16th International Workshop on

Vortex Matter in Superconductors

VORTEX2017

Abstract Book

International Institute of Physics, UFRN, Natal, Brazil - May 28th to June 2nd, 2017

Cover photo: *Ponta Negra - Natal (Brazil), September 7th, 2016 (05 h 36' AM), by Lincoln B. L. G. Pinheiro.*

Contents

Aim and Scope

The 16^{th} edition of the International Workshop on Vortex Matter in Superconductors (VORTEX2017) addresses theoretical and experimental aspects of vortex matter found in the new and in the traditional compounds, in all scales, ranging from bulk to reduced dimensionality. The workshop objectives are to achieve understanding in the fundamental and applied aspects of vortex physics and to promote international collaboration and exchange of ideas among the participants. The topics comprised by VORTEX2017 are the traditional ones covered in previous workshops of the series, started in 1994, plus a number of new correlated themes found in superconductivity, superfluidity and magnetism, such as the onset of novel topological states. Since 2011, the International Workshop on Vortex Matter awards the Abrikosov prize to physicists who have made distinguished contributions to the field of vortex physics.

In the 2017 edition, we follow the drive of previous editions to incorporate new ideas and subjects. The present program integrates new topics into the usual discussions of vortex physics, providing a varied set of topics among the following ones.

- Vortex dynamics and pinning — phase diagrams
- Thermal and disorder induced transitions
- Strong pinning regime
- Vortices in nanostructured and irradiated superconductors
- Interface superconductivity — vortex pinning in 2D and layered superconductors
- Quantum behavior in low dimensional superconductors
- Vortices in iron superconductors
- Topological insulators and superconductors
- Vortex imaging in real and reciprocal space
- Vortex matter in a magnetic background — coexistence of magnetism and superconductivity
- Mesoscopic effects in conventional and exotic superconductors
- Critical currents, critical fields, power applications
- Devices for high frequency radiation and detection
- Vortex matter in multiband superconductors
- Novel electronic and vortex states
- Vortices in strongly correlated electron superconductors
- Vortices in cold-atom systems
- Bose-Einstein condensates

- Vortices in superconductor–ferromagnetic hybrids
- New technical improvements; novel insights to the vortex properties
- Magnetic skyrmions: lattices and dynamics
- Other topological excitations

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The 16th Workshop on Vortex Matter in Superconductors is held at the International Institute of Physics, located in the city of Natal, the state capital of Rio Grande do Norte, Brazil. The International Institute of Physics is part of the Universidade Federal do Rio Grande do Norte and more information about its activities can be found in the web site http://www.iip.ufrn.br/.

Abrikosov prize

Alexei Alexeyevich Abrikosov studied under Lev Landau in the former Soviet Union and predicted the existence of type-II superconductivity in 1957. He has given many other contributions to condensed matter physics and was awarded the 2003 Nobel Prize in Physics. He was born in Moscow, Russia (June 25th, 1928) and has recently passed away in Sunnyvale, California, USA (March 30th, 2017).

The International Workshop in Vortex Matter on Superconductors is proud to award distinguished scientists for their contribution to the field of VORTEX PHYSICS with a prize in his honor.

The international Abrikosov Prize aims at recognizing outstanding achievements in the basic science of vortex behavior and correlated topics.

The Abrikosov Prize in Vortex Physics 2017 is awarded jointly to

Johann W. Blatter, Mikhail V. Feigel'man, Vadim B. Geshkenbein and Valerii M. Vinokur

"for the development of pioneering concepts describing vortex matter in type II superconductors including theories of collective pinning and dynamics, for their seminal work establishing the theoretical foundations of vortex physics, and for sustained contributions to superconductivity and condensed matter physics".

Abstracts

Direct imaging of vortex matter in iron-selenide superconductors

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We study the structural properties of vortex matter in single crystals of β-FeSe and $FeSe_{0.95}S_{0.05}$ by means of the Bitter decoration technique. We are able to image individual vortex positions only up to 5 Oe. At larger fields the gradient of the local magnetic induction associated to each vortex decreases and we loose single-vortex resolution. All samples present lines with higher vortex density that we associate to twin-boundaries between crystallographic orthorhombic domains with different orientations. The observed vortex structure presents distorted hexagonal symmetry and local regions with square-like symmetry. We discuss on the origin of this unconventional vortex lattice.

Imaging of super-fast dynamics and flow instabilities of superconducting vortices

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Nano-SQUIDs residing on the apex of a quartz tip, suitable for scanning probe microscopy with record size, spin sensitivity and operating magnetic fields are presented [1,2]. We have developed a SQUID-on-tip made of Pb with an effective diameter of 46 nm and flux noise of $\Phi_n = 50$ nΦ_0/Hz$^{1/2}$ at 4.2 K that is operational up to unprecedented high fields of 1 T [1]. 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 dynamics under strong currents. Super-fast vortices are imaged, penetrating into a superconducting Pb film microbridge at rates of tens of GHz and moving at velocities up to tens of km/s, while preserving their integrity as topological defects. Such high velocities are not only larger than the speed of sound but also greatly exceed the pair-breaking speed limit of the Cooper-pair condensate. These experiments reveal striking formation of vortex channels which undergo cascades of bifurcations as the current and magnetic field increase.

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Evolution from Superconducting to Antiferromagnetic Ground State in $Y_{1-x}Gd_xPb_3$ ($0 \leq x \leq 1$)

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The coexistence between superconductivity and magnetism has been an exciting topic of research during the past years. Here we report a study of the evolution from the superconductor YPb_3 with critical temperature $T_c = 4.6$ K to the antiferromagnet $GdPb_3$ with $T_N = 14$ K [1]. When Gd impurities are embedded in the superconductor, T_c presents an initial linear decrease in agreement with the Abrikosov-Gorkov (AG) [2] theory. However, the T_c suppression rate is surprisingly small, corresponding to $< J^2(q) >_{AG}^{1/2} = 0.17$ meV, and implying in an unusually broad region of coexistence between superconductivity and magnetism. Additionally, DC susceptibility measurements show a gradual increase of the negative Curie-Weiss temperature (Θ_C) as the Gd concentration increases, even at low concentrations. Preliminary Gd^{3+} ESR results indicate the existence of three different regimes: i) low concentration ($x \leq 0.04$), dominated by crystal electric field effects (CEF) and narrowing of the fine structure via a Korringa relaxation mechanism; ii) intermediate region ($0.07 \leq x \leq 0.15$), dominated by the competition between $4f$ - conduction electrons (ce) and $4f$ - $4f$ interactions (Korringa-like and spin-spin mechanisms) characterized by different values of the exchange interactions; and iii) high concentration regime ($0.15 \leq x \leq 1.00$), characterized by only the $4f$ - $4f$ interaction, as expected. These results show how the interplay of the exchange interaction between localized spins and ce plays an important role in the subtle coexistence of magnetism and superconducting ce.

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Quantum Turbulence in a Bose-Condensate: a tangle vortices configuration

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Turbulence, the complicated fluid behavior of nonlinear and statistical nature, arises in many physical systems across various disciplines, from tiny laboratory scales to geophysical and astrophysical ones. The notion of turbulence in the quantum world was conceived long ago by Onsager and Feynman as a tangle configuration of vortices, but the occurrence of turbulence in ultra-cold gases has been studied in the laboratory only very recently. Albeit new as a field, it already offers new paths and perspectives on the problem of turbulence. Herein we review the general properties of quantum gases at ultra-low temperatures paying particular attention to vortices, their dynamics and turbulent behavior. We review the recent advances both from theory and experiment. We highlight, moreover, the difficulties of identifying and characterizing turbulence in gaseous Bose-Einstein condensates compared to ordinary turbulence and turbulence in superfluid liquid helium and spotlight future possible directions. The use of many recent tools to investigate turbulent clouds using correlation functions and extended entropy will be discussed. The connection of turbulent cloud in expansions and speckle fields will be explained. For a general reference see the review of Ref. [1]. This work has the collaboration of: E. Henn, K. Magalhaes, G. Roati (Italy), V. Yukalov (Russia), G. Telles, , P. Castilho, P.E. Tavares M. C. Tsatsos, A. R. Fritsch, , F. E. A. dos Santos, M. A. Caracanhas, P. E.S. Tavares, E. Gutierez, A. Orozco. Financial support from FAPESP and CNPq.

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Evidence of superconducting and magnetic fluctuations both above and below T_c in $BaFe_{2-x}Co_xAs_2$ single crystals

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The doping phase diagram in Pnictide superconductors has magneto-structural transformation boundaries interrupted by a superconducting dome. With doping, long range magnetic order gets suppressed and superconductivity emerges in these compounds. MuSR studies on $Ba(Fe_{1-x}Co_x)_2As_2$ have shown that while Co doping results in loss of long range magnetic order, short range order may still be present in the system. Using high sensitivity magneto-optical imaging technique and SQUID magnetization measurements, we probe the behavior of local and bulk magnetization response measured in, under, optimally and over, doped, superconducting $BaFe_{2-x}Co_xAs_2$ single crystals [1]. At low applied H for $T < T_c$, local magnetization measurements shows the presence of weak positive magnetization response in the optimally doped crystal. The local positive magnetic response transforms into a diamagnetic response with increasing H. Just above T_c, in all the crystals the bulk magnetization response becomes positive and exhibits a maxima along with a long tail extending upto high T. Through analysis of this maxima feature in bulk magnetization and electrical conductivity measurements in the normal state along with sensitive imaging of local magnetic field distribution, we show [1] the presence of superconducting fluctuations above T_c (see figure). At $T > T_c$ the local regions with superconducting response coexist with regions having magnetic fluctuations. We observe that the crystal with optimum doping concentration exhibits the strongest effect of magnetic fluctuations and it also possesses the highest superconducting volume fraction above T_c. Using these data, we construct $H - T$ phase diagrams for each doping concentration in which the superconducting and magnetic fluctuation regimes are identified. We believe our results suggest the importance of magnetic fluctuation in mediating superconducting order in the $BaFe_{2-x}Co_xAs_2$ system. Another aspect of this work we will touch upon is how magnetic fluctuations affect the vortex distribution deep in the superconducting state [2].

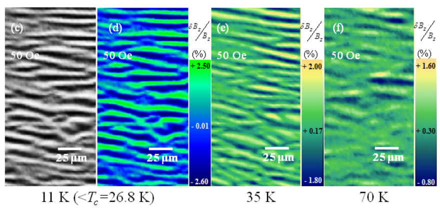

Figure 1: Imaging of regions with diamagnetic fluctuations (bluish regions) coexisting along with magnetic fluctuations (greenish shade regions) both above and below $T_c(= 26.8K)$ in optimally doped $BaFe_{2-x}Co_xAs_2$ single crystal [1].

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Charge Berezinskii-Kosterlitz-Thouless transition in superconducting NbTiN films

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The superconductor-insulator transition (SIT) is a quantum phase transition in disordered superconducting films that occurs at the point where two inherently two-dimensional topological phase transitions – charge and vortex Berezinskii-Kosterlitz-Thouless (BKT) transitions [1,2,3] – terminate each other. Applied magnetic fields can tune the SIT with high resolution, offering a window into relatively unexplored electronic functionalities. While the superconducting side of the SIT is well understood, the nature of the highly resistive superinsulating state that terminates two-dimensional superconductivity at the quantum critical point remains an open question [4,5,6,7,8,9,10]. We report the magnetic field driven SIT in NbTiN films and demonstrate that the highly resistive state is an ordered charge BKT state. We observe nonmonotonic behaviour of the charge BKT transition temperature with magnetic field and resolve a long-standing question of the origin of a giant magnetoresistance peak in the insulating state. Our findings establish that BKT physics is a universal platform for the dual superconducting and superinsulating states. T.I.B. acknowledges support from the Consejería de Educación, Cultura y Deporte (Comunidad de Madrid) through the talent attraction program, Ref. 2016-T3/IND-1839.

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Topological Excitations in Planar Systems

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We describe a procedure to investigate topological excitations in planar systems with the use of a single real scalar field. It was developed in the recent works [1,2,3] and shows that spherically symmetric structures in two spatial dimensions may map helical excitations in magnetic materials that can be used to model skyrmion-like structures. We model and solve the problem analytically, and show how the solutions appear in materials that engender distinct, very specific physical properties, and use them to describe their topological features. In particular, we find a way to model skyrmion with a large transition region correlated with the presence of a two-peak skyrmion number density. We also show how to control the internal structure of the topological excitations that provide a possibility to describe vortices and skyrmions in magnetic materials.

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How disorder in the vortex positions changes the local density of states inside vortex cores: a real-space approach to Bogoliubov-de Gennes equations

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We present a method allowing one to solve the Bogoliubov-de Gennes equations of superconductivity on the lattice, with emphasis on the mixed state [1]. The method gives unprecedented access to the regimes of low to intermediate fields and disordered vortex configurations. These regimes are particularly relevant for the copper-oxide materials, where investigations of the vortex cores by scanning tunneling spectroscopy have given results at odds with the theoretical expectations [2,3]. We will show that a finite number of vortices, regardless how large, does not provide a good model for an infinite vortex lattice. The latter limit can however be reached with a specific choice of gauge, in which each vortex is represented by a short-range disturbance of the order parameter. We apply the method to study the influence of nearby vortices on the local density of states inside one vortex core of a d-wave superconductor, both for ideal and disordered vortex lattices. We find that a new emerging length scale controls the mutual influence of neighboring cores. Recent calculations that reproduce new tunneling measurements in YBCO will also be briefly described.

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Strong pinning theory of vortices in type II superconductors

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Strong pinning allows for a quantitative assessment of vortex pinning in type II superconductors. It is defined through a precise criterion involving the (negative) curvature of the pinning potential of individual pins, the so-called Labusch criterion, and applies to the case of a dilute density of strong pins. After its first inception by Labusch and by Larkin and Ovchinnikov in the 70-ies of last century, further progress has been made recently in developing a more complete theory of strong pinning, its connection to weak collective pinning, and an intriguing relation to the Landau theory of phase transitions. New results include a force-density diagram delineating various regions characterized by one- and three-dimensional weak and strong pinning, including the evolution of the critical current density through these regimes [1], the determination of the current-voltage characteristic exhibiting an excess-current characteristic [2], the quantitative assessment of the Campbell length and its relation to the critical current density [3], and the effect of thermal fluctuations leading to thermal depinning and strong creep. Experiments support various aspect of these theoretical considerations.

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Thermal creep of vortices within strong pinning theory

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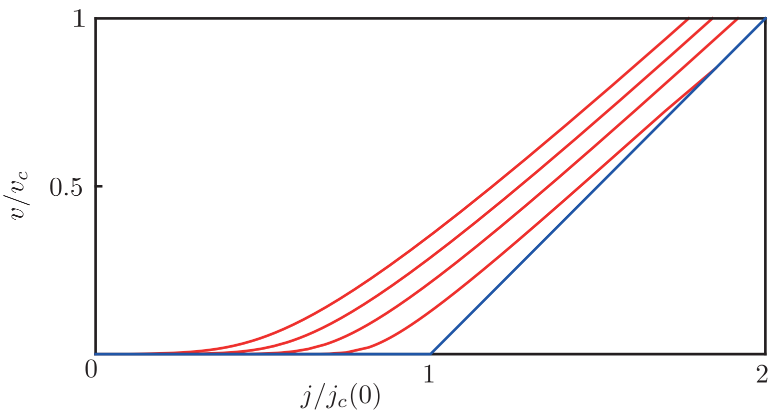
We study vortex pinning and creep in type-II superconductors produced by a low density n_p of strong defects. Extending the strong pinning theory to account for thermal fluctuations, we provide a first quantitative treatment of vortex creep. Strong pinning is characterized by the appearance of bistable solutions and an asymmetric occupation of pinned and free branches under the action of an external driving current j. The critical pinning force F_c or current j_c is given by the maximally asymmetric occupation and can be expressed through the energy difference Δe between branches where they terminate. At finite temperatures T, thermal fluctuations tend to bring this asymmetric non-equilibrium occupation closer to the symmetric thermal equilibrium one. *At large drives* $j \sim j_c$, thermal fluctuations lead to a renormalized energy difference $\Delta e(v, T)$ (v the vortex velocity) and a reduction in the critical current $1 - j_c(T)/j_c(0) \propto (T/e_p)^{2/3} \log[(T/e_p)^{1/3}/(n_p a_0 \xi^2)]^{2/3}$, where e_p is the pinning potential depth and $n_p a_0 \xi^2 \ll 1$ in the low density limit where strong pinning applies (a_0 and ξ are the vortex separation and core size). The current–velocity characteristic near depinning assumes the form $v = v_0\, e^{-U(j)/T}$. The activation barrier decays as $U(j) = \alpha e_p [1 - j/j_c(0)]^{3/2}$ for $j < j_c(T)$ (with α a known constant), saturates at a finite value at $j = j_c(T)$ and varies only logarithmically with current for $j > j_c(T)$. The critical current $j_c(T)$ separates the region of flux creep with exponentially small resistivity from the high-resistivity region of depinned flux flow. *At small drives* $j \sim (T/e_p)\, j_c(0)$, the branch occupation is close to thermal equilibrium, the barrier $U(j)$ assumes a finite value $U_0 = \alpha' e_p$, and the energy difference $\Delta e(v, T)$ vanishes. The pinning force is determined by a shifted equilibrium occupation of the pinned and free branches, resulting in a linear current–voltage characteristic $v \propto j \exp(-U_0/T)$ (TAFF).



Current-voltage characteristic in the strong pinning scenario for fixed defect density $n_p a_0 \xi^2 = 10^{-3}$ and different temperatures (from right to left) $T/e_p = (0,\ 0.5,\ 1,\ 1.5,\ 2) \times 10^{-2}$. The velocity axis is rescaled by v_c denoting vortex velocity at driving current $j_c(0)$ in absence of pinning.

Interference of antiferromagnetic ordering and superconductivity

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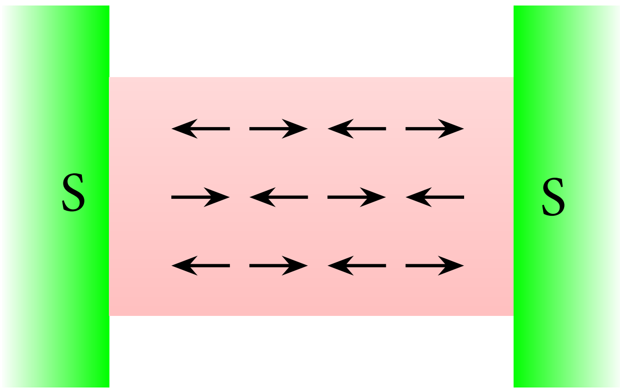
We consider superconducting systems with localized magnetic moments such as MRh_4B_4, MMo_6S_8, MNi_2B_2C and $(BETS)_2MBr_4$ where M stand for the ion with magnetic moment. In such antiferromagnets with RKKY coupling of localized and conducting electrons the exchange field with the amplitude h varying in space with the wave vector $\vec{Q}$ induces the energy splitting of Cooper pair electrons $\epsilon_a \approx \mu_B^2 h^2/v_F Q$ of the order of the Neel temperature T_N. Here v_F is the electron Fermi velocity. At $\mu_B h/v_F Q \ll 1$ suppression of superconducting order parameter by this splitting is negligible but the splitting may result in significant phase difference accumulation $\epsilon_a L/v_F$ on the distance L. It was shown in Ref. [1] that in clean superconductors, due to the effective magnetic field ϵ_a/μ_B, superconducting state below T_c becomes nonuniform, Fulde-Ferrell-Larkin-Ovchinnikov like, if T_c is well below T_N while $\mu_B h > T_c/\mu_B$. Nonuniformity of superconducting order parameter in such state may be probed by tunneling measurements. Due to the splitting ϵ_a, one can reach a π-junction state in the Josephson junction superconductor-antiferrimagnet-superconductor when electron scattering inside junction is weak enough, i.e. when the electron mean free path exceeds the junction width d and $\epsilon_a d/v_F > \pi$.



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Theoretical Investigation of Two Vortex Shells Dinamics in Pinning-Free Superconducting Disk in the Corbino Geometry

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A superconducting disk into which an applied electrical current is injected in its center and collected at the edge is in the so-called Corbino geometry. The non-uniform current density drives vortices to rotate with a force which varies inversely proportional with the distance to the disk center. In this system at least two dynamical phases are expected [1] in a pinning-free sample: For applied currents below a threshold current $I < I_{\rm dc}$, the vortex configuration rotates as a rigid body, although deformed compared to the stable configuration (for $I = 0$); For high applied currents $I > I_{\rm dc}$, the two shells decouple and rotate with different angular velocities. These observations were also theoretically studied for large vortex systems either in the continuum limit or using computer simulations [2,3]. More recently vortex systems containing few vortices were investigated numerically [4]. Interesting phenomena were observed in these systems, such as a nonmonotonic dependence of the critical current $I_{\rm dc}$ on the applied magnetic field and multi-step decoupling of vortex rings.

In this talk we report on the intershell rotational dynamics of two vortex shells in a pinning-free superconducting thin disks in the Corbino geometry [5]. Two situations were investigated theoretically, both with the inner shell composed of vortices: In one case the outer shell is constituted by antivortices. Such configurations are possible when an out-of-plane magnetic dipole is close to the disk. In the other case, the superconducting disk is in the presence of an external homogeneous magnetic field and both shells are composed of vortices. These vortex systems were studied within the London approach, with the vortex overdamped dynamics given by the Bardeen-Stephen equation. For equal number of vortices (or antivortices) in each shell and assuming that each shell rotates rigidly we obtained analytical expressions which describe the two expected regimes of the intershell dynamics. For commensurate vortex shells these results can be extended by using a suitable *Ansatz*. Our analytical results are in excellent agreement with molecular dynamics simulations [6].

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Phase transition of ultracold atoms immersed in a BEC vortex lattice

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We investigate the quantum phases of ultracold atoms trapped in a vortex lattice using a mixture of two bosonic species (A and B), in the presence of an artificial gauge field. Heavy atoms of species B are confined in the array of vortices generated in species A, and they are described through a Bose-Hubbard model. In contrast to the optical-lattice setups, the vortex lattice has an intrinsic dynamics, given by its Tkachenko modes [1]. Including these quantum fluctuations in the effective model for B atoms yields an extended Bose-Hubbard model, with an additional "phonon"-mediated long-range attraction. The ground-state phase diagram of this model is computed through a variational ansatz and the quantum Monte Carlo technique. When compared with the ordinary Bose-Hubbard case, the long-range interatomic attraction causes a shift and resizing of the Mott-insulator regions [2]. Finally, we discuss the experimental feasibility of the proposed scheme, which relies on the proper choice of the atomic species and on a large control of physical parameters, like the scattering lengths and the vorticity.

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Study of Critical Forces at Submatching Fields in Superconducting Thin Films With Triangular Pinning

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Commensurability effects in type II superconducting thin films under the influence of periodic pinning has been extensively investigated recently. Several types of periodical pinning lattices have been studied both experimentally and theoretically. In these works, a wide variety of commensurability effects have been found in dynamical properties of vortices, such as critical forces, dynamic phases, vortex-flow resistance, and magnetization. For the specific case of the triangular pinning lattice, S. Ooi *et. al.* [1] studied experimentally critical currents in 2D thin films with same pinning lattice finding matching peaks at $B/B_\phi = 1/4, 1/3, 1/2, 2/3, 3/4, 6/7$ and 1. Bothner *et. al.* [2] also investigated the same system finding peaks at $B/B_\phi = 1/4, 1/3, 2/3, 3/4$ and 1. However, Reichhardt and Grønbech-Jensen [3] simulated this same system finding critical force peaks at $B/B_\phi = 1/7, 1/4, 1/3, 2/3, 6/7$ and 1, for high values of pinning strength, and additional force peaks at $B/B_\phi = 1/9$ and $1/2$ for lower values of pinning strength. However, the current peak at $B/B_\phi = 3/4$, which was found in recent experimental results [1,2], was not predicted. In this work, we numerically study the commensurability effects in the critical forces in a superconducting film with triangular pinning lattice at fractional matching fields and zero temperature. The analysis is made applying a transport force in two mutually perpendicular directions while applying a magnetic field perpendicular to the film surface. The results show critical force peaks at fractional matching fields as a direct consequence of the commensurability effects. As a consequence, we were able to simulate the sequence of force peaks detected in recent experiments. Anisotropic effects in the critical forces are also reported, in analogy with that found at higher fields [4].

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Infuence of Domain Size on the Magnetic Properties of Superconducting Spin Valves

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Superconductor/ferromagnetic (SC/FM) hybrid systems often exhibit unusual physical behavior. This includes anomalous magnetic responses, which are present below the critical temperature (T_c). In a recent study, we show the occurrence of anti-Lenz supercurrents in superconducting spin valves [1]. Here, we present a characterization study, via X-ray reflectivity, electrical transport, magnetic hysteresis, AFM and MFM, of two superconducting spin-valves, which have the same structure Si (111)/Ta (150 Å)/IrMn (150 Å)/NiFe (50 Å)/Nb (450 Å)/NiFe (50 Å)/Ta (50 Å). Both samples exhibit different magnetic behavior below Tc. In particular, one sample presents anti-Lenz super-currents, while the other one shows the trivially expected behavior. The MFM measurements suggest that this is directly related to the roughness of the FM layers. These differences could define which factors (structural, electrical and magnetic) are relevant for the presence of unusual effects in hybrid systems SC/FM. We therefore believe that the existence of theses phenomena, like anti-Lenz currents, is extremely sensitive to layers quality.

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Understanding and manipulating vortex creep in superconductors

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Thermal and quantum fluctuations have only minor effects on the vortex properties of many conventional LTS, but they dramatically influence vortex matter in HTS such as oxides and Fe-based, creating 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). This produces fascinating physics that has been a topic of continuous interest for decades, but on the other hand is detrimental for applications. The much stronger thermal fluctuations in HTS are due to the small coherence length (ξ), the large anisotropy (γ) and high transition temperatures (T_c) 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. For instance, Gi is several orders of magnitude higher in YBa2Cu_3O_7 ($Gi \sim 10^{-2}$) as compared to Nb ($Gi \sim 10^{-9}$), naturally accounting for the much faster creep rate (S) in the former. We have found that, for strong pinning superconductors (SC) in the Anderson-Kim (A-K) creep regime, there is a universal minimum attainable $S \sim Gi^{1/2}(T/Tc)$ [1]. This lower limit has been achieved in a few SC 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. This hard constraint has two important, broad implications: first, the creep problem in HTS cannot be fully eliminated and there is a limit to how much it can be ameliorated, and secondly, we can confidently predict that any yet-to-be-discovered HTS will have fast creep. On the other hand, many SC exhibit S values higher, sometimes orders of magnitude higher, than the lower limit. This includes Fe-based HTS, in particular compounds of the AFe_2As_2 family ($Gi \sim 10^{-5}$ to 10^{-4}), as well as LTS such as $NbSe_2$ ($Gi \sim 10^{-6}$). The reason is that Gi only sets the lowest limit for S, but in order to achieve the pinning landscape must be optimized. I will show that S can be dramatically reduced, in some cases all the way down to the lower limit imposed by Gi, by appropriate engineering of the pinning landscape. I will finally discuss our efforts to obtain a generalized model for the lower achievable S outside the A-K regime, at higher T and H where collective effects and glassy dynamics are relevant.

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Crossing fields in thin films of isotropic superconductors

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We have studied magnetic flux cutting effects by imaging the vortex dynamics in Nb films of different thickness in the crossing in-plane ($H_{||}$) and perpendicular fields ($H_{\perp}$). [1] For $H_{||}$ = 1 kOe the motion of the perpendicular vortices in thick (200 nm) Nb film is found to be strongly anisotropic. At T$>$Tc/2 we observe a noticeable delay in the vortex propagation across $H_{||}$. With rotation of the in-plane field, such a behavior follows the direction of $H_{||}$. At T$<$Tc/2 , when the normal vortex entry occurs via thermomagnetic flux jumps, the branches of the emerging vortex dendrites tilt perpendicular to the in-plane field direction. In the thinner (100 nm) Nb film, the normal flux dynamics turns out to be isotropic and practically independent of $H_{||}$. Our calculations of the thermodynamic potential for the in-plane vortices predict their existence at $H_{||}$ = 1 kOe only in the 200 nm film. In the 100 nm sample, $H_{||}$ monotonously changes through the film thickness. We conclude that the observed delay of the normal flux motion across $H_{||}$ in the thicker film is due to the vortex cutting-reconnection of the perpendicular and in-plane vortices. The resulting enhanced slope of the pinning potential for motion across $H_{||}$ explains also the tilt of the dendrite branches at T$<$Tc/2.

This work was supported by the U.S. Department of Energy, Office of Science, Materials Sciences and Engineering Division. The work of F. Colauto at Argonne National Laboratory was supported by the Sao Paulo Research Foundation FAPESP (grant Nº 2015/06.085-3). We used sample manufacturing facilities of Laboratório de Conformação Nanométrica (IF-UFRGS), Laboratório de Microfabricação (LNNanto-CNPEM), and Center for Nanoscale Materials (CNM-ANL), the latter is supported by the U. S. DOE, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

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Magnetism and superconductivity: topology and quantum fluctuation effects

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About fifty years ago, a Pandora box was open giving rise to an extraordinary development of new concepts and discoveries, with great impact on condensed matter physics. The concept of scaling and the tools provided by the renormalization group have allowed us to deal with divergences that plagued field-theoretic techniques, leading to the idea of universality and deep insights in the realm of phase transitions and critical phenomena. Model systems became popular amongst theorists and, in attempting to go beyond mean field versions, reality imposed strong barriers to detour, or to tunnel, in order to properly treat the defying effects of thermal and/or quantum fluctuations in strongly correlated many-particle systems. In particular, the role of spatial dimensionality, and that of effective dimension due to real or imaginary time, became a big issue, and nontrivial distinctions of behavior between low-dimensional systems (d=1 up to 2) and systems in higher dimensions were unveiled. In this context, topological concepts have played a fundamental role. Needless to say that for a type 2 superconductor in the presence of a magnetic field, the occurrence of vortex matter is a quantum topological event, and that the discovery of high-Tc superconductivity was one of the greatest discovery in the past century. Last year, the Royal Swedish Academy of Sciences decided to pay a great tribute to physicists that made exceptional theoretical contributions to the area described above. In this context, I think it will be stimulating to digress on the physics underlying these exceptional contributions. In addition, I also hope to please you by presenting some work of our group that illustrates these findings.

Lifshitz transition in an electronic layer and the condensate of zero helicity states

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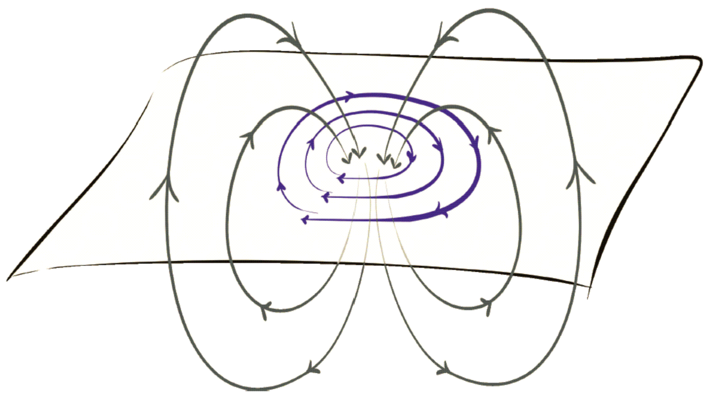
In 1998 A.A. Abrikosov explained the linear magneto-resistance in non-stoichiometric silver chalcogenides observed at very low magnetic field [1] through the ad-hoc assumption that carriers obey a two-dimensional Dirac equation. Thus the use of the two-component Dirac (Weyl) equation in electronic matter preceded the discovery of graphene in 2004. The linear magneto-resistance has been found in many other systems, including graphene, and the so-called topological insulators. These studies triggered the development of novel concepts in condensed matter physics, such as that of the Lifshitz transition, the Weyl semi-metals, and the notion of topological protected states, which warrant the stability of the gapless state that arise in the limit of the Dirac spectrum. The manifestation of such phenomena found in distinct materials sets a quest for a general mechanism able to explain these common features of layered systems. Here we show that such concepts can be straightforwardly derived from the standard non-relativistic gauge invariant kinetic energy [2] for carriers with charge and spin degrees of freedom confined to move along a two-dimensional layer, albeit the three-dimensional magnetic field that results from their motion. The time and the reflection symmetries remain broken through the Lifshtiz transition and there are closed magnetic field streamlines piercing the layer that bring topological stability to the electronic states through a Chern number. Remarkably the magnetic interaction is purely attractive in the Dirac cone limit, thus suggestive of a condensate of zero helicity states.



The topologically stable states are formed by closed magnetic field streamlines that pierce the layer twice and give rise to circulating surface currents.

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Dissipative mechanisms and thermal diffusion in the annihilation of kinematic vortex-antivortex pairs

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Transport currents applied in superconducting stripes can induce the formation of kinematic vortices (KVs) as previously studied by Ref. [1,2] where the time dependent Ginzburg-Landau (TDGL) equations were solved. Basically, the KVs are very fast and the elongated form that acquire causes a line with zero superconducting order parameter, ψ. In such cases, a resistive state takes place, however, the dissipation process caused by the KVs motion remains unexplored.

In a previous work, A. Schmid used the TDGL equations to study the resistive state of gapless superconductors using the free energy theorem [3]. In the present work, we generalized the Schmid solution's of the superconducting free energy theorem using the generalized time-dependent Ginzburg-Landau (GTDGL) equation [4]. Such solution was applied to study the energy dissipation during the annihilation process of a kinematic vortex-antivortex (V-AV) pair in a gap-like superconductor. The dissipative mechanisms were considered as been due to the normal current density, the coupled between the relaxation of ψ, and the ohmic dissipation by the normal excitation of the vortex core (when the scalar potential is present). This the last mechanism is due to the relaxation of the density of superconducting electrons. As the dissipated energy diffuses by the system, the thermal diffusion equation was coupled to the GTDGL one to map the increasing temperature during the kinematic V-AV motion and annihilation. One of the consequences of the thermal diffusion is an increase in the number of created V-AV pairs when compared to a similar system where dissipation processes were not taken into account.

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Anti-Lenz Supercurrents in Superconducting Spin Valves

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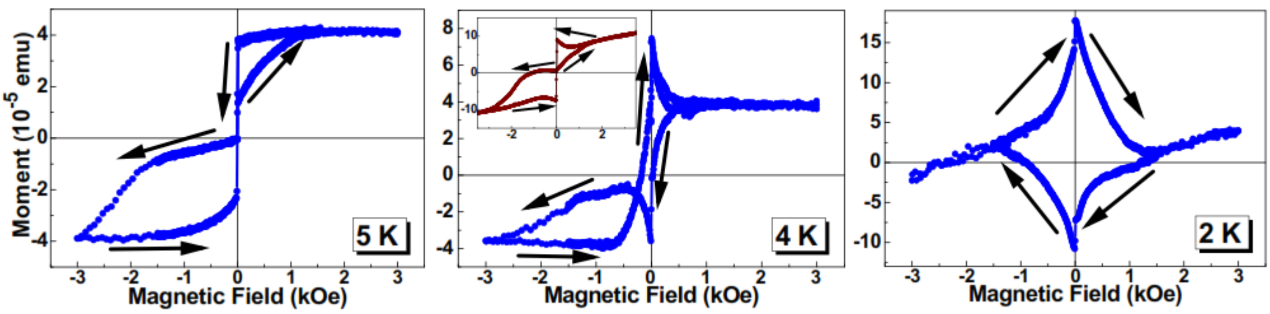
Certain configuration of superconducting spin valves can exhibit extremely surprising magnetic behavior. Specifically, we have recently shown that the supercurrents in these interlayer systems can be contrary to what would be dictated by Lenz' rule [1]. In our samples, a superconducting Nb-layer contributes strongly to the magnetization, and manifests itself in an anomalous hysteresis loop. While the hysteresis loop is seemingly similar to what is generally expected from hard superconductors and many superconductor/ferromagnet hybrid systems, its direction is inverted when compared to what is generally observed, as is demonstrated in this Figure. Thus, the samples show paramagnetic behavior for up sweeping fields and diamagnetic behavior for down sweeping fields. This means that the respective samples exhibit Anti-Lenz supercurrents, which is very likely related to the creation of triplet pairs in the ferromagnetic layers.



The hysteresis loop of one of our samples. The critical temperature of the sample if 4.8 K. Thus, the 5 K curve shows the typical behavior of a non-superconductive spin valve. Below T_c, the superconductor generates paramagnetic supercurrents for upsweeping fields and demonstrates diamagnetic behavior for downsweepeing fields.

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Direct Evidence for an Internal Degree of Freedom and Broken Time Reversal Symmetry in the B-phase of UPt_3

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With three different superconducting mixed (vortex) phases the heavy-fermion material UPt_3 can be considered a paradigm for unconventional superconductivity. Despite more than three decades of study, a definitive understanding of the superconducting state in this material has remained elusive. The order parameter structure that is consistent with a number of experiments is an odd-parity, f-wave orbital state of E_{2u} symmetry. Here the order parameter is chiral and breaks time reversal symmetry in the low-temperature superconducting B-phase.

We have performed small-angle neutron scattering (SANS) studies of the vortex lattice (VL) in UPt_3 in the B- and C-phases with $H \parallel c$. This led to the discovery of a previously unknown field-induced VL rotation in the B-phase. Furthermore, the magnitude of the VL rotation show a subtle magnetic field history dependence; VLs prepared with the field parallel or anti-parallel with respect to initial direction with which one enters the B-phase are rotated by different amounts. This demonstrates an internal degree of freedom associated with the vortex cores, and provide direct evidence for broken time reversal symmetry in the B-phase of UPt_3 in non-zero fields by a bulk measurement. We propose that this correspond to an order parameter chirality that is respectively in the same or opposite sense as the VL supercurrent circulation.

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Kinematic and Structural Studies of Metastable Vortex Lattice Phases in MgB_2

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I will discuss our recent studies of the VL in MgB_2, where one observes an unprecedented degree of metastability in connection with a second order (continuous) VL rotation transition. This phenomenon represents a novel kind of collective vortex behavior, which cannot be understood from the single VL domain free energy or from vortex pinning. Rather, we speculate that it is due to VL domain jamming, reminiscent of behavior observed for colloids or granular materials.

To better understand the metastable VL phases in MgB_2 we have studied their kinematic as well as their structural properties using small-angle neutron scattering (SANS). Using a stop-motion technique we imaged the VL as it was driven from the metastable phase to the ground state by a controlled number of small-amplitude ac magnetic field cycles, either parallel or perpendicular to the dc field. Our results show a dichotomy in the behavior for the metastable configurations induced by crossing the equilibrium, second order phase transition in different directions. For a metastable state induced by super heating, the VL returns to the ground state through a continuous domain rotation. In contrast, in the super cooled case, the transition to the ground state takes on a first order nature with VL ground state domains that nucleate and grow at their final orientation. In the latter case the metastable VL volume fraction may be determined, and is found to follow a power law with an exponent that increases with increasing AC field amplitude. Both metastable and ground state configurations show correlations along the field (vortex) direction that are comparable to the sample thickness. Finally, spatially resolved measurements (scanning-SANS) show a spatial variation in the VL domain population on length scales of the order 100 μm.

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Enhancement of penetration field due to surface Andreev bound states in vortex nanocrystals of $Bi_2Sr_2CaCu_2O_{8-\delta}$

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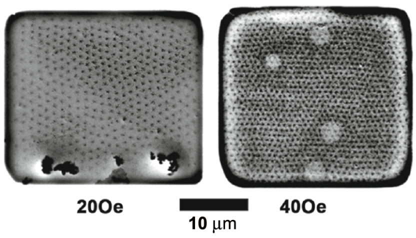
The nucleation of nanocrystalline vortex matter with a large surface-to-volume vortex ratio in micron-sized superconducting samples opens the possibility of studying the influence of surface effects on its magnetic properties. For instance, theoretical studies predict that the penetration and depinning fields for vortices in d-wave superconductors is altered by fermionic Andreev-bound states appearing at the sample surface [1]. These states, that can exist at zero excitation energy depending on the relative orientation of the the sample-surface to the d-wave gap function, generate an anomalous Meissner current running opposite to the supercurrents. The Bean-Livingston surface barrier limiting vortex entry at intermediate temperatures is altered by these surface states and as a consequence the penetration field H_p depends on the orientation of the surface of the sample to the d-wave superconducting order parameter [2]. An experimental study indeed detected a tiny crystal-orientation dependence of H_p in relatively macroscopic samples [2]. In this work we study vortex nanocrystals with 10-1 % surface-to-volume vortex ratio nucleated in cuboid $Bi_2Sr_2CaCu_2O_{8-\delta}$ samples of 50 to 20 μm width and roughly 2 μm thickness (see Fig. 1). The engineering method we use [3,4] allowed us to generate two sets of micro-cuboids, one with the edges aligned along the nodal and another along the anti-nodal d-wave order parameter directions. By means of Hall probe magnetometers with active areas of $16 \times 16\,\mu\mathrm{m}^2$ we measure local dc and ac-magnetization. We detect that the penetration field is enhanced when the edges of the micro-cuboids are parallel to the nodal direction of the d-wave order parameter. This result, in agreement with the theoretical predictions, has only been detected thanks to the combination of low-noise local magnetic techniques and the nucleation of vortex nanocrystals with a significant surface-to-volume vortex ratio.



Nanocrystalline vortex matter nucleated in field-cooling processes in $Bi_2Sr_2CaCu_2O_{8-\delta}$ cuboids with 30 μm sides and 2 μm thickness. Magnetic decorations were performed at 4.2 K and at applied fields of 20 (left panel) and 40 Oe (right panel).

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Transport properties and new emergent phases in the cuprate superconductors

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We investigate the influence of the Θ_{II}-loop-current order on the d-wave charge-density-wave/pair-density-wave (CDW/PDW) composite order that emerges in an effective hot spot model, which is relevant to the phenomenology of the cuprate superconductors. This study is motivated by the compelling evidence that such a loop-current phase may explain groundbreaking experiments such as spin-polarized neutron scattering performed in these materials. We demonstrate that the Θ_{II}-loop-current order clearly coexists with bidirectional (i.e. checkerboard) d-wave CDW and PDW orders along axial momenta, but is detrimental to the unidirectional (i.e. stripe) case [1]. We show that this result is in good agreement with recent experiments [2]. Next, we move on to perform a controlled calculation of the dc resistivity as a function of temperature of the "strange-metal" phase, which emerges in the vicinity of a spin-density-wave quantum phase transition that takes place in the presence of weak disorder [3]. We use the Mori-Zwanzig memory-matrix approach that allows the calculation of all transport coefficients of the model beyond the quasiparticle paradigm. As a consequence, we are able to establish the temperature and doping dependence of the resistivity at intermediate temperatures of such a quantum critical metallic state with the important addition of a composite operator that couples the order-parameter fluctuations to the entire Fermi surface. Lastly, we argue that our theory provides a good basis in order to unify the experimental transport data, e.g., in the cuprate superconductors, within a wide range of doping regimes.

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Superconducting properties of $LaAlO_3/SrTiO_3$ interfaces in magnetic fields

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The two-dimensional electron liquid present at the $LaAlO_3/SrTiO_3$ interface exhibits superconductivity and hosts a large spin-orbit interaction. In field effect devices, both phenomena can be tuned by a gate voltage, revealing a dome-like phase diagram for the superconducting state with a critical temperature T_c reaching 300 mK.
We have mapped [1,2,3] the evolution of the superconducting properties in magnetic fields applied parallel and perpendicular to the conducting plane, revealing that: a) the critical parallel fields beat the Chandrasekhar-Clogston limit; b) the critical perpendicular fields scale with T_c; c) the estimation of the thickness of the superconducting layer changes across the phase diagram.

Funding from Swiss NSF and ERC is acknowledged.

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Nanoscale assembly of superconducting vortices with scanning tunnelling microscope tip

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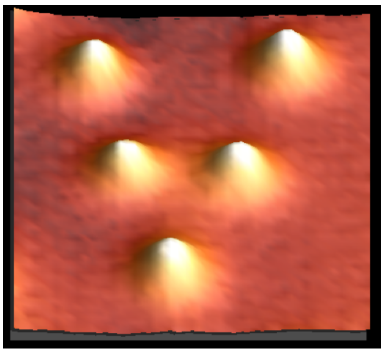
Vortices play a crucial role in determining the properties of superconductors as well as their applications. Therefore, characterization and manipulation of vortices, especially at the single vortex level, is of great importance. Among many techniques to study single vortices, scanning tunneling microscopy (STM) stands out as a powerful tool, due to its ability to detect the local electronic states and high spatial resolution. However, local control of superconductivity as well as the manipulation of individual vortices with the STM tip is still lacking. Here we report a new function of the STM [1], namely to control the local pinning in a superconductor through the heating effect. Such effect allows us to quench the superconducting state at nanoscale, and leads to the growth of vortex-clusters whose size can be controlled by the bias voltage. We also demonstrate the use of an STM tip to assemble single quantum vortices into desired nanoscale configurations.



A vortex pattern 'V' short for vortex is assembled by using the STM tip.

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Vortex in the maze

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Recent advances in vortex imaging allow for tracing the position of individual vortices with high resolution. By pushing an isolated vortex with a transport current and measuring the linear ac response of the vortex, its trajectory and the associated pinning energy has been found in selected regions of the pinning landscape [1]. Injecting the vortex into the sample at different locations and pushing the vortex through the sample with the help of the tunable transport current resembles the dexterity game where a ball is balanced through a maze. Similar to the ball probing the maze, the vortex probes the relevant regions of the pinning landscape and thus gives access to its microscopic structure. Analyzing the full two-dimensional problem, we show that the "broken spring" effect reported in [1] finds a natural explanation in terms of a vortex escape in the direction transverse to the applied force. Extending the analysis to include high-frequency response data, we show that the pinning potential can be systematically reconstructed. We introduce the Hessian, the determinant of second derivatives, as a new quantity characterizing a two-dimensional pinning landscape. The regions where vortices can assume an equilibrium position under the action of a homogeneous external force, and hence be observed in vortex imaging, involve positive Hessian. We calculate the area of such stable regions for different types of disorder potentials, that provides information on what part of the landscape can be mapped.

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Paramagnetic excited vortex states in superconductors

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Since individual vortices in type II superconductors were first seen by Essmann and Trauble through the Bitter decoration technique [1] there has been huge advancements in visualization techniques that now opens the gate to investigate new properties, such as those of the excited vortex state (EVS) [2].

A type II superconductor in presence of an external applied magnetic field contains vortices in its interior whose density is fixed by the external applied magnetic field. Once the applied field is switched off this state becomes unstable and vortices must leave the superconductor. However, their exit can be hindered by microscopic inhomogeneities, which pin them inside the superconductor. Here we make an important distinction concerning this remaining vortex state according to how its energy compares with that of the normal state. In case this energy difference is positive one expects the collapse of the superconducting state and the onset of the normal state, possibly because of the presence of nonlinear thermal effects. Although the remaining vortex state is also unstable in case the energy difference is negative, we do not expect this collapse because of an EVS.

We show that the EVS is paramagnetic and present a general method to obtain its Gibbs' free energy through conformal mapping. The method is based on the first-order equations used by Abrikosov to discover vortices [3].

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Superconductor-insulator transition in nanohole thin films with bond and magnetic flux disorder.

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We study the superconductor to insulator transition in nanohole thin films in a transverse magnetic field [1,2] by numerical simulation of a Josephson-junction array model [3]. Bond disorder due to spatial variations in the Josephson coupling and magnetic flux disorder due to variations in the plaquette areas are considered. Monte Carlo simulation in the path integral representation of the model is used to determine the critical behavior and the universal resistivity at the transition as a function of disorder and average number of flux quantum per cell, f_0. The results show that bond disorder leads to a rounding of the first-order phase transition for $f_0 = 1/3$ to a continuous transition. In present of flux disorder, the resistivity at the transition increases with disorder for noninteger fo while it decreases for integer f_0, and reaches an approximately common value in a vortex glass regime above a critical value of the flux disorder D_c^f. The estimate of D_c^f and the resistivity increase for noninteger fo are consistent with experimental data on ultrathin superconducting films with positional disordered nanoholes [1] . For integer f_0, the decrease of the critical coupling parameter with flux disorder for a honeycomb lattice is significantly smaller from that on a square lattice.

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Scanning tunneling microscopy studies of the vortex lattice in pnictide superconductors

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High critical temperature superconductivity, and in particular iron based superconductivity, often appears in doped materials with some sort of substitutional disorder. Scanning tunneling microscopy provides detailed measurements of the local electronic density of states, which can be used to image at the same time vortices and the effect of impurities or disorder on the local superconducting properties. Potentially, it could thus be used to obtain conclusive insight into the features responsible for vortex pinning and better understand the value of the critical current. However, this is difficult to achieve in systems where the local superconducting properties change a lot as a function of the position due to intrinsic disorder.

Recently, a new stoichiometric compound, $CaKFe_4As_4$ that belongs to the so-called 1144 family was synthesized with a critical temperature T_c=35 K comparable to the optimal T_c obtained usually in doped pnictides. This compound does not show the structural transitions observed in doped systems. Here I will show tunneling spectroscopy measurements and vortex lattice imaging in this compound. We obtain multigap superconductivity consistent with s$\pm$ pairing and a hexagonal disordered vortex lattice under magnetic fields. Thanks to the absence of intrinsic disorder, we also show that vortices are pinned to places where the local density of states is disturbed by pair breaking at a defect.

I will also present STM experiments in Co-doped $CaFe_2As_2$. We observe that the superconducting density of states at the Fermi level strongly changes at boundaries due to orthorhombic/tetragonal domains, indicating that the sample is inhomogeneous. The electronic structure shows nematic order at local scale, associated to the orthorhombic distortion. Interestingly, vortices appear arranged along the boundaries.

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Generation of vortex-antivortex pairs by moving vortices and a dynamic phase slip transition in long Josephson junctions.

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We show that a uniformly moving Josephson vortex driven by a strong dc current can produce vortex-antivortex pairs caused by Cherenkov radiation. These vortices and antivortices then become spatially separated and accumulate continuously on the opposite sides of an expanding dissipative domain. Numerical simulations which took into account nonlocality of Josephson electrodynamics for different junction geometries have shown that this effect becomes particularly pronounced in moderately underdamped thin film junctions where a vortex moving with a constant velocity can switch the whole junction into a resistive state at currents well below the Josephson critical current [1]. As a result, a single moving vortex can destroy the global Josephson phase coherence in a way similar to the dynamic dislocation pileup during the crack propagation in solids.

We obtained an exact solution for an Abrikosov-Josephson vortex driven by an arbitrary, time-dependent current in an overdamped junction of finite length where the vortex turns into a phase slip in a junction shorter than a critical length. We also performed numerical simulations of vortices driven by strong dc and ac currents in finite junctions, taking into account the Josephson nonlocality, Cherenkov radiation and the vortex bremsstrahlung caused by attraction of vortices to the edges of the junction. We observed dynamic transitions of vortices into phase slips as the current increases, the mechanism of this transition depending on a damping parameter. In overdamped junctions vortices expand as them move faster and turn into a phase slip as the current increases. In underdamped junctions vortices entering from the edges become unstable due to Cherenkov radiation and produce cascades of expanding vortex-antivortex pairs, which drive the entire junction into a phase slip state. We simulated vortices under dc and ac currents and calculated hysteretic current-voltage characteristics which have jumps and regions with negative differential resistance resulting from transitions from oscillating to ballistic propagation of vortices and their interaction with pinning centers and standing waves in the junction.

This work was supported by US DOE under Grant No. DE-SC0010081.

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Landau-Zener-Stückelberg interferometry for Majorana qubits

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We propose a new way for manipulating Majorana qubits in nanowire topological superconductors [1]. The prototype setup consists of two one-dimensional topological superconductors coupled by a quantum tunneling junction [2]. We show theoretically that injecting current into the system induces a Landau-Zener-Stückelberg interference between the parity states of Majorana bound states. Adjusting the current pulse and the gate voltage at junction, one can build a Landau-Zener-Stuckelberg interferometry as a universal gate for the Majorana qubit. The quantum mechanical dynamics of Majorana qubit can be monitored by analyzing spectra of microwaves radiated from the system, which includes a novel spectrum peak induced by the fractional Josephson effect associated with Majorana bound states, in addition to that due to conventional Josephson effect of Cooper pairs. Our work is expected to enhance the exploration of Majorana physics [3,4] and eventually the implementation of topological quantum computation.

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Quantum Phase Transitions in Gate-Induced 2D Superconductors

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In the past decade, technological advances of materials fabrication have led to discoveries of a variety of highly crystalline two-dimensional (2D) superconductors at heterogeneous interfaces and in ultrathin films [1]. These systems are offering opportunities of searching for superconductivity at higher temperatures as well as investigating the intrinsic nature of 2D superconductors, which are distinct from the conventional 2D superconductors with the amorphous or granular structure, which were extensively investigated in the last century. Thus the new 2D superconductors could be a new plat form of physics of 2D superconductivity. In this presentation, we report recent progress on gate-induced superconductivity of exfoliated layered materials, such as ZrNCL and MoS2, which has become an archetypal 2D superconductor with high crystallinity [2]. Discussion is given on the quantum phase transitions at low temperatures [3] and the peculiar transport reflecting the broken inversion symmetry of the crystals [4].

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Superconducting states in the topological surface state of β-$PdBi_2$

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β-$PdBi_2$($T_c = 5.4$ K [1]) is known to possess a topologically nontrivial and a trivial spin-polarized surface states at the Fermi level (E_F) in the normal state [2]. In this situation, unusual surface superconducting (SC) states such as a mixing of spin-singlet and triplet Cooper pairing [3] and the possibility of Majorana zero mode in a vortex core [4] are theoretically expected. However, experimental investigations of such SC states have remained elusive. In this study, we perform low temperature scanning tunneling microscopy/ spectroscopy (STM/STS) measurements to investigate the surface states and their superconducting states of β-$PdBi_2$. Characteristic quasiparticle interference patterns are clearly explained in terms of spin-dependent scattering, strongly supporting the existence of the spin-polarized surface states near E_F. We observe a fully-opened SC gap ($\Delta = 0.8$ meV) in the surface states. Considering a possible mixing of odd- and even parity orbital functions in C_{4v} group symmetry reduced from D_{4h} near the surface, we suggest that the observed SC gap could be attributed to the mixture of s- and p-wave SC gap functions in the two-dimensional state.

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Reconfigurable ordering, frustration and stability of vortex matter via network science

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Transport properties of vortices in type-II superconductors have been widely studied. Compared with fixed attractive pinning structures in previous work, here we present a study with tunable pinning configurations containing both attractive and repulsive centers. This reconfigurable energy landscape is realized by in-situ tunable artificial spin ice, arrays of nanoscale single-domain bar magnets, coupled with a superconducting film. By controlling the artificial spin ice structure, we can realize reconfigurable states of ordering and frustration in the vortex ensemble, which leads to emergence of fractional filling matching effects and ratchet effects. For a systematic study of the configuration stability under different conditions, we propose a novel method based on a network science approach, using k-core analysis of the energy landscape. As first shown by Stillinger and Weber [1], the metastable states (vertices) and the transition states between them (edges) form a complex network with graph theoretical properties that correlate with energetic properties, the stability of metastable n-body configurations and the transitions between them. This network mapping provides a reduced degree of complexity in describing the n-body system, yet it is detailed enough to capture novel features as a function of the confinement geometry and pinning potential configuration.

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Terahertz Emission from High-Tc Superconductor Bi2212 Mesa Structures with Higher Symmetry

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Ten years have passed after the discovery of terahertz emission from the mesa structure of Bi2212 single crystals[1]. The superconducting $\mathrm{CuO_2}$ double layers are build in a unit cell of the Bi2212 crystal and are sandwitched by the insulating $\mathrm{Bi_2O_2}$ layers, forming a stack of intrinsic Josephson junctions (IJJs). Since the electronic structure as a result of this crystal structure is highly two dimensional, the superconducting (Josephson) coupling is extremely weak as measured by the c-axis critical current $J_\mathrm{c}^\mathrm{c} = 10^2$ - 10^3 A/cm^2 compared with $J_\mathrm{c}^\mathrm{ab} = 10^6$ - 10^7 A/cm^2, resulting in the reduction of the superconducting plasma frequency to the level of $f_\mathrm{J} \sim 10^{11}$ c/s ($0.2 \sim 1$ meV), which is well below the superconducting gap $\Delta = 30$ meV. This Josephson plasma mode can be excited by the dc-current through the nonlinear Josephson coupling effect and the coherent THz emission is generated due to the ac-Josephson oscillation with the frequency $f_\mathrm{J} = (2e/h)v_\mathrm{J}$, when it matches well the cavity mode frequency. Although the understanding has already been well established by various experiments [2], the practical limitation of the device is not well understood yet. For example, the most significant two issues are on what determines the maximum power extracted, and what limits the maximum frequency. The essential parameter related to two issues is evidently the thermal effect due to the Joule heating by the dc-current (10 - 50 mW), which produces heat of $\sim$ MW/cm^3 and naturally causes a serious temperature rise and inhomogeneity often called as a hot-spot. It has been disclosed that the formation of the hot-spot gives a detrimental effet on the THz radiation phenomena so that it is better to avoid it and conntrol it to make the influence minimum on the THz emission. The heating issue has recently been studied intensively [3]. So far, we have achieved a frequency of 2.4 THz with a power of 30 μW [4].

Recently, we have done a systematic case study on the rectangular, square, circular, triangular mesas, *etc.* and found an interesting fact. That is concerning with the missing modes, which are expected to be as the strong emission modes but systematically disappear or are missing, perhaps, due to very weak intensities, especially in the degenerated symmetric cases often occurring in square and circular mesas. We argue this effect as a mode cancellation in the degenerated cavity modes in a symmetric mesa.

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Mapping superfluid density near the superconductor insulator phase transition

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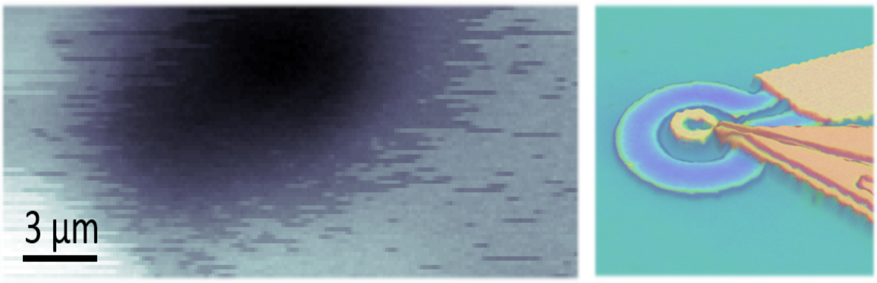
The behavior near the superconductor-insulator transition (SIT) is governed by quantum fluctuations. Direct experimental study of such fluctuations is challenging, and not easily probed by conventional measurements such as transport and magnetoresistance. We use scanning superconductor quantum interference device (SQUID) to simultaneously track magnetometry, susceptometry and local flow of current in a series of TiNbN samples spanning the SIT. Maps of the diamagnetic response provide information about the local superfluid density. Our measurements reveal electronic superconducting granularity which fluctuates in time and space at temperatures well below Tc. The temperature regime of these fluctuations grows as the SIT is approached indicating their quantum nature.



Quasiparticle excitations of FeSe in the vicinity of the BCS-BEC crossover

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The BCS-BEC crossover bridges the two important theories of bound particles (Bardeen-Cooper-Schrieffer theory and Bose-Einstein condensation) in a unified picture with the ratio of the attractive interaction to the Fermi energy as a tuning parameter. Recently, there is growing evidence that FeSe, the simplest iron-based superconductor with $T_c \sim 9$ K, is at the verge of the BCS-BEC crossover [1,2]. Here, we discuss several unique properties of FeSe with respect to the crossover physics, with emphasis upon (1) its extraordinarily small Fermi surface, which strongly deviates from the predictions of first-principles calculations [1,2], (2) giant superconducting fluctuations by far exceeding the standard Gaussian theory [1,2], and (3) emergence of distinct field-induced superconducting phase with an unprecedented large spin imbalance [1, 4]. In particular, the observation of field-induced phase provides insights into previously poorly understood aspects of the highly spin-polarized Fermi liquid in the BCS-BEC crossover regime.

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Probing superconductity and magnetism in unconventional superconductors with positive muons

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The muon-spin rotation (μSR) technique is a powerful tool for investigating magnetic properties of superconductors and magnetic systems. The positive muon with a spin $S = 1/2$ serves as microscopic magnetic probe to detect local magnetic fields in the bulk of a solid. In many cases μSR has provided important information on the microscopic magnetic properties of these materials, which are hardly obtained with other experimental techniques.

After a short introduction to the basic principles of the μSR technique and a brief history of μSR in the field of high-temperature superconductivity, some typical examples of the application of μSR for investigating local magnetic properties of cuprate and related high-temperature superconductors (HTSs) are presented. By means of μSR the local magnetic field distribution $p(B)$ in the mixed state of a type II superconductor can be determined, allowing to explore the complex static and dynamic vortex structure (vortex matter) in cuprate and related HTSs on a microscopic scale. These *microscopic* studies may be complemented by *macroscopic* experiments, e.g. by means of SQUID and torque magnetometry. Furthermore, zero-field μSR is an ideal tool to investigate the magnetic phases and its coexistence with superconductivity of cuprate and iron-based HTSs. There are several motivations to investigate HTS multilayer structures containing superconducting and insulating (or metallic) layers. The low-energy μSR technique (LEμSR) developed at the Paul Scherrer Institute (PSI), Switzerland, is well suited for investigating multilayer structures: slow positive muons of tunable energy between 1 keV and 30 keV can be implanted at a very small and controllable depth below the surface of a sample on a nanometer scale. This allows all the advantages of standard μSR to be obtained in thin samples, near surfaces, and as a function of depth below surfaces [1].

In order to demonstrate the unique power of μSR the following representative topics are discussed:
- Measurements of the magnetic penetration depth in type-II superconductors
- Study of the vortex phase diagram (flux-lattice melting, 3D-2D crossover, vortex fluctuations) of cuprate HTSs
- Coexistence of superconductivity and magnetism in cuprate and iron-based HTSs
- Searching for spontaneous magnetic fields (orbital currents) in the pseudogap phase of cuprate HTSs
- Study of spin-stripe order in cuprate HTS systems
- Study of thin-film HTS multilayer structures by means of LEμSR

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Coherent emission from the intrinsic Josephson junctions in thermally-managed, high-symmetry $Bi_2Sr_2CaCu_2O_{8+\delta}$ devices

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The emission of coherent radiation from the intrinsic Josephson junctions in the high transition temperature T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) arises from two sources: (1) the uniform part of the ac Josephson current satisfying the Josephson relation $f = f_J = 2ev/h$, where e is the electronic charge, v is the applied voltage per junction, and h is Planck's constant, and (2) when $f = f_c(n, m)$ matches that of the (n, m)th electromagnetic geometrical cavity mode of the thin device, the emission power can be greatly enhanced [1]. For conventional devices such as mesas carved from the top of a Bi2212 single crystal [2-4], the Bi2212 substrate not only absorbs much of the emission nearly parallel to the substrate [1], but its poor thermal conductivity leads to Joule heating, $f < 1$ THz, and the inevitable formation of hot spots, inside of which the local temperature $T(\mathbf{r}) > T_c$ [5]. However, "thermally-managed stand-alone" devices constructed by removing the mesa from its Bi2212 substrate, covering its top and bottom surfaces with Au and sandwiching it between sapphire plates [3,6], narrow-linewidth emission at the world-record 2.4 THz from a superconductor was observed [7], placing a lower limit of $\Delta_{\min} \geq 9.8$ meV on the bulk Bi2212 gap function, and filling the "THz gap" with a tunable, continuous-wave emitter. Moreover, the emission spectra from that high-symmetry disk [7] and unpublished high-symmetry square devices strongly suggest that only cavity modes obtained from wave functions that are one-dimensional representations of the appropriate point group can lead to electromagnetic cavity mode enhancements [3,7-9]. A theoretical explanation of this previously unknown restriction is presented.

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Vortex matter close to the crossover between antiferromagnetic and paramagnetic ground states in iron-based superconductors

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Parent compounds of 122 family iron-based superconductors (IBS) are antiferromagnetic (AF). Substitution on either sublattice leads to depression of magnetic transition and emergence of superconductivity (SC). Generic composition-temperature phase diagram of Fe-based superconductors shows dome shaped SC region, intersected by magnetic, spin density wave (SDW) transition line. On the slightly underdoped side of superconducting dome, unique scenario occurs. On cooling, SDW order develops, and at lower temperature superconductivity emerges from magnetic state. Coexistence or competition of SDW and SC orders on microscopic scale is a challenging experimental problem due to the difficulty to change composition in a controlled way. We apply an alternative approach to $Ba(FeAs_{1-x}P_x)_2$ crystals, tuning of the phase diagram by irradiation-induced disorder. We introduced vacancy type defects on all sublattices by low temperature irradiation with 2.5 MeV electrons. It results in strong downward shift of SDW transition, easily identified on resistivity vs. temperature curves. For the composition close to optimal ($x = 0.28 - 0.29$), SDW phase can be suppressed completely and the sequence of transitions on cooling: from paramagnetic (PM) to AF and from AF to SC is replaced by direct transition from PM to SC state. This leads to essentially different vortex states in SC region. From the resistive transition we can distinguish low pinning (critical current) state arisen from AF background and high pinning state emerged from PM ground state. Hall array magnetometer provided us more insight to the vortex state in the vicinity of intersection of SC dome with SDW transition line. Identification of two distinct SC states, based on jump in critical current, allows us to draw new reentrant transition line extending from SDW-SC crossing point. Our observation points to the presence of tetracritical point and coexistence on the microscopic scale of magnetic and superconducting orders in the underdoped part of SC dome.

Universal metal-insulator-like transition and topologically-protected states

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Numerous experiments performed on materials belonging to different classes, such as superconductors, metals, Weyl, Dirac and "simple" semimetals, Kondo-systems, revealed an universal metal-insulator-like transition (MIT) driven by quenched disorder, applied magnetic field, or pressure. A salient feature of all the observations is the low-temperature resistance saturation at the "insulating" side of the transition, in many cases attributed to topologically-protected conducting surface states. It appears, that MIT measured in all these systems can be well described using two-parameter scaling analysis proposed in Ref. [1] to characterize the Bose metal (non-superconducting state of Cooper pairs) - insulator transition. This has been exemplified for graphite and bismuth semimetals [2]. In this presentation we shall emphasize the universality of the MIT in question, taking into consideration a multiband character of studied materials, dimensionality of electron system as well as effects of electron-electron and electron-hole interaction. We shall discuss effects of magnetic field and pressure in the presence of structural disorder within a framework of available condensed matter theoretical models.

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Strong Landau-quantization effects in high-magnetic-field superconductivity of clean two-dimensional metals with deep and shallow bands

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We investigate the superconducting instability in magnetic field for a clean multiple-band superconductor in the vicinity of the Lifshitz transition when one of the bands is very shallow [1]. Such situation is realized in several iron-based superconductors. Due to small number of carriers in the shallow band, the quasiclassical approximation breaks down and Landau quantization has to be taken into account. The quantum effects have only been studied for single-band materials where the cyclotron frequency at the quasiclassical upper critical field H_{c2} is much smaller than the Fermi energy [2,3]. In multiband superconductors, the depletion of just one band may weakly affect the transition temperature. In such materials, the cyclotron frequency can be made comparable with the Fermi energy of the shallow band at $H \sim H_{c2}$. We focus on the two-dimensional case in which the quantum effects are the strongest. In this system the transition temperature $T_{C2}(H)$ is resonantly enhanced at the magnetic fields corresponding to full occupancy of the Landau levels in the shallow band. This enhancement is especially pronounced for the lowest Landau level. As a consequence, the reentrant superconducting regions appear at low temperatures near the magnetic fields at which the chemical potential matches the Landau levels, see the figure. The specific behavior depends on the relative strength of the intraband and interband pairing interactions and the reentrance is most pronounced in the purely interband coupling scenario. The reentrant behavior is suppressed by the Zeeman spin splitting in the shallow band, the separated regions disappear already for very small spin-splitting factors. On the other hand, the reentrance is restored in the resonance cases when the spin-splitting energy exactly matches the separation between the Landau levels [3]. The predicted behavior may realize in the FeSe monolayer.

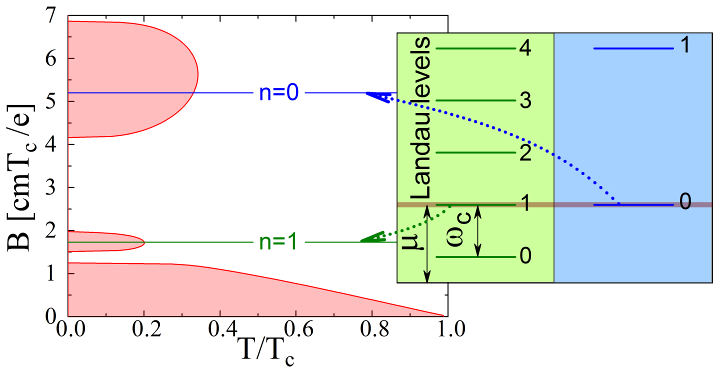

Figure 2: The typical phase diagram for a 2D two-band superconductor with the shallow band in the case of dominating interband coupling and zero spin splitting.

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Mapping the local superfluid density with scanning SQUID microscopy

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Maps of the diamagnetic response of superconducting samples provide information about the local superfluid density and can reveal valuable information about the superconductivity in different materials. We use scanning superconductor quantum interference device (SQUID) to simultaneously track magnetometry, susceptometry and local flow of current. In my poster I will focus on two material systems where susceptibility mapping provide a unique view. One, superconducting thin films deposited on $SrTiO_3$ (STO) reveal large-scale modulations of the superfluid density and the critical temperature due to domains and domain walls in the STO. The second system is a set of TiNbN samples spanning the superconductor-insulator transition (SIT). Near the SIT, our measurements reveal electronic superconducting granularity which fluctuates in time and space at temperatures well below T_c.

Mesoscopic Josephson networks on topological surfaces

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Recent discovery of surface superconductivity at remarkably high temperatures in a topological system Sb_2Te_3 [1] has brought to the fore the importance of disorder in inducing strong particle correlations on topological surfaces. The picture that has emerged from transport, magnetic susceptibility and STM experiments implies a mesoscopic system of Dirac puddles embedded in a 'normal' metal matrix comprising the 2DEG subsurface states, with global superconducting coherence mediated by interpuddle diffusion of quasiparticles through a mesoscopic Josephson (JJ) network. Here I will discuss the nature of the host 2DEG matrix and the JJ network it supports, and particularly the role of sharp Te resonances in the observed magnetic response. The resonances in *ac* magnetic susceptibility $\chi(\omega, B)$ found in the superconducting samples at fields above the paramagnetic field limiting field are amplified and broadened. These resonances are non-dispersive in field and they appear not connected to the overall diamagnetism of Dirac puddles. A comparison of ARPES and micro-ARPES band structures of 2DEG matrix in superconducting and non-superconducting Sb_2Te_3 allows us to glean at the unusual linear dispersion and a 'petal-like' 3-fold-degenerate 2D subsurface states at the Γ point in the Brillouin zone that control resistive T_c.

* Work was supported in part by the NSF grants DMR-1420634, DMR-1312483, and HRD-1547830.

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Type-II Superconductivity in Arrays of Nanostructured β-Gallium

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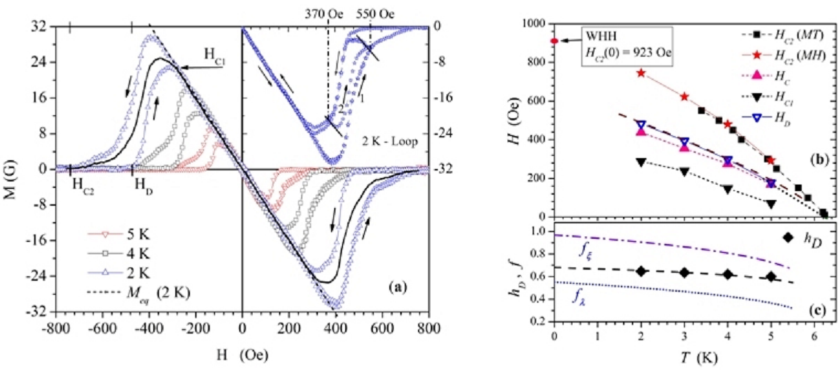
Samples of nanostructured β-Ga wires were synthesized by a novel method of metallic-flux nanonucleation [1,2,3]. Several superconducting properties were determined, revealing an interesting dimensionality induced stabilization of a weak-coupling type-II superconductor with $T_c \approx$ 6.2 K and Ginzburg-Landau parameter κ_{GL} = 1.18. This contrasts a type-I superconductivity observed for the majority of Ga phases, including small spheres of β-Ga with diameters around 15 μm. Remarkably, our magnetization curves (Figure 1) reveal a crossover field H_D, where the Abrikosov vortices are exactly touching their neighbors inside the Ga nanowires. A phenomenological model is proposed to explain this result by assuming that only a single row of vortices is allowed inside a nanowire under perpendicular applied field, with an appreciable depletion of Cooper pair density at the nanowire edges. These results are expected to enrich the growing area of mapping superconducting properties in nanostructured materials.



(a) Magnetization as a function of perpendicular applied field. Definitions for the lower critical field (H_{c1}), upper critical field (H_{c2}) and crossover field (H_D) are shown. The curve for 2 K is repeated (open stars) between 0 and 800 Oe to execute a minor hysteresis loop; (b) Critical field lines; (c) Closed black diamonds represent the reduced crossover field $h_D = H_D/H_{c2}$ and the dashed line represent the fitted function for h_D. The dash-dotted and dotted lines represent the calculated depletion parameters f_ξ and f_λ, respectively.

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Hyperuniform disorder of the vortex lattice

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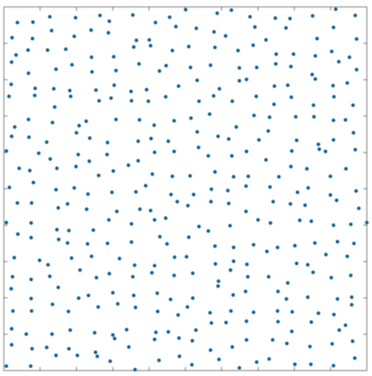
A 2D random distribution of particles shows bunching, resulting in spatial fluctuations of the density that increase together with the area.That is, if we consider particles within a circular area with radius r, the density fluctuations increase with r^{α} and α=2. This also means that the structure factor does not go to zero for small k and the corresponding distribution of particles has been termed "hyperuniform" [1,2]. Interactions among particles often decrease bunching, resulting in distributions where the density fluctuations increase with $\alpha < 2$ and the structure factor decreases with k^{β} and $\beta > 0$.

Here we analyze images of disordered superconducting vortex lattices taken with a scanning tunneling microscope. We start by analyzing the potential that creates the disorder influencing the vortex lattice and present two limiting cases, random pinning and uncorrelated long range disorder created by a 1D potential at an angle with the vortex lattice. The latter is a hyperuniform potential in a somewhat trivial way, because it results from a discommensuration between two ordered lattices.

We find that in both cases, the structure factor of the vortex lattice decreases to zero for large wavelengths with power laws ranging between k^1 and k^2. It has been recently shown that the vortex lattice is in itself always hyperuniform, as a result of the repulsive interaction. And that a hyperuniform distribution of pinning centers is favorable to increase the critical current, because it reduces the appearance of channels for vortex transport and allows for a larger occupancy of pinning sites. Vortex arrangements stabilized by a hyperuniform potential appear between the Bragg glass and the disordered (liquid) vortex lattice [3]. We discuss imaging experiments showing vortex motion and their relevance for the proposed phenomena.



Hyperuniform lattice.

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Effects of the manufacturing process of MgB_2 cables on the superconductor precursor material

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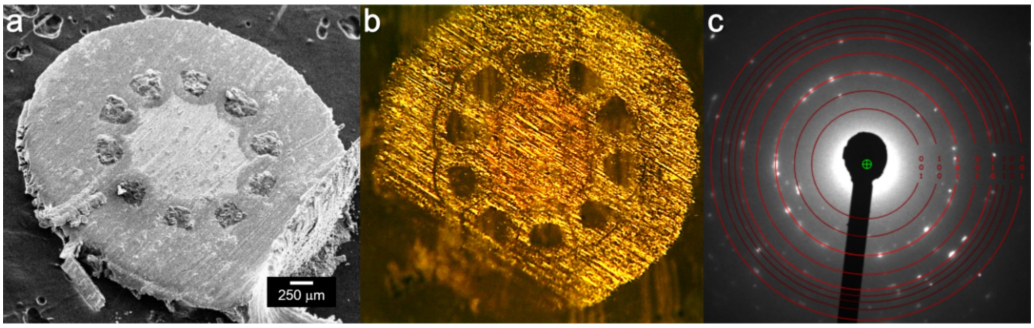
Pinning of vortices is a field of great interest for applications of superconductivity. The ability of avoiding vortex movement is directly related to avoiding dissipation of energy in the material. Natural and artificial defects are able to work as pinning centers for vortices in superconductors. In that way, the study of different kind of defects like impurity inclusions, segregated phases or grain boundaries is important from an application point of view.

In this work we present a study of the grain size of MgB_2 as the precursor material for superconductor cables [1]. We compared particles of the precursor before and after the drawing and analyzed how microstructure changes in function of it. The role of the grain size and their possible consequences is also discussed. Cases for several configurations are compared.



(a). SEM image of a slice of superconductor cable of ten MgB_2 filaments. (b). Optical image showing a detail of superconducting nuclei and individual filaments. (c). Diffraction pattern of MgB_2 precursor powder. Related planes have been indexed in some rings at the pattern.

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Pinning force estimation method based on a vortex position analysis

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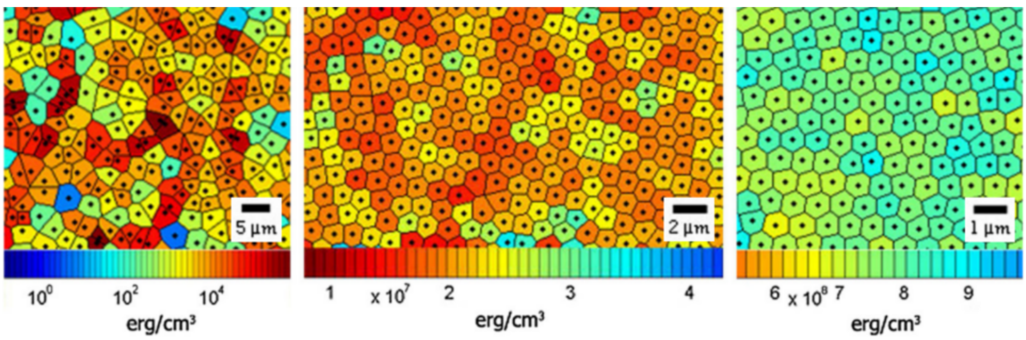
Vortex positions at the flux line lattice (FLL) carry on with huge amount of information. Interactions of vortices with material defects as well as other vortices are responsible of each vortex positions at the system. A proper analysis of these positions could show us local information of material properties through the interaction energy that locate vortices at particular places.

We present here a model able to associate a potential energy to each vortex position at the FLL [1]. This potential energy is directly related to local pinning energy of the material. Results coming from Bitter decoration experiments on $YBa_2Cu_3O_{7-d}$ (YBCO) single crystals and thin films with different kind of defects are shown. Applying our model, we observe a pinning energy at least 3 times higher for thin films in comparison with pinning energy quantifies for single crystals. Also, comparing surface linear defects generated artificially on samples, our model points out a strong pinning energy, at least twice, for nano-indented defects in comparison with ion irradiated defects.

Finally, a further basic emulation of vortex positions, formulated in accordance with our model, allows to perform a special analysis of surface linear defects artificially generated. In this way, we were able to estimate a minimum pinning energy for nano-indented defects of 3 times the interaction vortex energy working at low magnetic fields, according to Bitter decoration experiments on YBCO single crystals.



Maps of interaction vortex energies for vortex positions at the FLL (black dots at images). Results come from Bitter decoration experiments performed on YBCO single crystals at 16.5 Oe, 33 Oe and 66 Oe (respectively) under field cooling conditions. Changes in the FLL order are clearly exposed.

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Vortex pinning and relaxation in high-J_c 122 type pnictide superconducting tapes

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122 type pnictide superconductors are of particular interest for high-field applications because of their large upper critical fields H_{c2} ($>$100 T) and low anisotropy γ ($<$2). Here we report our recent achievement in the developing 122 type Fe-based tapes with transport J_c up to 50 kA/cm^2 at 27 T and 4.2 K. The high density nano-scale defects formed within superconducting grains may account for this large in-field J_c. By measuring the magnetization and its relaxation, vortex pinning and dynamics were systematically studied in high performance Sr-122 tapes. The temperature dependence of critical current density was found to be in agreement with the model of vortices pinned via spatial fluctuation of charge carrier mean free path. Magnetic relaxation measurement indicates a logarithmic dependence on time. The rather small relaxation rate has a weak temperature and field dependence in the low and intermediate temperature region. A crossover from elastic creep to plastic creep regime was observed. Finally, a vortex phase diagram was concluded for the high performance $Sr_{0.6}K_{0.4}Fe_2As_2$ superconducting tapes.

Effect of magnetic field on electronic superstructures in cuprate superconductors

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The electronic structure in cuprates exhibits the nodal-antinodal dichotomy identified by the low-energy Bogoliubov quasiparticles near the nodal region and the high-energy pseudogap (PG) states around the antinodal region that are associated with broken-spatial-symmetry states [1,2]. The relation among superconductivity, PG, and broken-spatial-symmetry states has been a long-standing issue in cuprates. Although the competitive relation between superconductivity and the broken-spatial-symmetry states has been suggested based on the fact that a magnetic field induces or enhances various electronic superstructures [3,4], their real-space structure and energy-scale are still unclear. To address this issue, we have performed spectroscopic-imaging scanning tunnelling microscopy on optimally-doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ under a magnetic field (B). Our results indicate that two distinct electronic superstructures are enhanced in the vortex core at different energy scales. In the low-energy range, where the nodal Bogoliubov quasiparticles are well-defined, we observe the so-called 'vortex checkerboard' [5]. The wavevectors of the observed 'vortex checkerboard' follow the Bogoliubov quasiparticle dispersion, suggesting that the 'vortex checkerboard' is attributed not to an electronic order but to the coherence-factor-enhanced quasiparticle interference [6]. In the high energy range, where the PG develops, the broken-spatial-symmetry states preexisting at B = 0 T are locally enhanced in the vortex core. This consolidates the competitive relation between superconductivity and the broken-spatial-symmetry states associated with the pseudogap [7]. We will also present the results in underdoped $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$, to further discuss the relation between superconductivity and the broken-spatial-symmetry states.

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d-wave vortex cores revealed by Scanning Tunneling Spectroscopy of $YBa_2Cu_3O_{7-\delta}$

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Scanning tunneling spectroscopy (STS) of vortex cores in the high-temperature cuprate superconductors has been challenging theory for years, since most of the observations made until now could not be easily explained. As a matter of fact, the detection of a robust pair of electron-hole symmetric states at finite subgap energy in $YBa_2Cu_3O_{7-\delta}$ (Y123) [1] was in total contradiction with the expected signature of a d-wave superconductor vortex core, characterized by a strong zero-bias conductance peak. Recent STS data on very homogeneous Y123 at 0.4 K revealed that these subgap features are not exclusively linked to the vortex cores: they are actually observed everywhere along the surface with high spatial and energy reproducibility, and even in the absence of magnetic field [2]. We show that these states, which remain unaffected by the opening of the superconducting gap, might belong to an incoherent channel which contributes to the tunneling signal in parallel with the superconducting density of states. When this incoherent contribution is subtracted from the total tunneling conductance, the remaining coherent channel exhibits the expected signature of a pure d-wave superconductor, for spectra acquired not only outside but even at the center of the vortex cores where a zero-bias anomaly emerges. Microscopic modeling reveals that the spatial evolution of the local DOS in the presence of vortices is strongly linked both to the material band structure and also to the exact position of the vortices around the measurement location. The tunneling spectra acquired by STS in a 6 T magnetic field are in remarkable agreement with the local DOS calculated in a model where the vortex landscape accurately matches the actual distribution of the flux lines [3].

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Nonuniform vortex configurations in type-II superconductors

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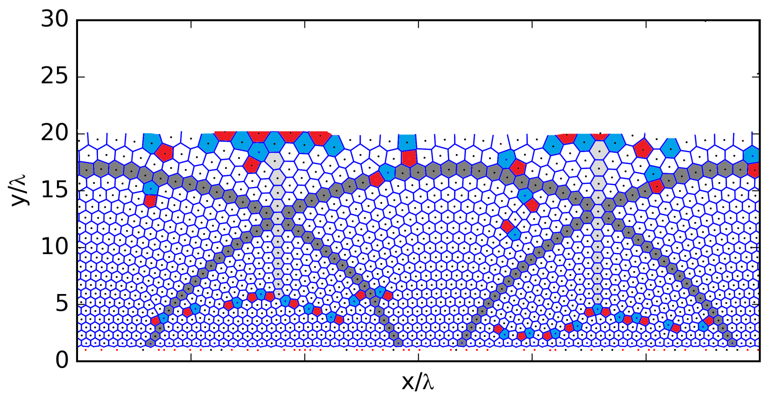
In situations of uniform vortex distributions, the vortex lattice tends to form the well known Abrikosov lattice. However, little is known about which structures the vortex lattice can form when subjected to nonuniform density. In this work we present, through numerical simulation results, possibilities of obtaining ordered configurations in a nonuniform vortex distribution. After performing many realizations of a Langevin minimization procedure of a large number of vortices subjected to different forms of a confinement potential, we found that vortices can self-organize in a structure of arches and pillars in order to accommodate to the high potential gradients. In the special case of a sawtooth potential (constant force field), the most frequent low-energy configuration (shown in the Figure) resembles the *gravity rainbow* structure of magnetized spheres confined in 2D and subjected to a gravitational field [1]. Such structure is a quasi-conformal crystal in the sense that it can be approximately mapped from a triangular lattice via a conformal transformation. In the vortex case, the uniform force field can be induced by a uniform current density applied perpendicularly to the vortices and parallel to planar defects (such as twin boundaries), which would act as barriers avoiding vortex flow. By performing Langevin simulations of vortices in a twinned, otherwise clean, superconducting crystal after the sudden application of a uniform current density, the compressed vortex system evolves to the gravity rainbow configuration, thus suggesting that this structure could be reproduced experimentally.



Typical low-energy configuration of vortices (dots) in a sawtooth confining potential and respective Voronoi construction (lines).

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Anomalous Magnetic Contributions in Magneto-Transport Properties of Iron Pnictides Ba($Fe_{1-x}Mn_x$)$_2$As$_2$

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This work presents an experimental investigation on the magnetotransport properties of single-crystal samples of the compounds Ba($Fe_{1-x}Mn_x$)$_2$As$_2$, with x = 0, 2.57, 5.16, 9.27 e 14.7 at% Mn. These compounds order into a Spin Density Wave (SDW) antiferromagnetic ground state. In low Mn concentrations, a structural transition from a high-temperature paramagnetic and tetragonal phase to a low-temperature antiferromagnetic and orthorhombic phase is observed. The planar magnetoresistance was measured with fields up to μ_0H = 9 T applied along the c-axis. These results show characteristic contributions from two-band conduction (electrons and holes). Also observed is the progressive suppression of a significant spin-disorder contribution that occurs when the applied magnetic field is increased to the highest studied values. Hall resistivity measurements performed according the same geometry reveal the occurrence of a quantitatively relevant anomalous contribution in the magnetically ordered phase. To extract the anomalous Hall effect term, magnetization data from Ref [1] were used. Due to the linearity between the anomalous Hall effect coefficient and the resistivity, we propose that the asymmetric skew-scattering mechanism by magnetic ions is the responsible for the anomalous contribution to the Hall effect in the Ba($Fe_{1-x}Mn_x$)$_2$As$_2$ system. The strong correlation between magnetoresistance, magnetic measurements and Hall resistivity suggest that the role of the anomalous contribution related to the magnetic ordering should be considered in addition to effects of two-band conduction to completely explain the magnetotransport properties of the ferropnictides.

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Superconductivity in atomically thin MgB_2

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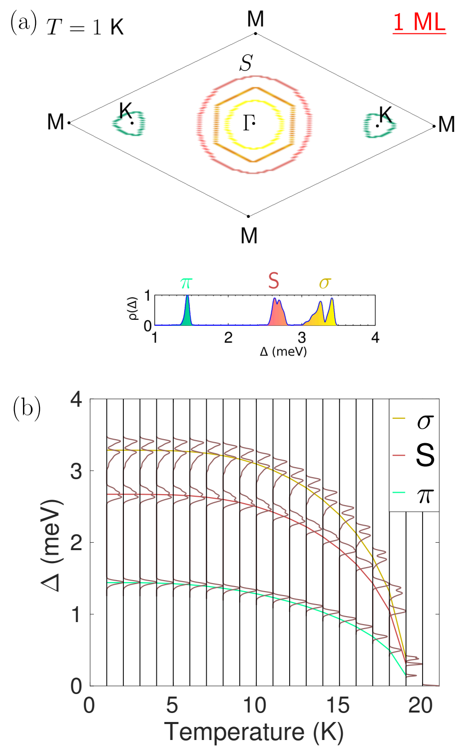
Multigap superconductivity is a fertile ground for novel phenomena and exciting vortex matter [1], with two-gap MgB_2 as an archetypal example. In that sense, one expects the superconductors with three or more gaps to be particularly exciting, due to additional competing effects and possible quantum frustration between the condensates . To date demonstrated effects specific to multi-gap superconductors include novel vortical and skyrmionic states [2], giant-paramagnetic response [3], hidden criticality [4], and time-reversal symmetry breaking [5], to name a few.

In this talk, I will discuss the evolution of multigap superconductivity in MgB_2 at its ultrathin limit. Atomically thin MgB_2 is distinctly different from bulk MgB_2, in that both free Mg- and B-surfaces contribute additional surface electronic state, comparable in electronic density to the bulk-like σ- and π-bands. Using the *ab initio* electron-phonon coupling and anisotropic Eliashberg equations, we show that these surface states strongly recast superconductivity in MgB_2 at few-monolayer thickness, providing the gap that hybridizes with σ-gap for 4+ monolayer films, but shifts towards the π-gap in thinner structures. As a consequence, the observable superconducting properties and vortex matter radically change with every added monolayer in the thinnest limit. Furthermore, a single monolayer of MgB_2 develops **three distinct superconducting gaps**, on completely separate parts of the Fermi surface (see Fig.a). We show that this three-gap superconductivity is robust over the entire temperature range that stretches up to considerably high critical temperature of 20 K (Fig.b). We also reveal that T_c can be boosted to $>$55 K under tensile strain of $\sim 4\%$.



(a) Superconducting gap spectrum of one monolayer MgB_2 at 1 K, calculated using anisotropic Eliashberg theory, and plotted on its Fermi surface. The distribution of the gaps $\rho(\Delta)$ shows three separate gaps on the π, S and σ sheets. (b) The evolution of the gap spectrum with temperature. The gap averages per sheet are also plotted, showing the persistence of three-gap superconductivity over the entire temperature range.

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Vortices in the pair-density wave phase of multilayer superconductors

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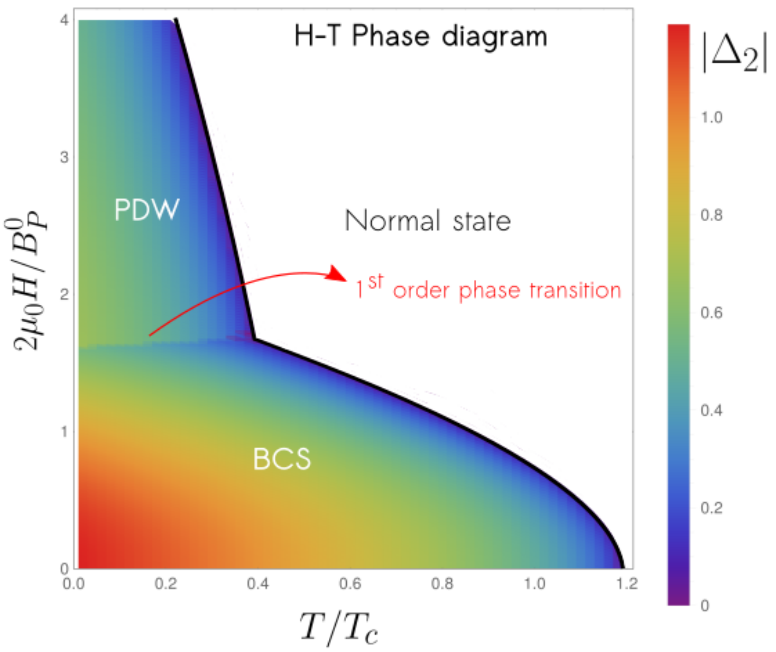
We investigate the role of magnetic vortices in the pair-density wave (PDW) phase of multilayer superconductors in the context of a Ginzburg-Landau theory. In superconducting multilayer systems, due to local inversion symmetry breaking at the outer layers, a Rashba spin-orbit coupling is induced. This combined with a perpendicular Pauli limiting magnetic field stabilizes a pair-density wave (PDW) phase, which is achieved through a first-order phase transition. The PDW phase is robust against magnetic fields as is shown in the figure. The PDW phase needs the presence of a strong paramagnetic Cooper depairing effect. We discuss the relative influence of orbital depairing (vortex physics) on the PDW phase in superconducting multilayer systems.



Typical magnetic field–temperature phase diagram of a parity-mixed three-layer system obtained within a Ginzburg-Landau theory. Δ_2 shows refers to the order parameter of the middle layer. A first order phase transition separates the low field BCS from the high field PDW region. Here T_c is the superconducting critical temperature of a single layer, which shows that a three-layer system has its critical temperature increased.

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Current-Phase Relations in Superconducting Rings

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In this talk, I will describe how to use experimental measurements of the current in a ring geometry to access fundamental and topological properties. We will start with a fast tour of currents and phases in common and exotic quantum materials: vortices in 3D and 2D superconductors, persistent currents in gold rings, and fluctuations in superconducting aluminum. The strong agreement of theory and experiment in many materials sets the stage to study superconducting rings interrupted by a single, potentially exotic Josephson junction. Scanning SQUIDs with integrated field coils and background cancellation allow us to measure the current-phase relation, a fundamental and informative property of any junction, in many individual junctions. The skewness of the current-phase relation indicates the transmission of the Andreev bound states. The current-phase relation could theoretically be 4π-periodic in junctions tuned to a topological state. I will report on progress towards both of these important signatures for Majorana bound states in gate-tuned InAs nanowires.

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Magnetic Imaging of AC Susceptibility in Superconducting Thin Films

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One of the most interesting issues in the study of vortex matter in superconducting films is the occurrence of abrupt flux invasions, called *flux avalanches*. In magnetic hysteresis loops, the signature of the flux avalanches is a jumpy behavior – the so-called flux jumps – whereas in the direct observation of the magnetic flux across the sample using Magneto-optical Imaging (MOI), these avalanches present an astonishing dendritic morphology, resembling a tree [1]. In temperature-dependent AC susceptibility measurements, the fingerprint of flux avalanches is a paramagnetic reentrance below a characteristic temperature, due to partial reuse of most of the dendritic tracks, in the process of entrance and exit of flux during the application of a train of AC cycles [2,3]. In the present work, we have investigated such reentrance in AC susceptibility measurements taking into account the magnetic history of the specimen, i.e., considering the residual state left by the AC field applied previously, for instance, at lower temperatures. This procedure has allowed us to visualize the process of melting of the dendritic tracks imprinted on the superconducting film during the avalanches. Melting of the dendrites occurs just above the characteristic temperature where only smooth penetration takes place. Besides that, the reversibility of these AC susceptibility curves has been studied for both, smooth and abrupt penetration conditions. These investigations have been conducted in superconducting films of Nb and of amorphous Mo alloys with and without an array of antidots. Therefore, the complementary experiments employing MOI, AC susceptibility, and DC magnetization provided the so far lacking information needed to ensure a broader and deeper comprehension of the intriguing reentrance of the susceptibility, a feature which has long been recognized as associated to the occurrence of flux avalanches.

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Time-reversal symmetry breaking phase, gapped surface states, and vortex-antivortex pairs in d-wave nanoislands

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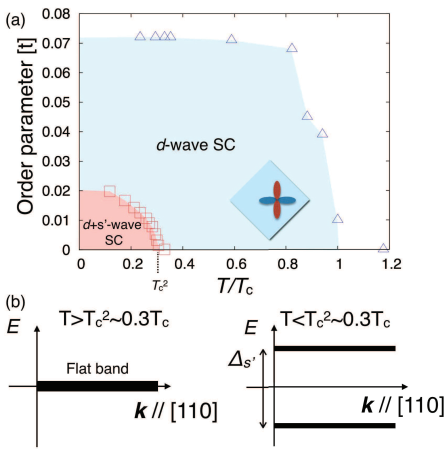
Sato et al. have shown the bulk-edge correspondence between the zero-energy Andreev bound states on [110] surfaces of a high-Tc cuprate superconductor and a topological invariant protected by time-reversal symmetry (TRS) [1]. We show that spontaneous disappearance of topological protection occurs with an alternative superconducting order parameter appearing on a surface [2]. We self-consistently solve the Bogoliubov-de Gennes equations and the d-wave gap equation in a d-wave nanoisland. Time-reversal symmetry is spontaneously broken at a lower temperature than the superconducting transition temperature. We find that this phase transition is of second order. This order parameter has extended s-wave symmetry and it characterizes the energy gap of the split Andreev bound states on the surfaces, as schematically illustrated in Fig. (b).

Furthermore, the disappearance of topological protection brings about novel vortex phenomena near the surfaces. We show that vortex-antivortex pairs are formed in the extended s-wave order parameter along the surfaces if the side length of a nanoisland or the width of an infinitely long nanoribbon is relatively large.



(a) Temperature dependence of the order parameters in the d-wave nanoisland. (b) Schematic illustration of the eigenvalues around zero energy. The zero-energy Andreev bound states on the [110] surface are gapped because of spontaneous time-reversal symmetry breaking. The gap size is characterized by the extended s-wave order parameter that is induced along the surfaces [2].

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Interfacial effect on high-T_c superconductivity in FeSe electric double layer transistors

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The superconductivity in the thin limit or at the interface has been a new trend to explore novel quantum phenomena containing vortex physics. Especially, the discovery of high-T_c superconductivity in monolayer FeSe on $SrTiO_3$ with gap closing temperature of 65 K in in-situ spectroscopy [1,2] and the onset T_c of 40 K in ex-situ transport measurements [1] accelerate the researches in this area. The electric double layer transistor (EDLT), which can accumulate the wide range of conduction carriers around interface between solid and ionic liquid electrostatically, is a good playground for the thin film or interface superconductor researches [3]. On the other hand, we have recently developed another aspect of EDLT, an electrochemical etching occurring at higher gate voltages and temperatures beyond the usual electrostatic region, which enables us to tune the film thickness close to one-unit cell using the identical sample [4]. In this talk, we demonstrate our systematic transport studies on the superconductivity in EDLT of FeSe as a function of thickness, substrate material, electric field and magnetic field by employing the combination of electrostatic and electrochemical means [5].

The maximum value of the onset T_c reaches 40 K for all the FeSe on various substrates, such as $SrTiO_3$, MgO and $KTaO_3$, with thinning. In addition, we found a universal relationship between the Hall coefficient in normal state and T_c regardless of different film thickness and substrate materials. The achieved results evidence that the high-T_c superconductivity at around 40 K does not primarily originate from a specific interface combination but from a charge carrier filling to the extent that it modifies the electronic band structure from that of bulk. From the thickness dependence of transport, we show how the order parameter evolves both at the FeSe/ionic liquid and FeSe/substrate interfaces and between them, resulting in the emergence of high-T_c superconductivity. As a related subject, we will also discuss the anisotropy of the upper critical field of the FeSe ultrathin films comparing with that of bulk.

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Kinematic Vortex Dynamics inside a weak-link and its dependence with the size of the electric contacts

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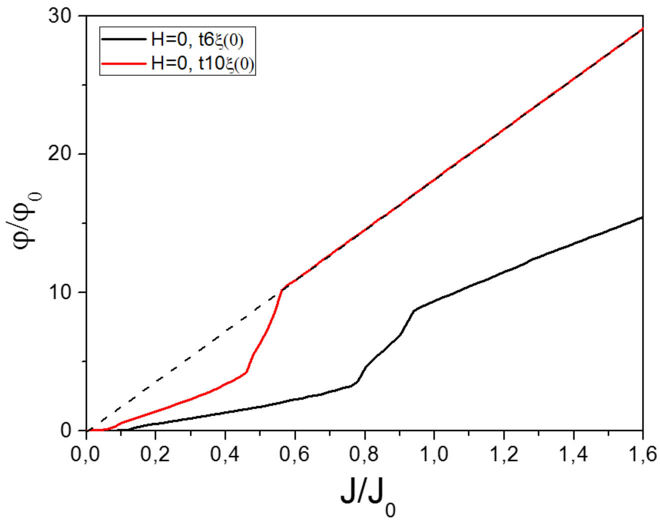
The study of the vortex dynamics in superconducting materials is of great importance either for future application of these materials, or to improve existing devices such as single photon detectors [1]. Transport currents in mesoscopic superconductors can generate kinematic vortices (kV) [1,2], which arise due to a local order parameter perturbation and, as we will show, their formation is facilitated when there is also a non-uniformity of the currents along the material [2].

In this work, we studied the relationship between the size of the electric contacts, t, and the formation of kinematic vortex-antivortex, kVA, pairs inside a weak-link. Rectangular samples with sizes of $20\text{x}10\xi(0)$ were simulated using the generalized time-dependent Ginzburg-Landau (GTDGL) theory. The weak-link was considered as a slit with width of $2\xi(0)$ dividing vertically the sample in two equal portions. Inside the weak-link, ψ present a value lower than in the rest of the sample.

As a result, we show that t influences the formation of kinematic vortices. For $t = 6\xi(0)$ (red line in the Figure a resistive state occurs for higher applied currents than for $t = 10\xi(0)$.



Voltage as a function of the applied current density without external magnetic field. (a) Constriction due to two blind slit (b) Constriction crossing all sample width.

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Phase transitions of small mesoscopic superconductor at the critical limit $\kappa = 1/\sqrt{2}$

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Recently we found a threshold temperature where the mesoscopic superconductors at the critical limit, $\kappa_c = 1/\sqrt{2}$ interchange from Type-I to Type-II. This temperature $T^\star$ presents a strongly dependence with the size of the sample. [1] For mesoscopic superconductors equal or larger than $5\xi_0$, the $T^\star$ divide exactly these two regimes. The magnetization curves present a first-order phase transition above $T^\star$, and a second-order phase transition below.The value of $T^\star$ decreases abruptly for samples with sizes smaller than $5\xi_0$, and it goes to zero for sample with side $L = 2\xi_0$, and in this case, the temperature $T^\star = T_c$.

For samples with sizes smaller than $5\xi_0$ the phase transition are second order in agreement with the Geim results [2]. The figure below shows the two cases. The left graphic presents the magnetization curves for sample with $L = 4\xi_0$, where for all temperatures, the transitions are of the second-order. In this case, one can see, for temperatures below the $T^\star$, that there are first-order transition in superconducting state. In my presentation I will talk about the competition between the size of the sample and the temperature of the system in order to describe the phase transition from superconducting to normal state.

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Reversible tuning of spin textures and resistance states in High Temperature Superconducting films

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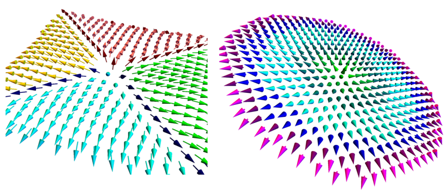
High temperature superconductivity (HTS) is one of the key technologies of the 21st century which will bring new breakthroughs in the fields of electric power technology, medicine, fusion energy, environmental control, information technology and others. Here we will present different strategies to exploit the outstanding properties of strongly correlated cuprate superconductors as energy-efficient approaches to encode and manipulate information.

The capability to prepare and modify non-uniform spin configurations at the nano- and micro-scale, in the form of magnetic domain walls, vortices, monopoles, or skyrmions, represents a very promising approach for non-volatile, high-density memory applications. Geometrical frustration has been the main strategy to generate nontrivial, monopolar-like defects and other exotic states in magnetic materials such as spin ice systems or magnetic nanowires. However, these strategies often involve complex procedures and are sometimes restricted to confined regions of the phase diagram. We introduce a completely new and versatile approach, based on the use of an artificial hybrid material, to encode a large manifold of non-trivial magnetic states in ferromagnetic thin films. We use high temperature superconducting $YBa_2Cu_3O_{7-x}$ (YBCO) dots (patterned with different shapes) combined with a continuous thin ferromagnetic Permalloy (Py) layer, in a hitherto unexplored way to design and generate multiple exotic magnetic states on demand (Figure) [1].

Memory devices based on the resistive switching effect (non-volatile field-induced reversible switch between two different resistance states) are also attracting a great attention for non-volatile memory applications due to their simple structure, high density integration, low-power consumption, and fast operation. YBCO films appear as particularly interesting materials showing resistive switching since a metal insulating transition (MIT), with large resistance variations, can be induced by hole doping their CuO_2 planes. The mechanism underlying the generation of a MIT in these material is still unclear though oxygen vacancies is believed to have a key role. We will evaluate new opportunities to locally modulate the superconducting order parameter in YBCO thin films for novel devices in logic and memory applications.



3D Py spin texture in a squared (top) and circular (bottom) hybrid structure determined from micromagnetic simulations.

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Hysteretic effective pinning and vortex lattice reordering near the order-disorder transition: An interplay between plastic and elastic energy barriers?

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History effects related to plasticity, glassy behavior and metastable configurations in the vicinity of an order-disorder transition (ODT) are common features in a variety of systems, among which vortex matter becomes a prototype model. In superconducting materials with randomly distributed weak pinning centers, as clean $NbSe_2$, the stable vortex phase at low temperature and low magnetic fields is an ordered Bragg Glass (BG) that, with increasing field and/or temperature, undergoes an ODT to a strongly pinned disordered phase, whose fingerprint is the Peak Effect (PE) anomaly. It is well known that a field-cooled vortex lattice (VL) remains trapped below the PE in a more strongly pinned disordered configuration; with the help of high dc currents or large shaking magnetic fields the system can reach the stable ordered BG, free of dislocations, which has lower effective pinning. In the last years, direct evidence confirmed the existence of a narrow in-between transitional region, where a dynamic assistance gives rise to bulk VL configurations with intermediate degree of dislocation density. These dynamically-originated configurations correlate with the observed intermediate linear ac response, associated with the effective pinning. On the other hand, hysteretic effective pinning observed after cooling and/or warming the system without any dynamic assistance are poorly understood up to now.

In this talk I will briefly review the key results supporting the existence of the transitional region and the VL dynamic reordering [1,2,3]. I will then present new results [4] that reveal qualitative differences between thermal and dynamic history effects. By combining small angle neutron scattering (SANS) with ac susceptibility measurements in clean $NbSe_2$ single crystals, we carried out a systematic study of the effective pinning and structural characterization of the VL after various thermal histories. We observed metastable superheated and supercooled VL configurations that coexist with a hysteretic effective pinning response due to thermal cycling of the system. A novel scenario, governed by the interplay between (lower) elastic and (higher) plastic energy barriers, is proposed as an explanation for our observations: Plastic barriers, which prevent the annihilation or creation of topological defects, require dynamic assistance to be overcome. Conversely, thermal hysteresis in the pining response is ascribed to low energy barriers, which inhibit rearrangement within a single VL correlation volume and are easily overcome as the relative strength of competing interactions changes with temperature. Our findings suggest a novel scenario to describe the order-disorder transition and the PE anomaly.

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Vortex dynamics in superconductor/ferrromagnet hybrids

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Superconductor (S) ferromagnet (F) multilayered structures have been a subject of intensive research in the past decade because of the exotic physical properties that arise in the superconductor by placing it next to a ferromagnet. During this talk I will focus on investigations on S/F hybrids where exiting properties related to vortex dynamics have been discovered. In S/F bilayers structures; Nb/Co and Nb/Py, we have found that the superconductor critical current can be controlled by the domain state of the neighboring ferromagnet. Critical current and magnetorestistance (close to T_c) measurements of Nb/Co structures with ferromagnet thickness $d_F > 30$ nm reveal sudden drops and peaks respectively in two very defined steps. These disappear for ferromagnet thickness below 30 nm. The drops are accompanied by vortex flux flow. These results are explained as being due to spontaneous vortex formation and flow induced by Bloch domain walls of the ferromagnet underneath. We argue these Bloch domain walls produce a 2D vortex-antivortex lattice structure. This is further supported by magnetization measurements carried out on these bilayer structures.

On the other hand in Ni/Nb/Ni/CoO and Co/Nb/Co/CoO spin valve structures, we have reported in-plane magnetization measurement with one of the ferromagnetic layers pinned by an antiferromagnetic layer. In samples with Ni below the superconducting transition T_c, our results show strong evidence of vortex flipping driven by ferromagnet magnetization. This is a direct consequence of the proximity effect that leads to vortex supercurrent leakage into the ferromagnets. Here, the polarized electron spins are subject to the vortices' magnetic field, occasioning vortex flipping. Such a novel mechanism has been made possible by fabrication of the ferromagnet/ superconductor/ ferromagnet/ antiferromagnet multilayered spin valves with an S layer thin enough to barely confine vortices inside as well as F layers thin enough to align and control magnetization within the plane. When Co is used, the vortex flipping effect is not observed. This is attributed to the shorter coherence length of Co. Interestingly, a reduction in the pinning field of about 400 Oe is observed instead when the Nb layer is in the superconducting state. This effect cannot be explained in terms of vortex fields. In view of these facts, any explanation must be directly related to the proximity effect and thus a remarkable phenomenon that deserves further investigation.

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Tackling the flux line lattice structure in Niobium using neutron scattering.

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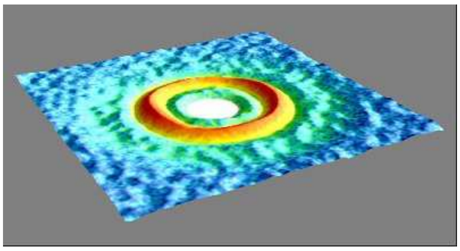
Small angle neutron scattering is a dedicated experimental probe of static and dynamical properties of a superconducting vortex lattice. It is a bulk probe, very tunable in terms of field/temperature range and dc or ac excitation can be applied to measure flux line induced distortion and metastable effects [1]. Some limitations concern the restricted resolution in S(Q) partly due to the dispersion in neutron wavelenght, and in the very low field limit (i.e very large small diffusion vector Q) for conventional small angle neutrons spectrometer. We will present results focusing on the two preceding points, using Niobium as a sample under test. Using the time of light mode to limit the wavelength dispersion and improve the Bragg peak definition, we measure the finite size of a bulk flux line lattice crystallite as function of the magnetic field [2]. Also, using the new Very Small Angle Neutron scattering TPA at the LLB-Saclay (France), we studied the formation of intermediate mixed state (IMS) of a Niobium slab and presents direct evidence of phase coexistence between Abrikosov cristallites and clusters with attracting vortices, in agreement with the first order character of the transition IMS/Mixed state.



VSANS image of coexisting disordered Abrikosov lattice and vortex clusters in pure Niobium (100G, 8K).

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Some new experimental insights into the surface superconducting state

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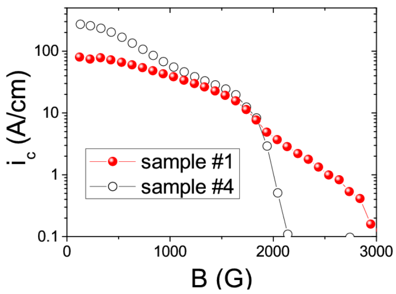
A superconducting sheath survives up to a third critical field $B_{c3} \approx 1.69\ B_{c2}$ for magnetic field parallel to an ideal boundary of a type II superconductor [1]. Similar effect is is not expected for the perpendicular geometry. However, this regime of surface superconductivity has been often reported for field applied to large facets of different bulk or thin superconductors (e.g. [2]), for reasons that deserve more attention. Pure Niobium is known to show a substantial surface superconductivity regime, and, despite the absence of bulk superconductivity, the pinning/dynamics of small Kulik's vortices are the cause of electromagnetic properties (V(I), magnetization, noise) with strong similarities with the more conventional mixed state [3]. Moreover, we show that the hysteretic surface current for $B_{c2} < B < B_{c3}$ can be fully tuned by different surface treatments, and the the existence of surface superconductivity for the perpendicular geometry is proved to be due to small scale surface roughness allowing for the respect of local boundary conditions [4].



Persistent current measured in a Niobium slab for after two different surface treatments. Note the collapse of the surface critical current for $B > Bc2 \approx 0.19$T for the sample labelled ♯4 (smooth surface).

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Flux dynamics of type I superconductors

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The magnetic flux domains in the intermediate state of type-I superconductors [1] are known to resemble fluid droplets, and their dynamics in applied electric current is often cartooned as a 'dripping faucet'. Using the time-dependent Ginzburg-Landau formalism we investigate the dynamics of intermediate state flux structures in a current carrying type-I superconductor in the presence of nanoengineered obstacles. Different from fluids [2], the flux-droplets in superconductors are quantized and dissipative objects, and their pinning/depinning, nucleation, and splitting occurs in a discretized form. These dynamic effects result in noticeable traces in the voltage signal across the sample. However, such single flux-discretized dynamical processes do not affect the size and shape of the resulting flux configurations. In the presence of obstacles, i.e. repulsive centers, splitting of flux tubes is observed. At larger currents, such obstacles can result in branching of laminar structures or transformation of them into topological mobile tubular patterns, as observed in experiments [3].

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Pseudo-gap manifestations in the kinetic energy density of $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals

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The decrease in the density of states (DOS) at the Fermi level of the high temperature superconducting cuprates (HTSC), which occurs in under-doped compounds well above the superconducting critical temperature, commonly known as pseudo-gap, manifests in several physical properties of these materials. Here, we report manifestations of the pseudo-gap phenomenon in the behavior of the in-field kinetic energy density (E_k) in the superconducting state of single-crystal samples of $Bi_2Sr_2CaCu_2O_{8+\delta}$. The kinetic energy is induced by an external magnetic field in the charge carriers forming vortices. Our samples were synthesized by solid state reaction. Using appropriated thermal treatments, specimens with hole concentrations p = 0.092; 0.099; 0.121; 0.127; 0.140, 0.187; and 0.194 were obtained. Zero field cooling (ZFC) and field cooling (FC) magnetization measurements were performed in fixed applied fields ranging from 1 mT up to 500 mT.

To calculate the kinetic energy density, we use the relation $E_k = -\mathbf{M} \cdot \mathbf{B}$, where $\mathbf{M}$ is the magnetization and $\mathbf{B}$ is the magnetic induction [1]. The measurements were taken in the magnetically reversible region, where pinning effects are not important. Our results show that, in any fixed field and temperature, E_k follows the overall behavior of the superconducting dome when plotted as a function of the hole concentration, i.e., in the underdoped region E_k continuously grows with the carrier content, and it is maximal for optimal doping; conversely, in the overdoped region E_k decreases upon further increasing the carrier concentration. We interpret the dependence of E_k with p as a consequence of the pseudo-gap. Thus, the increasing kinetic energy density with increasing oxygen content (hole doping) in the under-doped region would be a manifestation of the increasing DOS accompanied by a pseudo-gap reduction. We consider this fact as an evidence that the superconducting and pseudo-gap phases coexist below the critical temperature. On the other hand, the reduction in E_k in the overdoped region is attributed to the reduction in the DOS near a van Hove singularity, which is known to occur at approximately $p \sim$ 0.19 in several HTSC [2].

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Effects of thickness inhomogeneities on the flux avalanches in superconducting films

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Researchers in solid state physics usually produce samples and devices on highly flat and uniform surfaces, such as silicon wafers or other cleaved single-crystals, using well-known nanofabrication methods while taking advantage of the chemical stability of such substrates. Nevertheless, some of the new superconducting devices based on thin films, such as superconducting radio-frequency cavities for accelerators, whose internal surfaces have complex 3D shapes, cannot be produced from a selected region of a pristine specimen, so that the final product may result in non-uniform thicknesses across the surface area [1]. Local variations on the critical values of current density and temperature can lead to unpredicted deformation of the flux entrance profile, and even to the undesirable flux avalanches. The origin of these avalanches is associated with the occurrence of thermomagnetic instabilities [2], which can lead to abrupt invasions of magnetic flux rushing into the sample, while leaving behind a trail of overheated material. Avalanches in superconducting films constitute a complex and rich phenomenon, worth to study in depth, but on the other hand, they might be detrimental to potential applications. The V_3Si thin films studied in the present work were grown from a stoichiometric target on a $LaAlO_3$ substrate, by use of Pulsed Laser Deposition in high vacuum [3]. Deviations from uniformity in the film thickness along its area were estimated by measuring the Si intensity peaks by using Energy Dispersive X-ray Spectrometry taken during Scanning Electron Microscopy measurements. A thickness variation was observed in this superconducting film, which accounts for a large transition width as detected by magnetic measurements. Besides that, magneto-optical images of the penetrated flux profile clearly indicate an anisotropic distribution of the critical currents, which affects the way flux penetrates the film, both in the smooth and in the avalanche regime.

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Indirect evidence for magnetic enhancement of pinning in substituted (Ba, Sr)Fe_2As_2 single crystals

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Since the discovery of the Fe based superconductors in 2008, the scientific community has given great attention to these compounds due to the presence of a superconducting state with high transition temperature (T_c), which can be induced by the suppression of an antiferromagnetic ordering (spin density wave) similar to other unconventional superconductors, such as the heavy fermions and cuprates. These superconductors share the same layered crystal structure and it is well known that the addition of localized magnetic moments (pinning centers) in the antiferromagnetic layers leads to an enhancement of the critical current (J_c), as seen before for some cuprates. In this way, one could expect that the Fe based superconductors show a similar behavior. Therefore, we have performed critical current measurements in Cu, Co/Eu, Co/Mn and P substituted $BaFe_2As_2$ and Co substituted $SrFe_2As_2$ single crystals as a function of temperature and pressure (up to 27 kbar) with magnetic fields up to 9 T to directly investigate the effects of pressure in the Fe 3d partially-localized moments and its relation with J_c. In general, we have found that J_c always followed the behavior of T_c. However, detailed analysis of the T_c and J_c pressure/magnetic field dependence reveal an indirect evidence for a magnetic enhancement of the pinning effect associated with the presence of Cu^{2+} localized and Fe^{2+} partially-localized at low pressures. In the studied pressure range, there was no evolution of the localized character Mn^{2+} and Eu^{2+} local moments, indicating an absence of hybridization effects in these samples, which is in contrast to the Cu substituted ones. As such, we have found no evidence for pinning enhancement as function of pressure/field associated with the Mn^{2+} and Eu^{2+} local moments. We will discuss our results considering the effects of applied pressure and chemical substitution in the spin density wave phase to achieve a better understanding of the evolution of J_c in these systems.

Magneto-optical study of grain boundary transparency in thin Yb(Ca)-123 bi-crystal films managed by heat treatment in oxygen atmosphere

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Low angle grain boundaries (GB) are still the most important current-limiting mechanism operating in rare earth barium copper oxide (REBCO) coated conductors. While Ca-doping is found to improve the transparency of low angle GBs in weak fields at high temperatures, the growing interest of building high field magnets using REBCO coated conductors requires evaluating the effectiveness of Ca-doping more broadly. In this study Magneto-Optical-Imaging (MOI) was used to quantitatively evaluate the transport property of low angle grain boundary (GB) in $(Yb_{0.7}Ca_{0.3})Ba_2Cu_3O$ PLD thin films grown on 6^o and 9^o SrTiO3 [001] tilt bi-crystals in a broad temperature range. J_c^{GB} and J_c^{grain} are independently and unambiguously determined by analyzing the MO images. The non-intrusive nature of the MOI technique also enables the monitoring of the evolution of J_c^{GB} and J_c^{grain} of one and the same film through various post-growth annealing steps. We found that Ca-doped GBs have temperature dependence quite different from that of GBs in pure REBCO films. Starting from T=0.5-0.6 T_c, the ratio J_c^{GB}/J_c^{grain} of a Ca-doped GB shows a sharp upturn with temperature, which is not observed for pure GBs. On the other hand, the beneficial effect of Ca-doping in improving GB transparency is very limited in the low temperature range. The local strain and charge differences drive a strong Ca-segregation to the GB dislocations and desegregation in the channels that dominate supercurrent transport. Such a non-uniform Ca distribution along the GB causes the channel part of the GB to have a T_c higher than that of the grain, which amplifies the effectiveness of Ca-doping at temperatures close to T_c. Another finding is that post-growth annealing affects J_c^{GB} and J_c^{grain} quite differently. During 760 Torr oxygen annealing of the as-grown films, J_c^{GB} saturates much faster than J_c^{grain}. On the other hand, J_c^{GB} is less depressed by annealing in a reduced oxygen atmosphere below 2.5 Torr.

Acknowledgement: This work was performed at the National High Magnetic Field Laboratory, which is supported by the National Science Foundation Cooperative Agreement No. DMR-1157490.

Spin texture on top of flux avalanches in $Nb/Al_2O_3/Co$ thin film heterostructures

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We report on magneto-optical imaging, magnetization, Hall effect and magneto-resistance experiments in $Nb/Al_2O_3/Co$ thin film heterostructures. The magneto-transport measurements were performed in samples where electrical contacts were placed on the Co layer The magnetic field was applied perpendicularly to the plane of the film and lead to abrupt flux penetration of dendritic form. A magnetization texture is imprinted in the Co layer in perfect coincidence with these ramifications. The spin domains that mimic the flux dendrites are stable upon the field removal. Moreover, the imprinted spin structure remains visible up to room temperature. In the region of the field - temperature diagram where thermomagnetic flux instabilities are known to occur in single Nb films, irregular jumps are observed in the magnetic hysteresis and the magneto-resistance and the Hall resistivity show a noisy behavior when measured in fixed temperatures under slowly varying magnetic fields. The noise in the magneto-transport measurements ceases at a characteristic field which depends on the temperature. Using the magneto-resistance and Hall resistivity data we were able to define the boundary of the instability region for the flux penetration. Due to the similarities between the vortex lattice in superconductors and the skyrmion lattice in magnetic materials, we discuss the possibility that the magnetization texture observed in the Co layer of our $Nb/Al_2O_3/Co$ hybrid is partially formed by skyrmions or some other non-conventional spin chiral-type or vortex-type structures when examinated at the microscopic scale.

Magnetic field induced emergent inhomogeneity in a superconducting film with weak and homogeneous disorder

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Over the last decade, the emergence of a granular superconducting state has been established as a hallmark of superconductors with strong but homogeneous disorder. Detailed studies using low temperature scanning tunnelling spectroscopy on a variety of systems (NbN,InO_x,TiN) revealed that in the presence of strong homogeneous disorder, the superconducting state gets segregated into domains with lateral size of the order of the coherence length, which are weakly coupled through insulating regions. Consequently, the global zero resistance state gets destroyed through phase fluctuations between these domains even while the pairing amplitude remains finite, giving rise to a pseudogap state, earlier thought to be a unique feature of unconventional High Temperature superconductors. It has also been demonstrated that above a critical disorder Cooper pairs can get localised giving rise to a Cooper pair insulator.

In this talk, I will present a microscopic picture of the magnetic field evolution of the disordered superconducting state using scanning tunnelling spectroscopic imaging down to 450 mK. Starting with a weakly disordered NbN thin film, I will show that under application of magnetic field, lines of vortices proliferate in regions where the superconducting order parameter is small. Riding on the top of an inhomogeneous background these vortices wipe out the pairing amplitude in a region of linear size of about the coherence length, ξ, by accommodating the phase-twist around itself. Consequently, the superconducting state fragments into domains, in a manner similar to what disorder alone would have done at much larger strength. This leads to the formation of a pseudogap state that progressively widens with increasing magnetic field. This results are backed by detailed numerical simulations which corroborate this scenario.

[1] http://arxiv.org/abs/1703.04667.

Dynamic Phases and Hall Effect for Driven Skyrmion Lattices

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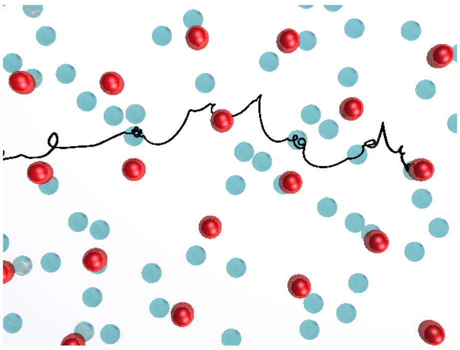
Skyrmions are particle-like objects that were discovered in chiral magnets in 2009 [1]. They have many similarities to vortex lattices in type-II superconductors in that they can be pinned by defects in the sample and set into motion with an applied drive. One pronounced difference is that the dynamics of skyrmions is dominated by a nondissipative Magnus force, in contrast to the superconducting vortex system which is dominated by damping. Here we analyze the dynamics of current-driven skyrmions moving over random pinning arrays, as illustrated, and show how distinct dynamic phases arise that can be identified through characteristics of the structure factor, noise fluctuations, and transport curves. We also show that the skyrmion Hall angle develops a drive dependence due to the Magnus term, which also produces a side jump effect as the skyrmion moves through the pinning sites. Similar effects have recently been observed experimentally [2,3]. We discuss how the Magnus term changes the nature of the effective shaking temperature experienced by the moving skyrmions compared to that in vortex systems, and that this results in dynamic phases that are distinct from those observed for superconducting vortices. Finally, we show that the commensuration effects and ratchet effects observed in superconducting samples with nanostructured pinning arrays also occur, with some modifications, in skyrmion systems.



Real-space image of skyrmions (dark red dots) driven through randomly arranged pinning sites (light blue dots) in a plastic flow phase. The trajectory of a single skyrmion is highlighted, and reveals spiraling motions of the skyrmions inside the pinning sites.

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Hyperuniformity in Vortex Systems

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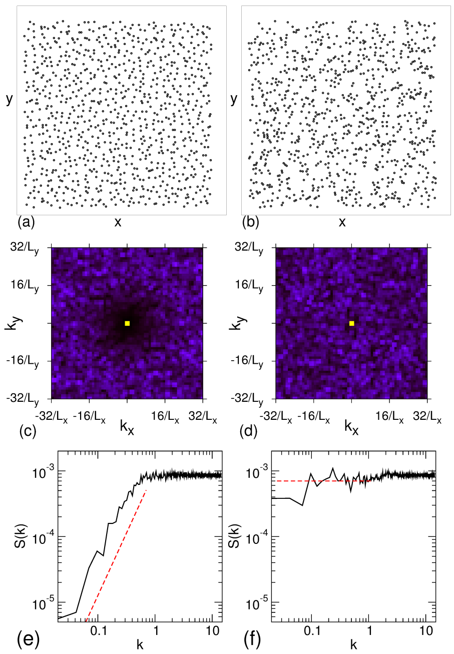
Hyperuniformity is a new class of matter which has both solidlike properties, in that density fluctuations are suppressed, and liquidlike properties, in that there are no symmetry breaking directions of the type found in crystals [1,2]. Hyperuniform states have recently been identified for jammed particle assemblies, biological cell organization, and at certain nonequilibrium critical points, and can be described by the scaling behavior of the structure factor and the number variance. Here we show using numerical simulations that pinning sites placed in a hyperuniform arrangement exhibit enhanced pinning compared to a random pinning arrangement due to increased pinning occupancy. We also find that even for random pinning arrays, the positions of the vortices themselves exhibit hyperuniformity, and we conjecture that this could indicate that there are different types of vortex glass, including a disordered hyperuniform state in which vortex-vortex interactions are important and a random vortex glass where the randomness of the pinning dominates. We also discuss other types of hyperuniform pinning geometries that could be realized and show evidence that there may also be different dynamically hyperuniform states related to the depinning and motion of the vortices.



Pinning site locations for (a) a hyperuniform distribution and (b) a random distribution. (c) Structure factor $S(\mathbf{k})$ for the hyperuniform pinning array showing that the weight vanishes at small $\mathbf{k}$ and that the system is isotropic. (d) $S(\mathbf{k})$ for the random pinning array, where the system is isotropic but the weight goes to a finite value at small $\mathbf{k}$. (e) $S(k)$ vs k for the hyperuniform array, where the dashed line is a fit to $S(k) \propto k^{1.9}$. (f) $S(k)$ vs k for the random array showing that $S(k)$ goes to a constant value at small k.

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Superconducting properties and hydrostatic pressure effect on $BaBi_3$ and $SrBi_3$ single crystals

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Bismuth is a very interesting element for condensed matter physics due to its electronic behavior: low carrier density, small effective mass, high mobility, long mean free path, and a large g-factor. Because of such interesting electronic properties, bismuth plays an important role in the discovery of new superconducting compounds such as the topological superconductors. Despite having already been studied in the past, Bi rich superconductors ABi_3 (A = Ba, Sr) have attract renewed attention in recent times. The older studies on these materials resulted rather limited in depth, probably due to their rather complex synthesis and air sensitivity. We report on the synthesis and superconducting properties of $BaBi_3$ and $SrBi_3$ single crystals, obtained by the self-flux growth method. $BaBi_3$ is well crystallized in tetragonal structure with space group P4/mmm and $SrBi_3$ has been crystallized in a cubic structure with space group Pm-3m. The magnetic susceptibility and electrical transport measurements confirmed BaBi3 to be superconducting below 6 K, which is slightly higher than the earlier reported value of 5.6 K [8] and $SrBi_3$ is superconducting below 5.6 K. Both compounds are highly metallic in normal state electrical resistivity measurements and the calculated upper critical field (H_{c2}) through resistivity under magnetic field $\rho(T)_H$ data are 22 kOe for $BaBi_3$ and 2.9 kOe for $SrBi_3$. The heat capacity measurements for the studied BaBi3 single crystal shows a weakly coupled superconductor while the $SrBi_3$ single crystal is a strongly coupled superconductor. The dc magnetic susceptibility under hydrostatic pressure studies for BaBi3 single crystal reveal positive pressure coefficient of dT_c/dP = 1.22 K/GPa and negative pressure coefficient dT_c/dP = -0.43 K/GPa for $SrBi_3$. This is the first report of superconductivity under hydrostatic pressure on the $BaBi_3$ and $SrBi_3$ superconducting compounds.

Coherent quantum phenomena in superconducting atomic monolayers Pb/Si(111): A STM study

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In 1964 V. L. Ginzburg predicted that new superconducting phases could appear in ultrathin films deposited on insulating surfaces. In 2010 superconductivity below 2K was discovered in some crystalline atomic monolayers of Pb grown on atomically clean Si(111) [1,2]. Though, the amorphous Pb monolayer was found non-superconducting, but rather a correlated metal. Interestingly, Pb-monolayers can be on-demand made amorphous or crystalline, with or without presence of bulky superconducting Pb-nano-islands. This makes the Pb/Si(111) system useful to probe superconducting correlations in the vicinity of S-N or S-S' interfaces by STM [3,4].

When two superconducting Pb-islands are linked together by a few nanometer wide non-superconducting amorphous atomic layer of Pb, superconducting correlations may propagate between the two islands, allowing a dissipation-less Josephson current to flow through the link. In the presence of a magnetic field, the Josephson vortices are expected to appear in such S-N-S Josephson junction. 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.

In our lecture we describe a series of recent experiments which mapped superconducting correlations in the vicinity of S-N junctions [3,4] as well as inside SNS proximity Josephson junctions using scanning tunneling microscopy [5]. 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 [5].

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One-dimensional p-wave superconductor toy-model for Majorana fermions in multiband semiconductor nanowires

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Majorana fermions are particles indentical to their antiparticles proposed theoretically in 1937 by Ettore Majorana as real solutions of the Dirac equation [1]. The candidates in High Energy Physics for such particles are the neutrinos, although there is no experimental evidence of such character until now. On the other hand, it was proposed by Alexei Kitaev that such particles should emerge in condensed matter systems as zero modes excitations in p-wave superconductors [2], with possible applications in quantum computation due to their non-abelian statistics [3]. The search for Majorana zero modes in condensed matter systems had one of the first realistic models based in a semiconductor nanowire with high spin-orbit coupling and induced superconducting s-wave pairing and Zeeman spliting [4]. Soon, it was realized that size-quantization effects should generate sub-bands in this systems that could even allow the emergence of more than one Majorana mode in each edge [5]. Size quantization effects are considered one of the reasons the zero bias signature of these modes were not detected as predicted theoretically [6]. In this work we provide an one-dimensional toy-model based on the Kitaev chain that have the same effective Hamiltonian of a multi-(sub)band nanowire and discuss the advantage of an one-dimensional model to understand the phenomenology of the system, including the competition between the different effects presented. We also discuss about the topological classification of the system, showing that the introduction of an artificial time-reversal symmetry could lead the system to BDI classification, and an introduction of a winding number can describe all different emergent phases.

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Phase coexistence of superconductivity and magnetism driven by a spinorial order parameter in heavy fermion compounds

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We study the phase coexistence between superconductivity and magnetism using the Ginzburg-Landau approach [1]. The order parameter in this case will be of spinorial nature and will use it to describe the superconducting phase [2,3] and the hidden order phase [4] in a broad variety of heavy fermion compounds. We will consider various parameters that control the anisotropies of the lattice and pairing mechanism, then we will obtain limits for the coexistence of the superconducting and hidden order phases in the absence of applied magnetic field, i.e., only equilibrium and homogeneous states are considered. Special attention is devoted to the case of superconductivity triggered by magnetism and the characteristics of the hidden order phase. In the present work, we will present analytical and theoretical results and point the forthcoming studies. This work is partially supported by the Brazilian agencies CNPq and FACEPE.

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First-order vortex phase transition in $Bi_2Sr_2CaCu_2O_{8-\delta}$ with low doses of correlated disorder revisited

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The impact of moderate disorder generated by a low density of columnar defects in the first-order phase transition of layered vortex matter has been the subject of various studies. The interest in this problem comes from the possibility of tuning the nature of the transition (first or second order) with controlled amount of disorder and therefore using layered vortex matter as a playground to test basic thermodynamic and structural phases in soft condensed matter. Differential magneto-optical measurements in $Bi_2Sr_2CaCu_2O_{8-\delta}$ suggested that for matching fields smaller than 50 G a critical point between a first-order (low fields) and a second-order (high fields) melting transition occurs. [1] However, direct imaging with individual vortex resolution revealed no significant changes in the in-plane structural properties of the solid vortex phase for fields larger or smaller than the critical point [2]. These latter results cast doubt on the proposal of the change of the nature of the transition being a resolution-limit or disorder-tuning driven statement. We therefore revisited this problem by applying DC and AC Hall probe local magnetization techniques in a different batch of $Bi_2Sr_2CaCu_2O_{8-\delta}$ samples irradiated with low doses (up to 60 G matching fields) of columnar defects introduced by irradiation with Xe heavy ions. We find that the high-temperature paramagnetic peak in ac-transmittivity persists even for a sample with a dose of columnar defects corresponding to a 60 G matching field. We also present preliminary results of magnetic decoration experiments in the same samples.

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Targeted Pinscape Evolution in Superconductors for Optimal Critical Current

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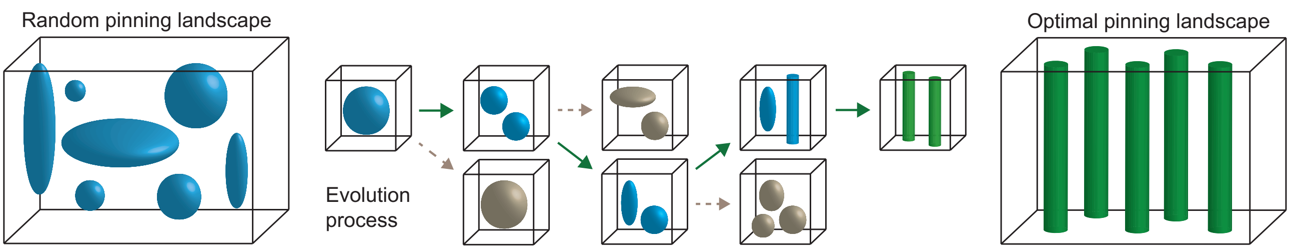
Understanding the dynamic behavior of vortex matter in complicated pinning landscapes is a major challenge for both fundamental science and energy applications. The critical current in the presence of external magnetic fields is mostly defined by non- superconducting inclusions within the superconductor, which prevents (pins) magnetic vortices from moving and, as a result, increases its critical current. Therefore, the critical current can be significantly enhanced by optimizing the type, size and density of these inclusions in the pinning landscape. Using large-scale time-dependent Ginzburg-Landau simulations for vortex dynamics we studied the interplay between vortex-vortex and vortex-inclusion interactions in the presence of various inclusion types [1,2].

With recent progress in advanced computing, a new paradigm has emerged that aims at the simulation-assisted design of defect structures having predictive capabilities [3]. The critical-current-by-design concept aims at predicting the optimal defect landscape for targeted applications by elucidating the vortex dynamics responsible for the critical current [4,5].



Sketch of the evolution process. A randomly generated pinscape is 'mutated' by adding/removing, moving, and reshaping defects. After each mutation the configuration with maximal critical current is chosen.

To achieve maximal critical current, we compared several known local and global numerical optimization methods for arbitrary types of defects, e.g. spherical, elliptical, or columnar, and their combination. We demonstrated that these methods are suitable for pinning landscapes characterized by up to 6–8 parameters. For larger parameter spaces, we developed a generic evolutionary-based approach, see the Figure. In this algorithm position, size, and shape of each of the defect are varied individually. In general, this approach can predict optimal configuration of defects without specific assumptions about their type and shape.

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Vortices and antivortices in two-dimensional ultracold Fermi gases

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In two-dimensional superfluids quantized vortices play a key role in determining finite-temperature properties, as the superfluid phase and the normal state are separated by a vortex unbinding transition, the Berezinskii-Kosterlitz-Thouless transition [1,2]. Very recent experiments with two-dimensional superfluid fermions made of alkali-metal atoms [3,4,5] motivate the present work: we present theoretical results based on the renormalization group, showing that the universal jump of the superfluid density and the critical temperature crucially depend on the interaction strength [6,7], providing a strong benchmark for forthcoming investigations.

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Dynamics of quantum vortices in Bose-Einstein condensates

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This work rectifies the hydrodynamic equations commonly used to describe the superfluid velocity field in such a way that vortex dynamics are also taken into account. In the field of quantum turbulence, it is of fundamental importance to know the correct form of the equations which play similar roles to the Navier-Stokes equation in classical turbulence. Here, such equations are obtained by carefully taking into account the frequently overlooked multivalued nature of the $U(1)$ phase field. Such an approach provides exact analytical explanations to some numerically observed features involving the dynamics of quantum vortices in Bose-Einstein condensates, such as the universal $t^{1/2}$ behavior of reconnecting vortex lines. It also expands these results beyond the Gross-Pitaevskii theory so that some features can be generalized to other systems such as superfluid ^{4}He, dipolar condensates, and mixtures of different superfluid systems [1].

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Between types I and II: Intertype vortex patterns in thin superconductors

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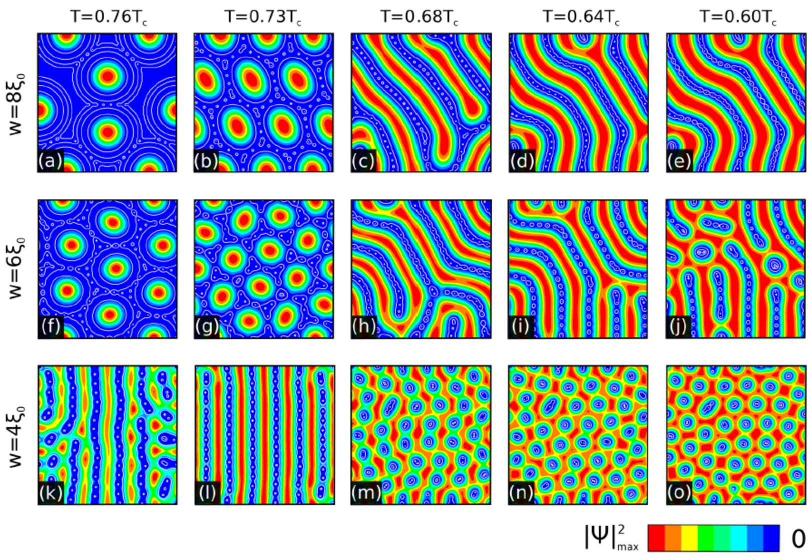
The Bogomolnyi point [1] separates superconductivity types I and II while itself hiding infinitely degenerate magnetic flux/condensate configurations, including exotic vortex patterns. When the degeneracy is removed, the Bogomolnyi point unfolds into a finite, intertype (IT) domain in the phase diagram between types I and II [2]. In this case the unconventional vortex patterns can shape the internal structure of the IT domain. Our calculations reveal [3] that such exotic flux distributions are indeed stable in the IT regime of thin superconductors made of a type-I material, where the Bogomolnyi degeneracy is removed by stray magnetic fields. They can be classified into three typical patterns (see Figure): lattices of superconducting islands separated by vortex chains; stripes and labyrinths of vortices; and mixtures of giant vortices and vortex clusters. Our findings shed new light on the problem of switching between types I and II, raising questions on the completeness of the textbook classification of the superconductivity types.



In-plane distributions of the condensate density for film thicknesses $w = 4\xi_0,\ 6\xi_0$, and $8\xi_0$ [ξ_0 the Cooper-pair radius] and temperatures $T/T_c = 0.76, 0.73, 0.68, 0.64, 0.6$. White points (circles) in the blue background mark centers of vortices. The lattices of superconducting islands can be seen in panels (a), (b), (f), and (g). Stripes and labyrinths are in (c)-(e), (h)-(j), and (k), (l). Giant vortices and vortex clusters are in panels (m)-(o).

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A novel approach towards manipulation of vortex matter in a superconductor with micromagnetic structures

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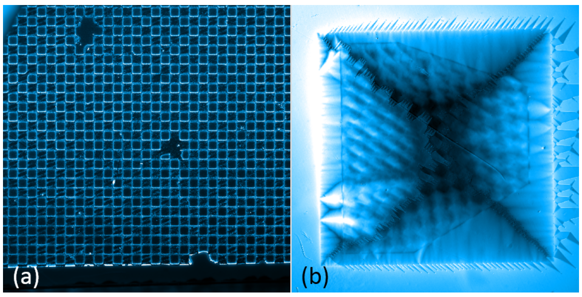
Though Superconductor/Ferromagnet hybrids is a widely studied system, application of hard magnetic materials as sources of vortex pinning remains relatively unexplored. They offer a number of advantages over softer magnetic materials, like greater stability and larger magnetic field amplitudes. Recently, a promising technique, thermomagnetic patterning (TMP) [1], has been developed to prepare micromagnets, which serve as micro flux sources to produce magnetic fields spatially modulated at the micron scale. Permanent magnetic structures prepared using TMP present an interesting and so far unexplored option for controlled artificial pinning.

We have investigated the vortex matter in superconductor/TMP micromagnet heterostructures (Nb-NdFeB) using quantitative Magneto-Optical Imaging (MOI). Comprehensive protocols have been developed for calibrating and converting Faraday rotation data acquired by MOI to magnetic field maps. These protocols reveal the comparatively weaker magnetic response of the superconductor from the background of larger fields associated with the magnetic layer in its vicinity. Further, TMP micromagnet structures have been imprinted in a permalloy (Py) layer following a protocol reported earlier [2] to obtain flexible magnetic landscapes for flux guidance in a Nb layer below it. Both smooth flux penetration and vortex avalanches in Nb are observed to be strongly influenced by the micromagnetic patterns. Our study offers new insights into the peculiarities of the vortex state in these superconductor-micromagnet heterostructures [3].



(a) MO image of Nb-NdFeB at 10 K, 59 Oe, showing TMP chessboard pattern in NdFeB. (b) MO Image of Nb-Py at 6 K, 59 Oe, showing smooth flux penetration in Nb guided by chessboard pattern imprinted in Py.

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Superconducting weak links created by electromigration

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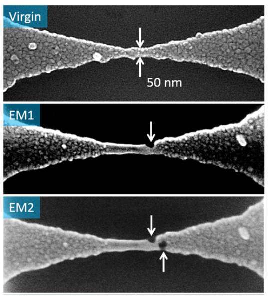
In this presentation we introduce in-situ controlled electromigration as a method to fabricate superconducting weak links. We show evidence that in Al a transition from thermally assisted phase slips (TAPS) to quantum phase slips may takes place when the effective cross section becomes smaller than $\sim$150 nm^2 [1]. In the regime dominated by quantum phase slips the nanowire loses completely its capacity to carry current without dissipation, even at the lowest possible temperature. We also discuss the origin of negative magnetoresistance at low magnetic fields in the bow-tie shaped constrictions. Strikingly, the detrimental effect caused by the repeated electromigration can be healed by simply inverting the current direction. These findings reveal perspectives of the proposed fabrication method for exploring various fascinating superconducting phenomena down to atomic size constrictions.



Ex-situ scanning electron images illustrating the shrinking of the constriction due to subsequent electromigrations. The upper panel corresponds to the virgin sample with arrows indicating the approximate width. The middle and lower panels represent, respectively, the sample after the first and the second run of electromigration with arrows pointing out the created voids in the junction.

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Effective artificial pinning center introduction on MgB2 superconducting bulks

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Since the discovery of the MgB2 as a superconducting material in 2001, many groups around the world work on an attempt to improve the transport properties for technologic application. Defects in superconducting materials can be an efficient mechanism to improve the transport properties due to the pinning of the magnetic flux lines penetrating in the material under an applied magnetic field.

In the present work it is described a methodology to optimize the critical current densities in MgB2 bulk superconductors. The method uses the mixture of the MgB2 superconductor with addition of VB2, which has the same C32 hexagonal structure of the MgB2, in an attempt to introduce crystalline defects in the MgB2 superconducting matrix. Defects in the material can act as an effective pinning center, enhancing the transport properties of the superconducting.

The mechanical mixture of the powders, obtained by ball milling, was important to improve densification and grain boundary connectivity, and has a positive influence on the final crystalline structure, maintaining the hexagonal structure of the matrix, and generating intragranular and intergranular pinning centers. Magnetic superconducting characterization using PPMS was performed and showed an improvement of the critical current densities. Optical analysis was realized using a micro-Raman, and the E2g phonon (responsible for the strong electron-phonon ctinhooupling) was analyzed. Microstructural characterizations, performed using SEM, TEM, HRTEM and XRD, were extremely important to determine the distribution and compositional characterization of the defects in the material.

Conformal Vortex Crystals

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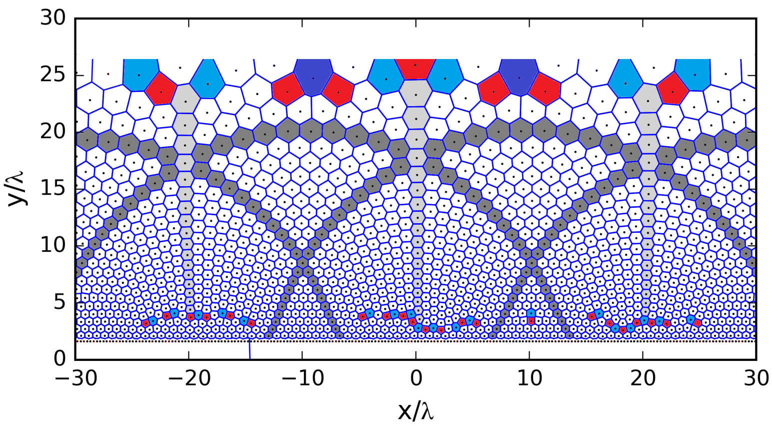
Six decades after its discovery, the uniform Abrikosov lattice remains as the only known ordered state of quantized vortices in type-II superconductors. Recently, nonuniform vortex distributions have been investigated in the context of the critical state in samples with random, periodic and graded arrays of defects (see e.g. [1,2] and references therein). But, to date, no ordered nonuniform vortex state has been reported. In this work, we present analytical and numerical simulation results that demonstrate the possibility of stabilizing ordered nonuniform vortex lattices. For that, we develop a simple model to estimate a suitable external potential capable of accommodating vortices in a conformal density profile. After performing a series of Langevin dynamics simulations of thousands of vortices in such potential, we have found that vortices always tend to self-organize into a nonuniform, topologically ordered, conformal crystal, in a way as to minimize the total energy.

In the figure, we present a typical configuration found in the simulations. The face color of the Voronoi polygons depict the local topological charge $q = \nu_0 - \nu$, where ν is the coordination number of the vortex and ν_0 the corresponding value expected for a topologically flat vortex configuration, i.e., $\nu_0 = 6$ (4), for a vortex in the system bulk (edge). The gray shades are guides to the eye for better identification of the conformal curvature. The peculiar topological charge distribution, with dislocation lines (of total charge +1) at the top bottom and almost isolated disclinations (of charge -1) at the top, guarantees the necessary deformation of lattice lines imposed by the conformal configuration. Apart from the topological defects, this configuration can be mapped almost perfectly from a triangular lattice via a logarithmic conformal (angle preserving) transformation [3].



Typical low-energy configuration of vortices (dots) in a conformal confining potential and respective Voronoi construction (lines).

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Scanning tunneling microscopy of vortices in tilted magnetic fields

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Very low temperature Scanning Tunneling Microscopy STM probes the superconducting density of states as a function of the position. Since the seminal experiments by Hess et al in Bell labs during the late eighties, STM has been used to image vortex lattices in many different compounds. The spatial resolution goes well below the superconducting coherence length, so that the superconducting properties of the vortex core can be imaged too. STM images typically show Caroli de Gennes Matricon localized states that appear inside the vortex core. Hess managed to understand most features of his data with magnetic fields perpendicular to the surface in terms of such states. He also provided measurements in tilted magnetic fields. The latter, however, remain largely un-understood. I will here review STM measurements of the tilted vortex lattice in different situations. In the simple isotropic s-wave superconductor β-Bi_2Pd we show for the first time that vortices bend to exit perpendicular to the surface and that their interaction is dominated by the stray magnetic field. In the anisotropic system 2H-$NbSe_2$ we make a new and systematic study of the behavior in tilted fields. We find features that allow us to provide an understanding of the patterns imaged in STM. We compare these two situations with the well-studied case of crossing Abrikosov/Josephson vortex lattices of extremely anisotropic superconductors.

Vortex-glass transformation in the surface mixed-state of $Mo_{1-x}Re_x$ superconductors

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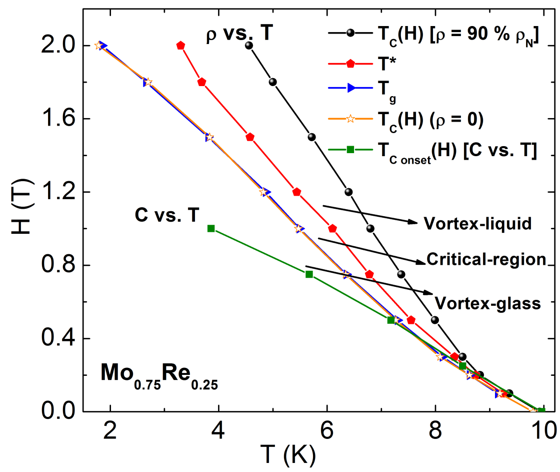
We report experimental results on temperature dependence of electrical resistivity, $\rho(T)$, and heat capacity, $C(T)$, of β-phase $Mo_{1-x}Re_x$ alloy superconductors, with $T_c \sim 10$ K. In presence of magnetic field, $\rho(T)$, goes to zero well above the bulk superconducting transition temperature, obtained through $C(T)$ measurement. This suggests the presence of surface superconductivity in these alloys, which was confirmed by performing $\rho(T)$ measurements on copper and silver coated $Mo_{1-x}Re_x$ samples. It is observed that the surface superconductivity is suppressed in the metal coated samples, which strongly suggests its existence in these alloys [1]. The superconducting transition broadening ΔT_c, shows a linear variation with H, which rules out the possibility of spatial distribution of T_c in the sample [2]. The vanishing resistivity well above the bulk superconducting transition is interpreted as due to the pinning of surface vortices in the surface sheath of superconductor. In this case, quasi 2D pancakelike vortices are described using the flux-spot model [3]. Experimental evidence in support of the surface mixed-state and the occurrence of a vortex-liquid to vortex-glass transition is presented with a detailed H-T phase diagram (See figure). The critical exponents associated with the vortex-glass state support the 2D nature of vortex-glass state in the surface region of these superconductors.



H-T phase-diagram of $Mo_{0.75}Re_{0.25}$ alloy superconductor

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Dynamics of kinematic vortices in gap and gapless superconductors

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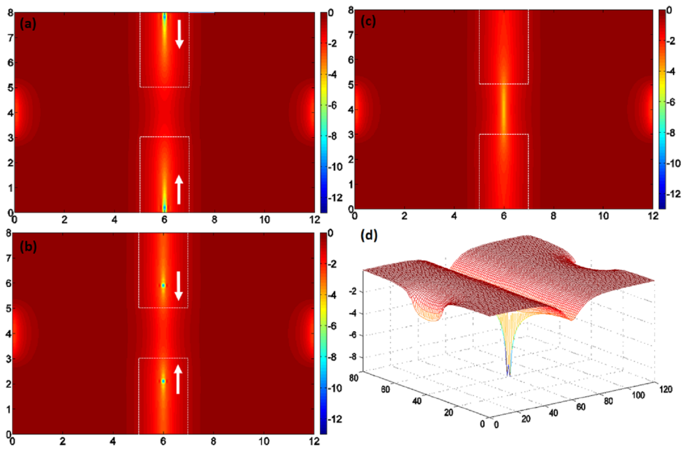
Under an applied current, a resistive state can appear in mesoscopic superconductors as a consequence of the creation of kinematic vortices (KVs) [1,2]. Theoretical studies of KVs commonly use the generalized equation of Ginzburg-Landau, GTDGL [3]. In such theory the gap-like behavior is associated with a relaxation of the superconducting order parameter, ψ. However, even in the absence of this relaxation, KVs can be created in gapless superconductors [4].

In the present work, the dynamics of kinematic vortex-antivortex, KVA, pairs in gap and gapless superconductors was studied in the framework of the GTDGL. The studied samples consisted of a superconducting stripe, 12x$8\xi(0)^2$, with a central square constriction with lateral size of $2\xi(0)$, as shown in the figure. The constriction was built considering two blind slits (weak links) in the upper and lower edge of the sample. In the figure is shown the map of log(ψ) where from figures (a) to (c) is depicted the sequence of the KVA pair motion. In the figure(d) is shown a surface distribution of log(ψ) just before the annihilation.



Map of the log(ψ) during the annihilation process of a KVA pair. From (a) to (c) is shown the motion sequence of the pair. In (d) is shown a surface log(ψ). Note that ψ remains very small along the line of the KVA motion in a instant just before the annihilation.

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Anomalous Peak Effect in (Ba,K)Fe_2As_2 with Splayed Columnar Defects

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Since the discovery of iron-based superconductors (IBSs) in 2008, extensive research efforts have been devoted to elucidate their peculiar physical properties, mechanism of superconductivity, and vortex physics related to their practical applications. IBSs not only have high transition temperature (T_c) and large upper critical field (H_{c2}) but also can sustain large critical current density (J_c) over 1 MA/cm^2 at low temperatures. Further enhancement of J_c can be achieved by introducing artificial defects in terms of high-energy particle irradiations [1]. We have demonstrated five-fold enhancement of J_c even at low temperatures by introducing columnar defects through irradiation of 200 MeV Au ions into Ba(Fe,Co)$_2$As$_2$ single crystal [2,3]. Further enhancement of J_c reaching $\sim$15 MA/cm^2 has been also demonstrated in (Ba,K)Fe_2As_2 by irradiating 2.6 GeV U ions [4]. A theoretical study has suggested even stronger enhancement of J_c by splaying the direction of columnar defects [5]. This idea has been demonstrated in $YBa_2Cu_3O_{7-\delta}$ by achieving four-fold enhancement of J_c by splaying the direction of columnar defects by $\pm 5^\circ$ [6]. We apply the same technique to (Ba,K)Fe_2As_2, and achieve J_c=17.5 MA/cm^2 by irradiating 2.6 GeV U at angles of $\pm 5^\circ$ [7]. Interestingly, when the splay angle is increased to $\pm 20^\circ$, an anomalous peak effect starts to show up at $\sim B_\Phi$/3 when the external magnetic field is applied along the average direction of the two angles. The peak effect is suppressed quickly as the direction of the external field is tilted from the average direction. The optimum splay angle that produces the anomalous peak effect changes with the energy of the ions. We compare this anomalous peak effect with another peak effect reported in cuprates with parallel columnar defects [1], and discuss its origin.

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Dynamical decay of quadruply quantized vortices in a Bose-Einstein condensate

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Vortices are, often observed in classical and quantum gases and fluids. In quantum fluids and gases, the circulation associated with the vortices is quantized. Bose-Einstein condensates (BEC) may acquire angular momentum per particle equal to or larger than $\hbar$, and vortices can be nucleated as one multiply quantized vortex or a few singly quantized vortices, each with $\hbar$. Vortices are excited states of motion, energetically unstable, and are expected to decay back to the ground state. The kinetic energy of atoms circulating around the vortex core is proportional to the square of the angular momentum, therefore the kinetic energy of a multiply charged vortex is larger than the total kinetic energy of the singly quantized vortices with the same angular momentum. Multiply quantized vortex can decay coherently, by splitting into singly quantized vortices, and then transferring the extra kinetic energy to the available coherent excitation modes.

Quantized vortices, topologically imprinted in dilute Bose-Einstein condensates (BECs), have been intensively studied in the last decade [1], contributing to the early studies carried out in standard superfluids and superconductors [2]. In this work, we present results from quadruply quantized vortices, which were topologically imprinted in $|F = 2, m_F = 2 >{}^{87}$Rb Bose-Einstein condensates [1], produced and held in a QUIC trap. We investigated the vortex complex split decay process using $2-$axis absorption imaging, and observed the spontaneous decay into four single charged vortices. Moreover, we report the experimental observation of the twisted split decay of the quadruply charged vortices magnetically imprinted in the BEC. The observations were supported by numerical simulations showing that the process takes place in the shape of helical waves, finally splitting into separate singly-charged vortices as expected. We believe that the effect may be exploited to generate an almost isotropic state of turbulence, which we characterize in terms of the velocity statistics. This work is supported by CNPq and FAPESP, via CEPID funding grant.

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Direct observation of condensate and vortex confinement in nanostructured superconductors using STM

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Confinement effects play an important role in different physical phenomena especially in quantum systems like Bose-Einstein condensates, superconductors and superfluids. Therefore, the ability to structure these systems at length scales comparable to the characteristic size of the superconducting condensate opened a vast world of possibilities to explore quantum phenomena in nanoscale superconducting structures and devices. For example, confinement of the superconducting wave function, describing the cooper pair (pairs of electrons) density, is expected to result in vortex patterns reflecting the underlying symmetry of the nanostructure [1,2,3].

Although fabrication of these nanostructures is straightforward, using conventional e-beam lithography, there is a lack of direct experimental evidence for checking theoretical predictions. We developed a way to create e-beam defined superconducting nanosquares covered by gold allowing the visualization of the confined vortex patterns by scanning tunneling microscopy (STM) [4]. The obtained spectroscopic maps reveal the spatial evolution of both the superconducting condensate and the screening currents as a function of the applied magnetic field. The symmetry of the nanostructure is imposed on the condensate and it controls the distribution of the vortices inside the nanosquare. Our local study allows exploring the impact of small structural defects, omnipresent in these kind of structures, on both the supercurrent and vortex distribution. As a result, direct experimental evidence of vortex pinning and current crowding at the nanoscale has been obtained.

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Vortices on the move: Probing nanomagnets with different magnetic states.

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Superconductivity and magnetism are two long range order cooperative effects which compete with each other. Recently, this antagonist behavior has been turned around, since magnetic nanostructures could enhance superconducting properties, among many examples could be the so-called domain wall superconductivity, see for instance the work by Yang et al [1]. In the present work, we have followed the opposite approach; we show that superconductivity is an appropriate tool to probe the magnetic behavior of tiny nanomagnets. Superconducting films in direct contact with nanomagnet arrays are fabricated on Si substrates using a combination of different techniques as sputtering, electron beam lithography, and reactive ion etching. The hybrid samples are patterned to a bridge which allows magnetotransport measurements with the applied magnetic field applied perpendicular to the films. We show that the superconducting vortices discriminate among different magnetic states including magnetic vortex states. Superconducting vortices are sensible to the magnetic vortex state cores which show very small stray magnetic fields. The magnetoresistance curves probe and distinguish the presence of magnetic vortices, in-plane magnetization and perpendicular magnetization in the remanent state of magnetic nanodots. The study is realized using different magnetic backgrounds provided by nanodots of Fe single crystals [2], nanodots fabricated with multilayers of Pd/Co [3] and nanodots based on amorphous NdCo5 thin films [4].

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Critical behavior at the vortex Mott transition

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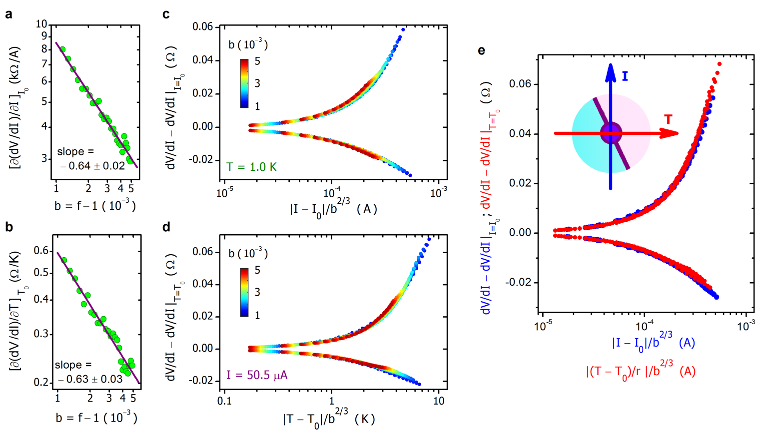
We report the critical behavior of the vortex system as it crosses the dynamic Mott insulator-to-metal transition line, driven by either current or temperature. We find universal scaling with respect to both, expressed by the same scaling function and characterized by a single critical exponent coinciding with the exponent for the thermodynamic Mott transition. We develop a theory for the DMT based on the parity reflection-time reversal ($\mathcal{PT}$) symmetry breaking formalism and find that the nonequilibrium-induced Mott transition has the same critical behavior as thermal Mott transition. Our findings demonstrate the existence of physical systems in which the effect of nonequilibrium drive is to generate effective temperature and hence the transition belonging in the thermal universality class.



a,b Log-log plots of $[\partial(dV/dI)/\partial I]_{I_0}$ and of $[\partial(dV/dI)/\partial T]_{T_0}$ vs. b. **c,** The semi-log plot of $dV/dI - dV/dI|_{I=I_0}$, as function of $|I-I_0|/b^{2/3}$. Collapse onto two generic scaling curves for $I < I_0$ and $I > I_0$ at $\epsilon_I = 2/3$ evidences the critical behaviour of the current-driven vortex Mott transition. **d,** The semi-log plot of the differential magnetoresistances $dV/dI - dV/dI|_{T=T_0}$ as function of the scaling variable $|T-T_0|/b^{2/3}$. **e,** The plots from panels **c** (blue symbols) and **d** (red symbols) perfectly collapse on top of each other upon rescaling the abscissa of the panel **d** by factor $1/r$ with $r = 1.5 \cdot 10^4$ K/A, evidencing the identity of the scaling functions for temperature- and current-driven transitions.

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Influence of Pinning Strength and Size on Type II Superconducting Thin Films With Kagomé Pinning

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Vortex dynamics in type II superconducting thin films under the influence of periodic pinning has been extensively studied during the last years. A wide range of dynamic and commensurability effects such as, reduction of vortex mobility, change in the dynamic phases and increase of the critical currents has been explored in these systems. For the specific case of films with Kagomé pinning lattice, it was shown experimentally the presence of submatching features at $B/B_\phi = 1/3$, $2/3$ and 1 [1], where B is the applied magnetic field and B_ϕ the first matching field. However, no pronounced matching features were found in previous simulations for any value of $B/B_\phi < 1$, arguing the absence of and ordered vortex lattice [2]. In this work, we intend to elucidate this discrepancy by simulating the system varying the pinning strength and using a pinning radius close to the experimental value [1]. We show that pinning radius may dramatically change the vortex ground state and consequently the sequence of pronounced force peaks. Our results show that commensurability is not the only requirement to have pronounced force peaks, they must also be associated to an ordered vortex state. On the other hand, we show that the increase in the pinning strength weakens the commensurability effects and may diminish some force peaks, in agreement with previous simulations [3]. As a consequence, our simulations show peaks of critical force at submatching fields for both transport force directions, which agree with experimental results [1], and elucidate the disagreement afore mentioned. Furthermore, we investigated the depinning process, and as opposed to cases where $B/B_\phi > 1$, the depinning process at submatching fields begins with vortices weakly trapped on top of a pinning site and not with interstitial ones. The critical forces also show anisotropic behavior that depends on the value of the applied magnetic field.

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Dynamic Phases Induced by Surface Effects in Type II Superconducting Strips With Triangular Pinning Arrays

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Superconducting samples of width comparable to the London penetration depth λ_L have been well investigated both experimentally and theoretically. Most of these works analyze vortex states, magnetization curves and critical currents [1,2,3]. However, there are few works investigating vortex dynamic phases in these systems. Reis *et. al*. [4] simulated the dynamical behavior of the vortex lattice in a strip with the presence of a random pinning distribution. In infinite samples with random pinning distribution, the vortex system show plastic flow, smectic flow and the frozen transverse solid phases. Instead of that, they showed that the presence of the surface reduces the vortex diffusion in the transverse direction, precluding in finite systems the smectic regime predicted for infinite samples. However, strips were not investigated under the influence of periodic pinning distributions. In this work, we simulate using Molecular Dynamics technique, a type II superconducting strip under the influence of a triangular pinning lattice at zero temperature. The system considered is finite in x direction and infinite along y with a fixed value of applied magnetic field perpendicular to the sample surface. We used simulated annealing to find the vortex ground state for $H/H_\phi = 1$ driven force was applied in y direction and vortices start to move in four well defined channels. Two of them, which are not commensurate and located close to the strip surface, begin to move before. After a further increase of the current, the commensurate vortices, located close to the center of the sample, start to move. Different to the vortex behavior in infinite films, in the present case the surface effects induce vortices to move in narrow channels without interconnectivity.

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Magnetic guides and gates for Abrikosov vortices

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We study effects of regular arrays of magnetic permalloy stripes lithographically patterned on a niobium superconducting film on the dynamics of Abrikosov vortices. By rotating polarization of the stripes using small in-plane magnetic fields we change the distribution and strength of magnetic charges at the stripe edges. These magnetic charges yield strings of tunable potential barriers or valleys for the vortices generated by a normal magnetic field and result in a pronounced anisotropy in the vortex motion. Using magneto-optical imaging technique we find that transversely polarized stripes can accelerate Abrikosov vortices moving along them, while longitudinally polarized stripes can generate an efficient barrier for the vortices moving across them. Thus, the array of parallel magnetic stripes is similar to the grid electrode in an electronic triode, where the grid potential controls the flow of electrons. We discuss the interactions between the magnetic stripe edges and normal vortices in terms of the coupling between linear magnetic charges and magnetic monopoles, yielding a simple intuitive picture of the observed effects. Furthermore, following Pearl's formalism we calculate the force between the stripe edges and vortices accounting for the superconducting screening of the magnetic stray fields at the edges. In the talk we will present intriguing details of the vortex guiding and gating effects induced by the magnetic stripes and discuss their application for possible single vortex manipulation in ferromagnetic/superconducting hybrid architectures.

This work was supported by the U.S. Department of Energy, Office of Science, Materials Sciences and Engineering Division. The work of F. Colauto at Argonne National Laboratory was supported by the Sao Paulo Research Foundation FAPESP (grant No. 2015/06.085-3). Samples were manufactured using facilities at the Center for Nanoscale Materials supported by the U. S. DOE, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

Reconfigurable Vortex Pinning with Magnetic Charge Ice

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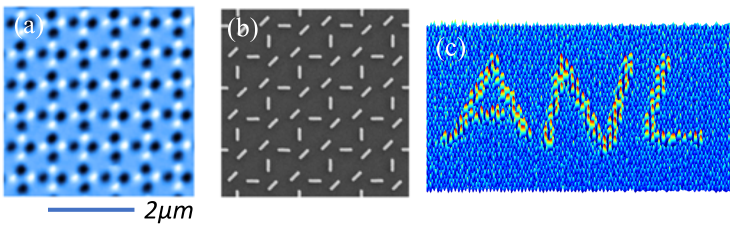
We present a novel FM/SC hybrid structure consisting of a unique artificial magnetic charge ice structure deposited onto a superconducting MoGe film. The magnetic charge ice structure mimics the ground state of a square artificial spin ice structure, with the advantage that long-range ordering of multiple magnetic structures can be easily realized and manipulated with an in-plane magnetic field [1]. The stray fields emanating from our reconfigurable magnetic nanostructure can affect the behavior of proximal superconducting vortices in the MoGe film. The novelty of the magnetic ice structure and its impact on vortex matching effect and dynamics will be presented. The globally reconfigurable and locally writable magnetic charge ice structure could provide a new setting for designing and controlling the properties of superconducting films and other two-dimensional materials.

This work was supported by the U.S. Department of Energy (DOE), Office of Science, Office of Basic Energy Sciences, Materials Sciences and Engineering Division. Z.-L.X. and J.X. were supported by NSF grant no. DMR-1407175. Use of the Center for Nanoscale Materials, an Office of Science user facility, was supported by the DOE, Office of Science, Office of Basic Energy Sciences, under contract no. DE-AC02-06CH11357.



(a) Magnetic force microscopy (MFM) image of Type I, square spin ice magnetic ground state obtained from (b) nanomagnetic bar pattern. (c) Write, read and erase function of our magnetic charge ice pattern.

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Search for Topological Superconductivity in $Sr_xBi_2Se_3$ and Pressure Induced Superconductivity in Weyl Semimetal TaP

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Topological superconductor is a very interesting and frontier topic in condensed matter physics. It is predicted that the surface of 3D topological superconductor exhibits the topologically protected in-gap states which are also known as the Majorana states. Despite the tremendous efforts in exploring the topological superconductivity, its presence is however still under heavy debates. In this talk, we will report three progresses: (1) The surface Dirac electrons can be driven into Cooper pairs [1], and (2) There is a two-fold symmetric superconductivity [2] in $Sr_xBi_2Se_3$. (3) We find pressure induced superconductivity in Weyl semimetal TaP. By doing systematic study of scanning tunneling microscope/spectroscopy on $Sr_xBi_2Se_3$, we find that the surface Dirac electrons will simultaneously condense into the superconducting state when the energy is smaller than the bulk superconducting gap. This vividly demonstrates how the surface Dirac electrons are driven into Cooper pairs. Furthermore, By using a Corbino-shape like electrode configuration, we measure the c-axis resistivity of the recently discovered superconductor $Sr_xBi_2Se_3$ with the magnetic field rotating within the basal planes, and find clear evidence of two-fold superconductivity. The Laue diffraction measurements on these samples show that the maximum gap direction is either parallel or perpendicular to the main crystallographic axis. This observation is consistent with the theoretical prediction and strongly suggests that $Sr_xBi_2Se_3$ is a topological superconductor. Finally we will show the pressure induced superconductivity in the Weyl semimetal TaP. A structure transition occurs at about 70 GPa leading to the phase of P-6m2 which is superconductive with still the Weyl semimetal feature [3].

In collaboration with: Guan Du, Jifeng Shao, Xiong Yang, Zengyi Du, Delong Fang, Jinghui Wang, Kejing Ran, Jinsheng Wen, Changjin Zhang, Huan Yang, Yuheng Zhang, Hai Lin, Yufeng Li, J. Schneeloch, R. D. Zhong and Genda Gu.

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Room temperature skyrmions and robust metastable skyrmion states in Co-Zn-Mn alloys

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Magnetic skyrmions are nanometric-sized, topologically non-trivial spin vortex-like objects that bear a clear resemblance with superconducting vortices. Like vortices, skyrmions arrange into a hexagonal closed-packed lattice when stabilised by an applied magnetic field, and can be studied using both real-space and reciprocal space imaging techniques. The skyrmion state is quite difficult to find however, and is only stabilised under the particular conditions found in a select few noncentrosymmetric magnets. Among them, the chiral cubic magnets are well-known as hosts of the hexagonal close-packed skyrmion lattice as a thermodynamic equilibrium state. However, typically this state exists at cryogenic temperatures, and is stable only over a narrow temperature and magnetic field region just below the transition temperature - see Ref. [1] for a review.

In this talk I will introduce the recent discovery of chiral cubic Co-Zn-Mn alloys as a versatile host system of skyrmion lattice states [2]. For example, by tuning the composition, skyrmion lattices can be stabilised either below, at, or well beyond room temperature. In addition, we report the creation of remarkably robust metastable skyrmion states in the room-temperature skyrmion host material $Co_8Zn_8Mn_4$ [3]. These metastable states, created by a conventional field-cooling through the equilibrium skyrmion state, survive over the major part of the phase diagram, including down to zero temperature and up to the critical magnetic field of the ferromagnetic transition. Furthermore, the metastable skyrmion lattice is observed to transform between conventional hexagonal and novel square-like coordinations upon varying the temperature and magnetic field. These findings exemplify the topological robustness of the once-created skyrmions, and establish metastable states as a promising technological platform.

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Appearance of flux creep upon cooling anisotropic superconductors in tilted magnetic fields

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Vortices in type-II superconductors aim at reaching an equilibrium configuration, typically in the form of an Abrikosov lattice. Upon creating an out-of-equilibrium state, the system's relaxation can be impeded by material defects, pinning vortices in metastable traps. The relaxation dynamics is then usually determined by thermal (as opposed to quantum) activation of vortices over their pinning barriers U_b, a slow process known as vortex creep. We propose a novel feature of vortex creep upon cooling anisotropic superconductors in tilted magnetic fields. In fact, the uniaxial anisotropy of the layered crystalline structure causes a misalignment between the direction of the magnetic field and the flux lines; a misalignment that in turn is sensitive to the sample's temperature. As a result, for a fixed external field direction, the equilibrium vortex orientation changes as a function of the temperature. At high temperatures, when vortex creep occurs faster than the timescale of the experiment, vortices follow the equilibrium orientation 'instantaneously'. Once the sample is cooled below a cross-over temperature, typically when $T \sim U_b/k_{\mathrm{B}}$, the vortex motion towards the equilibrium orientation involves creep; a motion that can be detected in experiments.

This dynamic feature has directly been observed in the anisotropic superconductor 2H-NbSe$_2$ using scanning tunneling microscopy at 150 mK. In a first stage, we created a non-equilibrium vortex by rotating the external magnetic field to a finite polar angle. We find that the vortex lattice creeps at small velocities in the range of tens of nanometer per hour, independent on the in-plane direction of the tilt. This motion stops when the sample is heated from the base temperature to 2 K. Upon cooling the sample back to the base temperature, the vortex motion resurrects and is in quantitative agreement with the proposed model. The new creep dynamics reported here is a generic feature of anisotropic superconductors with (weak) pinning in tilted magnetic fields.

Exploring strong pinning regimes with Ginzburg-Landau simulations

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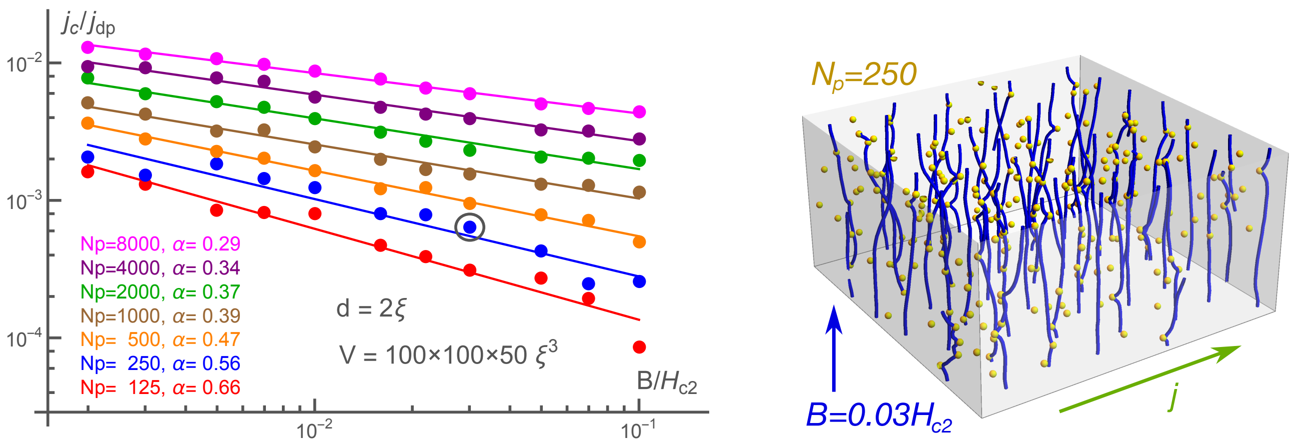
Understanding the mechanism of vortex pinning is a central prerequisite for pushing beyond todays current-carrying capabilities of superconductors. Already the evaluation of the critical current j_c, necessary to detach a *single* vortex from a low density n_p of strong defects, is a nontrivial problem. In this 1D strong-pinning regime the critical current is expected to grow as $j_c \propto n_p^{1/2}$ and is independent of the field B [1,2]. The high-field regime, where vortices are weakly deformed away from an ideal Abrikosov lattice, pinning is described within the (3D) strong pinning theory [1,3]. In this limit the critical current is expected to grow linearly with the defect density n_p, while decreasing as $B^{-\alpha}$ with increasing field B. Depending on the mechanism of vortex-line trapping, the power index α may take values $1/2$ or $5/8$ [1,3]. It is clear, however, that these theoretical estimates do not provide a full picture. In order to arrive at a complete quantitative description of strong-pinning regimes, we explore the density/field-diagram with time-dependent Ginzburg-Landau simulations [4]. We uncovered a wide parameter range where defects strongly disturb the vortex order while vortex-vortex interactions are still strong. In particular, for spherical defects of size $d = 2\xi$, we find a power-law $j_c \propto B^{-\alpha}$ with α monotonically increasing from $\alpha \approx 0.29$ to $\alpha \approx 0.66$ upon reducing the defect density n_p, see the Figure. The local order in the lattice progressively improves with the increasing magnetic field and decreasing defect density. We discuss a theoretical model to describe this regime. Combining numerical and analytical results, we establish new pinning regimes and define limits of applicability for the conventional theories.



Critical current j_c as a function of field B for different defects densities $n_p = N_p/V$, with V the simulation volume. The power α is extracted from a linear fit (lines) in the log-log representation. For the encircled point, the vortex configuration is shown.

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Current-induced SQUID behavior of superconducting Nb nano-rings

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We demonstrate current-induced switching between Little-Parks and SQUID magnetoresistance oscillations in a superconducting nano-ring without Josephson junctions. Our measurements in Nb nano-rings show that as the bias current increases, the parabolic Little-Parks magnetoresistance oscillations become sinusoidal and eventually transform into oscillations typical of a SQUID. We associate this phenomenon with the flux-induced non-uniformity of the order parameter along a superconducting nano-ring, arising from the superconducting leads ('arms') attached to it. Current enhanced phase slip rates at the points with minimal order parameter create effective Josephson junctions in the ring, switching it into a SQUID.

Kinematic vortices induced by constriction in gapless superconductors

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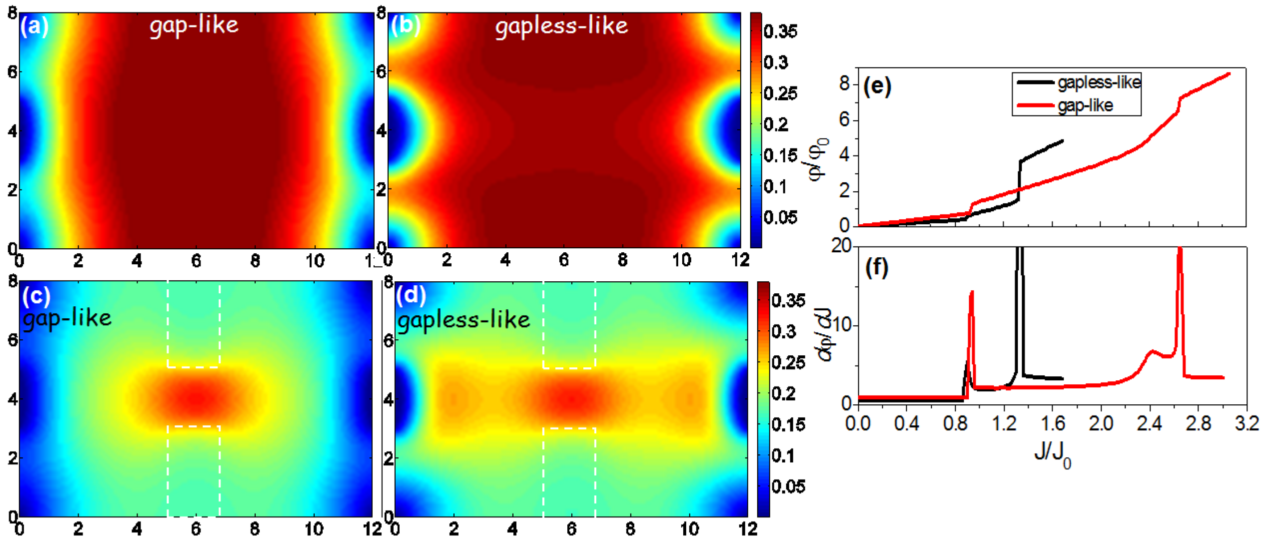
When a transport current is applied in small superconductors, kinematic vortices, KVs, can be induced and a local resistive state takes place [1]. The study of KVs can be carried out in the frame work of the generalized time-dependent Ginzburg-Landau theory, GTDGL [2] where γ is introduced as a factor which represents a relaxation of the superconducting order parameter. Gapless-like superconductors are take into account when $\gamma = 0$.

In the present work, we concluded that the presence of KVs in gap-like superconductors ($\gamma \neq 0$) is due to a crowding of the currents in the center of the sample. Then, in a gapless-like superconductor, a crowding of the currents was induced building a constriction in the sample with two blind slits. With such geometry a local resistive state rises from the appearance of KVs.

The figure shows some aspects of the studied systems. In (a) and (b) is shown the map of the modulus of the superconducting current, J_s, in the gap-like and gapless-like samples respectively. Note that J_s is maximum along the central part of sample (a). In (c) and (d) a crowding is induced by constriction in both studied samples. In figure (e) is shown the normalized electric potential as a function of the normalized applied current, $\varphi(J)$ and (f) the differential resistance of the gap and gapless-like samples.



Map of the modulus of the superconducting current, J_s. (a) and (b) homogeneous gap-like and gapless-like samples, respectively. (c) and (d) gap-like and gapless-like samples with constriction, respectively.(e) is the $\varphi(J)$ for the gap and gapless-like samples and (f) is the differential resistance.

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Scanning SQUID-on-tip nanomagnetometry and nanothermometry of quantum systems

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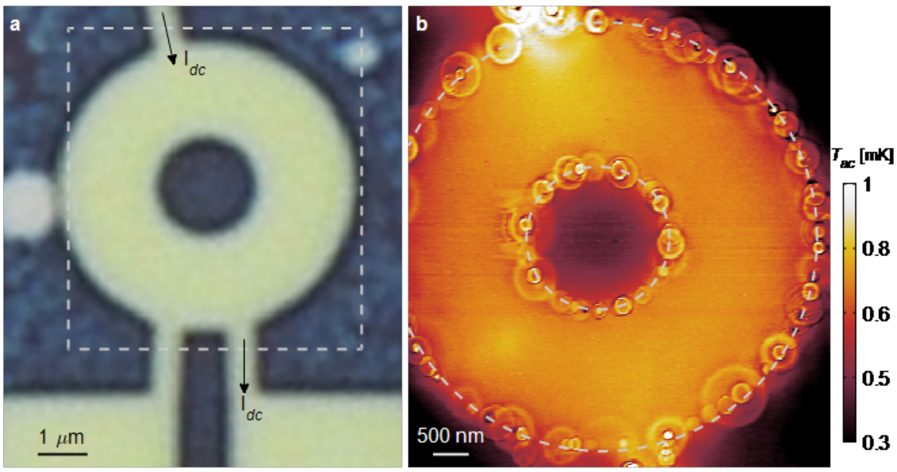
Energy dissipation is a fundamental process governing the dynamics of physical systems. In condensed matter physics, in particular, scattering mechanisms, loss of quantum information, or breakdown of topological protection are deeply rooted in the intricate details of how and where the dissipation occurs. Despite its vital importance, direct imaging of dissipation in quantum systems is currently impossible because the existing thermal imaging methods lack the necessary sensitivity and are unsuitable for low temperature operation.

We developed a scanning SQUID with sub 50 nm diameter that resides at the apex of a sharp pipette [1]that can act 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/Hz$^{1/2}$ [2]. The non-contact non-invasive thermometry allows thermal imaging of very low nanoscale energy dissipation down to the fundamental Landauer limit of 40 fW for continuous readout of a single qubit at 1 GHz at 4.2 K. These advances enable observation of changes in dissipation due to single electron charging of individual quantum dots in carbon nanotubes. Our thermal imaging study of hBN encapsulated graphene reveals a fascinating dissipation mechanism due to resonant localized states at the edges of graphene providing the first visualization of inelastic electron scattering mechanism on the nanoscale, opening the door to direct imaging of microscopic dissipation processes in quantum matter.



(a) Optical image of hBN/graphene/hBN structure patterned into a washer shape (bright). (b) Thermal image of the outlined area in (a) in presence of I_{dc}= 6 μA at 4.2 K. The necklace of rings reveals the presence of resonant states along the edges of graphene that serve as local centers of energy dissipation.

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