Long-range spin transport in superconductors

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Experiment – *samples*

- film thickness $\sim 12$ nm
- contact distances $d \sim 0.5 \mu m – 8 \mu m$
- magnetic field $B \parallel$ iron wires
- parallel magnetization alignment


normal-state spin-valve:
$\rightarrow$ spin diffusion length $\lambda_N = 370$ nm
Experiment – *junction characterization*

local conductance
Zeeman splitting in the magnetic field
**Model – Zeeman splitting**

Zeeman-splitting of DOS (semiconductor model)

\[ n_{\downarrow,\uparrow}(E) = n(E \pm \mu_B B) \]

Charge current

\[ I = \frac{1}{e} \int [G_{\downarrow} n_{\downarrow}(E) + G_{\uparrow} n_{\uparrow}(E)]\{f(E - eV) - f(E)\}dE \]

Tedrow & Meservey, PRL 26, 192 (1971)

\[ G_{\downarrow,\uparrow} = \frac{G_N}{2} (1 \pm P) \]
Experiment – *junction characterization*

Al/Al\textsubscript{2}O\textsubscript{3}/Fe

\begin{align*}
T &= 50 \text{ mK} \\
1 + P &\quad \text{and} \quad 1 - P
\end{align*}

\[ g_{\text{loc}} (\text{mS}) \]

\[ V_{\text{inj}} (\mu\text{V}) \]

Superconductor acts as spin filter

Asymmetry

\[ P = \frac{G_\downarrow - G_\uparrow}{G_\downarrow + G_\uparrow} \]

\[ P = 19 \% \]

(consistent with spin-valve experiments)
Experiment – *local vs nonlocal conductance*

\[ B = 0 \]

Al/Al\(_2\)O\(_3\)/Fe

<table>
<thead>
<tr>
<th>density of states</th>
<th>charge imbalance</th>
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\[ d = 1 \mu m \]


Experiment – *local vs nonlocal conductance*

$$E = \sqrt{\epsilon^2 + \Delta^2}$$

![Graph showing quasiparticle dispersion](image)

$$\epsilon = \frac{\hbar^2 k^2}{2m} - \mu$$

Charge imbalance

- Clarke, Phys. Rev. Lett. 28, 1363 (1972)
- Tinkham & Clarke, Phys. Rev. Lett. 28, 1366 (1972)
Experiment – *local vs nonlocal conductance*

$B > 0$

**Local conductance**

- Broadening and Zeeman splitting

**Nonlocal conductance**

- Asymmetric features appear
Experiment – *local vs nonlocal conductance*

\[ B \gg 0 \]

Zeeman splitting grows

features broaden
Experiment – *normal vs ferromagnet*

**NISIN**

- \( B = 0 \)
- \( 0.20 \text{T} \)
- \( 0.50 \text{T} \)
- \( 0.75 \text{T} \)
- \( 1.00 \text{T} \)
- \( 1.15 \text{T} \)

\[ g_{nl}/G_{inj} G_{det}(\Omega) \]

\[ V_{inj} (\mu \text{V}) \]

\( d = 360 \text{ nm} \)

**FISIF**

- \( B = 0 \)
- \( 0.25 \text{T} \)
- \( 0.50 \text{T} \)
- \( 0.75 \text{T} \)
- \( 1.00 \text{T} \)
- \( 1.25 \text{T} \)
- \( 1.50 \text{T} \)

\[ g_{nl}/G_{inj} G_{det}(\Omega) \]

\[ V_{inj} (\mu \text{V}) \]

\( d = 1 \mu \text{m} \)

only charge imbalance  
charge imbalance + asymmetry

similar results: Quay et al., Nat. Phys. 9, 84 (2013)
Experiment – *local conductance*

\[
I = \frac{1}{e} \int \left[ G_\downarrow n_\downarrow (E) + G_\uparrow n_\uparrow (E) \right] \{ f(E - eV) - f(E) \} dE
\]

wedge-shaped regions: only one spin band contributes superconductor acts as spin filter
Experiment – *predicted spin injection*

Spin current

\[ I_s = \frac{1}{e} \int [G_\downarrow n_\downarrow(E) - G_\uparrow n_\uparrow(E)] \{f(E - eV) - f(E)\} dE \]

\[ I_s \propto \frac{G_\downarrow - G_\uparrow}{G_\downarrow + G_\uparrow} + \frac{n_\downarrow - n_\uparrow}{n_\downarrow + n_\uparrow} \]

see also Giazotto & Taddei, Phys. Rev. B **77**, 132501 (2008)
Experiment – *spin injection vs signal*

nonlocal conductance follows spin injection
Model – *injection*

- **hole-like**
- **electron-like**

- Charge imbalance: $Q_{\downarrow}^* < 0$
- Spin accumulation: $S_{\downarrow} > 0$

- $I \propto G_{\downarrow}$
- $V < 0$

Inject spin-down electrons
Model – injection

\[ I \propto G_{\uparrow} \]

\[ V > 0 \]

extract spin-up electrons

\[ Q_{\downarrow}^* > 0 \]

\[ S_{\downarrow} > 0 \]
Model – charge relaxation

charge relaxation for $d > \lambda_{Q^*}$

fast for $E \gtrsim \Delta$
Model – detector current

\[ I_{\text{det}} = (G_\downarrow + G_\uparrow)(Q_\downarrow^* + Q_\uparrow^*) - (G_\downarrow - G_\uparrow)(S_\downarrow - S_\uparrow) \approx -(G_\downarrow - G_\uparrow)S_\downarrow \]

\[ I \propto G_\uparrow \]

\[ V = 0 \]

\[ Q_\downarrow^* \approx 0 \]

\[ S_\downarrow > 0 \]

see Zhao & Hershfield, PRB 52, 3632 (1995)
Interpretation – detector current

injector polarisation $P_{\text{inj}}$
→ different peak heights

detector polarisation $P_{\text{det}}$
→ sign of nonlocal current
Interpretation – negative nonlocal signal

at positive bias: inject holes, get electrons. looks like crossed Andreev reflection. why? charge relaxation (no coherence needed)
Experiment – distance dependence

- peak area decreases with contact distance
- signal persists up to 8 µm
- relaxation length $\lambda_S = 5 - 10$ µm
  (compare to $\lambda_N = 370$ nm)
- what is the relaxation mechanism?
**Experiment – separating spin and charge**

- direct comparison of charge and spin signal in same sample
- spin injection from normal metal


contact distance 6 µm
no more charge at all
but: still spin
Conclusions & Outlook

Conclusions

• Long range spin transport in Zeeman-split superconductors
• model for relaxation needed

Outlook

• thermoelectric effects
• manipulate and utilize spin currents

Thank you for your attention!


http://www.int.kit.edu/english/606.php