Superspintronics: Spintronic aspects of superconducting nanostructures

Wolfgang Belzig

Quantum Transport Group, Fachbereich Physik, Universität Konstanz
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Collaborations

- Yu. V. Nazarov (TU Delft)
- A. Cottet, C. Bruder, M. Lee (Basel)
- M. Zareyan (IASBS Zanjan, MPIPKS Dresden)
- N. M. Chtchelkatchev (Landau Institute)
- J.-P. Morten, A. Brataas (Trondheim)
- D. Huertas-Hernandez (Yale)
- M.-S. Choi, K. Kang (Korea University)
Superconductor(S)/Ferromagnet(F) heterostructures

- Motivation
- Density of states oscillations (SF)
- $\pi$-Josephson junctions (SFS)
- Supercurrent through a quantum dot (SDS)
- Spin valve/spin diffusion
- Conclusions/Outlook
Superconductor (S)
- macroscopic quantum-phase state i.e. characterized by macroscopic wave function $\Delta e^{i\phi}$
- Cooper pairs are spin-singlets

Ferromagnets (F)
- macroscopic quantum-spin state, i.e. finite polarization and spin splitting $\vec{m}$
- building block is spin-triplet

S and F are antagonistic quantum states

Possibility of manipulation in heterostructures
**General properties of SF**

**Superconductor:** attractive interaction through virtual phonons

\[ k_{\uparrow} - k_{\downarrow} = 0 \]

**Magnetism:** Bandsplitting by exchange interaction

\[ E_{\text{ex}} - E_{k_{0}} + q \epsilon(k) \]

Spin splitting \( k_{\uparrow} \neq k_{\downarrow} \)

[Fulde+Ferrel (1964); Larkin+Ovchinnikov (1965)]

Cooper pairs with momentum \( 2q = \frac{2E_{\text{ex}}}{\hbar v_{F}} = \frac{1}{\xi_{F}} \neq 0 \)

Macroscopic wave function: \( \Delta \cos(2qr) \) or \( \Delta e^{i2qr} \)

spin dependent pair wave function/supercurrent!
Density of states oscillations

Can we detect the spatial structure $\sim \cos(2qr)$?

Difficult in bulk!

- thermodynamic properties almost unchanged
- strong suppression by disorder

**Heterostructures**: ferromagnetic layer on S

- magnetization is separated from superconductor
- Cooper pair extends into F $\rightarrow$ finite $q$
- superconducting properties oscillate with distance

Example: BCS density of states $N_{BCS}(E) = |E|/\sqrt{E^2 - \Delta^2}$

$$N_F(E, x) - 1 \approx \gamma N_{BCS}(E) \cos(x/\xi_F) e^{-x/\xi_F}$$
Experimental observation

**Tunnel spectroscopy** in SFI-structure: [Kontos et al. PRL (2001)]

weak ferromagnet:
\[ \text{Pd}_{1-x}\text{Ni}_x \], \( x = 1-10\% \), \( T_c = 0 - 100K \)

thin F layers: \( x = 1 - 10\text{nm} \approx \xi_F \)

low temperature: \( 100mK \)

Detection of \( \cos(2qx) \)-oscillations
Theoretical explanation

**Thin SF-layer** with diffusive interface scattering

[Zareyan, Belzig, Nazarov, PRL (2001); PRB (2002)]

Oscillation of Andreev states:

\[ E_B(L) = \Delta \cos(\alpha(L) + 2qL) \]

\( \alpha(L) \): normal phase shift

Averaging over length distribution

\[ N(E) = N_0 \int dL p(L) \delta(E - E_B(L)) \]
/accounts for interface roughness

Model explains experimental observation of \( \cos(2qr) \)
Summary on SF-DOS oscillations

- detection of $\cos(2qr)$ Cooper pairs wave function
- explanation by Andreev state oscillations

Other works:
- diffusive (strong) ferromagnets [Buzdin, 02]
- minigap in diffusive (weak) ferromagnets [Fazio+Lucheroni, 99]
- experimental characterization of pair breaking by F [Kontos et al., 04]
Spin-dependent Josephson contacts (SFS)

**Josephson contact** (without F):

\[ E^0_J(\phi) \text{ depends on phase difference } \phi \]

Supercurrent:

\[ I_S(\phi) = -\frac{2e}{\hbar} \frac{\partial E_J(\phi)}{\partial \phi} \]

Phase-dependent band structure

**magnetic layer:**

spin-dependent phase shift

\[ \delta \phi = 2qL = 2\frac{h_{ex}L}{\hbar v_F} \]

Result:

Spin-dependent band splitting:

\[ E_J(\phi, H_{ex}) = \frac{1}{2} \left[ E^0_J(\phi + \delta \phi/2) + E^0_J(\phi - \delta \phi/2) \right] \]

- spin-up band
- spin-down band
0-\(\pi\) transition for a tunnel contact

Band splitting in a magnetic tunnel junction \((T \ll 1)\)

**normal junction**

\[
E^0_J = \frac{\hbar}{2e} I_c \cos(\phi)
\]

**Spin-splitting**

\[
E_J(\phi) = -\frac{\hbar}{2e} I_c(\delta\phi) \cos(\phi)
\]

\(I_c(\delta\phi) = I_c \cos(\delta\phi)\)

**SFS junction**

\[
\Sigma
\]

\[
\delta\phi = 0.4\pi
\]

**reduced amplitude**

Result:

\[
E_J(\phi) = -\frac{\hbar}{2e} I_c(\delta\phi) \cos(\phi)
\]

\[
I_c(\delta\phi) = I_c \cos(\delta\phi)
\]

**sign change for** \(\delta\phi > \pi/2\)

\[
\delta\phi = \pi/4, \pi/2, 3\pi/4, \pi
\]

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0-π transition for open contacts

Open contacts: Andreev bound states

Energy of the bound state:

\[ E_{B\sigma}(\phi) = \pm \Delta \cos((\gamma(\phi) + \sigma \delta \phi)/2) \]

\[ \cos(\gamma(\phi)) = 1 - T + T \cos(\phi) \]

depends strongly on phase shift \( \delta \phi \)

(Plot: \( T = 0.7, \delta \phi = \pi/2 \))

Temperature-dependent 0-π transition

- \( \pi \) phase at high temperature
- non-monotonic temperature dependence
- sharp 0-π-transition
- \( I_c = 0 \) at transition only for \( T \ll 1 \)

[Chchelkatchev, Belzig, Nazarov + Bruder, JETPL (2001); Chchelkatchev, Belzig + Bruder, JETPL (2002)]
Experimental observation of temperature transition

[Ryazanov et al. PRL 01]

- Observation of non-monotonic temperature dependence
- Varies with layer thickness
- No direct proof of $\pi$ shift
Experimental observation of phase shift

[Bauer et al. PRL 04]

- observation of spontaneous supercurrent in \( \pi \)-SQUID
- unique proof of \( \pi \)-phase shift
Summary on SFS Josephson current

- **experimental observation** of SFS Josephson temperature dependence/π-shift
- current-phase relation strongly **non-sinusodial** (theory)

Other works
- determination of current-phase relation [Ryazanov et al.; Strunk et al.]
- SFS in diffusive junctions [Golubov et al.]
- SFS in magnetic dots [Fogelström et al.]
Superconductor and localized spins

**Quantum dots**: spin 1/2
(Coupling $\Gamma$)

- virtual tunneling
  (incl. interaction $U$)
- Abrikosov-Suhl resonance
- Kondo temperature

$$T_K = \sqrt{\frac{\Gamma U}{2}} e^{\frac{\pi \epsilon_d (\epsilon_d + U)}{2\Gamma U}}$$

Properties of the resonance:
bound singlet-state

**With superconductivity**:
Energy scales $\Delta$ und $k_B T_K$

$$\Delta \gg k_B T_K\quad k_B T_K \gg \Delta$$

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Limiting cases [Glazman+Matveev, JETPL 89]

weak coupling \( (T_K \ll \Delta) \): no resonance formed \( \rightarrow \) Coulomb blockade

4th-order perturbation \( I_c = \frac{2e\Gamma^2}{\hbar \Delta} \)

supercurrent \( I(\phi) = -I_c \sin \phi \rightarrow \pi\)-junction

Explanation:
[Spivak+Kivelson, PRB 90]

order interchanged

strong coupling \( (T_K \gg \Delta) \): Kondo resonance \( \rightarrow \) open contact

critical current \( I_c = \frac{2e}{\hbar} \Delta \equiv I_0 \)

supercurrent \( I(\phi) = I_c \sin(\phi/2) \)

Current phase relation: \( 0 - \pi \) transition
(from strong to weak coupling)
**Full crossover regime:** numerical renormalization group
[Choi, Lee, Kang + Belzig, PRB (2004)]

- $0-\pi$ transition for $\Delta/T_K < 2.6$ and universal scaling with $\Delta/T_K$
- Transition point depends on phase difference

\[ \frac{\Delta}{T_K} = 1.6 \]
\[ \frac{\Delta}{T_K} = 10 \]
\[ \frac{\Delta}{T_K} = 0.1 \]
Comparison with experiment on carbon nanotubes

**Model:**
overdamped Josephson contact
(with external resistance/capacitance)

\[ I_c, R, C \]

\[ k_B T \]

\[ \phi \]

\[ 0-\pi \text{ transition} \]

[Choi, Lee, Kang + Belzig, PRB (2004)]

**Experiment:**

Parameters: \( \delta E \sim 0.6 \text{meV}, E_c = 0.4 \text{meV} \)
\( \Gamma = 0.3 \text{meV}, \Delta = 0.2 \text{meV} \)

Butelaar, Belzig, Nussbaumer, Babic, Bruder + Schönenberger, PRL (2003)]
Summary on SDS

- $0 - \pi$ transition is governed by $\Delta / T_K$
- singlet/doublet transition depends on phase difference

Other works

- SDS Josephson current
  - modified mean field approach [Rozhkov and Avoras, PRB 00]
  - non-crossing approximation [Clerk and Ambegaokar, PRB 00]
  - interpolative approach [Vecino, Rodero + Levy Yeyati, PRB 03]
  - quantum Monte Carlo calculation [Siano and Egger, PRL 04]

- non-equilibrium multiple Andreev reflections [Avishai, Golub + Zaikin, PRB 02]
- Andreev scattering through interacting dot [Fazio + Raimondi; Clerk + Ambegaokar; Cuevas, Levy Yeyati, Martin-Rodero, PRB 01]
0 - \pi transition: 0-\pi_{th} \neq \pi-0_{exp}

SDS: different results from different methods → more work needed (finite Temperature, asymmetric coupling, etc.)

SDS: non-equilibrium properties (i.e. multiple Andreev reflections + Kondo effect)

Spin pumping/noncollinear magnetizations for SF heterostructures

Experiments
superconductors and ferromagnets = antagonistic quantum states
possibility of manipulated transport properties (coherently)
density of states oscillations (detection of \( \cos 2\pi r \))
0 \( \to \pi \) transition of supercurrent for magnetic layers (detection of \( e^{i2\pi r} \))
0 \( \to \pi \) transition of supercurrent though quantum dot Kondo correlations enhance supercurrent