Superspintronics: Spintronic aspects of superconducting nanostructures

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Outline

Superconductor(S)/Ferromagnet(F) heterostructures

- Motivation
- Density of states oscillations (SF)
- π-Josephson junctions (SFS)
- Supercurrent through a quantum dot (SDS)
- Spin valve/spin diffusion
- Conclusions/Outlook

Motivation

Superconductor (S)

- macroscopic quantum-phase state i.e. characterized by maroscopic 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

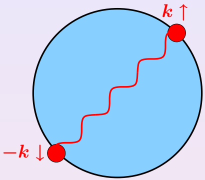
S and F are antagonistic quantum states

Possibility of manipulation in heterostructures

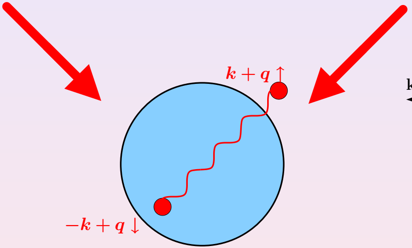
General properties of SF

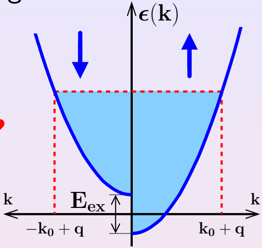
Superconductor: attractive interaction through virtual phonons

Magnetism: Bandsplitting by exchange interaction



total momentum
$k_\uparrow - k_\downarrow = 0$





Spin splitting
$k_\uparrow \neq k_\downarrow$

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

Cooper pairs with momentum $2q = \dfrac{2E_{ex}}{\hbar v_F} = \dfrac{1}{\xi_F} \neq 0$

Macroscopic wave function: $\Delta\cos(2qr)$ or Δe^{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

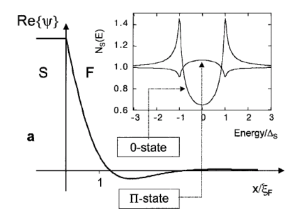
- magnetization is separated from superconductor
- Cooper pair extends into F $\longrightarrow$ finite q
- superconducting properties oscillate with distance

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)]

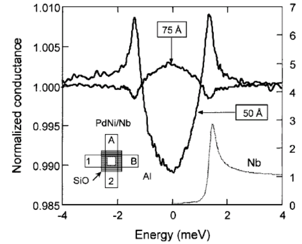


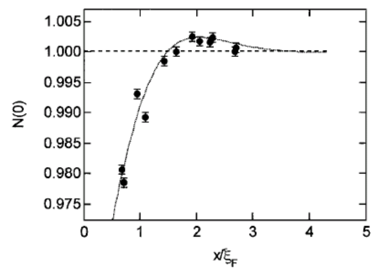
weak ferromagnet:

$Pd_{1-x}Ni_x$, x=1-10%, $T_c = 0 - 100$K

thin F layers: $x = 1 - 10$nm $\approx \xi_F$

low temperature: $100mK$

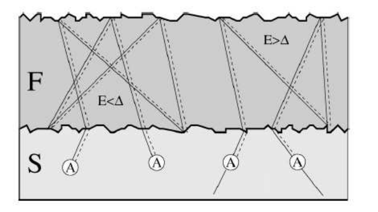




Detection of $\cos(2qx)$-oscillations

Theoretical explanation

Thin SF-layer with diffusive interface scattering
[Zareyan, Belzig, Nazarov, PRL (2001); PRB (2002)]



Oscillation of Andreev states:

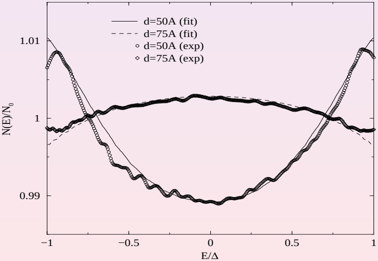
$$E_B(L) = \Delta\cos(\alpha(L) + 2qL)$$

$\alpha(L)$: normal phase shift

Averaging over length distribution

$$N(E) = N_0 \int dLp(L)\delta(E - E_B(L))$$

accounts for interface roughness



Model explains experimental observation of $\cos(2qr)$

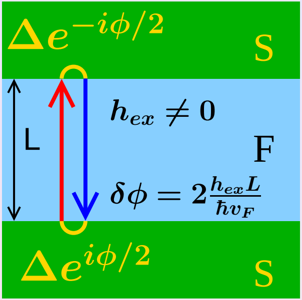
Summary on SF-DOS oscillations

- 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):

$E_J^0(\phi)$ depends on phase difference ϕ

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:

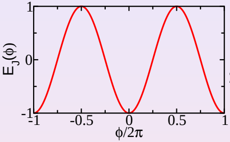
Spin-dependent band splitting:

$$E_J(\phi, H_{ex}) = \frac{1}{2}\Big[\underbrace{E_J^0(\phi + \delta\phi/2)}_{\text{spin-}\uparrow\text{ band}} + \underbrace{E_J^0(\phi - \delta\phi/2)}_{\text{spin-}\downarrow\text{ band}}\Big]$$

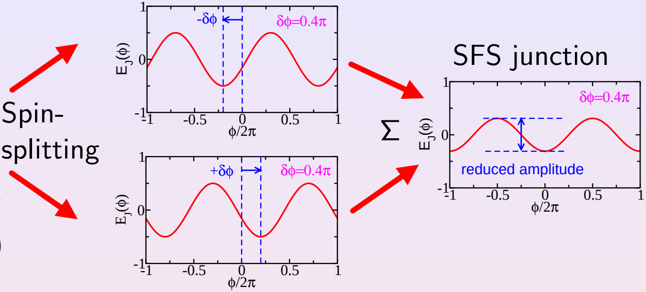
0-π transition for a tunnel contact

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

normal junction



$E_J^0 = \frac{\hbar}{2e} I_c \cos(\phi)$

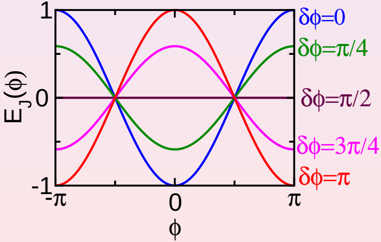


Result:

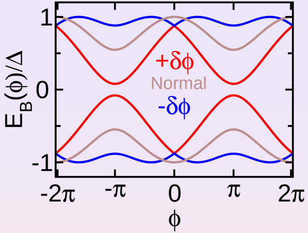
$$E_J(\phi) = -\frac{\hbar}{2e} I_c(\delta\phi) \cos(\phi)$$

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

sign change for $\delta\phi > \pi/2$



Open contacts: Andreev bound states

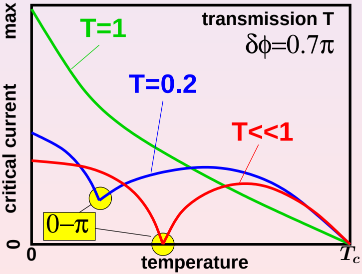


Energy of the bound state:

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

$$\cos(\gamma(\phi)) = 1 - T + T\cos(\phi)$$

depends strongly on phase shift $\delta\phi$
(Plot: $T = 0.7$, $\delta\phi = \pi/2$



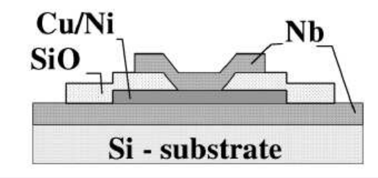
Temperature-dependent 0-π transition

- πphase at high temperature
- non-monotonic temperature dependence
- sharp 0-π-transition
- $I_c = 0$ at transition only for $T \ll 1$

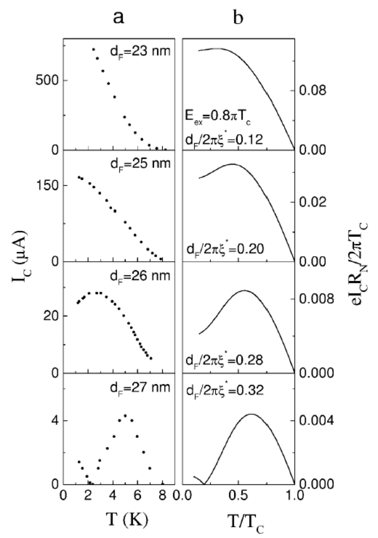
[Chtchelkatchev,Belzig,Nazarov+Bruder, JETPL (2001);Chtchelkatchev,Belzig+Bruder, JETPL (2002)]

Experimental observation of temperature transition

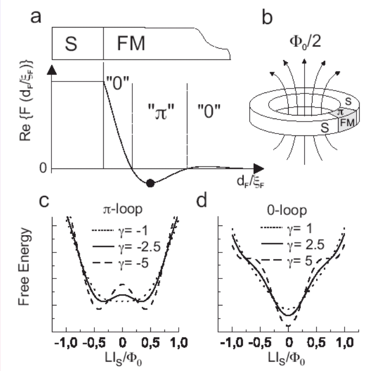
[Ryazanov *et al.* PRL 01]

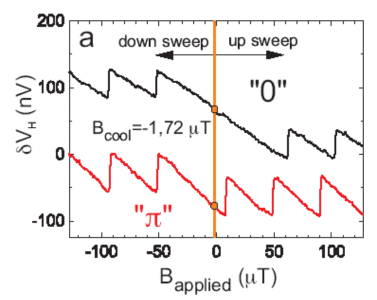


- observation of non-monotonic temperature dependence
- varies with layer thickness
- no direct proof of π shift



[Bauer *et al.* PRL 04]





- observation of spontaneous supercurrent in π-SQUID
- unique proof of π-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

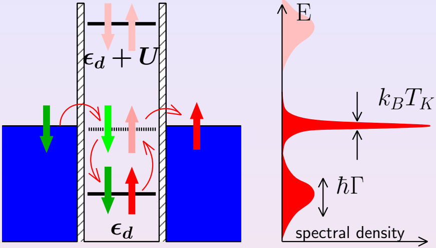
- determination of current-phase relation [Ryazanov *et al.*; Strunk *et al.*]
- SFS in diffusive junctions [Golubov *et al.*]
- SFS in magnetic dots [Fogelström *et al.*]

Superconductor and localized spins

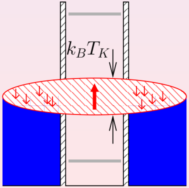
Quantum dots: spin 1/2
(Coupling Γ)

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

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

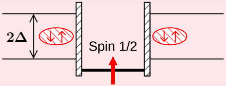


Properties of the resonance:
bound singlet-state

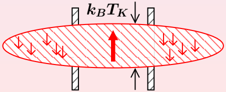


With superconductivity:
Energy scales Δ und $k_B T_K$

$\Delta \gg k_B T_K$



$k_B T_K \gg \Delta$

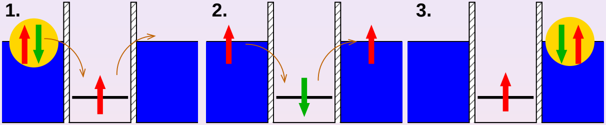


Josephson current through quantum dots

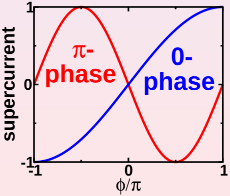
Limiting cases [Glazman+Matveev, JETPL 89]

weak coupling ($T_K \ll \Delta$): no resonance formed ⟶ Coulomb blockade
4^{th}-order perturbation $I_c = \frac{2e}{\hbar}\frac{\Gamma^2}{\Delta}$
supercurrent $I(\phi) = -I_c \sin\phi$ ⟶ **π-junction**

Explanation:
[Spivak+Kivelson, PRB 90]
order interchanged

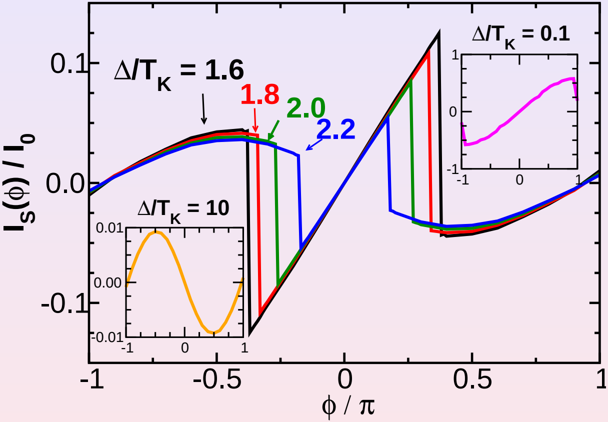


strong coupling ($T_K \gg \Delta$): Kondo resonance ⟶ open contact
critical current $I_c = \frac{2e}{\hbar}\Delta \equiv I_0$
supercurrent $I(\phi) = I_c \sin(\phi/2)$



Current phase relation: $0-\pi$ **transition**
(from strong to weak coupling)

Full crossover regime: numerical renormalization group
[Choi,Lee,Kang+Belzig, PRB (2004)]

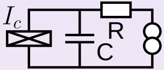


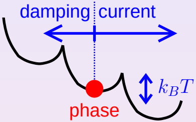
- 0-π transition for $\Delta/T_K < 2.6$ and universal scaling with Δ/T_K
- transition point depends on phase difference

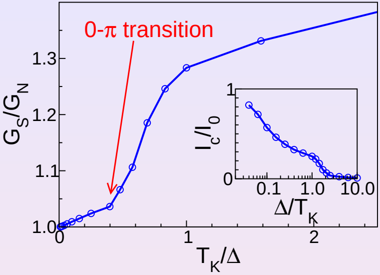
Comparison with experiment on carbon nanotubes

Model:

overdamped Josephson contact
(with external resistance/capacitance)

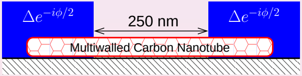




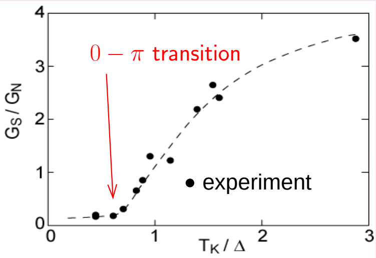


[Choi,Lee,Kang+Belzig, PRB (2004)]

Experiment:



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



[Buitelaar,Nussbaumer+Schönenberger, PRL (2002)
Buitelaar,Belzig,Nussbaumer,Babic,Bruder+Schönenberger, PRL (2003)]

Summary on SDS

- $0 - \pi$ transition is governed by Δ / 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]

Outlook

- $0-\pi$ transition: 0-$\pi_{th} \neq \pi$-0_{exp}
- SDS: different results from different methods $\longrightarrow$ 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**

Summary

- superconductors and ferromagnets = antagonistic quantum states
- possibility of manipulated transport properties (coherently)
- density of states oscillations (detection of $\cos 2qr$)
- $0-\pi$ transition of supercurrent for magnetic layers (detection of e^{i2qr})
- $0-\pi$ transition of supercurrent though quantum dot
  Kondo correlations enhance supercurrent