Advances in Studies of Superconducting Hybrids: Theory and Modeling vs Experiment

COST MP1201 Workshop

Arcachon-France, May 16-19, 2015

Programme and Abstract Book

Conference Chairmen:
Alexander Buzdin and **Dimitri Roditchev**

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Shybrids

The workshop "**Advances in Studies of Superconducting Hybrids: Theory and Modeling vs Experiment**" aims bringing together leading scientists to discuss the recent progress in physics of Superconducting Hybrids. Special attention will be paid to the theory and modeling of these systems, and we expect that the clear recommendations for the experiments will be presented. The Conference should stimulate an active dialogue between experiment, computational approaches, and theory.

-The conference is organized within the framework of current COST (European Cooperation in Science and Technology) projet "Nanoscale Superconductivity (NanoSC) - Novel Functionalities through Optimized Confinement of Condensate and Fields" - Action MP1201.

-The French Physics Society (Société Française de Physique - SFP) co-organizes this event.

-The French National Research Agency (Agence Nationale de la Recherche) partially supports the conference via the project 'ELECTROVORTEX' between research laboratories LOMA (Bordeaux) and INSP (Paris).

	Sunday, May 17th	Monday, May 18th	Tuesday, May 19th
08 :50-09 :00	Opening		
09 :00	**Iavarone**	**Blamire**	**Leridon**
09 :25	**Anahory**	**Meyer**	**Karapetrov**
09 :50	**Mel'nikov**	**Mironov**	**Attanasio**
10 :15	**Ishida**	**Aarts**	**Bergeal**
10 :40-11 :10	*Coffee break*	*Coffee break*	*Coffee break*
11 :10	**Vinokur**	**Indekeu**	**Gariglio**
11 :35	**Silhanek**	**Ryazanov**	**Caprara**
12 :00	**Milosevic**	**Golubov**	**Houzet**
12 :25	*Lunch*	*Lunch*	**Varlamov**
12 :50-14 :00			*Lunch*
14 :00	**Moshchalkov**	**Linder**	*Departure*
14 :25	**Kontos**	**Bergeret**	
14 :50	**Aliev**	**Dobrovolskiy**	
15 :15	**Cren**	**Eschrig**	
15 :40-16 :10	*Coffee break*	*Coffee break*	
16 :10	**Silva**	**Sidorenko**	
16 :35	**Herrera (15')**	**Magrini (15')**	
16 :50	**Goldobin**	**Samokhvalov**	
17 :15	**Tafuri**	**Bill**	
17 :40	**Samuely**	**Stolyarov**	
18 :05	**Maggio-Aprile**	**Jelic (15')**	
20 :00	*Dinner*	*Dinner*	

Shybrids

Programme

Program of the workshop ‘SHybrids’

Arcachon, May 16-19, 2015

Saturday, May 16

14:00-16:00 ***Arrivals***

16:00-20:00 Round table discussion

20:00 ***Dinner***

Sunday, May 17

08:50-09:00 **Opening of the Workshop**

09:00 -09:25 **Maria Iavarone**

Emergence of superconductivity and vortex confinement in superconductor/ferromagnet hybrids

09:25-09:50 **Yonathan Anahory**

Vortex dynamics at the sub-nanometer scale

09:50-10:15 **Alexander Mel’nikov**

Interplay of charge and vorticity quantization in superconducting Coulomb blockaded island

10:15-10:40 **Takekazu Ishida**

Vortices in small concave decagon $Mo_{80}Ge_{20}$ plate

10:40-11:10 ***Coffee break***

11:10-11:35 **Valerii Vinokur**

Dynamic vortex Mott transition

11:35-12:00 **Alejandro Silhanek**
Classical analogy for the deflection of flux avalanches by a metallic layer

12:00-12:25 **Milorad Milosevic**
Emergent phenomena in two-gap superconductors

12:25-14:00 ***Lunch***

14:00-14:25 **Victor Moshchalkov**
Scanning Hall probe microscopy

14:25-14:50 **Takis Kontos**
Coherent coupling of a single spin to microwave cavity photons

14:50-15:15 **Farkhad Aliev**
Microwave-stimulated superconductivity due to presence of vortices

15:15-15:40 **Tristan Cren**
Direct observation of Josephson vortex cores

15:40-16:10 ***Coffee break***

16:10-16:35 **Enrico Silva**
Microwave measurements in Nb/PdNi/Nb heterostructures: 0–π transition, vortex state and structural properties

16:35-16:50 **Edwin Herrera** (15')
Density of states and tilted vortex lattices of the multiband superconductor β-Bi_2Pd

16:50-17:15 **Edward Goldobin**

φ, φ_0 and $\varphi_0 \pm \varphi$ Josephson junctions based on a 0–π SQUID

17:15-17:40 **Francesco Tafuri**

Escape dynamics from Josephson to phase slip modes

17:40-18:05 **Peter Samuely**

Bi_2Pd, the multiband superconductor.

18:05-18:30 **Ivan Maggio-Aprile**

New light on the electronic vortex core structure and normal state in $YBa_2Cu_3O_{7-d}$

20:00 ***Dinner***

Monday, May 18

09:00-09:25 **Mark Blamire**

Epitaxial Rare-Earth / Superconductor Spin Valves

09:25-09:50 **Julia Meyer**

Multi-terminal Josephson junctions as topological materials

09:50 -10:15 **Sergey Mironov**

Double path interference and magnetic oscillations in Cooper pair transport through a single nanowire

10:15-10:40 **Jan Aarts**

Large proximity effects in superconducting spin valves involving CrO_2

10:40 -11:10 ***Coffee break***

11:10-11:35 **Joseph Indekeu**
Proximity-induced interface delocalization in type-I superconductors

11:35-12:00 **Valery Ryazanov**
Superconducting hybrids: from sandwiches to planar structures

12:00-12:25 **Alexander Golubov**
Properties of double-barrier SISFS Josephson junctions

12:25-14:00 ***Lunch***

14:00-14:25 **Jacob Linder**
Tunnel spectroscopy and critical temperature in SF hybrids with Rashba-Dresselhaus spin-orbit coupling

14:25-14:50 **Sebastian Bergeret**
Charge, spin and heat transport in superconducting hybrid devices

14:50-15:15 **Oleksandr Dobrovolskiy**
Superconducting proximity effect in Pb/Au nanowires

15:15-15:40 **Matthias Eschrig**
Challenges for Modeling Superconducting Hybrids involving Strongly Spin-Polarized Ferromagnets

15:40-16:10 ***Coffee break***

16:10-16:35 **Anatolie Sidorenko**
Detection of the triplet pairing and memory effect in superconductor/ /ferromagnet hybrid nanostructures

16:35 -16:50 **William Magrini** (15')

Direct evidence of the flexomagnetoelectric effect revealed by single molecule spectroscopy

16:50-17:15 **Alexey Samokhvalov**

Long-range singlet Josephson current through ballistic ferromagnetic nanowires

17:15-17:40 **Andreas Bill**

Persistence of singlet correlations: a comparative study of superconducting-magnetic hybrid structures

17:40-18:05 **Vasily Stolyarov**

Vortices at the surface of a normal metal coupled by proximity effect to a superconductor

18:05-18:30 **Zeljko Jelic** (15')

Influence of the dynamic pinning geometry on the stroboscopic phenomena in superconductors

20:00 ***Dinner***

Tuesday, May 19

09:00 -09:25 **Brigitte Leridon**

Confinement of superconducting fluctuations due to emergent electronic inhomogeneities in ultrathin NbN films

09:25-09:50 **Goran Karapetrov**

STM investigation of $Fe_{1-x}Se_x$

09:50 -10:15 **Carmine Attanasio**

Change of the topology of a superconducting thin film electromagnetically coupled with an array of ferromagnetic nanowires

10:15-10:40 **Nicolas Bergeal**

Field-effect control of superconductivity and Rashba spin-orbit coupling in $LaAlO_3$/$SrTiO_3$ devices

10:40-11:10 ***Coffee break***

11:10-11:35 **Stefano Gariglio**

Study of superconductivty at $LaAlO_3$/$SrTiO_3$ interface by field effect

11:35-12:00 **Sergio Caprara**

Inhomogeneous superconductivity at oxide interfaces

12:00-12:25 **Manuel Houzet**

Quasiclassical theory of disordered Rashba superconductors

12:25-12:50 **Andrey Varlamov**

How the phase slips in a current-biased narrow superconducting stripe?

12:50-13:00 ***Closing of the workshop***

13:00 ***Lunch***

Departure

Abstracts

Emergence of Superconductivity and Vortex Confinement in Superconductor/Ferromagnet Hybrids

Maria Iavarone[1], Steven A. Moore[1], Jan Fedor[1], Valentyn Novosad[2], J. Pearson, , Samuel T. Ciocys [3], and Goran Karapetrov[4]

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Magnetically coupled superconductor-ferromagnet systems have been studied by low temperature Scanning Tunneling Microscopy and Spectroscopy.

The stray field of the ferromagnet induces a non-uniform superconducting state characterized by a local superconducting critical temperature Tc and a non monotonic behavior of Tc vs H close to the critical temperature [1,2].

We studied Pb/[Co/Pd] systems and we visualized the emergence of superconductivity in regions above the separation between adjacent magnetic domains, as well as reverse domain wall superconductivity[3]. Moreover, deep in the superconducting state vortices of opposite polarity are induced by the stray field of the ferromagnet in zero applied external field and they are strongly confined on the stripe of the same polarity. The nucleation of spontaneous vortex-antivortex strongly depends on the domain width.

Our results demonstrate that such S/F structures are attractive model systems that offer the possibility to control the strength and the location of the superconducting nuclei.

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[3] M. Iavarone, S. A. Moore, J. Fedor, S. T. Ciocys, G. Karapetrov, J. Pearson, V. Novosad and S. D. Bader, *Nature Communications* **5**, 4766 (2014)

Vortex dynamics at the sub-nanometer scale

Y. Anahory[1], L. Embon[1], A. Suhov[1], D. Halbertal[1], J. Cuppens[1], A. Yakovenko[1], Y. Myasoedov[1], M.L. Rappaport[1], M.E. Hubert[2], A.V. Gurevich[3] and E. Zeldov[1]

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[2] *Department of Physics, University of Colorado Denver, Denver, USA, 80217*
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NanoSQUIDs residing on the apex of a quartz tip (SOT), suitable for scanning probe microscopy with record size, spin sensitivity, and operating magnetic fields, are presented[1]. We have developed SOT made of Pb with an effective diameter of 46 nm and flux noise of $\Phi_n = 50\ n\Phi_0/Hz^{1/2}$ at 4.2 K that is operational up to unprecedented high fields of 1 T[2]. The corresponding spin sensitivity of the device is $S_n = 0.38\ \mu_B/Hz^{1/2}$, which is about two orders of magnitude more sensitive than any other SQUID to date.

We use this technique to study vortex matter in superconductors. At low vortex density and low currents, we measure the fundamental dependence of the elementary pinning force of multiple defects on the vortex displacement. The outstanding magnetic sensitivity of the SOT allows probing vortex displacements as small as 10 pm[3]. This study reveals rich internal structure of the pinning potential and unexpected phenomena such as softening of the restoring force and abrupt depinning. The results shed new light on the importance of multi-scale random disorder on vortex dynamics and thermal relaxation.

[1] A. Finkler, Y. Segev, Y. Myasoedov, M. L. Rappaport, L. Neeman, D. Vasyukov, E. Zeldov, M. E. Huber, J. Martin and A. Yacoby, Nano Lett. 10, 1046 (2010)

[2] D. Vasyukov, Y. Anahory, L. Embon, D. Halbertal, J. Cuppens, L. Neeman, A. Finkler, Y. Segev, Y. Myasoedov, M. L. Rappaport, M. E. Huber, and E. Zeldov, Nature Nanotech. 8, 639 (2013).

[3] L. Embon, Y.Anahory, A. Suhov, D. Halbertal, J. Cuppens, A. Yakovenko, A. Uri, Y. Myasoedov, M.L. Rapparport, M.E. Huber, A. Gurevich and E. Zeldov, Scientific Reports 5 (2015) 7598

Interplay of charge and vorticity quantization in superconducting Coulomb blockaded island

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The angular momentum or vorticity of Cooper pairs is shown to affect strongly the charge transfer through a small superconducting island of a single electron transistor (SET) shown in Fig.1. This interplay of charge and rotational degrees of freedom in a mesoscopic superconductor occurs through the effect of vorticity on the quantum mechanical spectrum of electron-hole excitations. The subgap quasiparticle levels in vortices can host an additional electron, thus, suppressing the so-called parity effect in the superconducting island. We propose to measure this interaction between the quantized vorticity and electric charge via the charge pumping effect caused by alternating vortex entry and exit controlled by a periodic magnetic field. Vortex entry and exit from the sample is accompanied by synchronized entry and exit of a single electron charge. Applying the bias voltage and oscillating magnetic field one can observe a vortex governed turnstile phenomenon: the switching between the Meissner and vortex states periodically opens the device for single charge transfer. Thus, we have demonstrated that the SET devices provide a unique tool for manipulating the collective dynamics of charge and vorticity in mesoscopic superconducting samples.

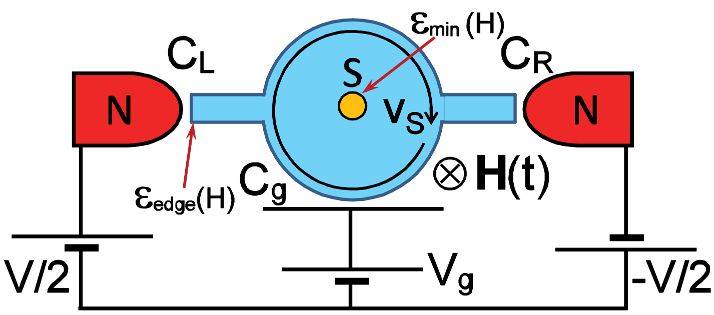

Figure 1: Setup of the NISIN SET with a bias voltage ±V/2 applied to the normal metal electrodes tunnel coupled to the central S disc with capacitances C_L and C_R. Magnetic field is applied perpendicular to the disc plane.

This work has been supported in part by Academy of Finland though its LTQ CoE grant (project no. 250280), the European Union Seventh Framework Programme INFERNOS (FP7/2007-2013) under Grant Agreement No. 308850, by the Russian Foundation for Basic Research, the Russian president foundation (SP- 491.2012.5), and the grant of the Russian Ministry of Science and Education No. 02.B.49.21.0003.

Vortices in Small Concave Decagon $Mo_{80}Ge_{20}$ Plate

Hitoshi Masutmoto[1], Hiroki Miyoshi[1], Takuto Okamoto[1], Vu The Dang[*1,2], Ho Thanh Huy[1,2], Shigeyuki Miyajima[1,3], Hiroaki Shishido[1,3], Masaru Kato[2,4], Masahiko Hayashi[5], Takekazu Ishida*[1,3]

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Vortices tend to form a triangle lattice in a bulk type-II superconductor due to repulsive interaction between vortices [1]. However, it is interesting to explore exotic vortex states in restricted small-sized superconducting plates. We reported the vortex profile of the pentagon in our preceding work [2]. A regular concave decagon has ten edges and two sets of five vertices. Especially, a role of concave inner angle (> 180 degree) seems to be interesting to understand the way how to penetrate vortex penetration a restricted regime. Amorphous superconducting $Mo_{80}Ge_{20}$ films were deposited by a DC sputtering apparatus, and were patterned in a desired shape with the aid of electron beam lithography (EB) and a lift-off technique. The circumradius of a concave decagon plate is 70 μm and thickness is 200nm. We investigated the vortex distribution in the plate by using a scanning SQUID microscope (see Fig. 1). We also compare experimental results of vortex configuration for the concave decagon with theoretical calculations based on the nonlinear Ginzburg-Landau (GL) equation. We also apply the numerical method to improve the spatial resolution of the scanning SQUID microscope in terms of the inverse Biot-Savart law [3].

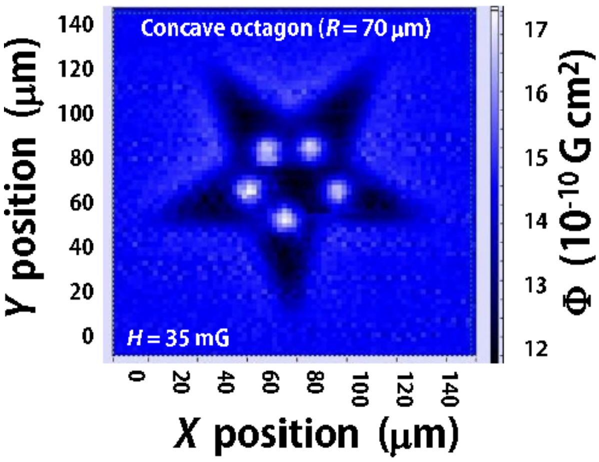

Figure 1. Vortices in concave decagon measured by a scanning SQUID microscope.

References

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Acknowledgments

This work was partly supported by Grant-in-Aid for challenging Exploratory Research (No. 25600018) from the MEXT, Japan, Grant-in-Aid for Young Scientists (B) (No. 26820130 and No. 26800192) from JSPS, and Grant-in-Aid for Scientific Research (S) (No. 23226019) from JSPS.

Dynamic Vortex Mott Transition in a Proximity Array of Superconducting Islands

Valerii M. Vinokur,[1] Nikola Poccia[2,3], , Francesco Coneri[2], Cor G. Molenaar[2], X. Renshaw Wang[2], Ginestra Bianconi[4], Alexander Brinkman[2], Hans Hilgenkamp[2], Alexander A. Golubov[2,5], and Tatyana. I. Baturina[6,7]

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Transport measurements on a square array of superconducting islands placed on a normal metal reveal vortex Mott insulator and dynamic Mott insulator-to-metal transition. We demonstrate dynamic scaling behaviour of differential resistivity near the Mott critical points as function of the applied current and magnetic field and establish that Mott dynamic transitions at integer and fractional filling factors belong in different universality classes. Using quantum mechanics-statistical physics mapping we derive critical exponents for Mott transition. The experimentally determined critical exponents are in excellent agreement with the values expected from the out-of-equilibrium mean field considerations. We demonstrate that the dynamics of the vortex Mott state is governed by the thermally activated vortex motion establishing thus the real physical content of the quantum mechanics-statistical physics mapping where thermally activated dynamics of classical objects corresponds to quantum tunnelling of quantum particles.

Classical analogy for the deflection of flux avalanches by a metallic layer

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Motivated by the experimental observation of the exclusion of magnetic flux avalanches in a superconducting sample partially covered by a conducting capping layer[1], we have investigated the simplified case of the interaction of a magnetic charge (monopole and dipole) with a semi-infinite conducting plane[2]. We have found that early theoretical descriptions for the damping enhancement due to the metallic sheet[3] needed a correction at large vortex velocities where a decrease of the damping coefficient is expected. We also demonstrate that vortex trajectories are strongly modified when penetrating into the area covered by the metallic sheet and may even be fully diverted from that area thus providing a qualitative explanation for the bending of the trajectories of flux avalanches. Our findings may be extended to study the damping of Larkin-Ovchinnikov vortex instabilities and phase-slip lines in current driven systems.

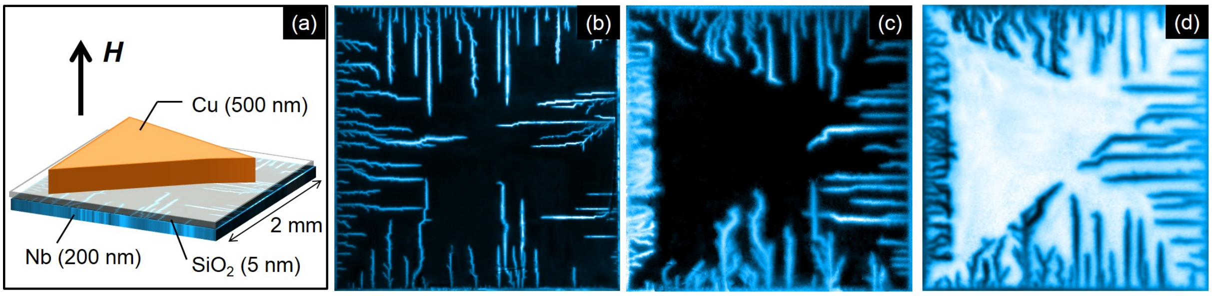

Figure 1: (a) Sketch of the sample layout. Panels (b) and (c) show magneto-optical images (MOI) taken at $T = 2.5$ K after zero-field cooling in $H = 10$ Oe for the Nb sample before (b) and after (c) covering it with the Cu triangle. The bright areas correspond to the highest magnitudes of the magnetic field, while the dark areas represent the lowest fields. In (d) a MOI picture of the Nb sample with the Cu triangle after field-cooling in $H = 10$ Oe down to $T = 2.5$ K and subsequently turning off the magnetic field. In (d) the color bar has been inverted such that antivortex avalanches appear as brighter.

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Hybrid phenomena in two-gap superconductors

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Multiband/gap superconductivity is emerging as a complex quantum coherent phenomenon with physical consequences which are different from or cannot be found at all in single-gap superconductors. This became particularly relevant after the recent discoveries of predominantly multi-band/gap superconducting materials, e.g. transition metal-borides, iron pnictides and chalcogenides. In these materials the cross-pairing between bands is typically disfavored energetically, hence multiple coupled condensates coexist, hybridize and govern the overal superconducting behavior. The increased number of degrees of freedom allows for novel effects which are unattainable otherwise.

In this talk, I will focus on few such effects, and discuss their theoretical predictions, simulations and experimental evidences. In particular, I will discuss the emergence and stabilization of fractional-flux vortices [1], their dynamics and observation in magnetic and transport measurements, then hidden criticality [2] where lengthscales of involved condensates become radically disparate, and unusual magnetic behavior that cannot be classified into standard types [3] and can lead to e.g. *giant* paramagnetic response [4].

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Scanning Hall probe microscopy of vortex matter in S/F hybrids, type-1, type-1.5 and type-2 superconductors (*)

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Scanning Hall probe microscopy (SHPM) has been used to directly visualize vortex matter in S/F hybrids, type-1, type-1.5 and type-2 superconductors. In S/F hybrids domain wall and reverse domain superconductivity has been investigated. Vortex matter modifications in Pb wedge sample covering all the ranges from type-2 to type-1 superconductivity has been studied. Vortices in the intermediate state of a thick type-1 superconducting Pb film have been visualized for different Pb thicknesses. In low fields we have observed the presence of stable (or quasi stable) single flux quantum vortices, as well as a few flux quanta vortices. Unusual vortex patterns have been observed in the type-II/1 and type-II-2 regimes in the vicinity of the dual point $\lambda/\xi=1/\sqrt{2}$. The role of surface barriers in stabilizing these vortex patterns has been discussed.

The existence of the novel superconducting state has been demonstrated in two-component high quality MgB_2 single crystals where a unique combination of both type-1 and type-2 conditions is realized in the same material: $\lambda_1/\xi_1<1/\sqrt{2}$ for the first and $\lambda_2/\xi_2>1/\sqrt{2}$ for the second component of the order parameter. Such materials are, in fact, neither type-1 nor type-2 superconductors and can be introduced as "*type-1.5 superconductors"*. This leads to an appearance of unconventional vortex arrangements such as stable *vortex stripes*, *clusters and gossamer-like vortex patterns.* We have directly visualized these novel patterns by using scanning Hall probe microscopy (SHPM), Bitter decoration and scanning SQUID microscopy. The observed vortex patterns are in a good agreement with the molecular dynamics simulations based on the vortex-vortex interaction corresponding to type-1.5 superconductivity. In higher applied fields normal type-2 vortex patterns are recovered in MgB_2.

(*) In collaboration with: J.Y. Ge, J. Gutierrez, M. Timmermans, J. Van de Vondel, A.V. Silhanek, T. Nishio, Q.H. Chen, L.J. Li, V. H. Dao, L.F. Chibotaru, B.Y. Zhu, V. Gladilin and J.T. Devreese

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Coherent coupling of a single spin to microwave cavity photons

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Electron spins and photons are complementary quantum mechanical objects which can be used to carry, manipulate and transform quantum information. Combining them into a scalable architecture is an outstanding challenge. In this context, the coherent coupling of a single spin to photons stored in a superconducting resonator is an important milestone. Using a circuit design based on a nanoscale spin-valve, we implement an artificial spin-orbit interaction and coherently hybridize the individual spin and charge states of a double quantum dot made in a single wall carbon nanotube while preserving spin coherence. This scheme allows us to increase by five orders of magnitude the natural (magnetic) spin-photon coupling, up to the MHz range at the single spin level. Our coupling strength yields a cooperativity which reaches 2.3, with a spin coherence time of about 60ns. We thereby demonstrate a mesoscopic device which could be used for non-destructive spin read-out and distant spin coupling.

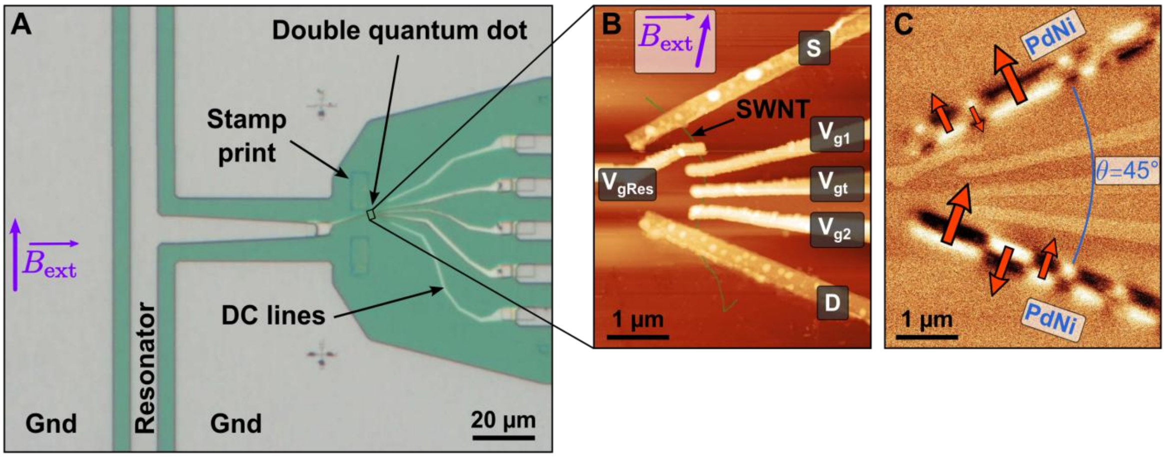

Figure 1: **A.** Optical micrograph of the main part of the device. **B.** AFM picture of the carbon nanotube double quantum dot **C.** Magnetic force microscope picture of the non-collinear ferromagnetic electrodes inducing the artificial spin-orbit interaction needed for the coherent spin/photon interface.

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Microwave-stimulated superconductivity due to presence of vortices

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The response of superconducting devices to electromagnetic radiation is a core concept implemented in diverse applications, ranging from the currently used voltage standard to single photon detectors in astronomy. At temperatures sufficiently below the critical temperature, the microwave radiation in the GHz range may depin vortices. In plain superconducting Pb films it can be observed a distribution of depinning frequencies [1] which manifest themselves in the form of flux avalanches. Covering a periodic array of Permalloy dots in the magnetic vortex state with thin Pb films may result in a single vortex depinning frequency coexisting with spin wave modes in Py and with ferromagnetic resonance in magnetically saturated state.

Surprisingly, a sufficiently high power subgap (GHz) radiation not far below the critical temperature may stimulate superconductivity itself [2]. Here we report on the possibility of stimulating also a type II superconductors, in which the radiation may cause a nonlinear response of the vortex core [3]. We investigate microwave-stimulated superconductivity due to presence of vortices in superconducting Pb films grown over arrays of Permalloy dots in magnetic vortex state and compare our results with a reference plain Pb films. The stimulation effect is more clearly observed in the upper critical field and less pronounced in the critical temperature. The magnetic field dependence of the vortex related microwave losses in a film with periodic pinning reveals a reduced dissipation of mobile vortices in the stimulated regime due to a reduction of the core size. This hypothesis has been confirmed by numerical simulations. The study of magnetic hysteresis of the microwave stimulated effects show that due to their minimum stray magnetic fields, Py dots seem to pin superconducting vortices mainly by vortex cores and through a periodic disturbance of the regular pinning potential as long as they are covered by superconducting films and not vice versa. Finally, we show that microwave stimulation effects due to the presence of vortices open the possibility of effective control over vortex avalanches. We observe that microwave stimulated superconductivity induces a notable increase of microwave depinning power needed to trigger avalanches in the proximity of vortex depinning frequencies. Our findings open new ways to tune vortex dissipation and depinning in plain films and superconductor-ferromagnet hybrids by superconductivity stimulation.

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Direct Observation of Josephson Vortex Cores

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Superconducting correlations may propagate between two superconductors separated by a tiny insulating or metallic barrier, allowing a dissipationless electric current to flow[1,2]. In the presence of a magnetic field, the maximum supercurrent oscillates[3], each oscillation corresponding to the entry of one Josephson vortex into the barrier. Josephson vortices are conceptual blocks of advanced quantum devices such as coherent terahertz generators or qubits for quantum computing, in which on-demand generation and control is crucial. Here, we map superconducting correlations inside proximity Josephson junctions using scanning tunneling microscopy. Unexpectedly, we find that such Josephson vortices have real cores, in which the proximity gap is locally suppressed and the normal state recovered. By following the Josephson vortex formation and evolution we demonstrate that they originate from quantum interference of Andreev quasiparticles, and that the phase portraits of the two superconducting quantum condensates at edges of the junction decide their generation, shape, spatial extent and arrangement. Our observation[4] opens a pathway towards the generation and control of Josephson vortices by applying supercurrents through the superconducting leads of the junctions, that is, by purely electrical means without any need for a magnetic field - a crucial step towards high-density on-chip integration of superconducting quantum devices.

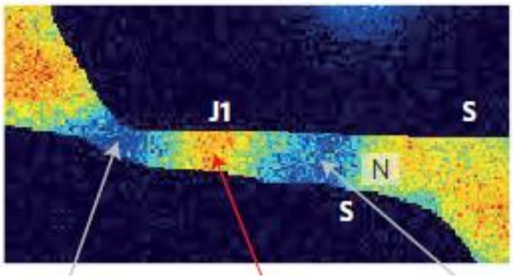

Figure 1: Josephson vortex core (marked by red arrow) inside SNS junction[4].

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Microwave measurements in Nb/PdNi/Nb heterostructures: $0-\pi$ transition, vortex state and structural properties.

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Superconducting/ferromagnet (S/F/S) heterostructures show a variety of interesting and complex phenomena [1], due to the interplay of two different and competing orderings. Owing to the short ferromagnetic coherence length ξ_f (a few nm) of strong ferromagnets, weak ferromagnets have been often employed, e.g. in Josephson-junction-like experiments, due to easier control of the geometrical conditions. In this work we adopt a different approach: we measure the microwave response of unpatterned Nb/PdNi/Nb trilayers, thus probing the S/F/S structure as a whole. We have used a combination of resonant (8 GHz dielectric resonator) and wideband (2-20 GHz Corbino disk) methods. Measurements of the surface impedance variations with magnetic field H ($\leq H_{c2}$) and temperature T (≥ 3 K) yielded several physical observables: the T-shift of the London penetration depth, the H and T dependence of the free flux flow resistivity ρ_{ff} and of the pinning constant.

The microwave measurements on fresh samples gave evidence of the thermodynamic nature of the temperature–induced $0-\pi$ transition in the sample with appropriate F layer thickness $d_f = 2$ nm [2]. The signature was a nonmonotonous temperature dependence of the order parameter, that could be very well described by the theory developed for thin F layers sandwiched between thick S layers with transparent interfaces [2]. Anomalous ρ_{ff}, well in excess of the conventional Bardeen-Stephen value, was found in samples with F layers thick enough that the π state is supposed to be realized. Extensive measurements showed that the crossover from conventional to unconventional behaviour arises by crossing the critical thickness ($d_f = 2$ nm) where the $0-\pi$ transition is observed.

Finally, measurements on samples aged more than 12 months yielded surprising effects: the signature of the $0-\pi$ transition appeared in the sample with thicker $d_f = 8$ nm, albeit broadened, and it moved much closer to T_c in the sample with $d_f = 2$ nm. Motivated by these results, we have explored the local atomic structure by X–ray Absorption Fine Structure spectroscopy (at the Ni, Nb and Pd absorption K edges), and the chemical composition along the sample thickness by ToF-SIMS. We have found evidence of interdiffusion (Ni–Nb and Pd–Nb phases), of a change in the composition of the F alloy with respect to the nominal composition, of a deterioration of the interfaces and of a reduction of the F thickness in samples with larger d_f. The fact that the signatures of the $0-\pi$ transition are still present, but in the sample with thicker d_f, indicates that the transition is robust with respect to interface nonidealities. Thus, a full theory for S/F/S heterostructures should allow also for nonideal interfaces.

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Density of states and tilted vortex lattices of the multiband superconductor β-Bi_2Pd

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We present scanning tunneling microscopy (STM) experiments on single crystalline samples of the superconductor β-Bi_2Pd. We measure at 150 mK and find surfaces showing the square atomic lattice and spatially homogeneous superconducting density of states following single gap s-wave BCS theory. We find multiband features in $H_{c2}(T)$ and in the magnetic field dependence of the intervortex density of states. The orientation of the hexagonal vortex lattice, observed up to $H_{c2}(T)$ is locked to the square crystalline lattice. We show how the mixed phase of superconductors is influenced by multiband features of the Fermi surface, even when the zero field gap structure follows single gap s-wave BCS theory. We make a detailed study of tilted vortex lattices, in practically all azimuthal and polar angles. We find, through a comparison with expectations with an isotropic superconductor, the correlation between the four-fold square atomic lattice and tilted vortex lattices. β-Bi_2Pd turns out to be a model crystalline superconductor with an excellent surface, an isotropic gap and anisotropic crystalline properties that result in a mixed phase.

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φ, φ_0 and $\varphi_0 \pm \varphi$ Josephson junction based on a 0-π SQUID

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Recently, our group has demonstrated experimentally[1] the first φ Josephson junction (JJ) based on a superconducting-insulator-ferromagnet-superconductor (SIFS) heterostructure with tailored F-layer. Such a φ JJ has very unusual properties[2], e.g., a doubly degenerate ground state phase $\pm\varphi$, two critical currents $I_{c\pm}$ and non-trivial retrapping dynamics[3]. The first potential applications were demonstrated, e.g., a memory cell[4]. Although the proposed system behaves as a φ JJ, it has several bottlenecks. For example, the φ domain, where the developed theory works, is extremely slim. Also, scaling down the size of the junction is not easy.

Here we consider theoretically and model numerically a very similar discrete system — a 0-π SQUID with asymmetric inductances and critical currents of the JJs in two branches. By considering such a SQUID as a black box with two electrodes we calculate its effective current-phase relation $I_s(\psi)$ and Josephson energy $U(\psi)$, where ψ is the phase drop across the black box (SQUID). We show that there is domain of parameters where the black box has the properties of φ JJ (with degenerate ground state $\psi \pm \varphi$) or φ_0 JJ (with unique ground state $\psi = \varphi_0$). The φ domain is rather large, so one can easily construct φ JJ experimentally. The current phase relation can be tuned *in situ* by applying an external magnetic flux resulting in a continuous transition between the systems with the ground states $\psi = \pm\varphi$, $\psi = \varphi_0$ and even $\psi = \varphi_0 \pm \varphi$. The dependence of φ_0 on applied magnetic flux is not 2π periodic, i.e., the period is *not* equal to one flux quantum.

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Escape dynamics from Josephson to phase slip modes

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We have characterized the escape dynamics of different types of Josephson junctions also in unconventional regimes, through the measurement of switching current distributions (SCD). We have used SCD as a sophisticated detector at the same time of resistance and phase dynamics in an unprecedented energy range. We observe a transition from classical Josephson phase dynamics, which takes place in junctions characterized by low values of critical current density Jc, to a regime in which dissipation is driven by local heating processes, for high values of Jc. These results point to a more articulate phase diagram of weak links in terms of electrodes coupling and dissipation.

This transition is of relevance for all kinds of weak links including the emergent family of nano-hybrid junctions, including nanowires, two-dimensional graphene and topological insulator flakes as barriers. Information on the search of quantum phase slips can be also derived.

Bi_2Pd, the multiband superconductor. Thermodynamic and STM studies of the superconducting energy gap

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Imai and coworkers [1] suggest that the β-Bi_2Pd compound is another example of a multi-band/multi-gap superconductor. The first principle calculations [2] and ARPES measurements [3] approve unusual 2D/3D type of multi-sheet Fermi surface, which comprises four main hole- and electronic-like pockets. Here, we report a bulk calorimetric study and a surface sensitive STM spectroscopy performed on the superconducting single crystals of β-Bi_2Pd with the critical temperature T_c close to 5 K with different residual resistivities. The measurements have been done by a sensitive *ac* technique in the temperature range down to 0.6 K and magnetic fields up 1 Tesla. All the measurements show sharp and well defined specific heat anomaly at the superconducting transition, however the overall temperature dependence of specific heat indicates an existence of only single energy gap in the system. We will analyze the results in terms of the superconducting coupling strength, the upper critical fields and their temperature and angular dependence. The subkelvin STM measurements yield also a single superconducting gap in the system.

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New light on the electronic vortex core structure and normal state in $YBa_2Cu_3O_{7-\delta}$

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The interaction responsible for high-temperature superconductivity in the cuprates has remained elusive until now. Various charge orders suggest that the electronic matter in these compounds experiences competing interactions, while some spectroscopic data support the scenario of preformed pairs gaining coherence at low temperature. The vortices offer a chance to disentangle the spectral features related to pairing from those that are unrelated. In this context, the observation of discrete low-energy states in the vortex cores [1] has been a considerable challenge for the theory, because the expected tunneling spectrum in a vortex of d_{x2-y2} symmetry presents a broad continuous maximum centered at zero bias. We performed high-resolution STM measurements in optimally doped $YBa_2Cu_3O_{7-\delta}$ single crystals, and found that the low-energy states are not exclusively bound to vortices. This spectral feature is ubiquitous in zero field, even in spectra without superconducting coherence peaks. The new phenomenology reshuffles the cards for the theory of vortex cores.

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Epitaxial Rare-Earth / Superconductor Spin Valves

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The superconducting spin valve (SSV) exploits proximity-coupling between a superconductor and two ferromagnet (F) layers such that the exchange-induced suppression of the critical temperature (T_c) is controlled by the relative magnetization orientation of the F layers [1]. To date, experimental realization of this effect has been limited to transition metal (TM) F layers and the maximum ΔT_c between parallel (P) and antiparallel (AP) orientation is about 40 mK, with a T_c below 0.4 K [2]. In all cases ΔT_c is much smaller than theoretically predicted.

Here we report results from SSVs comprising two epitaxial rare earth (RE) films, either Ho or Dy, sandwiching epitaxial Nb which showed an irreversible zero-field critical temperature change (ΔT_{c0}) ≈ 700 mK between spin-spiral (S) [3] and parallel ferromagnetic (P) states and a reversible ΔT_{c0} ≈ 400 mK between P and antiparallel ferromagnetic (AP) states (see Fig. 1).

To compare our results with theory, the T_{c0} of the three states (S, P, AP) were found by solving the linearized Usadel equation via a self-consistent numerical procedure. This model can quantitatively fit the experimental results for the RE thickness dependence of ΔT_{c0}; however, while most of the fitting parameters are within reasonable ranges, the fitted exchange energy E_{ex} for both Ho and Dy are extraordinarily small (~ 1 meV) and several orders of magnitude smaller than the calculated and inferred 5*d*/6*s* and 4*f* exchange splitting for Res. The issue of the how to define the effective E_{ex} *as seen by the Cooper pairs* is thus a question which needs detailed consideration.

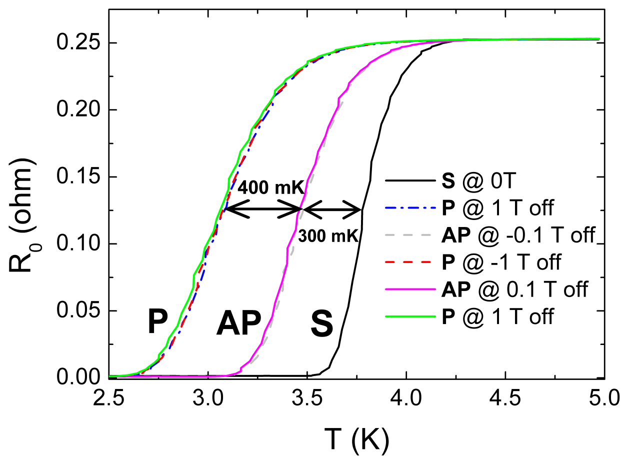

Figure 1: Zero-field resistance versus temperature curves of a Ho/Nb/Ho SSV following different set field histories different which correspond to different states (S, P, and AP)

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Multi-terminal Josephson junctions as topological materials

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Topological materials and their unusual transport properties are now at the focus of modern experimental and theoretical research. Their topological properties arise from the bandstructure determined by the atomic composition of a material and as such are difficult to tune and naturally restricted to ≤ 3 dimensions.

We put forward an idea that looks both striking and very simple. Namely, we establish the occurence of topological transitions in multi-terminal superconducting junctions with conventional superconductors. A junction with $n \geq 4$ terminals provides an opportunity to realize a topological material in $n-1$ dimensions, an opportunity that did not seem realistic so far. In particular, we find that the Andreev subgap spectrum of the junction can accommodate Weyl singularities in the space of the $n-1$ independent superconducting phases, which play the role of bandstructure quasimomenta.

The topology can be easily probed experimentally. It manifests itself in the transconductance between two voltage-biased terminals being quantized in fundamental units of $2e^2/(\pi\hbar)$. This resembles the integer Quantum Hall effect although based on a completely different physical mechanism.

Double path interference and magnetic oscillations in Cooper pair transport through a single nanowire

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We show that the critical current of the Josephson junction consisting of superconducting electrodes coupled through a nanowire with two conductive channels can reveal the multi-periodic oscillations as a function of the magnetic field H directed perpendicular to the wire [1]. The multi-periodicity originates from the quantum mechanical interference between the channels affected by both the strong spin-orbit coupling and Zeeman interaction. This minimal two-channel model is shown to explain the complicated interference phenomena observed recently in Josephson transport through Bi nanowires [2].

The Zeeman interaction produces the spatial oscillation of the Cooper pair wave-function at the scale $\hbar v_F/g\mu_B H$ (similar to the ones in superconductor-ferromagnet structures [3]) which result in the magnetic oscillations of the critical current with the period $\hbar v_F/g\mu_B L$, where L is the channel length.

The orbital effect causes a standard phase-gain $\sim 2\pi HS/\Phi_0$ ($\Phi_0 = \pi\hbar c/|e|$ is the flux quantum) in the electronic wave-function similar to the one appearing in the Aharonov-Bohm effect. Here S is the area enclosed by the pair of the interfering paths projected on the plane perpendicular to the magnetic field. The interfering quantum mechanical amplitudes in this case cause the magnetic oscillations in the total transmission amplitude with the period $2\Phi_0/S$. The Andreev reflection at the superconducting leads can double the effective charge in the oscillation period and, we demonstrate that in the general case the resulting critical current oscillates with the competing periods $2\Phi_0/S$ and Φ_0/S.

The spin-orbit coupling can substantially change the current-phase relation of the Josephson junction and produce the spontaneous Josephson phase difference φ_0 in the ground state [4]. Despite this anomalous Josephson effect was found within several different theoretical models its microscopical origin still remains disputable. We clarify this question and show that the key ingredient for the φ_0-junction formation is the nonparabolicity of the electron energy spectrum, which in the presence of spin-orbit coupling gives rise to the dependence of the Fermi-velocity on momentum direction. Under the influence of the Zeeman field such specific dependence results in the spontaneous Josephson ground state phase φ_0 and in the renormalization of the above magnetic oscillation periods.

This work was supported by the French ANR "MASH," NanoSC COST Action MP1201, the Russian Foundation for Basic Research, the Russian Presidential foundation (grant SP-6340.2013.5), and Russian Ministry of Science and Education (grant 02.B.49.21.0003).

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Large proximity effects in superconducting spin valves involving CrO_2

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Combining superconductors (S) and ferromagnets (F) offers the opportunity to create a new class of superconducting spintronic devices. In particular, the S/F interface can be specifically engineered to convert singlet Cooper pairs to spin-polarized triplet Cooper pairs. The efficiency of this process can be studied using a so called triplet spin valve (TSV), which is composed of two F-layers and an S-layer. When the magnetizations in the two F-layers are not collinear, singlet pairs are drained from the S-layer, and triplet generation is signalled by a decrease of the critical temperature T_c. Here, we build highly efficient TSVs using a 100% spin polarized half-metallic ferromagnet, CrO_2 and Cu/Ni/MoGe stacks to generate triplets. The application of out-of-plane magnetic fields results in an extremely strong suppression of T_c (measured as 50% of the resistive transition) by 0.5 K in a field of 0.25 T (see Fig. 1), and well over a Kelvin in fields above a Tesla. The observed effect is an order of magnitude larger than previous studies on TSVs with standard ferromagnets. Furthermore, we shall demonstrate that this triplet proximity effect is strongly dependent on the transparency and spin activity of the interface.

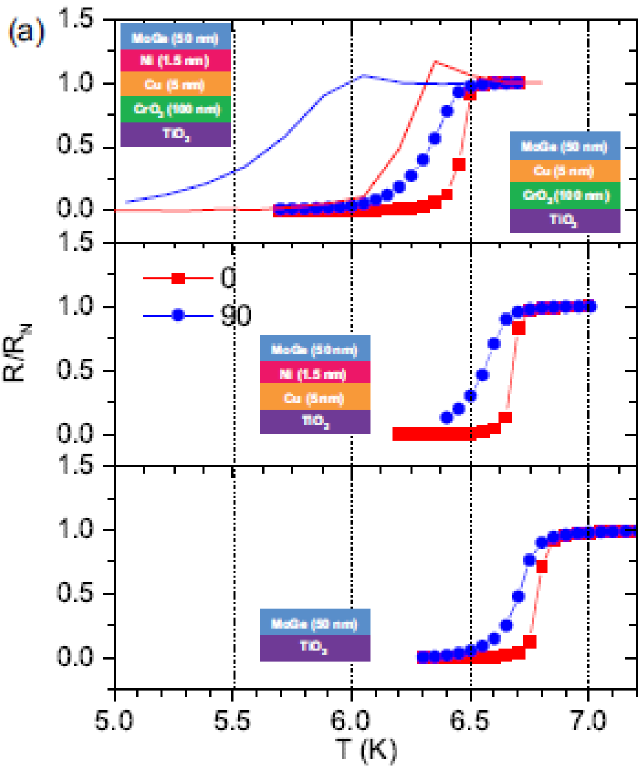

Figure 1: Top panel : the drawn lines show the resistive transitions (R-T) for a MoGe(50 nm) / Ni(1.5 nm) / Cu (5 nm) / CrO_2 stack in zero field and in a perpendicular field of 0.25 T. The dots show R_T for a similar stack but without the Ni layer. The middle and bottom panels show the other non-triplet-generating layer combinations MoGe(50nm) / Ni(1.5 nm) / Cu(5 nm) on TiO_2 (middle), and MoGe(50 nm) on TiO_2 (bottom

Proximity-induced interface delocalization in type-I superconductors

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When the surface of a superconductor in the normal state is in contact with another material that is already superconducting in bulk, then, by the proximity effect, a superconducting surface sheath is present. The investigation of the question whether the thickness of the sheath diverges when the (parallel) critical field $H_c(T)$ is approached from above, has led to an interface delocalization phase diagram which resembles very closely the standard prewetting phase diagram for adsorbed fluids with a first-order prewetting line terminating at a simple prewetting critical point. While the interface delocalization transition in superconductors [1] has been observed experimentally for a single material [2], the proximity-induced variant [3,4] has not yet been verified. Further experimental investigation is called for, using Polarized Neutron Reflectometry and Low-Energy Muon Spin Rotation [5].

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Superconducting hybrids: from sandwiches to planar structures

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Josepson hybrids based on superconductors (S), normal metals (N) and ferromagnets (F) attract increasing attention in the last decade [1-7]. The most interesting and important observations were made mainly on S/F/S and S/F/N/S sandwiches [3-7]. Among them it should be noted the implementation of π-junction (superconducting phase inverter) [3-5], observation of the spin-triplet superconductivity [6], realization of SFS switches for ultra-low-power, high-density cryogenic memorie [7,8]. Modern fundamental and applied researches make the actual implementation and study of planar multiterminal S/F/N structures. Planar Josephson S-(F/N)-S structures with complex bilayered (F/N) barriers were proposed recently in [9] and realized in [10]. The structure, which we studied in [10], included a Cu/Fe bilayer forming a bridge between two superconducting Al electrodes. The appreciable critical current was detected up to 120 nm of the bridge length. It was observed a double-peak peculiarity in differential resistance of the S-(N/F)-S structures at a bias voltage corresponding to the superconducting minigap. The splitting of the minigap was explained by the electron spin polarization in the normal metal which was induced by the neighbouring ferromagnet. Our new observations are related to quasiparticle- and spin-injection to banks and barriers of planar Josephson junctions. First results were published in [11].

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Properties of SISFS Double-Barrier Josephson Junctions

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In recent years Josephson junctions with ferromagnetic (F) barriers became quite desirable and actively developed devices in superconductive electronics. Among them are memory elements, improved RSFQ circuits and metamaterial structures. Still, characteristic voltage, I_CR_N, of most existing SFS junctions is much smaller than that of tunnel SIS devices.

In this work we suggest SIsFS structures with complex interlayer consisting of tunnel barrier 'I', ferromagnetic layer 'F' and thin superconductor layer 's' and study modes of operation of these devices. We show that these structures may achieve high I_CR_N and therefore are promising for the use as high-speed π junctions or memory elements [1-2].

We study in detail the pairing state in a thin middle superconducting film 's' under proximity effect with ferromagnetic layer. The state of the 's' film is controlled by inhomogeneities in ferromagnetic layer. We study the impact of different types of inhomogeneities including domain walls and normal phase inclusions on supercurrent transport in SIsFS structures.

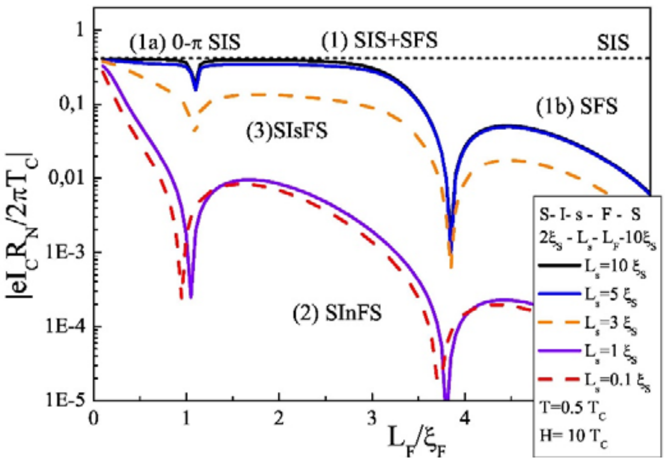

Fig.1. Operational modes of SIsFS structure: characteristic voltage I_CR_N versus thickness of the F-layer L_F for various s-layer thicknesses L_S

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Tunnel Spectroscopy and Critical Temperature in SF Hybrids with Rashba-Dresselhaus Spin-Orbit Coupling

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We study the proximity effect in superconductor-ferromagnet structures in the presence of an intrinsic antisymmetric spin-orbit coupling [1], taken to be of Rashba-Dresselhaus type for concreteness. Both a bilayer setup and a Josephson system are considered, where the proximity-altered spectroscopic features are sensitive to the superconducting phase-difference in the latter case. Utilizing a quasiclassical approach with the Usadel equation [2] and boundary conditions extended to incorporate the presence of antisymmetric spin-orbit coupling, we find that the spin-orbit coupling strongly modifies the density of states and its phase-dependence [3]. Unlike previous works that considered the effect of spin-orbit coupling only in the weak proximity effect regime, we derive a set of equations valid for an arbitrarily large proximity effect by using a Ricatti-parametrization [4]. This enables access to explore all types of strong spectroscopic features such as full minigaps and zero-energy peaks, which is important for experimental comparison. Moreover, we show that the presence of spin-orbit coupling allows for a control over T_c in a SF bilayer with a single ferromagnet by changing the magnetization orientation [3]. This is different from previous works, where a spin-valve setup with two ferromagnets has been required in order to control T_c via the relative magnetization orientation. Finally, we discuss ways in which our results can be probed experimentally.

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Charge, spin and heat transport in superconducting hybrid devices

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I will first present an interesting analogy between the spin diffusion process in normal metals and the generation of the triplet components of the condensate in a diffusive superconducting structure in the presence of spin-orbit coupling (SOC)[1]. From this analogy it turns out naturally how to include generic spin fields, as for example SOC, into kinetic equations for the superconducting state. As an example, I will show that SOC is an additional source of the long-range triplet component (LRTC) besides the magnetic inhomogeneities studied in the past. This opens a range of possibilities for the generation and manipulation of the triplet condensate in hybrid structures. In particular, I will demonstrate that a normal metal with a SO coupling can be used as source of LRTC if attached to a superconductor-ferromagnet (S-F) bilayer.

In the second part of the talk, I will focus on charge and heat currents in superconducting structures with ferromagnetic insulators (FI). The spin-splitting of the BCS density of the states induced in the superconductor leads to very interesting phenomena which I will illustrate by discussing : (i) a huge thermoelectric effect in a N-FI-S structure[2] , (ii) a magnetothermal valve based on a ferromagnetic Josephson junction[3], (iii) creation of magnetic fields induced by a temperature gradient[4] and (iv) an efficient temperature-to-frequency converter[5].

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Superconducting proximity effect in Pb/Au nanowires

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Our recent finding [1] of the long-range, odd-frequency spin-triplet proximity effect in polycrystalline Co nanowires revealed a large resistance contribution [2] stemming from the defect-rich areas of the nanowire underneath the focused ion beam-deposited W-based floating electrode. To obtain contacts eventually free of this drawback, an artificial, lead-based superconductor with $T_c \sim 7$ K was prepared for the first time [3] by much less destructive focused electron beam induced deposition (FEBID). The superconducting properties of Pb-FEBID nanowires are reported and the proximity effect in Au nanowires (width: 150 nm; thickness: 60 nm; e-beam lithography) in contact with Pb-FEBID leads is analyzed. In particular, the resistance data reveal that the Au nanowire goes completely superconducting over a length of at least 700 nm, see Fig. 1, thereby making the reported approach promising for the preparation of more sophisticated superconductor/ferromagnet hybrids [4] with laterally adjustable magnetic hardness of the ferromagnet [5,6].

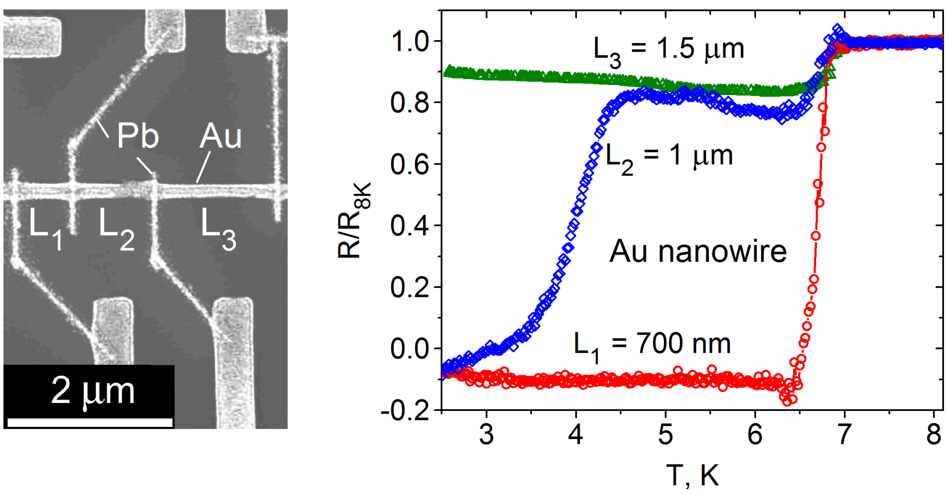

Figure 1: Left panel: SEM micrograph of the Au nanowire in contact with Pb-FEBID voltage leads. Right panel: Proximity-induced resistance drops of the three nanowire sections, as indicated. The resistance undershooting is attributed to quasiparticles imbalance effects [7].

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Challenges for Modeling Superconducting Hybrids involving Strongly Spin-Polarized Ferromagnets

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The field of superconducting spintronics, or "superspintronics", which emerged during the past 15 years, combines the phenomena of quantum coherence and interference with the phenomena of spin-selectivity and spin magnetism. The building blocks are spin-triplet Cooper pairs, which are generated at the interface between a superconducting and a ferromagnetic material. Non-collinear magnetic inhomogeneity creates long-ranged equal-spin Cooper pairs in the ferromagnet [1], and non-coplanar inhomogeneity introduces geometric phases giving rise to unusual current phase relations and to spin currents [2].

Whereas the theory for ballistic transport is well developed, for diffusive transport an appropriate set of boundary conditions was lacking for the case of hybrid structures with strongly spin-polarized ferromagnet. We have derived new boundary conditions for equilibrium and non-equilibrium quasiclassical Green functions for diffusive superconducting hybrid structures in terms of interface scattering matrices. These boundary conditions are appropriate for any spin polarization, transmission probability, and spin-mixing angle (spin dependent scattering phases). This generalizes the previously derived boundary conditions of Nazarov [3], and of Cottet et al. [4], which are applicable for small transmission probability, small spin polarization, and small spin-mixing angles for each transport channel of the interface. It also generalizes the phenomenological boundary conditions of Bergeret, Verso, and Volkov [5]. Our general boundary conditions for Usadel theory complement the previously derived general boundary conditions for Eilenberger-Larkin-Ovchinnikov theory [6].

We discuss various results for spin-valve geometries and point to the challenges which hybrid structures with strongly spin-polarized parts pose for realistic theoretical models. Our goal is to provide an appropriate framework for studying recent experimental results for hybrid structures involving ferromagnets like, e.g., iron, cobalt, nickel, CrO2, Heusler alloys, EuO, EuS, or $Y_3Fe_5O_{12}$.

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Detection of the triplet pairing and memory effect in superconductor/ferromagnet hybrid nanostructures

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Theory of superconductor-ferromagnet (S-F) heterostructures with two and more ferromagnetic layers predicts generation of a long-range, odd-in-frequency triplet pairing at non-collinear alignment (NCA) of the F-layers magnetizations [1]. Following the ideas of the superconducting triplet spin-valve [2-4] we have detected that triplet pairing: switching of the proximity effect coupled Co/CoO_x/$Cu_{41}Ni_{59}$/Nb/$Cu_{41}Ni_{59}$ heterostructures from normal to superconducting state. The resistance of the sample as a function of an external magnetic field shows that the system is superconducting at the collinear alignment of the $Cu_{41}Ni_{59}$ and Co layers magnetic moments, but switches to the normal conducting state at the NCA configuration. The existence of the T_c minimum at the NCA regime is consistent with the theoretical prediction of the long-range triplet pairing appearance.

The Co/CoO_x/$Cu_{41}Ni_{59}$/Nb/$Cu_{41}Ni_{59}$ layered heterostructures were prepared by magnetron sputtering on silicon substrate covered by a silicon buffer layer prior the heterostructures deposition [5]. The Co/CoO_x composite layer provided strong exchange biasing (~ 1800 Oe) of the adjacent hard ferromagnetic $Cu_{41}Ni_{59}$ alloy layer, while the outer soft $Cu_{41}Ni_{59}$ alloy layer could be remagnetized by a weak external magnetic field creating controllable alignments with respect to the hard interior $Cu_{41}Ni_{59}$ alloy layer and the metallic Co layer as well. Upon cycling the in-plane magnetic field in the range ± 6 kOe and keeping temperature close to the superconducting transition, a memory effect has been detected. If the magnetic field was dropped to zero from the initial field-cooling direction at 10 kOe, the heterostructures resistance dropped down to the almost superconducting low-resistive state. Changing polarity of the field, raising its magnitude to -6 kOe and driving the field to zero again brought the system to the resistance at the normal conducting state. The bistability was repeatedly reproduced upon further cycling along the full magnetic hysteresis loop of the heterostructures. Both low- and high-resistive states at zero magnetic field were determined solely by pre-history of the field cycling and did not need biasing field to keep them steady.

The observed memory effect, caused by generation of the triplet pairing at non-collinear magnetic configurations in the investigated nanostructures, seems to be promising for practical applications in superconducting spintronics.

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Direct evidence of the flexomagnetoelectric effect revealed by single molecule spectroscopy

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Interplay between magnetism and electricity in multiferroic materials attracts growing theoretical and experimental interests. Indeed, these materials offer the possibility to control the magnetization without applying electric currents, opening the way for the development of new nanoscale memory elements with low power consumption. An inhomegeneous magnetization can induce an electric polarization in systems with broken inversion symmetry. Although this « flexomagnetoelectric » effect was theoritecally predicted more than twenty years ago [1], its unambiguous experimental evidence is still lacking. Here, we report direct evidence of the electric field induced by a magnetization inhomogeneity in an iron garnet film created by the non uniform magnetic fields generated at domain boundaries of a Type-I superconductor in the intermediate state. At liquid Helium temperatures, Stark shifts of sharp single molecule zero-phonon-lines were used to probe the local electric fields generated by this flexomagnetoelectric effect [2]. This observation paves the way to the use of ultra-sensitive nanometric probes such as single fluorescent molecules to directly investigate local electric fields in the condensed matter and to probe nanomechanical motions of charged oscillators.

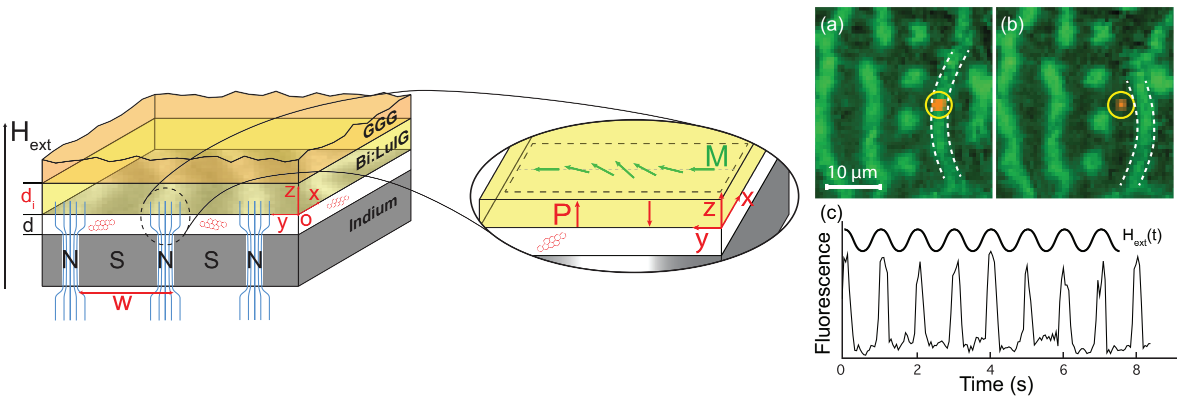

Figure: Left: Scheme of the sample under external magnetic field. A hexadecane layer dopped with dibenzanthanthrene molecules is squeezed between an indium film and a Bi:LuIG layer grown on a GGG substrate. Right: Single molecule imaging with simultaneous MO-imaging of normal phase domains in the Indium film. H_{ext} is modulated in order to shake domain. The laser frequency is fixed to the flank of the Lorentzian-shaped molecular line. (a) $H_{ext} = 29\ Oe$. A single molecule (circled bright spot) is chosen above a normal phase domain (delimited by dashed lines). (b) Image of the same area at $H_{ext} = 31\ Oe$ illustrating the motion of the domain boundaries. (c) Temporal evolution of the fluorescence intensity of that molecule probing the flexomagnetoelectric effect.

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Long–Range Singlet Josephson current through ballistic ferromagnetic nanowires

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We suggest a new way of control of the singlet Cooper pairs flow through a superconductor/ferromagnet/superconductor (SFS) junction in the ballistic regime [1]. The method consists in creation of thin non-collinear domain $d_2 \sim \xi_h \ll d_1$, d_3 ($\xi_h = \hbar V_F/2h$) of the exchange field h near the center of a ferromagnetic weak link using a magnetic tip/probe (see Fig.1a). The field domain generated by the probe, induces a special scattering of Cooper pairs which corresponds to the spin-flip transition of electrons forming a pair. As a result the scattered pair has a reversed spin arrangement with respect to the fixed exchange field, and reversed total momentum. At a symmetric domain d_2 position ($d_1 \simeq d_3$) the total phase gain γ between the electron- and hole-like parts of the wave function should be cancelled ($\gamma \sim (d_1 - d_3)/\xi_h \to 0$) and the long–range singlet Josephson transport in SFS link becomes possible. It means that the presence of a small region with a non-collinear exchange field near the center of a ferromagnetic weak link restores the critical current inherent to the normal metal. The long–range critical current I_c^{LR} is very sensitive to the position of the central domain, and is negative at $d_1 = d_3$. This means that the spin-flip scatterer produces the π-shift effect and generates a π-Josephson junction. With a displacement of the domain d_2 the SFS junction can be switched from π to 0 state (Fig.1b). The above phenomenon opens a way to control singlet Josephson current through ballistic ferromagnetic nanowires. An additional functionality of the considered device can be achieved by electric biasing of the magnetic gate via the field effect.

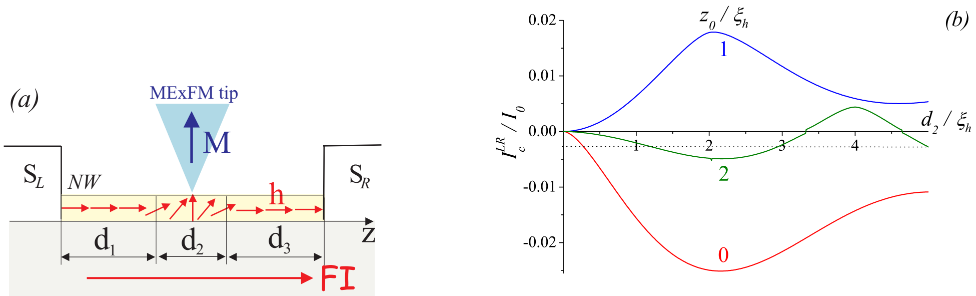

Figure 1: (a) The schematic sketch of the SFS constriction under consideration: normal metal nanowire (NW) in contac with a superconductor (S) and a ferromagnetic insulator (FI). (b) The dependence of the maximal Josephson current I_c^{LR} on the thickness d_2 of the 90° domain for different values of the shift $z_0 = (d_1 - d_3)/2$ of the domain with respect to the weak link center. Dotted line shows the value of I_c in absence of domain d_2.

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Comparative study of Superconducting-Magnetic Hybrid Structures and the Persistence of Singlet Correlations

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We present a comparative study of pair correlations in diffusive Josephson junctions involving two classes of magnetic systems: multilayers with homogeneous misaligned magnetization (including spin valves and canted S5FS layers), and continuously rotating magnetizations, to which belong helical configurations and the flexible exchange spring domain wall [1]. By analyzing the Gor'kov functions we demonstrate that the two classes display qualitatively different mixtures of correlations. In particular, singlet correlations persist throughout a continuously rotating magnetization. The cascading effect sheds light on the difference between hybrid structures [1, 2]. We also discuss the importance of *magnetic* boundary conditions that determine the stability of the magnetic configuration. Finally, we propose several experiments that reveal different correlation admixtures in magnetic Josephson junctions.

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Vortices at the surface of a normal metal coupled by proximity effect to a superconductor

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We report the experimental observation of vortices on the surface of a 50nm-thick layer of Cu in the hybrid structure Cu/Nb with ultra-low temperature Scanning Tunneling Spectroscopy (STS). In the studied samples the non-superconducting Cu-layer acquires superconducting correlations due to the proximity effect with 100 nm-thick superconducting Nb. To avoid the oxidation at Cu-surface and allow STS, the samples were *ex-situ* grown on SiO_2/Si in the inversed order, i.e. Cu was deposited directly on the substrate, Nb was deposited on Cu. Then the samples were introduced to the UHV STM chamber and cleaved *in-situ*. The structural analysis showed that upon cleavage the samples break at $Cu - SiO_2$ interface, thus exposing fresh Cu surface.

The presence of the proximity effect at the Cu film surface was first evidenced by observation of a proximity gap in the tunneling conductance spectra $dI(V)/dV$, in clear relation to the value of the superconducting gap of bulk Nb. The evolution of the proximity spectra with temperature was also studied in the range (0.3-4.2)K. Upon application of an external magnetic field, spatial variations of the tunneling conductance spectra were observed. These variations appear in the detailed STS maps as round nm-size spots, in the centers of which the proximity gap vanishes. The density of spots rises continuously with magnetic field; it corresponds perfectly to the expected density of Abrikosov vortices in Nb. We identify the observed spots as proximity induced vortices in the normal Cu. On the basis of our STS data, we have determined the size and shape of the proximity vortex cores, and evaluated the coherence length in Cu. *The autors thanks the RFBR 14-02-31798*

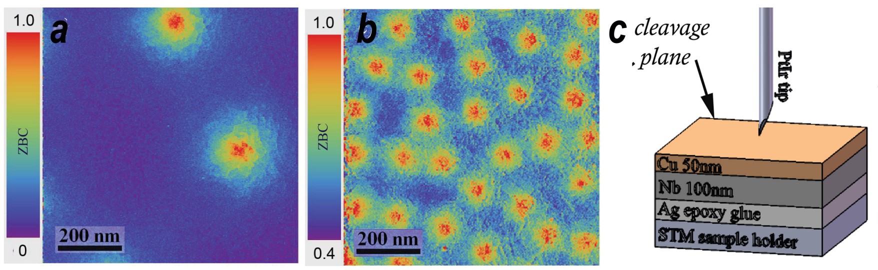

Figure 1: a-b) STS tunneling conductance maps acquired at 0.3K on Cu-surface of Cu/Nb: a) B = 0.005 mT. b) B = 0.05 mT. c) - schematic process of measurements [V.S. Stolyarov, at all, APL 104 (2014) 172604]

Influence of the dynamic pinning geometry on the stroboscopic phenomena in superconductors

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We report time-dependent Ginzburg-Landau simulations of the flux flow regime in superconductors with a dynamic pinning landscape, for example, the one achieved by inhomogeneous light distribution using (pulsed) laser interferometry. We consider a current carrying superconducting bridge in a perpendicular magnetic field, where by adjusting the temporal oscillations of the pinning landscape it is possible to localize vortices both spatially and temporally in a particular region of the superconductor, and achieve resonant features in I-V characteristics of the sample. We investigate the influence of the chosen geometry of the pinning on those stroboscopic effects, and point out discovered subtleties related to the vortex pinning-depinning under spatial and/or temporal matching conditions, appearance of temporary phase slips, the features related to time-dependent SNS Josephson phenomena, and Shapiro steps in both the current-voltage characteristics and magnetoresistance.

Confinement of superconducting fluctuations due to emergent electronic inhomogeneities in ultrathin NbN

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The question of homogeneity, granularity, or glassiness of materials on the verge of a superconductor/insulator transition is fundamental and hotly debated. It is also of particular relevance for applications such as single photon detectors built with ultra thin NbN stripes [1].

Here, by combining transport and scanning tunneling spectroscopy studies of superconducting ultrathin NbN films, we reveal some nanoscopic electronic inhomogeneities that emerge when the film thickness is reduced. STS measurements show that these inhomogeneities persist above the critical temperature T_C and their correlation length L_i is the same below and above T_C. They are also shown to be independent from the structural inhomogeneities.

While thicker films display a purely Aslamazov-Larkin [2] two-dimensional behavior in the fluctuation conductivity, we demonstrate an Aslamazov-Larkin zero-dimensional regime [3] in the superconducting thermal fluctuations for the thinner samples.

Remarkably, the typical length scale, 20-40 nm, extracted from the fluctuation conductivity coincides with the correlation length of the electronic inhomogeneities revealed by local scanning tunneling spectroscopy.

In addition, the critical exponents inferred from the study of the magnetic-field-tuned transition at low-temperature are consistent with a two-dimensional quantum XY model, suggesting that these inhomogeneities behave like an assembly of "supergrains" coupled by Josephson effect.

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STM Investigation of $Fe_{1-x}Se_x$

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FeSe has the simplest structure among the Fe-based superconductors, and this very simplicity could provide the most appropriate venue of understanding the superconducting mechanism of Fe-based superconductors. High quality FeSe single crystals were grown in evacuated quartz ampoules using a KCl/AlCl flux and the structure of tetragonal P4/nmm was demonstrated by x-ray diffraction. Low temperature STM measurements were performed on $FeSe_{1-\delta}$ and $FeSe_{1-x}S_x$ with x=0.04 and 0.09. Effects of multiband superconductivity and vortex matter as a function of doping will be presented.

Change of the topology of a superconducting thin film electromagnetically coupled with an array of ferromagnetic nanowires

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Nanoporous Si templates can be used, through a double-step anodization process, to grow dense arrays of ferromagnetic nanowires whih act as magnetic pinning centers in nearby Nb superconducting thin films. The method allows to use robust supports to deposit superconducting thin films [1-4] and for this reason it can be conveniently considered for useful applications. Here, we report on the superconducting properties of a Nb thin film deposited, with an interleaved insulating layer to avoid the proximity effect, on an array of Ni nanowires embedded in a porous template. By investigating the $T_c(H)$ phase boundary and by measuring $V(I)$ characteristics and critical currents as a function of the applied magnetic field, we find that the Nb film exhibits properties similar to those of a network of one-dimensional superconducting nanowires. We attribute this behavior to the stray fields of the magnetic dipoles, which create an almost regular lattice of normal regions in the superconductor, ultimately changing its topology. Furthermore, there is evidence that the magnetic pinning of vortices is negligible in this structure.

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Field-effect control of superconductivity and Rashba spin-orbit coupling in $LaAlO_3/SrTiO_3$ devices

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Recent results show material and electronic complexity in transition metal oxides Transition metal oxides display a great variety of quantum electronic behaviors where correlations often play an important role. The achievement of high quality epitaxial interfaces involving such materials gives a unique opportunity to engineer artificial materials where new electronic orders take place. It has been shown recently that a superconducting two-dimensional electron gas 2DEG could form at the interface of two insulators such as LaAlO3 and SrTiO3 or LaTiO3 (a Mott insulator) and SrTiO3 [1]. An important feature of these interfaces lies in the possibility to control their electronic properties, including superconductivity and spin-orbit coupling (SOC) with field effect [3-5]. However, so far, experiments have been performed almost exclusively with a metallic gate at the back of the substrate, which makes difficult to control these properties at a local scale.

In this presentation, we will report on the realization of a top-gated LaAlO3/SrTiO3 device whose physical properties, including superconductivity and Rashba SOC, can be tuned over a wide range of electrostatic doping. In particular, we will present a phase diagram of the interface and compare the effect of the top-gate and back-gate on the mobility, superconducting properties and Rashba SOC [6]. Finally, we will discuss the field-effect modulation of the Rashba spin-splitting energy extracted from the analysis of magneto-transport measurements. Our result paves the way for the realization of mesoscopic devices where both superconductivity and Rashba SOC can be tuned locally.

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Study of Superconductivity at $LaAlO_3/SrTiO_3$ Interfaces by Field Effect

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The discovery of a superconducting 2D electron liquid at the interface between the two oxides $LaAlO_3$ and $SrTiO_3$ has provided a platform to study superconductivity in reduced dimensionality [1]. Moreover, the confinement between the two insulating materials offers a natural setting for field effect experiments [2].

In this presentation, I will discuss field effect experiments aimed at modulating the electron liquid properties [3], with particular emphasis on the tuning of the superconducting state.

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Inhomogeneous superconductivity at oxide interfaces

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The two-dimensional electron gas formed at the $LaXO_3/SrTiO_3$ (X = Al or Ti) interface becomes superconducting when the carrier density is tuned above a threshold value by means of gating. Several experiments reveal that superconductivity at these oxide interfaces is inhomogeneous: Hall measurements highlight the presence of two kinds of carriers (with low and high mobility), and superconductivity seems definitely connected to the appearance of the high-mobility carriers. We shall show that the measured resistance, superfluid density, and tunneling spectra result from the percolative connection of superconducting *puddles* with randomly distributed critical temperatures, embedded in a weakly localizing metallic matrix, with a sizable fraction of the system becoming superconducting by proximity to the superconducting puddles. This scenario is consistent with the characteristics of the magnetic-field-driven superconductor-to-metal transition observed in these oxide interfaces. A multi carrier description of the superconducting state within a weak-coupling BCS-like model will be also discussed.

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Quasiclassical theory of disordered Rashba superconductors

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The interplay of Zeeman fields and spin-orbit coupling has been predicted to yield interesting effects in bulk superconductors, as well as in Josephson junctions. Namely, their combined effect favors an helical phase with a spatial modulation of the superconducting order parameter along a direction perpendicular to the field [1], whereas in Josephson junctions it may induce a Josephson current at zero phase difference [2, 3].

Up to now, the fact that the system possesses two bands with different Fermi momenta had hindered a quasi-classical description in the disordered case, where impurities lead to scattering between the bands. We derive the quasi-classical Usadel equation in the regime where the scattering rate is larger than the order parameter, but smaller than the spin-orbit scale. This theory, which accounts for the helical phase, greatly simplifies the description of the bulk system and paves the way for studies of the proximity effect in two-dimensional electron gases with large spin-orbit coupling.

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How the Phase Slips in a Current-Biased Narrow Superconducting Stripe?

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The fundamental property of dissipationless current flow through the superconducting components underlies operation of numerous nano-electronic devices. One of such components is a narrow superconducting stripe (NSS) and the role of thermal and quantum fluctuations in formation of the resistive state in it is a problem of great importance. Various models have been proposed to explain the appearance of non-zero resistance of NSS and its temperature dependence in the region of low temperatures.

The role of thermal fluctuations in the energy dissipation in the process of current flow through the one-dimensional superconductor for the first time was considered in the paper of Langer and Ambegaokar [1] almost fifty years ago. Publication of this paper has strongly influenced all further research in this field, it became classical, and corresponding results were included in multiple monographs and handbooks on superconductivity.

It is necessary to mention that the "one-dimensional superconductor" *de facto* often is a narrow stripe with finite width L, much less than the Ginzburg-Landau coherence length. The energy dissipation in it is related to the phase slip processes consisting in the crossing of the stripe by the vortices. It is clear, that such events cannot be realized remaining in the frameworks of the one-dimensional model. Indeed, the solution found in Ref. [1] shows that even when the density of the flowing through the one-dimensional superconductor current reaches its critical value $J_{\rm c}$, the minimal value of the order parameter is $(2/3)^{1/2}\,\Delta_{\rm BCS}$, while in order to perform the phase slip event it should turn zero at least at one point.

We resolve the mentioned paradox, describing the true mechanism of phase slip events in NSS and determining the corresponding value of the activation energy. We demonstrate that the saddle point solution of Ginzburg-Landau equation for the order parameter in presence of a fixed current J, possessing at least one vortex, exists only for weak enough currents $J < J_{\rm c1} = 0.0312\,(L/\xi_{\rm GL})\,J_{\rm c}$. In the case of "strong currents" $J_{\rm c1} < J < J_{\rm c}$ the saddle point solutions of GL equations, possessing vortices, do not exist more, the described above scenario is exhausted, but another mechanism comes in play. In this interval the minimal activation energy is reached at some function $\Delta_{\rm v}\,(x, y, J, \mathbf{r}_1)$ corresponding to the state with the single vortex. In order to determine the order parameter in the state with vortices we use the variational principle. One of its free parameters is the distance r_1 from the edge of the stripe to the center of vortex. We look for its maximum value for which the conditional extremum of the free energy functional still exists.

Finally we find the value of voltage appearing in the sample as the function of temperature and bias current. Our careful analysis of vortex crossing of the stripe results in considerable increase of the activation energy with respect to the result of Ref. [1].

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Shybrids

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