osborn Dr., Ames, IA 50011-1026, USA*
[5] *Scottish Universities Physics Alliance, School of Physics & Astronomy, University of St. Andrews, St. Andrews KY16 9SS, United Kingdom*

**Presenting author: elena.gati@cpfs.mpg.de*

In recent years, anisotropic strains have emerged as an excellent tool to study the competition of ordered phases in high-temperature superconductors. Among the family of iron-based superconductors, $CaKFe_4As_4$ has been identified as an exceptional member with a remarkable phase interplay for several reasons. First, it is a stochiometric superconductor at ambient pressure with high critical temperature T_c~35 K. Second, this superconducting phase can be found in close proximity to a so-called hedgehog vortex magnetic order (SVC), which does preserve tetragonal symmetry. This is in contrast to the ubiquitous stripe-type magnetic order (SSDW) in the Fe-based superconductors that is accompanied by a vestigial nematic phase. Therefore, $CaKFe_4As_4$ is an unique candidate material to investigate the interplay of superconductivity with different magnetic orders and nematicity.

In this talk, we will first introduce the experimental capabilities to study high-temperature superconductors under anisotropic strains. Then we will discuss, based on experimental studies and DFT calculations, how anisotropic strains are the ideal tuning parameters to disentangle the interplay of superconductivity, SVC and SSWD magnetism and nematicity in $CaKFe_4As_4$. We will argue that the high T_c in $CaKFe_4As_4$ is related to the near-degeneracy of SVC, SSDW and nematic order.

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Friday 21 April
08:55-09:20 Jelena Pešić

EVOLUTION OF VIBRATIONAL MODES OF FeSe UNDER UNIAXIAL STRAIN

J. Pešić*, A. Šolajić, A. Milosavljević and N. Lazarević

Center for Solid State Physics and New Materials, Institute of Physics Belgrade, University of Belgrade, Pregrevica 118, 11080 Zemun, Serbia

**Presenting author: yelena@ipb.ac.rs*

Application of strain is one of the effective ways to engineer the various properties of materials. Iron-based superconductors are suitable materials to study the strain dependence on physical properties due to their high sensitivity to variations in the local crystal structure. Among the iron-based superconductor family, FeSe is prominent example of the interplay between superconductivity, magnetism, and electronic nematicity, which can be tuned both by chemical substitution and application of physical pressure.

Here we present the first principle study compared with Raman spectroscopy of evolution of vibrational modes of the strained FeSe superconductor. We performed systematic computational study on bulk FeSe crystals with applying in-plane uniaxial strain ranging from -2% to 2% using density functional theory formalism. We focus on the effect of the straining of the lattice constant, and consequent symmetry distortion, on characteristic A_{1g} and B_{1g} modes of FeSe. These numerical findings are compared with experimental data from Raman measurements studying the trend of changes of A_{1g} and B_{1g} modes with applied strain.

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Friday 21 April
09:20-09:45 Adrian Crisan

Very High Pinning Potential in $CaKFe_4As_4$ Single Crystals from Magnetization Relaxation Studies

Adrian Crisan[1,*], Alina M. Ionescu[1], Ion Ivan[1]

[1]*National Institute of Materials Physics, 405A Atomistilor Str., 077125 Magurele, Romania*

**Presenting author: acrisan652@gmail.com*

Among the iron-based superconductors (IBS), superconductors based on $AEFe_2As_2$ (*AE* being alkali-earth metal Ca, Sr, Ba) parent compound, the so-called 122 system, became the most popular materials for both physical explorations and wire applications because of their T_c as high as 38 K, very high upper critical fields $\mu_0 H_{c2}$ (> 70 T) and low anisotropies γ (<2). Superconductivity in $AEFe_2As_2$ is primarily induced by alkali metal (*A* = Na, K, Rb, Cs) substitution at *AE* sites. More recently, a new type of IBS has been reported, having a new structure, abbreviated as *AEA*1144, most studied being $CaKFe_4As_4$ (CaK1144) due to its excellent superconducting properties. In these cases, because *A* does not mix with *AE* due to the large difference in atomic radii, *AEA*1144 crystallizes through alternate stacking of the *AE* and *A* layers across the Fe_2As_2 layer. Preliminary studies of the superconducting transition and of the isothermal magnetization loops confirmed the high quality of the samples, while temperature dependence of the AC susceptibility in high magnetic fields show absolutely no dependence on the cooling conditions, hence, no magnetic history. From magnetization relaxation measurements were extracted the values of the normalized pinning potential U^*, which reveal a clear crossover between elastic creep and plastic creep. The extremely high values of U^*, up to 1200 K around the temperature of 20 K lead to a nearly zero value of the probability of thermally-activated flux jumps at temperatures of interest for high-field applications. The values of the creep exponents p in the two creep regimes resulted from the analysis of the magnetization relaxation data are in complete agreement with theoretical models [1]: negative for plastic creep (– 0.35 in 1 T, – 0.54 in 5 T, in good agreement with theoretical predictions $p = -0.5$ for dislocation-mediated plastic creep); in the elastic creep regime in 1 T $p = 1.47$ is practically 3/2 as predicted by the elastic creep of small vortex bundles, while in higher fields, 3 and 5 T, p values of 2.58 and, respectively, 2.84 are comparable with the theoretical prediction from the elastic manifold theory in the small vortex bundle creep regime $p = 5/2$.

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Vortex devices

Friday 21 April
10:15-10:40 Oleksandr Dobrovolskiy

FLUXON COUNTING AND VELOCIMETRY IN NANOENGINEERED SUPERCONDUCTORS

O. V. Dobrovolskiy

University of Vienna, Faculty of Physics, Nanomagnetism and Magnonics, Superconductivity and Spintronics Laboratory, Boltzmanngasse 5, 1090 Vienna, Austria

**Presenting author: oleksandr.dobrovolskiy@univie.ac.at*

The maximal speed v^* for magnetic flux quanta is determined by the energy relaxation of unpaired electrons [1] and is essential for superconducting microstrip single-photon detectors (SMSPDs) [2]. However, the deduction of v^* from the current-voltage (*I-V*) curves at zero magnetic field is hindered by the unknown number of vortices, n_v, as a small number of fast-moving vortices can induce the same voltage as a large number of slow-moving ones [3]. Recently, we have introduced an approach for the quantitative determination of n_v and v^*. The idea is based on the Aslamazov and Larkin prediction [4] of kinks in the *I-V* curves of wide and short superconducting constrictions when the number of fluxons crossing the constriction is increased by one. We realize such conditions in wide MoSi thin strips with slits milled by a focused ion beam and reveal quantum effects in a macroscopic system [5]. By observing kinks in the *I-V* curves with increase of the transport current, we evidence a crossover from a single- to multi-fluxon dynamics and deduce $v^* \simeq 12$km/s. Our experimental observations are augmented with numerical modeling results which reveal a transition from a vortex chain over a vortex jet to a vortex river with increase of n_v and the vortex velocity. By keeping the isthmus width constant, we realize a transition from the 1D vortex-chain regime for microbridges with two slits and reminiscent of wide Josephson junctions to a 2D vortex-jet regime in microbridges with one slit [6]. Additionally, novel approaches such as machine learning and inverse design are explored for the realization of fluxonic gates. In all, our findings are essential for the development of 1D and 2D few-fluxon devices and provide a demanded approach for the deduction of v^* at the SMSPD operation conditions.

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Friday 21 April
10:40-11:05 Maciej Zgirski

PROBING VORTICES WITH A SUPERCONDUCTING NANOBRIDGE

M. Foltyn[1], K.Norowski[1], M.J.Wyszyński[2], M.V.Milosevic[2,3] and M.Zgirski[1*]

[1]Institute of Physics, Polish Academy of Sciences, Aleja Lotników 32/46, PL 02668 Warsaw, Poland
[2]Department of Physics & NANOlab Center of Excellence, University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerp, Belgium
[3]Instituto de Fisica, Universidade Federal de Mato Grosso, 78060-900 Cuiaba, Mato Grosso, Brazil

**Presenting author: zgirski@ifpan.edu.pl*

We present a very simple all-superconducting device consisting of a nanosquare(s) and an adjacent nanobridge [1]. We develop the electrical protocol allowing us to trap on demand the various superconducting vortex configuration in the field-cooled nanosquare, and test the trapped configurations by measuring the switching current of a Dayem nanobridge (Fig.1). Our measurements exhibit unprecedented precision and ability to detect the first and successive vortex entries into all fabricated traps, from few hundred nm to 2 μm in size.

Additionally, we perform experimental studies of hot electron diffusion in the presence of superconducting vortices. We obtain suppression of the diffusion signal due to existence of a single vortex trapped in the box on the way between the source of hot electrons and the detecting nanobridge. In other words, we can see the single vortex by the influence it exerts on the flux of diffusing quasiparticles.

An ease of integration and simplicity make our design a convenient platform for studying dynamics of vortices in strongly confining geometries, involving a promise to manipulate vortex states electronically with simultaneous *in situ* control and monitoring. We present the state-of-the-art experiment together with the supporting Ginzburg-Landau simulations.

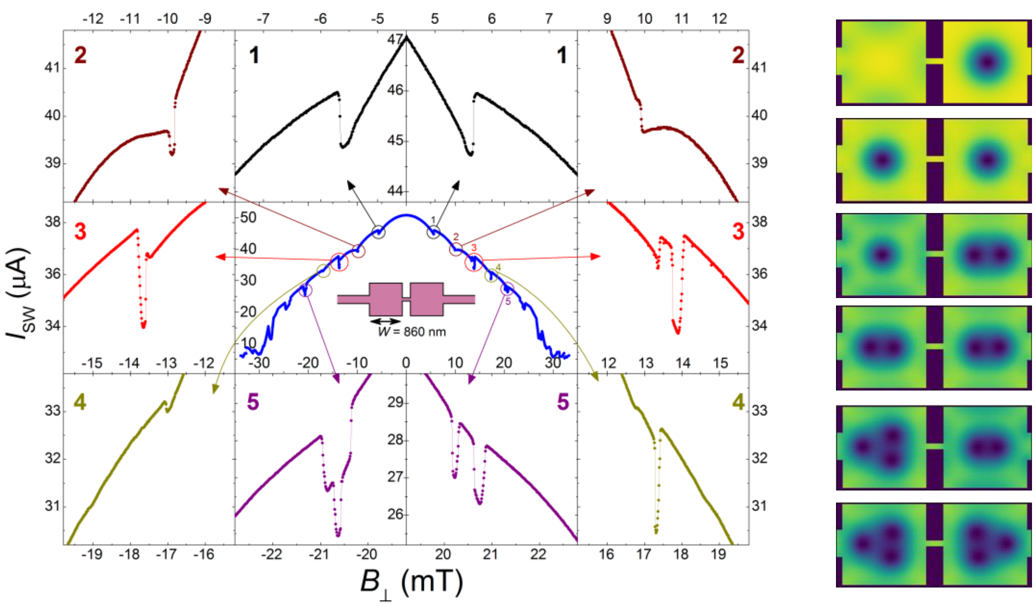

Fig.1. (Left) The switching current I_{sw} vs. the perpendicular magnetic field for the nanobridge connecting two vortex traps, both with side of W = 860 nm (see inset). Zooms show transitions to the next vorticity levels. (Right) The corresponding vortex maps calculated with GL approach.

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VORTEX CONFINEMENT IN SUPERCONDUCTOR OPEN NANOTUBES

V. M. Fomin[1,2*], I. Bogush[1,2]

[1]*Faculty of Physics and Engineering, Moldova State University, MD-2009, Chişinău, Moldova*
[2]*Institute for Emerging Electronic Technologies, Leibniz IFW Dresden, D-01069 Dresden, Germany*

**Presenting author: v.fomin@ifw-dresden.de*

We analyze the order parameter dynamics in superconductor Nb open nanotubes under a strong transport current in an external homogeneous magnetic field using the time-dependent Ginzburg-Landau equation. Since the thickness of a nanotube is small, only the normal component of the magnetic field plays an important role in the order parameter evolution. An open nanotube is a simple example of a curved nanoarchitecture with a nontrivial profile of the normal magnetic field [1], which introduces new effects such as hysteresis in current—voltage characteristics [2]. We investigate the generation of alternating voltage at the contacts of the nanotube. Vortices nucleate at the edge of each half-cylinder, move along the cylinder and denucleate at the opposite edge, generating voltage. In both half-cylinders, vortices move in the opposite directions in a correlated way. The number of vortices varies because it depends on the nucleation frequency and the time-of-flight of vortices along the cylinder, which are functions of the transport current density and the magnetic field. The induced voltage is alternating and possesses a non-trivial spectrum due to a variable number of vortices and a non-uniform vortex motion. In nanotubes of large radius, vortices move within zones of the cylinder, which are wide in comparison with the vortex size, and form different patterns, including lattices. In nanotubes of small radius (200 nm and less), the zone with a strong magnetic field normal to the surface is narrow in comparison with the vortex size, and vortices move along the nanotube confined into this narrow zone. This leads to the ordered motion of vortices in the nanotube, generating a clear non-chaotic voltage signal in a wide range of magnetic field magnitudes, while in the larger nanotubes, the vortex motion is ordered over a smaller range of the magnetic field magnitude. The position of the vortex zone and the ratio of the number of vortices in the half-cylinders can be controlled by the orientation of the nanotube with respect to the magnetic field. For some orientations, one of the vortex zones can disappear. In small nanotubes, the neighboring vortices in both half-cylinders interact strongly enough to have an impact on the motion of each other. The fly-by of a vortex near the edge of the nanotube can provoke the vortex nucleation in another half-cylinder. This leads to the occurrence of jumps in the voltage spectrum as a function of the magnetic field.

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Friday 21 April
11:30-11:55 Alexander Buzdin

Optical methods of flux manipulation in superconductors

A. Buzdin[1*]

[1]*University of Bordeaux, LOMA UMR-CNRS 5798, Talence, France*

**Presenting author: alexandre.bouzdine@u-bordeaux.fr*

Although the average properties of the vortex matter in superconductors can be tuned with magnetic fields, temperature or electric currents, handling of individual Abrikosov vortices remains challenging and has been demonstrated only with sophisticated scanning local probe microscopies. Recently we have proposed a far-field optical method based on local heating of the superconductor with a focused laser beam to realize a fast and precise manipulation of individual vortices, in the same way as with optical tweezers [1]. This open a way to create laser-driven Josephson junctions controlled by the optically driven Abrikosov vortex [2].

Important challenge is on-demand optical generation of single flux quanta. We discuss a far-field optical method to generate permanent single vortices at any desired position in a superconductor. It is based on the fast quench following the absorption of a tightly focused laser pulse (so called Kibble-Zurek effect) that locally heats the superconductor above its critical temperature. We achieve ex-nihilo creation of a single vortex pinned at the center of the hotspot, while its counterpart opposite flux is trapped tens of micrometers away at its boundaries [3].

Another method for the single flux quanta manipulation may be related with the so-called inverse Faraday effect - a circularly polarized radiation interacting with a superconducting condensate acts as an efffective magnetic field that can generate supercurrents and DC magnetic moments [4]. Using the time-dependent Ginzburg–Landau equation formalism, the current-carrying states of a small superconducting ring illuminated by such radiation are analysed [5]. Numerical simulations demonstrate the possibility to on-demand switch between current-carrying states in the superconductor by controlling the helicity of the electromagnetic field polarization [6]. This result opens the way to all-optical operation of superconducting devices.

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LIST OF PARTICIPANTS