Teilprojekt B2.06

Theory of Superconducting and Ferromagnetic Heterostructures

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Introduction

Quasiclassical many-body techniques provide a powerful framework for the microscopic description of electron transport in solids, in particular for the analysis of interaction and disorder effects or of inhomogeneous systems, interfaces, surfaces, and nanostructures. The quasiclassical approximation, leading to Boltzmann-Landau transport equations, allows in many cases for a complete transport theory. It is suited for problems which do not require atomic resolution but are inhomogeneous on a nanoscopic scale. In addition, it covers non-equilibrium effects. Within the quasiclassical approximation, when applied to ferromagnets and heterostructures thereof we found that we can describe two important cases. The first is the case of *weak ferromagnets* where the exchange splitting between the spin-up and spin-down quasiparticle bands are on the same scale as the superconducting energy gap or transition temperature. We found that in this case the important ingredients of devices containing superconducting and ferromagnetic parts are domain walls near the interfaces between the superconductor and the ferromagnet. The second case, which up to date has been studied much less, is the case of *strong ferromagnets* where the exchange splitting between the bands is large compared with the typical superconducting energy scales, reaching the order of the Fermi energy. In this case we found that the important physics is the modification of the superconducting order near the interfaces. In both cases, for weak or strong ferromagnets coupled to superconducting materials, the important new aspects are the presence of *long-range triplet correlations* near the interface. In the case of a weak ferromagnet such correlations are induced by domain walls, whereas in the case of strong ferromagnets such correlations are induced directly at the interfaces between a singlet superconductor and the ferromagnet.

We have studied both devices containing weak ferromagnets and strong ferromagnets. In the latter case we made predictions, some of which have been confirmed in the meantime, while some are still to be tested experimentally. Within the CFN several collaborations with experimental groups have emerged, in particular with the Teilprojekt B2.7.

We proceed now with the description of the specific projects.

1. Proximity effect between superconductors and strongly spin-polarized ferromagnets

Interfaces between materials with different ordered phases present unique opportunities to study the competition between the different underlying mechanisms. One example is the interface between a singlet superconductor, where Cooper pairing occurs between electrons with opposite spin, and a half-metallic ferromagnet, which displays 100% spin polarization. Since these two orders cannot coincide one could expect a very short penetration depth of the proximity effect and a strong suppression of the Josephson coupling. In an earlier funding period within the project B2.6 we have predicted a new type of proximity effect accompanied by a new type of Josephson effect [1]. This proximity effect operates in the presence of spin flip centers in the interface region via spin triplet pairing correlations at the superconducting side of the interface. Based on these ingredients we predicted a Josephson effect in a superconductor-half metal-superconductor heterostructure with a decay length of the order of the usual superconducting correlation length. Our predictions have been confirmed in a first experiment by the observation of a supercurrent through half-metallic CrO_2 [2] and very recently in a number of different setups [3].

Since the materials used in the experiments are not in the ballistic limit, we extended during the reporting period our earlier work to include impurity scattering. We could perform calculations beyond the usual diffusive approximation, allowing us to bridge the entire range from the ballistic to the diffusive limit within a selfconsistent Born approximation. Our results are published in

Nature Physics [B2.6:14]. We have suggested a conversion mechanism from spin singlet to spin triplet supercurrents in the experiment of the Klapwijk group [2] that is based on electron spin precession together with triplet pair rotation at interfaces with broken spin-rotation symmetry. In the diffusive limit the triplet supercurrent is dominated by inter-related odd-frequency s-wave and even-frequency p-wave pairs. In the crossover to the ballistic limit additional symmetry components become relevant. The interface region exhibits a superconducting state of mixed-spin pairs with highly unusual symmetry properties that opens up new perspectives for exotic Josephson devices.

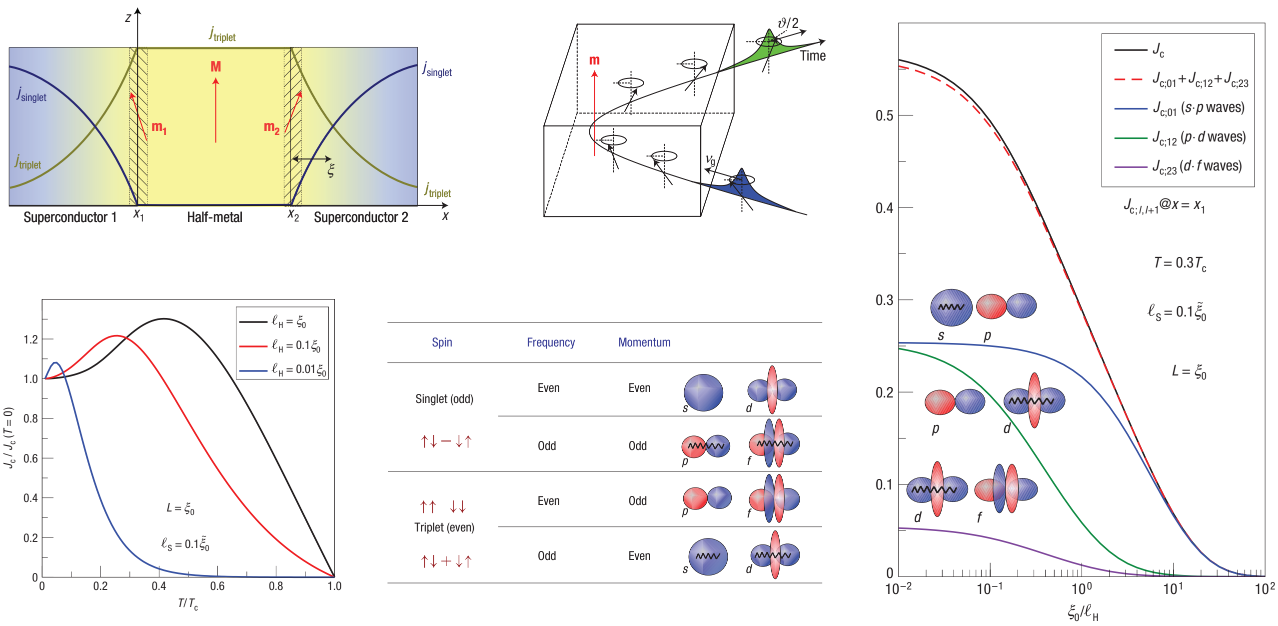

Figure 1. Superconducting pairing correlations of different symmetries in a superconductor/ half-metallic ferromagnet/superconductor Josephson heterostructure shown in the top left. Triplet superconducting correlations are induced by a process that involves the rotation of the quasiparticle spin during reflection processes off the interface between superconductor and ferromagnet, as shown in the middle picture in the top. As a result, an equal-spin-triplet supercurrent flows in the completely polarized ferromagnet, with an unusual temperature dependence of its critical value (shown in the lower left). The decomposition of the supercurrent in its symmetry components is illustrated in the table. In the diffusive limit, toward the right in the right panel, so-called odd frequency s-wave pairing amplitudes are of critical importance. From Ref. [B2.6:14].

The Josephson junction, shown in Fig. 1 top left, consists of a half metal sandwiched between two singlet superconductors. When a phase difference exists between the superconducting order parameters an exotic form of Josephson effect occurs: a singlet supercurrent, $j_{singlet}$ (blue in Fig. 1), is converted to an equal-spin-triplet supercurrent $j_{triplet}$ (yellow), within an interface layer extending for a superconducting coherence length into the electrodes. The equal-spin triplet supercurrent flows through the half-metallic material, whereas the singlet part is completely blocked. The sum of the singlet and triplet currents is constant, obeying the continuity equation.

The conversion process between the singlet and equal-spin triplet supercurrents is triggered by two important phenomena taking place at the interface: (1) spin mixing provides S=1, m=0 triplet correlations near the interface, and (2) breaking of spin-rotation symmetry with respect to the magnetization axis **M** in the half metal enables this m=0 triplet to be rotated into an S=1, m=1 triplet amplitude. Both phenomena are required for a non-vanishing Josephson effect. Spin mixing is the result of different scattering phase shifts that electrons with opposite spin acquire when scattered (reflected or transmitted) from an interface. It results from either a spin polarization of the interface potential or a wave-vector mismatch for spin-up and spin-down particles at the two sides of the interface, or both. It is a robust and ubiquitous feature for interfaces involving strongly spin-polarized ferromagnets. Another, equivalent way of discussing spin mixing, shown in Fig. 1 in the middle of the top raw, is in terms of a spin precession around the interface magnetization vector when wave packets penetrate the interface region.

We find that a peak in the temperature dependence of the critical current, shown in the lower left panel of Fig. 1, is a robust feature for clean and disordered half metals. In order to connect to recent discussions in the community we studied the symmetry properties of the Cooper pairs involved [B2.6:14, B2.6:6]. The four symmetry types of Cooper pair allowed by the Pauli exclusion principle are listed in the table in Fig. 1. The dependence of the several symmetry components on the quasiparticle mean free path is illustrated in Fig. 1, right panel. In moderately disordered half metals the supercurrent is carried predominantly by odd-frequency *s*-wave and *d*-wave amplitudes, multiplied with even-frequency *p*-wave and *f*-wave amplitudes. In the diffusive limit, the supercurrent is dominated by the product of the *s*-wave and the *p*-wave amplitudes.

The mechanism of the current conversion we proposed in [B2.6:14] leads to a natural explanation of several findings of the experiment [2]:

- a finite Josephson current in the half metal;
- hysteretic shifts of the equilibrium phase difference over the junction depending on the magnetic pre-history;
- after subtraction of the hysteretic shifts the Josephson junctions involving half metals are π-junctions;
- sample-to-sample fluctuations in the magnitude of the critical current.

In Ref. [B2.6:23] we extended our theory from half-metallic ferromagnets to ferromagnets with strong, but not complete spin-polarization, appropriate for most ferromagnetic elements, like Fe, Ni, Co. The complications arising in this regime are mainly due to the necessity of matching three quasiclassical propagators at the interface, since there exist now a second band in the FM. This first required a generalization of the known boundary conditions for the quasiclassical Green's function, which was recently derived by one of us [B2.6:26]. The presence of a minority band in the FM leads to important new physical effects. We found that the temperature anomaly predicted for the half metallic case is suppressed with decreasing spin-polarization (Fig. 2, left). The interaction of the two FM spin-bands at the interfaces via spin-flip scattering entails an exotic current-phase relation, if the junction is not in the tunneling limit. It led us to the prediction of a pure spin-supercurrent in a SC/FM bilayer terminated by a spin-active surface (Fig. 2, right).

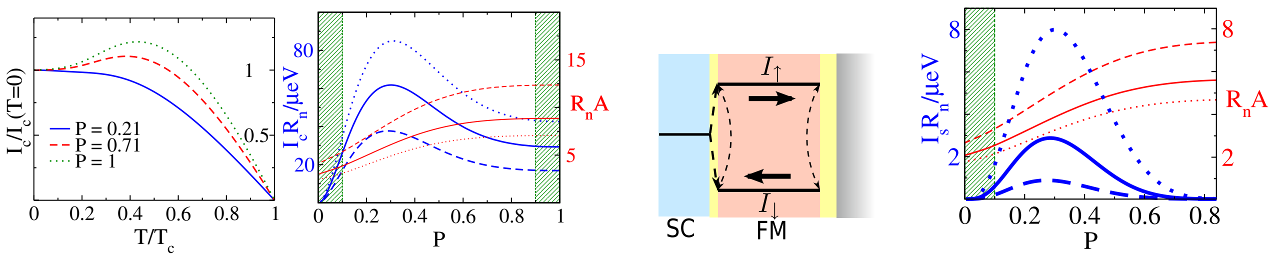

Figure 2. Supercurrents through strongly spin-polarized ferromagnets. The plot on the left shows the disappearance of the temperature anomaly with decreasing spin-polarization P. The plot next to it shows the critical current and the normal state resistance of the junction as a function of P. The supercurrent is maximal for an intermediate value of P. The sketch shows the spin-supercurrent induced in a bilayer structure by spin-active scattering. As shown on the right, this effect vanishes both in the half metallic (P=1.0) and in the non-magnetic (P=0) limit. From Ref. [B2.6:23].

In another approach [B2.6:16] we extended our theory by describing the dc Josephson effect and Andreev bound states in superconducting junctions with a half metal. For sufficiently clean metals we provided a complete non-perturbative description of the Josephson current for arbitrary transmissions and spin-flip scattering parameters for both interfaces. Our analysis demonstrates that both the Josephson current and the Andreev bound states crucially depend on the strength of spin-flip scattering and show a rich variety of features which can be tested in future experiments.

Recently, two experimental groups found evidence for a triplet Josephson effect with Co, using Holmium resp. a multilayer structure of magnetic materials [3] as spin-active interlayer. We therefore believe that our predictions will be an important stimulus for further experimental activity in this field.

2. Multiple Andreev reflections in diffusive heterostructures

The odd-frequency pairing correlations mentioned above play an important role in diffusive heterostructures. We have recently studied resonant Andreev processes in a superconductor/normal metal bilayer with a spin-active interface for quasiparticles below the Thouless energy of the normal metal [B2.6:21]. For spin-inactive interfaces the normal metal exhibits the famous minigap that scales with the Thouless energy and with the interface transmission probability. We have found that the above-mentioned spin rotation of the quasiparticle spin, when reflecting off an interface, leads to dramatic consequences, which are illustrated in Fig. 3. If the value for the spin rotation angle exceeds the value for the tunneling probability, singlet correlations are completely suppressed at the chemical potential in favor of odd-frequency triplet correlations. This can be seen in Fig. 3 for low values of the tunneling probability $T_0<\theta_N$. The local density of states at the top of the bilayer is at the same time enhanced in the region where the minigap would occur if the interface would be spin-inactive. In Ref. [B2.6:28], we have shown that this transition is a robust effect, it prevails in the presence of spin-orbit scattering and appears for different limiting cases of the Fermi-surface geometry.

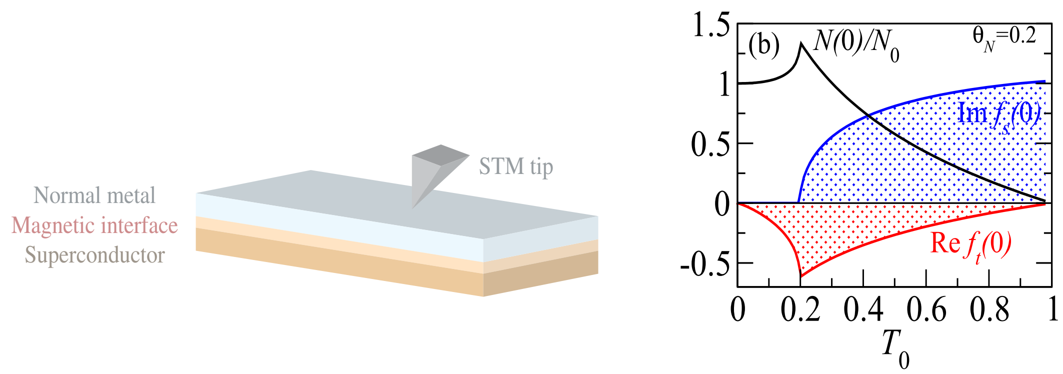

Figure 3. The local density of states on top of a normal metal is enhanced for sufficiently weak tunneling probability T_0, when the interface is spin active with spin rotation angle θ_N. At the same time, the pairing correlations are pure odd-frequency triplet correlations, $f_t(0)$. Only above a critical value of T_0 singlet correlations $f_s(0)$ are present as well. From Ref. [B2.6:21].

We have presented in Ref. [B2.6:2] a theory of the current-voltage characteristics in diffusive superconductor–normal-metal–superconductor junctions. By solving the time-dependent Usadel equations we were able to describe the phase coherent transport for arbitrary length of the normal wire. We show how the interplay between proximity effect and multiple Andreev reflections gives rise to a rich subgap structure in the conductance and how it is revealed in the nonequilibrium distribution function. Our main results are that (i) we describe the subgap structure in the conductance for the whole range of lengths from the short-junction limit to the incoherent regime, (ii) we reproduce an additional peak above the superconducting gap in the conductance, in agreement with experiments, and (iii) we predict the signatures of the proximity effect in the distribution function, which can be measured.

3. Point-contact Andreev spectroscopy and the role of spin-active scattering

Since spin-active scattering in the interface region between superconducting and ferromagnetic materials turned out to be of crucial importance for the creation of triplet pairing correlations in heterostructures, we decided to investigate the mechanisms underlying these effects in more detail. As discussed earlier, we identified the spin-rotation effect and spin-flip scattering as the decisive ingredients of the long-range triplet proximity effect. It is therefore obvious to ask for the magnitude of these effects given a microscopic model of the interface region. For this purpose we considered an interface scattering potential on the microscopic scale [B2.6:27] and numerically derived the normal state scattering matrix of the interface, which enters the boundary conditions for the quasiclassical Green's function. We found that a ferromagnetic interface region, i.e., a spin-split scattering potential, leads naturally to a spin-rotation effect. However, for the usually considered box or delta-function potentials, this effect is rather weak, while the more realistic case of a scattering potential that is smooth on the interatomic scale leads to a sizable magnitude of the spin rotation angle, ϑ (Fig.4). Moreover, we found that due to kinematic constraints for the scattered quasiparticles, the Fermi-surface geometry of the bulk materials adjacent to the interface will play an important role.

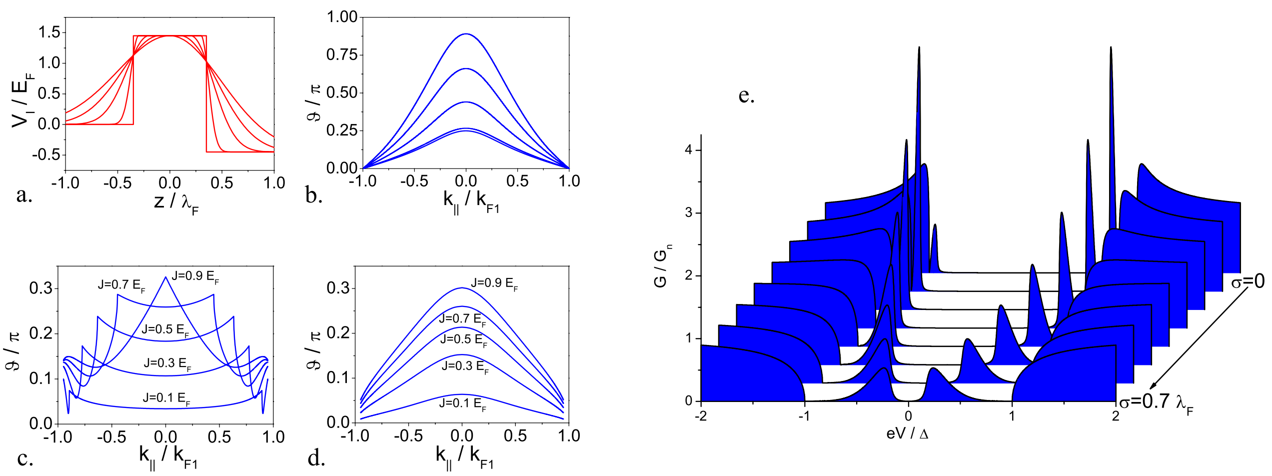

Figure 4 Spin-mixing angle and Andreev bound states - a. scattering potential as function of the position, b. spin-mixing angle as function of the conserved momentum component (momentum parallel to the interface) of the incident quasiparticle for the scattering potentials displayed in a. The value of the ferromagnetic exchange field is J=0.7 E_F. . The mixing-angle increases as the potential becomes smoother. c. and d. spin-mixing angle for a box-potential with a potential width of 0.5 π/λ_F (c.) and 2.0 π/λ_F (d.) for different values of the exchange field J. The anomalous features in c. are related to the Fermi-surface geometry and disappear for an interface in the tunneling limit (d.), e. Andreev spectra at zero temperature for the scattering potentials displayed in a. The potential becomes smoother from back to front. Andreev bound states emerge due to the spin-mixing and move deeper into the energy gap as the spin-mixing angle increases. From Ref. [B2.6:27].

Since such interface properties cannot be probed directly, we generalized the standard Blonder-Tinkham-Klapweijk (BTK)-theory of conductance spectra of metallic superconducting contacts [4] to fully account for spin-active scattering and a spin-polarized Fermi-surface. This leads to several important effects. The spin-mixing effect itself leads to spin-polarized bound states at the interface (Fig.4), which, given a sufficiently strong spin-rotation effect, will show up as subgap peaks in the conductance spectrum. Furthermore, spin-flip scattering will induce a new type of Andreev reflection where the transmitted particle and the coherently reflected hole have the same spin. This process can not be suppressed by the spin-polarization of the FM and will lead to important modifications of the spectrum if the spin-polarization is high.

Evidence for the above-mentioned bound states has recently been found by an experimental group within the CFN (D. Beckmann, B2.7). In collaboration with an experimental group from Nottingham and a theorist from Prague we successfully used this theory to explain the conductance spectra of (Ga,Mn)As [B2.6:34], which is one of the candidates for ferromagnetism at room temperature in semiconductors and hence a promising material for spintronics applications. It was known that the usual extended-BTK model was not able to fit these spectra and had to introduce an 'effective' temperature which was much higher than the actual temperature of the sample. Our theory was able to fit the experimental data with the real temperature by taking into account a spread resistance related to the poor conductivity of the sample (Fig.5). For nominally 7% Mn doped GaAs, we find a spin-polarization between 55 and 59%, which is substantially lower than what has been predicted based on the BTK-theory. We also show that electronic structure calculations based on the k*p kinetic exchange model for (Ga,Mn)As support an intermediate spin-polarisation at this doping level.

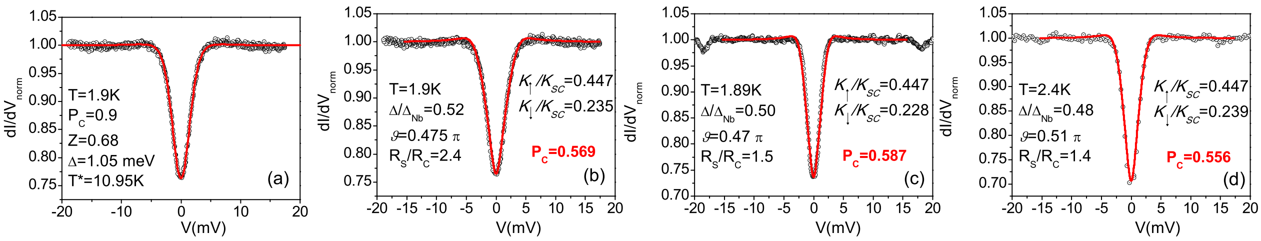

Figure 5. GaMnAs PCAR-spectra, fitted with the BTK-model and an effective temperature of T*=10.95K (on the left), and three fits of different samples with the spin-active model. From Ref. [B2.6:33].

As a second application of our theory we performed a reanalysis of various conductance spectra of CrO_2 available in the literature [B2.6:33]. These data had all been fitted with the BTK-theory. A general problem of this procedure was that it gave a large spread in the extracted spin-polarization of the material, which was believed to be at least close to half metallic, i.e. P≈100%, as confirmed by other experimental techniques [4]. Since the triplet Josephson-current through CrO_2 already indicated that spin-active scattering was likely to play a role, we decided to fit these data with our theory, keeping P fixed at 100%, and found that our fitting works equally well or even better, since no suppression of the SC gap needs to be taken into account (Fig.6, left). In particular, this resolves the above-explained contradiction. To eventually settle this issue in a new generation of experiments, we identified two characteristic features that allow for a clear distinction between the two models. First, the conductance at zero bias and zero temperature will always be zero in the spin-active model (using P=100%), while the BTK model predicts a finite zero bias conductance if P<100%. Hence, measuring spectra at even lower temperatures may help to identify the right model. Second, there is clear difference in the excess current (defined as the difference between the current in the superconducting and the normal state of the junction at high voltage) between the two models for a wide range of interface transparencies (Fig.6, right).

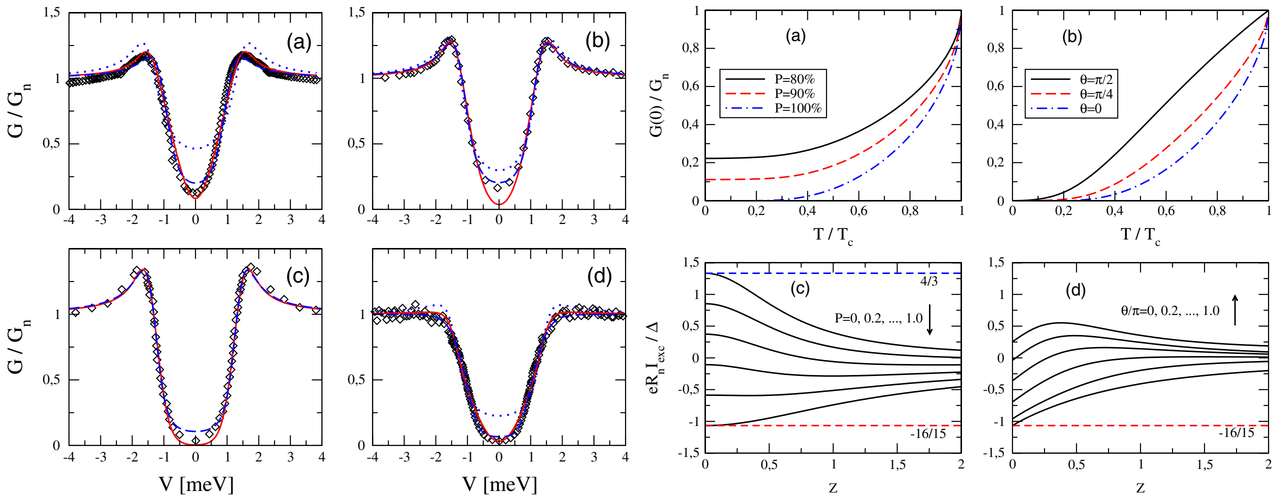

Figure 6. Andreev spectra of CrO_2 . Fits to four data sets are shown on the left, the spin-active model (red) is compared to the BTK fit (blue dashed with the SC-gap as fit parameter, blue dotted using the bulk value of the SC-gap). On the right, the zero-bias conductance is plotted against temperature in the top panel, (a) BTK-model, (b) spin-active model. In the lower panel, the excess current is plotted against Z, the parameter controlling the transparency of the interface, for (c) the BTK-model and (d) the spin-active model. From Ref. [B2.6:33].

4. Superconducting proximity effects in systems with spiral magnetic structures

Recently there has been rapid progress in the field of chiral magnetism that raises the expectations for applications of chiral magnets in spintronics. Chiral order occurs in inversion asymmetric magnetic materials that in the presence of spin-orbit coupling give rise to a Dzyaloshinskii-Moriya interaction. This interaction favors a directional noncollinear (spiral) spin structure of a specific chirality over the usual collinear arrangement favored by the Heisenberg exchange interaction. A well-studied chiral magnet (CM) is the transition-metal compound MnSi, with the spiral wave length of 180 Angstrom. Nanoscale magnets or magnetic systems with reduced dimensionality that frequently lack inversion symmetry due to interfaces and surfaces are expected to exhibit chiral magnetism. This has been confirmed by the recent observation of a spin spiral structure in a single atomic layer of manganese on a tungsten substrate. In an earlier funding period, we have studied in a number of publications the superconducting proximity effect with a magnet that exhibits a spiral magnetic order [5-7].

In Ref. [B2.6:15] we studied the π phase in a superconductor-ferromagnet-superconductor Josephson junction with a ferromagnet showing a cycloidal spiral spin modulation with in-plane propagation vector. Our results reveal a high sensitivity of the junction to the spiral order and indicate the presence of 0-π quantum phase transitions as function of the spiral wave vector. We find that the chiral magnetic order introduces chiral superconducting triplet pairs that strongly influence the physics in such Josephson junctions, with potential applications in nanoelectronics and spintronics.

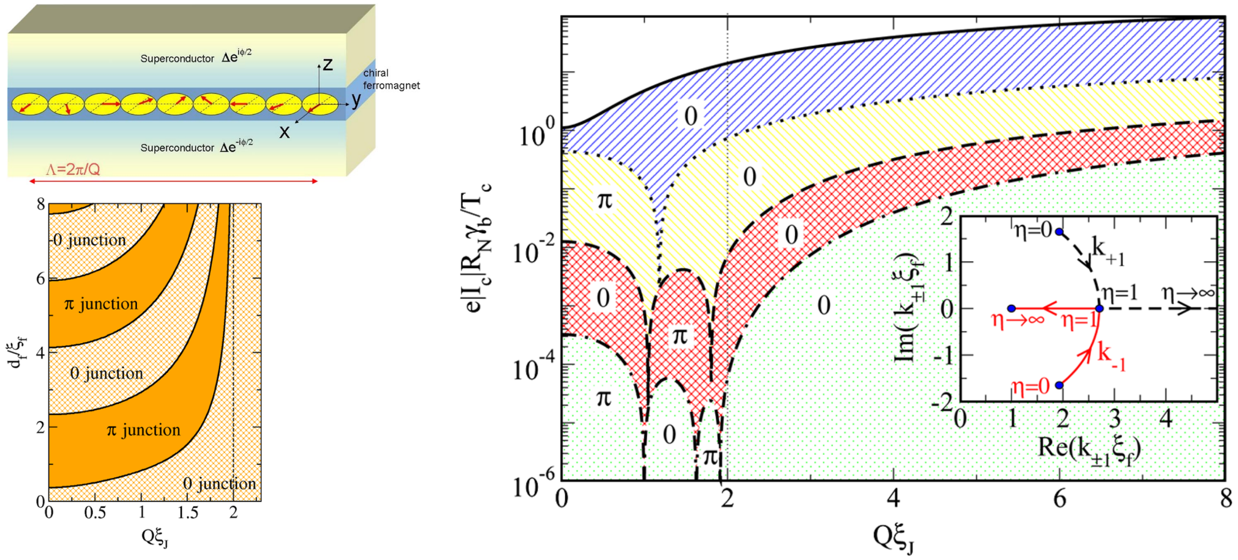

Figure 7 Left top: S-CM-S Josephson junction where CM is a chiral ferromagnet; the spins are confined to a plane (the *x*-*y* plane) parallel to the spiral propagation direction (the *y* axis). Bottom: corresponding (d_f - Q) phase diagram. Right: Josephson critical current I_c vs the spiral wave vector Q for a few thicknesses of the ferromagnet: curves from top to bottom d_f/ξ_f = 0.1, 1, 3, 5. The inset shows the flow of the real and imaginary parts of the momentum eigenvalues with varying $\eta=(Q\xi_J)^2/4$ for the first Matsubara frequency. All results are for $T=0.1T_c$ and $J=20T_c$. From Ref. [B2.6:15].

The presence of a spin spiral can change the ground state of the Josephson junction and lead to a transition between a π junction and a 0 junction for a critical spiral wave vector. This effect is shown in Fig. 7. The dependences of the Josephson effect on magnet thickness and temperature depend sensitively on the wave vector of the chiral order in the magnet. We predict that a quantum-critical point should exist in the phase diagram for suitably chosen sample parameters, with a phase diagram as in the lower left of Fig. 7.

5. Spin-polarized Andreev states in non-centrosymmetric materials

The role of chirality and spin-orbit coupling in materials and nanostructures is a very active subject in the fields of spintronics, superconductivity, and magnetism. The unusual properties of non-centrosymmetric (NCS) materials originate from the crystal structure that lacks a center of inversion, allowing for pronounced spin-orbit (SO) coupling that is odd in the electron momentum, and leading to a chiral ground state. The resulting two-band nature of NCS metals leads to effects reminiscent of semiconductor physics, such as birefringence and spin polarization of the electron wave packet. Especially promising is the presence of charge-neutral spin currents in the ground state. The recently discovered class of NCS superconductors combines the strong SO coupling that governs the metallic bands with a nontrivial spin structure of the superconducting (SC) order parameter due to lack of parity. As a result, one may expect that spin transport in the SC phase exhibits novel features compared to usual superconductors. These features are especially prominent near surfaces and interfaces, where the physics is controlled by the Andreev bound states, built as a result of particle-hole coherent scattering.

We have investigated in a number of publications [B2.6:18-20] the ground state properties of a non-centrosymmetric superconductor near a surface. We have determined the spectrum of Andreev bound states due to surface-induced mixing of bands with opposite spin helicities for a Rashba-type spin-orbit coupling. We find that the order parameter suppression qualitatively changes the bound state spectrum. The spin structure of Andreev states leads to a spin supercurrent along the interface, which is strongly enhanced compared to the normal-state spin current. Particle and hole coherence amplitudes show Faraday-like rotations of the spin along quasiparticle trajectories.

We consider the Rashba-type spin orbit coupling entering the Hamiltonian as

$$\mathcal{H}_{\text{kin}} = \sum_{\mathbf{k}\mu\nu} c^{\dagger}_{\mathbf{k}\mu}(\xi_{\mathbf{k}} + \alpha \mathbf{g}_{\mathbf{k}} \boldsymbol{\sigma})_{\mu\nu} c_{\mathbf{k}\nu}$$

that defines for each Fermi surface point a spin orbit vector g_k. The corresponding vector field is shown in Fig. 8 on the left. It results in spin polarized surface Andreev bound states. As a result, there are spontaneous spin currents in the ground state (shown in the right subpanels), that have a spin polarization pointing in the z-direction at the surface (in Fig. 8, the surface normal is the x-direction). The spatial oscillations of the spin currents are determined by the spin-orbit strength α and appear due to Faraday-like rotations of the spin coherence functions along quasiparticle trajectories. We also found that the suppression of superconductivity near the surface gives rise to a finite-bias peak in the surface density of states that can be probed by point contact tunneling. Our predictions open the route to future investigations and applications of spin transport in systems containing superconductors without center of inversion, and for their use in spin-based devices.

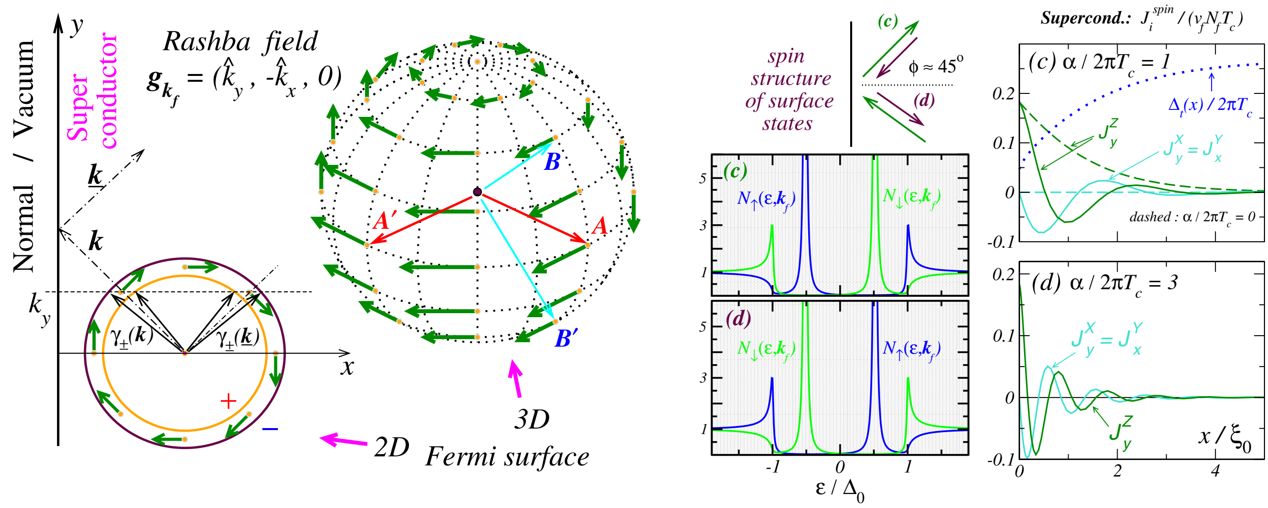

Figure 8. Left: A map of the spin-orbit vector in momentum space for the Rashba form. On reflection the spin-orbit vector g_k may change, e.g., from *A* to *A'*, or not, e.g., from *B* to *B'*. The scattering geometry is shown on the left. Right: Spin-resolved surface DOS for two trajectories, that are indicated on top. The spin polarization of the Andreev bound states leads to ground state spin currents that are shown in the right two subpanels for two different values of spin-orbit interaction. Here, J_i^{α} denotes the current in *i*-direction (*i=x,y,z*) of spin in α direction (α*=x,y,z*). From Ref. [B2.6:19].

6. Crossed Andreev reflections

We have carried out intensive investigations of both local and non-local spin-sensitive Andreev reflection in hybrid metallic structures containing superconducting (S) and normal/ferromagnetic (N/F) electrodes [B2.6:8,10-12, 17, 24, 25, 29]. The term non-local conductance refers to transport processes in multi-terminal devices which correlate charge transfer at different contacts. In practice, this can be quantified by the conductance dI_1/dV_2, i.e. the current at contact 1 derived with respect to the voltage at contact 2. It was known for a while that at low temperatures and bias voltages the non-local conductance of a NSN structure is dominated by only two processes. Elastic co-tunneling (EC), which implies the tunneling of a quasiparticle from one N-electrode to the other through the superconductor, gives a negative contribution to dI_1/dV_2. Crossed Andreev reflection (CAR), the Andreev process where the incident particle enters from one contact and the coherently reflected hole is emitted into the other, provides a positive contribution. CAR may be seen as a source of spatially separated, entangled quasiparticles, which motivates the interest in such devices. To lowest order of the perturbation theory in the small transparency of the junctions, the two contributions cancel and dI_1/dV_2=0. Consequently, much effort – both experimentally and theoretically – is devoted to identifying scenarios where this cancellation can be overcome.

In [B2.6:8,11,12,29], a microscopic theory of non-local electron transport in ballistic three-terminal FSF and NSN structures with spin-active interfaces was developed in the frame of the quasiclassical Eilenberger formalism. This theory demonstrates that crossed Andreev reflection in such devices is highly sensitive to electron spins and yields a rich variety of properties of non-local conductance which are described non-perturbatively at arbitrary voltages, temperature, spin-dependent interface transmissions and their polarizations. One of the striking predictions of this theory is that no crossed Andreev reflection can occur in structures with fully open interfaces [B2.6:8,11].

Further interesting effects in these structures are related to spin-sensitive Andreev reflection emerging in FSF structures in the limit of a 'strong' ferromagnet (or a half metal) [B2.6:11]. In particular, the presence of spin-active scattering at the magnetic interfaces leads to a complicated subgap structure of the non-local conductance. Recently [B2.6:29], we were able to show that this can be fully understood by CAR und EC processes mediated by the interface bound states, which are induced by the spin-rotation effect (Fig.9) at both interfaces. Moreover, we found that these bound states effectively interact, repelling each other if the junction is short and if the states are degenerate in energy. This resembles the hybridization of atomic orbitals when atoms are bonded in a molecule.

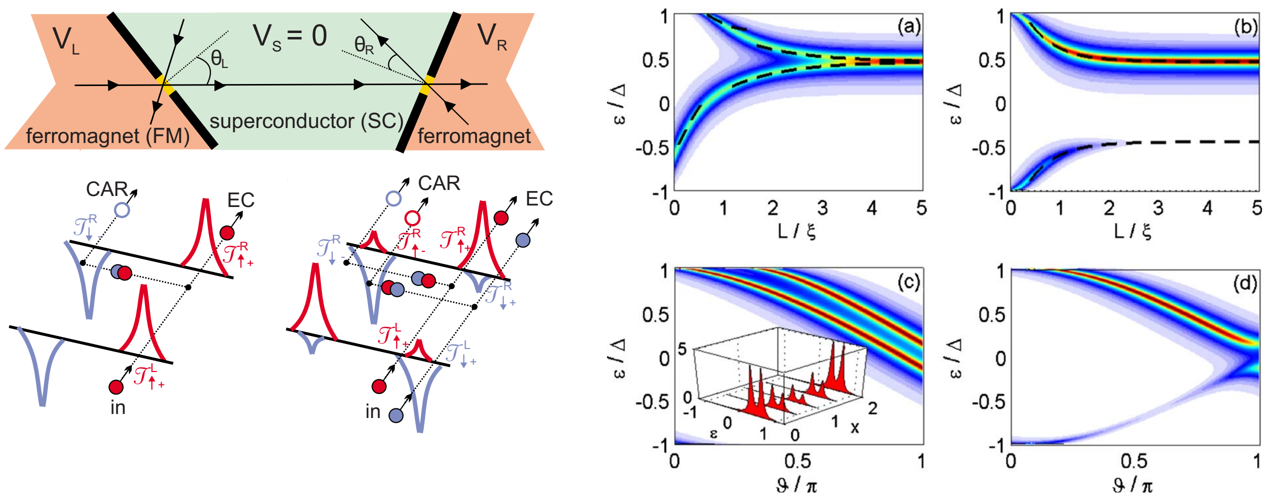

Figure 9. The setup is shown in the upper left, two ferromagnetic electrodes are attached to a superconductor. Spin-active scattering at the two interfaces results in two pairs of Andreev bound states interacting with each other. On the right, the bound state energy is plotted against the length of the junction (top panel) for parallel (left) and antiparallel (right) orientation of the magnetization in the two FM electrodes. In the lower panel, the bound state position is plotted against the spin-rotation angle theta. The sketch on the lower left illustrates how the CAR and EC contribution to the non-local conductance can be understood as tunneling processes through these interface bound states. From Ref. [B2.6:29].

Complementary to the work on ballistic heterostructures, we also investigated non-equilibrium and disorder effects in NSN structures. This includes in particular the interplay between crossed Andreev reflection (CAR), elastic co-tunneling (EC), and charge imbalance, the latter being a difference in the chemical potentials of quasiparticles and pairs induced by quasiparticle injection. In [B2.6:10] we studied three-terminal NSN structures modeled by a chaotic superconducting quantum dot attached to one superconducting and two normal electrodes. This formulation allows accounting for non-equilibrium effects and disorder in the superconductor. We could demonstrate [B2.6:10,17] that the combination of two competing processes – Andreev reflection and charge imbalance – yields a pronounced peak in the temperature dependence of non-local resistance, which fits to recent experimental observations by Beckmann et al. (CFN subproject B2.7).

In Ref. [B2.6:24] we have incorporated the following additional effects into the theory: (i) proximity effect in the normal leads, (ii) inverse proximity effect in the superconductor and (iii) arbitrary transparency of the junctions. We have demonstrated that the combined effect of all these phenomena results in negative dI_1/dV_2, i.e. EC turns out to be stronger than CAR. At the same time, in the experiments positive dI_1/dV_2 is also often observed. In particular, the experiment [B2.6:30] suggests that positive value of the non-local conductance is most probably related to the Coulomb interaction between electrons. We have shown that positive dI_1/dV_2 may indeed be a result of Coulomb interaction in a certain range of parameters [B2.6:31]. It may also be observed under ac bias [B2.6:25].

7. International Workshop

The physics described in the report above was in part the subject of an international Workshop on "Spin helicity and chirality in superconducting and semiconductor nanostructures: novel phenomena and emergent functionality'', which M. Eschrig and G. Schön had organized in Karlsruhe together with Ilya Vekhter. Details of the workshop are shown below.

For references labeled as [B2.6:…] see the list of publications of the subproject.
Additional References:

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International Workshop in Karlsruhe

"Spin helicity and chirality in superconducting and semiconductor nanostructures: novel phenomena and emergent functionality''

July 13-17 2008, Karlsruhe
Web page: http://i2cam.org/conference/Karlsruhe2008/

Organizers:
Matthias Eschrig and Gerd Schön (University of Karlsruhe, Germany)
Ilya Vekhter (Louisiana State University, USA)

We have organized a highly interactive workshop involving researchers working in areas of:

- spin quantum hall effect and chiral transport in semiconductors,
- superconductor-chiral magnet nanostructures,
- chiral spin order in magnetism and superfluidity,
- superconductivity without inversion symmetry,
- adjacent fields.

Since there is much overlap between methods and phenomena in these diverse areas, the workshop aimed to establish the connections and foment new understanding across the subfield boundaries among both theorists and experimentalists who participate in the workshop.

The workshop has been partially financed by I2CAM, USA (30.000 $), partially by CFN (8.000 €), and partially by Forschungszentrum Karlsruhe (5.000 €).

Participants:
Prof. Phil Adams, LSU, USA
Dr. Sergey Artyukhin, Groningen, Netherlands
Prof. Yasohiro Asano, Hokkaido, Japan
Dr. Samvel Badalyan, Regensburg, Germany
Dr. Detlef Beckmann, Karlsruhe, Germany
Dr. Kirsten v. Bergmann, Hamburg, Germany
Dr. Benedikt Binz, Köln, Germany
Prof. Alexei Bogdanov, Dresden, Germany
Dr. Philip Brydon, Stuttgart, Germany
Prof. Maximilien Cazayous, Paris 7, France
Prof. Thierry Champel, CNRS, France
Dr. Olga Dimitrova, ICTP, Italy
Prof. Konstantin Efetov, Bochum, Germany
Prof. Yakov Fominov, Landau Institute, Russia
Dr. Gernot Goll, Karlsruhe, Germany
Prof. Daniel Khomskii, Köln, Germany
Dr. Alexey Kovalev, Texas A&M , USA
Dr. Miodrag Kulić, Q-Spintronics
Dr. Tomas Löfwander, Chalmers U, Sweden
Sabrina Leslie, Berkeley, USA
Jacob Linder, Trondheim, Norway

Dr. Dirk Manske, Stuttgart, Germany
Prof. Jan Martinek, Poznan, Poland
Prof. Eugene Mishchenko, Utah, USA
Prof. Laurens Molenkamp, Würzburg, Germany
Prof. Dirk Morr, UI-Chicago, USA
Prof. Satoru Nakatsuji, Tokyo, Japan
Dr. Tamara Nunner Berlin, Germany
Prof. Victor Petrashov, Royal Holloway, UK
Prof. Christian Pfleiderer, Munich, Germany
Dr. Jana Poltierova Vejpravova, Prague, Czech Rep.
Dr. Stephan Rachel, Karlsruhe, Germany
Prof. Zoran Radović, Belgrade, Serbia
Prof. Anatoli Sidorenko, Kishinev, Moldova
Prof. Manfred Sigrist, Zurich, Switzerland
Mihail Silaev, Nizhni Novgorod, Russia
Prof. Jairo Sinova, Texas A&M, USA
Prof. Masahito Ueda, Tokyo, Japan
Dr. Anton Vorontsov, Wisconsin-Madison, USA
Prof. Shoucheng Zhang, Stanford, USA
Prof. Guo-qing Zheng, Okayama, Japan

ICAMNEWS
A Quarterly Newsletter of the Institute for Complex Adaptive Matter

Spin Helicity Workshop Aims to Bring Together Several Communities of Electron Physicists

The idea that future devices may rely on manipulating electrons not through their charge, but through their intrinsic magnetic moment, or spin, has inspired research on how to control the transport, or movement, of spins and how to manipulate and utilize the magnetic texture of new compounds. Some materials and man-made structures that are being explored in this context include

- interfaces between superconductors and magnets;
- chiral (preferentially left- or right-handed) magnetic order in bulk and at surfaces;
- spin current and the spin quantum Hall effect in semiconductors and nanodevices;
- superconductivity without inversion symmetry;

and other subjects. Although these are diverse areas, there is much overlap between the phenomena they study and methods they employ. Matthias Eschrig and Gerd Schön of the Universität Karlsruhe and Ilya Vekhter of Louisiana State University hope to involve theorists and experimentalists from all these subfields in discussion, to explore the connections and promote new understanding. They are organizing an I2CAM Exploratory Workshop entitled “Spin Helicity and Chirality in Superconductor and Semiconductor Nanostructures” to be held in Karlsruhe, Germany July 13-17.

The idea for this conference grew out of an ICAM Junior Fellow award, in which Vekhter and Eschrig collaborated with former postdoc Anton Vorontsov in studying the interfaces of superconductors with no inversion symmetry. Eschrig has expertise in studying ordering phenomena near interfaces, while Vekhter has a longstanding interest in exotic superconductivity. They soon realized that similar phenomena appear in different contexts in their work and that of their colleagues, and thought it would be exciting to bring the experts in several fields together to discuss diverse subjects with the same underlying principle. Together with Gerd Schön, who is a renowned expert in mesoscopic physics, they decided to organize a workshop to achieve this goal.

The workshop will be structured so that each day will focus on a different class of phenomena, beginning with a plenary talk outlining the issues for an audience that knows the general language but not the specifics of the problem. These will be followed by invited and contributed talks, with discussion time built in, as well as poster sessions and informal discussion. Speakers will be required to stay at least three days and participants for the entire workshop, to encourage cross-fertilization of ideas.

Topics of invited talks will include ferromagnet-superconductor interfaces, superconductors without inversion symmetry, spin transport in semiconductors, exotic helical and chiral magnetic states, and selected experimental structures and exotic materials. The University of Karlsruhe includes a Center for Functional Nanostructures and an active research program on some of the subjects discussed.
For further information on this event, visit the website http://www.i2cam.org/conference/Karlsruhe2008/.

By Karie Friedman, ICAMNews, April 2008