TT 28: Superconductivity: Heterostructures, Andreev Scattering, Proximity Effect, Coexistence

Time: Wednesday 15:15–18:00 Location: HSZ 105

Invited Talk TT 28.1 Wed 15:15 HSZ 105

Unconventional Superconductivity induced by Interfaces and Surfaces — •Matthias Eschrig — Institut für Theoretische Festkörperphysik and DFG-Center for Functional Nanostructures, Universität Karlsruhe, D-76128 Karlsruhe, Germany

Ordered many-body states in solids are often characterized by an order parameter that breaks one or more of the symmetries of the crystal. Such unconventional states lead to interesting new physics associated with the spontaneously broken symmetries. However, in order that such a symmetry breaking can occur it has to be energetically favored. Some of the most interesting symmetry broken states have never been found experimentally in bulk materials for that reason.

However, symmetries can be broken also by introducing interfaces with other materials. In this case, the evasive unconventional states might be induced locally near the interface, and can then penetrate as correlations into bulk materials. The properties of the induced states depend on the scattering characteristics of the interfaces and on the proximity induced states produced by the adjacent materials.

We discuss in particular interface-induced unconventional superconductivity in heterostructures with magnetically active materials, that may exhibit e.g. odd-frequency pairing or equal-spin triplet pairing states. We study the conditions under which such unconventional pairing amplitudes are induced and demonstrate how they can be tested in experiment and used for quantum devices.

TT 28.2 Wed 15:45 HSZ 105

Broken time-reversal-symmetry in triplet superconductor junctions — •Philip Brydon[1], Christian Iniotakis[2], Dirk Manske[3], and Manfred Sigrist[2] — [1]Technische Universität Dresden, Dresden, Germany — [2]ETH Zürich, Zürich, Switzerland — [3]Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany

A rich variety of unconventional Josephson effects have been predicted for junctions combining magnetism and triplet superconductivity (e.g. P. M. R. Brydon *et al.*, Phys. Rev. B **77**, 104504 (2008); P. M. R. Brydon, D. Manske and M. Sigrist, J. Phys. Soc. Japan **77**, 103714 (2008)). Previous works assume, however, that the properties of the barrier material are independent of the two superconductors. We demonstrate that this assumption fails in a scenario where time-reversal symmetry is broken by the misalignment of the **d**-vectors of the triplet superconductors on either side of the junction. This allows the stabilization of a barrier magnetization, creating an exotic Josephson state distinguished by the existence of fractional flux quanta at the junction barrier. There is also a pronounced enhancement of the critical current through the junction at temperatures below the magnetic transition.

TT 28.3 Wed 16:00 HSZ 105

Non-local transport in normal-metal/superconductor hybrid structures: the role of interference and interaction — •Jakob Brauer[1], Detlef Beckmann[1], Florian Hübler[1], and Hilbert v. Löhneysen[2] — [1]Forschungszentrum Karlsruhe, Institut für Nanotechnologie, P.O.-Box 3640, D-76021 Karlsruhe — [2]Forschungszentrum Karlsruhe, Institut für Festkörperphysik, P.O.-Box 3640, D-76021 Karlsruhe and Physikalisches Institut, Universität Karlsruhe, D-76128 Karlsruhe, Germany

We present experimental results on non-local conductance in multi-terminal hybrid structures, where two normal metal contacts are attached to a single superconductor. For contacts with an insulating tunnel barrier, and at energies below the energy gap of the superconductor, the non-local conductance is determined by the competition of crossed Andreev reflection (CAR) and elastic cotunneling (EC). The contributions of CAR and EC are expected to cancel each other in the tunneling limit. Recently [Russo et al., Phys. Rev. Lett. 95, 027002 (2005)], a non-vanishing signal has been observed in such structures, with an additional energy scale below the gap. So far, quantum interference and Coulomb interaction have been suggested to lift the cancellation of CAR and EC, but no established theory exists for this signal. We observe similar signals in our structures, and demonstrate that the origin is quantum interference.

TT 28.4 Wed 16:15 HSZ 105

Crossed Andreev reflection and dynamical Coulomb blockade — •Andreas Baumgartner, Andreas Kleine, Jelena Trbovic, and Christian Schönenberger — Institute of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland

A natural source of entangled electrons is the nonlocal process of crossed Andreev reflection (CAR) [1]. In CAR the two electrons of a Cooper pair in a superconductor coherently tunnel into two spatially separated normal metal contacts. This process is expected to produce a negative nonlocal voltage, U_{nl}, in a four terminal device with two normal (injector and detector) and two superconducting contacts. However, recent experiments have shown that elastic cotunneling (EC) and charge imbalance (CI) lead to $U_{\mathrm{nl}} > 0$ and can mask CAR [2].

In this contribution we show that U_{nl} can be negative for all subgap biases, which suggests that CAR can dominate all other processes, as required for a solid-state entangler. We fabricated a series of lateral multiterminal $Al/Al_2O_3/Pd$ hybrid structures with contact distances smaller than the superconducting coherence length and with different barrier resistances. We show that for a small window of injector and detector resistances CAR is the dominant nonlocal subgap process, and that for larger resistances the CAR and CI rates are reduced. We tentatively ascribe these systematic changes with barrier resistance to dynamical Coulomb blockade [1].

[1] Recher *et al.*, PRL 91, 267003 (2003).

[2] Cadden-Zimansky *et al.*, PRL 97, 237003 (2006), Russo *et al.*, PRL 95, 027002 (2005), Beckmann *et al.*, PRL 93, 197003 (2004)

15 min. break

TT 28.5 Wed 16:45 HSZ 105

Hybrid normal-superconducting systems comprising interacting quantum dots — •Michele Governale[1], Marco G. Pala[2], David Futterer[1], and Jürgen König[1] — [1]Theoretische Physik, Universität Duisburg-Essen, D-47048 Duisburg, Germany — [2]IMEP-LAHC, INP MINATEC, Centre National de la Recherche Scientifique, F-38016 Grenoble, France

Quantum dots tunnel-coupled to both normal and superconducting leads exhibit a very rich physics due to the presence of superconducting correlations, quantum fluctuations, strong electron-electron interaction, and non-equilibrium. In order to study these systems, we have developed a real-time diagrammatic expansion in the tunnel coupling to the leads [1], which describes both the equilibrium and non-equilibrium superconducting proximity effects in the quantum dot. In the limit of a large superconducting gap, all orders in the tunnel-coupling strength to the superconductors can be included within an exact resummation scheme. Corrections due to finite values of the gap are evaluated within a $1/\Delta$ expansion. This theory is applied to a single-level quantum dot tunnel coupled to two phase-biased superconducting leads and one voltage-biased normal lead. The normal lead is used to drive the dot out of equilibrium. We compute both the Josephson current between the two superconductors and the Andreev current in the normal lead, and analyze their switching on and off as well as transitions between 0- and π-states as a function of gate and bias voltage.

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

TT 28.6 Wed 17:00 HSZ 105

Spin-Supercurrents in SC/FM Heterostructures — •Roland Grein, Georgo Metalidis, Matthias Eschrig, and Gerd Schön — Institut für theoretische Festkörperphysik, Universität Karlsruhe and DFG-Center for Functional Nanostructures (CFN), D-76128 Karlsruhe, Germany

We consider a hybrid structure of a superconductor (SC) and a ferromagnet (FM) with a strong exchange field ($J \approx E_{\mathrm{F}}$). To model this system, we use an extension of the quasiclassical theory of superconductivity. Recent experimental results indicate that spin-active scattering in the interface regions between the different materials is of crucial importance for understanding the transport properties of such systems. We use a microscopic model based on wave function matching to describe this spin-active scattering. It turns out that superconducting correlations, which are transmitted through such interfaces, acquire spin-dependent scattering phases. For a Josephson junction, these scattering phases lead to a renormalization of the current-

phase relation. In particular, this leads us to the prediction of a spin-supercurrent in a FM layer which is coupled to only one superconducting electrode, provided that inter-band scattering is possible at the interface and the outer surface of the FM.

TT 28.7 Wed 17:15 HSZ 105

Superconducting spin valves based on epitaxial [Fe/V]-superlattices — •Gregor Nowak[1], Moreno Marcellini[2], Hartmut Zabel[1], Björgvin Hjörvarsson[2], and Kurt Westerholt[1] — [1]Experimentalphysik/Festkörperphysik, Ruhr Universität Bochum — [2]Department of Physics, University of Uppsala, Sweden

In superconducting spin valves of the type S/F1/N/F2 or F1/S/F2 with a superconducting layer S, two ferromagnetic layers F1 and F2 and a normal metallic layer N, the superconducting transition temperature T_S depends on the relative magnetization direction of the ferromagnetic layers F1 and F2. The difference of the transition temperature $\Delta T_S = T_S^{AP} - T_S^{P}$ with the magnetization direction of F1 and F2 either antiparallel or parallel is called the superconducting spin valve effect [1]. We observed a superconducting spin valve shift of up to ΔT_S=200 mK when aligning the sublattice magnetization in an external magnetic field in S/F1/N/F2 type of spin valves. In the F1/S/F2-type spin valves the ferromagnetic layer F1 was either a [Fe/V] or a [Fe_xV_{1-x}/V] superlattice, the F2 layer was a Fe-, a Co- or a Fe_xV_{1-x} film. Using weakly ferromagnetic Fe_xV_{1-x} alloy layers as F1 and F2 we find a spin valve effect of up to ΔT_S=24 mK. We also present experimental evidence for a drastic reduction or even a sign reversal of the superconducting spin valve effect in the presence of perpendicular magnetic stray fields from ferromagnetic domain walls.

[1] J.Y. Gu, C.-Y. You, J. S. Jiang, J. Pearson, Ya. B. Bazaliy, and S. D. Bader, Phys. Rev. Lett. 89, 267001 (2002)

TT 28.8 Wed 17:30 HSZ 105

Magnetic properties and local critical currents of cobalt covered MgB_2 films — •Sebastian Treiber[1] and Joachim Albrecht[2] — [1]Max Planck Institut für Metallforschung, D-70569 Stuttgart, Germany — [2]HTW Aalen, Beethovenstr. 1, D-73430 Aalen, Germany

At Temperatures below 10K the critical state in MgB_2 thin films gets unstable, the magnetic flux percolates filamentary into the superconductor. This state evolves due to chaotic motion of magnetic vortices and leads to dendritic flux density patterns. Since the critical current vanishes inside the dendrites this effect leads to a strong suppression of possible transport currents. We have found, that ferromagnetic cobalt cover layers can influence the flux pinning scenario in the superconductor. Therefore a heterostructure of MgB_2 and cobalt was investigated using SQUID magnetometry and magneto-optical (MO) imaging. Two different effects are observed. On the one hand the temperature for the occurrence of flux avalanches is shifted to lower temperatures as observed by MO studies. On the other hand magnetic hysteresis loops obtained by SQUID measurements show a significant asymmetry with respect to the $H_{ext} = 0$ axis attributed to magnetic effects on flux line pinning [1].

[1] S. Treiber, B. Stuhlhofer, H. - U. Habermeier and J. Albrecht, SUST (submitted)

TT 28.9 Wed 17:45 HSZ 105

Superconductivity and Magnetism in Cuprate Heterostructures Studied by Low Energy μSR — •Bastian M. Wojek[1,2], Elvezio Morenzoni[1], Dmitry G. Eshchenko[1,2], Andreas Suter[1], Thomas Prokscha[1], Edmond Koller[3], Emmanuel Treboux[3], Øystein Fischer[3], and Hugo Keller[2] — [1]Labor für Myonspinspektroskopie, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland — [2]Physik-Institut der Universität Zürich, 8057 Zürich, Switzerland — [3]DPMC, Université de Genève, 1211 Genève 4, Switzerland

Heterostructures consisting of magnetic/superconducting layers juxtaposed to each other are ideal systems to investigate the interplay of the two order parameters and to study possible interlayer coupling. Recently, so called giant proximity effects have been reported in Josephson devices consisting of HTS electrodes and a barrier of a cuprate in the pseudogap or AF state. Low energy μSR offers the unique possibility to measure on a nanometer scale local field distributions and identify superconducting and magnetic fractions. We used polarized low energy muons to investigate the local properties of single, bi- and tri-layers composed of superconducting $YBa_2Cu_3O_{7-\delta}$ and semiconducting $PrBa_2Cu_3O_{7-\delta}$. Zero field measurements show that the PBCO layers (thickness 50-75 nm) display in all structures the known AF ordering. However, measurements of the field profile $B(z)$ in the Meissner state show that below the critical temperature of YBCO, supercurrents flow without dissipation over the 50 nm thick AF barrier. The measurements indicate that a finite superfluid density may be induced in the AF layer adjacent to the superconducting layer.