XVII INTERNATIONAL WORKSHOP ON

Vortex Matter in Superconductors

Antwerp, Belgium

20-25 May, 2019

ABSTRACT BOOK

This conference is organized within the framework of

EU-COST **Action CA16218**:

Nanoscale Coherent Hybrid Devices for Superconducting Quantum Technologies

This event is supported by:

Abrikosov award sponsored by:

Best poster prizes provided by

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INTRODUCTION

XVII International Workshop on Vortex Matter in Superconductors

This Workshop continues the tradition of International Workshop on Vortex Matter in Superconductors, which began in 1994. The purpose of the Workshop is to promote international collaboration and exchange of ideas in this fascinating field of science. This time the workshop will be held in Antwerp, Belgium, a vibrant merchant city at the crossroads between main European centers, beautifully combining long history and tradition with progressive and modern aspects of contemporary lifestyle. In that spirit, the topics of the Workshop are expanded to various topological matter and frontier research beyond just superconductivity.

The Workshop will welcome 120 pre-selected participants from all over the world. The scientific program will allow for in-depth discussions but also allow for rich social activities and ample time to enjoy the city of Antwerp.

Specific Workshop **topics** in vortex physics and superconductivity include:

- Vortex phase diagram
- Vortex dynamics
- Vortex imaging
- Josephson phenomena
- Emergent flux patterns in unconventional superconductors
- Vortices in meso- and nanoscale systems
- Vortex pinning and its applications
- Superconducting devices
- Vortex matter vs. pairing symmetry
- Multi-component superconductivity
- Topological superconductors and hybrids
- 2D and interface superconductivity
- Novel superconducting materials and heterostructures

We look forward to your participation and your contribution to lively and fruitful discussions in the best spirit of the VORTEX tradition.

On behalf of the VORTEX2019 committees,

Conference Chairman

Milorad V. Milošević
milorad.milosevic@uantwerpen.be

Conference Committees

Organizing committee:
Milorad Milošević, UAntwerp, Belgium
Alejandro Silhanek, ULiege, Belgium
Luc Piraux, UCLouvain, Belgium
Joris Van de Vondel, KULeuven, Belgium

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Valerii Vinokur, Argonne National Laboratory, USA
Hai-Hu Wen, Nanjing University, China
Eli Zeldov, Weizmann Institute of Science, Israel

COST-Action CA16218 NANOCOHYBRI

The COST Action Nanocohybri is open to scientists from 27 European countries and collaborators all over the world. Nanocohybri kicked-off in November 2017 and will last until end of April 2021. Nanocohybri provides instruments for networking activities aimed to fulfil the objectives of the Action and managed using simple rules. Nanocohybri organizes approximately two meetings each year, promotes exchanges through short term visits and provides opportunities for young researchers to present work related to the Action in other meetings. The Management Committee approves activities following COST excellence and inclusiveness policy. All details, including time and budgetary frames as well as eligibility issues are available at the COST Vademecum.

Nanocohybri is triggered by the amount of fundamental knowledge obtained in superconducting systems and the recently acquired ability to control magnetic flux, electron charge and spin in devices. Much of the topical research in this area is being carried out all over Europe in the subfields of low dimensional systems, hybrids between superconductors and magnets or semiconductors, and nanoscale engineering for current carrying applications. The scientific and methodological approaches in these fields are similar and there is an important potential for cross-fertilization. The challenge is to use the understanding achieved and control the main superconducting parameters in devices to produce radically new behaviour. The Action has three working groups:

- Working group 1 (WG1). **Low dimensional and hybrid systems.** WG1 deals with two-dimensional and ultra-thin film superconductors. Nanofabrication techniques include lithography, controlled constrictions, exfoliation and systems capable to produce devices composed of layers of different materials. Characterization is made through photoemission spectroscopy, tunnelling microscopy, micro-Raman, quantum transport or ultrafast optics. New imaging techniques available at large-scale infrastructures (such as X-ray holography at synchrotron radiation sources) are also used. Theory analyses quantum transport from numerical studies using standard systems for superconductivity and ab-initio calculations. WG1 is led by Brigitte Leridon.

- Working group 2 (WG2). **Novel devices from hybrid interfaces.** The involved groups aim to integrate materials where the Cooper pair wave function has a sign change into devices, for example cuprates or topological insulators and other materials with topologically non-trivial surface states into Josephson junction circuits. We also study superconductor/ferromagnetic hybrids in detail, looking at novel modulated phases. Techniques include microscopic bandstructure calculations and measurements of the Josephson effect using transport experiments. We use advanced microscopies, including SQUID-on-a-tip and magnetic force. WG2 is led by Alexander Buzdin.

- Working group 3 (WG3). **Hybrids with nanoscale vortex pinning and nanofabrication for high magnetic fields.** We explore vortex pinning and current transport at low temperatures and high magnetic fields, in cuprate as well as in pnictide superconductors. We control fabrication techniques allowing to make pinning on demand and to study the collective behaviour of the vortex lattice in presence of patterned arrays of nanostructures. We also address the influence of structural or electronic distortions (such as nematicity), particularly close to quantum criticality, in the enhancement of superconducting parameters. Working methods include microscopy, correlated with transport calculations in superconductors, three-axis nanoSQUID and vortex manipulation. WG3 is led by Dieter Kölle.

The Action's short term visits and conference grants are examined by a committee led by Gleb Kakazei. The Action includes working groups responsible for dissemination (led by Yonathan Anahory), collaboration with industrial partners (led by Teresa Puig), gender monitoring (led by Floriana Lombardi) and a virtual laboratory to promote exchanges among participants (led by Daniela Stornaiolo). The entire Action is chaired by Hermann Suderow, with Francesco Tafuri as a vice-chair. Please feel free to approach relevant persons during the VORTEX workshop, for any additional information regarding the Action.

SCIENTIFIC PROGRAMME

Programme matrix

VORTEX 2019 schedule

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
8:00	Registration desk open					
9:00	**Opening address**	Grigorieva	Kwok	Zeldov	Krasnov	Borisenko
9:25	Guillamon	Bekaert	Sanchez	Buzdin	Tafuri	Lazarevic
9:50	Roditchev	Hasegawa	Dobrovolskiy	Palau	Koelle	Maeda
10:15	Ujfalussy	Gurevich	Eremin	Kadowaki	Villegas	Ma
10:40	Coffee break	Coffee break	Coffee break	Coffee break	Coffee break	Coffee break
11:20	Suderow	Van Bael	Yu	De Moor	Cren	Konczykowski
11:45	Bending	Janko	Snezhko	Ding	Wen	Shi
12:10	Klemm	Doria	Reichhardt	Lombardi	Chen	Banerjee
12:35	Koshelev	Yeshurun	Kakazei	Krusin-Elbaum	Tian	Fasano
13:00	**Lunch on site**	**Lunch on site**	**Lunch on site**	**Lunch on site**	**Lunch on site**	Closing remarks
14:00	Civale	Moshchalkov		Verbeeck	Mel'nikov	Buffet and free discussions
14:25	Cooley	Babaev		Tempere	Berthod	
14:50	Buchacek	Anahory		Neilson	Ichioka	
15:15	Maiorov	Eskildsen		Gladilin	Maggio-Aprile	
15:40	Coffee break	Coffee break		Coffee break	Coffee break	
16:20	Puig	Black-Schaffer	Free discussions	Vinokur	Tserkovnyak	
16:45	Tamegai	Aarts		Bezryadin	De Teresa	
17:10	Vanderheyden	Hu		Kalisky	Vodolazov	
17:35	Willa	Stolyarov		Jin	Menghini	
18:00	Meet the Editors: EPL	Sponsor's moment: QDesign		**"Rising stars" poster session**	Steering committee meeting	
18:15	Welcome reception	**Invited ("super") posters**		and competition, with buffet		
19:00		with buffet				
20:00		and Antwerp beers	**Concert**		**Conference dinner**	
21:00			**Abrikosov prize ceremony**		& poster prizes	
22:00			**Reception**			

Day	Session topic	Chair
mon	Coexistance and competition of orders	Suderow
mon	Emergent phenomena in layered superconductors	Blatter
mon	Pinning in superconductors I	Konczykowski
mon	Pinning in superconductors II	Civale
tue	Ultrathin superconductivity	Peeters
tue	Mesoscopic superconductivity	Grigorieva
tue	Novel vortex matter	Janko
tue	Novel Josephson phenomena	Krasnov
wed	Artificial s-f hybrids	Bending
wed	Vortices in magnetic systems	Eremin
thu	Innovative devices	Aarts
thu	Topological superconductivity I	Wen
thu	Vortices in auxiliary systems	Vinokur
thu	Phenomena at superconductor-insulator transition	Mel'nikov
fri	Josephson devices	Zeldov
fri	Topological superconductivity II	Lombardi
fri	Electronic properties of vortices	Cren
fri	Vortex dynamics	Reichhardt
sat	Iron-age surprises	Banerjee
sat	Pinning in superconductors III	Borisenko

Chronological Order of Presentations and Links to Abstracts

Monday, May 20, 2019

8:00 AM	-	Registration desk open	
9:00 AM	9:25 AM	Milorad Milosevic: Opening address	
		Coexistence and competition of orders [chair: Suderow]	
9:25 AM	9:50 AM	Isabel Guillamon: Modifications in the superconducting gap and vortex lattice induced by the coexistence of superconductivity with charge and magnetic order	Mon.01
9:50 AM	10:15 AM	Dimitri Roditchev: Quantum Turing-like patterns in the phase diagram of the magnetic superconductor $EuFe_2(As_{0.79}P_{0.21})_2$	Mon.02
10:15 AM	10:40 AM	Balazs Ujfalussy: Unconventional pairing states from first principles	Mon.03
10:40 AM	11:20 AM	Coffee break	
		Emergent phenomena in layered superconductors [chair: Blatter]	
11:20 AM	11:45 AM	Hermann Suderow: Characterizing and manipulating vortices in uniaxial superconductors in tilted magnetic fields	Mon.04
11:45 AM	12:10 AM	Simon Bending: Tuning the Josephson vortex lattice structure with pancake vortices in $Bi_2Sr_2CaCu_2O_{8+d}$ single crystals	Mon.05
12:10 PM	12:35 PM	Richard Klemm: Microscopic model of the Knight shift in anisotropic superconductors	Mon.06
12:35 PM	1:00 PM	Alexei Koshelev: Quantum FFLO state in clean superconductors	Mon.07
1:00 PM	2:00 PM	Lunch on site	
		Pinning in superconductors I [chair: Konczykowski]	
2:00 PM	2:25 PM	Leonardo Civale: Glassy and plastic vortex creep regimes in superconductors	Mon.08
2:25 PM	2:50 PM	Lance Cooley: Experiments probing the boundaries of flux pinning in magnet conductors	Mon.09
2:50 PM	3:15 PM	Martin Buchacek: Signatures of strong pinning from current-voltage measurements	Mon.10
3:15 PM	3:40 PM	Boris Maiorov: Fast moving superconducting vortices and determination of the critical current in high pulsed magnetic fields	Mon.11

3:40 PM	4:20 PM	Coffee break	
		Pinning in superconductors II [chair: Civale]	
4:20 PM	4:45 PM	Teresa Puig: New approaches in vortex pinning of high critical current YBCO nanocomposite films grown from chemical solutions: correlations with microstructure	Mon. 12
4:45 PM	5:10 PM	Tsuyoshi Tamegai: Peak effects in heavy-ion irradiated $NbSe_2$	Mon. 13
5:10 PM	5:35 PM	Benoît Vanderheyden: Magnetic flux penetration in superconducting films with border defects	Mon. 14
5:35 PM	6:00 PM	Roland Willa: Hessian character of pinning landscape	Mon. 15
6:00 PM	6:15 PM	Meet the Editors: Europhysics Letters	
6:15 PM	8:00 PM	Welcome reception	

Tuesday, May 21, 2019

		Ultrathin superconductivity [chair: Peeters]	
9:00 AM	9:25 AM	Irina Grigorieva: Superconductivity in atomically thin crystals: the case of $NbSe_2$	Tue.01
9:25 AM	9:50 AM	Jonas Bekaert: Hydrogen-induced high-temperature superconductivity in two-dimensional materials: the case of hydrogenated monolayer MgB_2	Tue.02
9:50 AM	10:15 AM	Yukio Hasegawa: Roles of structural defects on vortices in atomically-thin superconductors	Tue.03
10:15 AM	10:40 AM	Alex Gurevich: Tuning vortex fluctuations and superconducting transitions in thin film bilayers	Tue.04
10:40 AM	11:20 AM	Coffee break	
		Mesoscopic superconductivity [chair: Grigorieva]	
11:20 AM	11:45 AM	Margriet Van Bael: Phonon confinement in superconducting nanostructures	Tue.05
11:45 AM	12:10 AM	Boldizsar Janko: Network science approach to confined vortex matter	Tue.06
12:10 PM	12:35 PM	Mauro Doria: Surface effects on the definition of type 1 and 2 superconductors	Tue.07
12:35 PM	1:00 PM	Yosi Yeshurun: Current-Induced Crossover of Flux Periodicity from h/2e to h/e in a Superconducting Nb Nano-Ring	Tue.08

1:00 PM	2:00 PM	Lunch on site	
		Novel vortex matter [chair: Janko]	
2:00 PM	2:25 PM	Victor Moshchalkov: New forms of exotic vortex matter in superconductors	Tue.09
2:25 PM	2:50 PM	Egor Babaev: Broken time-reversal symmetry in s+ is and s+ id states of multi-band superconductors: vortices, skyrmions, domain walls and spontaneous magnetic fields.	Tue.10
2:50 PM	3:15 PM	Yonathan Anahory: Observation of a gel of quantum vortices in a superconductor at very low magnetic fields	Tue.11
3:15 PM	3:40 PM	Morten Eskildsen: Structural transition kinetics and activated behavior in the superconducting vortex lattice	Tue.12
3:40 PM	4:20 PM	Coffee break	
		Novel Josephson phenomena [chair: Krasnov]	
4:20 PM	4:45 PM	Annica Black-Schaffer: Josephson current from odd-frequency superconductivity in Weyl nodal loop semimetals	Tue.13
4:45 PM	5:10 PM	Jan Aarts: Chiral domain walls in micronstructured Sr_2RuO_4	Tue.14
5:10 PM	5:35 PM	Xiao Hu: Topological Josephson plasma in honeycomb junction array	Tue.15
5:35 PM	6:00 PM	Vasily Stolyarov: Josephson vortex generation and manipulation with a Magnetic Force Microscope	Tue.16
6:00 PM	6:15 PM	Sponsor's moment: LOT-Quantum Design	
6:15 PM	9:00 PM	**Invited ("super") posters** with buffet and Antwerp beers	

Wednesday, May 22, 2019

		Artificial superconductor-ferromagnet hybrids [chair: Bending]	
9:00 AM	9:25 AM	Wai-Kwong Kwok: Vortex dynamics via in-situ magnetic texturing	Wed.01
9:25 AM	9:50 AM	Alvaro Sanchez: Controlling magnetic fields by superconductor-ferromagnetic hybrid metamaterials	Wed.02
9:50 AM	10:15 AM	Oleksandr Dobrovolskiy: Magnon-Fluxon interaction in a ferromagnet/superconductor heterostructure	Wed.03
10:15 AM	10:40 AM	Ilya Eremin: Magnetic chiral skyrmions at topological insulator surfaces and in proximity to a superconductor	Wed.04

10:40 AM	11:20 AM	Coffee break	
		Vortices in magnetic systems [chair: Eremin]	
11:20 AM	11:45 AM	Xiuzhen Yu: Imaging various vortex-like magnetic textures by using atomic-resolution TEM	Wed.05
11:45 AM	12:10 AM	Alexey Snezhko: Emergent dynamics of active magnetic colloids	Wed.06
12:10 PM	12:35 PM	Charles Reichhardt: Skyrmion lattices in random and ordered potential landscapes	Wed.07
12:35 PM	1:00 PM	Gleb Kakazei: Overcoming the limits of vortex formation in magnetic nanodots	Wed.08
1:00 PM	2:00 PM	Lunch on site	
2:00 PM	8:00 PM	Free discussions	
8:00 PM	10:00 PM	**Concert / Abrikosov prize ceremony / Reception** **Sponsored by attocube**	

Thursday, May 23, 2019

		Innovative devices [chair: Aarts]	
9:00 AM	9:25 AM	Eli Zeldov: SQUID-on-tip imaging of work and dissipation in the quantum Hall state	Thu.01
9:25 AM	9:50 AM	Alexander Buzdin: Spontaneous vortex state in spin-orbit coupled superconducting ring	Thu.02
9:50 AM	10:15 AM	Anna Palau: New functionalities for energy-efficient superconducting electronic devices	Thu.03
10:15 AM	10:40 AM	Kazuo Kadowaki: High resolution and high sensitivity molecular spectroscopy using THz emitters of high-T_c superconducting Bi-2212 mesa structures	Thu.04
10:40 AM	11:20 AM	Coffee break	
		Topological superconductivity I [chair: Wen]	
11:20 AM	11:45 AM	Michiel De Moor: Majorana physics in hybrid superconductor-semiconductor nanowires	Thu.05
11:45 AM	12:10 AM	Hong Ding: Topological superconductivity and Majorana bound state in Fe-based superconductor	Thu.06

12:10 PM	12:35 PM	Floriana Lombardi: Induced unconventional superconductivity in 3D topological insulators revealed by nanoscale Josephson junctions	Thu.07
12:35 PM	1:00 PM	Lia Krusin-Elbaum: New quantum anomalous Hall platform for chiral topological superconductivity	Thu.08
1:00 PM	2:00 PM	Lunch on site	
		Vortices in auxiliary systems [chair: Vinokur]	
2:00 PM	2:25 PM	Jo Verbeeck: Experimenting with free space electron vortices	Thu.09
2:25 PM	2:50 PM	Jacques Tempere: Soliton decay into vortices in superfluid Fermi gases	Thu.10
2:50 PM	3:15 PM	David Neilson: Superfluidity in bilayer graphene	Thu.11
3:15 PM	3:40 PM	Vladimir Gladilin: Vortex interactions and dynamics in polariton condensates	Thu.12
3:40 PM	4:20 PM	Coffee break	
		Phenomena at superconductor-insulator transition [chair: Melnikov]	
4:20 PM	4:45 PM	Valerii Vinokur: Bose metal as a bosonic topological insulator	Thu.13
4:45 PM	5:10 PM	Alexey Bezryadin: Superconductor-insulator quantum transition in 1D chains of superconducting islands	Thu.14
5:10 PM	5:35 PM	Beena Kalisky: Imaging phase transitions with scanning SQUID	Thu.15
5:35 PM	6:00 PM	Kui Jin: A new superconductor in spinel oxides	Thu.16
6:00 PM	8:00 PM	**"Rising stars" poster session** with buffet and poster competition	

Friday, May 24, 2019

		Josephson devices [chair: Zeldov]	
9:00 AM	9:25 AM	Vladimir Krasnov: Abrikosov vortex as a Josephson phase shifter	Fri.01
9:25 AM	9:50 AM	Francesco Tafuri: Comparative study of dissipation in ferromagnetic Josephson junctions	Fri.02
9:50 AM	10:15 AM	Dieter Koelle: Nanoscale devices fabricated by focused ion beam irradiation of YBCO thin films	Fri.03

10:15 AM	10:40 AM	Javier Villegas: Andreev reflection and electron interference in graphene/high-temperature superconductor junctions	Fri.04
10:40 AM	11:20 AM	Coffee break	
		Topological superconductivity II [chair: Lombardi]	
11:20 AM	11:45 AM	Tristan Cren: Vortex like pair of zero mode states in a 2D topological superconductor	Fri.05
11:45 AM	12:10 AM	Hai-Hu Wen: Vortex bound states and zero energy mode in $FeTe_{0.55}Se_{0.45}$ and $Bi_2Te_3/FeTe_{0.55}Se_{0.45}$	Fri.06
12:10 PM	12:35 PM	Chen Chen: Majorana zero mode in the vortex core of iron-based superconductor	Fri.07
12:35 PM	1:00 PM	Mingliang Tian: Quantum Transport Properties in Topological Semimetal $PtBi_2$ and pressure-induced multiband superconductivity	Fri.08
1:00 PM	2:00 PM	Lunch on site	
		Electronic properties of vortices [chair: Cren]	
2:00 PM	2:25 PM	Alexander Mel'nikov: Electronic properties of vortex matter in nanostructured and hybrid superconducting systems	Fri.09
2:25 PM	2:50 PM	Christophe Berthod: Particle-hole crossover in the vortex cores of the multiband superconductor $FeTe_{0.55}Se_{0.45}$	Fri.10
2:50 PM	3:15 PM	Masanori Ichioka: Local electronic states around a vortex near the surface in inclined magnetic fields	Fri.11
3:15 PM	3:40 PM	Ivan Maggio-Aprile: A “BCS flavour” from vortex cores in a high-T_c cuprate superconductor	Fri.12
3:40 PM	4:20 PM	Coffee break	
		Vortex dynamics [chair: Reichhardt]	
4:20 PM	4:45 PM	Yaroslav Tserkovnyak: Putting charge-vortex duality to work in spintronics	Fri.13
4:45 PM	5:10 PM	Jose Maria De Teresa: Vortex in superconductors grown by Focused Ion Beam Induced Deposition	Fri.14
5:10 PM	5:35 PM	Denis Vodolazov: Photon triggered instability of the flux flow regime in strongly disordered superconducting strip	Fri.15
5:35 PM	6:00 PM	Mariela Menghini: Vortex dynamics on superconducting and non-superconducting arrays	Fri.16
6:00 PM	7:00 PM	Steering committee meeting	
7:00 PM	10:00 PM	**Conference dinner & poster prizes**	

Saturday, May 25, 2019

		Iron age surprises [chair: Banerjee]	
9:00 AM	**9:25 AM**	Sergey Borisenko: Nematicity in iron-based superconductors from ARPES	Sat.01
9:25 AM	**9:50 AM**	Nenad Lazarevic: Frustration and fluctuations in FeSe: A Raman scattering study	Sat.02
9:50 AM	**10:15 AM**	Atsutaka Maeda: Synthesis and physical properties of $FeSe_{1-x}A_x$ (A=Te, S) epitaxial films	Sat.03
10:15 AM	**10:40 AM**	Yanwei Ma: Transport properties and flux pinning analysis of high-performance $Ba_{0.6}K_{0.4}Fe_2As_2$ superconducting tapes	Sat.04
10:40 AM	**11:20 AM**	Coffee break	
		Pinning in superconductors III [chair: Borisenko]	
11:20 AM	**11:45 AM**	Marcin Konczykowski: Interplay of weak collective and strong pinning regimes in iron based superconductors tuned by disorder	Sat.05
11:45 AM	**12:10 AM**	Zhixiang Shi: Flux pinning and vortex dynamics of iron-based superconductors	Sat.06
12:10 PM	**12:35 PM**	Satyajit Banerjee: Disorder induced lowering of vortex dimension in Pnictide superconductor and precipitation of thermal melting of a dilute vortex solid phase	Sat.07
12:35 PM	**1:00 PM**	Yanina Fasano: Unveiling the vortex glass phase in the surface and volume of a type-II superconductor	Sat.08
1:00 PM	**1:15 PM**	Closing remarks	
1:15 PM	**3:00 PM**	Buffet and free discussions	

Invited "super" poster session, 6:15 PM, Tuesday 21 May

Carmine Attanasio: Proximity effect in noncentrosymmetric-superconductor/ferromagnet hybrid structures	SP.01
Tomasz Cichorek: Symmetry of order parameters in the multiband superconductors $LaRu_4As_{12}$ and $PrOs_4Sb_{12}$ probed by local magnetization measurements	SP.02
Adrian Crisan: Vortices in YBCO thin films with complex pinning structure investigated by AC susceptibility measurements	SP.03
Vladimir Fomin: Vortex matter in advanced superconductor nanoarchitectures	SP.04
Vadim Geshkenbein: Hall effect at the superconductor-insulator transition	SP.05
Taras Golod: Planar Josephson junction as an element for novel superconducting devices	SP.06
Gaia Grimaldi: Vortex lattice instability in superconducting materials	SP.07
Serghei Klimin: Collective excitations in two-band Fermi superfluids at finite temperatures	SP.08
Brigitte Leridon: Interplay between superconductivity and charge-density-wave domains in $La_{2-x}Sr_xCu_2O_4$ superconductors	SP.09
Tadashi Machida: Nature of the zero-energy vortex bound state in the superconducting topological surface state of Fe(Se,Te)	SP.10
Salvatore Mesoraca: Proximity effects in high-Tc superconductor/half-metallic ferromagnet vertical junction	SP.11
Grigorii Mikitik: Critical current in thin flat superconductors with Bean-Livingston and geometrical barriers	SP.12
Ivan Sadovskyy: Large and uniform critical currents in finite magnetic fields	SP.13
Alejandro Silhanek: Electromigration in the dissipative state of high temperature superconducting bridges	SP.14
Alexei Vagov: Exotic vortex matter and other spontaneously appearing patterns in superconductors between type I and II	SP.15
Joris Van de Vondel: Nano-SQUIDs with controllable weak links created via current-induced atom migration	SP.16
Artjom Vargunin: 0-π transitions and flux-flow resistivity in superconductor-ferromagnet-superconductor sandwich with Abrikosov vortices	SP.17
Maciej Zgirski: How to measure temperature by flipping a coin?	SP.18
Ling-Feng Zhang: Electronic properties of emergent topological defects in chiral *p*-wave superconductors and topological phase transitions in small disks	SP.19

"Rising stars" poster session, 6:00 PM, Thursday 23 May

Halima Giovanna Ahmad: Tuning of magnetic activity in spin-filter Josephson junctions towards spin triplet transport	RSP.01
Morten Amundsen: Vortex simulation with the Usadel equation	RSP.02
Alexander Backs: Universal behavior of the transition to the intermediate mixed state in the type-II/1 superconductor niobium	RSP.03
Sylvain Blanco Alvarez: Statistics of thermomagnetic breakdown in Nb superconducting films	RSP.04
Ievgenii Borodianskyi: Josephson emission from $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesa structures	RSP.05
Loïc Burger: Numerical investigation of critical states in superposed superconducting films	RSP.06
Qihong Chen: Transport at the superconductor-normal junction in ionic gated MoS_2	RSP.07
Wilmer Yecid Córdoba Camacho: Quasi-one-dimensional vortex matter in superconducting nanowires	RSP.08
Maria D'Antuono: Ferromagnetic and superconducting oxides 2DEG systems	RSP.09
Raí de Menezes: Manipulation of magnetic skyrmions in chiral ferromagnetic and superconducting heterostructures	RSP.10
Marek Foltyn: Flipping coin experiment for studying switching in Josephson junctions and superconducting wires	RSP.11
Jesus Gonzalez: Modulaton of the superconducting properties of an ultrathin Pb island	RSP.12
Olena Kapran: S/F/S Josephson junctions with a strongly ferromagnetic Ni barrier	RSP.13
Ahmed Kenawy: Phase slips in voltage-biased superconducting rings	RSP.14
Zefeng Lin: An investigation on superconductivity of FeSe coated Nb structure	RSP.15
Pablo Orus: Vortex transport in superconducting W-C nanostructures	RSP.16

Ritika Pangothra: Magnetic field induced 2D to 1D crossover in SNS Josephson junction arrays as revealed by mutual phase locking	RSP.17
Antonine Rochet: Optical generation of single vortex/anti-vortex pairs in superconducting films	RSP.18
Victor Rollano: Rectified superconducting vortex motion topologically protected by spin-ice nanomagnets	RSP.19
Daniele Torsello: Transition from s ± to s ++ order parameter driven by disorder in iron-based superconductors	RSP.20
Albert Varonov: Determination of effective Cooper pair mass by electrostatic doping of fluxoids of superconductor surface. Theory	RSP.21
Irene Zhang: Imaging anisotropic vortex pinning in FeSe	RSP.22

Mon.01

Modifications in the superconducting gap and vortex lattice induced by the coexistence of superconductivity with charge and magnetic order

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Charge order and magnetism often coexist with high or moderate temperature superconductivity. For example, partial charge order along certain directions of the Fermi surface in single crystals is compatible with anisotropic superconductivity, as shown in the exemplary material 2H-$NbSe_2$. But the consequences of charge order can be very different and lead to profound modifications of the superconducting state. Here I will present STM measurements in 2H-$NbSe_2$ with Se substituted by S and show how the disorder induced by the S substitution strongly supresses long-range spatial correlations in the charge density wave. I will discuss how to characterize the associated length scales and the changes induced in the superconducting gap and vortex lattice. I will also show how nematic electronic order and magnetism influence superconductivity in the pnictide superconductors, discussing two cases, Ni-CaK1144 and P-Ba122. In both systems, optimal superconductivity appears at a second order quantum critical point. We find that the coexistence of superconductivity with the antiferromagnetic phase induces additional anisotropy in the superconducting gap and disorder in the vortex lattice. Finally, I will update the recent efforts made in STM for very high magnetic fields, presenting first images taken at 20 T.

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Quantum Turing-like patterns in the phase diagram of the magnetic superconductor $EuFe_2(As_{0.79}P_{0.21})_2$

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The interplay between superconductivity and magnetism is one of the oldest enigmas in physics. Usually, the strong exchange field of ferromagnet suppresses singlet superconductivity via the paramagnetic effect. In $EuFe_2(As_{0.79}P_{0.21})_2$, a material that becomes not only superconducting at 24.2 K but also ferromagnetic below 19 K, the coexistence of the two antagonistic phenomena becomes possible because of the unusually weak exchange field produced by the Eu subsystem. We demonstrate experimentally and theoretically [1,2] that when the ferromagnetism adds to superconductivity, the Meissner state becomes spontaneously inhomogeneous, characterized by a nanometer-scale striped domain structure. At yet lower temperature and without any externally applied magnetic field, the system locally generates quantum vortex-antivortex pairs and undergoes a phase transition into a domain vortex-antivortex state characterized by much larger domains and peculiar Turing-like patterns. We develop a quantitative theory of this phenomenon and put forth a new way to realize superconducting superlattices and control the vortex motion in ferromagnetic superconductors by tuning magnetic domains - unprecedented opportunity to consider for advanced superconducting hybrids.

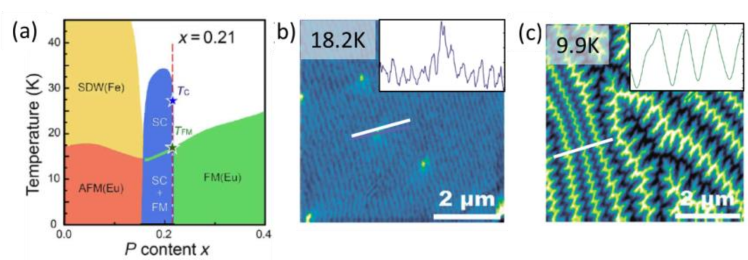

Fig. (a) – phase diagram of $EuFe_2(As_{0.79}P_{0.21})_2$; vertical dashed line denotes the studied sample; (b) – Domain Meissner State phase, just below Curie temperature; (c) - Turing-like Domain Vortex State is realized at low temperatures.

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Unconventional pairing states based on first principles

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We have combined the relativistic spin-polarized version of Korringa-Kohn-Rostoker method for the solution of the Dirac-Bogoliubov-de Gennes equations with a semi-phenomenological parametrization of the pairing interaction. We employ this method to both $LaNiGa_2$ and its non-centrosymmetric relative $LaNiC_2$ which show spontaneous magnetism in the superconducting state. Based on symmetry considerations it was already shown that the breaking of time-reversal symmetry is only compatible with non-unitary triplet pairing states in these crystals. Our method allows to study different on-site triplet equal-spin pairing models involving the first-principles band structure. We compare our predictions for the temperature dependence of the specific heat and it is found that it can be described by an interorbital equal-spin pairing on the nickel which breaks the time-reversal symmetry. It is shown that this pairing induces nodeless, two-gapped quasiparticle spectrum and finite magnetisation due to the redistribution of Cooper pairs in spin space. The method is also applied to Nb/Au/Fe multilayer system where we show that the existence of spin-polarized quantum well states can lead to FFLO-like oscillations of the order parameter in the normal metal.

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Characterizing and manipulating vortices in uniaxial superconductors in tilted magnetic fields

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Many practical applications of high Tc superconductors involve layered materials and magnetic fields applied on an arbitrary direction with respect to the layers. The shape and properties of single vortices in titled magnetic fields in such a situation is largely unknown. I will first discuss imaging experiments in the anisotropic superconductor 2H-NbSe2 and show that in-plane magnetic fields lead to vortices that strongly change when modifying the direction of the magnetic field within layers and relate this finding to the superconducting gap anisotropy [1]. I will then discuss the situation in Bi2212, where the anisotropy is very large, with intertwined lattices of Josephson and Abrikosov vortices. I will show magnetic force microscopy experiments where we trigger Abrikosov vortex motion in between Josephson vortices, and find that Josephson vortices in different layers can be brought on top of each other [2]. This suggests that vortex manipulation is much easier in tilted magnetic fields and may be used to entangle vortex bound states. I will finally make the point about recent advances in measuring the Josephson effect using superconducting tips [3].

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Tuning the Josephson vortex lattice structure with pancake vortices in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals

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The structure and ordering of vortices nucleating in the highly anisotropic superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ depend strongly on the angle the applied field makes with the CuO layers; stacks of pancake vortices form when the field is perpendicular to these and elliptical Josephson vortices in a highly stretched rhombic lattice form when it is parallel to them. For tilted magnetic fields, pancake and Josephson vortices coexist and interact in very complex ways to form vortex chains and composite vortex lattices, reflecting the delicate balance between attractive and repulsive interactions. We have used high-resolution scanning Hall microscopy to map the rich tilted-field vortex phase diagram in an underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal. We find that the Josephson vortex lattice spacing has an unexpected non-monotonic dependence on pancake vortex density, and show that this is linked to a field-driven structural transformation with increasing out-of-plane fields. We establish the precise evolution of vortex-chain phases as the out-of-plane field is increased and identify particularly stable chain structures that are spaced by exactly an integer number of rows of 'free' interstitial pancake vortex stacks (c.f., Figure 1). Our experimental results are in good semi-quantitative agreement with a theoretical model based on anisotropic London theory [1].

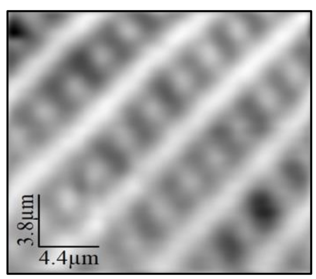

Figure. 1 Extremely stable composite vortex state formed when exactly one row of 'free' interstitial pancake vortices occupies the spaces between vortex-chains.

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Microscopic model of the Knight shift in anisotropic superconductors

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Previous works on the development of a microscopic model of the Knight shift in anisotropic and correlated metals [1] and superconductors [2] have been extended to construct a fully Lorentz-invariant model of an anisotropic superconductor with one or more ellipsoidal Fermi surfaces. This new model exhibits equivalent Landau-level and Zeeman-energy splittings for all magnetic induction directions. In these models, the leading contribution to the Knight shift arises from the hyperfine interaction of the probed nucleus with one of its orbital electrons, which then enters one of the conduction bands and returns to orbit the same probed nucleus [1,2]. Thus, electrons that enter open orbits have a very low probability of returning to the same nucleus, and therefore do not contribute to the Knight shift, even in the normal state.
The fully Lorentz-invariant version of this model shows that quasi-one-dimensional superconductors such as $(TMTSF)_2PF_6$ should have very weak Zeeman energy splittings, and consequently little temperature dependence to the Knight shift in the superconducting state. Similarly, for the field parallel to the layers of a quasi-two-dimensional material such as Sr_2RuO_4, the Knight shift is likely to be independent of the temperature as it decreases below the superconducting critical temperature. Although the case of the applied field normal to the layers of a layered superconductor has not yet been analyzed theoretically, experiments on the singlet pair-spin superconductors $YBa_2Cu_3O_{7+\delta}$ and LiFeAs have shown that anomalous, temperature-independent behavior in the superconducting state, arises when the applied field is sufficiently strong. This model has profound implications for many Knight shift measurements that may have been misinterpreted in the literature.

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Quantum FFLO state in clean superconductors

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We investigate the influence of Landau quantization on the superconducting instability for a pure layered superconductor in the magnetic field directed perpendicular to the layers [1]. We demonstrate that the quantization corrections to the Cooper-pairing kernel with finite Zeeman spin splitting promote the formation of the Fulde-Ferrell-Larkin-Ovchinnikov [FFLO] state [2], in which the order parameter is periodically modulated along the magnetic field. The conventional uniform state experiences such quantization-induced FFLO instability at low temperatures even in a common case of predominantly orbital suppression of superconductivity when the Zeeman spin splitting is expected to have a relatively weak effect. The maximum relative FFLO temperature is given by the ratio of the superconducting transition temperature and the Fermi energy. This maximum is realized when the ratio of the spin-spitting energy and the Landau-level separation is half-integer. The quantum FFLO state is rapidly suppressed by impurity scattering. These results imply that the FFLO states may exist not only in the Pauli-limited superconductors but also in very clean materials with small Zeeman spin-splitting energy. We expect that the described quantization-promoted FFLO instability is a general phenomenon, which may be found in materials with different electronic spectra and order-parameter symmetries.

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Glassy and plastic vortex creep regimes in superconductors

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Vortex matter in oxide and Fe-based HTS is strongly affected by thermal and quantum fluctuations, which give rise to a variety of vortex liquid phases that occupy substantial portions of the phase diagram as well as fast dynamics of the metastable states (flux creep). The strong thermal fluctuations in HTS are due to the small coherence length, the large anisotropy and high transition temperatures in these materials, as quantified by the Ginzburg number (*Gi*) that measures the ratio of the thermal energy to the condensation energy in an elemental superconducting volume. We had previously found that, for strong pinning superconductors in the Anderson-Kim (A-K) creep regime at $T \ll T_c$, there is a universal minimum attainable creep rate $S_{min} \sim Gi^{1/2}(T/T_c)$. This lower limit has been achieved in a few materials including $YBa_2Cu_3O_7$, MgB_2 and our $BaFe_2(As_{0.67}P_{0.33})_2$ films and, to our knowledge, violated by none. On the other hand, many SC exhibit *S* values higher, sometimes orders of magnitude higher, than S_{min}.

Recently we focused our efforts on obtaining a general understanding of the lower achievable *S* outside the A-K regime, at higher *T* and *H* where collective effects and glassy dynamics are relevant. To that end we studied a broad spectrum of systems, including conventional $NbSe_2$ single crystals with columnar defects created by heavy ion irradiation, clean HTS such as single crystals of YBCO and Hg1201, ReBCO films and coated conductors with the strongest pinning in any known superconductor, and single crystals of the magnetic superconductor $RbEuFe_4As_4$. We categorize several glassy and plastic regimes, the boundaries among which are determined either by intrinsic vortex properties or by thickness effects. In the strong pinning systems we find a “second A-K regime” at high *T*, and extend our previous result to identify the lowest *S*(*T*,*H*) limit in thin samples.

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Explorations of the limit of flux pinning in magnet conductors

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Accelerator magnets place perhaps the highest demand on flux-pinning performance. Over the years, the quest for ultimate pinning performance has led to explorations of novel artificial pinning-center configurations in Nb-Ti conductors and theoretical discussions about periodic and gradient pin arrangements, which has overlap with topics explored by VORTEX workshops. The presentation will recall some of these discussions. Nb_3Sn is the present workhorse material for accelerator magnets and the current target of ultimate pinning discussions. Nb_3Sn lacks a dense arrangement of added pinning centers like BZO nanorods in REBCO, or precipitates or artificial pinning centers in Nb-Ti. Accordingly, recent research has sought to add intragranular pinning centers. One set of experiments has augmented grain-boundary pinning with intragranular damage clusters created by irradiation, which has a side effect of increasing electron scattering and the upper critical field [1]. A second group of experiments has sought to reduce grain size to < 50 nm by addition of zirconia and rare-earth oxide nanoparticles, which could also function as point pins [2],[3]. In both cases, the shape of the bulk pinning-force curve improves for high-field applications, where the peak of the curve shifts from 20% to >30% of the irreversibility field, and new records of pinning force are being attained at 16 T, where future colliders might operate. Some insight about pinning limits can be obtained by making analogy to strengthening mechanisms in metals, since the elementary pinning forces are strong enough to cause plastic deformation of the flux lattice. For REBCO and Nb-Ti, each flux line has available a corresponding pinning center, so the flux-pinning situation may be analogous to an extreme degree of precipitate hardening like martensite in steel. This suggests that further strengthening may be difficult to attain in those materials. Strong pinning in Nb_3Sn starts with the natural grain boundaries, where flux lines intersecting boundaries of ~100 nm grains effectively cage groups of ~ 50 flux lines. The situation may then be analogous to Hall-Petch strengthening, which builds in an inverse grain-size dependence and quantifies improvement for added intragranular pinning sites. Here, grain-boundaries attain a strong elementary pinning force due to conversion of Abrikosov vortices to hybrid Abrikosov-Josephson vortices [4]. This implies that detailed study of the grain boundary transparency could be illuminating.

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Signatures of strong pinning from current-voltage measurements

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The strong pinning theory describes vortex pinning in the regime of low density of strong defects and allows for quantitative treatment of vortex dynamics and creep. It yields a simple result [1] for the current-voltage (*I*-*V*) characteristic predicting a subcritical thermal creep region with exponentially suppressed voltage followed by an ohmic regime shifted by a temperature-dependent excess (critical) current. Here we analyse *I*-*V* measurements on $NbSe_2$ [2], InO [3] and MoGe [4] that exhibit the ohmic regimes at large drives characteristic for strong pinning and show that they are in excellent agreement with the theoretical predictions over a voltage range spanning several orders of magnitude. The density of defects as well as the field- and temperature dependence of the activation barrier are extracted directly from the fitting parameters. We further challenge the common perception of the activation barrier regarded as function of driving current and show that if barriers and creep effects persist beyond the critical current, it becomes more convenient to describe them through the Lorentz force lowered by the viscous force. This observation combined with some features of the experimental data leads to a proposal of an elegant phenomenological theory directly relating the vanishing of activation barrier upon approaching criticality to the current-voltage characteristic.

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Fast moving superconducting vortices and determination of the critical current in high pulsed magnetic fields

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Expanding non-linear transport (I-V) studies to magnetic fields above those accessible by DC magnets can bring valuable information about systems such as superconductors, charge-density waves and topological semi-metals. All-superconducting very-high field magnets also make it technologically relevant to study vortex matter in this regime. However, pulsed magnetic fields reaching 100T in milliseconds impose technical and fundamental challenges that have prevented the realization of these studies. Here, we present a fast I-V DC technique that enables determination of the superconducting critical current in pulsed magnetic fields, beyond the reach of DC magnets. We demonstrate this technique on $YGdBa_2Cu_3O_{7-\delta}$ coated conductors with and without $BaHfO_3$ nanoparticles with excellent agreement with DC field measurements [1]. The I-V characteristics change with the magnetic field rate (dH/dt). We capture this unexplored vortex physics through a model based on the broken symmetry of the vortex velocity profile produced by the applied current [1].

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New approaches in vortex pinning of high critical current YBCO nanocomposite films grown from chemical solutions: correlations with microstructure

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Vortex pinning is probably the most relevant physical property for large current applications of superconducting materials, especially at high magnetic fields. Therefore, artificial pinning centers engineering and design has always been a crucial subject for the community. After 20 years of intense research in $YBa_2Cu_3O_7$ coated conductors, they are now considered a mature technology for many potential applications at liquid nitrogen and also down to liquid helium temperatures where they can envisage ultrahigh magnetic fields. However, the cost is still an important issue, so Chemical solution deposition (CSD) methods arose as low cost, scalable methods which could compete in performance, while high growth rate methods have recently attracted much attention. In that direction, many efforts have been done to find scalable processes for artificial pinning centers engineering in CSD methods. The best strategy resulted in the so-called nanocomposites [1] where strain-associated vortex pinning mechanisms where proposed [2]. In this presentation, I will revise our latest understanding on vortex pinning of CSD nanocomposites. On one hand, special emphasis will be devoted to the use of colloidal solution of preformed nanoparticles were the nanoparticles size can be better controlled [3]. On the other, I will present a new approach to reach CSD nanocomposites through a transient-liquid assisted growth (TLAG) method, enabling ultrafast growth rates in the range of 100 nm/s, demonstrated by in-situ XRD synchrotron experiments [4], with new opportunities for vortex pinning and where nanoparticles behave differently. In all this study, deep analysis correlating vortex physics with defects microstructure and associated strains have been crucial. Atomic-scale aberration-corrected scanning transmission electron microscopy and angular dependent in-field transport measurements have enabled us to underpin the most favorable pinning centers for each temperature and magnetic field range.

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Peak Effects in Heavy-ion Irradiated $NbSe_2$

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Columnar defects (CDs) created by heavy-ion irradiation are very effective in enhancing the critical current density (J_c) in superconductors. Such an enhancement of J_c was first demonstrated in cuprate superconductors [1], and similar enhancements of J_c was reported in conventional [2] and iron-based superconductors [3]. However, how the enhancement of J_c occurs depends strongly on the materials, energy and density of heavy-ions, and configuration of CDs, parallel or splayed (having angular dispersions). In some cases, J_c is monotonically enhanced, while in other cases, non-monotonic magnetic field dependence of J_c, peak effect, is observed after the introduction of CDs. The mechanism for the peak effect in superconductors with CDs is still unclear as well as the peak effect in pristine superconductors. For example, a novel peak effect is observed at ~1/3B_Φ (B_Φ: matching field) in (Ba,K)Fe_2As_2 when CDs are introduced from two directions at $\pm\theta_{CD}$ from the *c*-axis [4]. Recently, a similar peak effect at some fraction of B_Φ has been reported in $NbSe_2$ with CDs tilted 30^o from the *c*-axis [5]. In this talk, we present a systematic study on magnetic field dependence of J_c in $NbSe_2$ with CDs created by 320 MeV Au and 800 MeV Xe irradiations. Depending on the ion species and/or its energy, two kinds of peak effects are observed when the CDs are introduced in a splayed manner. The peak field B_p in both cases depends strongly on θ_{CD} and its behavior is different from that found in (Ba,K)Fe_2As_2 with splayed CDs. We summarize the condition for the peak effect and its behaviour, and discuss possible origin.

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Magnetic flux penetration in superconducting films with border defects

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Defects can have a large impact on the magnetic response of superconducting thin films by forcing changes in the path of the induced electrical currents. When the magnetic flux creep exponent is high, the associated perturbation is typically damped over a distance that can largely exceed the size of the defects. The current flow is then reorganized in large domains with different orientations of the electrical current density, separated by narrow domain walls. In the critical state limit with an infinite creep exponent, the domain walls degenerate into discontinuity lines, or d-lines. In this talk, I consider the penetration of magnetic flux perpendicularly to a Nb superconducting film containing edge indentations and/or defects. It has recently been shown, by means of magneto-optical imaging and numerical simulations, that the detailed shape of the d-lines generated by lithographically-defined micro-indentations carry information about their size and shape, and vary with temperature [1]. In this talk, I examine macroscopic models, constructed over length scales of many vortices, which can be used to describe the d-lines. I discuss the effects of temperature, demagnetization, and flux creep, as well as the influence of a field-dependent critical current density on the distribution of the magnetic field. The models are applied to both indentations and defects arising from inhomogeneous properties of the film. A comparison between the model predictions and the experimental data points to the importance of a lowered surface barrier in the presence of the defects. It is argued that indentations and defects help in releasing the magnetic flux pressure, and, thereby, help in avoiding thermomagnetic instabilities.

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Hessian character of pinning landscape

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Recent advances in vortex imaging allow for tracing the position of individual vortices with high resolution. Pushing an isolated vortex through the sample with the help of a controlled dc transport current and measuring its local ac response, the pinning energy landscape could be reconstructed along the vortex trajectory [1]. This setup with linear tilts of the potential landscape reminds about the dexterity game where a ball is balanced through a maze. The controlled motion of objects through such tilted energy landscapes is fundamentally limited to those areas of the landscape developing local minima under appropriate tilt. We introduce the Hessian stability map and the Hessian character of a pinning landscape as new quantities to characterize a pinning landscape. We determine the Hessian character, the areal fraction admitting stable vortex positions, for various types of pinning potentials: assemblies of cut parabolas, of Lorentzian and Gaussian wells, as well as a Gaussian random disordered energy landscape, with the latter providing a universal result of 21% of stable area. Furthermore, we discuss various aspects of the vortex-in-a-maze experiment.

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Superconductivity in atomically thin crystals: the case of $NbSe_2$

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It is well known that superconductivity in thin films is generally suppressed with decreasing thickness. This suppression is normally governed by either disorder-induced localization of Cooper pairs, weakening of Coulomb screening, or generation and unbinding of vortex-antivortex pairs as described by the Berezinskii-Kosterlitz-Thouless (BKT) theory. Defying general expectations, few-layer $NbSe_2$ – an archetypal example of ultrathin superconductors – has been found to remain superconducting down to monolayer thickness. I will describe our recent experiments where we measured both the superconducting energy gap Δ and critical temperature T_C in high-quality monocrystals of few-layer $NbSe_2$, using planar-junction tunneling spectroscopy and lateral transport. We observed a fully developed energy gap that rapidly reduces for devices with the number of layers $N \leq 5$, as does their T_C. The observed reduction cannot be explained by disorder, and the BKT mechanism can also be excluded as T_{BKT} transition temperature for all N remains very close to T_C. We attribute the observed behavior to changes in the electronic band structure predicted for mono- and bi- layer $NbSe_2$ combined with inevitable suppression of the Cooper pair density at the superconductor-vacuum interface. Our experimental results for $N > 2$ are in good agreement with the dependences of Δ and T_C expected in the latter case while the effect of band-structure reconstruction is evidenced by a stronger suppression of Δ and the disappearance of its anisotropy for $N = 2$. The spatial scale involved in the surface suppression of the density of states is only a few angstroms but cannot be ignored for atomically thin superconductors.

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Hydrogen-induced high-temperature superconductivity in two-dimensional materials: The case of hydrogenated monolayer MgB_2

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In seminal work of 1968 Ashcroft showed that dense metallic hydrogen, if ever produced, could be a high-temperature superconductor, owing to its very high Debye temperature, as a result of its minimal mass, enabling very strong phonon-mediated superconducting pairing according to the Bardeen-Cooper-Schrieffer (BCS) theory [1]. Currently, it has been well established that hydrogen-based compounds under ultra-high pressure, such as the polyhydrides H_3S [2] and LaH_{10} [3,4], superconduct through the conventional electron-phonon coupling mechanism to attain the record critical temperatures (T_c) known to date.

We will demonstrate that the intrinsic advantages of hydrogen for phonon-mediated superconductivity can be exploited in a completely different system, namely two-dimensional (2D) materials [5]. Namely, we found that hydrogen adatoms can strongly enhance superconductivity in 2D materials. Firstly, Van Hove singularities in the electronic structure, originating from atomic-like hydrogen orbitals, lead to a strong increase of the electronic density of states, thus enhancing the electron-phonon coupling. Furthermore, the emergence of high-frequency hydrogen-related phonon modes in this system boosts the electron-phonon coupling further.

As a concrete example, we will focus on the effect of hydrogen adatoms on the superconducting properties of monolayer MgB_2 [6,7], which we investigated by solving the fully anisotropic Eliashberg equations, in conjunction with a first-principles description of the electronic and vibrational states, and the coupling between them. We will show that hydrogenation leads to a high T_c of 67 K, which can be boosted to over 100 K by biaxial tensile strain. This proves that hydrogenation of a 2D material can indeed induce strong electron-phonon coupling and high-T_c superconductivity, as exploited in the bulk hydride compounds with record T_c's to date [3,4], yet without the need to apply excessively high pressures that hamper practical applications.

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Roles of structural defects on vortices in atomically-thin superconductors

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Surface state superconductivity, which emerges in metallic electronic states formed by a few-monolayer deposition of metallic elements on a semiconducting substrate, has unique properties if compared with other two-dimensional (2D) superconductors. Because of the thermal stability through the self-organized structural reconstruction, atomically well-ordered structures can be formed in macroscopic dimensions. Basic properties such as atomic structure and electronic states are well characterized by standard surface science techniques including scanning tunneling microscopy (STM), and one can modify the properties through controlled deposition on them.

One ubiquitous feature of the 2D electronic systems is the natural presence of atomic steps. Atomic steps are considered to strongly affect electron transport because they potentially decouple neighbouring surface terraces. So far, we have demonstrated that the steps of the √3x√3-In/Si(111) surface superconductor behave as a Josephson junction and hold elongated vortices called Josephson vortices, whose elongation depends on the coupling strength [1]. On striped incommensurate (SIC) phase of Pb/Si(111) the steps are found to block the propagation of the superconducting proximity effect and enhance it when they are located within the coherence length [2].

In two-dimensional superconductors usual orbital pair breaking of the superconductivity by in-plane magnetic field can be suppressed, allowing the Zeeman pair breaking to determine the critical magnetic field. Unfortunately, they do not have protection against perpendicular fields. In the present study using STM, we found the protection of the superconductivity under perpendicular magnetic field in narrow terraces of the Pb/Si(111) surface superconductor whose width is comparable to the coherence length. It is presumably due to the suppression of orbital pair breaking by the step confinement. Unlike the case of nanowire network [3], where the protection persist until the magnetic length becomes equal to the half of the terrace width, the step-confined terrace survives up to the magnetic length equal to quarter of the terrace width, indicating the different role of the steps from the edge of the samples. Since the density and the coupling strength of the steps can be controlled, our study opens a way to design 2D superconductors that maintain the pairing under magnetic field in all directions.

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Tuning vortex fluctuations and superconducting transitions in thin film bilayers

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The ways by which the temperature of the resistive transition T_r of a superconducting film can be increased by a thin superconducting or normal overlayer are discussed. For instance, deposition of a metallic thin overlayer onto a dirty superconducting film can give rise to an "anti-proximity effect" which manifests itself in an initial increase of $T_r(d)$ with the overlayer thickness d followed by a decrease of $T_r(d)$ at larger d. Such a nonmonotonic thickness dependence of $T_r(d)$ results from the interplay of the increase of a net superfluid density and the suppression of the critical temperature T_c due to the conventional proximity effect. This behavior of $T_r(d)$ is obtained by solving the Usadel equations to calculate the temperatures of the BKT transition and the resistive transition due to thermally-activated hopping of vortices in dirty bilayers [1]. The theory incorporates relevant materials parameters such as thicknesses and conductivities of the layers, interface contact resistance between them and the subgap quasiparticle states which affect both the phase fluctuations and the proximity effect suppression of T_c. The transition temperature T_r can be optimized by tuning the overlayer parameters, which can significantly weaken vortex fluctuations and nearly restore the mean-field critical temperature. The calculated $T_r(d)$ may account for the nonmonotonic dependence of $T_r(d)$ observed on (Ag, Au, Mg, Zn)-coated Bi films, Ag-coated Ga and Pb films or NbN and NbTiN films on AlN buffer layers [2-5]. Bilayers can be used as model systems for systematic investigations of optimization of phase fluctuations in superconductors.

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Phonon confinement in superconducting nanostructures

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The critical temperature (T_c) of a superconductor can be significantly affected by reducing the size of the superconducting sample below its characteristic length scales (correlation length, magnetic penetration length). Depending on the bulk value of the electron-phonon coupling strength, electronic and phonon confinement effects will play different roles in the modification of T_c. It still remains a challenge to experimentally measure the phonon density of states (PDOS) of nanoscale superconductors [1], which is a prerequisite to quantify and disentangle the contributions of electronic and phonon confinement. We have succeeded in measuring the PDOS and the critical temperature T_c of arrays of Sn nanowires with diameters of 18, 35, and 100 nm embedded in Al_2O_3 porous matrices in order to quantify the influence of phonon confinement on superconductivity. The T_c was found to increase with decreasing nanowire diameter. The PDOS of the different nanowire samples have been determined by nuclear inelastic scattering of synchrotron radiation and compared with the PDOS of a bulk sample. Using the measured PDOS, the electron-phonon coupling strength and the critical temperature have been determined using the Allen-Dynes correction of the McMillan expressions [2]. We observe clear changes in the PDOS of nanowire samples compared to the bulk sample, with a shift of the phonon frequency towards the low-energy region and an enhancement of the electron-phonon coupling constant, which can account for the measured increase in the critical temperature [3].

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Network Science Approach to Confined Vortex Matter

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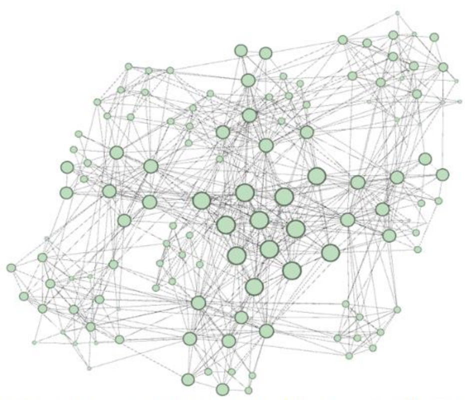
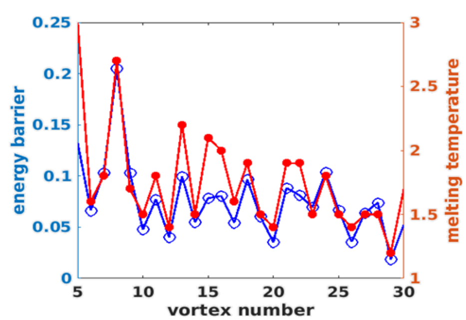
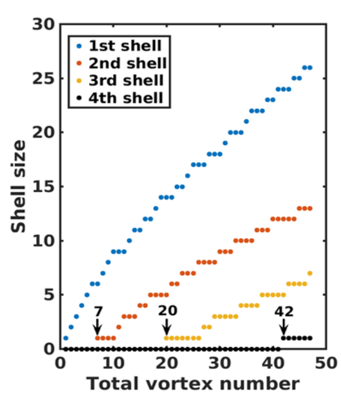
Previous studies of confined vortex matter typically focus on the ground state and a few elementary dynamical processes and excitations near the ground state configuration. Although metastable states are less studied, they are important to the dynamics and stability of the system. Based on a network science approach, which was first introduced to explore the energy landscape of Lennard-Jones clusters [1], we performed a systematic study of vortices confined in a mesoscopic container. By connecting two metastable states (local minima) via a transition state (1^{st} order saddle point), the network representation of the potential energy landscape is constructed. The properties of the network are studied as a function of vortex number and confinement geometry. We show that the ground state is always at the "core" of this network, which justifies the implementation of simulated annealing via molecular dynamics simulations during the search for the ground state. Furthermore, from transition properties restricted by network topology, we study the stability of vortex matter as well as identify "magic number" configurations, i.e., ground states with high stability at specific vortex numbers. The sequence of "magic number" is governed by the container size and symmetry.



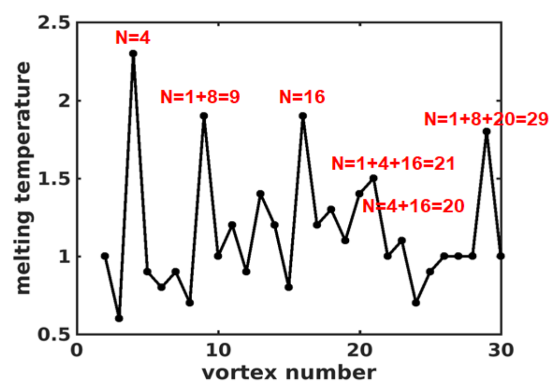
Network Representation of Potential Energy Landscape of 47 Vortices Confined in Square Container



Correlation of transition energy barrier and melting temperature (circular container)



Shell Structure Observed in Simulation (Circular Container)



"Magic Number" in Square Container

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Surface effects on the definition of type 1 and 2 superconductors

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In 1956 A.A. Abrikosov has shown that bulk superconductors fall into two categories, namely, type 1 and 2, and only the latter possesses vortex states. However, it has been known since long ago that an external surface can affect this view making the distinction between type 1 and 2 superconductors elusive. Superconductivity remains in a thin layer around the external boundary with thickness defined by the coherence length until the critical surface field, H_{c3}, is reached [1]. Superconductors of type 1 and 2 satisfy the inequalities $H_{c2}<H_c$ and $H_{c2}>H_c$, respectively, but since $H_{c3}>H_{c2}$ two type 1 superconductors are possible, namely, $H_{c2}<H_{c3}<H_c$ and $H_{c2}<H_c<H_{c3}$. Long ago M. Thinkham [2] has named the latter case as type 1.5 superconductors and pointed this as a questionable classification since its validity depends on the nature of the boundary condition at the sample surface and not on the intrinsic properties of the bulk of the material. Recent numerical studies of the Ginzburg-Landau theory [3,4] have also shown that mesoscopic type 1 superconductors have vortices due to their enhanced volume to area ratio. Here we show that type I and 2 superconductors must be redefined in presence of an external surface and this results is a straightforward consequence of the Ginzburg-Landau theory proven by the same method used by Abrikosov to obtain his seminal conclusions from this theory, but now extended to include an external boundary [5]. Basically, the critical coupling κ_c that splits the two categories of superconductors is affected by the presence of the external boundary and becomes much smaller than $1/\sqrt{2}$. We consider an infinitely long cylinder of radius R under an external applied field along the major axis which is then isothermally lowered and enters the superconducting state below the critical field. Superconductivity sets in a thin layer around the external boundary where paramagnetic currents are established and a giant vortex with vorticity defined by the trapped flux, HR^2 is then formed. We find that type 2 superconductors sustain this vortex state for $H<H_{c2}$, as expected, but surprisingly, type 1 superconductors unfold a new critical field, H_m, found to disappear in the limit of a very large cylinder. Therefore, type I superconductors are found to sustain giant vortices for finite R but in the regime $H_{c2}<H<H_m$. The present approach gives a new derivation of the surface field H_{c3}, based on the stability of the kinetic energy of the condensate.

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Current-Induced Crossover of Flux Periodicity from h/2e to h/e in Superconducting Nb Nano-Rings

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Magnetoresistance measurements in a granular Nb nano-ring reveal current-induced crossover between two distinct quantum coherence effects. At low bias currents, Cooper-pair coherence is manifested by Little−Parks oscillations with flux periodicity of *h/2e*. At high bias currents, magnetoresistance oscillations with flux periods of *h/e* are observed and interpreted as Aharonov−Bohm oscillations, reflecting the phase coherence of individual quasi-particles. The model explaining these data views the ring as a chain of superconducting grains weakly coupled by tunnel junctions. Low bias currents allow coherent tunnelling of Cooper pairs between the grains. Increasing the current above the critical current of all the junctions creates a quasi-particles conduction channel along the ring, allowing for quantum interference of quasi-particles.

* Work done in collaboration with Omri Sharon, Avner Shaulov, Jorge Berger, Amos Sharoni, and Richard Berkovits.

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New forms of exotic vortex matter in superconductors

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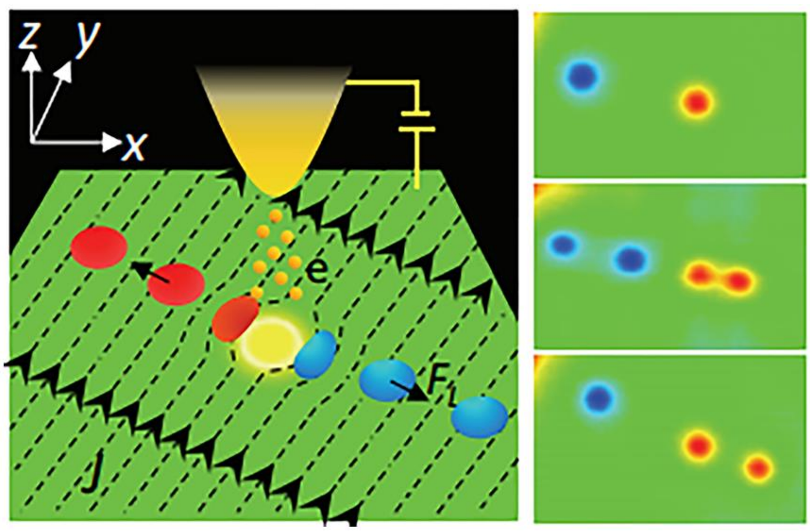
A brief overview is given of recently discovered new forms of exotic vortex matter in superconductors: *Karman vortex streets, giant vortices, vortex chains and vortex clusters and chains in type-1.5 superconductors, symmetry-induced antivortices*. Direct experimental observation of magnetic dipoles generated by the Meissner current at topological defects (antidots) in superconducting film will be also discussed. Each magnetic dipole can be considered as a pair of fluxoids with opposite polarities. Remarkably, the magnetic flux of each pole and antipole is not necessarily quantized and can carry all non-integer momenta between integer values. However, the total magnetic flux of each dipole remains zero, which fully complies with the quantum character of superconductivity. The magnetic dipoles also provide an efficient way to measure the local intensity and direction of flowing supercurrent, which is rather difficult to realize in any other way. (*Nature Com. 6, Article No: 6573, 2015; NANO LETTERS Volume: 17 Issue: 8 Pages: 5003-5007, 2017; Nature Communications Volume: 7 Article Number: 13880, 2016)*



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Broken time-reversal symmetry in s+ is and s+ id states of multi-band superconductors: vortices, skyrmions, domain walls and spontaneous magnetic fields

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The recent experiments on Iron-based superconductors reported two interesting situations: the formation of s-wave superconducting state in Ba1−xKxFe2As2 that breaks time-reversal symmetry (BTRS) (i.e. the so-called s+is state) and disorder-driven crossover from s+- to s++ state. Both of these situations should be accompanied by unconventional physics that will be discussed in this talk. I will discuss the origin of the spontaneous magnetic fields in the s+is state [1], unconventional topological excitations arising due to BTRS such as domains walls and Skyrmions [2], the breakdown of type-I/type-II dichotomy due to a divergent coherence length ξ at the s-wave to s+is and the s-wave to s+id transitions causing the magnetic field penetration length λ to be intermediate length scale ξ1<λ< ξ2 [3,4] (the type-1.5 regime): resulting in vortex clustering, and a rather generic coexistence of the s+- and s++ states near the s+- to s++ crossover [5].

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Observation of a gel of quantum vortices in a superconductor at very low magnetic fields

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A gel consists of a network of particles or molecules formed for example by the sol-gel process, by which a solution transforms into a porous solid. Particles or molecules in a gel are mainly organized on a scaffold that makes up a porous system. Vortices in type II superconductors can freeze into an amorphous solid, particularly at low magnetic fields where vortices are nearly noninteracting. Here we present high-resolution imaging of the vortex lattice displaying dense vortex clusters separated by sparse or entirely vortex-free regions in β-Bi_2Pd superconductor containing one-dimensional structural defects. In contrast to the amorphous state, we find that the vortex distribution follows a multifractal behavior and the variance of intervortex distances diverges upon decreasing the magnetic field. These properties, characteristic of gels, establish the presence of a novel vortex matter phase, distinctly different from the well-studied disordered and glassy phases observed in high-temperature and conventional superconductors. The vortex gel is expected to be generic to type-II superconductors at low magnetic fields containing strained extended defects, which could be engineered for isolating and manipulating clusters of quantum vortex states.

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Structural Transition Kinetics and Activated Behavior in the Superconducting Vortex Lattice

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We have studied nonequilibrium phase transitions in the vortex lattice (VL) in superconducting MgB_2, where metastable states are observed in connection with an intrinsically continuous rotation transition. This represent an unconventional kind of collective vortex behavior, not governed by pinning, most likely due to the nucleation and growth of equilibrium VL domains. Using small-angle neutron scattering and a stop-motion technique, we investigated the manner in which the metastable VL returns to the equilibrium state under the influence of an ac magnetic field. We find a qualitative difference between the supercooled case which undergoes a discontinuous transition and the superheated case where the transition to the equilibrium state is continuous [1,2]. However, in both cases the VL exhibits an activated behavior, where the ac field amplitude and cycle count are equivalent to, respectively, an effective “temperature” and “time.” The activation barrier increases as the metastable state is suppressed, corresponding to an aging of the VL. Structural studies of the VL, as it is gradually driven from metastable to equilibrium states, find a longitudinal correlation length that remains constant and comparable to the sample thickness [3]. Correspondingly, the VL may be considered as a system of straight rods, where the formation and growth of equilibrium state domains only occurs in the two-dimensional plane perpendicular to the applied field direction. Spatially resolved raster scans of the sample were performed with apertures as small as 80 μm, corresponding to ~10^6 vortices. These revealed spatial variations in the metastable and equilibrium VL populations, but individual domains were not directly resolved. A statistical analysis of the data indicates an upper limit on the average domain size of approximately 50 μm.

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Josephson current from odd-frequency superconductivity in Weyl nodal loop semimetals

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Weyl nodal loop semimetals (WNLs) host a closed nodal line loop Fermi surface in the bulk and protected zero-energy flat band, or drumhead, surface states that are fully spin-polarized. The large density of states of the drumhead states makes WNLs exceedingly prone to electronic ordering. At the same time, the spin-polarization naively prevents conventional superconductivity due to its spin-singlet nature. Here we show the complete opposite: WNLs are extremely promising materials for superconducting Josephson junctions, entirely due to odd-frequency superconductivity.

First, by sandwiching a WNL between two conventional superconductors we theoretically demonstrate the presence of very large Josephson currents, even up to orders of magnitude larger than for normal metals. The large currents are generated both by an efficient transformation of spin-singlet pairs into odd-frequency equal-spin pairing by the Weyl bulk dispersion and the drumhead states ensuring exceptionally strong proximity effect at the surface [1]. Second, by attaching conventional superconducting leads on the same WNL surface, we also find a finite Josesphson effect entirely due to odd-frequency superconductivity, but limited by the flat dispersion of the surface state. By placing an additional ferromagnet in the junction we corroborate the equal-spin nature of the supercurrent [2]. As a result, WNL Josephson junctions offer unique possibilities for detecting and exploring odd-frequency superconductivity.

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Chiral domain walls in microstructured Sr_2RuO_4

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Sr_2RuO_4 is expected to be a spin-triplet chiral p-wave superconductor, where the chirality means that the ground state is two-fold degenerate, with two different directions of the Cooper-pair orbital angular momentum. We fabricated Sr_2RuO_4 microrings and performed resistance (*R*) and critical-current (I_c) measurements in an axial magnetic field. In some such rings, Little-Parks magnetoresistance oscillations are observed close to the transition temperature T_c as recently reported [1]. In other rings, however, we find that I_c oscillates with a period corresponding to the fluxoid quantization down to temperatures far below T_c. This behavior resembles that of a superconducting quantum interference device (SQUID) and suggests that a pair of weak links of an intrinsic origin is spontaneously formed in the arms of the ring. Such weak links are most naturally attributable to domain walls separating domains with different chirality, which is also the outcome of order parameter calculations. We believe this to be strong new evidence for the chiral superconducting state in Sr_2RuO_4.

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Topological Josephson Plasma in Honeycomb Junction Array

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Topology in condensed matter physics is attracting significant interests [1]. This concept has also been extended to electromagnetic waves and other systems with the bosonic feature, which provides a new facet towards realizing novel properties and functionality based on the topological interface transport immune to back scattering and robust to disorder [2-4]. Here we report our recent work on Josephson junction arrays (JJA) [5]. The system consists of a honeycomb JJA with superconducting islands residing on sites of honeycomb lattice and JJ on the links between sites; each superconducting island is connected by a capacitor to the common ground. Interestingly, the system exhibits a Dirac-like linear frequency dispersion similar to that seen in graphene, which one can call an artificial graphene. We reveal that assigning a two-valued texture in critical Josephson current I_c, whereby I_c inside the hexagonal unit cells is smaller than I_c between the unit cells, opens a gap in the Dirac dispersion, and that a topological Josephson plasma mode appears accompanied by a p-d band inversion [5]. We are going to show the details of our theory and discuss experimental realizations as well as possible merits for applications.

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Josephson vortex generation and detection with a Magnetic Force Microscope

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Josephson vortices play an important role in superconducting quantum electronics devices. Often seen as purely conceptual topological objects, 2Pi-phase singularities, their observation and manipulation is challenging. Here we show that in Superconductor - Normal metal - Superconductor lateral junctions Josephson vortices have a peculiar magnetic fingerprint that we reveal in Magnetic Force Microscopy (MFM) experiments. Based on this discovery, we demonstrate the possibility of the Josephson vortex generation and manipulation by the magnetic tip of a MFM, thus paving a new way for the remote inspection and control of individual nano-components of superconducting quantum circuits.

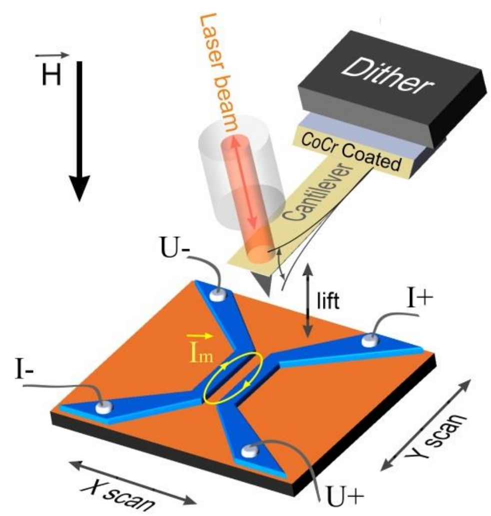

Fig.1. Experimental setup: 100 nm thick Nb leads (in blue) are patterned on a 50nm thick Cu layer (in orange); the leads are bonded for transport measurements. The ellipse marks the junction region 2500 nm x 200 nm. The MFM cantilever with a Co/Cr-coated tip oscillates, excited by a dither; an optical fiber is used for the oscillation readout.

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Vortex Dynamics via In-situ Magnetic Texturing

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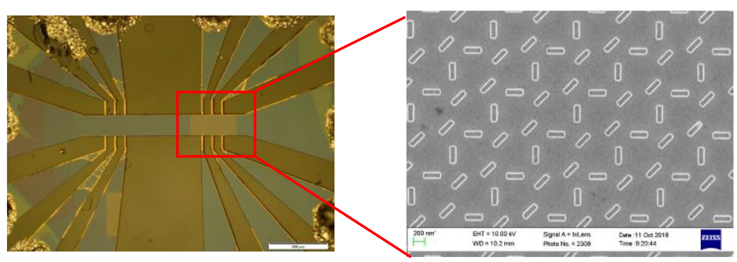
The advent of nanofabrication has opened new venues for controlling vortex matter, which is responsible for the electro-magnetic response of all applied superconductors. Nano-hole structures with innovative patterns have emerged as a versatile platform for controlling and optimizing vortex pinning in superconductors for enhanced critical current. Magnetic field pinning of vortices with nanoscale structures has also shown great potential for in-situ manipulation of vortex behaviour. Here, I will present brief highlights of our work on tailoring vortex dynamics with magnetic texturing. In particular, we use nano-magnetic patterned structures based on spin-ice rules [1] to explore the effect of pinning, dynamic rectification and geometric frustration in a flux quanta system [2] in the vortex solid and liquid state.



BSCCO single crystal microbridge 80μm(L) x 60μm(W) x 60μm(H) **Magnetic Charge Ice Structure**

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Controlling magnetic fields by superconductor-ferromagnetic hybrid metamaterials

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In this work we present recent advances that magnetic metamaterials have offered in the control of static and low-frequency magnetic fields. Traditionally, magnetic fields are being shaped by employing magnetic materials (e. g. soft ferromagnets in transformer cores). Here we explain how tailored combinations of superconducting and ferromagnetic materials can create novel possibilities for shaping static and low-frequency magnetic fields along several relevant directions. These new ways of manipulating magnetic fields include magnetic cloaking, concentration of magnetic energy in space -even at a distance-, transferring static fields to long distances, and disguising the response of a magnetic material as it was a different one (e. g. transforming the response of a ferromagnet into that of a superconductor). These properties will be demonstrated both theoretically and with proof-of-concept experiments. Finally, future research lines on these fields, including possible implementations of these ideas at the micro- or nanometer scales, will be discussed.

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Magnon-Fluxon interaction in ferromagnet/superconductor heterostructures

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Ferromagnetism and superconductivity are most fundamental cooperative phenomena in condensed matter physics. Entailing opposite spin orders, they share an important conceptual similarity: Disturbances in magnetic ordering in magnetic materials can propagate in the form of spin waves (magnons) while magnetic fields penetrate type II superconductors as a lattice of magnetic flux quanta (fluxons). Despite a rich choice of wave and quantum phenomena predicted [1-3], magnon-fluxon coupling has lacked experimental scrutiny so far.

In this talk, a selection of our recent results [4] on the interaction of spin waves with a flux lattice in ferromagnet/superconductor Py/Nb bilayers will be presented. In particular, it will be shown that, in this system, the magnon frequency spectrum exhibits a Bloch-like band structure which can be tuned by the biasing magnetic field. Furthermore, the frequency spectra of spin waves scattered on a flux lattice moving under the action of a transport current in the superconductor exhibit Doppler shifts. The resonance absorption of spin waves is explained by their scattering on the vortex lattice constituting a reconfigurable magnonic crystal [5]. The observed Doppler shifts arise due to the modified dispersion relation for spin waves scattered on the moving vortex lattice constituting a moving Bragg grating. In addition, manipulation of spin waves and tailoring of their transmission spectra in Py will be exemplified by using adjacent Nb layers with nanofabricated pinning potential landscapes.

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Magnetic skyrmions at topological insulator surfaces and in proximity to a superconductor

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In the fisrt part of my talk I will analyze a hybrid heterostructure with magnetic skyrmions (Sk) inside a chiral ferromagnet interfaced by a thin superconducting film via an insulating barrier. The barrier prevents the electronic transport between the superconductor and the chiral magnet, such that the coupling can only occur through the magnetic fields generated by these materials. We find that Pearl vortices (PV) are generated spontaneously in the superconductor within the skyrmion radius, while anti-Pearl vortices (PV) compensating the magnetic moment of the Pearl vortices are generated outside of the Sk radius, forming an energetically stable topological hybrid structure. Finally, we analyze the interplay of skyrmion and vortex lattices and their mutual feedback on each other. In particular, we argue that the size of the skyrmions will be greatly affected by the presence of the vortices offering another prospect of manipulating the skyrmionic size by the proximity to a superconductor [1].

In the second part we will the effective magnetic interactions at a topological insulator-ferromagnet interface. We show that by integrating out the Dirac fermion fluctuations an effective Dzyaloshinskii-Moriya interaction and magnetic charging interaction emerge. As a result individual magnetic skyrmions and extended skyrmion lattices can form at interfaces of ferromagnets and topological insulators[2], the first indications of which have been very recently observed experimentally.

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Imaging various vortex-like magnetic textures by using atomic-resolution TEM

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The nanometer-scale vortex-like spin textures, such as vortex-anrivortex pairs in ferromagnetic (FM) domain walls [1], votices in superconductors [2], skyrmion (lattice) [3] and antiskyrmions [4] in magnets with inversion symmetry, have recently attracted enormous attention owing to their emergent phenomena [5]. To confirm such minute complex spin textures and their dynamics with external stimuli, ultrafast real-space high-resolution imaging technique, such as time-resoved X-ray microscopy or Lorentz transmission electron microscopy (TEM) is useful.

In this talk, I will present several vortex-like spin textures realized by Lorentz TEM with atomic resolution in several systems, such as chiral magnets, ferromagnets with uniaxial anisotropy and the fluctrated magnets with Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction. In addition to the hexagonal skyrmion lattice (hex-SkL), a square lattice of merons and antimerons (sq-ML)—topologically distinguish with skyrmions—have been observed [6]. By finely varying the external magnetic fields, the transformation between the sq-ML and a hex-SkL have been induced. We found that the skyrmions were very robust, lasting even as we lowered the temperature of the thin plate, but the merons and antimerons were much more sensitive, and relaxed into spin helices as the temperature fell.

Furthermore, the transition between skyrmions (topological "particles") and antiskyrmions ("antiparticles") via non-topological magnetic bubbles have been also demonstrated by means of the *in-situ* Lorentz TEM observations in a chiral system with D_{2d}-symmetry. The control of topological nature among various magnetic vortices with external stimuli will be shown.

These works have been done in collaboration with Profs. Yoshinori Tokura, Naoto Nagaosa, Taka-hisa Arima, Yusuke Tokunaga, Shinichiro Seki and Fumitaka Kagawa, and with Drs. Wataru Koshibae, Yasujiro Taguchi, Khanh Nguyen, Daisuke Morikawa, Naoya Kanazawa, Tomoyuki Yokouchi, Kiyou Shibata, Licong Peng and Yoshio Kaneko.

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Emergent dynamics of active magnetic colloids

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Strongly interacting colloids driven out-of-equilibrium by an external periodic forcing often develop nontrivial collective dynamics. Active magnetic colloids proved to be excellent model experimental systems to explore emergent behavior and active (out-of-equilibrium) self-assembly phenomena. While colloidal systems are relatively simple, understanding their collective response, especially in out of equilibrium conditions, remains elusive.Dispersions of magnetic particles suspended at a liquid-air or liquid-liquid interface and driven far-from-equilibrium by a transversal alternating magnetic field develop nontrivial dynamic self-assembled structures [1-3]. Experiments revealed new types of nontrivially ordered phases emerging in such systems in a certain range of excitation parameters. These remarkable magnetic non-equilibrium structures emerge as a result of the competition between magnetic and hydrodynamic forces.

Ferromagnetic micro-particles immersed in water and sedimented on the bottom surface turn into colloidal rollers when energized by a single-axis homogeneous alternating magnetic field applied perpendicular to the surface supporting the particles. The activity in this system originates only from spinning degrees of freedom and self-propulsion emerges due to the presence of a solid interface. The rolling motion emerges as a result of spontaneous symmetry breaking of the particle rotations in external field in a certain range of excitation parameters. Experiments reveal a rich collective dynamics of magnetic rollers including a formation of chiral (polar) states – roller vortices [4]. Self-organized roller vortices have an ability to spontaneously switch the direction of rotation and move across the surface. We reveal the capability of certain non-active particles to pin the vortex and manipulate its dynamics [5]. Complex multi-vortex states are revealed.

In a related system ferromagnetic microparticles, suspended at a liquid interface and energized by a uniaxial in-plane alternating magnetic field, spontaneously form arrays of self-assembled spinners rotating in either direction. The spinners, emerging as a result of spontaneous symmetry breaking of clock/counterclockwise rotation of self-assembled particle chains generate vigorous vortical flows at the interface. An ensemble of spinners exhibits chaotic dynamics due to self-generated advection flows. The same-chirality spinners (clockwise or counterclockwise) show a tendency to aggregate and form dynamic clusters. Erratic motion of spinners at the interface generates chaotic fluid flow reminiscent of two-dimensional turbulence [6].

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Skyrmion Lattices in Random and Ordered Potential Landscapes

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Since the initial discovery of skyrmion lattices in chiral magnets [1], there has been a tremendous growth in this field as an increasing number of compounds have been identified with extended regions of stable skyrmion lattices [2] even close to room temperature [3]. These systems have significant promise for applications due to their size scale and the low currents needed to move the skyrmions [4]. Another interesting aspect of skyrmions is that their equations of motion contain a significant non-dissipative or Magnus term, making skyrmions unique among systems exhibiting collective driven dynamics and distinct from vortex lattices in type-II superconductors, sliding charge density waves, or frictional systems. We examine the driven dynamics of skyrmions interacting with random and periodic substrates using both continuum based modeling and particle-based simulations. In clean systems, we study the skyrmion motion as a function of magnetic field and current, and show that current-induced creation or destruction of skyrmions can occur. When random pinning is present, we find a finite depinning threshold and demonstrate that the Hall angle depends strongly on the disorder strength. We correlate features in the transport curves with different skyrmion flow regimes, including skyrmion glass depinning, skyrmion plastic flow, and a transition to a dynamically reordered skyrmion crystal at high drives. We find that increasing the Magnus term depresses the depinning threshold due to a combination of skyrmions undergoing complex orbits within the pinning sites along with skyrmion-skyrmion scattering effects. For skyrmion motion over a periodic substrate, as the drive increases, the Hall angle changes in quantized steps that correspond to periodic skyrmion trajectories that lock to symmetry directions of the substrate potential.

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Overcoming the limits of vortex formation in magnetic nanodots

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Magnetic vortices are simplest topologically nontrivial magnetic states having promising applications in spin-torque oscillators, magnetic memory, etc. In the most of works common Bloch magnetic vortices in sub-micron soft ferromagnetic disks with thickness above 10-20 nm were studied.

We propose a way to achieve magnetic vortex state with unconventional structure in nanoscale soft ferromagnetic disks. Our approach is based on the application of hybrid nanostructure, in which a soft magnetic nanodot (thickness t_D) is placed within an antidot in a hard magnetic layer (thickness $t_{HL} > t_D$) with perpendicular magnetization. The diameter of dot is slightly smaller than the diameter of antidot, providing only dipolar coupling between subsystems. By means of micromagnetic simulations and analytical calculations we show that, depending on the strength of dipolar field form the hard layer, the ground state of the soft layer can be either radial (Neel) vortex, or a magnetic vortex with a complex structure, which is an intermediate (or mixture) between Neel and Bloch vortices.

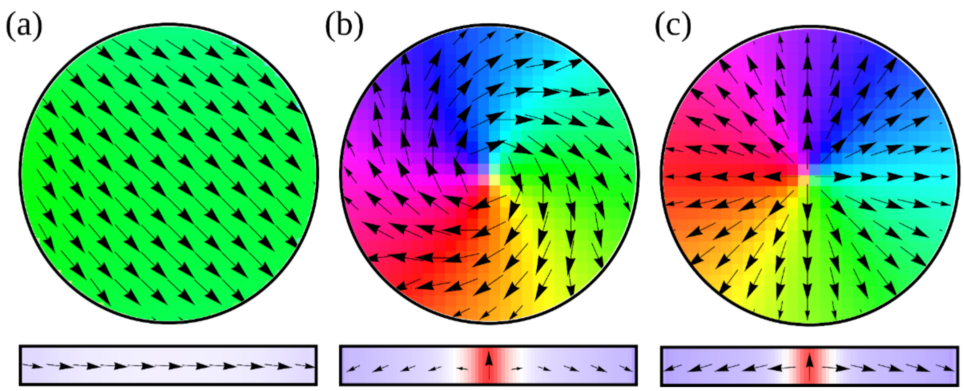

Fig. 1. Magnetization configuration of the 70-nm-diameter dot in a (a) single-domain state (hard layer thickness t_{HL}=6nm), (b) curled vortex state (t_{HL}=15nm), and (c) radial vortex state (t_{HL}=24nm). Top: Top view. Bottom: y−z cross section. The dot thickness t_D=3nm.

Moreover, dipolar coupling to a hard layer also reduce the characteristic sizes of a vortex. Therefore, vortex ground state in the studied nanostructure can be achieved in much smaller disks comparing to an isolated disk. For example, we observe formation of Neel vortices in Permalloy disks as small as 50 nm in diameter and 1-2 nm thickness, that is far beyond the limits of the vortex formation in an isolated disk.

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SQUID-on-tip imaging of work and dissipation in the quantum Hall state

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We developed a scanning nanoSQUID-on-tip with sub 50 nm diameter that resides at the apex of a sharp pipette acting simultaneously as nanomagnetometer with single spin sensitivity and as nanothermometer providing cryogenic thermal imaging with four orders of magnitude improved thermal sensitivity of below 1 μK [1]. The non-contact non-invasive thermometry allows thermal imaging of minute energy dissipation down to the level of direct visualization and control of heat generated by electrons scattering off a single atomic defect in graphene [2]. Utilizing this tool we image and investigate microscopic mechanisms undermining the topological protection in the quantum Hall state in graphene. The simultaneous nanoscale thermal and scanning gate microscopy reveals that the dissipation is governed by crosstalk between counterpropagating downstream and upstream channels that appear at graphene boundaries because of edge reconstruction. Instead of local Joule heating, the dissipation mechanism comprises two distinct and spatially separated processes, which we resolve and image independently. The work generating process involves elastic tunneling of charge carriers between the quantum channels, which directly affects the transport properties but does not generate local heat. The heat and entropy generation process occurs nonlocally upon inelastic resonant scattering off single atomic defects at graphene edges. The findings offers insight into the mechanisms responsible for the breakdown of topological protection and suggest venues for engineering more robust quantum states for device applications.

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Spontaneous vortex state in spin-orbit coupled superconducting rings

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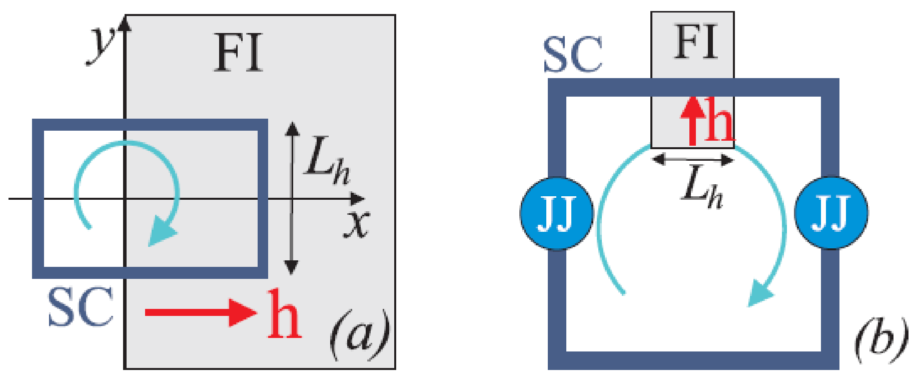
The interaction of interface superconductivity with materials exhibiting strong spin-orbit coupling and magnetic exchange fields offers enormous potential for the discovery and control of new physical phenomena. We demonstrate that the exchange spin-orbit coupling leads to spontaneous currents in a closed superconducting loop in which the superconductor (SC) is partially-coupled to a ferromagnetic insulator (FI). The chirality of the current is controllable through the magnetization alignment of the ferromagnetic insulator. We predict a non-trivial interplay between the Little-Parks effect and helical current carrying states. Even in zero external magnetic field, spontaneous vortex currents are generated in the ground state. More generally, the revealed mechanism of the spontaneous current generation permits to realize a phase battery, which can be easily incorporated in different superconducting circuits, enhancing their functionality.



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New functionalities for energy-efficient superconducting electronic devices

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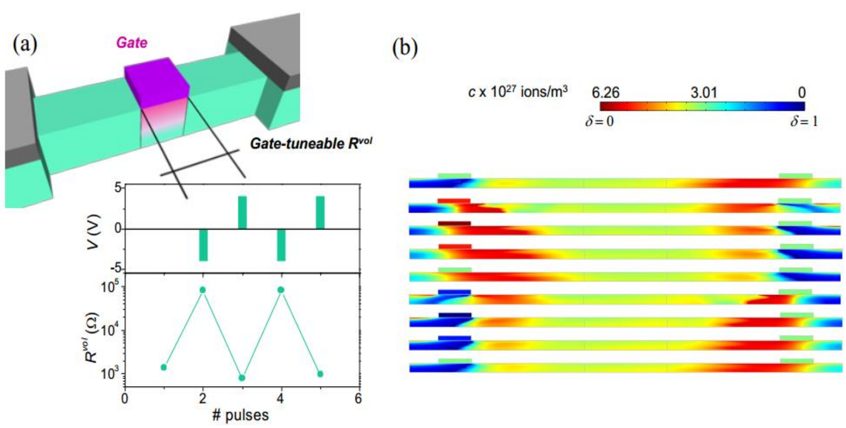
Next decade of research in condensed matter physics will be driven by the development of novel materials and hybrid systems for the design of new electronic functional devices featuring low energy dissipation. Strongly correlated metal oxides, showing metal-insulating transitions (MIT), appear as particularly interesting materials, offering the unique opportunity to induce large resistance variations with small tuning of their carrier concentration. The ability to continuously tune the electrical resistance through a field induced MIT modulation, as well as to obtain high nonlinear behaviour, positions them ideal candidates for memory and logic devices. In this context, one promising technology is indeed the use of superconductors, which could have a substantial impact by virtue of their inherent energy-efficiency. Field-effect tuning of the carrier density in strongly correlated superconducting cuprates, not only allows us to modulate the MIT but also enables to induce a reversible Superconductor-Insulator quantum phase transition (SIT), offering unique scientific and technological opportunities in this rapidly emerging field.

Here I will present the potential of the electric manipulation of the superconducting parameter in $YBa_2Cu_3O_{7-\delta}$ films, for the design for multi-terminal memristive transistorlike devices, with loss-less superconducting drain-source channels (Figure 1(a)) [1]. Both normal state resistance and the superconducting critical temperature can be reversibly manipulated in confined active volumes of the film by gate-tuneable oxygen diffusion. The key advantage of these materials is the possibility to homogeneously modulate the oxygen vacancy diffusion not only in a confined filament or interface, as observed in widely explored insulating strongly correlated oxides, but also toward the whole film thickness, thus providing the basis for the design of robust devices. We analyse the experimental results in light of a theoretical model, which incorporates thermally activated and electrically driven volume oxygen diffusion (Figure 1 (b)).



(a) Scheme of a transistor-like device (top). Voltage pulses and volume bridge resistance evolution obtained for a 50 nm thick $YBa_2Cu_3O_{7-\delta}$ device. (b) Oxygen diffusion simulation at different stages of the switching process. Colors show the oxygen concentration.

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High Resolution and High Sensitivity Molecular Spectroscopy Using THz Emitters of High-Tc Superconducting Bi-2212 Mesa Structures

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High-*T*c superconductors with highly 2D layered structures of CuO2 plane, which is responsible for the high-*T*c superconductivity, like a Bi2Sr2CaCu2O8+δ (Bi-2212) compound can generate rather intense THz electromagnetic waves after proper mesa structures were fabricated with certain dimensions and shapes [1]. The emission frequency spreads over a wide range of frequency domain from 0.3 THz to 2.4 THz more or less continuously [2] and the intensity can be up to 640 mW in case of three mesas synchronously operated [3]. The spectrum of THz radiation is sharp, a few tens of MHz due to synchronization of a few thousands of intrinsic Josephson junctions in a stack along the c-axis. The mechanism of such a synchronized radiation can essentially be understood by the same mechanism as one on the LASER. Because of sharp spectrum of the THz radiation, the peak spectral intensity is extremely high, about 10^3-10^4 times stronger in the THz region than that of Hg lamp sources commonly used as a THz source. Using this characteristic feature of IJJ THz emitters, it is possible to construct high sensitivity spectrometer.

This spectrometer is planned to use for the various applications. One of the interesting applications is to selectively detect and analyze unknown organic compounds contained in lipids produced by algae as byproducts, such as Botryococcene oil from Botryococcus braunii, Squalene or Squalane from Aurantiochytrium, *etc*. This subject is very important for future health sciences to support a long healthy human life society in near future.

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Majorana Physics in Hybrid Superconductor-semiconductor nanowires

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Majorana Zero Modes (MZMs) have attracted attention in recent years due to fundamental interest in their predicted non-Abelian exchange statistics and their applications in topological quantum computation. The leading platform for realizing MZMs is the hybrid semiconductor nanowire-superconductor system, in which signatures of Majorana modes were first measured as a zero bias conductance peak in tunnelling spectroscopy experiments in 2012 [1]. Advances in material science [2,3] have since lead to strongly improved experimental results [4], culminating in the experimental realization of the theoretically predicted conductance quantization of the zero bias state [5]. However, despite significant progress, a definitive conclusion on the nature of this state has not been reached, and alternative explanations are being debated to this day.

In this talk, we present the state-of-the-art in Majorana nanowire experiments. We discuss the hybridization of superconductor and semiconductor materials which is crucial for the creation of MZMs, and how it is affected by external magnetic [6] and electric fields [7]. Finally, we give an overview of several alternative explanations for the observed zero bias conductance peak, in particular a scenario involving smooth parameter variations in space [8,9].

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Topological superconductivity and Majorana bound state in Fe-based superconductor

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In this talk I will report our recent discoveries of topological superconductivity and Majorana bound state in Fe-based superconductors, mostly in Fe(Te, Se) single crystals. We have discovered a superconducting topological surface state of Fe(Te, Se) with Tc ~ 14.5K by using high-resolution ARPES [1] . By using high-resolution STM on this material, we clearly observe a pristine Majorana bound state inside a vortex core, well separated from non-topological bound states away from zero energy due to the high ratio between the superconducting gap and the Fermi energy in this material [2]. This observation offers a new, robust plat-form for realizing and manipulating Majorana bound states, which can be used for quantum computing, at a relatively high temperature. I will also present some of our new results on this material. In addition, we have also found that most of Fe-based superconductors [3], including monolayer Fe(Te, Se)/STO [4], have similar topological electronic structures.

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Induced unconventional superconductivity in 3D topological insulators revealed by nanoscale Josephson junctions

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Topological superconductivity is central to a variety of novel phenomena involving the interplay between topologically ordered phases and broken-symmetry states. An important outcome of this interplay is the possibility to realize Majorana bound states on topological surfaces, which are of great interest in fundamental physics and for topological quantum computation. The key ingredient for such an observation is an unconventional order parameter (OP), with an orbital component assuming the form of a chiral $p_x + ip_y$ wave.

Josephson junctions involving a conventional superconductor and an exotic conductor, represented by the surface of a 3D topological insulator (TI), a Dirac semimetal or the edge states of two-dimensional quantum wells, are ideal systems to emulate topological superconductivity.

Here I will report our results on phase-sensitive measurements, based on the quantum interference in a Josephson junction, realized using Al-Bi_2Te_3-Al devices. The experiment allows to establish that the proximity with a conventional superconductor induces an order parameter in the surface states of the topological insulator Bi_2Te_3, which is consistent with a chiral $p_x + ip_y$ (p-wave) order parameter (OP). This is achieved by measuring the magnetic field pattern of the junctions which shows a dip at zero external magnetic field, a signature of the simultaneous existence of "0" and "π" coupling within the junction, inherent to an OP with a non trivial phase[1]. The peculiar nano-textured nature of the morphology of the Bi_2Te_3 flakes, and the dramatic role played by thermal strain are the surprising key factors for the display of an effective induced chiral $p_x + ip_y$ OP.

To reduce the number of modes and to reveal the 4pi-periodic current-phase relation inherent to Majorana bound states in superconducting hybrids we have also realized Josephson junctions using 3DTI nanowires [2]. In such devices we observe a contribution of 4pi-periodic Majorana bound states to the supercurrent in Al-Bi_2Se_3-Al devices revealed by studying the junction under GHz microwave irradiation and the Josephson current as a function of the temperature.

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New quantum anomalous Hall platform for chiral topological superconductivity

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Dissipationless transport of charge is one of the most consequential manifestations of quantum mechanics on macroscopic scales. It is an essential property of two remarkable states of quantum matter: superconductivity and quantized Hall effects. The first state emerges from strong electron correlations and the second from nontrivial band topology ─ both extremely challenging to unpack on a fundamental level and both with a tremendous technologically-transformative potential in energy transfer, quantum information processing, and quantum electronics. Superconductivity paired with nontrivial band topology can lead to exotic chiral superconducting state carrying non- Abelian Majorana zero modes that harbor at vortex cores. It has been proposed that a quantum anomalous Hall (QAH) state near the plateau transition and in proximity to a fully gapped *s*-wave superconductor may realize the chiral topological superconducting state. Here I will report on the previously unknown Berry-phase-driven QAH regime at above-Kelvin temperatures [1] with dissipationless edge currents we uncovered in a dilute intrinsically-proximal magnetic Bi_2Te_3 where Mn ions self-organize into a superlattice of ferromagnetic monolayers. The eminently tunable topological electronic bandstructure of this system by the high energy electron beams [2] and thermal redistribution of vacancies provides a realistic platform for chiral superconducting state.

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Experimenting with free space electron vortices

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Vortex phenomena are fascinating areas of research in almost all fields of physics covering the range from the ultra-small to ultra-large. In this conference, vortices are often related to the quantum state that describes the phenomena of superconductivity in matter and lead to a rich set of experimentally observable phenoma and insights for designing new materials and devices.

In this talk, I will give an overview of experiments with vortex phenomena occurring in single electron quantum states of accelerated electrons in free space. We make use of a customized transmission electron microscope that serves as an electron-optical bench providing a beam of coherent single-electron states. Making use of a range of methods, we readily transform these electron states into states carrying a pre-defined orbital angular momentum (OAM) while still being able to localise them to the atomic scale. In this way we produce electron states that have similarities with electron states in atomic orbitals, having similar spatial extension and OAM properties. We explore the basic properties of such electron beams and demonstrate that many of the effects present in superconductivity, e.g. Landau levels, also occur here and lead to interesting possibilities to measure properties of materials interacting with such beams. Indeed, the selection rules for the scattering of vortex electron beams with atoms provides ways to measure magnetism in materials. Explorations in the role of the quantum state on the interaction with atoms and materials is currently pushing us into the direction of a versatile programmable phase plate for electrons, which will allow full control over the quantum state of the electrons and provide a way to prepare and project states onto any basis of choice. We will explore the potential for quantum measurements that this brings and compare the benefits with respect to more conventional measurement setups in the electron microscope.

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Soliton decay into vortices in superfluid Fermi gases

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Quantum gases offer the possibility to study the physics of topological excitations such as vortices and solitons in a very controllable environment. Since Bose condensates are well described by a nonlinear Schrödinger equation, they allow for solitons, i.e. solitary waves that preserve their shape while propagating. However, dark solitons (propagating as dips in the density) are known to decay in superfluid Bose gases through the snake instability mechanism, unless they are strongly confined. The resulting decay products are solitonic vortices. Recent experiments have extended the study of these objects to superfluid Fermi gases. Also here, soliton decay into vortices was observed. For the Fermi superfluids, we have developed an effective field theory describing the pair condensate with a macroscopic wave function [1] – this theory is the fermionic counterpart of the Gross-Pitaevskii equation for the Bose gases. We use this theory to demonstrate that there is a qualitative difference between the soliton decay in the BEC and BCS regimes for the Fermi superfluid. In the BEC regime of tightly bound pairs, one obtains the expected characteristic snaking deformations, induced by the amplitude fluctuations of the order parameter. However, in the BCS regime of weakly bound Cooper pairs, fluctuations of the phase destroy the soliton core through the formation of local Josephson currents [2]. We obtain these results not only in simulations based on the effective field method, but also through a small-amplitude perturbation analysis of the soliton order parameter. The latter allows to interpret the decay as a coupling of the (localized) soliton amplitude and phase modes to the Bogoliubov modes of the fermi superfluid. The Josephson mechanism identified in this work is qualitatively different from the snaking instability and the difference should be experimentally observable.

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Electron-hole superfluidity in 2D van der Waals heterostructures

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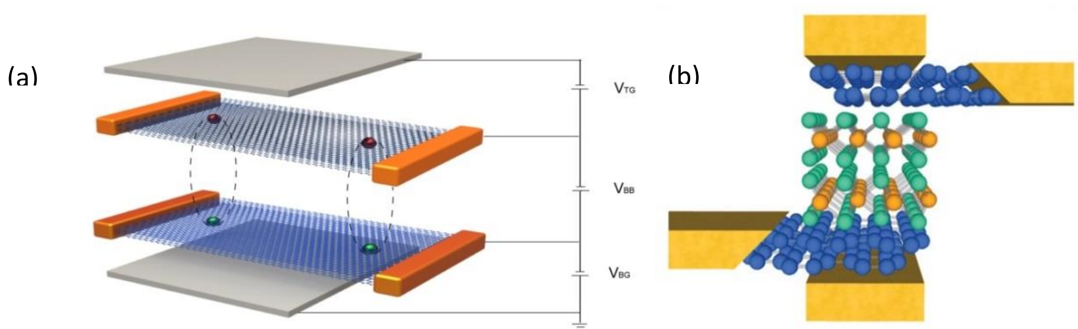
Now that 2D superfluidity in electron-hole double graphene bilayers has been observed [1] – in precisely the same system as had been theoretically proposed in Ref. [2] – there is potential for opening up a new field in vortex physics. This new field could be of particular interest to the vortex community, because some of the operating rules of this superfluid system differ strikingly from those for superconductivity. It is likely that the phenomenon will be found in many of the new van der Waals heterostructures.

Characteristics of this electron-hole superfluidity that differ markedly [2]-[5] from familiar superconducting systems are: (i) the long-range nature of the Coulomb pairing interaction makes screening a central feature of the phenomenon; (ii) by varying the carrier concentration from high density to low density, the strength of the coupling can be tuned continuously from weak-coupled BCS to strong-coupled BEC; (iii) in the strong-coupled BEC regime the compact pairs are nearly neutral; (iv) in the BCS-BEC crossover regime the pairs form dipoles that remain weakly interacting; (v) in what should be the weak-coupled BCS regime, strong screening kills the superfluidity.

I will go through these properties and then raise the question of what implications these unusual properties might have for vortices in these systems.



(a) Proposed system from Ref. [2]: electron-hole graphene bilayers with independent contacts and separated by 1 nm hBN insulator. Top and bottom gates tune the carrier densities
(b) Experimental system from Ref. [1]: e-h graphene bilayers separated by 1.4 nm WSe2 insulator.

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Vortex interactions and dynamics in polariton condensates

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We study numerically the motion of vortices in polariton condensates that are described by a generalized Gross-Pitaevskii equation. We analyze how the vortex properties are modified when moving away from equilibrium [1]. We find that far from equilibrium, the radial component dominates over the azimuthal one in the distribution of vortex currents at large distances from the vortex core. The modification of the current pattern has a strong effect on the vortex-antivortex interaction energy that can become entirely repulsive. The modified interaction energy affects the motion of vortices. For example, for moderate nonequilibrium, the trajectories of a vortex-antivortex pair are no longer parallel. For stronger nonequilibrium, the vortex motion becomes complicated, due to a self-acceleration mechanism: vortices are dragged by their slowly relaxing flow field.

We analyze the impact of the aforementioned, rather unusual vortex properties on the behavior of multivortex systems [2]. We show that at strong nonequilibrium the repulsion between vortices and antivortices leads to a dramatic slowdown of their annihilation. Moreover, in finite-size samples, relaxation of multivortex systems can lead to the formation of metastable vortex-antivortex clusters, whose shape and size depend on the sample geometry, boundary conditions and deviations from equilibrium. We further demonstrate that at strong nonequilibrium the interaction of self-accelerated vortices with inhomogeneous condensate flows can lead to generation of new vortex-antivortex pairs. Such a situation is realized, in particular, for vortices approaching sample boundaries. Another striking example is the appearance of two or more new vortex pairs as a result of a vortex-antivortex collision.

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Bose metal as a bosonic topological insulator

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Transport measurements of the superconductor-insulator transition (SIT) in disordered two-dimensional films and Josephson junction arrays showed the existence of an anomalous metallic phase that persists to low temperatures. The nature of this mysterious phase, often referred to as "Bose metal," remains unclear. We develop a gauge theory of the Bose metal as the phase in which Cooper pairs and vortices are out of the Bose condensate due to strong quantum fluctuations and form an incompressible liquid of intertwined Aharonov-Bohm-Casher loops. As a result, the Bose metal emerges as an integer (Z) bosonic topological insulator in which bulk transport is suppressed by topological mutual statistics interactions, the Hall resistance vanishes, and longitudinal charge transport is mediated by U(1)-symmetry-protected gapless edge modes. The transport measurements in NbTiN films across the disorder- and magnetic field-driven SIT and observe a disorder and magnetic field–tuned transition from a true superconductor to a metallic phase with saturated longitudinal resistivity.

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Superconductor-insulator quantum transition in 1D chains of superconducting islands

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A quantum phase transition (QPT) is a ground-state transition occurring at zero temperature and caused by tuning a critical parameter which changes the Hamiltonian and generates a discontinuous modification of the ground state of the system. Yet, if an effective Hamiltonian is applicable, which includes some temperature-dependent parameters, then a temperature-controlled quantum transition (TC-QPT) can occur. Here we present a TC-QPT between superconducting and insulating regimes in a chain of weakly coupled superconducting islands. The transition appears at a temperature where the Josephson energy equals the effective Coulomb charging energy, defined by the capacitance between the islands. The insulating state is manifested by a resistance peak, characterized by an exponential growth of resistance with cooling, while the superconducting state is represented by an exponential drop of the resistance with cooling. A scaling analysis is presented, which takes into account the temperature-dependent critical parameter of the observed TC-QPT.

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Imaging phase transitions with scanning SQUID

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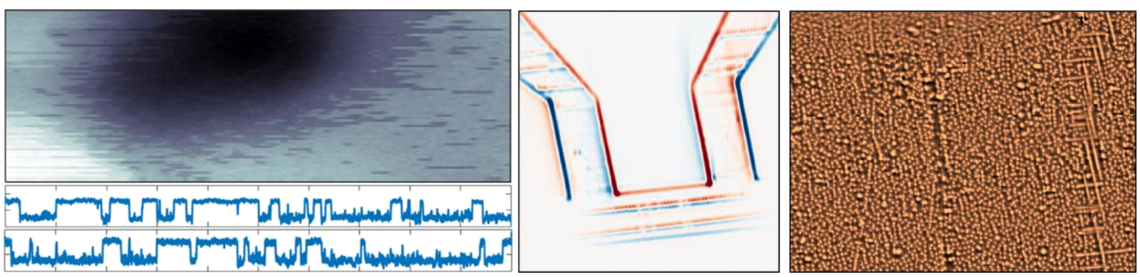
Close to critical points, systems become susceptible to small perturbations, such as defects and disorder. Understanding how these perturbations affect the system near the transition, is key to understanding the underlying electronic phases involved.

I will describe how we use sensitive magnetic imaging to track the spatial distribution of electronic states in systems undergoing phase transitions. Near the superconductor-insulator transition in NbTiN we use scanning superconducting quantum interference device (SQUID) susceptometry to track superconducting fluctuations and detect non-trivial behavior near the quantum critical point. Near the metal to insulator transition at the 2D $LaAlO_0/SrTiO_3$ interface we use SQUID magnetometry and identify how different types of defects control the current distribution near the transition.



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A new superconductor in spinel oxides

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Spinel compounds have demonstrated rich functionalities but rarely shown superconductivity. $LiTi_2O_4$ (LTO) discovered in 1973 was the only known spinel oxide superconductors [1].Owing to a serious aging effect, not until stabilized LTO films were obtained did the research on this unique compound experience a renaissance. Several years ago we were able to synthesize high-quality LTO thin films, assisting in understanding the nature of this material. For instance, we find that there exists an orbital-related state above the superconducting transition, which may persist into the superconducting state, evident from the unusual relation between the energy gap and the magnetic field [2]. Such superconductor becomes more and more attractive because of its anomalies in el-ph coupling [3,4], magnetoresistance [5], and the upper critical field [6], but meanwhile, its sister material has been highly desired. In this talk, I will briefly review these achievements on LTO and then report our discovery of a spinel oxide superconductor, which was known to be a robust insulator. The superconductivity emerges by piling such material on top of another insulator and engineering the crystal lattice. The superconducting transition temperature can be tuned as the crystal lattice parameter is manipulated. In a word, the spinel oxide is providing a good platform to investigate the interplay between the superconductivity and other exotic states.

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Abrikosov vortex as a Josephson phase shifter

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Growing power consumption in supercomputers is becoming an increasing problem. For an exaflop computer it is predicted to be on a 100 MW level [1]. Management of such a power would be very difficult for the present semiconductor-based technology. The corresponding maintenance costs exceed the cost of refrigeration to cryogenic temperatures. Therefore, efforts are taken for development of superconducting computers, which would not only drastically decrease the consumed power, but could also greatly increase the operation speed [2]. Lack of suitable cryogenic random access memory (RAM) is the "main obstacle to the realization of high performance computer systems and signal processors based on superconducting electronics" [3].

Superconducting electronics usually operates with the phases of wave functions of the superconducting condensate. Abrikosov vortex is a robust topological object in a superconductor with a 2π phase rotation. This phase rotation can induce a Josephson phase shift in a nearby Josephson junction. We demonstrate that the phase shift is close to the polar angle of the vortex within the junction length [4]. When the vortex is close to the junction it induces a π-step in the Josephson phase difference, leading to a controllable and reversible switching of the junction into the 0-1 state. The vortex may hence act as a tunable‘‘phase battery’’ for quantum electronics as well as a memory bit.

Non-volatile quantized states are ideal for realization of classical Boolean logics. A quantized Abrikosov vortex (AV) represents the most compact magnetic object in superconductors, which can be utilized for creation of high density digital cryo-electronics. In this talk I will describe our recent efforts towards creation of a novel AVRAM memory cell, in which a single Abrikosov vortex is used as an information bit [5]. We demonstrate high endurance write operation and two different ways of readout using a spin valve or a Josephson junction. AVRAM cells are characterized by an infinite magnetoresistance between 0 and 1 states, a short access time, a scalability to nm sizes and an extremely low write energy 10^{-18} J/bit. Non-volatility and perfect reproducibility are inherent for such a device due to the quantized nature of the vortex.

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Comparative study of dissipation in ferromagnetic Josephson junctions

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Josephson coupling between two superconductors (S) and a ferromagnet (F) has been shedding light on the 'interplay and cooperation' of two competing ordered phases in these two last decades [1,2]. More recently there is a growing awareness that these devices may provide new solutions for superconducting electronics and quantum circuits.

We will carry out a comparative study of different types of Josephson junctions employing ferromagnetic barriers with a special focus on their dissipation and electrodynamic properties down to the lowest temperatures. A consistent picture emerges from the comparison of the phenomenology of ferromagnetic Josephson junctions where the barrier is composed by pure metallic ferromagnetic layers (SFS), or by an insulating barrier and a ferromagnetic metallic layer (SIFS), or by a ferromagnetic-insulator barrier (SIFS) [3-5] respectively. Low temperature properties of the junctions are particularly revealing. Measurements of switching current distributions allow to identify different transport mechanisms and to classify dissipation regimes. This study provides the electrodynamic characterization [3-5] necessary for the possible use of these systems in more complex circuits, as cryogenic memories or spintronic devices, and suggests new solutions of hybrid JJs in superconducting qubits.

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Nanoscale devices fabricated by focused ion beam irradiation of $YBa_2Cu_3O_7$ thin films

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Recent advances in focused ion beam (FIB) techniques have opened new opportunities for nanoscale milling and local modification of thin film superconductors. We present various FIB-based approaches to produce devices in thin films of the cuprate superconductor $YBa_2Cu_3O_7$ (YBCO). By Ga FIB milling, we fabricated YBCO nanoSQUIDs on bicrystal substrates with ultra-low flux noise in the thermal white noise limit [1]. Such devices offer detection of magnetization reversal processes in individual magnetic nanoparticles or nanowires [1-3]. By He FIB irradiation, it is possible to locally drive YBCO from the superconducting to the insulating state, with high spatial resolution, and hence to “write” Josephson barriers into thin films [4]. We present here a comprehensive analysis of the electric transport properties at 4.2 K of He-FIB produced YBCO Josephson junctions [5]. The critical current density j_c can be adjusted by irradiation dose D, with an exponential decay of $j_c(D)$. A transition from flux-flow to Josephson behavior occurs when j_c decreases below ~2 MA/cm^2. For Josephson devices we find an approximate scaling of the characteristic voltage $V_c \propto j_c^{1/2}$, and current-voltage characteristics that are well described by the resistively and capacitively shunted junction model, without excess currents for $V_c < 1$ mV. The He-FIB technique provides the possibility to place junctions at arbitrary location, with different orientation and shape, and even with different j_c on the same chip. Moreover, He-FIB irradiation with high dose produces highly resistive walls or areas. We used this feature to produce dc SQUIDs with sub-µm loop sizes and very low flux noise. Altogether, the He-FIB technique provides a promising tool for nanoscale patterning of advanced devices, e.g. Josephson junction arrays, in YBCO thin films.

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Andreev reflection and electron interference in graphene/high-temperature superconductor junctions

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Proximity-induced superconductivity is particularly interesting in graphene. Among other reasons, because that effect can be externally controlled by tuning the Fermi energy (and vector) via electrical gating.

In this talk, we will discuss two examples of that, based on transport experiments in high-temperature superconductor $YBa_2Cu_3O_7$/graphene planar junctions.

Fist we will describe gate-controlled superconducting electron interferences that allow modulating the Andreev reflection at the superconductor/graphene interface via Klein tunnelling of electron/hole pairs. [1]

Second, we will discuss experiments in the same type of junctions, in which a different type of interferences –this time controlled by the bias voltage– are observed which are due to geometrical resonances and coherent propagation of electron/hole pairs across a graphene channel. This is substantiated by the relationship of the oscillations period and the graphene channel length (up to hundreds on nm), as well as by numerical simulations of the device conductance -which reproduce both the observed resonances and the background conductance.

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Vortex like pair of zero mode states in a 2D topological superconductor

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The examination of supposedly well-known condensed matter systems through the prism of topology has led to the discovery of new quantum phenomena that were previously overlooked. Just like insulators can present topological phases characterized by Dirac edge states, superconductors can exhibit topological phases characterized by Majorana edge states. In particular, one-dimensional topological superconductors are predicted to host zero energy Majorana fermions at their extremities. Zero bias anomalies localized at the edge of proximity induced superconducting wires were recently interpreted as fingerprints of the emergence of topological superconductivity [1,2].

By contrast, two-dimensional (2D) superconductors have a one-dimensional boundary which would naturally lead to propagating Majorana edge states characterized by a Dirac-like dispersion. We have recently observed some hint of dispersive Majorana edge states in a single atomic layer Pb superconductor. This material has strong triplet correlations but is not topological by itself [3]. We will show that by applying a Zeeman field with the help of a buried Co-Si nano-magnet one can provoke a transition to a topological state [4].

In addition to their dispersive edge states, 2D topological superconductors are also supposed to support localized Majorana bound states in their vortex cores. However in addition to zero energy states one usually get also a very large amount of Caroli-Matricon de Gennes states that fill the gap. However we will show that one can find vortex like phase defect in a U(1) gauge field that induce zero energy Majorana bound states without additional low energy states. In particular, our recent calculations predict that a phase defect in the spin-orbit field can lead to the formation of energetically isolated pairs of Majorana zero mode in a hard gap of a 2D topological superconductor. Our recent measurements seem to support this theoretical prediction [5].

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Vortex bound states and Majorana mode in $FeTe_{0.55}Se_{0.45}$ and $Bi_2Te_3/FeTe_{0.55}Se_{0.45}$ hetero-structures

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Topological superconductor is a timely and frontier topic in condensed matter physics. By measuring the spatial evolution of tunnelling spectra on the surface of $FeTe_{0.55}Se_{0.45,}$ we observed the long sought discrete Caroli-de Gennes-Matricon bound states[1] within some vortex cores. By analyzing the energies of the lowest level and the interval between the energy levels, we found that the iron based superconductor $FeTe_{0.55}Se_{0.45}$ has the shallow band with the Fermi energy of about 5-20 meV, indicating the possibility of a crossover from BEC-BCS. Furthermore we have measured the vortex core bound states on many other vortices in different areas and/or different samples, and found that, in some vortices there is a strong bound state peak locating at zero energy. With the rather symmetric shape at the gap edge, we would conclude that it may correspond to the Majorana mode[2]. With increase the magnetic field, the zero energy mode of the vortices locating at the same position is systematically suppressed. Meanwhile, we also find that the probability of observing the zero energy mode decreases with increasing the magnetic field. We find no clear connection between the surface concentration of Te/Se ratio. By increasing temperature, the zero energy mode is suppressed quickly and merged into the side peak in the occupied state at about 4K.

We deposit Bi_2Te_3 thin film on the $FeTe_{0.55}Se_{0.45}$ substrate and get the proximity induced superconductivity. By using the quasiparticle interference technique, we demonstrate clear evidence of twofold symmetry of the superconducting gap. The gap minimum is along one of the main crystalline axis following the so-called Δ_{4y} notation. This is also accompanied by the elongated vortex shape. Within the vortex core, along the stretched direction, a zero energy peak appears and stays until going out of the vortex. Our results reveal the direct evidence of superconductivity with two-fold symmetry in Bi_2Te_3 thin film[3] .

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Majorana zero mode in the vortex core of iron-based superconductor

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The Majorana zero modes (MZM) in many topological superconductors are often not clean or robust, due to the necessity of impurities or large Fermi energy, which hampers further manipulations of Majorana fermions. Using scanning tunneling spectroscopy, we found that a zero-bias conductance peak (ZBCP) well separated from the other discrete Caroli-de Gennes-Matricon states exists ubiquitously in all cores of free vortices in the defect free regions of $(Li_{0.84}Fe_{0.16})OHFeSe$, which has a superconducting transition temperature of 42 K. Moreover, a Dirac-cone-type surface state is observed by angle-resolved photoemission spectroscopy, and its topological nature is confirmed by band calculations. The observed ZBCP can be naturally attributed to a MZM arising from this topological surface states of a bulk superconductor. $(Li_{0.84}Fe_{0.16})OHFeSe$ thus provides an ideal platform for studying MZMs and topological quantum computing. [1]

On $FeSe/SrTiO_3$, we show that neither MZMs exist in the vortex cores nor do they show up on the iron impurities, which suggests the band inversion along k_z is critical for the realization of topological superconductivity in FeSe based systems. [2]

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Quantum Transport Properties in Topological Semimetal $PtBi_2$ and pressure-induced multiband superconductivity

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We report the angular-dependent magnetoresistance measurements on $PtBi_2$ single crystal under high magnetic fields and pressure. The crystals exhibit extremely large unsaturated magnetoresistance (XMR) up to 1.2×10^6 % at T=1.8 K in a magnetic field of 33 T and significant Shubnikov–de Hass quantum oscillations with a nontrivial Berry phase. The ab initio calculations suggest that pyrite $PtBi_2$ is a topological semimetal. When the crystal was applied a high pressure, a pressure-induced superconductivity was found at $P_c \sim 13$ GPa with an onset critical temperature T_c of ~2.2 K. Upon further compression, T_c remains almost unchanged up to 50.0 GPa; No evident trace of structural phase transitions is detected through synchrotron x-ray diffraction over the measured pressure range of 1.5–51.2 GPa. These results highlight a multiband characteristic of the observed superconductivity, making pyrite $PtBi_2$ unique among the compensated XMR materials where the pressure-induced superconductivity usually links to structural transitions and carrier imbalance.

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Electronic properties of vortex matter in nanostructured and hybrid superconducting systems

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We report on the results of our recent theoretical studies of the electronic structure of vortex states in various nanostructured and hybrid superconducting (S) systems in the context of their applications in quantum computing and single electronic devices.

In particular, we show that the semiconducting (Sm) nanowires fully covered by a thin S shell trapping vortices in an external magnetic field host an unusual modification of the subgap Caroli - de Gennes - Matricon (CdGM) quasiparticle (QP) states. The spectrum of these modes propagating along the vortex axis is strongly affected by the interplay of spin-orbit coupling inside the nanowire and the normal and Andreev reflections at the SmS interface. This interplay increases the group velocity of the CdGM states along the vortex line and transforms them into the waveguide type modes with quite exotic behavior. We study such CdGM waveguides within the framework of the Bogoliubov - de Gennes theory and predict a number of fascinating phenomena such as the giant oscillations of the CdGM levels, the closure and reopening of the hard gap in the QP spectrum controlled by the vortex entry/exit and the formation of the Majorana-type evanescent modes bound to the nanowire ends.

Focusing then on the dirty limit we consider the electronic structure of the giant vortex states in a mesoscopic superconducting disk using the Usadel approach. The local density of states profiles are shown to be strongly affected by the effect of QP tunneling between the states localized in the vortex core and the ones bound to the sample edge. Decreasing temperature leads to a crossover between the edge-dominated and core-dominated regimes in the magnetic field dependence of the tunneling conductance. This crossover is discussed in the context of the efficiency of quasiparticle cooling by the magnetic-field-induced QP traps in various mesoscopic superconducting devices.

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Particle-hole crossover in the vortex cores of the multiband superconductor $FeTe_{0.55}Se_{0.45}$

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The Abrikosov vortices in type-II superconductors have unique position-dependent spectral signatures, which can be probed with the scanning tunneling microscope. In the quantum regime, where the size of the vortices is comparable with the Fermi wavelength, the theory predicts experimentally resolvable discrete levels in the vortex cores for superconductors without nodes in the order parameter. Recent experiments [1, 2] have reported vortex spectra with discrete levels for the iron-chalcogenide $FeTe_{0.55}Se_{0.45}$. This low-density multi-band system with nearly compensated electron and hole carriers realizes the quantum regime and is furthermore microscopically disordered, which is expected to affect the vortices due to their small sizes. We present a microscopic multi-band tight-binding model to describe $FeTe_{0.55}Se_{0.45}$ and investigate the discrete vortex-core states [3]. We determine their angular momenta and observe a crossover from hole-like to electron-like behavior with increasing energy, a feature that is impossible in single-band systems. We also find that the vortex properties are only weakly affected by the chemical disorder and we study how the observed disorder in vortex positions influences the vortex-core spectroscopy.

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Local electronic states around a vortex near the surface in inclined magnetic fields

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Vortex structures and the local density of states are theoretically studied near the surface plane (z=0) in type-II superconductors when the magnetic field orientation is inclined θ away from the z-axis. In the inclined magnetic field orientation, the observation of STM experiment suggested a vortex line bending near the surface [1] . In 2H-$NbSe_2$, STM experiment by Hess *et al.* reported the distortion of the star-shaped vortex core image to a "spiky comet shape" when the magnetic field orientation is tilted into the surface plane [2].

In this study, the calculation method of self consistent Eilenberger theory is developed for the studies of vortex states near the surface under the inclined fields, assuming specular reflection of quasiparticles at the surface. The calculation is performed for six-fold symmetric anisotropic s-wave pairing as a model of 2H-$NbSe_2$, which reproduces a star-shaped vortex core image in the local density of states [3]. After the self consistent calculation of the pair potential and the quasiparticle states, in the spatial structure of the pair potential $\Delta(\boldsymbol{r})$, a vortex line bending occurs near the surface under the inclined magnetic fields as shown in Fig. 1. There, the tilt angle of the vortex line becomes smaller with approaching the surface. In the calculation of the local density of states $N(E,\boldsymbol{r})$ at the surface, we will discuss how the star-shaped vortex core image [3] is changed by inclining the magnetic field orientation.

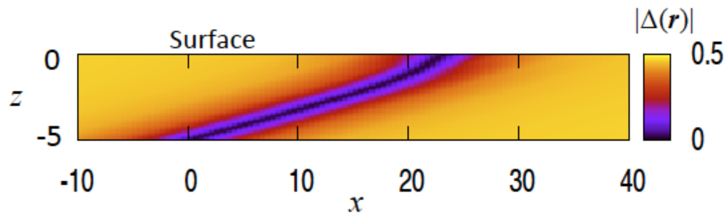

FIG. 1. Density plot of the pair potential's amplitude $|\Delta(\boldsymbol{r})|$ in the x-z plane. The surface is located at the plane z=0. The magnetic field is inclined θ =80º away from the z axis. Dark region of the vortex core shows a vortex line bending near the surface.

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A "BCS flavour" from Vortex Cores in a high T_c Cuprate Superconductor

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Most of the observations made by scanning tunnelling spectroscopy (STS) in the vortex cores of high-temperature cuprate superconductors (HTCS) have revealed unusual features. At first sight, these measurements suggest that the cores in these materials do not match BCS expectations: while vortices in Bi-based HTCS compounds reveal a pseudogap-like quasiparticle DOS, $YBa_2Cu_3O_{7-\delta}$ (Y123) cores exhibit a pair of electron-hole symmetric states at finite subgap energy [1]. The absence of a clear zero-bias anomaly in the conductance spectra was apparently in total contradiction with the expected signature of a d-wave BCS vortex core, raising many interrogations about the true electronic nature of the cores in these compounds.

In recent STS experiments on Y123, we found that the subgap states are not a specific signature of the vortices, but belong to an electronic background uniformly measured across the surface, whether a magnetic field is applied or not [2]. This finding led us to consider a model where the total tunnelling current is the combination of two additive channels: one associated with the quasiparticle excitations of a *d*-wave superconductor, and the other corresponding to a non-superconducting background. Comparing our data with theoretical model based on a Bogoliubov-de Gennes framework, we demonstrate that the vortex cores in Y123 really present the expected BCS quasiparticle LDOS [3]. The model provides further insight into the vortex-core structure, which is different for each vortex due to an irregular lattice and depends on the Fermi surface topology more than on the gap symmetry.

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Putting charge-vortex duality to work in spintronics

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I will discuss two different but related problems that concern vortex dynamics in the context of spintronics. First is a proposal of nonlocal spin transport mediated by a vortex liquid in superconductors [1]. Departing from the conventional view on superconducting vortices as a parasitic source of dissipation for charge transport, we propose to use mobile vortices as topologically stable information carriers. In particular, we show that a superconducting vortex liquid can serve as a spin-transport channel between two dynamic magnetic insulators by encoding spin information in the vorticity. Secondly, we extend the idea of the topological vorticity transport to Heisenberg magnets, which allows us to envision functional vortex-based circuits based entirely on magnetic insulators [2].

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Vortex in superconductors grown by Focused Ion Beam Induced Deposition

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Focused Ion Beam Induced Deposition (FIBID) using a Ga^{+} FIB source and $W(CO)_6$ precursor gas permits the growth of W-C superconducting (nano)structures with T_C of 5 K [1], which have been used in the past to investigate the Abrikosov vortex phase diagram [2] and the interaction of the vortex lattice with built-in periodic pinning potentials [3]. When the lateral dimension of FIBID-grown W-C nanowires is 50 nm, a re-entrance of superconductivity as a function of field is observed, arising from vortex confinement [4]. As will be shown in the present contribution, in such narrow nanowires, long-distance (10 μm) non-local vortex transportation has been found [5], with potential for applications based on individual vortex manipulation. On the other hand, we have recently shown that FIBID using a He^{+} FIB source and $W(CO)_6$ precursor gas permits the growth of W-C superconducting nanotubes with T_C of 6.4 K and tunable inner and outer diameters [6]. The He^{+} FIB source, with a better resolution than the Ga^{+} FIB source, allows the growth of smaller superconducting nanostructures by FIBID and non-local vortex transportation is also observed, opening new perspectives in the field [7].

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Photon triggered instability of the flux flow regime in strongly disordered superconducting strip

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We theoretically study single photon response of strongly disordered thin superconducting strip (with short electron-electron inelastic scattering rate) being in the flux flow state. We find that the jump from the resistive (flux-flow) state to the normal one at the current I larger than the critical one Ic could be triggered by absorption of the single optical photon. The absorbed photon creates the belt-like region with suppressed superconductivity and fast moving Josephson-like vortices across the strip. The formed Josephson-like link is unstable in such kind of superconductor and evolves in the normal domain which expands along the superconducting strip, leading to its transition to the normal state.

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Vortex Dynamics on Superconducting and Non-superconducting Arrays

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Superconducting vortices are robust topological defects which allow studying a lot of distinct topics and scenarios. Vortex lattice on the move is a powerful tool to probe superconducting materials. In this talk we focus on the outcomes that arise when the vortex lattice moves on array of defects. Vortex lattice dynamics on non-superconducting arrays has led to very interesting physics and a flood of papers, the field seems to be almost exhausted. Conversely, the reversed situation, when the array of defects is made of superconducting materials, has called the attention of a few experimental researchers [1-3]. We have tackled this topic studying vortex dynamics of hybrids samples which have been made of arrays of superconducting niobium triangles embedded in superconducting vanadium films. In these samples, the superconducting critical temperature of the array is higher than the superconducting critical temperature of the plain film. We will show and explore the main findings of vortex dynamics on this peculiar system. In brief: i) strong anomalies in the well-known commensurability effects between the vortex lattice and the array unit cell, ii) enhancement of the vortex liquid phase, iii) unexpected behaviour of the matching effects angular and temperature dependences.

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Nematicity in iron-based superconductors from ARPES

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Nematicity plays an important role in the physics of iron-based superconductors (IBS). Its microscopic origin and in particular its importance for the mechanism of high-temperature superconductivity itself are highly debated. A crucial knowledge in this regard is the degree to which the nematic order influences the electronic structure of these materials. Earlier angle-resolved photoemission spectroscopy (ARPES) studies found that the effect is dramatic in three families of IBS including 11, 111 and 122 compounds: energy splitting reaches 70 meV and Fermi surface becomes noticeably distorted. More recent experiments, however, reported significantly lower energy scale in 11 and 111 families, thus questioning the degree and universality of the impact of nematicity on the electronic structure of IBS. Here we revisit the electronic structure of undoped parent $BaFe_2As_2$ (122 family). Our systematic ARPES study including the detailed temperature and photon energy dependencies points to the significantly smaller energy scale also in this family of materials, thus establishing the universal scale of this phenomenon in IBS. Our results form a necessary quantitative basis for theories of high-temperature superconductivity focused on the nematicity [1]. Intriguingly, it may turn out that the former causes the latter [2].

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Frustration and fluctuations in FeSe: A Raman scattering study

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FeSe, the simplest of the iron based superconductors, is a puzzling material. As opposed to the related iron pnictides and FeTe, no long range magnetic order is found down to lowest temperatures. Here, we use Raman scattering as a function of temperature and polarization to probe charge and spin dynamics in FeSe. In agreement with numerical simulations of a spin-1 Heisenberg model several peaks in all Raman active symmetries can be assigned to spin excitations. The dominating feature is a peak in B_{1g} symmetry around 500 cm^{-1} which shows distinct temperature dependence. Further comparison of the simulations to neutron scattering data furnishes evidence for FeSe hosting nearly frustrated stripe order of local spins.

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Synthesis and physical properties of $FeSe_{1-x}Ae_x$ (A=Te, S) epitaxial films

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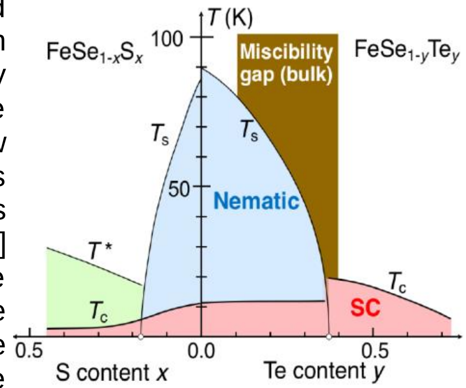

Fig. 1 Experimentally obtained phase diagram of Fe chalcogenide film

Fe chalcogenides, $FeSe_{1-x}A_x$ (A=Se and S) have focused attention, because of (1) large increase of T_c by the application of pressure, intercalation, *etc*, (2) high T_c superconductivity (SC) in ultrathin films on some oxide substrate, (3) possible BCS-BEC crossover, and (4) absence of magnetic order at low temperatures. Previously, we succeeded in preparing a series of $FeSe_{1-x}A_x$ thin film samples (A=Te, S) with different *x* values for wide range of Te concentration, *x* (typically $0<x<1.0$)[1,2] (bulk Te substituted material cannot be synthesized because of the phase separation), and found that T_c behavior at the orthorhombic–tetragonal (O-T) phase boudary is contrastive (Fig. 1)[2]. This casts a serious question on the role of the nematic fluctuation on SC. We have investigated various physical properties both in the normal state and in the SC state, such as resistive transition under finite magnetic fields[3], ARPES, optical, THz and microwave conductivity, Nernst effect, *etc*. Detailes will be discussed in the wrokshop. In S substituted film samples in the tetragonal phase, another anomaly at *T*" takes place[3], which we consider is due to the antiferromagnetic transition. What is surprising is that the T_c vs *x* behavior is almost similar between bulk crystals and epitaxial films for S-substituted case. This might also suggests that the antiferromagnetic fluctuation does not affect SC. Thus, the key factor to determine T_c of Fe chalcogenides is becoming of central interest. To answer this question, we investigated the magneto-resistivity and Hall effect[4]. The results show that the carrier concentration is a key factor dominating T_c in all cases. This is in accordance with our previous results on film samples with different degree of lattice strain[5]. These results also provide an important clue to another key question on SC of Fe chalcogenides; What are different among three different classes of SC in these materials?; (1) 25-30 K class in our films and pressurized bulk crystals, (2) 50 K class in the EDLT structure[6] and also c-axis elongated materials, and (3) 65 K (or more) class reported in ultrathin film samples.

We also investigate SC fluctuation. Our microwave conductivity result[7] and a recent torque magndetometry result[8] show that SC is just large in the conventional GL sense, and not so anomalous in FeSe and Fe(Se,Te).

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Transport properties and flux pinning analysis of high-performance $Ba_{0.6}K_{0.4}Fe_2As_2$ superconducting tapes

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Iron-based superconductors (IBS), especially 122 type, are very promising candidates for high-field applications because of its ultrahigh H_{c2} > 70 T at 20 K, low anisotropy (γ < 2 for 122) , and ease of fabrication. Recently, significant progresses on the IBS wires have been made in terms of Jc enhancement, e.g., the highest transport J_c values have achieved 0.15 MA/cm^2 (I_c = 437 A) at 4.2 K and 10 T in densified and textured 122 tapes. The transport J_c measured at 4.2 K under high magnetic fields of 27 T is still on the level of 55 kA/cm^2. Herein we compared the T_c and J_c distributions of K-doped FeAs122 tapes by a calorimetric method. We found that hot-pressing provides a better environment for a complete chemical reaction and a more homogenous dopant distribution, which are beneficial to the global current of a superconductor. We further study the vortex dynamics of the hot-pressed high-Jc tapes. We found that magnetization relaxation rate below 10 K shows a temperature insensitive plateau with a value comparable to that of low temperature superconductors. Moreover, the relaxation rate below 20 K tends to saturate with the increasing field which is beneficial for high field application. Our results indicate that the high-performance K-doped FeAs122 tapes have promising potential to be applied not only in liquid helium, but also in liquid hydrogen or at the temperature accessible with cryocoolers.

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Interplay of weak collective and strong pinning regimes in iron based superconductors tuned by disorder

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Irreversible magnetization of almost all iron based superconductors exhibits ubiquitous magnetic field dependence commonly attributed to superposition of currents arising from distinct types of vortex pinning:

(1) Strong pinning regime giving rise to star shaped hysteresis loop with $1/\sqrt{B}$ variation of the critical current [1].

(2) Second peak at higher magnetic fields originating from weak collective pinning [2].

In exceptionally clean materials ($Ba(FeAs_{1-x}P_x)2$, $CaK(FeAs)_4$) second contribution may be small and hard to detect. Introduction of point defects by low temperature 2.5-MeV electron irradiation leads to increase of weak collective pinning contribution and emergence of second magnetization peak. Low temperature heavy ion irradiation producing correlated disorder leads to ultimately strong pinning and localisation of vortices in form of Bose-glass. To illustrate the effect of modification of pinning landscape, I will present a systematic study of pinning and creep measured on pristine and irradiated $Ba_{1-x}K_xFe_2As_2$ and $CaK(FeAs)_4$ crystals.

We found that weak collective and strong pinning are not simply additive contributions. The introduction of point disorder lowers not only critical temperature but reduces condensation energy and strong pinning by large defects. Magnetic relaxation was measured by miniature Hall sensor array on pristine and irradiated samples. Separation of pinning contributions based on the analysis of flux creep [3] was attempted. However, the sustainable currents accessed in real experiments on iron-based superconductors are close to ½ of J_c, far from regime of $J<<J_c$ common in high T_c cuprates. This requires careful analysis of range of applicability of models developed for the later regime [4].

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Flux pinning and vortex dynamics of iron-based superconductors

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Investigation of vortex pinning and its dynamics is of great importance for both the microscopic physics and technological applications in the field of superconductivity. In this talk, we will discuss some of our results on vortex physics of two distinct systems of iron-based superconductors (IBSs), $Ca_{0.8}La_{0.2}Fe_{0.978}Co_{0.022}As_2$ (FeAs-112-type) [1] and $Li_{0.8}Fe_{0.2}$OHFeSe (FeSe-11111-type) [2]. The magnetization hysteresis loop exhibits a pronounced second peak effect in $Ca_{0.8}La_{0.2}Fe_{0.978}Co_{0.022}As_2$ while it is absent in $Li_{0.8}Fe_{0.2}$OHFeSe. Detailed analyses suggest that the second peak is strongly associated with a crossover from elastic to plastic vortex creep. To better understand the second peak phenomenon, related physical scenarios as well as the affecting factors in the second peak occurrence are demonstrated (Figure (a)-(c)). Besides, the obtained creep exponent μ based on the collective creep theory is ~1.21 in $Ca_{0.8}La_{0.2}Fe_{0.978}Co_{0.022}As_2$, which is close to many other IBSs. But the value of μ in $Li_{0.8}Fe_{0.2}$OHFeSe is found to be ~4.1 much larger than the predicted maximum value. Such a large value of μ may be originated from the weakening of coupling between the vortices in neighboring layers by elongating the layer distance. It may indicate that the vortex structure of $Li_{0.8}Fe_{0.2}$OHFeSe is in the crossover regime between elastic Abrikosov vortices to stacks of pancake vortices. Finally, the flux pinning mechanism and vortex phase diagram of both systems are also discussed.

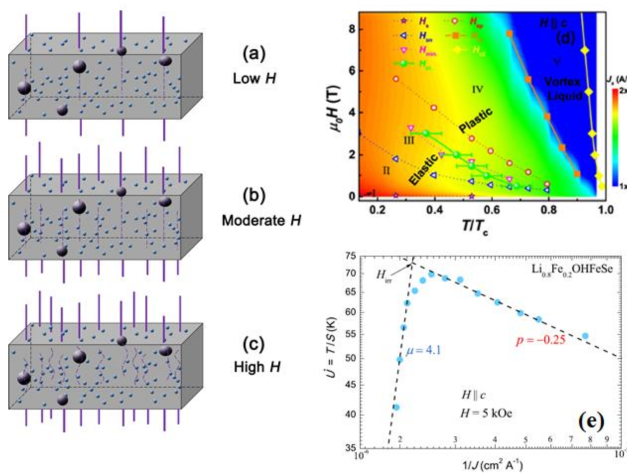

Figure caption: (a)-(c) The schematic diagrams for the vortex configurations under low, moderate, and high field. (d) Vortex phase diagram of $Ca_{0.8}La_{0.2}Fe_{0.978}Co_{0.022}As_2$ with various characteristic *H*(T). (e) Inverse current density dependence of effective pinning energy U^* at 5 kOe in $Li_{0.8}Fe_{0.2}$OHFeSe single crystal.

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Disorder induced lowering of vortex dimension in Pnictide superconductor and precipitation of thermal melting of a dilute vortex solid phase

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Abstract body: Theoretically the vortex state is expected to melt at both, low and high magnetic fields at a fixed temperature [1,2]. While the high field melting has been extensively investigated in high Tc cuprates, the low field melting phenomena in presence of disorder hasn't been well explored. Using bulk magnetization measurements and high-sensitivity differential magneto-optical imaging technique we detect a low-field vortex melting phenomenon in a single crystal of Ba0.6K0.4Fe2As2 [3]. The low-field melting is accompanied with a significant change in local magnetization ~ 3 G, which decreases with increasing applied field. The observed vortex solid to liquid transformation phenomena is traced on a field temperature phase diagram and its behavior is shown to be partially obeying the theoretical Lindemann-criterion based low field vortex melting line equation. Our analysis shows a Lindemann number cL = 0.14 associated with the low field melting. Imaging of low-field vortex melting features shows the process nucleates via formation of extended finger like projections which spread across the sample with increasing field or temperature, before entering into an interaction-dominated vortex solid phase regime. Magnetization scaling analysis reveals that the dimensionality of the vortices which melt, is close to one. Angular dependence studies of bulk magnetization hysteresis loop in the sample, shows the presence of extended defects. From our studies, we propose the sample contains a peculiar geometry of extended defects arranged in a plane in the sample, with these planes extending through the sample thickness. In the weak intervortex interaction limit, we argue that reduced vortex dimensionality due to pinning by these peculiar extended defect planes strongly enhances thermal fluctuations. Thus it is the effect of disorder, viz., the confining effect of extended defects planes in the crystal which lowers the vortex dimension, inturn triggering a low field melting in the pnictide superconductor [3].

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Unveiling the Vortex Glass Phase in the Surface and Volume of a Type-II Superconductor

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Order-disorder transitions between glassy phases are quite common in nature and yet a detailed description of the structural changes entailed at microscopic scales remains elusive. This issue is experimentally challenging since scales are typically tiny, constituents move rapidly, and few of them, in most cases, take part in the structural transformation. Vortex matter in type-II superconductors is a playground where some of these difficulties can be tackled by conveniently choosing the host superconducting sample. $Bi_2Sr_2CaCu_2O_{8+y}$ is a paradigmatic type-II superconductor presenting a glassy-to-glassy first-order transition between the Bragg and the vortex glass phases on increasing vortex density (magnetic field). The structural properties of the quasicrystalline Bragg glass have been extensively studied, but in the case of the vortex glass phase this information has remained elusive up to now. Here we image with single-vortex resolution the structural changes occurring at this order-disorder transition and reveal large field-of-view snapshots of the vortex glass phase. By combining real-space surface magnetic decoration and reciprocal-space bulk small-angle neutron scattering imaging techniques we found that this phase presents large crystallites with a proliferation of bounded and unbounded edge dislocations at the surface. Within the crystallites, the exponentially decaying orientational order and the fast-algebraic growth of the positional displacement correlator are at odds with a hexatic phase. In addittion, in the vortex glass the radial and azimuthal in-plane correlation lengths are depleted at the surface as well as at the volume of the sample. Nevertheless, no dramatic change in the correlation length along the direction of vortices is observed within our improved experimental resolution, ruling out the possibility of the vortex glass being a glassy phase with layered vortices internally decoupled along the thickness of the sample.

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Proximity effects in noncentrosymmetric-superconductor/ferromagnet hybrids

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It is established theoretically that in the presence of spin orbit coupling (SOC) and a Zeeman field, unconventional pairing correlations can arise at an s-wave spin-singlet superconductor interface. For example, SOC in combination with a ferromagnetic exchange field is predicted to generate long-range spin-triplet pairs at a superconductor/ferromagnetic (S/F) interface [1,2]. Recent experiments have investigated these predictions in devices containing Pt [2-4].

Here we present experiments involving the proximity-coupling between the non-centrosymmetric superconductor $Nb_{0.18}Re_{0.82}$ (NbRe) [5,6], which has large intrinsic SOC, and the strongly ferromagnetic transition metal Co. Transmission electron microscopy confirms single phase growth of sputter-deposited NbRe with a homogeneous distribution of Re and Nb throughout and a sharp interface with silicon. In-plane magnetization *vs*. magnetic field [$M(H)$] hysteresis loops on NbRe/Co bilayers demonstrate bulk properties and a negligible magnetically dead layer of 1.5 nm. The superconducting critical temperature (T_c) is found to decay slowly with Co layer thickness (d_{Co}), compared to T_c (d_{Co}) for Nb/Co.

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Symmetry of order parameters in the multiband superconductors $LaRu_4As_{12}$ and $PrOs_4Sb_{12}$ probed by local magnetization measurements

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The temperature dependencies of the lower critical field $H_{c1}(T)$ of several As-based filled-skutterudite superconductors as well as $PrOs_4Sb_{12}$ were probed by local magnetization measurements. For the fully-gaped superconductor $LaRu_4As_{12}$ with the greatly enhanced critical temperature T_c = 10.4 K, we observe a sudden increase in $H_{c1}(T)$ deep in superconducting state below ~0.35T_c that is hardly dependent on the crystallographic orientation. Remarkably, a rapid rise of $H_{c1}(T)$ at ~0.25T_c is also seen in the heavy-fermion superconductor $PrOs_4Sb_{12}$ ($T_c \approx 1.80$ K), in fair accord with the previous macroscopic studies [1]. A lack of similar anomalies in the isostructural superconductors $PrRu_4As_{12}$ and $LaOs_4As_{12}$ with similar three-dimensional Fermi-surface topologies highlights a minor significance of anisotropy effects. The pronounced enhancements of $H_{c1}(T)$ for $LaRu_4As_{12}$ and $PrOs_4Sb_{12}$ reflect rarely observed multiband superconductivity due to nearly decoupled bands. Whereas $LaRu_4As_{12}$ is established as an *s*-wave two-band superconductor, open question remains the symmetry of a smaller gap in $PrOs_4Sb_{12}$. For this multicomponent superconductor with broken time-reversal symmetry, a non-saturating behaviour of $H_{c1}(T)$ is observed down to ~0.09T_c.

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Vortices in YBCO thin films with complex pinning structure investigated by AC susceptibility measurements

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We investigated the AC magnetic response of a $YBa_2Cu_3O_7$ film with embedded $BaZrO_3$ (BZ) nanorods and Y_2O_3 nanoparticles in a static magnetic field H_{dc} lower than the matching field H_Φ=4T. AC-susceptibility measurements have been performed using PPMS equipment (Quantum Design) after the sample was cooled down from temperatures $T > T_c$ to 50 K in the DC field H_{dc} perpendicularly oriented to the film surface. The AC-field amplitude h_{ac} was between 0.5 – 6 Oe at frequencies f between 11 and 5555 Hz. The measurements were performed in static DC magnetic fields of 2, 10, and 30 kOe. Complementary zero-field cooling DC magnetic relaxation curves, with the applied DC-magnetic field H_{DC} applied perpendicular to the film surface, were registered with a MPMS (Quantum Design) magnetometer.

The response of the vortex system to the AC excitation is rather complex but extremely useful for the characterization of the vortex dynamics. At small enough amplitude of the AC-field, the slow deformation of the vortex lattice at the surface propagates into the interior and vortices oscillate inside the pinning potentials. In this so-called Campbell regime, with a h_{ac}-independent screening current, it is possible to determine the average curvature of the pinning potential and to investigate the field and temperature dependence of the critical current density [1]. At higher h_{ac}, vortices overcome the pinning well and the flux line system enters into a more dissipative regime with h_{ac}-dependent AC-susceptibility in which the effective vortex activation energy U_{eff} has a logarithmic dependence on the AC field induced current density J.

Current densities and electric fields were extracted from AC and DC magnetic measurements using the critical state model in the Clem-Sanchez approach [2]. Pinning energy U_c(85.5K) obtained from both $E(J)$ characteristics and $J(t=1/f)$ dependence at short time scale is about 900 K (k_B=1), much higher than the ones obtained from DC magnetic measurements. It was found that, for H_{DC} = 2 kOe, the flux velocity during AC measurements is v=0.3 cm s−1 and only 1 nm s−1 in DC relaxation measurements. Thus, the thermal smearing of the potential walls is reduced in AC experiments and the obtained U_c is always higher than U_c determined from DC magnetic measurements.

The dynamic critical current J_d induced for AC driven forces at depinning frequencies was experimentally obtained by measuring the in-phase and out-of-phase magnetic responses (m', m'') as a function of T, at various H_{DC}, f and h_{ac}. The depinning frequency f_d extracted by the extrapolation of J to the order of magnitude of $J_d \sim 10^5$ A cm−2 is in agreement with the values obtained from microwave impedance measurements.

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Vortex matter in advanced superconductor nanoarchitectures

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Advances in the high-tech fabrication methods have provided novel rolled-up architectures at nano- and microscale, for example, open nanostructured nanotubes and helical nanocoils including superconductor (SC) layers (e.g., InGaAs/GaAs/Nb), which opens up new avenues for tailoring the vortex matter properties in SCs [1]. Rolling up SC Nb nanomembranes into open tubes allows for a new, highly correlated vortex dynamics regime that shows a three-fold increase of a critical magnetic field for the beginning of vortex motion and a transition magnetic field between single- and many-vortex dynamic patterns [2]. In the helical SC nanocoils, the distribution and number of vortices in a quasi-stationary pattern can be controlled by the helical radius, pitch distance and stripe width [2]. A quasi-degeneracy of vortex patterns, which emerges under the condition that the total number of vortices is incommensurable with the number of half-turns, opens up new possibilities for bifurcations and the related control of the vortex transport in the helical SC nanocoils. These results demonstrate pathways of tailoring nonequilibrium properties of vortices in curved SC nanoarchitechtures leading to their application as tuneable superconducting flux generators for fluxon-based information technologies. An inhomogeneous transport current, which is introduced through multiple electrodes in an open SC Nb nanotube, is shown to lead to a controllable branching of the vortex nucleation period. Using an inhomogeneous transport current allows for a significant reduction of the average number of vortices in the nanotube. Open SC nanotubes produce less dissipation as compared to the planar structures under the same magnetic field and transport current, what is of importance for extending the spectrum of SC-based sensors to the low-frequency range. The voltage generated by moving vortices as a function of the applied magnetic field provides useful insight into spatial reorganization of the dynamical vortex patterns in rolled up open SC nanotubes. An increase of the number of vortex chains in a SC nanotube results in a 6-fold decrease of a slope of the induced voltage as a linear function of the magnetic field [3]. The magnetoresistance in an open SC nanotube as a function of the magnetic field reveals an expressed geometry-induced effect due to the occurrence of a phase slip in the area with small absolute values of the normal-to-the-surface magnetic field component. I acknowledge fruitful collaboration with R. R. Rezaev, E. A. Posenitskiy, E. I. Smirnova, E. A. Levchenko and O. G. Schmidt. I thank the Center for Information Services and High Performance Computing (ZIH) at TU Dresden for enabling computations on the HPC system. I gratefully acknowledge the support by the European Cooperation in Science and Technology COST Action "Nanoscale Coherent Hybrid Devices for Superconducting Quantum Technologies" CA16218 and the German Research Foundation (DFG) under grant #FO 956/5-1.

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Hall effect at the Superconductor-Insulator transition

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I would like to discuss recent Hall effect studies close to the Superconductor-Insulator transition in thin films [1,2]. The results found in this works are very similar to the old data on High Temperature Superconductors, [3,4]. In both cases one observes vanishing of the Hall resistivity and the Hall angle in superconducting state.In particular it was predicted in Ref. [5] and experimentally confirmed [3,4] that vortex pinning doesn't effect the Hall conductivity. Since longitudinal conductivity vanishes due to pinning the Hall resistivity goes to zero as a square of the longitudinal one, $\rho_{xy} = \sigma_{xy}\rho_{xx}^2$. This result is dual to that for the Hall effect in normal metals. There Hall resistivity $\rho_{xy} = B/nec$ doesn't depend on scattering time. Simple picture of it is that transfer of momentum in scattering is along the average electron velocity and thus scattering doesn't contribute to transverse current and to the Hall resistivity. Vortices are dual to electrons. They move under the action of current and their motion produces voltage. Average pinning force (analog of scattering of electrons) is opposite to the vortex velocity and has no transverse to it component. As a result it is Hall conductivity that is not renormalised by pinning. In this sense superconducting phase is dual to the Hall insulator. I argue that the spatial inhomogeneities have no effect on Hall conductivity in superconducting state.

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Planar Josephson junction as an element for novel superconducting devices

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Planar Josephson junctions are formed at the edge between two superconducting films. They differ significantly from conventional overlap junctions. In particular, the electrodynamics of planar junctions is nonlocal when the electrode thickness is less than the London penetration depth. When a magnetic field is applied perpendicular to the film plane, Meissner screening leads to the spreading of magnetic-field lines along the surface. This causes flux focusing in the junction barrier, which greatly enhances the sensitivity to the magnetic field. Furthermore, the two-dimensional geometry of planar junctions allows flexible and easy design of new functional components on the chip. We argue that a combination of unusual physical properties and flexible 2D geometry makes planar junctions advantageous for applications in Josephson electronics.

In this work we demonstrate prototypes of two types of devices based on a planar Josephson junction:

(i) Magnetic scanning-probe sensor based on a single planar Josephson junction [1]. We fabricate and analyze experimentally sensor prototypes with a superparamagnetic Cu-Ni barrier. We demonstrate that the planar geometry facilitates an effective utilization of the self-field phenomenon for amplification of sensitivity and a simple implementation of a control line for feedback operation.

(ii) Abrikosov vortex-based memory cell. We use single Abrikosov vortex (AV) as an information bit and a planar Josephson junction for read-out of vortex state [2]. The AV is manipulated by short current pulses.

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Vortex Lattice Instability in Superconducting Materials

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Depending on material defects, vortex physics reveals a variety of static and dynamic phenomena that make up a complex magnetic field-temperature phase diagram for type-II superconducting materials. By driving at high velocities the vortex lattice under current bias, its stability can become challenging and in recent years, an overall study has been carried out on how to tune this instability by acting on material pinning and sample geometry [1-6]. In low and high temperature as well as in Fe-based superconductors, this instability occurs with different features also related to the material under investigation [7-8]. Nevertheless, a common phenomenological scenario of critical vortex velocities as a function of temperature and magnetic field intensity can be empirically depicted by measurements. Additionally, the size effects have been systematically studied by playing either with a mesoscopic scale or with a nanoscale geometry of the samples [9]. We finally draw a reference picture in which by changing width or thickness of the bridge samples, as well as temperature and material pinning under investigation, it allows for a predictable behaviour of the critical vortex velocity as a function of the applied magnetic field. A further degree of freedom which has been considered is the angular field orientation, that provides a tool to explore the anisotropy of the material through the instability parameters dependence on this angle variation. In this framework, we present the case study of a layered material which belong to the 11-family of the iron-based superconductors, and we compare the results with two-dimensional materials, such as the HTS BSCCO and LTS ultra-thin films. Our findings unveil an unexpected behaviour within the current theoretical framework for the Fe(Se,Te) superconductor.

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Collective excitations in two-band Fermi superfluids at finite temperatures

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Recently, the two-band superfluidity has found an experimental realization through the so-called orbital Feshbach resonance (OFR) [1, 2]. The interaction strength parameters of Fermi gases under OFR are highly tunable, allowing for regimes from BEC to BCS [3]. This has stimulated theoretical studies of multiband condensed Fermi gases.

The present work is devoted to collective excitations in a one- and two-band Fermi gas with *s*-wave pairing in the BCS-BEC crossover at nonzero temperatures, being particularly focused on phononic and Leggett modes. The treatment is performed using the Gaussian pair fluctuation effective action for a two-band system within the path integral formalism, derived in Ref. [4].

We show that beyond the weak interband coupling regime, the frequently used low-energy expansion of the effective action fails for Leggett modes. The frequencies and the damping factors for Leggett modes are then determined in a self-consistent non-perturbative way through complex poles of the fluctuation propagator, similarly to Refs. [5], where this method has been applied to pair-breaking and phononic collective excitations in ultracold Fermi gases.

The spectra of Leggett modes are investigated as a function of the coupling parameters, temperature, and the detuning parameter δ, which characterizes the band offset between the two bands. With increasing δ, the Leggett mode frequency may reach and cross the pair-breaking continuum edge, showing an interplay with pair-breaking modes. In the BEC regime, when pair-breaking collective excitations absent [5], the Leggett mode passes the pair-breaking continuum edge acquiring a finite damping, but does not dissolve. At the BCS side, the Leggett modes avoid crossing with the pair-breaking continuum. Strong coupling regimes are favorable for the experimental observation of Leggett modes.

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Interplay between superconductivity and charge-density-wave domains in $La_{2-x}Sr_xCu_2O_4$ superconductors

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A systematic study of the resistivity as a function of magnetic field and temperature has been performed on a series of $La_{2-x}Sr_xCu_2O_4$ thin films with various doping levels corresponding to different Sr content *x*. The transport experiments were carried out using perpendicular pulsed high magnetic field as a control parameter and revealed for a given range of x in the underdoped part of the phase diagram two critical regimes. The first one is at high temperature and low field 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 is derived, which takes into account the full *R(H,T)* behaviour. By comparing this phase diagram to a theoretical prediction obtained by assuming a situation where a momentum-space-ordered state competes (such as superconductivity) with a real-space-ordered state (such as charge-density-wave), we infer the existence of a low-temperature superconductivity filamentary phase surviving in the domain of stability for the charge density wave. This low temperature filamentary phase is indeed responsible for the existence of these two critical regimes.

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Nature of the zero-energy vortex bound state in the superconducting topological surface state of Fe(Se,Te)

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Vortex cores of topological superconductors are predicted to be an ideal platform of Majorana fermions. Although several experimental efforts have been made to detect Majorana fermions in the vortex cores as a zero-energy vortex bound state (ZVBS) [1- 3], existence of the Majorana fermions is still controversial [4]. Using a dilution- refrigerator scanning tunneling microscope [5], we have systematically inspected a large number of vortices in the superconducting topological surface state of $FeTe_{0.6}Se_{0.4}$ with unprecedentedly high energy resolution of ~20 μeV. We found that a certain number of vortices possess the ZVBS below 20 μeV, which suggests its Majorana bound-state origin. However, we also found vortices without the ZVBS. Interestingly, emergence of the ZVBS is not related to the preexisting quenched disorders, and that the fraction of vortices with the ZVBS decreases with increasing magentic field [6]. These findings suggest that inter-vortex interaction plays an important role in the ZVBS formation.

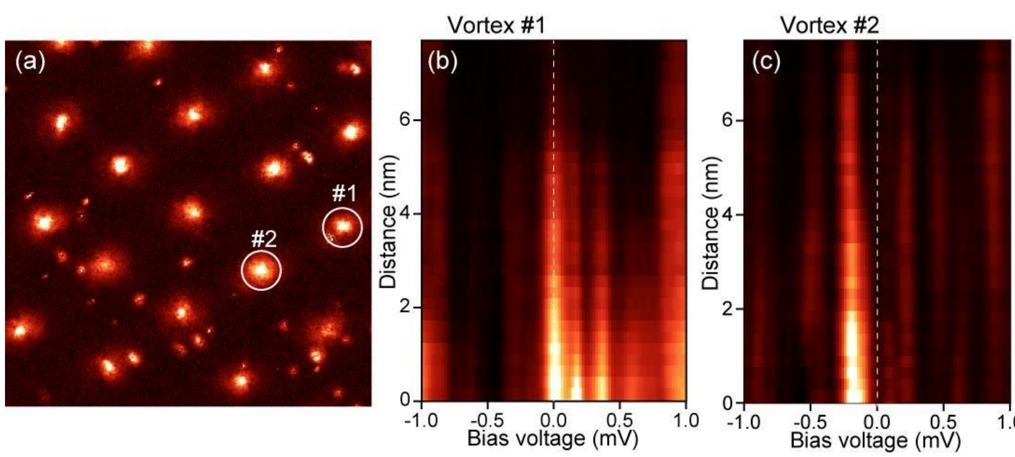

Figure 1. (a) A zero bias conductance map on a 187 nm x 187 nm field of view at a set point at V = -10 mV and I = 100 pA. (b) and (c) Line profiles of high energy resolution tunneling spectra around the vortex core with and without the ZVBS, respectively.

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Proximity effects in high-T_c superconductor/half-metallic ferromagnet vertical junction

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The interaction between superconductors (S) and ferromagnets (F) is emerging as a major research field due to the possibility of creating spin-triplet Cooper pairs at the S/F interface. These equal-spin correlations can propagate over long distances into the F and thus have potential for novel spintronics applications.

The aim of this study is to investigate triplet proximity effects and, in particular, the generation of equal-spin triplet by comparing low-temperature magneto-transport measurements of S/F/S vertical junctions based on half-metallic F ($La_{0.7}Sr_{0.3}MnO_3$ or $La_{0.7}Ca_{0.3}MnO_3$) with either a d-wave S ($YBa_2Cu_3O_7$) or a s-wave one ($Mo_{80}Si_{20}$). In addition, two junction geometries, namely three-probe vs. a novel four-probe junction scheme, will be investigated in order to separate conductance features linked to the top electrode's contact resistance from effects due to transport across the entire S/F/S junction.

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Critical current in thin flat superconductors with Bean-Livingston and geometrical barriers

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Dependence of the critical current I_c on the applied magnetic field H_a is theoretically studied for a thin superconducting strip of a rectangular cross section, taking an interplay between the Bean-Livingston and the geometric barriers in the sample into account. It is assumed that bulk vortex pinning is negligible, and the London penetration depth λ is essentially less than the thickness d of the strip. As is known, the Bean-Livingston barrier results from the attraction of vortices to the sample surface at distances of the order of λ, while the geometrical barrier is due to the shape of superconductors, and it develops on the scale of the order of d. In the familiar approach to the calculation of $I_c(H_a)$ [1], the sample is considered as an infinitely thin strip, and the barriers are modelled by the condition that the Lorentz force at the distance ~ d from the edge of the strip should reach a certain critical value for vortices to penetrate into the sample. However, to investigate the effect of these barriers on I_c more rigorously, one cannot neglect the thickness of the strip. In the present work a two-dimensional distribution of the current over the cross section of the sample is found under the assumption that a vortex dome exists in the strip. In obtaining this result the approach of [2] is exploited which is based on the methods of conformal mappings. With this distribution the dependence $I_c(H_a)$ is calculated. This dependence is determined by the ratio $p \equiv (\lambda/d)^{1/3}\kappa/\ln(\kappa)$, where κ is the Ginsburg-Landau parameter. If p exceeds a critical value, the critical current is mainly determined by the Bean-Livingston barrier, otherwise the geometrical barrier prevails at low H_a. In the latter case a crossover between the two types of the dependences $I_c(H_a)$ occurs with increasing magnetic field.

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Large and uniform critical currents in finite magnetic fields

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Loss-free superconducting transport is tremendously important for technological and energy applications. Heat dissipation from drifting magnetic vortices is one of the main limiting factors for superconductors usage. Here we discuss defect configurations that trap vortices almost independently of their direction. As a result, such pinning configurations produce near uniform critical current as a function of applied magnetic field angle. To cover the broadest class of pinning landscapes we employ a genetic algorithm varying the size, position, and orientation of each defect individually. We report several notable results and analyze them in details. The highest uniform critical current is 22% of the depairing current at the magnetic field 10% of the second critical field.

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Electromigration in the dissipative state of high-temperature superconducting bridges

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Commonly, superconducting nanocircuits are not concerned by atomic migration problems chiefly because in the non-dissipative superconducting state, there is no net momentum transfer between the carriers (Cooper pairs) and the atomic lattice. Furthermore, in low critical temperature superconductors, the critical current density J_C lies well below the current density J_{EM} needed to start displacing atoms.

Interestingly, this scenario may no longer hold for cuprate superconductors. The reason is twofold; on the one hand, the atomic diffusion barrier can be relatively weak for certain atoms like oxygen in $YBa_2Cu_3O_{7-d}$, consequently reducing J_{EM}. On the other hand, these compounds exhibit high superconducting critical current densities. Under these circumstances, when the dissipative state is accessed by applying a current density $J > J_C$, the component of the current carried by the quasiparticles can surpass J_{EM} and produce irreversible damage to the material even at local temperatures substantially lower than the melting point of the compound. This phenomenon has been largely oversighted so far.

In this work, the current stimulated atomic diffusion in $YBa_2Cu_3O_{7-d}$ superconducting bridges is investigated. A superconductor to insulator transition can be induced by the current controlled electromigration process, whereas the partial recovery of the superconducting state can be achieved by inverting the polarity of the bias. Interestingly, the temperature dependence of the current density $J_{EM}(T)$, above which atomic migration takes place, intersects the critical current density $J_C(T)$ at certain temperature T^*. Therefore, for $T<T^*$, the current-induced dissipative state cannot be accessed without leading to irreversible modifications of the material properties [1]. This phenomenon could also lead to the local deterioration of high critical temperature superconducting films abruptly penetrated by thermomagnetic instabilities.

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Exotic vortex matter and other spontaneously appearing patterns in superconductors between type I and II

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Between types I and II there is a regime of the inter-type (IT) superconductivity with non-conventional magnetic properties. This regime is a generic phenomenon taking place due to a proximity to the critical Bogomolnyi point, at which the condensate state is self-dual and infinitely degenerate [1]. IT superconductivity has distinctive characteristics, which cannot be described as a mixture of those in type I and II and should be regarded as a separate superconductivity type. It can take place in single- as well as multi-band superconductors and also in low-dimensional samples - films [2] and wires [3]. One of the key characteristics of the IT regime is very complex vortex interactions [4]. These are spatially non-monotonic and furthermore have sizeable many-vortex contribution that cannot be reduced to a pairwise potential [4]. Such interactions give rise to the spontaneous pattern formation in the mixed state – vortex clusters and multi-quantum vortices, vortex labyrinths and stripes of the condensate, vortex liquid droplets etc.

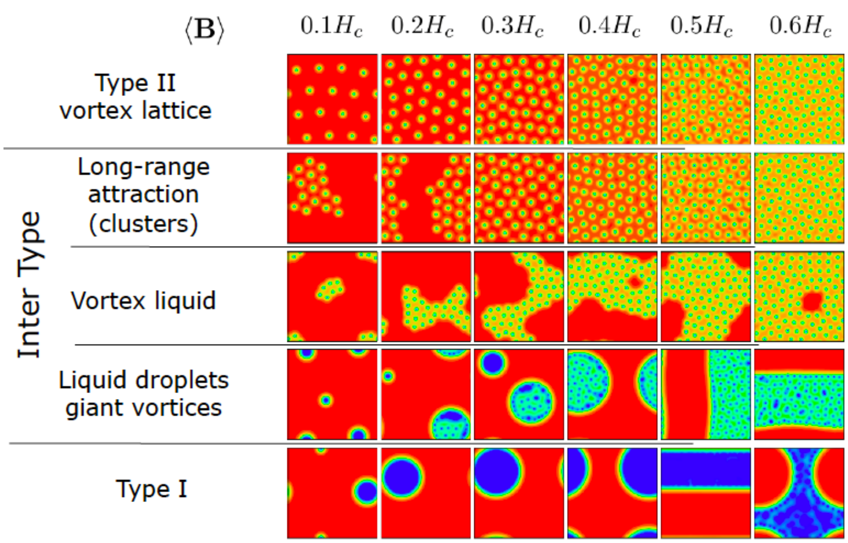

Figure 1. Vortex configurations in bulk IT superconductor.

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SP.16

Nano-SQUIDs with controllable weak links created via current-induced atom migration

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As the most sensitive magnetic field sensor, the superconducting quantum interference device (SQUID) became an essential component in many applications due to its unmatched performance. Through recently achieved miniaturization, using state-of-the-art fabrication methods, this fascinating device extended its functionality and became an important tool in nanomaterial characterization.

During the past years we have developed an accessible and yet powerful technique of targeted atom displacement in order to modify the properties of superconducting weak links. Recently, we showed that the sequential repetition of such customized electro-annealing in a single niobium (Nb) nanoconstriction can broadly tune the superconducting critical temperature T_c and the normal-state resistance R_n in the targeted area [1]. Once a sizable R_n is reached, clear magneto-resistance oscillations are detected along with a Fraunhofer-like field dependence of the critical current, indicating the formation of a weak link but with further adjustable characteristics.

In a next step we used electromigration on an Aluminium DC nano-SQUID to modify the parallel weak links beyond the limits of conventional lithography [2]. The controllability of our protocol allows us to characterize in situ the full superconducting response after each electromigration step. From this in-depth analysis, we reveal an asymmetric evolution of the weak links at cryogenic temperatures. A comparison with time resolved scanning electron microscopy images of the atom migration process at room temperature confirms the peculiar asymmetric evolution of the parallel constrictions. Moreover, we observe that when electromigration has sufficiently reduced the junction's cross section, superconducting phase coherence is attained in the dissipative state, where magnetic flux readout from voltage becomes possible.

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0-π transitions and flux-flow resistivity in superconductor-ferromagnet-superconductor sandwich with Abrikosov vortices

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We study non-equilibrium states of superconductor-ferromagnet-superconductor trilayer systems in the flux-flow regime. Our approach is based on the Keldysh-Usadel theory which combines self-consistent calculations of the order parameter and solving kinetic equations for non-equilibrium distribution functions.

First, we find the self-consistent single-vortex solution in the case of weak magnetic field applied perpendicular to the superconductor-ferromagnet interface. By using the derived free energy functional we discuss thermodynamic transitions in the sandwich hosting Abrikosov vortices. This transition between states characterized by 0 and π phase difference of condensates in different superconducting layers is induced by the changes in ferromagnetic layer thickness.

Second, we solve the full set of kinetic equations and calculate flux-flow resistivity of trilayer. We show that flux-flow resistivity exhibits a peak as a function of ferromagnetic layer thickness. The peak height depends on the magnitude of exchange interaction in the ferromagnet and points to the 0-π transition of trilayer as shown in Fig.1.

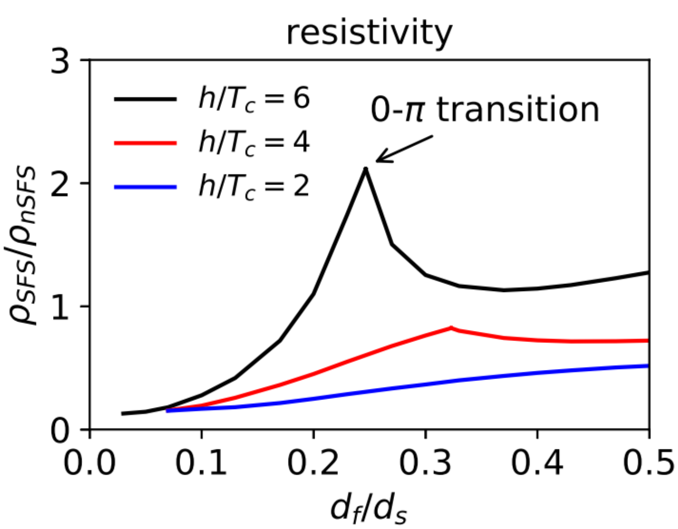

Fig. 1. Normalized flux-flow resistivity as the function of the thickness d_f of ferromagnetic layer. Different colors correspond to different values of exchange interaction of ferromagnet. Peak of flux-flow resistivity indicates the transition between states with 0 and π phase difference of the condensates in different superconducting layers.

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How to measure temperature by flipping a coin?

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Thermometry is a key in studies of thermodynamics - discipline investigating heat flows arising from difference in temperature between two bodies. In our pioneering experiments we employ a superconducting weak link (Fig.1) to measure rapidly changing electron temperature in a long superconducting nanowire with nanosecond resolution [1]. Investigation of thermal properties in nanoscale is much less common than corresponding electrical and magnetic studies. Partially it is because of the lack of fast thermometers that would be able to trace thermal transients appearing when electrical circuit is driven out of equilibrium due to, say, rapidly changing current responsible for Joule heating or photons absorbed in the bolometer. Yet, a proper understanding of thermal processes is essential for failure-free functioning of quantum circuits, involving design of nanoscale calorimeters and bolometers. In our quest to measure temperature even faster we utilized the ability of current-carrying superconducting weak link to instantaneously switch from superconducting to normal state. This switching depends on temperature, thus providing a feature required for a temperature sensor. The ease of integration, true nanometer size and simplicity make our thermometer a good candidate for exploring thermodynamics of low temperature quantum circuits. The method can prove to be very attractive in determination of vanishingly small heat capacities and studying heat exchange mechanisms involving real-time visualization of hot electron diffusion in nanostructures and calorimetric counting of single microwave photons.

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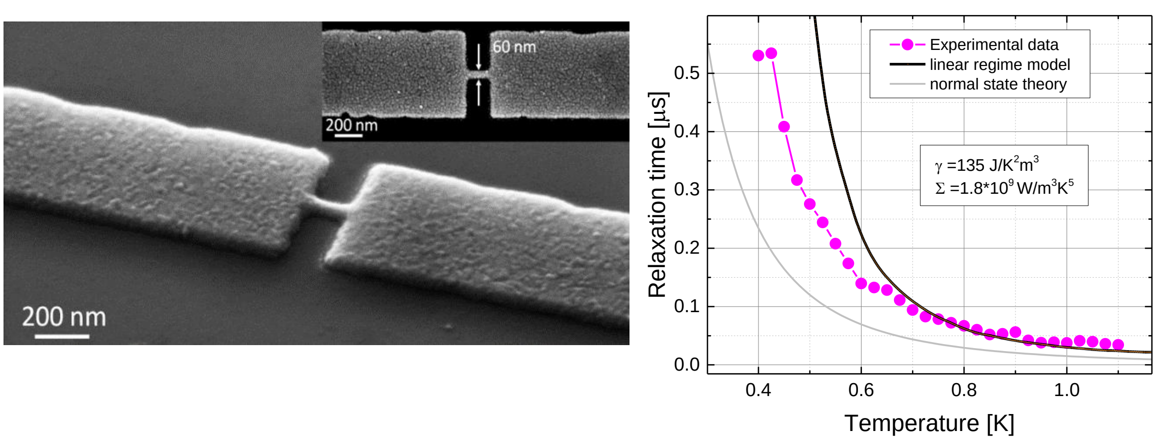

Fig.1. SEM image of the nanoscale thermometer and measured thermal relaxation times of a superconducting nanowire.

Electronic properties of emergent topological defects in chiral *p*-wave superconductors and topological phase transitions in small disks

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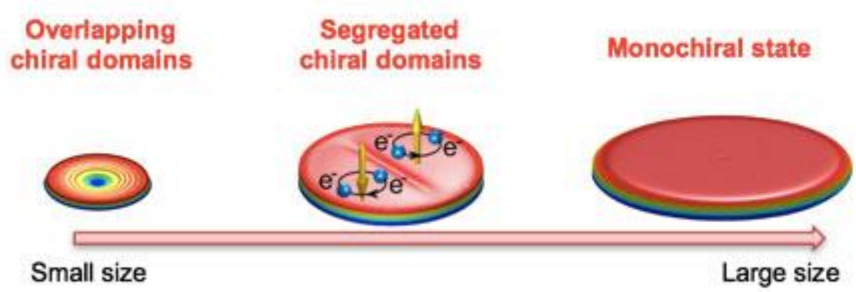
Chiral p-wave superconductors in applied magnetic field can exhibit more complex topological defects than just conventional superconducting vortices, due to the two-component order parameter (OP) and the broken time-reversal symmetry. By solving the Bogoliubov–de Gennes equations self-consistently, we first present the electronic structure of those exotic states [1], some of which contain skyrmionic character in the relative OP space. We reveal the link between the local density of states (LDOS) of the novel topological states and the behavior of the chiral domain wall between the OP components, enabling direct identification of those states in scanning tunneling microscopy. For example, a skyrmion always contains a closed chiral domain wall, which is found to be mapped exactly by zero-bias peaks in LDOS. Moreover, the LDOS exhibits electron-hole asymmetry, which is different from the LDOS of conventional vortex states with same vorticity. The skyrmion can be surprisingly large in size depending on magnetic field and temperature.

Next, we present the equilibrium phase diagram for small mesoscopic chiral p-wave superconducting disks in the presence of magnetic field [2]. In the ultrasmall limit, the cylindrically symmetric giant-vortex states form the ground state of the system. However, with increasing sample size, the cylindrical symmetry is broken as the two components of the order parameter segregate into domains, and the number of fragmented domain walls between them characterizes the resulting states. Such domain walls are topological defects unique for the p-wave order, and constitute a dominant phase in the mesoscopic regime. Moreover, there are two possible types of domain walls, identified by their chirality-dependent interaction with the edge states.



The total OP in a confined p-wave superconducting disk, showing the evolution of the lowest-energy state with increasing size of the p-wave superconductor, in absence of any magnetic field.

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RSP.01

Tuning of Magnetic Activity in Spin-Filter Josephson Junctions Towards Spin-Triplet Transport

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The interplay between the competitive superconducting S and ferromagnetic F order parameters in SFS Josephson junctions (JJs) can generate unconventional effects, such as long-range spin-triplet supercurrents and 0-π transitions[1]. Here we focus on an extensive characterization of the transport properties down to 0.3 K of JJs with a GdN insulating ferromagnetic barrier (SIfS JJs), in which novel phenomena occur because of the simultaneous presence of both tunneling conduction mechanism[2] and a non-trivial magnetic activity in the barrier[3].

These devices are featured by very low-dissipation, high values of I_cR_N product and a thickness-dependent spin-polarization due to the magnetic exchange energy induced splitting in the GdN insulator band structure[4]. The quality factors, the subgap resistances and the capacitances of these JJs were estimated within the conventional TJM (Tunnel Junction Microscopic) model[5]. Moreover, in highly spin-polarized devices the $I_c(T)$ measurements show an incomplete 0-π transition that can be explained only in terms of a progressive enhancement of the magnetic activity increasing the thickness and the spin-filtering efficiency. This points towards the first evidence in tunnel JJs of spin-triplet correlations[6] and suggests several applications in intrinsically low-dissipative spintronic devices and in high-performance active/passive circuits for quantum and classical computation[7,8,9].

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RSP.02

Vortex simulation with the Usadel equation

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The Usadel equation is known to provide a good description of superconducting hybrid structures in the diffusive limit of transport. Its solution in higher dimensions than one, which is necessary to study, for instance, vortex physics, have so far been quite scarce due to the complexity of the resulting equations of motion for the Green function. To the best of our knowledge, there exists only a few solutions of the self-consistent, non-linear Usadel equation in a 2D superconductor in the presence of a magnetic field, most of which are obtained by considering simple geometries wherein the numerics become more tractable. A numerical framework capable of accurately modelling experimentally relevant systems would be of fundamental interest since it would enable a microscopic and self-consistent description of vortex physics in mesoscopic superconductors and superconducting hybrid structures. Here, we demonstrate how vortex simulations can be performed in such systems by solving the Usadel equation with a finite element method, which allows us to access arbitrary model geometries.

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Universal behavior of the transition to the intermediate mixed state in the type-II/1 superconductor niobium

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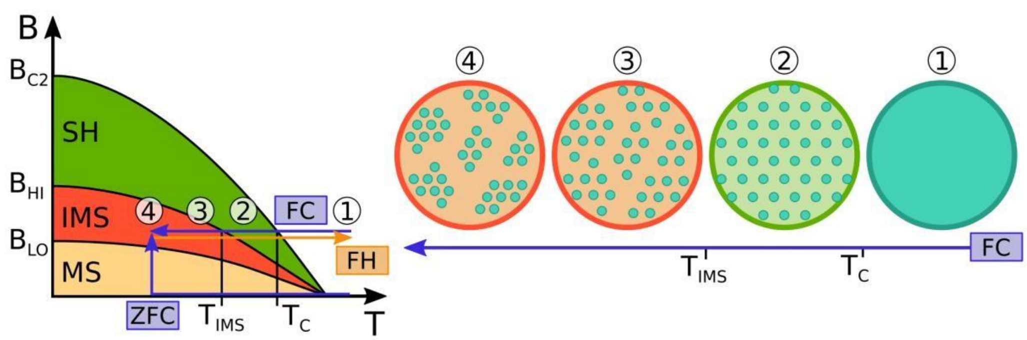
Besides the well-known Abrikosov vortex lattice (VL), superconductors of the type-II/1 exhibit the intermediate mixed state (IMS), where VL domains and Meissner domains coexist, due to an attractive component of the inter-vortex interaction [1]. Despite ongoing work since its discovery in the early 1970s, the IMS bulk properties remain elusive. Especially the interplay with vortex pinning, due to impurities and surface defects, as well as the sample geometry and connected demagnetization effects, play a crucial role. Using a multi scale approach by combining several neutron scattering techniques and bulk measurements, we have readdressed the IMS in a set of bulk niobium samples of varying purity [2,3]. In contrast to many previous studies, we have focused on the field cooled transition from a homogeneous VL in the Shubnikov state into the domain structure of the IMS. In combination with significant pinning, field cooling causes a flux freezing transition above the IMS which effectively suppresses a critical state like behavior. However, the vortex rearrangement in the IMS is not prevented, indicating a breakdown of pinning at the onset of vortex attraction. Independent of the sample quality, and hence pinning strength, we find a universal behavior of the IMS transition, which is, furthermore, unaffected by the measurement history. Especially the vortex spacing shows a distinctive temperature dependence, which is closely related to the superconducting penetration depth.



Schematic phase diagram of a type-II/1 superconductor, subdivided into the Meissner (MS, yellow), intermediate mixed (IMS, red) and Shubnikov (SH, green) state. Arrows depict different measurement protocols: FC, FC/FH and ZFC/FH. For FC measurements, the microscopic magnetic flux redistribution is shown, starting from the normal state (1) with a homogeneous flux distribution, to the regular VL in the SH (2). In the IMS (3, 4) the VL breaks up into small domains containing an increasingly dense VL.

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Statistics of thermomagnetic breakdown in Nb superconducting films

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Superconductors are well known for their ability to screen out magnetic fields. In type-II superconductors, as the magnetic field pressure is progressively increased, magnetic flux accumulates at the periphery of the sample, very much like charges accumulate in a capacitor when voltage is increased. As for capacitors, exceeding certain threshold field causes the blocked magnetic flux to abruptly penetrate into the sample. This phenomenon, triggered by a thermomagnetic instability, is somewhat analogous to the dielectric breakdown of the capacitor and leaves behind a similar Lichtenberg imprinting. Even though electrical breakdown threshold has been extensively studied in dielectrics, little information is known about the statistical distribution of the thermomagnetic breakdown in superconductors. In this work, we address this problem by performing magneto-optical imaging experiments on a Nb film where nanometric heating elements are used to rapidly erase the magnetic history of the sample. We demonstrate that the size and shape distributions of avalanches permits to unambiguously identify the transition between two regimes where either thermal diffusivity or magnetic diffusivity dominate. Clear criteria for discriminating dynamic avalanches from thermally driven avalanches are introduced. This allows us to provide the first precise determination of the threshold field of the thermomagnetic breakdown and unveil the details of the transition from finger-like magnetic burst to dendritic branching morphology. These findings open a new avenue in the interdisciplinary exploration of catastrophic avalanches through non-destructive repeatable experiments.

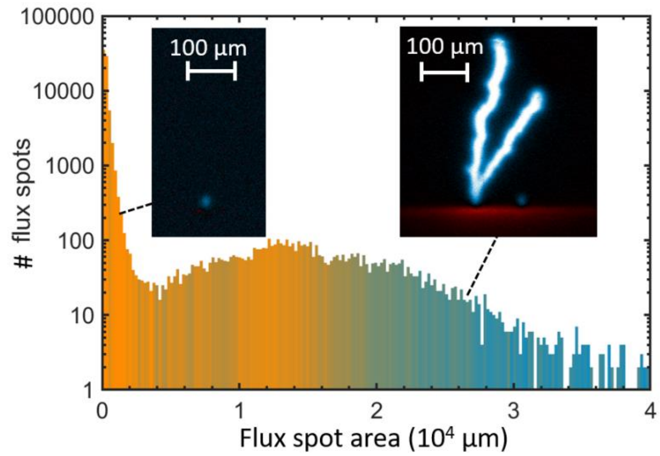

Figure 1: Distribution of the avalanche sizes obtained from 79726 recorded events during 813 field sweeps from 14 Oe to 25 Oe. The color in the histogram indicates the mean field value at which the avalanches occur, from H = 17.75 Oe (orange) to H = 24.75 Oe (blue). The insets show that dynamically driven avalanches (left) exhibit a rounded shape, whereas thermally driven avalanches (right) are elongated.

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Josephson emission from $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesa structures

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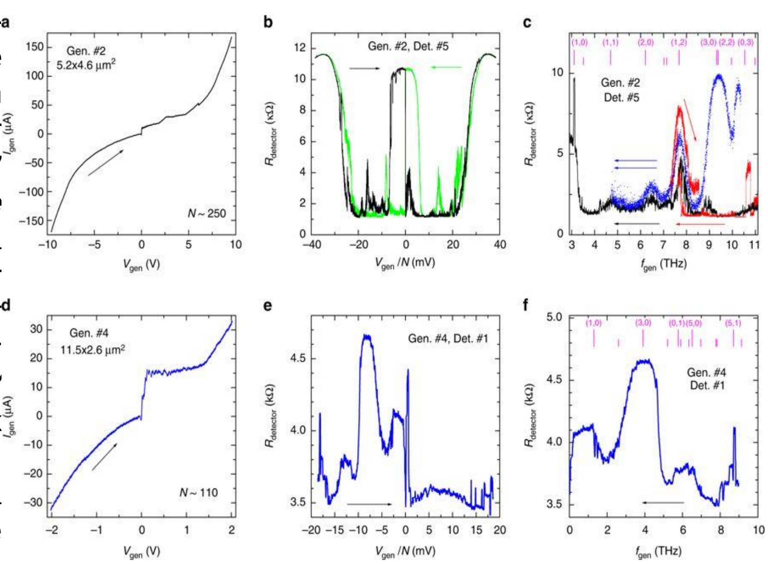
Mesa structures of $Bi_2Sr_2CaCu_2O_{8+\delta}$ **(Bi-2212)** high-temperature superconductor represent stacks of intrinsic Josephson junctions. Josephson junctions allow direct convertion of DC voltage into high-frequency electromagnetic waves with tunable frequency $f=(2e/h)V$ (=0.48359 THz/mV). Thus, superconductors can provide an alternative technology for creation of compact THz sources. It has long been anticipated that small Bi-2212 mesas may have many benefits as THz oscillators: (i) Edge effects and capacitive coupling persuade in-phase synchronization of junctions, needed for superradiance; (ii) Self-heating is reduced proportional to the mesa size, which allows operation at high voltages and frequencies; (iii) The frequency and the quality factor Q of the primary geometrical resonance (cavity mode) increase inversely proportional to the mesa size. Fiske steps with Q > 100 were reported for μm-size Bi-2212 mesas. This should strongly boost the emission efficiency because high-Q resonances enhance the emission power ∝Q2 and decrease the line-width ∝1/Q. (iv) Small mesas can be made free from defects and with identical junctions, simplifying their synchronization.

Here we demonstrate that small-but-high Bi-2212 mesas can be used as high-frequency electromagnetic wave generators in a record high frequency range up to 11 THz [1]. We argue that a threshold number of junctions N>100 is needed for coherent superradiant emission from the mesas. We demonstrate several ways of detection of radiation: using a nearby mesa on the same crystal as a switching current detector, or an external bolometer.

The Figure represents generation-dection experiment in the 1-11 Thz range with inbuilt detector. Two mesas with different sizes and detector configurations are presented. ***a, d*** I–V characteristics of generator mesas. ***b, e*** Measured detector responses as a function of the generator voltage per junction.***c, f*** Emission spectra: detector response vs. Josephson frequency for the falling parts of the generator *I*–*V* curves. Vertical bars on top of ***c, f*** mark expected frequencies of strong emitting inphase geometrical resonances in mesa with sizes ***Lx*Ly*** coresponding to those generators. The estimated maximum emission power~1μW indicates an encouraging DC to AC conversion efficancy.



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Numerical investigation of critical states in superposed superconducting films

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While offering enhanced or new functionalities, three-dimensional superconducting structures have a richer magnetic response than planar devices. A particular class of three-dimensional structures is obtained by stacking nanostructured superconducting layers, resulting in systems where the planar subcomponents are magnetically coupled with one another, thereby opening the possibilities of new magnetic flux penetration processes. In thin superconducting films, abrupt changes in the direction of shielding currents are manifested in the form of discontinuity lines (d-lines), which vortices cannot cross. For instance, in a square film, d-lines appear along the diagonals, while in a rectangular film, they follow a double Y shape. Such structures can be observed through magneto-optical imaging (MOI). When a rectangular superconducting thin strip is superimposed to a superconducting square film, the resulting d-lines do not correspond to a simple superposition of the d-lines of each individual film, additional d-lines appear [1].

In this work, we investigate the d-lines of bi-layered superconducting thin films numerically. We use a finite element H-φ formulation, where shell-transformations [2] are used in the far-field region outside the films, so that boundary conditions are applied at an infinite distance from the conductors. We show the key role of the magnetic field dependence of the critical current density $j_c(|\vec{B}|)$, which is modelled with Kim's law $j_c(|\vec{B}|) = j_{c0}/(1+|\vec{B}|/B_0)$, in the apparition of the additional d-lines. We demonstrate the modification in the shape of the d-lines with respect to the magnitude of the applied magnetic field, while it is increased and then decreased back to the remanent state. The influence of the spacing between both films, B_0, j_{c0} on the geometrical characteristics of the additional d-lines is also investigated.

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Transport at the superconductor-normal junction in ionic gated MoS_2

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Molybdenum disulfide (MoS_2) is a layered material similar to graphene that can be thinned down to a few atomic layers. Along with the superior electronic and optical properties that are promising for ultrathin electronic devices, applying strong field effect on MoS_2 can dope this intrinsic semiconductor into a superconductor [1-4]. In this study, we focus on the electrical transport properties at the superconductor-normal (SN) interface made on the surface of ionic gated few-layer MoS_2, either by partially covering the surface of MoS_2 with an h-BN flake or contacting with a normal metal. The magnetoresistance at the SN interface shows a non-monotonic behaviour, signifying the Andreev reflection as a function of the energy barrier height, the superconducting gap and the electron energy [5]. From the differential conductance measurement, we can extract the superconducting gap using the Blonder-Tinkham-Klapwijk (BTK) model [6]. The behaviour of the superconducting gap as a function of carrier density and electric field is discussed.

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Quasi-One-Dimensional Vortex Matter in Superconducting Nanowires

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Nanowires are quasi-1D objects, where the condensate and its possible vortex-matter state are inevitably affected by the confining potential of the boundaries. Therefore, the characterization and manipulation of vortices in such systems differ from bulk and require additional studies. In this work, we investigate the vortex formation in a single nanowire and also in an array of nanowires made of both type-I and type-II materials (as controlled by the material Ginzburg-Landau parameter κ) and placed in a perpendicular magnetic field. Our consideration is based on the time-dependent Ginzburg-Landau formalism. We demonstrate that in a sufficiently thin single nanowire the mixed state develops, where vortices tend to arrange themselves in a regular chain (1D Abrikosov lattice); this picture is independent of the value of κ. For an array of nanowires, the vortex configurations are more complex due to the competition between the vortex-vortex interaction inside each nanowire and the interaction of vortices from different nanowires. We find that the relevant vortex configurations can be significantly altered when changing the nanowire thickness as well as the distance between nanowires in the array.

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Ferromagnetic and Superconducting oxides 2DEGs systems

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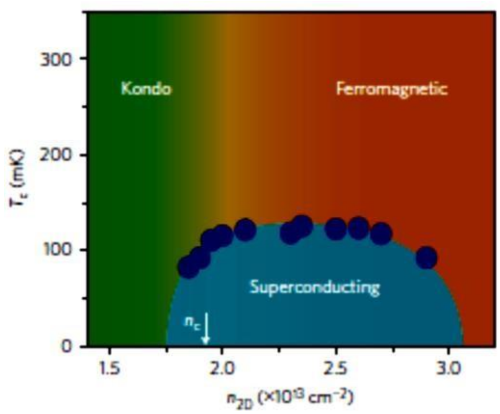
In 2004 Ohtomo and Hwang [1] reported on the formation of a high mobility 2-dimensional electron gas (2DEG) at the interface between two wide bandgap insulators oxides, namely $LaAlO_3$ (LAO) and $SrTiO_3$ (STO). This work stimulated a large interest in the scientific community. Recently, we demonstrated that the 2DEG created at the LAO/STO interface becomes spin polarized by introducing a few unit cells of delta doping $EuTiO_3$ (ETO), an antiferromagnetic (AF) insulator iso-structural to STO [2,3]. The occurrence of magnetic interactions, superconductivity and spin-orbit interactions in the same tunable 2DEG system makes the LAO/ETO/STO an intriguing platform for the emergence of novel quantum phases in low-dimensional devices. In this work we show how the rich phase diagram of this 2DEG can be tuned by electric field and by light.

Firstly, have investigated the interplay between ferromagnetism and Rashba spin-orbit interactions by studying the magnetoconductance curves of the 2DEG as a function of the applied gate voltage and temperature. In fact, the LAO/ETO/STO is one of the few systems where such interplay can be studied [4]. Under visible light, moreover, the interface exhibits a persistent photoconductivity and the magnetotransport measures shows also an anomalous Hall effect. This feature is probably related to different the nature of the photo-excited spin-polarized 4f carriers due to ETO [5].



Temperature versus carrier density phase diagram of the LAO/ETO/STO Heterostructure [3].

These results suggest that the LAO/ETO/STO spin-polarized 2DEG system is a possible candidate for new quantum spintronic applications.

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Manipulation of magnetic skyrmions in chiral ferromagnetic and superconducting heterostructures

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The dynamical evolution of magnetic skyrmions in thin ferromagnetic films has attracted much attention in the recent years due to their highly interesting physical properties and promising technological applications. Devising chiral magnetic heterostructures is a prominent pathway toward advanced confinement and control of magnetic skyrmions in potential devices. Here we discuss the behaviour of ferromagnetic and antiferromagnetic skyrmions in two types of heterostructures: (i) lateral ones, where skyrmions interact with heterochiral interfaces (where magnetic chirality changes) [1], and (ii) vertical ones, where skyrmions are coupled to superconducting vortices in ferromagnet-superconductor bilayers [2]. In either case, we employ numerical simulations and analytic arguments to show that the hybrid systems comprise a plethora of possibilities for manipulating and controlling skyrmions (and vortices), that are not feasible in homogeneous systems.

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Flipping coin experiment for studying switching in Josephson junctions and superconducting wires

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Josephson junctions (JJ) and superconducting wires (SW) when probed with current pulses exhibit stochastic switching from superconducting to a stable non-zero voltage state[1]. Electrical current dependence of the switching probability (so called S-curve) or switching current distribution is a fingerprint of the physics governing the escape process. Our work addresses, for the first time, the criterion of independent switching event, which is important for credibility of the switching measurements of superconducting wires and various Josephson junctions, involving superconductor-insulator-superconductor tunnel junctions, proximity junctions and Dayem nanobridges. Treating Josephson junction as an electrical coin with current-tuned switching probability we investigate, not studied before, effect of correlation between switching events on the switching statistics[2].

The JJ switching phenomenon is used for probing the state of superconducting quantum bits and development of superconducting quantum information devices. Hysteretic JJ and SW are desired for threshold detection of various physical signals. They were employed for on-chip current measurements, studying thermal dynamics of nanostructures and proposed for single photon counting.

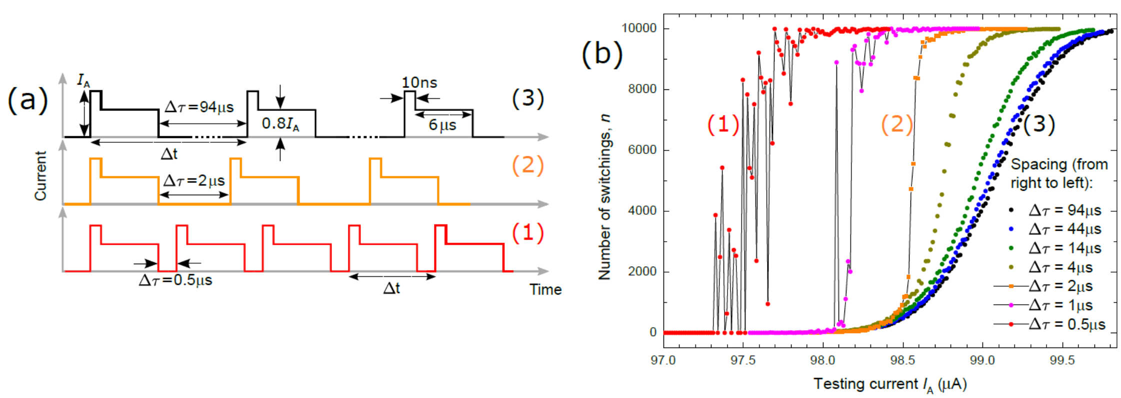

Fig.1. (a) Three trains of N=10000 current pulses used to probe the bridge with different Δτ yielding dependencies (1), (2) and (3) shown in (b). (b) Current dependencies of the switching number n for different spacing Δτ between probing pulses.

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Modulation of the superconducting properties of an ultrathin Pb island

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To date, plenty of measurements conducted on surface-confined superconducting Pb/Si(111) nano-islands have revealed that both the critical temperature and the gap diminish with decreasing film thickness. Also, due to the confinement in nano-islands, stable vortex arrangements, other than the triangular lattice, can be obtained [1-4]. Recent experimental data show how the confinement affects the vortex arrangement in Pb/Si(111) nano-islands of different geometry [5], that even can lead to formation of a giant (multi-quanta) vortex, or nontrivial vortex configurations in cases where the thickness of the island varies inside the sample [6].

We use advanced Ginzburg-Landau simulations (using Antwerp GLACE code) to study the effects emerging in vortex matter in Pb islands by modulation of material properties through in situ tailoring of the superconducting condensate. The spatially modulated quantities include the mean-free path, thickness, critical temperature, each of which lead to non-trivial changes in the behavior of the superconducting condensate and thereby the vortices as well.

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S/F/S Josephson junctions with a strongly ferromagnetic Ni barrier

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Josephson junctions with introduced ferromagnetic materials are actively studying and can be used as cryogenic memory devices. First we need to know how ferromagnets and superconductors compete in one system. In conventional strong ferromagnets (Fe,Co,Ni) the ferromagnetic exchange energy is much larger than the superconducting gap. Therefore, it was suggested that diluted weak ferromagnetic alloys are more suitable for fabrication of superconductor/ferromagnet/superconductor (SFS) Josephson junctions with significant Josephson critical current density. However, alloys are often characterized by a short mean-free path of electrons, which reduces the critical current.

Here we study experimentally SFS junctions with a pure strong ferromagnet Ni between Nb layers. The aim is to investigate if the strong F-barrier is suitable for preparation of SFS junction with significant Josephson coupling. We fabricate and study nano-scale Nb/Ni/Nb junctions with sizes down to 120 nm and with different thickness of Ni-barrier (2-20 nm), using 3D-FIB nanosculpturing technique. Junctions exhibit a significant critical current and Fraunhofer-like modulation $I_c(H)$ in the in-plane magnetic field, indicating good uniformity of the junctions. We demonstrate, that $I_c(H)$ patterns contain information about magnetization of a ferromagnetic nanoparticle, forming a junction barrier. By measuring $I_c(H)$ patterns in different field ranges we can extract small hysteresis loops of Ni nanoparticles.

We found that Nb/Ni/Nb junctions with Ni thickness less than 4 nm have irregular $I_c(H)$ patterns, indicating presence of microshots and discontinuity of the barrier. However, at larger thickness up to ~20 nm of Ni, junctions exhibit clean Fraunhofer-type modulation with significant critical current density, comparable to that of diluted F-layers with the same thickness. We argue that the observed large critical current density is due to cleanliness of pure Ni layer with the electron mean-free path larger than the layer thickness. Our observations allow to conclude that it is possible to build and to control Josephson devices based on a strong ferromagnet, like Ni.

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Phase Slips in Voltage-Biased Superconducting Rings

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Superconducting rings represent a versatile playground for studying various phenomena related to the phase coherence of the superconducting order parameter, among which are phase slips, topological fluctuations of the order parameter. Employing the time-dependent Ginzburg-Landau equations, phase-slips in voltage-biased superconducting rings are investigated. We demonstrate that the bias voltage locally suppresses the order parameter, resulting in two weak links in the ring. Eventually, for a high enough bias voltage, two simultaneous phase slips take place, corresponding to a vortex and an anti-vortex, thereby preserving the winding number of the superconducting ring. Furthermore, in the presence of a perpendicular magnetic field, the bias voltage can lead to oscillations between two successive fluxoid states. Accordingly, we explore the possibility of realizing a junctionless flux qubit where the in-plane electric field, arising from the bias voltage, is analogous to interrupting the superconductor with a thin insulator. One distinctive advantage of the proposed qubit is the electric-tunability of the transition frequency, a desired feature for multi-qubit systems since it renders the circuit more robust to magnetic noise. Improving the coherence time of superconducting qubits, along with electric tunability, constitute an essential building block for scaling up superconducting quantum computers.

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An investigation on superconductivity of FeSe coated Nb structure

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Bulk niobium superconducting radio-frequency (RF) cavities are widely used in different kinds of accelerators, whose performance was found to be limited by the superheating field H_{sh} when prepared using standard methods to avoid RF dissipation at high field. In order to push the theoretical limit, new materials and structures are needed [1] [2]. We discussed the preferential promising iron-based superconductors, and firstly showed some results of FeSe coated Nb superconductor-superconductor (SS') structure. The structural characterizations, transport properties and magnetic properties are given for this SS' structure and we found that this structure has potential applications in RF cavities.

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Vortex transport in superconducting W-C nanostructures

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The quantized nature of superconducting vortices in Type II superconductors makes them appealing candidates for the transfer of information in the form of discrete packets. In this contribution, we report the fabrication and investigation of superconducting nanowires (NWs) in which nonlocal resistances, generated solely by vortex motion, are detected in areas depleted of current. Specifically, by perpendicularly injecting a driving current at one end of NW, a Lorentz force is exerted on the present vortices, which push neighboring ones along the long axis of the NW. Vortices passing through the opposite end, free of current, generate measurable nonlocal voltages. [1]

The nanowires have been fabricated by means of Focused Ion Beam Induced Deposition, using a focused ion beam to decompose an organometallic gaseous precursor previously adsorbed onto the substrate surface. We have used $W(CO)_6$ as a precursor in combination with two different charged particles: Ga^+ ions, which are known to yield superconducting W-C [2] and are whose properties have been thoroughly studied by the group [3-5]; and He^+ ions, for which the group has shown that superconducting nanostructures are also obtained [6-7], and whose reduced beam size and scattering allow for patterning resolution down to a few nanometers. [8]

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Magnetic field induced 2D to 1D crossover in SNS Josephson junction arrays as revealed by mutual phase locking

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The Josephson effect arises when two superconductors are coupled by a weak link forming a Josephson junction (JJ). JJs have extraordinary properties when subjected to a high frequency radiation field (e.g. the Shapiro effect). However, the use of a single junction for practical high frequency applications is limited due to its low response. Coupling JJs into an array provides a natural alternative for the enhancement of the response.
We fabricated prototypical overdamped JJ arrays (JJAs) containing over 2000 superconductor-normal-superconductor (SNS) junctions as shown in figure 1a. The devices consist of a rectangular lattice of superconducting islands, which are deposited on a normal metallic gold film, having very different lattice parameters (defined by d_x and d_y).
The observation of pronounced Shapiro steps in the measured IV-characteristics when the fabricated JJAs are irradiated with a radiofrequency (RF) field indicates they present a self-synchronised and phase locked response, robust against intrinsic disorder within the array [1].
We demonstrate that the phase–locked response depends highly on the anisotropy (d_y/ d_x) parameters of the array, the properties of the RF drive, temperature and magnetic field induced frustration. For instance, we observe a field induced crossover from a 2D response, characterized by the presence of Shapiro steps only at matching conditions, to a 1D response, characterized by field independent Shapiro steps, in a device having a small anisotropy (Figure 1b). Whereas, a highly anisotropic device shows a pure 1D response modulated by flux quantization in the weak link area itself (Figure 1c). The obtained responses show excellent agreement with numerical simulations using an extended resistively shunted Josephson junction model.

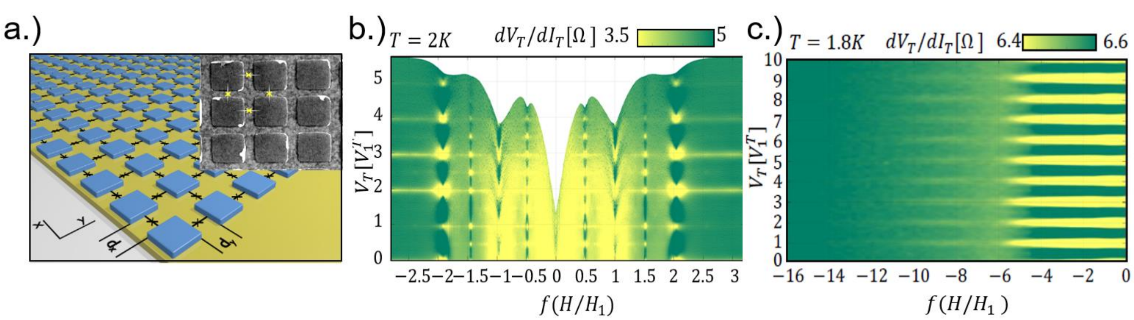

Fig 1(a). Schematic illustration of a JJA together with scanning electron microscopy image of an Au/MoGe based JJA with d_y/d_x=0.8. Fig 1(b). Frustration (Magnetic field) dependence of the Shapiro step response (corresponding with zones of reduced differential conductance, yellow) at low temperatures for Device 1 having d_y/d_x=0.8 and for Device 2, having d_y/d_x=4 (shown in Fig 1(c)).

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Optical generation of single vortex/anti-vortex pairs in superconducting films

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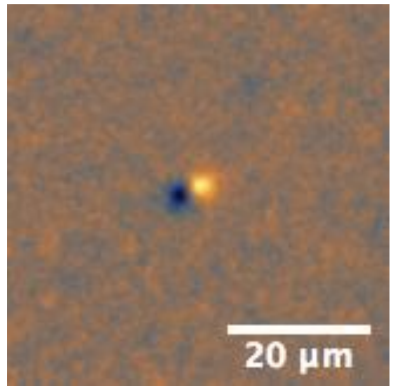
The penetration of vortices into a superconducting film is usually limited to the edges of the superconductor and is triggered by an external magnetic field or an electrical current. The generation of single vortices at any desired place deep inside a superconductor is thus challenging. This presentation will be dedicated to the first generation of a single vortex/anti-vortex pair inside a superconductor using far field optics. This new method is based on the generation of topological defects via the Kibble-Zurek effect which results from fast cooling after focusing a single laser pulse on a superconducting film initially free of vortex. Combined with the fast and precise optical manipulation of a single vortices [1], this result is promising in the view of ultrafast optical operation of superconducting devices such as Josephson junctions [2].



Magneto-optical image of a vortex/anti-vortex pair in a superconducting film of niobium

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RECTIFIED SUPERCONDUCTING VORTEX MOTION TOPOLOGICALLY PROTECTED BY SPIN – ICE NANOMAGNETS

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We have fabricated a hybrid spin-ice / superconductor device specially designed for testing rectified flux motion. Here, a robust superconducting ratchet arises from the interplay between the topologically frustrated magnetic texture in the spin ice and the superconducting vortex motion under alternating forces. The device consists of a Co honeycomb array embedded in a superconducting Nb film on a Si substrate. The honeycomb topology frustrates the in-plane magnetic moments in the array, giving rise to a magnetic charge distribution that can be ordered or disordered by applying in-plane saturation magnetic fields. These magnetic charges are originated by two Néel walls fixed, no matter the magnetic history of the nanomagnets, at each vertex. Thus, superconducting vortices driven by alternating forces and moving on this honeycomb pinning potential provided by the Néel walls profiles results in unidirectional net vortex flow. This ratchet effect is independent of the distribution of magnetic charges in the array.

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Transition from $s_{\pm}$ to s_{++} order parameter driven by disorder in Iron Based Superconductors

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We employed a microwave resonator technique [1-2], that allows us to determine the London penetration depth and the critical temperature, to show evidence of disorder- driven $s_{\pm}$ to s_{++} order parameter symmetry transition in $Ba(Fe_{1-x}Rh_x)_2As_2$ single crystals, where disorder was induced in the form of defects generated by 3.5-MeV proton irradiation.

This transition is expected in the presence of high levels of disorder that drives the system toward the convergence of the gaps values, and its signature was found as the predicted [3], but not yet observed [4], discontinuity in the low-temperature values of the London penetration depth.

These experimental observations are validated by multiband Eliashberg calculations in which the effect of disorder is accounted for in a suitable way. Our model reproduced exactly the experimental T_cs and semi-quantitatively the superfluid densities, with the $s_{\pm}$ to s_{++} symmetry transition at the expected disorder level [5].

Furthermore, we find that the low temperature electrodynamic properties of the superconductor drastically change upon entering the s_{++} state: the quasiparticle conductivity strongly increases and becomes monotonous in tempreature, the surface reactance drops whereas the surface resistance increases slightly [6].

These observations combined with the possibility of selective irradiation of portions or patterns of a large crystal or film could open the way to the study of interfaces between multiband superconductors with different pairing states and the development of novel devices.

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Determination of effective Cooper pair mass by electrostatic doping of fluxoids of superconductor surface. Theory

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We propose an experimental method for the determination of the effective Cooper pair mass m^* by electrostatic doping of Abrikosov vortices of a superconductor surface. To that end, a superconductor is placed in a constant external magnetic field, perpendicular to the superconducting planes. One of the electrodes is connected to the superconductor, while another one forms a capacitor with the superconductor itself. The nature of the insulator is irrelevant to the experiment. In some sense our experiment aims to measure is a new effect. After applying alternating voltage to the capacitor, electrostatic induction leads to oscillations of the magnetic moment. Those oscillations are detected by electromotive force inducted in a detector coil. The electric charges accumulated on the superconducting surface are partially superfluid and contribute to the magnetic field of the vortices. In addition to m^*, this experiment would determine the sign of the Cooper pair charge.

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Imaging Anisotropic Vortex Motion in FeSe

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Iron-based superconductors are known for their complex interplay between magnetic, nematic, and superconducting order. FeSe is an iron-based superconductor with a superconducting transition 8 K that is preceded by a structural transition at 90 K that is understood to be driven by electronic nematic order [1, 2, 3, 4]. The lack of magnetic order in FeSe allows us to probe the superconducting transition of an iron-based superconductor from a purely nematic phase. We study single crystal FeSe using a scanning SQUID microscope that has both a field coil to apply a local magnetic field and a pickup loop to measure the response of individual, isolated vortices. We model the effect of the SQUID geometry on vortex motion in an anisotropic pinning potential and find that SQUID orientation does not have a significant effect. We find that the pinning potential anisotropy is parallel to the direction of twin domain boundaries produced by the structural transition. These results are consistent with a scenario in which anisotropy arises from vortices pinning on the twin boundaries, as described by scanning tunneling microscopy studies of thin film FeSe [5].

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