TT 7: SC: Heterostructures, Andreev Scattering, Proximity Effect, Coexistence

Time: Monday 14:00–18:00 Location: H20

TT 7.1 Mon 14:00 H20

Spin-dependent boundary conditions for isotropic superconducting Green's functions — •Wolfgang Belzig[1], Audrey Cottet[2], Daniel Huertas-Hernando[3], and Yuli Nazarov[4] — [1]Fachbereich Physik, Universität Konstanz, Konstanz, Germany — [2]Ecole Normale Supérieure, Laboratoire Pierre Aigrain, Paris, France — [3]Department of Physics, Norwegian University of Science and Technology,Trondheim, Norway — [4]Kavli Institute of NanoScience, Delft University of Technology, Delft, The Netherlands

The quasiclassical theory of superconductivity provides the most successful description of diffusive hetero- structures comprising superconducting elements, namely, the Usadel equations for isotropic Green's functions. Since the quasiclassical and isotropic approximations break down close to interfaces, the Usadel equations have to be supplemented with boundary conditions for isotropic Green's functions (BCIGF), which are not derivable within the quasiclassical description. For a long time, the BCIGF were available only for spin- degenerate tunnel contacts, which posed a serious limitation on the applicability of the Usadel description to modern structures containing ferromagnetic elements. We close this gap and derive spin- dependent BCIGF for a contact encompassing superconducting and ferromagnetic correlations [1]. This finally justifies several simplified versions of the spin-dependent BCIGF, which have been used in the literature so far [2].

[1] A. Cottet, D. Huertas-Hernando, W. Belzig and Yu. V. Nazarov, Phys. Rev. B **80**, 184511 (2009)

[2] D. Huertas-Hernando, Yu. V. Nazarov, W. Belzig, Phys. Rev. Lett. **88**, 047003 (2002)

TT 7.2 Mon 14:15 H20

Doppler shift in Andreev reflection from a moving superconducting condensate in Nb/InAs Josephson junctions — Rohlfing Franziska[1], •Tkachov Grigory[1,2], Otto Florian[1], Richter Klaus[1], Weiss Dieter[1], and Strunk Christoph[1] — [1]Universität Regensburg — [2]Universität Würzburg

We present experimental and theoretical studies of narrow ballistic Josephson weak links in InAs quantum wells contacted by Nb electrodes and subject to an external magnetic field [1]. We find a dramatic magnetic-field suppression of the Andreev reflection amplitude, which occurs even for in-plane field orientation with essentially no magnetic flux through the junction. Our observations demonstrate the presence of a Doppler shift in the energy of the Andreev levels, which results from diamagnetic screening currents in the hybrid Nb/InAs banks. The data for conductance, excess and critical currents can be consistently explained by taking into accout the field- and geometry-dependent phase gradient of the superconducting order parameter and the McMillan energy, characterizing the proximity effect in the Nb/InAs banks. Our analysis suggests that a similar Doppler shift in Andreev reflection should, generally, be expected in other 2D hybrid systems such as, e.g., graphene-superconductor Josephson links [2].

[1] F. Rohlfing et al., Phys. Rev. B **80**(R) (2009).

[2] H. B. Heersche et al., Nature **446**, 56 (2007).

TT 7.3 Mon 14:30 H20

Charge and spin currents in a triplet superconductor-ferromagnet-singlet superconductor Josephson junction — Yasuhiro Asano[1], •Dirk Manske[2], and Philip Brydon[3] — [1]Department of Applied Physics, Hokkaido University — [2]Max Planck Institute for Solid State Research — [3]Institute for Theoretical Physics, TU Dresden

The study of triplet superconductor Josephson junctions with magnetically-active tunneling barriers has revealed an intimate connection between charge and spin supercurrents in these devices [1,2]. Here we generalize this analysis to tunneling between a spin-triplet and a spin-singlet superconductor through a magnetic barrier. Using a tunneling Hamiltonian analysis, we show how spin-flip tunneling processes produce a lowest-order Josephson coupling between the two superconductors, accomplishing both spin- and orbital-parity conversion for the tunneling Cooper pairs. Remarkably, in the triplet superconductor the charge current is accompanied by a phase-dependent spin current. We verify these predictions using a Bogoliubov-de Gennes technique, which reveals the importance of the orbital pairing state of the two superconductors for the appearance of these effects.

[1] P. M. R. Brydon, D. Manske, and M. Sigrist, J. Phys. Soc. Japan 77, 103714 (2008).

[2] P. M. R. Brydon and D. Manske, Phys. Rev. Lett. 103, 147001 (2009).

TT 7.4 Mon 14:45 H20

Spin current due to triplet superconductor - ferromagnet interfaces — •Philip Brydon — Technische Universität Dresden, Dresden, Germany

The interface between a superconductor and a ferromagnet is an ideal setting in which to study the complicated interplay of these two phases. Although the relevant physics is now very well understood for a spin singlet pairing state of the superconductor, qualitatively new phenomena can appear for a spin triplet pairing state due to the intrinsic spin structure of the superconductor. One such surprising result is the existence of a bulk spin supercurrent in the triplet superconductor due to spin-flip reflection of triplet Cooper pairs at the superconductor-ferromagnet interface [1,2]. The resulting spin current displays strong similarities to the spontaneous charge current in a conventional Josephson junction. The dependence of the spin current on a number of relevant parameters is studied e.g. the orbital pairing state of the superconductor and the exchange splitting of the ferromagnet. The possibility of unconventional dynamics of the magnetization of the ferromagnet is discussed.

[1] P. M. R. Brydon and D. Manske, Phys. Rev. Lett. 103, 147001 (2009).

[2] P. M. R. Brydon, cond-mat/0908.4065 (Phys. Rev. B, to be published).

TT 7.5 Mon 15:00 H20

Theory of superconductor-ferromagnet point-contact spectra: the case of strong spin-polarization — •Roland Grein[1], Tomas Löfwander[2], Georgo Metalidis[1], and Matthias Eschrig[3] — [1]Institut für Theoretische Festkörperphysik und DFG-Zentrum für funktionelle Nanostrukturen, Karlsruher Institut für Technologie, D-76128 Karlsruhe — [2]Department of Microtechnology and Nanoscience MC2, Chalmers University of Technology, S-412 96 Göteborg, Sweden — [3]Fachbereich Physik, Universität Konstanz, D-78457 Konstanz

We study the effects of spin-active scattering on superconductor-ferromagnet point-contact spectra using the quasiclassical theory of superconductivity. New boundary conditions for the quasiclassical Green's function allow for treating strongly spin-polarized systems with this approach. The theory describes the contact region by a general scattering matrix and various microscopic models of interfacial scattering are studied. We show that the shape of the interface potential plays a crucial role in spin-active scattering and that spin-flip processes can alter the spectra dramatically.

We show that our theory generalizes earlier models for electronic transport across such contacts based on the BTK-approach. They are contained as limiting cases in our formalism.

TT 7.6 Mon 15:15 H20

Re-analysis of experimental point contact Andreev spectra: the case of half-metallic CrO_2 — •Matthias Eschrig[1], Roland Grein[2], and Tomas Löfwander[3] — [1]Fachbereich Physik, Universität Konstanz, D-78457 Konstanz, Germany — [2]Institut für Theoretische Festkörperphysik und DFG-Zentrum für funktionelle Nanostrukturen, KIT, D-76128 Karlsruhe, Germany — [3]Department of Microtechnology and Nanoscience MC2, Chalmers University of Technology, S-41296 Göteborg, Sweden

Point-contact Andreev spectroscopy has been extensively used to probe the spin-polarization of strong ferromagnets. In this method a nanosized point contact is formed between a superconducting tip and the ferromagnetic material under investigation (or vice versa). The conductance-versus-voltage is recorded at a low temperature. Subsequently, a fitting procedure is undertaken to extract the polarization of the ferromagnet. We re-analyze existing data using a new theoretical treatment that accounts for spin-mixing effects and magnetic inhomogeneities, and that is based on a new formulation of boundary conditions taking into account these effects. We find that for the

prominent case of CrO_2 the data are consistent with a spin polarization close to 100%, in agreement with the notion of half-metallic behavior for this material.

TT 7.7 Mon 15:30 H20

High-resolution magnetization profiles in superconducting YBCO and ferromagnetic LCMO hybrid structures at low temperatures. — S. Brück[1], •J. Albrecht[2], S. Soltan[3,4], G. Christiani[4], H.-U. Habermeier[4], P. Audehm[5], S. Macke[5], and E. Goering[5] — [1]Universität Würzburg — [2]Hochschule Aalen — [3]Helwan University, Cairo, Egypt — [4]MPI für Festkörperforschung, Stuttgart — [5]MPI für Metallforschung, Stuttgart

At the interface between ferromagnetic (F) and superconducting (SC) thin films a fascinating competition of ordering parameters takes place. We have investigated a hybrid structure of $SrTiO_3$(substrate), ferromagnetic $La_{0.7}Ca_{0.3}MnO_3$ and superconducting $YBa_2Cu_3O_7$ using X-ray magnetic resonant reflectometry (XRMR) and x-ray magnetic circular dichroism (XMCD). In particular, the XRMR measurements provide element selective magnetic depth profiles of layered samples with an enhanced sensitivity for localized and or interface effects. A temperature-dependent investigation of the resonant reflectometry at the Mn L edge in the temperature range from T=40K to T=110K was carried out and the magnetic depth profile for Mn was extracted. It can be shown that both the interaction to the adjacent YBCO layer and to the STO substrate influence the magnetization inside the LCMO layer in a particular way which will be presented in detail. The experimental findings give new insight into the physics of multilayered oxidic structures at low temperatures.

15 min. break

Invited Talk TT 7.8 Mon 16:00 H20

Polar Kerr Effect of Unconventional Superconductors — •Aharon Kapitulnik — Stanford University, Stanford, CA, USA

BCS theory of conventional superconductivity can be described by a condensate of Cooper-pairs of time-reversed states. Such superconductors respect time reversal symmetry and are insensitive to nonmagnetic scattering (the Anderson theorem). For unconventional superconductors, sign-changes in different parts of the Fermi surface results is breakdown of Anderson theorem. In addition, the higher angular momentum state gives rise to the possibility of "chiral" order parameter for which time-reversal symmetry (TRS) is broken. A series of recent studies have shown that ultra-sensitive Polar Kerr effect measurements, using a Sagnac interferometer, can detect such TRS breaking effects in unconventional superconductors [1]. For example, Sr_2RuO_4 has been shown to break TRS, and together with other measurements seem to be consistent with some variant of a "p+ip" type order parameter, while ferromagnet/superconductor bilayer structures show signatures of the "inverse proximity effect" which was long sought after following its first theoretical prediction. In this talk we will review measurements on a variety of systems including the heavy fermion URu2Si2 which has mystified researchers since in this system superconductivity occurs deep inside a mysterious "hidden order" state (whose transition temperature is approximately 17.5 K).

[1] For a recent review of our studies see: Aharon Kapitulnik, Jing Xia, Elizabeth Schemm and Alexander Palevski, New J. Phys. 11 (2009) 055060.

TT 7.9 Mon 16:30 H20

Bias-resolved measurements of charge imbalance in superconductors at ultra-low temperatures — •Florian Hübler[1,2], Julien Camirand Lemyre[1], Detlef Beckmann[1], and Hilbert von Löhneysen[2,3] — [1]Karlsruher Institut für Technologie, Institut für Nanotechnologie — [2]Karlsruher Institut für Technologie, Institut für Festkörperphysik — [3]Karlsruher Institut für Technologie, Physikalisches Institut, Karlsruhe, Germany

In this study we explore charge imbalance in mesoscopic normal-metal/superconductor multiterminal hybrid structures at ultra-low temperatures ($T \ll T_c$). The investigated samples, structured by e-beam lithography and shadow evaporation, consist of a superconducting aluminum bar with several copper fingers forming tunnel contacts at different distances from each other. We measured in detail the local and non-local conductance of these structures as a function of the applied bias voltage V, the applied magnetic field B, the temperature T and the contact distance d. From these data the relaxation length λ_Q^* was derived. The bias-resolved measurements show a transition from dominant elastic scattering close to the gap to inelastic scattering at higher bias. We measured a strong suppression of charge imbalance with magnetic field, which can be directly linked to the pair breaking parameter. In contrast practically no temperature dependence of the charge imbalance signal was observed below 0.5K. These results are relevant for the investigation of other non-local effects such as crossed Andreev reflexion and spin diffusion.

TT 7.10 Mon 16:45 H20

Crossed Andreev Reflection and Charge Imbalance in Diffusive Normal-Superconducting-Normal Structures — •Dmitry Golubev[1], Mikhail Kalenkov[2], and Andrei Zaikin[1] — [1]Karlsruhe Institut für Technologie, Institut für Nanotechnologie, Karlsruhe, Germany — [2]I.E. Tamm Department of Theoretical Physics, P.N. Lebedev Physics Institute, Moscow, Russia

We formulate a microscopic theory of non-local electron transport in three-terminal diffusive normal-superconducting-normal (NSN) structures with arbitrary interface transmissions. At low energies ε we predict strong enhancement of non-local spectral conductance $g_{12} \propto 1/\varepsilon$ due to quantum interference of electrons in disordered N-terminals. In contrast, non-local resistance R_{12} remains smooth at small ε and, furthermore, is found to depend neither on parameters of NS interfaces nor on those of N-terminals. At higher temperatures R_{12} exhibits a peak caused by the trade-off between charge imbalance and Andreev reflection. Our results are in a good agreement with recent experimental observations and can be used for quantitative analysis of future experiments.

TT 7.11 Mon 17:00 H20

Andreev Bound States and Transport in a Kondo Quantum Dot with Superconducting Leads — •Tabea Mandt and Johann Kroha — Physikalisches Institut, Universität Bonn, Germany

Despite intense theoretical efforts the nature of Andreev bound states and the resulting Josephson current in a Kondo dot coupled to two symmetric s-wave superconductors has remained controversial. We investigate the temperature- and coupling-dependent spectral and transport properties of this system using an extension of the infinite-U non-crossing approximation (NCA) to describe superconducting leads. Using a conserving approximation (generating functional), we extend previous selfconsistent calculations [1] to include multiple Andreev-reflections by summing up the infinite series of ladder diagrams in the relevant anomalous channel (Cooper pair exchange) of the quantum dot Green's function. The *infinite* number of Andreev reflections is necessary to describe true bound states and, hence, to answer the open problems about the number of bound states and, possibly, their spectral width. For the evaluation, the summation is efficiently formulated in terms of coupled Bethe-Salpeter equations for the renormalized pseudoparticle vertices, which can be decoupled due to a separation of energy scales. The phase diagram of the junction and the Josephson current–phase relation are established and related to the phase-dependent position of the subgap bound states.

[1] G. Sellier, Th. Kopp, J. Kroha, Y. S. Barash, Phys. Rev. B **72**, 174502 (2005).

TT 7.12 Mon 17:15 H20

Pure spin current with interacting quantum dots — •David Futterer[1], Michele Governale[2], and Jürgen König[1] — [1]Theoretische Physik, Universität Duisburg Essen and CeNIDE, D-47048 Duisburg, Germany — [2]School of Chemical and Physical Sciences, Victoria University of Wellington, PO Box 600, Wellington, New Zealand

We investigate sub-gap transport through an interacting quantum dot tunnel coupled to a superconducting, a ferromagnetic and a normal conducting lead. Despite the tendency of a large charging energy to suppress the equilibrium proximity effect on the dot, a finite Andreev current can be achieved in non-equilibrium situations. Due to the coupling to a ferromagnet, spin can accumulate on the dot. We find situations in which a pure spin current, that is zero charge current together with a finite spin current, occurs in the normal lead. For our calculation we apply a real-time transport theory [1,2].

[1] M. G. Pala, M. Governale, and J. König, New J. Phys. **9**, 278 (2007).

[2] M. Governale, M. G. Pala, and J. König, Phys. Rev. B **77**, 134513 (2008).

TT 7.13 Mon 17:30 H20

Spin-controlled supercurrents in quantum-dot spin valves

with a superconducting lead — •Björn Sothmann[1], David Futterer[1], Michele Governale[2], and Jürgen König[1] — [1]Universität Duisburg-Essen and CeNIDE, 47048 Duisburg, Germany — [2]School of Chemical and Physical Sciences, Victoria University of Wellington, PO Box 600, Wellington 6140, New Zealand

Quantum dots coupled to ferromagnetic [1] or superconducting [2] electrodes exhibit interesting effects due to an interplay of strong Coulomb interaction, superconducting proximity effect and nonequilibrium spin accumulation as well as spin precession.

Here we investigate a quantum-dot spin valve, i.e., a single-level quantum dot coupled to two ferromagnetic leads with symmetrically applied bias, with an additional superconducting lead at zero chemical potential. Using a real-time diagrammatic approach [1,2] we compute the current taking into account the coupling to the superconductor exactly in the limit of infinite pair potential. For a symmetric coupling to the ferromagnets, the current into the superconductor vanishes in collinear geometries due to a combination of particle-hole and left-right symmetry. A finite supercurrent arises only for noncollinear magnetizations in the intermediate bias regime due to a breaking of the left-right symmetry by the spin accumulation. Due to the presence of an exchange field, the supercurrent shows a nontrivial bias dependence and can even change sign.

[1] M. Braun, J. König, J. Martinek, Phys. Rev. B. **70** (2004).
[2] M. Governale, M. Pala, J. König, Phys. Rev. B. **77** (2008).

TT 7.14 Mon 17:45 H20

The Josephson light-emitting diode — •Patrik Recher[1], Yuli Nazarov[2], and Leo Kouwenhoven[2] — [1]Institut für Theoretische Physik und Astrophysik, University of Würzburg, 97074 Würzburg, Germany — [2]Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, The Netherlands

We consider an optical quantum dot where an electron level and a hole level are coupled to respective superconducting leads. We find that electrons and holes recombine producing photons at discrete energies as well as a continuous tail. Further, the spectral lines directly probe the induced superconducting correlations on the dot. At energies close to the applied bias voltage $eV_{\rm sd}$, a parameter range exists, where radiation proceeds in pairwise emission of polarization correlated photons. At energies close to $2eV_{\rm sd}$, emitted photons are associated with Cooper pair transfer and are reminiscent of Josephson radiation. We discuss how to probe the coherence of these photons in a SQUID geometry via single photon interference.