TT 84: Focus Session: Nanoscopic Superconducting Heterostructures

In recent years superconducting nanostructures were the subject of intensive experimental and theoretical research activities. Boosted by the experimental observation of triplet superconductivity in heterostructures of non-collinear ferromagnets and superconductors, numerous novel applications have been suggested. Triplet supercurrents are simultaneous, dissipationless charge and spin currents. The magnetically induced spin-dependent density of states in superconducting films can carry spin currents over ultra long distances or yield giant thermoelectric effects, which might be useful in spintronic or caloritronic applications. Furthermore nanostructured high-temperature superconductors might open new possibilities to taylor unconventional transport properties. This Focus Session will highlight the most recent progress in this internationally active field.

Organizers: Wolfgang Belzig and Elke Scheer (Uni Konstanz)

Time: Thursday 9:30–13:15 Location: H 0104

Invited Talk TT 84.1 Thu 9:30 H 0104

Creating and Manipulating Nonequilibrium Spins in Nanoscale Superconductors — Michael J. Wolf[1], Florian Hübler[1,2], Stefan Kolenda[1], Christoph Sürgers[3], Gerda Fischer[3], Hilbert von Löhneysen[2,3], and •Detlef Beckmann[1] — [1]Institut für Nanotechnologie, Karlsruher Institut für Technologie — [2]Institut für Festkörperphysik, Karlsruher Institut für Technologie — [3]Physikalisches Institut, Karlsruher Institut für Technologie

We report on nonlocal transport in superconductor hybrid structures, with ferromagnetic as well as normal-metal tunnel junctions attached to the superconductor. In the presence of a strong Zeeman splitting of the density of states, we find signatures of spin transport over distances of several μm [1], exceeding other length scales such as the coherence length, the normal-state spin-diffusion length, and the charge-imbalance length [2]. Using a combination of ferromagnetic and normal-metal contacts, we demonstrate spin injection from a normal metal, and show a complete separation of charge and spin imbalance [3]. An exchange splitting induced by the ferromagnetic insulator europium sulfide enables spin transport at very small applied magnetic fields, and therefore paves the way to manipulating spin currents by local exchange fields [4].

[1] F. Hübler et al., Phys. Rev. Lett. **109**, 207001 (2012)
[2] F. Hübler et al., Phys. Rev. B **81**, 184524 (2010)
[3] M. J. Wolf et al., Phys. Rev. B **87**, 024517 (2013)
[4] M. J. Wolf et al., Phys. Rev. B **90**, 144509 (2014)

Topical Talk TT 84.2 Thu 10:00 H 0104

Non-Equilibrium Effects in a Josephson Junction Coupled to a Precessing Spin — •Mikael Fogelström — Department of Microtechnology and Nanoscience, Chalmers University of Technology, 42196 Göteborg, Sweden

I will discuss a theoretical study of s-wave superconductors coupled to a classical spin. When an external magnetic field is applied, the classical spin can be driven to precess with the Larmor frequency. This results in a time-dependent boundary condition for the superconducting quasiparticles, with different tunnelling amplitudes for spin-up and spin-down quasiparticles and where the precession produces spin-flip scattering processes. Andreev states develop at the interface with a non-equilibrium population which depend on how the spin is driven. The Andreev states carry a steady-state Josephson current whose current-phase relation could be used for characterising the spin. In addition to the charge transport, a spin current is also generated. This spin current will induce a torque and couple back to the dynamics of the classical spin.

Topical Talk TT 84.3 Thu 10:30 H 0104

Signature of Magnetic-Dependent Gapless Odd Frequency States at Superconductor / Ferromagnet Interfaces — •Jason Robinson — Department of Materials Science, 27 Charles Babbage Road, Cambridge, CB30FS UK

The theory of superconductivity developed by Bardeen, Cooper, and Schrieffer (BCS) explains the stabilisation of electron pairs into a spin-singlet, even frequency, state by the formation of an energy gap below which the density of states (DoS) is zero. At a superconductor interface with an inhomogeneous ferromagnet, a gapless odd frequency superconducting state is predicted in which the Cooper pairs are in a spin-triplet state. Although indirect evidence for such a state has been obtained, the gap structure and pairing symmetry have not so far been determined. In this talk I will present scanning tunnelling spectroscopy of Nb superconducting films proximity coupled to epitaxial Ho. These measurements reveal pronounced changes to the Nb sub-gap superconducting DoS on driving the Ho through a metamagnetic transition from a helical antiferromagnetic to a homogeneous ferromagnetic state for which a BCS-like gap is recovered. The results verify odd frequency spin-triplet superconductivity at superconductor / inhomogeneous magnet interfaces.

15 min. break.

Invited Talk TT 84.4 Thu 11:15 H 0104

Thermoelectric Effects and Spin Injection into Superconductors with Exchange Field — •Tero Heikkilä[1], Mihail Silaev[2,3], Pauli Virtanen[2], Francesco Giazotto[4], Asier Ozaeta[5], and Sebastian Bergeret[5] — [1]Dept Phys, Univ Jyväskylä, Finland — [2]O.V. Lounasmaa Lab, Aalto Univ, Finland — [3]Dept Theor Physics, KTH, Stockholm, Sweden — [4]NEST CNR-INFM and SNS Pisa, Italy — [5]CFM-CSIC and DIPC, San Sebastian, Spain

When a thin superconducting film is exposed to a longitudinal magnetic field or is in proximity to a ferromagnet, an exchange field separating the spin bands emerges in it. For low enough exchange fields superconductivity survives, but its response to external driving is strongly modified. In my talk I will show how at linear response such systems exhibit very strong thermoelectric response with an almost ideal efficiency. For strong driving, this effect creates a spin accumulation that can only relax via thermalization, and therefore at low temperatures has a very long range. Therefore our work explains recent observations of the long-range spin accumulation in spin-split superconductors. When injecting spin from injectors with non-collinear magnetization compared to the exchange field, the spins start to rotate around the latter. I will describe how superconductivity modifies this spin Hanle effect so that the resulting nonlocal magnetoresistance depends on the details of spin relaxation, therefore allowing for probing them.

Topical Talk TT 84.5 Thu 11:45 H 0104

Spin Injection and Relaxation in a Mesoscopic Superconductor — •Marco Aprili[1], Charis Quay[1], Denis Chevalier[1], Clement Dutreix[1], Cristina Bena[2], and Christoph Strunk[3] — [1]Laboratoire de Physique des Solides, CNRS UMR-8502, Bât. 510, Université Paris-Sud, 91405 Orsay Cedex, France — [2]Institut de Physique Théorique, CEA/Saclay, Orme des Merisiers, 91190 Gif-sur-Yvette Cedex, France — [3]Institute for Experimental and Applied Physics, University of Regensburg, 93040 Regensburg, Germany

Injecting spin-polarized electrons or holes into a superconductor and removing Cooper pairs creates both spin and charge imbalances. We have investigated the relaxation of the out-of-equilibrium magnetization induced by spin injection. First, we measured the spin and charge relaxation times (t_S and t_Q) by creating a dynamic equilibrium between continuous injection and relaxation, this leads to constant-in-time spin and charge accumulation proportional to their respective relaxation times. Using a mesoscopic "absolute" spin-valve, we obtained t_S and t_Q by probing the difference on the chemical potential between quasiparticles and Cooper pairs. We observed that spin (charge) accumulation dominates at low (high) injection current. This artificially generates spin-charge separation as theoretically first predicted by Kivelson and Rokhsar. Second, we directly measured the spin relaxation time in the frequency space and found $t_S = 1 - 10$ ns con-

sistent with results from constant current injection. Finally, we measured the spin coherence time of the out-of-equilibrium quasi-particles by performing an electron spin resonance experiment.

TT 84.6 Thu 12:15 H 0104

Probing odd-triplet contributions to the long-ranged proximity effect by scanning tunneling spectroscopy — •Simon Diesch[1], Christoph Sürgers[2], Detlef Beckmann[2], Peter Machon[1], Wolfgang Belzig[1], and Elke Scheer[1] — [1]Universität Konstanz, Konstanz, Germany — [2]Karlsruhe Institute of Technology, Karlsruhe, Germany

In conventional superconductors, electrons are bound in singlet Cooper pairs, i.e. with opposite spin. More recently, experiments on superconductor-ferromagnet-systems have shown Cooper pairs tunneling through ferromagnetic layers, indicating Cooper pairs of equal spin, thus corresponding to a long-range triplet proximity effect. Most experimental evidence for triplet superconductivity comes from observations of the thickness dependence of the Josephson current through a ferromagnetic barrier, but there is an increasing interest in obtaining direct spectroscopic evidence.

This project aims at analyzing the electronic density of states of a thin diffusive normal metal layer (Ag) coupled to a superconductor (Al) across a ferromagnetic insulator (EuS) using a scanning tunneling microscope in spectroscopy mode at 280 mK. For this purpose, we fabricated EuS films of different thicknesses and acquired spectroscopic data at different magnetic fields. We observe significant broadening of the superconductive energy gap and a variety of sub-gap structures including zero-bias conductance peaks induced by the presence of the ferromagnet.

TT 84.7 Thu 12:30 H 0104

Electronic heat, charge and spin transport in superconductor-ferromagnetic insulator structures — •Sebastian Bergeret — Materials Physics Center (CFM_CSIC), San Sebastian, Spain — Donostia International Physics Center (DIPC), San Sebastian, Spain

It is known for some time that a superconducting (S) film in contact with a ferromagnetic insulator (FI) exhibits a spin-splitting in the density of states (DoS). Recently we have explored different S-FI hybrid structures and predicted novel effects exploiting such spin-splitting of the DoS. In this talk I will briefly discuss (i) a heat valve based on a FI-S-I-S-FI Josephson junction; (ii) a thermoelectric transistor and (iii) the occurrence of a giant thermophase in a thermally-biased Josephson junction.

TT 84.8 Thu 12:45 H 0104

Correlation of 0-π transition with density of states measurements — •Ondrej Vavra[1,2], Petra Högl[3], Jaroslav Fabian[3], Hermann Kohlstedt[2], and Christoph Strunk[1] — [1]Inst. for Experimental and Applied Physics, University of Regensburg, Germany — [2]Nanoelektronik, Technical Faculty, University of Kiel, Germany — [3]Inst. for Theoretical Physics, University of Regensburg, Germany

We report on the proximity induced superconductivity in hybrid SFIFS (Nb-Fe-Al_2O_3-Fe-Nb) and SIFS (Nb-Al_2O_3-Fe-Nb) Josephson junctions. Differential conductance curves $dI/dV(V)$ were recorded with the lock-in technique on the SFIFS samples exposed to a small magnetic field that suppresses the critical current I_C. The $dI/dV(V)$ curves reveal a peak at a voltage 2.26 mV which is attributed to the sum of the gaps of individual Nb electrodes ($2\Delta_{Nb}$). Upon increasing iron thickness d_{Fe} a second peak develops at a voltage 1.3 mV which we attribute to the induced superconductivity in the Fe-layers. The peak height difference $|G_{Nb} - G_{Fe}|(d_{Fe})$ oscillates with zero crossings at 2.3 and 2.9 nm, respectively. Qualitatively, the Fe thickness dependence of $dI/dV(V)$ behavior is the same for both SFIFS and SIFS junctions, respectively. The shape of the $|G_{Nb} - G_{Fe}|(d_{Fe})$ curve with its oscillations is similar to the $I_C(d_{Fe})$ curves for Josephson junctions with F-interlayer and to the $T_C(d_{Fe})$ dependencies for the S-F multilayers. These oscillations are observed due to the phase transition from 0 to π and vice-versa. We will discuss the results of deconvolution of $dI/dV(V)$ curves and correlate these data with Fe thickness development of the critical current.

TT 84.9 Thu 13:00 H 0104

Controllable transfer of magnetism in superconducting spin-valve structures — •Matthias Eschrig — Royal Holloway, University of London, UK

During the past 15 years a new field has emerged, which combines superconductivity and spintronics, with the goal to pave a way for new types of devices for applications combining the virtues of both, namely quantum coherence and interference on one side, and spin-selectivity and spin magnetism on the other. The building block of this new "superspintronics" are spin-triplet Cooper pairs, which are generated at the interface between a conventional superconducting and a ferromagnetic material. Non-collinear magnetic inhomogeneity mixes triplet pairs among each other, thus creating long-ranged equal-spin Cooper pairs in the ferromagnet, and non-coplanar inhomogeneity introduces geometric phases giving rise to unusual current phase relations. We discuss recent experiments [1] on superconducting spin-valve structures reporting a controllable transfer of magnetism via equal-spin Cooper pairs. We present theoretical models for for such an effect and discuss its implications for applications.

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[1] M.G. Flokstra, N. Satchell, J. Kim, G. Burnell, S.J. Bending, P.J. Curran, S. Langridge, C.J. Kinane, J.F.K. Cooper, M. Eschrig, A. Isidori, N. Pugach, H. Luetkens, T. Prokscha, S. L. Lee, unpublished.