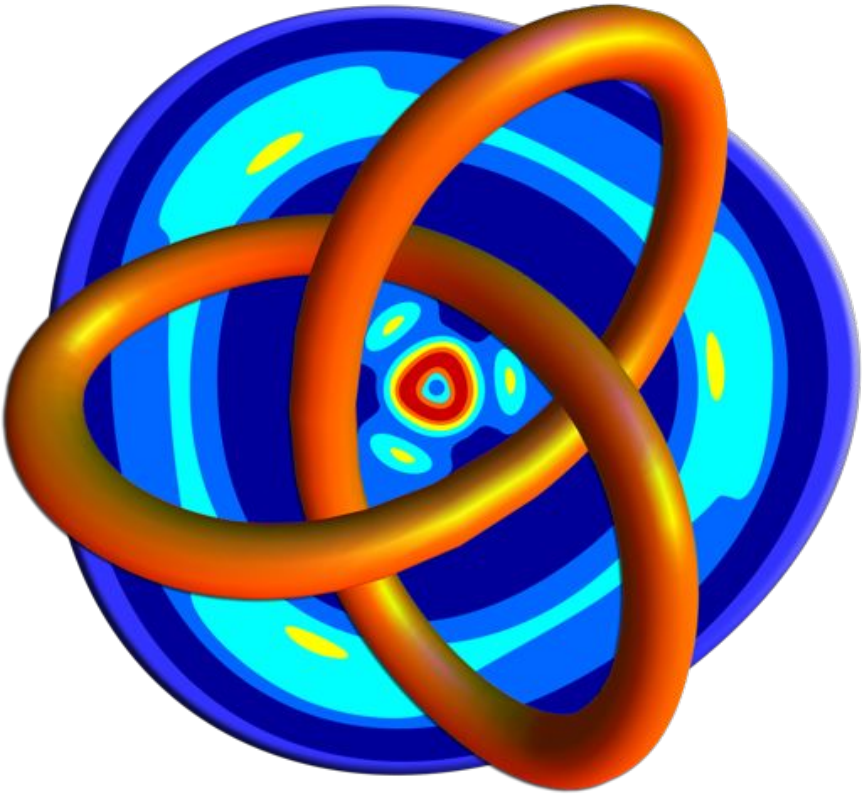
MTI and ITS Fall Workshop 2013

Coherent Hybrid Structures on the Mesoscale



October 13-18, 2013
Evanston, IL, USA

MTI Argonne NATIONAL LABORATORY UNIVERSITY OF NOTRE DAME

General information

The goal of the workshop is to bring together scientists from different communities actively working in the hybrid and nano structured materials areas, where quantum coherence plays a central role. We aim at interdisciplinary discussions and an active dialogue between experiment, computational approaches, and theory.

The scope of the Workshop includes, but is not restricted to the following topics:

- Josephson arrays and related structures
- Superconductor-insulator transitions and related effects
- Unconventional pairing in superconductor-ferromagnet proximity structures
- Proximity and Josephson effects in carbon nanotubes, graphene and topological insulators
- Quantum phase slips in superconducting nanowires and nanorings
- Crossed Andreev reflection in NS and FS structures
- Quantum transport in non-conventional insulators
- Quantum optics and quantum information processing in cavity QED systems
- Quantum coherence

The workshop will be held from October 13th to 18th, 2013 at the Hilton/Orrington in Evanston, IL, USA. October 13th is the arrival day with welcome reception; October 18th is the departure day.

Organizers: Andreas Glatz, Alexander Golubov, Boldizsar Janko, and Valerii Vinokur

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Website: mti.msd.anl.gov/workshops/CHS2013

Schedule

Sunday, October 13th – Friday, October 18th, 2013

	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
7:30-8:45		*Breakfast*				
8:45-9:00		*Opening*				
9:00-9:30		Szymanska	Gershenson	Sau	Bergeret	
9:30-10:00		Snoke	Pop	Hu	Attanasio	
10:00-10:30		Houzet	Cho	Brinkman	Cuoco	
10:30-11:00		*Coffee Break*				
11:00-11:30		Ryazanov	Catelani	Heikkila	Sidorenko	
11:30-12:00		Buzdin	Zaikin	Asano	Faoro	
12:00-13:30		*Lunch*				
13:30-14:00	*Arrival*		Koshelev	Efetov	Ioffe	
14:00-14:30		Schuster	Averin	Baturina	Xiao	
14:30-15:00		Golubov	Pekola	Sadovskyy	Milosevic	*Departure*
15:00-15:30		*Coffee Break*				
15:30-16:00		Glazman	Van Harlingen	Giazotto	Robinson	
16:00-16:30		Matveev	Chandra-sekhar	Csonka	Eschrig	
16:30-17:00		Kamenev		Bezryadin	Metlushko	
16:45-18:30			*Poster Session*			
17:00-19:00	*Reception*					
18:00-20:00				*Conference Dinner*		

Venue information

The workshop takes place in the Hilton/Orrington hotel in Evanston, IL, USA.

www.hotelorrington.com

- All oral presentations are held in the Hinman Auditorium located on the 9th floor.
- The poster session on Tuesday is located in the Rogers Room on the 9th floor. The poster boards are 122x91cm^2 (48x36 sq in) in size (landscape format).
- The welcome reception on Sunday evening (17-19) is held in the Heritage Ballroom on the 2nd floor. Non-alcoholic beverages are provided and a cash bar is available.
- Lunches are held in the Heritage Ballroom on the 2nd floor.
- The conference dinner is held in the Rogers Room on the 9th floor.
- *Please note: All meals are provided for registered participants only.*

Program

Monday, October 14

Morning Session - Chair: *Alexander Golubov*	
8:45 – 9:00	**Valerii Vinokur,** *Welcome*
9:00 – 9:30	**Marzena Szymanska**, University College London *Condensation, coherence and superfluidity in non-equilibrium*
9:30 – 10:00	**David Snoke**, University of Pittsburgh, Pennsylvania *Thermalization of long-lifetime polaritons in microcavities*
10:00 – 10:30	**Manuel Houzet,** CEA Grenoble, France *Superharmonic Josephson relation through a long diffusive ferromagnetic bilayer*
10:30 – 11:00	*Coffee Break*
11:00 – 11:30	**Valery Ryazanov**, Institute of Solid State Physics, Russia *Quasiparticle and spin-polarizad injection in coherent hybrid structures*
11:30 – 12:00	**Alexander Buzdin**, University Bordeaux 1, Talence, France *Interference phenomena and long-range proximity effect in SFS systems*
12:00 – 14:00	*Lunch*
Afternoon Session - Chair: *Alexander Buzdin*	
14:00 – 14:30	**David Schuster**, University of Chicago, Illinois *Cavity QED with electrons on helium*
14:30 – 15:00	**Alexander Golubov,** University of Twente, The Netherlands *Designing phase-sensitive tests for Fe-based superconductors*
15:00 – 15:30	*Coffee Break*
15:30 – 16:00	**Leonid Glazman,** Yale University, Connecticut *Topological superconducting phase in a helical Shiba chain*
16:00 – 16:30	**Konstantin Matveev,** Argonne National Laboratory, Illinois *Decay of fermionic quasiparticles in one-dimensional quantum liquids*
16:30 – 17:00	**Alex Kamenev,** University of Minnesota, Minneapolis *Anomalous transport properties of superconducting nano-wires*

Tuesday, October 15

Morning Session - Chair: *Tatyana Baturina*	
9:00 – 9:30	**Michael Gershenson**, Rutgers University, New Jersey *Protected Josephson rhombi chains*
9:30 – 10:00	**Ioan Pop**, Yale University, Connecticut *Coherent cancellation of superconducting quasiparticle dissipation*
10:00 – 10:30	**Sungjae Cho,** University of Illinois at Urbana-Champaign *Transport in 3D topological insulator nanostructures*
10:30 – 11:00	*Coffee Break*
11:00 – 11:30	**Gianluigi Catelani**, Forschungszentrum Jülich, Germany *Parity switching and decoherence by quasiparticles in transmons*
11:30 – 12:00	**Andrei Zaikin,** Karlsruhe Institute of Technology, Germany *Quantum decoherence of Cooper pairs*
12:00 – 13:30	*Lunch*
Afternoon Session - Chair: *Andreas Glatz*	
13:30 – 14:00	**Alexei Koshelev,** Argonne National Laboratory, Lemont, Illinois *Mesoscopic variations of local density of states in disordered superconductors*
14:00 – 14:30	**Dmitri Averin,** Stony Brook University, New York *Maxwell's Demon and statistics of mesoscopic heat transport*
14:30 – 15:00	**Jukka Pekola,** Aalto University School of Science, Aalto, Finland *Dissipation and Maxwell's demon in single-electron circuits*
15:00 – 15:30	*Coffee Break*
15:30 – 16:00	**Dale van Harlingen,** University of Illinois at Urbana-Champaign *Identifying and manipulating Majorana fermions in Josephson devices with topological barriers*
16:00 – 16:30	**Venkat Chandrasekhar,** Northwestern University, Evanston, Illinois *Nonlocal correlations in proximity coupled normal metals*
16:45 – 18:30	**Poster Session**

Wednesday, October 16

Morning Session - Chair: *Michael Gershenson*	
9:00 – 9:30	**Jay Deep Sau,** Harvard University, Cambridge, Massachusetts *The search for topologically degenerate Majorana modes in semiconductor/superconductor interfaces*
9:30 – 10:00	**Xiao Hu,** International Center for Materials Nanoarchitectonics, Japan *Nonlocal quantum entanglement between two quantum dots via Majorana fermions in nanowire*
10:00 – 10:30	**Alexander Brinkman,** University of Twente, The Netherlands *Superconductor-topological insulator hybrids*
10:30 – 11:00	*Coffee Break*
11:00 – 11:30	**Tero Heikkilä,** Aalto University, Finland *High-temperature surface superconductivity in rhombohedral graphite*
11:30 – 12:00	**Yasuhiro Asano,** Hokkaido University, Sapporo, Japan *Three-dimensional symmetry-breaking topological states*
12:00 – 13:30	*Lunch*
Afternoon Session - Chair: *Konstantin Matveev*	
13:30 – 14:00	**Konstantin Efetov**, University of Bochum, Germany *Pseudogap state from quantum criticality*
14:00 – 14:30	**Tatyana Baturina,** Rzhanov ISP, Novosibirsk, Russia *Optimized confinement for reentrant superconductivity and superconductor-insulator transition in nanoperforated films*
14:30 – 15:00	**Ivan Sadovskyy,** Argonne National Laboratory, Lemont, Illinois *Vortex dynamics simulations in large systems for energy applications*
15:00 – 15:30	*Coffee Break*
15:30 – 16:00	**Francesco Giazotto***, NEST Istituto Nanoscienze-CNR & Scuola Normale Superiore, Pisa, Italy* *Toward coherent caloritronics: Phase-coherent thermal transport in Josephson junctions nanocircuits*
16:00 – 16:30	**Szabolcs Csonka**, Budapest University of Technology, Hungary *Cooper pair splitting using InAs quantum dots*
16:30 – 17:00	**Alexey Bezryadin**, University of Illinois at Urbana-Champaign *Direct detection of single and double phase slips in superconducting nanowires*
18:00 – 20:00	**Conference Dinner**

Thursday, October 17

Morning Session - Chair: *Boldizsar Janko*	
9:00 – 9:30	**Sebastian Bergeret,** Centro de Física de Materiales, Spain *Singlet-triplet conversion in superconductor-ferromagnet structures with spin-filter barriers*
9:30 – 10:00	**Carmine Attanasio,** Università degli Studi di Salerno, Italy *Long-range coupling in Nb/Py/Nb trilayers: spin-triplet superconductivity*
10:00 – 10:30	**Mario Cuoco,** CNR-SPIN & University of Salerno, Italy *Spin-triplet superconductor interfaced to ferromagnet and magnetic edge states*
10:30 – 11:00	*Coffee Break*
11:00 – 11:30	**Anatolie Sidorenko,** Institute of Electronic Engineering and Nanotech *Detection of the triplet pairing and spin-valve-effect in superconductor/ferromagnet heterostructures*
11:30 – 12:00	**Lara Faoro,** LPTHE, CNRS, France *A semiempirical model for two-level system noise in high quality superconducting microresonators*
12:00 – 13:30	*Lunch*
Afternoon Session - Chair: *Valerii Vinokour*	
13:30 – 14:00	**Lev Ioffe,** LPTHE, Paris, France & Rutgers University, Piscataway, NJ *Phase slips in strongly disordered superconductors*
14:00 – 14:30	**Zhili Xiao,** Argonne National Laboratory, Lemont, Illinois *In-situ tunable vortex pinning by a ferromagnetic antidot array*
14:30 – 15:00	**Milorad Milosevic,** Universiteit Antwerpen, Belgium *Critical superconductors*
15:00 – 15:30	*Coffee Break*
15:30 – 16:00	**Jason Robinson,** University of Cambridge, UK *Spin-Triplet supercurrents*
16:00 - 16:30	**Matthias Eschrig,** Royal Holloway University of London, UK *Coherent transport in superconductor-ferromagnet hybrid systems*
16:30 - 17:00	**Vitali Metlushko,** University of Illinois at Chicago *Vortex transformation in 3D nanostructures*

Abstracts

Micron-ranged supercurrents in ferromagnets

J. Aarts

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From work in different research groups, there now is strong evidence that, by generating so-called odd-frequency triplet Cooper pairs, it is possible to have supercurrents flow through ferromagnets over lengths which are similar to those in normal metals. The mechanism under which triplets are generated is not fully understood as yet, but a spin-active interface between the superconducting (S) contact and the ferromagnet (F) is a prerequisite, meaning some form of inhomogeneous magnetization or a difference in the scattering of two spin channels. Earlier we showed that long-range supercurrents (order of 1 µm) could be found in CrO_2 films grown on sapphire, but not in similar films grown on TiO_2 [1]. Using the recent finding that a spin-active interface can be fabricated by inserting N/F*/N sandwich between S and F (N a normal metal and F* a different ferromagnet) [2], we show that micron-ranged supercurrents can also be induced in CrO_2 on TiO_2, by using a thin Cu/Ni/Cu intermediate layer.

[1] S. Anwar *et al.*, Phys. Rev. B **82**, 100501(R) (2010), Appl. Phys. Lett. **100**, 052602 (2012).
[2] T.S Khaire *et al.* Phys. Rev. Lett. **104,** 137002 (2010).

Quantum phase slip phenomena: physics and applications

K. Yu. Arutyunov[1,2], J. S. Lehtinen[1]

[1]*University of Jyväskylä, Department of Physics, NanoCentre, PB 35, 40014 Jyväskylä, Finland*
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The topic of quantum fluctuations in quasi-1D superconductors, also called *quantum phase slips* (QPS), has attracted a significant attention [1]. It has been shown that the phenomenon is capable to suppress the zero resistivity of ultra-narrow superconducting nanowires at low temperatures $T \ll T_C$ [2-4] and quench persistent currents in tiny nanorings [5]. The coherent QPS effect enables fabrication of the new generation of quantum logic devices – qubits [6]. It has been predicted that a superconducting nanowire in the regime of QPS is dual to a Josephson junction [7]. In particular case of an extremely narrow superconducting nanowire imbedded in high-impedance environment the duality leads to an intuitively controversial result: the superconductor can enter an insulating state [8]. Here we experimentally demonstrate that the I-V characteristic of such a wire indeed shows Coulomb blockade, which disappears with application of a critical magnetic field and/or above the critical temperature proving that the effect is related to superconductivity [9]. Such system can be considered as a junctionless single electron transistor (with charge *2e*), where the QPS provide the dynamic equivalent of weak links in conventional devices containing static (in space and time) tunnel junctions. Application of external RF radiation can be synchronized with the internal Bloch oscillations of the current-biased superconducting nanowire in the regime of QPS. The phenomenon is dual to the well-known Shapiro effect: the voltage steps for a Josephson junction are substituted by the current steps for a QPS wire: the proof-of-principle demonstration of the long-awaited metrological application - the quantum standard of electric current

[1] K. Yu. Arutyunov, D. S. Golubev, and A.D. Zaikin, *Phys. Rep*. 464, 1 (2008).
[2] M. Zgirski, K.-P. Riikonen, V. Touboltsev, and K. Arutyunov, *NanoLett.* 5, 1029 (2005).
[3] M. Zgirski, K.-P. Riikonen, V. Touboltsev and K.Yu. Arutyunov, *Phys. Rev. B.* 77, 054508 (2008).
[4] J. S. Lehtinen, T. Sajavaara, K. Yu. Arutyunov, M. Yu. Presnjakov and A. Vasiliev, *Phys. Rev. B* 85, 094508 (2012).
[5] K. Yu. Arutyunov, T. T. Hongisto, J. S. Lehtinen, L. I. Leino, and A. L. Vasiliev. *Nature: Sci. Rep*. 2, 293 (2012).
[6] O. V. Astafiev, L. B. Ioffe, S. Kafanov, Yu. A. Pashkin, K. Yu. Arutyunov, D. Shahar, O. Cohen, & J. S. Tsai, *Nature* 484, 355 (2012).
[7] J. E. Mooij and Yu. V. Nazarov, *Nature Physics* 2, 169 (2006).
[8] T. T. Hongisto and A. B. Zorin, *Phys. Rev. Lett*. 108, 097001 (2012).
[9] J. Lehtinen, K. Zakharov and K. Arutyunov, *Phys. Rev. Lett*. 109, 187001 (2012).

Three-dimensional symmetry-breaking topological states

Yasuhiro Asano and Tetsuro Habe

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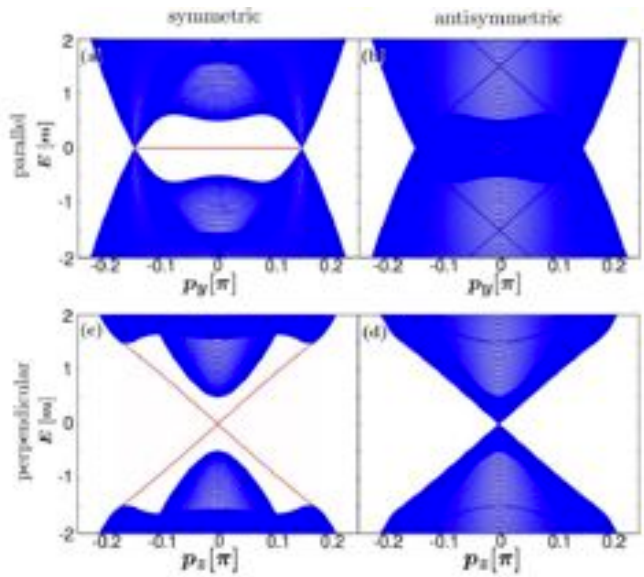
We discuss topological electronic states described by the Dirac Hamiltonian plus an additional one in three-dimension (3D). When the additional Hamiltonian is an element of an Abelian group, electronic states become topologically nontrivial even in the absence of the fundamental symmetries such as the time-reversal symmetry and the particle-hole one. Such symmetry-breaking topological states are characterized by the Chern number defined in the two-dimensional (2D) partial Brillouin zone. The topological insulators (TI) in Zeeman fields are an example of the symmetry-breaking topological materials. We show the crossover from the topological insulating phase to the topological semimetal one in strong Zeeman fields.



The figure shows the energy eigenvalues of the TI under the strong Zeeman field applied in the y direction plotted as a function of momenta in the y direction (upper figures) or those in the z direction (lower figures). We applied the Hard wall boundary condition in the x direction. The symmetric (antisymmetric) Zeeman field means g-factor of the two orbitals are equal (opposite) to each other. The both results show the semi-metallic properties. Although the TI no longer insulating in strong Zeeman field, the semi-metal phases are characterized the Chern number in the 2D partial Brillouin zone.

[1] T. Habe and Y. Asano, arXiv:1307.1531

Long-range coupling in Nb/Py/Nb Trilayers: spin-triplet superconductivity

C. Cirillo,[1] E. A. Ilyina,[1] A. Garcìa-Santiago,[2,3] J. M. Hernandez,[2,3] A. Verso,[4]
F. S. Bergeret,[4,5] J. Tejada,[2,3] and **C. Attanasio**[1]

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[5]Centro de Fìsica de Materiales (CFM-MPC), Centro Mixto CSIC-UPV/EHU,
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The temperature dependence of the parallel upper critical field, $H_{c2||}(T)$, was measured for proximity coupled Nb/Py/Nb trilayers in which the thickness of the Py layer, d_{Py}, changes from 20 nm up to 432 nm. When d_{Py} is in the range 150–250 nm a coupling between the two superconducting outer layers is observed with $H_{c2||}(T)$ showing a linear behavior from T_c down to temperatures of the order of $0.9T_c$. The value of d_{Py} is much longer than the singlet decay length, $x_F = (h/2pD_FE_{ex})^{1/2}$, which is of the order of 2 nm in our Py films (D_F and E_{ex} are the electron diffusivity and the exchange energy in the ferromagnet, respectively). We believe that the observed effect is due to a long-range proximity effect generated by the inhomogeneous magnetization present in thick Py layers.

Maxwell's Demon and statistics of mesoscopic heat transport

Dmitri Averin

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Information plays an important role in evolution of monitored classical and quantum mesoscopic systems. The most basic device illustrating the role of information in thermodynamics is Maxwell's Demon (MD), which employs the measurements and feedback to convert energy of thermal fluctuations into free energy. An ideal, fully reversible, MD would use only well-defined initial state of a memory register to achieve this task. Experimental demonstration of such MD is an open problem, with one of the main obstacles being the development of the thermodynamically reversible detectors. In the talk, I will discuss possible ways of implementing reversible electronic MD based on transport in single-electron structures and related statistics of generated heat in these systems. Connections to the fluctuation-dissipation theorem for thermal conductance will also be discussed.

Optimized confinement for reentrant superconductivity and superconductor-insulator transition in nanoperforated films

Tatyana I. Baturina

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In this talk we will present the results of comparative study of transport properties of continuous and nanoperforated TiN films. This enables us to investigate in detail the interplay between disorder and restricted geometry effects and construct a comprehensive picture of the resistive behavior of nanopatterned superconducting films. We show that oscillations of magnetoresistance arise from the combined action of Josephson coupling of a single junction enhanced by multiconnectivity effects, flux quantization, collective phase-frustration, and Berezinskii-Kosterlitz-Thouless transition in the system of Josephson vortices. Going over from low to moderate magnetic fields we discover that in optimally patterned films reentrance of superconductivity takes place, which we assign to the combined effects of surface superconductivity and formation of hypervortices. Moreover, we show that patterning the film into a square array of nanoscale holes stimulates both, the disorder- and magnetic field-driven superconductor-to-insulator transitions, pushing them to the lower degree of microscopic disorder. Depending on the original degree of disorder the nanopatterning either suppresses the critical temperature, or drives the initially superconducting film into an insulating state, or else, transforms the originally insulating film into an even more pronounced insulator.

Singlet-triplet conversion in superconductor-ferromagnet structures with spin-filter barriers

F. S. Bergeret

Centro de Física de Materiales, San Sebastian, Spain

It is commonly believed that singlet/ long-range triplet pairs conversion happens only in the presence of magnetic inhomogeneities. It will be shown, however, that there are other sources of the long-range triplet component and establish general conditions for their occurrence. First we derive a SU(2) covariant diffusive equation in the prototypical case of a linear in momentum generic spin-field, and show that the effective SU(2) electric field is responsible for the long-range proximity effect. Secondly, we extend our analysis to a generic ferromagnet and establish a universal condition for the long-range triplet component. In a second part of the talk I will focus on the transport through spin-filter barriers. By using special boundary conditions for the quasiclassical equations we obtain results for the Josephson current and conductance in S/F/S junctions, show how spin-polarized supercurrents can be generated in such structures, and compare our results with existing experimental data.

[1] F. S. Bergeret and I. Tokatly, Phys. Rev. Lett. 110, 117003(2013).
[2] F. S. Bergeret, A. Verso and A. F. Volkov, Phys. Rev. B 86, 214516 (2012)
[3] F. S. Bergeret, A. Verso and A. F. Volkov, Phys. Rev. B 86, 060506(R) (2012)

Direct detection of single and double phase slips in superconducting nanowires

Alexey Bezryadin

University of Illinois at Urbana-Champaign

Superconducting wires find applications in photon detection, quibit designs, and other electronic superconducting devices. Transport properties of a superconducting are defined, to a large extend by the rate of Little's phase slips [1] in them. Each phase slip changes the phase difference by 2Pi and causes dissipation. The phase slips are called quantum phase slips if the slippage process occurs by means of macroscopic quantum tunneling [2,3]. We present a superconducting device, based on a coplanar waveguide resonator, which allows us to detect single quantum phase slips (SPS) as well as double phase slips (DPS), in which the phase difference changes by 4Pi [4]. We observe that at low currents DPS exhibit a higher rate than SPS. This I explained in terms of Caldeira-Leggett quantum dissipation theory [5].

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[1] Little, W. A. Decay of Persistent Currents in Small Superconductors. *Phys. Rev.* **156**, 396 (1967).

[2] Sahu, M., Bae, M.H., Rogachev, A., Pekker, D., Wei, T. C., Shah, N., Goldbart, P. M., and Bezryadin, A. Individual Topological Tunneling Events of a Quantum Field Probed Through Their Macroscopic Consequences. *Nat. Phys.* **5**, 503 (2009).

[3] Aref, T., Levchenko, A., Vakaryuk, V., and Bezryadin, A. Quantitative Analysis of Quantum Phase Slips in Superconducting $Mo_{76}Ge_{24}$ Nanowires Revealed by Switching-Current Statistics. *Phys. Rev. B* **86**, 024507 (2012).

[4] Belkin, A., Brenner, M., Aref, T., Ku, J., and Bezryadin, A. Little–Parks Oscillations at Low Temperatures: Gigahertz Resonator Method. *Appl. Phys. Lett.* **98**, 242504 (2011).

[5] A. Belkin, M. Belkin, V. Vakaryuk, S. Khlebnikov, and A. Bezryadin, to be published.

Superconductor-topological insulator hybrids

A. Brinkman, M. Veldhorst, M. Snelder, C.G. Molenaar,
D.P. Leusink, H. Hilgenkamp, A.A. Golubov

MESA+ Institute for Nanotechnology, University of Twente, the Netherlands

Non-Abelian anyons are predicted to arise from a Majorana bound state in a superconductor-topological insulator hybrid device. We present direct evidence for a Josephson supercurrent in superconductor (Nb) – topological insulator (Bi_2Te_3) – superconductor e-beam fabricated junctions by the observation of clear Shapiro steps under microwave irradiation, and a critical current modulation by magnetic field [1].
The dependence of the critical current on temperature and electrode spacing shows that the junctions are in the ballistic limit on a length scale of 100 nm. Shubnikov-de Haas oscillations in magnetic fields up to 30 T reveal a topologically non-trivial two-dimensional surface state. We argue that the ballistic Josephson current is hosted by this surface state despite the fact that the normal state transport is dominated by diffusive bulk conductivity. Additionally, we provide an update on the progress of realizing supercurrents in topological insulators with no bulk shunt.
Nanostructured SQUIDs containing topological Josephson junctions are realized experimentally [2]. Clear critical current modulation of both the junctions and the SQUID with applied magnetic fields have been observed. We show that the SQUIDs have a periodicity in the voltage-flux characteristic of F_0 consistent with numerical expectations [3] and models based on the Bogoliubov-de Gennes equations [4]. We propose several strategies towards realizing a doubled periodicity, belonging to the presence of Majorana fermions.

[1] M. Veldhorst, M. Snelder, M. Hoek, T. Gang, V. Guduru, X. Wang, U. Zeitler, W.G. van der Wiel, H. Hilgenkamp, A. Brinkman, Nature Materials **11**, 417 (2012).
[2] M. Veldhorst, C.G. Molenaar, X.L. Wang, H. Hilgenkamp, and A. Brinkman, Appl. Phys. Lett. **100**, 072602 (2012).
[3] M. Veldhorst, C.G. Molenaar, C.J.M. Verwijs, H. Hilgenkamp, A. Brinkman, Phys. Rev. B **86**, 024509 (2012).
[4] M. Snelder, M. Veldhorst, A.A. Golubov, A. Brinkman, Phys. Rev. B **87**, 104507 (2013).

Interference phenomena and long-range proximity effect in SFS systems

Alexander Buzdin

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We study different mechanisms of long range proximity effect in superconductor – ferromagnetic structures both in clean and diffusive limits. Our consideration of these limits is based on the quasiclassical Eilenberger equations and Usadel theory, correspondingly. In the dirty limit a noticeable increase in the critical current appears only for a system with noncollinear magnetic moments. Even a small modulation of the exchange field along the quasiclassical trajectories is shown to provide a long range contribution to the supercurrent due to the interference effects. This modulation of the exchange field along trajectories experiencing multiple normal reflections at the system boundaries can appear either due to the domain structure or due to the momentum dependence of the exchange field caused by the spin-orbital effects.
The noncollinear magnetization of the layers provides the conditions necessary to generate the triplet superconducting correlations. It leads to the long-range induced magnetic moment, emerging in the superconducting layers and depending on the Josephson phase. By tuning the Josephson current, one may control the long-range induced magnetic moment. The induced magnetic moment controlled by the Josephson current may be used in spintronics devices instead of the spin-torque effect. The proposed mechanism seems to be attractive for superconducting spintronic devices with low dissipation because it provides a direct coupling between the superconducting current and magnetization.

Parity switching and decoherence by quasiparticles in transmons

G. Catelani

Forschungszentrum Jülich, Peter Grünberg Institut (PGI-2), 52425 Jülich, Germany

Transmons are at present among the most coherent superconducting qubits, reaching quality factors of order 10^6 both in 3D [1] and 2D [2] architectures. These quality factors enable the investigation of decoherence mechanisms with high accuracy. An *intrinsic* decoherence process originates from the coupling between the qubit degree of freedom and the quasiparticles that tunnel across Josephson junctions. After briefly reviewing the general theory of quasiparticle decoherence [3-5], valid both for equilibrium and non-equilibrium quasiparticles, I will focus on the single-junction transmon. In this system, tunneling of a single quasiparticle is associated with a change in parity; I will discuss the theory of the parity switching rate and compare it with recent measurements [6].

In a "split" transmon, a SQUID replaces the single junction, making the qubit tunable by applying a magnetic flux. The quasiparticle decoherence depends on the flux – this could provide an additional way to differentiate the quasiparticle-induced decoherence from other mechanisms.

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Nonlocal correlations in proximity coupled normal metals

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We report evidence of large, nonlocal correlations between two spatially separated normal-metals in superconductor/normal-metal (SN) heterostructures, which manifest themselves as nonlocal voltage generated in response to a driving current. Unlike prior experiments in SN heterostructures, the nonlocal correlations are mediated not by a superconductor, but by a proximity-coupled normal-metal. The nonlocal correlations extend over relatively long length scales in comparison to the superconducting case. At very low temperatures, we find a reduction in the nonlocal voltage for small applied currents that cannot be explained by the quasiclassical theory of superconductivity, which we believe is a signature of new long-range quantum correlations in the system.

Transport in 3D topological insulator nanostructures

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The three dimensional topological insulator (3D TI) is a new class of material having metallic surface states while bulk is insulting. The surface states have gapless Dirac dispersions with novel properties such as momentum-spin locking. Moreover, coupling the surface states to an s-wave superconductor is predicted to produce so-called Majorana fermions. I will discuss my transport experiments on Bi_2Se_3, a 3D TI having large bulk bandgap ~ 0.3eV and a single surface state. Thin (3-15 nm) Bi_2Se_3 films are exfoliated by mechanical exfoliation to fabricate gate tunable transport devices. Electrolyte gating and/or molecular doping methods are used to tune the chemical potential into the bulk bandgap through Dirac point. Electronic transport reveals an ambipolar gapless nature, and the minimum conductivity of the surface state is understood within the self-consistent theory of Dirac materials having charged impurities. Measurement of dc Josephson effects in TI-superconductor junctions reveals the nature of supercurrents in TIs implying the supercurrent is largely carried by surface states due to the topology of the bands. Thermally activated conductance was observed in thinner layer (~ 3 nm) of Bi_2Se_3 reflecting opening a bandgap. I will also briefly show my recent experimental results on Bi_2Se_3 nanowires. Two probe conductance measurement leads to observation of zero bias conductance peaks persistent with gate voltages, possibly related to Kondo effects in a quantum dot. As chemical potential is tuned near Dirac point, four-probe measurement of magneto-conductance shows a signature of 1D gapless mode at half magnetic flux quantum.

Cooper pair splitting using InAs quantum dots

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An elegant idea for the creation of entangled electrons in a solid-state device is to split Cooper pairs, which are in a spin singlet state, by coupling a superconductor to two parallel quantum dots (QDs) in a Y-junction geometry [1]. Such Cooper pair splitting (CPS) was successfully detected in recent transport experiments on devices based on InAs nanowires [2] and carbon nanotubes (CNTs) [3]. After reviewing these earlier experiments we present the operation of CPS at finite bias where the interplay of CPS and elastic cotunneling takes place [4]. Furthermore, it will be discussed how the splitting efficiency of CPS can be improved and how the singlet character of the spatially separated electrons can be detected.

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Spin-triplet superconductor interfaced to ferromagnet and magnetic edge states

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In this talk I will discuss two remarkable effects of spin-triplet superconductors (TSC): i) the spin-orbital coupling emerging at the interface with a ferromagnet (FM) [1], ii) the occurrence of magnetic Andreev states at their edge if the system allows for singlet pairing in a subdominant channel [2]. The orientation of the FM moment relative to the TSC vector order parameter is a crucial variable that controls the physical behavior. In addition to the pair breaking, spin-flip reflection processes at the interface with the FM scatter the triplet Cooper pairs between the spin up and down condensates, setting up a Josephson-like coupling between them. [3] The pair-breaking and spin Josephson coupling both make significant contributions to the free energy of a TSC-FM junction through the proximity effect, interface electronic reconstruction, and the variation of the TSC gap. Although these contributions depend upon the direction of the FM's exchange field, the two effects do not necessarily act constructively. For a single-component p-wave TSC, we find that the variation of the gap controls the orientation of the FM's moment via the change in condensation energy. The stable configuration is either parallel or perpendicular to the TSC vector order parameter, depending on the alignment of the TSC gap with respect to the interface, thus evidencing a unique form of spin-orbital coupling. The competing orbital components of the chiral p_x+ip_y state generate a non-unique behavior and a first-order transition from the perpendicular to the parallel configuration as the FM exchange field is increased. When the interface is imperfect, other processes play the decisive role in setting the easy axis in the FM. When considering the surface states of TSC, novel magnetic effects can occur if triplet and singlet pairing get mixed including a realistic surface barrier of finite width and height. We find that a) a subdominant *in-phase* s-wave superconducting order exists near the edge of the sample; b) the in-phase s-wave component gives a non-unitary superconducting state at the boundary; c) as a result, the bound states are spin-polarized, leading to a finite surface magnetization; d) spin current flows along the interface in this regime; e) surface charge currents exhibit anomalous dependence on the magnetization [2].

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Pseudogap state from quantum criticality

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In the standard picture of a quantum phase transition, a single quantum critical point separates the phases at zero temperature. Here we show that the two-dimensional case is considerably more complex. Instead of the single point separating the antiferromagnet from the normal metal, we have discovered a broad region between these two phases where the magnetic order is destroyed but certain areas of the Fermi surface are closed by a large gap. This gap reflects the formation of a novel quantum state characterised by a superposition of d-wave superconductivity and a quadrupole density wave, which builds a chequerboard pattern with a period incommensurate with that of the original spin density wave. At moderate temperatures both orders co-exist over comparatively large distances but thermal fluctuations destroy the long-range order. Below a critical temperature the fluctuations are less essential and superconductivity becomes stable. This phenomenon may help to explain the origin of the mysterious pseudogap state and of the high-temperature transition into the superconducting state in the cuprates. In particular, we show that the chequerboard order reveals itself upon performing spectroscopies on the oxygen and copper atoms.

Coherent transport in superconductor-ferromagnet hybrid systems

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We discuss the implications of singlet-triplet mixing due to quantum mechanical scattering phases at superconductor/ferromagnet (S/F) interfaces for quantum-coherent transport phenomena in S/F hybrid structures. Our results include the existence of ϕ-junctions, long-range triplet supercurrents, giant thermoelectric effects, as well as a new theory of point contact spectra.

The main quantum mechanical mechanism is a spin dependence of the phase delay of scattering waves in combination with a spin-filtering effect of the interface. Spin mixing and spin filtering are inherent to all interfaces that involve strongly spin polarized materials under the condiction of not too strong magnetic disorder. For equal-spin triplet pairing the filtering is achieved via a misalignment of the effective interface magnetic moment with respect to the bulk magnetization. The relative angle between the two interface magnetic moments in a Josephson device results for strongly spin-polarised ferromagnets in an effective phase difference of the proximity induced equal-spin pairs in the two spin channels. The competition of these two channels lead to the appearance of ϕ-junctions as well as an enhancement of crossed pair transmission with respect to single pair transmission.

The presence of spin-mixing in combination with spin-filtering also leads to giant thermoelectric effects in superconductor/ferromagnet devices. Here, the spin-mixing results into equal and opposite shifts of the low-energy spectrum of the two spin channels without the necessity to apply an external magnetic field. When this shift is comparable to the minigap energy scale for an equivalent superconductor/normal-metal structure, a large particle-hole asymmetry of the density of states appears for both spin channels. Spin filtering assures that the two spin channels do not lead to a cancellation, giving rise to a giant enhancement of thermoelectric effects.

A semiempirical model for two-level system noise in high quality superconducting microresonators

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Thin-film high quality superconducting resonators are important for a number of diverse applications that range from quantum computation to submillimeter and far-infrared astronomy. Their performance in these applications is limited by losses and low frequency noise that can be described as a jitter of the resonance frequency. The push for higher quality and more stable resonators resulted in a number of recent papers that studied these properties. Because these effects are associated with TLS these studies shed the light on the properties of TLS that were impossible to study before.

In this talk first we review recent experiments performed on high quality superconducting resonators where low frequency noise power spectra has been studied in varying temperature and microwave drive.

Then we formulate the empirical model that gives the results that agree well with the data. Main idea of the model is the assumption that the jitter in the resonator frequency is due to a population of slow TLS that couple to the resonator via intermediary fast resonant TLS. Stronger than usually assumed interaction between TLS together with their non-constant density of states leads to the observed temperature and power dependence of the noise spectra measured in high quality resonators as well as observed temperature dependence of TLS dephasing rate measured in phase qubits.

Protected Josephson rhombi chains

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Quantum computing requires the development of the quantum bits with a long coherence time and the ability to manipulate them in a fault tolerant manner. Both goals can be achieved by the realization of a protected logical qubit formed by a collective state of an array of faulty qubits (see, e.g. [1]). The building block (i.e. the faulty qubit) of the array is the Josephson element with an effective Josephson energy $E(\phi) = -E_2\cos(2\phi)$, which is π-periodic in the phase difference ϕ across the element (the so-called Josephson rhombi). Recently we made an essential step towards building a protected Josephson qubit by fabricating the simplest protected circuit and demonstrating that the low-energy quantum states of the circuit are protected from energy relaxation. The circuit contains two rhombi; novel design of these elements reduces their sensitivity to the offset charge asymmetry. We observed a ten-fold increase of the lifetime of the $|0\rangle$ state of this circuit due to the symmetry protection. The measured phase and charge dependences of the energies of the $|0\rangle - |1\rangle$ transition are in good agreement with our numerical simulations. This demonstrates the capability of realization of protected structures with the existing fabrication methods and the potential of Josephson rhombi as the elements of protected qubits. The experiments provide a solid foundation for the next stage – the implementation of a qubit based on larger arrays of $\cos(2\phi)$ elements where, according to the theoretical predictions, much improved coherence is expected.

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Toward coherent caloritronics: Phase-coherent thermal transport in Josephson junctions nanocircuits

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The Josephson effect [1] represents perhaps the prototype of macroscopic phase coherence and is at the basis of the most widespread interferometer, i.e., the superconducting quantum interference device (SQUID) [2]. Yet, in analogy to electric interference, Maki and Griffin [3] predicted in 1965 that thermal current flowing through a temperature-biased Josephson tunnel junction is a stationary periodic function of the quantum phase difference between the superconductors. The interplay between quasiparticles and Cooper pairs condensate is at the origin of such phase-dependent heat current, and is unique to Josephson junctions. In this scenario, a temperature-biased SQUID would allow heat currents to interfere [4,5] thus implementing the thermal version of the electric Josephson interferometer. The dissipative character of heat flux makes this coherent phenomenon not less extraordinary than its electric (non-dissipative) counterpart. Surprisingly, this striking effect has never been demonstrated so far.

In this presentation we shall report the first experimental realization of a heat interferometer [6,7]. We investigate heat exchange between two normal metal electrodes kept at different temperatures and tunnel-coupled to each other through a thermal "*modulator*" [5] in the form of a DC-SQUID. Heat transport in the system is found to be phase dependent, in agreement with the original prediction. With our design the Josephson heat interferometer yields magnetic-flux-dependent temperature oscillations of amplitude up to ~ 21 mK, and provides a flux-to-temperature transfer coefficient exceeding ~ 60 mK/Φ_0 at 235 mK (Φ_0 is the flux quantum). Besides offering remarkable insight into thermal transport in Josephson junctions, our results represent a significant step toward phase-coherent mastering of heat in solid-state nanocircuits, and pave the way to the design of novel-concept coherent caloritronic devices, for instance, heat transistors, thermal splitters and diodes [8] which exploit phase-dependent heat transfer peculiar to the Josephson effect.

In this latter context, we shall also present the concept for a further development of a Josephson heat interferometer based on a double superconducting loop [9] which allows, in principle, enhanced control over heat transport. We shall finally conclude presenting experimental results on a quite different prototypical thermal interferometer [10] which could add complementary flexibility in mastering heat flux at the nanoscale.

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Topological superconducting phase in a helical Shiba chain

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A magnetic impurity in a conventional superconductor creates a discrete energy level, known as the Shiba state, inside the gap of the quasiparticles spectrum. Recently, it has been suggested that topological superconductivity and Majorana end states can be realized in a chain of magnetic impurities imbedded in a superconductor and forming a spin helix. We investigate this possibility theoretically, accounting for the long-range nature of hopping and pairing of electrons populating the Shiba states. Using a combination of analytical and numerical methods, we determine the parameters domain allowing for the topological phase and investigate the structure of the Majorana states associated with it.

Designing phase-sensitive tests for Fe-based superconductors

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Five years after the discovery of the new family of high-T_c Fe-based superconductors (FeBS) [1] their pairing symmetry is still under dispute [2]. While most researchers favor the so-called s_{+-} pairing, whereupon the sign of the order parameters changes between the hole and the electron bands [3], some advocate [4] the more conventional anisotropic *s*. Despite recent progress in junction fabrication, no phase-sensitive experiments have been performed so far in FeBS-based Josephson junctions. One needs to design the experimental geometry in a special way so that the current in one contact would be dominated by the carriers having one sign of the order parameter, and in the other by carriers with the opposite sign. We have recently suggested experimental designs suitable to test pairing symmetry in multiband Fe-based superconductors [5]. These designs involve Josephson two-junction interferometers based on combinations of tunnel junctions and point contacts where currents are dominated by different type of carriers, electrons or holes. The suggested designs are accessible by available fabrication techniques and allow to probe pairing symmetry in FeBS.

To support these ideas quantitatively, we have calculated the Josephson current between an iron-based superconductor with s_{+-}-pairing and a conventional *s*-wave superconductor connected by single channel conducting nanowire [6]. We have considered two types of contacts between a nanowire and an iron-based superconductor: a point contact and a planar tunneling junction on the (001) surface. The calculations show that the band, which provides a dominant contribution to the Josephson current, depends on the junction type. As a result, in the point contact case, the junction behaves as a pi-junction, while it becomes 0-junction in a planar tunneling junction case.

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Identifying and manipulating Majorana fermions in Josephson devices with topological barriers

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We are studying the transport properties of hybrid S-TI-S nanoscale devices fabricated by depositing superconductor electrodes onto topological insulators. In top-gated Nb-Bi_2Se_3-Nb junctions, we have measured the Josephson supercurrent and conductance as a function of geometry, temperature, and gate voltage in order to determine the nature of the charge transport. The supercurrent exhibits a sharp drop as a function of gate doping that may be explained by the relocation of the topological surface state from above to below trivial conducting surface states formed by band-banding near the surface. We find that the magnetic field modulation of the supercurrent in Josephson junctions and dc SQUIDs exhibits anomalous features that we attribute to a $\sin(\phi/2)$ component in the current-phase relation that we attribute to the presence of Majorana bound states in the junction. We present a model for the current-phase relation that describes many of the observed features and predicts the nucleation and motion of the Majorana states with applied field.

We have also measured transport in TI-S-TI structures that allows us to search for crossed Andreev reflection and electron co-tunneling processes allowed by Cooper pair coherence. We find an anomalous asymmetry in the nonlocal transport that we attribute to a p-wave superconducting order parameter component induced in the topological insulator by the superconducting contact.

High-temperature surface superconductivity in rhombohedral graphite

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In this talk, I will discuss the possibility of the formation of a robust surface superconducting state in graphite with rhombohedral (ABC) stacking. In such a system superconductivity results from the formation of a topologically protected surface flat band [1,2,3], whose anomalous dispersion boosts superconductivity. In rhombohedral graphite this flat band is weakly broken by a higher-order hopping between the graphene layers, resulting into a quadratic dispersion of the surface state with a large effective mass [4,5]. We have shown that for weak pairing interaction, the flat-band character of the surface superconductivity transforms into a BCS-like relation with high critical temperature characterized by a higher coupling constant due to a much larger density of states than in the bulk. We have also shown that besides surfaces, such a high-temperature superconducting state may form at graphite twinning boundaries [4]. Our results offer an explanation for the recent findings of graphite superconductivity with an unusually high transition temperature.

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Superharmonic Josephson relation through a long diffusive ferromagnetic bilayer

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The superconducting proximity effect in a homogeneous ferromagnet is short-range due to the dephasing of electrons with opposite spins that is induced by the ferromagnetic exchange field. In contrast, for a non-colinear magnetic configuration, a long-range proximity effect can be generated in the triplet channels with parallel electron spins, as no such dephasing occurs in that case. Here we predict that this effect can be revealed by measuring the Josephson current through a long ferromagnetic bilayer. For non-colinear magnetizations, we find that the current-phase relation is dominated by its second harmonic, which corresponds to the long-range coherent propagation of two triplet pairs of electrons. The $\pi/2$-periodic Josephson relation can be viewed as the minimal coupling that can exists between the conventional even superconductor in one lead and the effectively odd-frequency superconductor generated by the long-range triplet proximity effect at the extremity of the ferromagnetic bilayer attached to the other lead

Nonlocal quantum entanglement between two quantum dots via Majorana fermions in nanowire

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Nonlocal entanglement between two quantum dots (QDs) close to the two ends of a nanowire topological superconductor can be generated through the two Majorana fermions. The two end Majorana fermions form a nonlocal electronic level, which couples in a tunneling way the electrons on the QDs, and brings the whole system into an entangled state even at sufficiently low temperatures and zero bias voltage. Introducing a charging energy by attaching a capacitor to the nanowire, entanglement of the whole system can manifest itself through the nonlocal entanglement between the two QDs. Explicitly, the conditional probabilities of electron occupation on one QD with and without electron occupation on the other QD deviate from each other, with the difference proportional to the concurrence of quantum entanglement between the two QDs. Therefore, detecting the difference in conditional probabilities measures on one hand quantitatively the nonlocal quantum entanglement in the hybrid system, and provides an evidence of the nonlocal nature of the fermion level constructed by the two end Majorana fermions on the other hand. This measurement, which is achievable experimentally by established techniques, provides a non-invasive way to approach Majorana fermions, different from all the other proposals such as current injection.

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Phase slips in strongly disordered superconductors

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I argue that the materials optimal for the observation of coherent phase slips are strongly disordered superconductors in the vicinity of superconductor-insulator transition that combine very small superfluid density with large gap. I construct the model that describes these superconductors and compute the phase slip amplitude. The results are compared with the recent data on InO, NbN and TiN films.

Anomalous transport properties of superconducting nano-wires

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Recent experiments of A. Goldman group on Zn and Al superconducting nano-wires revealed a number of unexpected features. Among them: enhancement of the critical current and the critical temperature by an applied magnetic field; time-dependent switching between superconducting and resistive state on a time scale of the seconds. We will discuss a simple phenomenological model, which is capable to account for these observations.

Mesoscopic variations of local density of states in disordered superconductors

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We explored correlations of inhomogeneous local density of states (LDoS) for impure superconductors with different symmetries of the order parameter (s-wave and d-wave) and different types of scatterers (elastic and magnetic impurities) [1]. It turns out that the LDoS correlation function of superconductor always slowly decreases with distance up to the phase-breaking length l_f and its long-range spatial behavior is determined only by the dimensionality, as in normal metals. On the other hand, the energy dependence of this correlation function is sensitive to symmetry of the order parameter and nature of scatterers. Only in the simplest case of s-wave superconductor with elastic scatterers the inhomogeneous LDoS is directly connected to the corresponding characteristics of normal metal. We found that in presence of pair-breaking scattering relative LDoS variations increase with decreasing energy.

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Decay of fermionic quasiparticles in one-dimensional quantum liquids

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The low energy properties of one-dimensional quantum liquids are commonly described in terms of the Tomonaga-Luttinger liquid theory, in which the elementary excitations are free bosons. To this approximation the theory can be alternatively recast in terms of free fermions. In both approaches, small perturbations give rise to finite life times of excitations. We evaluate the decay rate of fermionic excitations and show that it scales as eighth power of energy, in contrast to the much faster decay of bosonic excitations. Our results can be tested experimentally by measuring the broadening of power-law features in the density structure factor or spectral functions.

Vortex transformation in 3-D nano-structures

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We have shown that the formation of a magnetic vortex state can give rise to enhanced pinning of superconducting vortices [1]. Recently, we found that the topographical 3-D variations could drastically change the magnetic vortex dynamics and lead to unusual change in the vortex polarity.

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Critical superconductors

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Bogomolnyi critical point, although originating from the high-energy physics, is fundamental to superconductivity. At the critical temperature it marks a boundary between ideally diamagnetic bulk type-I materials and type-II superconductors that can host vortices. In this talk, we show that in materials with multiple overlapping bands, such as most of the recently discovered borides and iron-based superconductors, the Bogomolnyi point at lowered temperatures projects itself onto an extremely wide range of parameters. In this critical range, the infinitely degenerate superconducting state of the Bogomolnyi point opens into a series of novel equilibria and the customary understanding of superconducting phenomena does not suffice. Therefore, as a radical departure from traditional views, we introduce a paradigm of *critical superconductivity*. We discuss its distinct magnetic properties, advocate its subdivision in terms of possible intermediate states, and demonstrate its relevance to several recent multiband materials. Finally, we refer to old experiments on elementary superconductors, and in direct comparison with our analytical expressions demonstrate that critical type of superconductivity perfectly complements existing types I and II, and unifies all earlier incomplete attempts to classify superconducting behavior outside the type-I/II dichotomy.

Dissipation and Maxwell's demon in single-electron circuits

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Energy fluctuations play an important role in small systems. The distribution of entropy production and the work performed under non-equilibrium conditions are governed by fluctuation relations. We apply these concepts to a single-electron box, and present experiments on various fluctuation relations in them [1,2]. Single-electron circuits provide a basic set-up for realizing a Maxwell's Demon, where information can be converted into energy; here the information is collected by a detector with single-electron sensitivity. At the end I discuss the subtle issues of work and heat in open quantum systems. I use superconducting qubits as examples of driven systems in this context.

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Coherent cancellation of superconducting quasiparticle dissipation

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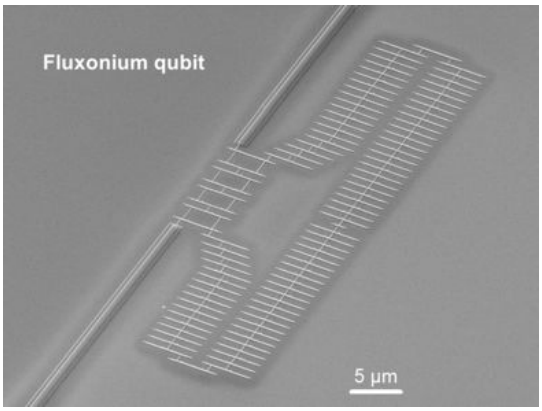
The Josephson junction is a "work horse" of superconducting quantum information devices. One junction can provide enough anharmonicity to isolate the first two levels of a microwave electrical oscillator, implementing the logical 0 and 1 states of a quantum bit. In order to preserve a given quantum state of the logical qubit, the physical system has to be as immune as possible to dissipation.



We characterize different dissipation mechanisms using a fluxonium qubit (represented in the electron beam image to the right). The keystone of the fluxonium qubit [1] is the superinductance [2], which consists of an array of 100 "large" Josephson junctions. The superinductance shunts the smaller nonlinear junction, providing protection from charge noise. As the magnetic flux threading the loop formed by the superinductor and the tunnel junction is swept from zero to half a flux quantum, the 0-1 transition frequency varies between one sweet spot around 10GHz and another at a few hundreds of MHz. When the loop is biased around half a flux quantum, the quasiparticle dissipation channels coherently cancel [3] and we observe a remarkable increase of the energy relaxation time. Precisely at the half flux quantum sweet spot, we measure energy relaxation times exceeding one millisecond.

Although we envisage significant design evolutions in the future, the successful operation of this fluxonium qubit proves that long coherence times, large anharmonicity and fast coupling rates to a cavity bus are all compatible in one circuit.

This research was supported by IARPA, ARO and NSF

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Spin-triplet supercurrents

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Upon injection into a ferromagnet from a superconductor, spin-singlet supercurrents rapidly decay within a few nanometers unless the superconductor / ferromagnet interface (S/F) allows spin-aligned triplet Cooper pairs to form [1]. It is now established that such triplet pairs form when the magnetization at the S/F interface is non-collinear with respect to the magnetization in the F layer [1]. Because such pairs carry spin in addition to charge it is possible that triplet supercurrents could be used in superconducting-bsed spintronic circuits in order to control the electronic state of a device [2].

Our group has discovered a variety of ways to generate spin-aligned triplet pairs and in this talk I will provide an overview of our recent experimental results in this area; in particular, I will discuss S/F junctions containing synthetic antiferromagnets [3,4], rare earth magnetic spirals such as Ho and Gd [5-8], and ferromagnetic multilayers with controlled anisotropy.

Funding for this work was provided by the Royal Society through a University Research Fellowship.

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Quasiparticle and spin-polarizad injection in coherent hybrid structures

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We have investigated the charge-imbalance relaxation in planar Josephson S-(N/F)-S structures. For a planar sample geometry we have observed nonlocal Josephson effect excited by nonlocal quasiparticle injection. The experimental results were discussed using the Kadin-Smith-Skocpol approach [1]. We have compared the charge-imbalance relaxation length for quasiparticle injection from normal and ferromagnetic injectors. Spin-diffusion and spin-injection in a normal-metal barrier of a Josephson S-(N/F)-S junction was studied too. Recently we have observed a double-peak peculiarity in differential resistance of the Al-(Cu/Fe)-Al structure at a bias voltages corresponding to the superconducting gap and minigap [2]. We claim that this effect (the splitting of the minigap) is due to an electron spin polarization in the copper layer which is induced by the single-domain iron sublayer. Our new results are related to spin-injection effects. We have observed narrow peaks on voltage vs. spin-polarized current characteristics in perpendicular magnetic field which may be explained by spin-resonance effect due to Josephson frequency and spin-pumping.

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Vortex dynamics simulations in large systems for energy applications

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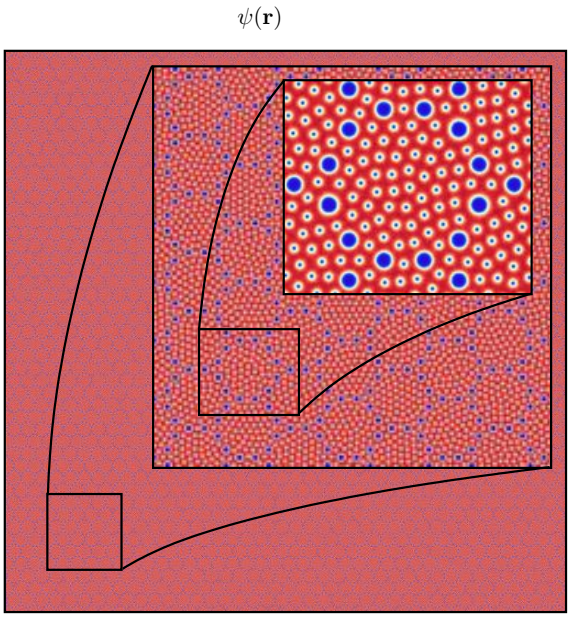
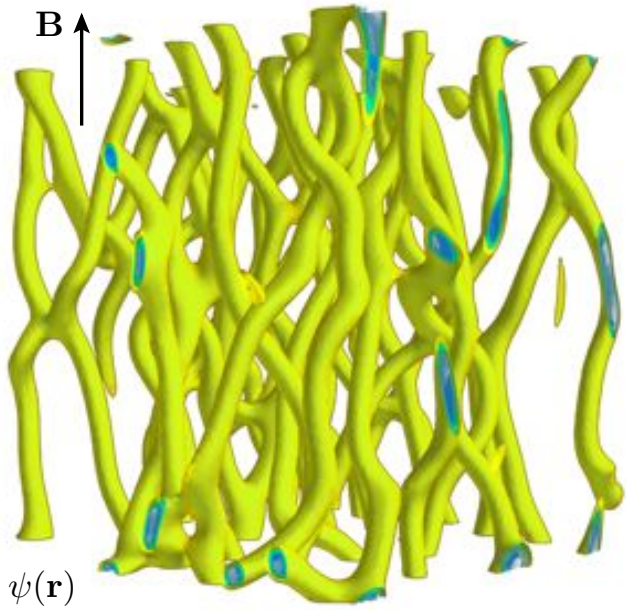
Most energy applications of superconductivity, such as electric power transmission over superconducting cables or powerful magnets, require low energy dissipation in high-temperature superconductors. Restricting the mobility of the vortices carrying magnetic field in the superconducting material by pinning them with admixed inclusions or confining their motion geometrically can minimize dissipation.





We present modern simulation results of the time-dependent Ginzburg-Landau equation for large-scale mesoscopic superconductors, like narrow superconducting strips and nano-patterned superconductors. In particular, we discuss the case of nano-scale extended pinning inclusions, whose geometry has a non-trivial influence on the current-voltage characteristics. The required large-scale simulations were made possible with recent GPU computing techniques. The figure shows a surface plot of the amplitude of the superconducting order parameter in a superconducting film, when two rows of vortices enter the film from two of its edges.

The search for topologically degenerate Majorana modes in semiconductor/superconductor interfaces

Jay Deep Sau

Harvard University, Cambridge, Massachusetts

Majorana fermions are fermion-like excitations that were originally proposed in particle physics by Ettore Majorana and are characterized as being their own anti-particle. In condensed matter systems Majorana fermions occur as fractionalized excitations with topologically protected degeneracy associated with such excitations. In this talk, I will discuss a recent set of proposals for realizing Majorana modes in a large class of spin-orbit coupled, time-reversal symmetry broken superconducting systems. The simplicity of this class of systems has resulted in several experimental attempts, which have successfully observed preliminary evidence for the Majorana modes in the form of zero-bias conductance peaks and doubled Shapiro steps. Following this I will then discuss future possibilities in terms of modifications to the experiments to help confirm the presence of Majorana modes.

Cavity QED with electrons on helium

David Schuster

University of Chicago, Illinois

Electrons nearing the surface of liquid helium can become weakly bound to the interface, floating several nanometers above the surface. Levitating essentially in vacuum, electrons on helium have the highest known electron mobility and extremely long predicted spin coherence. Further, it has recently become experimentally possible to manipulate thousands of floating electrons in parallel using CCD's much like those used in digital cameras. Yet thus far the coherence of individual electrons has eluded measurement. I will present a new cavity quantum electrodynamics inspired technique for both detecting the quantum state of the electron's spin and motion as well performing gates between electrons. Finally, I will describe present preliminary results on electron trapping and detection.

Detection of the triplet pairing and spin-valve-effect in superconductor/ferromagnet heterostructures

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Theory of superconductor-ferromagnet (S-F) heterostructures predicts generation of a long-range, odd-in-frequency triplet pairing in samples with two ferromagnetic layers at non-collinear alignment (NCA) of the magnetizations of the F-layers. This triplet pairing we have detected experimentally in a $Nb/Cu_{41}Ni_{59}/NL/Co/CoO_x$ spin-valve type proximity effect coupled heterostructure (whith a very thin Nb film between the F-layers served as a spacer of normal conducting metal, NL-layer). The resistance of the sample as a function of an external magnetic field shows that the system is superconducting at a collinear alignment of the $Cu_{41}Ni_{59}$ and Co layers magnetic moments, but switches to the normal conducting state at a NCA configuration. The last is the evidence that the superconducting transition temperature T_c for NCA is lower than the fixed measuring temperature. The existence of a minimum T_c, at the NCA regime below that one for parallel or antiparallel alignments of the F-layer magnetic moments, is consistent with the theoretical prediction of the appearance of the long-range triplet pairing.

Thermalization of long-lifetime polaritons in microcavities

David Snoke

University of Pittsburgh

Polaritons are quasiparticles, which arise as mixed states of photons and electronic excitations; in a microcavity these can be tuned to have very light mass (four orders of magnitude less than an electron) and relatively strong interactions. One can call them photons dressed with mass and hard-sphere interactions; as such, they obey the equations of bosonic atoms and can undergo Bose-Einstein condensation, but at much higher temperature. Until recently, polaritons in semiconductor microcavities had short lifetime so that they did not reach complete equilibrium. Our new samples, grown by the group of Loren Pfeiffer at Princeton, have world-record lifetimes. We have seen ballistic, coherent transport of the polaritons over hundreds of microns up to a millimeter, and we can also confine the polarition gas in a trap. We have seen that the trapped polariton gas can truly thermalize to the background bath temperature; from this we deduce the phase diagram for Bose condensation of the polariton gas, and show that the critical temperature increases linearly with increasing temperature, consistent with the prediction for a weakly interacting Bose gas. I will also discuss very recent results with ring trap for the polaritons, i.e., a Mexican-hat potential that allows circulation.

Condensation, coherence and superfluidity in non-equilibrium light-matter systems

Marzena Szymanska

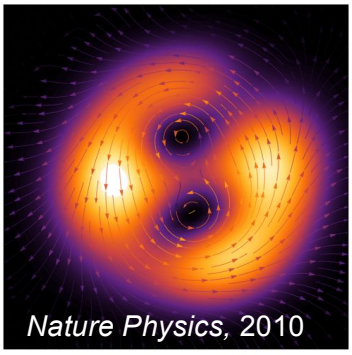
Department of Physics & Astronomy, University College London, Gower Street, London WC1E 6BT, UK

Since the first realisation of a microcavity polariton condensate in 2006, strongly coupled light-matter systems have been extensively used to explore a variety of out of equilibrium quantum collective phenomena. I will discuss some of the most recent developments in this rapidly growing field.

Firstly, I discuss how polaritons allow to unify not only BCS and BEC type of condensates, but also the equilibrium condensates and lasers, which are limiting cases of one theory captured by a single mean-field equation, able to describe laser-BCS-BEC crossover as a function of external driving and non-equilibrium [1].

Further, I show that the Berezinskii-Kosterlitz-Thouless (BKT) phase order i.e. the power law decay of spatial correlations in two-dimensional condensates is not an artifact of equilibrium but survives more generally in a non-equilibrium context. Recent observation of a larger value of the coefficient of that power-law that it is possible in equilibrium [2] indicates that the BKT-like ordered phase is in fact more robust against external noise in driven systems than thermal noise in equilibrium.

Despite the fact that the polariton superfluid does violate the Landau criterion, it supports persistent currents, quantised vortices [3] and frictionless flow, which are the paradigmatical properties of equilibrium superfluids. I identify those topological defects, which confirm the "super" nature of the fluid, and those that arise purely due to the dissipative and driven environment of the polariton system.



Vortices in a polariton superfluid

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In-situ tunable vortex pinning by a ferromagnetic antidot array

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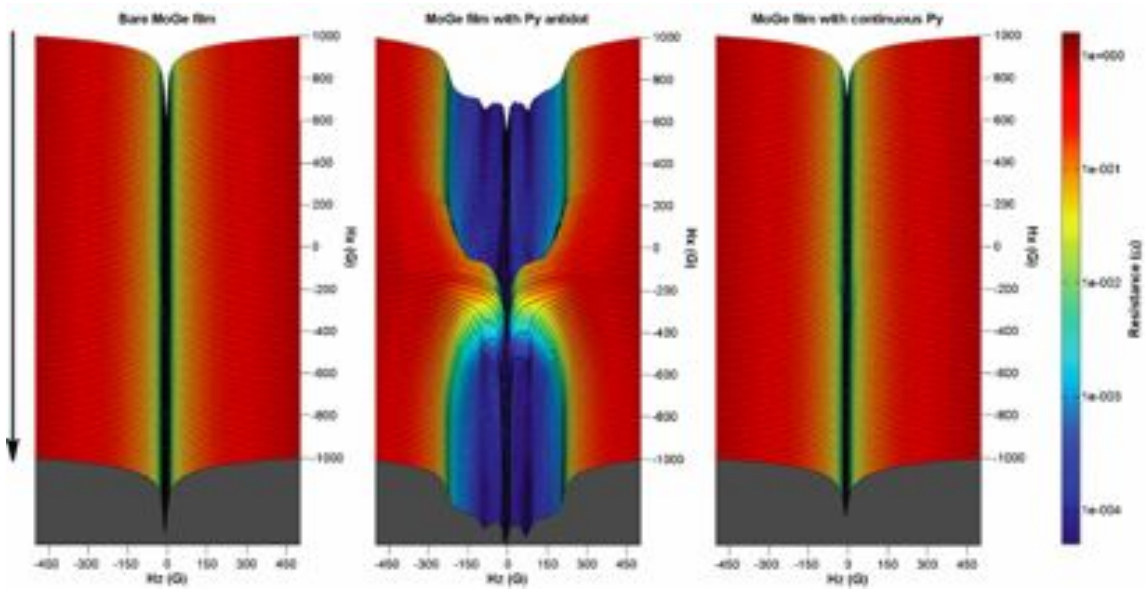
[4]*Departments of Physics, Electrical and Mechanical Engineering, University of Illinois at Chicago, USA*

We report experiments investigating the pinning effects of a ferromagnetic antidot array on vortices in a superconducting film. A square antidot array of 30 nm thick permalloy (Py) was introduced onto a MoGe film with thickness of 100 nm. No significant pinning enhancement by the Py antidot array was observed for perpendicular magnetic fields (Hz). By adding an independently controllable in-plane field (Hx), however, we found that Py antidot array can provide excellent vortex pinning, which can be attributed to the periodic pinning potential induced by the stray field of the Py antidot array in the presence of an in-plane field.



We systematically measured the perpendicular field (Hz) dependence of the critical current and magentoresistance at different fixed in-plane field (Hx) values. We also conducted magnetic force microscopy (MFM) imaging and micromagnetic simulations to map the stray field distribution. MoGe films without a Py antidot array and with a continuous Py film were also studied for comparison.

This work was supported by DOE BES under Contract No. DE-AC02-06CH11357 which also funds Argonne's Center for Nanoscale Materials (CNM) where the nanopatterning was performed.

Quantum Decoherence of Cooper pairs

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We argue that electron-electron interactions yield dephasing of Cooper pairs penetrating from a superconductor (S) into a diffusive normal metal (N). At low temperatures this phenomenon imposes fundamental limitations on the proximity effect in NS hybrids restricting the penetration length of superconducting correlations into the N-metal to a temperature independent value and thereby defining a new length scale – *decoherence length for Cooper pairs.*

We evaluate the subgap conductance of NS hybrids in the presence of electron-electron interactions [1] and demonstrate that this new fundamental decoherence length can be directly extracted from conductance measurements in such structures. Our results agree qualitatively with earlier experimental observations [2] showing that the low temperature magnetoconductance of NS structures is determined by phase coherent electron paths with a typical size restricted by the temperature independent dephasing length rather than by the thermal length diverging in the low temperature limit. We also analyze the effect of electron-electron interactions on the critical Josephson current in diffusive hybrid SNS structures [3] and demonstrate that this current gets exponentially suppressed even at zero temperature provided the thickness of the N-layer exceeds the dephasing length for Cooper pairs. This our prediction appears to be consistent with recent experimental observations [4].

It is remarkable that the Coper pair dephasing length established both for NS- and SNS-systems up to a numerical prefactor coincides with zero temperature decoherence length obtained within totally different theoretical framework [5] for a different physical quantity – the so-called weak localization correction to the normal metal conductance. This agreement emphasizes fundamental nature of low temperature dephasing by electron-electron interactions which universally occurs in different types of disordered conductors, including normal-superconducting hybrids. At the same time, dephasing of Cooper pairs by electron-electron interactions turns out to be different from that for single electrons in a normal metal in several important aspects to be explained in details in this talk.

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Abstracts:
Poster Session

Nonlinear current-voltage characteristics due to quantum tunneling of phase slips in superconducting Nb nanowire networks

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We report on the transport properties of an array of $N \sim 30$ interconnected Nb nanowires, grown by sputtering on robust porous Si substrates. The analyzed system exhibits a broad resistive transition in zero magnetic field, H, and highly nonlinear $V(I)$ characteristics as a function of H which can be both consistently described by quantum tunneling of phase slips.

Control of spin-polarised supercurrents in ferromagnetic Josephson junctions

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Department of Materials Science and Metallurgy, University of Cambridge, United Kingdom

Ferromagnetic Josephson junctions containing inhomogeneous magnetism at the superconductor/ferromagnet interface converts a short-ranged spin singlet supercurrent into a long-ranged triplet supercurrent consisting of equal spin Cooper pairs [1]. Although considerable amount of experimental efforts in the past few years have been directed towards the detection and optimisation of triplet supercurrents in different systems [2-5], it has not been possible to precisely control its generation and modulation in a single device. Here, I will address this issue by reviewing our recent results on Josephson junctions composed of a dual spin valve type ferromagnetic barrier where the relative magnetic orientations of the layers can be controlled by applying small magnetic fields. This produces dramatic field-induced modifications of the junction critical current which in the light of conventional triplet proximity theory [6] possibly indicates at a fundamental modulation of the triplet current by the magnetic state of the device. The realisation of controlled triplet current generation opens up many interesting possibilities including the study of the physics of singlet-triplet crossover and providing a direct measure of the spin supercurrent.

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The superconductor-to-insulator transition at the $LaAlO_3/SrTiO_3$ interface

M. M. Mehta, D.A. Dikin, C.W. Bark,S. Ryu, C.M. Folkman,
C.B. Eom, and **V. Chandrasekhar**[1]

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The superconductor-to-insulator transition (SIT) is studied in the two dimensional electron gas that forms at the $LaAlO_3/SrTiO_3$ (LAO/STO) interface, both by electrostatic tuning and by magnetic field. The coexistence of ferromagnetism with superconductivity at this interface results in a novel manifestation of the phenomenon of charge-vortex duality. Charge-vortex duality has been proposed as a model to understand the SIT in some two dimensional systems. In this model, on the superconducting side, one has delocalized Cooper pairs but localized vortices; while on the insulating side, one has localized Cooper pairs but mobile vortices. As a consequence, in the electrostatically tuned SIT, the effect of the magnetization dynamics in the ferromagnet on the conduction layer result in an increase in resistance on the superconducting side of the transition, but an increase in conductance on the insulating side, in the magnetoresistance of the system. If the magnetization dynamics of the ferromagnet are eliminated (by pinning the magnetization of the ferromagnet with an external parallel field), the perpendicular field magnetoresistance shows a manifestation of the magnetic field tuned SIT in the system. The critical exponents obtained in the scaling of the magnetoresistance indicate that the magnetic field tuned SIT is governed by quantum percolation effects.

Andreev spectroscopy of hybrid superconductor/topological insulator devices at high magnetic fields

Aaron Finck

University of Illinois at Urbana-Champaign

It has been predicted that exotic bound states analogous to Majorana fermions can form in topological insulators (Tis) with induced superconductivity and in the presence of time-reversal breaking fields, such as vortices and Zeeman fields. These Majorana bound states possess non-abelian statistics and can be used to implement a topological quantum computer. Here we present Andreev spectroscopy measurements of TI devices attached to both superconducting and normal metal leads. We find a pronounced re-entrant resistance effect, signifying transparent contacts between the TI and the leads. In the presence of an out-of-plane magnetic field, we find abrupt changes in the small bias transport just beyond specific magnetic field values. Additional features in the *I*-*V*s appear at low bias at these fields, whose qualitative shape can be tuned by a back gate. The abrupt changes in the low bias transport are accompanied by a pair of very narrow resistance peaks occurring at bias voltages at are very sensitive to small changes in the magnetic field. We discuss how our results are spectroscopic evidence of magnetically-induced transitions in the TI with proximity-induced superconductivity. Such transitions could be either due to the appearance of vortices within the TI or a topological phase transition resulting from the Zeeman effect.

Superconducting VI characteristics and tunneling simulations in films of lead clusters near the percolation threshold

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The ability to pattern structures with dimensions on which fundamental quantum mechanical phenomena become important is a key aspect of nano-scale studies of structural, chemical, and electronic properties of novel materials. Cluster-deposited devices allow independent control of particle size and spacing while the small size and high degree of control allows us to study properties such as quantized conduction and quantum confinement[1], and macroscopic quantum effects such as superconductivity. We present results from the electrical characterization of percolating films of 10-30 nm Pb nanoclusters deposited using an inert gas aggregation source on silicon substrates at temperatures from 10-300K.

The connections between groups of clusters range from nanometers to several clusters in width which leads to complex 2D films on both sides of the percolation threshold and a wealth of interesting physics. Strongly hysteric VI curves have been observed in thick cluster deposited films, showing increasing hysteresis with coverage. Critical currents vary significantly from sample to sample but collapse to a universal curve comparable to a previous report though inconsistent with basic Josephson coupling critical currents[2] The observed VI characteristics is also shown to be similar to that observed in high temperature superconductors which are dominated by grain boundary percolation, with a similar power law dependence[3], in contrast to Kosterlitz-Thouless transitions reported in thin films and Josephson junction arrays[4].

We have also prepared cluster films well below the percolation threshold, where the coupling between adjacent groups of particles is in the tunneling regime, and have observed clear signs of superconductor to insulator transitions[5]. Such films have also been simulated to look for possible tunneling percolation transitions. Above the superconducting transition temperature a typical Efros-Shklovskii $T^{-1/2}$ hopping dependence is also observed, comparable to granular films.

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Duality of weak and strong scatterer in a luttinger liquid coupled to massless Bosons

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We study electronic transport in a Luttinger liquid with an embedded impurity, which is either a weak scatterer (WS) or a weak link (WL), when interacting electrons are coupled to one-dimensional massless bosons (e.g., acoustic phonons). We find that the duality relation, $\Delta_{WS}\,\Delta_{WL}=1$, between scaling dimensions of the electron backscattering in the WS and WL limits, established for the standard Luttinger liquid, holds in the presence of the additional coupling for an arbitrary fixed strength of boson scattering from the impurity. This means that at low temperatures such a system remains either an ideal insulator or an ideal metal, regardless of the scattering strength. On the other hand, when fermion and boson scattering from the impurity are correlated, the system has a rich phase diagram that includes a metal-insulator transition at some intermediate values of the scattering.

Gate and phase tunable supercurrents in topological devices

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A mesoscopic ring containing topologically non-trivial Josephson junctions is a promising platform to realize zero-energy Majorana bound states (MBS)[1]. One can obtain phase-sensitive signatures of those states by studying the magnetic response of Josephson current induced in topological weak links[2]. We employ various superconducting quantum interference devices (SQUIDs) consisting of Nb/Bi_2Se_3/Nb double or tri-junctions incorporated into a Nb loop. The Josephson junctions in the devices are electrostatically top-gated to be able to deplete the 2DEGs present beneath the surface states in the conduction band of Bi_2Se_3. Upon applying negative bias to the gates, the system goes through a topological phase transition[3], leading to a dramatic reduction and finally saturation in the critical current. Further, the temperature dependence of the critical current demonstrates a clear trend indicating the junction dynamics changes from ballistic to diffusive near this topological phase transition. The magnetic diffraction pattern resulting from the flux inserted into the individual junctions as well as the SQUID oscillations generated by the flux threading the Nb loop reveal evidence for an anomalous component in the current-phase relationship. We believe that such a component would result from a pair of MBS and expand our understating of data through a simple qualitative model for the current-phase relationship.

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Superconducting fluctuations in films of lead clusters near the percolation threshold

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The phase slips are responsible for the electrical resistance of low dimensional superconductors. In low dimensional superconductors it is well known that at higher temperatures phase slips occur via the process of thermal barrier crossing by the order parameter field, thermally activated phase slips (TAPS)[1,2]. At low temperature, the phase slips should proceed via quantum tunnelling events, which are known as quantum phase slips (QPS)[3-6].
We use an inert aggregation cluster source to deposit percolating lead (Pb) thin films of 10 – 30 nm Pb nanoclusters on silicon nitride substrates at 10 K. We prepare samples with different normal state resistances (R_N) and study the low temperature properties. Here we study a finite resistance at low temperature as well as finite width for the superconducting transition in the Pb percolating thin films. In the prepared samples, groups of superconducting samples are separated by small necks, and we have evidence that phase slips occur in those small necks. The observed behaviour can be described by considering TAPS models close to critical temperature (T_C) and QPS models at low temperatures.

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Large tunable inductance of the decorated Josephson chain

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We discuss the new design of a tunable superconductive inductance made from the decorated frustrated Josephson junction chains frustrated by magnetic field. We show that for the optimal choice of parameters the inductance of this chain varies in a very wide range as a function of the magnetic field. The resulting plasma frequency may exceed the value of quantum resistance that characterizes superinductance. The important distinction of this design from the chain of dc-SQUIDs loops is the absence of phase slips at all magnetic fields. We present the results of the extensive numerical simulations that confirm these expectations.

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Effect of bulk charged charged impurities on the bulk and surface transport in 3D topological insulators

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In the three-dimensional topological insulator (TI), the physics of doped semiconductors exists literally side-by-side with the physics of ultra-relativistic Dirac fermions. This unusual pairing creates a novel playground for studying the interplay between disorder and electronic transport. Here I focus on the disorder caused by the three-dimensionally distributed charged impurities that are ubiquitous in TIs, and outline the effects it has on both the bulk and surface transport. In particular, I show that bulk charged impurities significantly enhance the bulk transport by providing low-energy percolation pathways for activated conduction, while the same impurities somewhat deplete the surface transport by producing long-ranged fluctuations in the surface disorder potential.

Effects of impurities on the electronic structure of multiquantum giant vortex phases

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In a recent experiment on nanoscale Pb islands, giant vortex phases with multiple flux quanta were observed directly by scanning tunnelling spectroscopy [1]. The tunnelling spectra, however, revealed the zero-bias conductance peaking at the centre of a giant vortex regardless of the number of flux quanta carried by it. This contradicts previous theoretical predictions, whereby the zero-bias conductance vanishes at the vortex centre for an even number of flux quanta. Motivated by this experiment, we study the effects of impurity scattering on the electronic structure of a multiquantum giant vortex by means of self-consistent microscopic calculation. We find in the case of an even flux quanta that the zero-bias peaks – which are away from the vortex centre in the clean limit – move towards the vortex centre as the impurity scattering rate increases. Our calculated tunnelling density of states in the limit of strong impurity scattering is consistent with the measured spectra.

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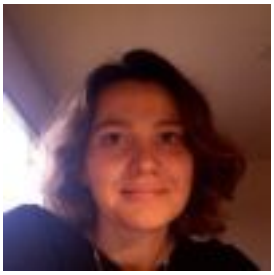

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Additional information

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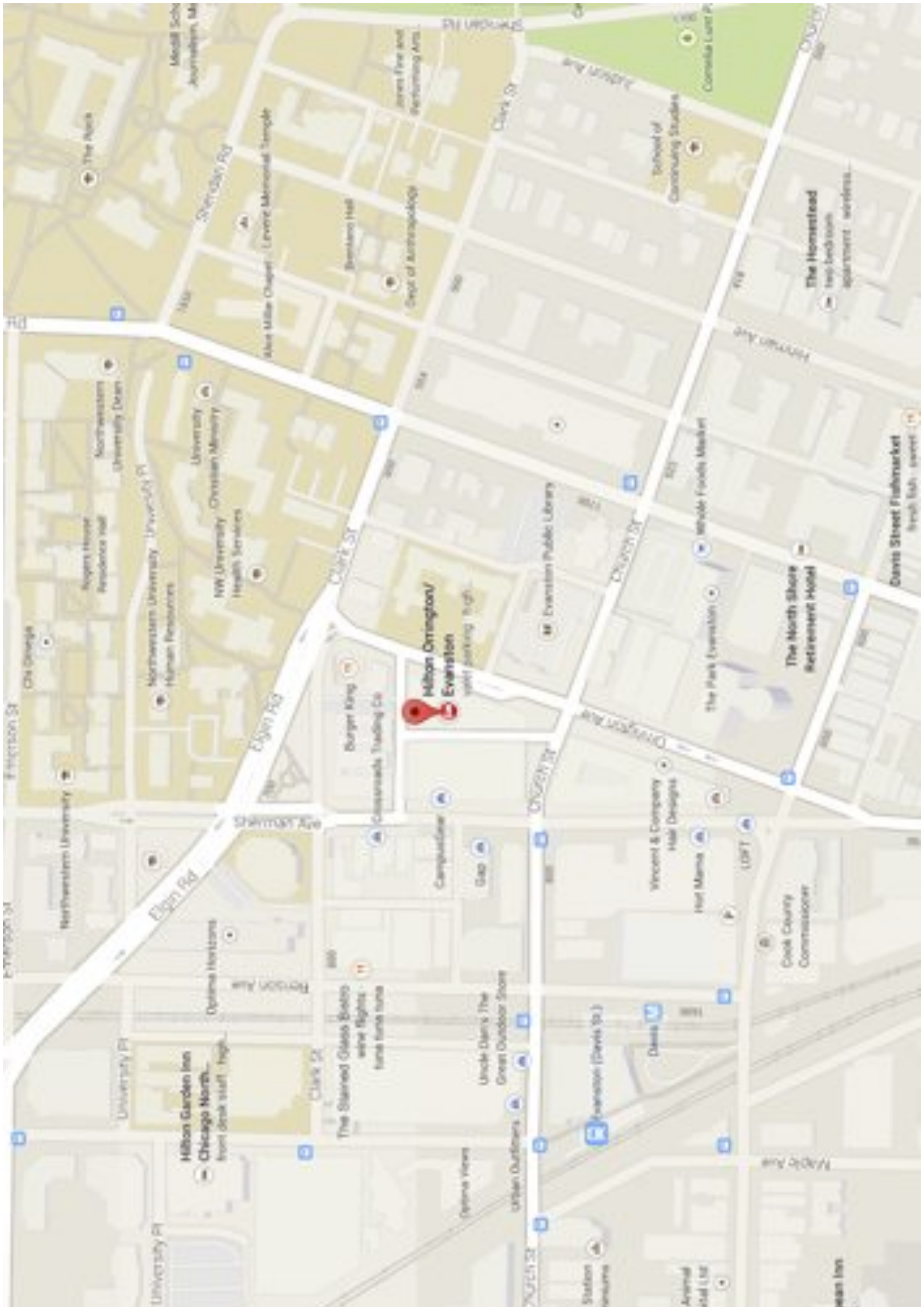
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The North Shore Retirement Hotel
Davis Street Fishmarket
The Homestead
Hilton Garden Inn Chicago North
Burger King
Gap
University Pl

Restaurants in Evanston

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Bar Louie (X2)	Davis St. Fish Market (P1)
Celtic Knot (O3)	KOI Restaurant (Chinese & Sushi) (V3)
Dave's Italian Kitchen (P2)	Farmhouse (in hotel)
Prairie Moon (X1)	Millers (Steakhouse) (V2)
Tapas Barcelona (P2)	Stained Glass (F2)
Tommy Nevins Pub (X1)	Quince (Q1)