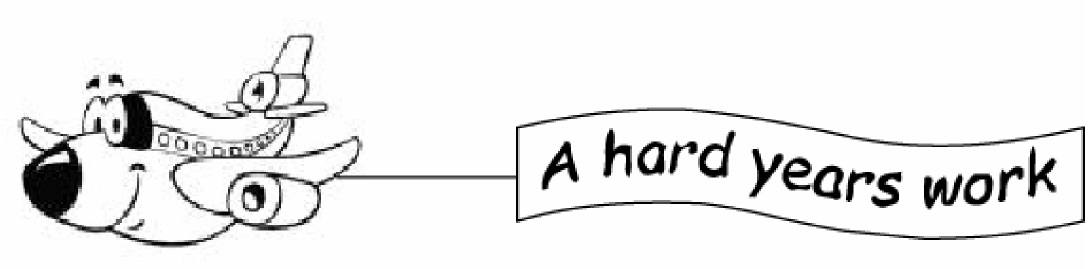
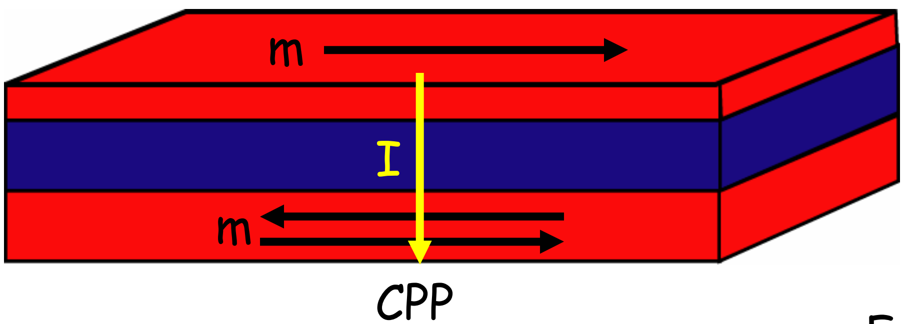
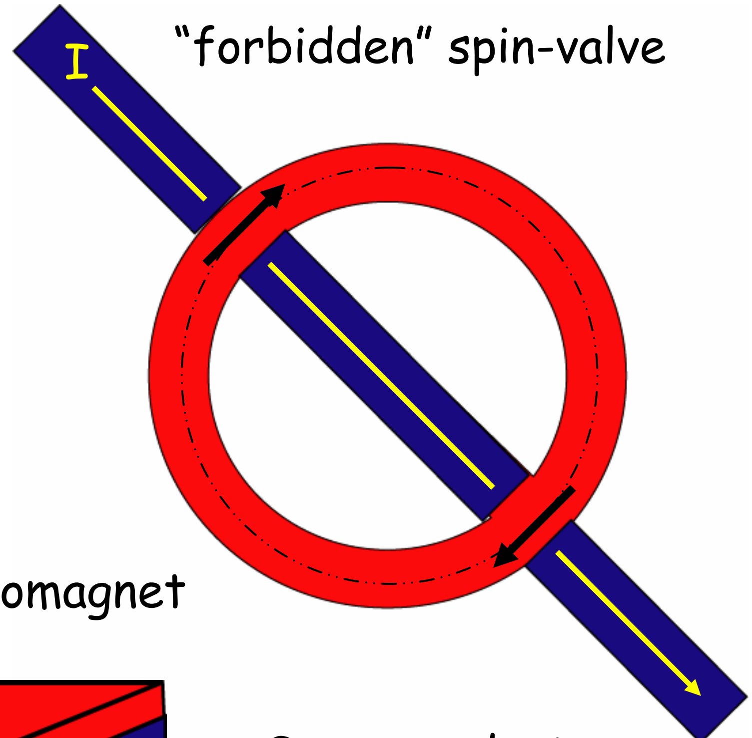
Mysteries of F/S systems



Standard spin-valves





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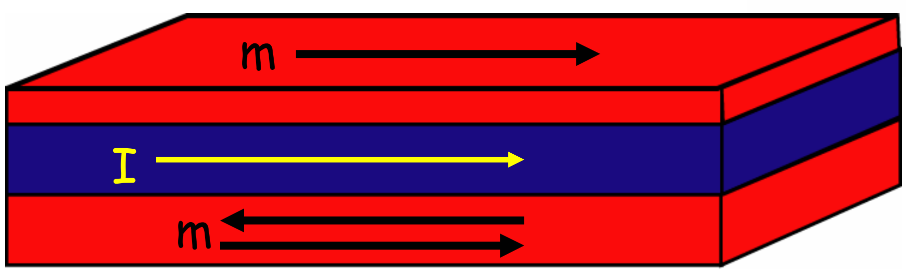
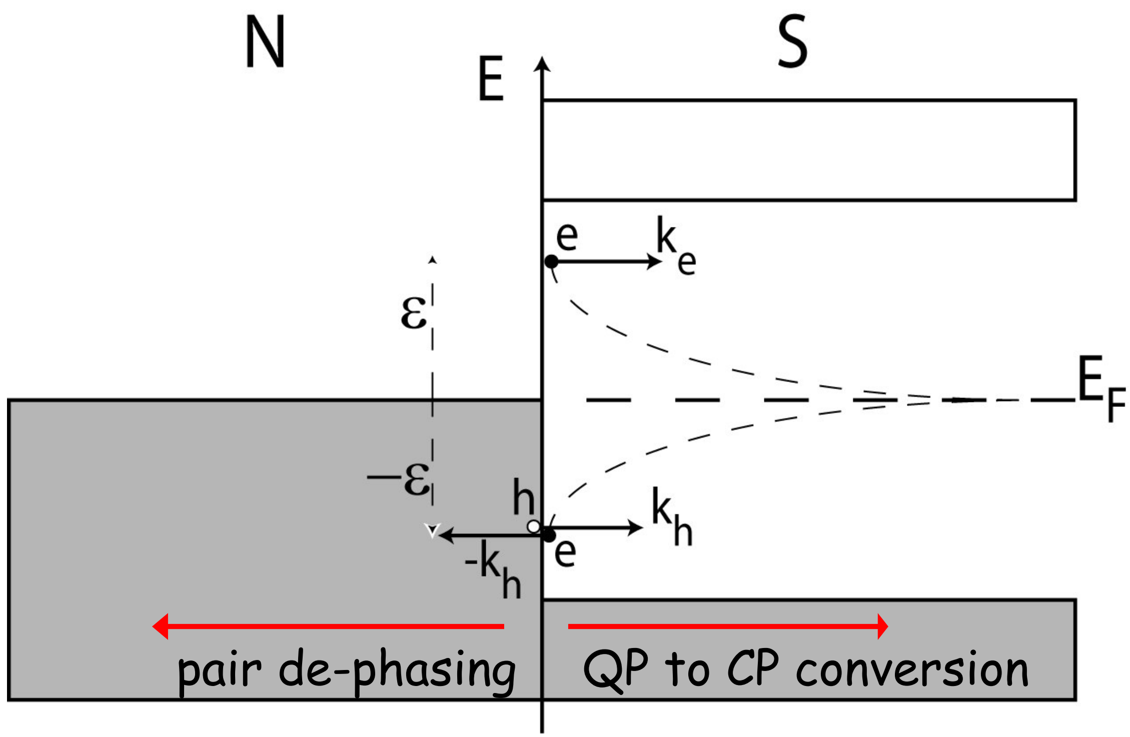


Outline

- The N/S proximity system
  - The basics
  - NSN “critical voltage” (non-equilibrium / driven system)
- The F/S proximity system
  - How the basics change: oscillatory decay
  - Pairing types: singlet, triplet (1 x short-range, 2 x long-range)
  - Length scales
  - The FSF spin-valve
- Current experiments
  - Long-range triplet detection in a “forbidden” FSF structure
  - The physics beyond weak (exchange) limit

The (S/N) proximity effect



Characteristic length scales

$$\xi = \sqrt{\frac{\hbar D}{E_{dom}}}$$

$$E_{dom} = \begin{cases} \Delta \\ k_B T \\ h_{exchange} \\ E_{Thouless} \end{cases}$$

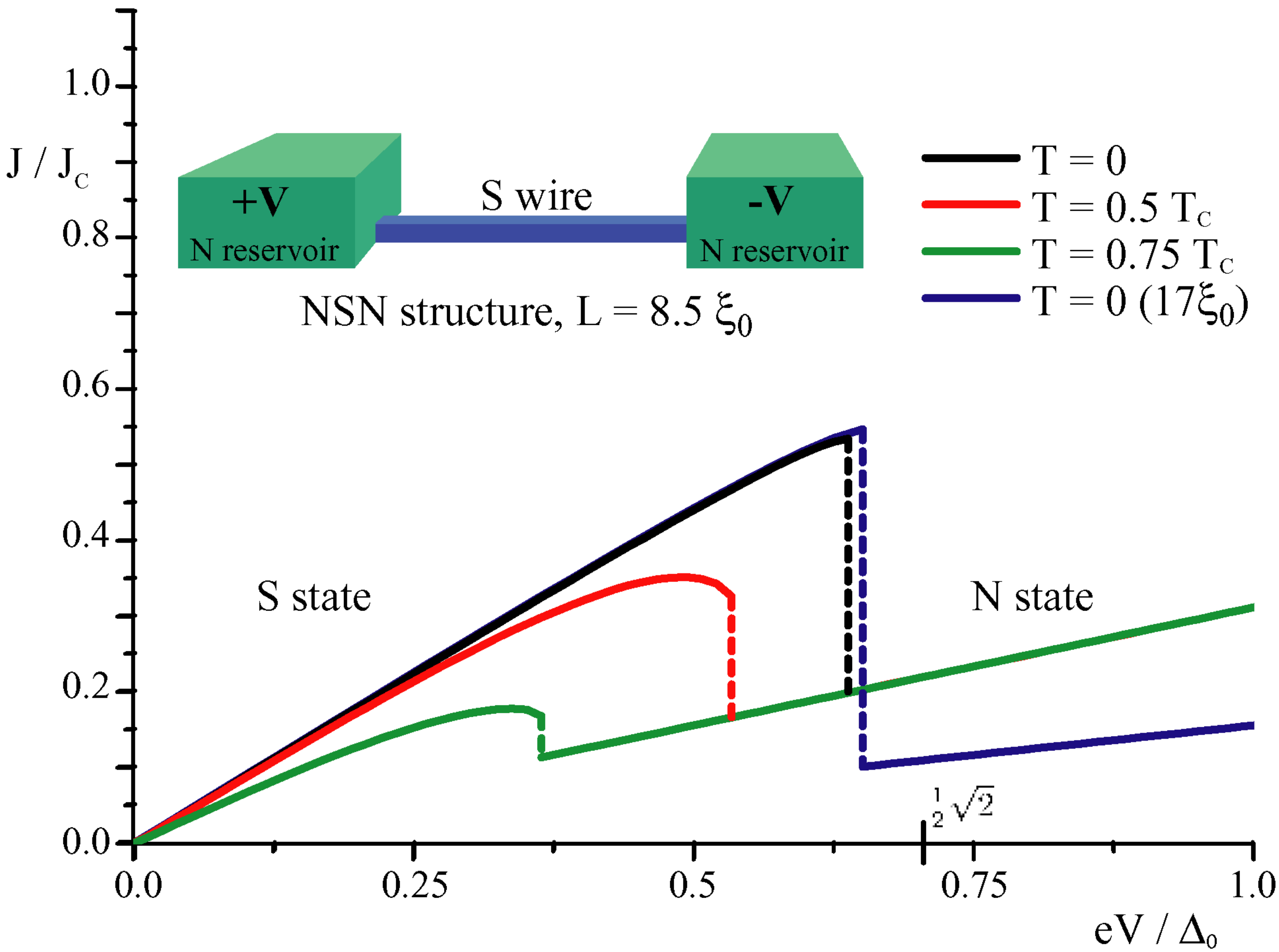
Superconducting correlations "leak" into N (near the interface)

- S becomes weaker (reduction of Δ)
- N obtains superconducting properties

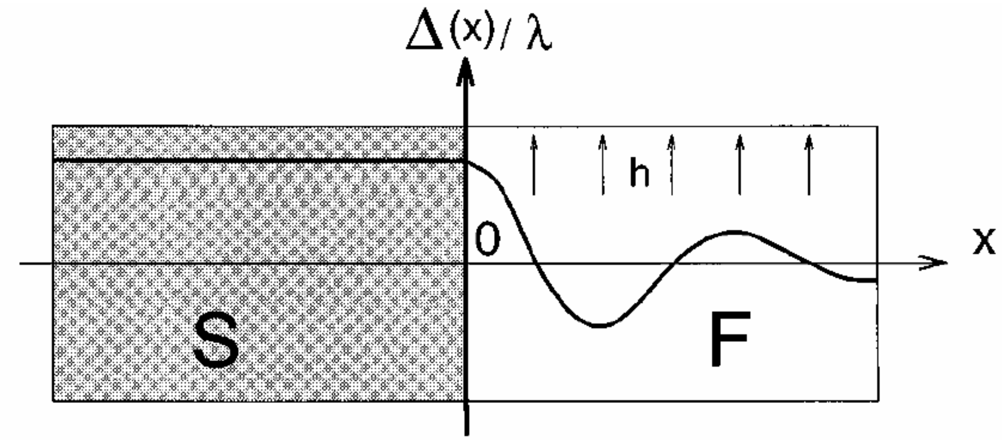
This is "old" physics… are there still interesting things in standard N/S hybrids ?

Applying a voltage over an NSN junction gives an answer!!

Critical voltage



Inclusion of exchange field



Demler et al, PRB **55**, 1997

Why oscillations?

• Up and down potential energies are shifted differently.

• To balance total energy, kinetic energies are adjusted.

• Result: interfering wave functions (due to different phase evolution)

What new physics to expect due to the exchange field?

• Oscillatory behavior with distance in (all) parameters depending on the gap
• Tuning device properties by adjusting the exchange field (like direction)
• Appearance of triplet pairing wave functions (in conventional S, only singlet)

Length scales of the oscillation

Linearized Usadel equation:

$$\left(\hbar\omega_n + ih_{ex} - \frac{1}{2}\hbar D\nabla^2\right)F(\omega_n, x) = 0$$

(eigen)energy — field contribution — kinetic term — pair amplitude

General solution:

$$F(\omega_n, x) = Ae^{-x(k_1+ik_2)} = Ae^{-xk_1}\left(\cos(xk_2) + i\sin(xk_2)\right)$$

with

$$k_{1,2} = \frac{1}{\xi_F}\sqrt{\sqrt{1+\left[\frac{\hbar\omega_n}{h_{ex}}\right]^2} \pm \frac{\hbar\omega_n}{h_{ex}}}$$

and

$$\xi_F = \sqrt{\frac{\hbar D}{h_{ex}}}$$

k_1^{-1}	characteristic decay length
$2\pi k_2^{-1}$	period of the oscillation

Some typical numbers

	h_{exchange}	ξ_F
PdNi	5-20 meV	18-36 nm
Py	135 meV	7 nm
Fe	~5 eV	1.5 nm

Not practical yet due to ω_n

Solution: take limit of T close to T_c

then $\omega_n \approx \omega_0 = \pi k_B T = \pi k_B T_c$

Limit of strong field (w.r.t. $k_B T_c$) $k_1^{-1} = k_2^{-1} = \xi_F$

Limit of zero field (normal metal) $k_1^{-1} = \sqrt{\hbar D / (2\pi k_B T_c)}$ $k_2^{-2} = \infty$

What do these results imply?

stronger $h_{ex} \xrightarrow{\text{results in}}$ k_2 closer to k_1 but always $k_1 \geq k_2$

decay < oscillation

To see oscillatory behavior we need:

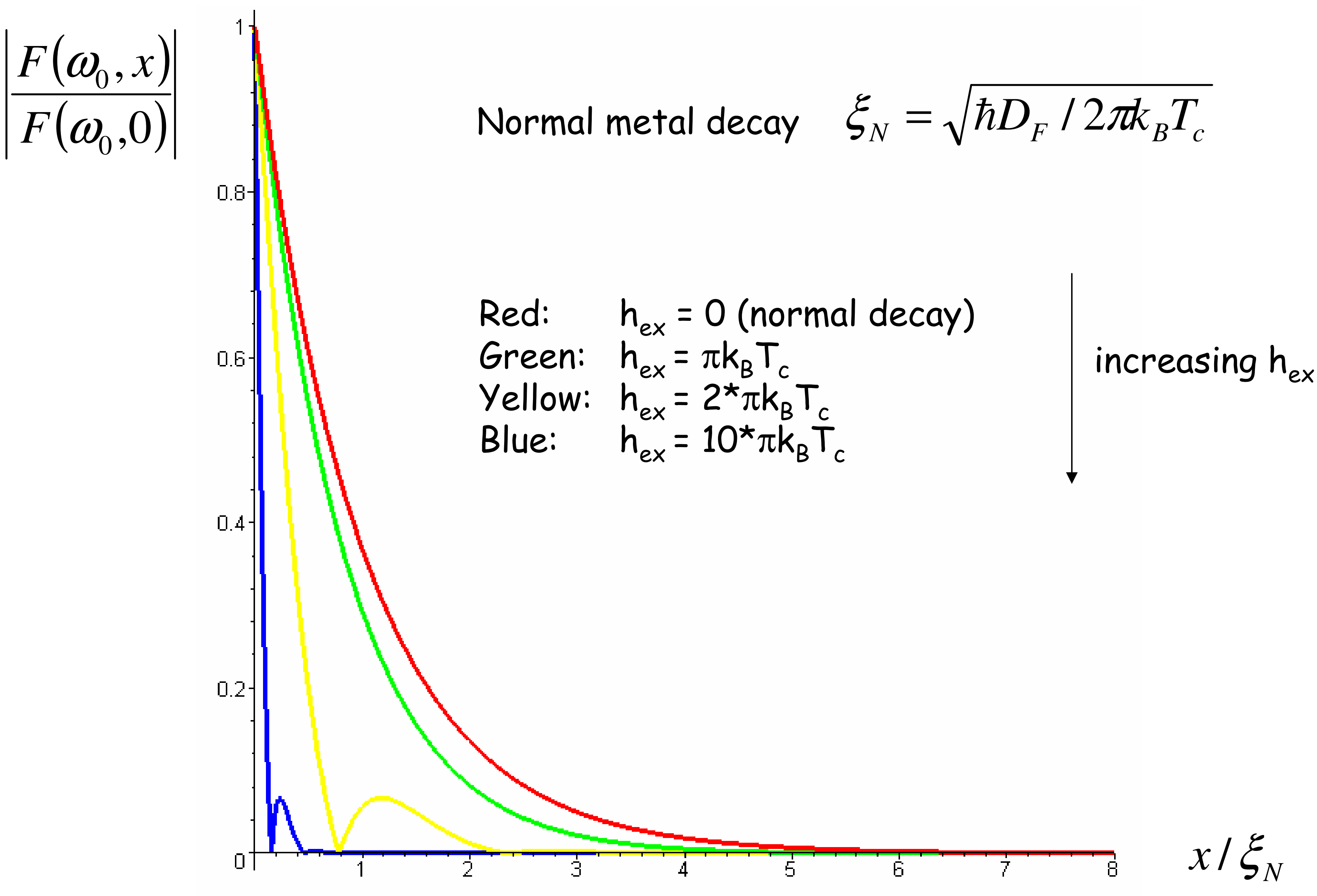
A periode not much longer then the decay length

At best (strong field) we have $k_1^{-1} = k_2^{-1}$

But even then, the period is over 6 times the decay length

We can't expect to see many oscillations !!!

Oscillatory decay near Tc



What is the oscillation

Singlet: $\Psi^S = \left\langle \uparrow_\varepsilon \middle| \downarrow_{-\varepsilon} \right\rangle - \left\langle \downarrow_\varepsilon \middle| \uparrow_{-\varepsilon} \right\rangle$

Triplets:
$$\begin{cases} \Psi^T &= \left\langle \uparrow_\varepsilon \middle| \downarrow_{-\varepsilon} \right\rangle + \left\langle \downarrow_\varepsilon \middle| \uparrow_{-\varepsilon} \right\rangle \\ \Psi^T_{m=1} &= \left\langle \uparrow_\varepsilon \middle| \uparrow_{-\varepsilon} \right\rangle \\ \Psi^T_{m=-1} &= \left\langle \downarrow_\varepsilon \middle| \downarrow_{-\varepsilon} \right\rangle \end{cases}$$

Adding the energy of the exchange field (+ phase evolution term)

$$\left| \uparrow_\varepsilon \right\rangle \to \left| \uparrow_{\varepsilon + h_{ex}/2} \right\rangle e^{ith_{ex}/(2h)} \qquad \left| \downarrow_\varepsilon \right\rangle \to \left| \downarrow_{\varepsilon - h_{ex}/2} \right\rangle e^{-ith_{ex}/(2h)}$$

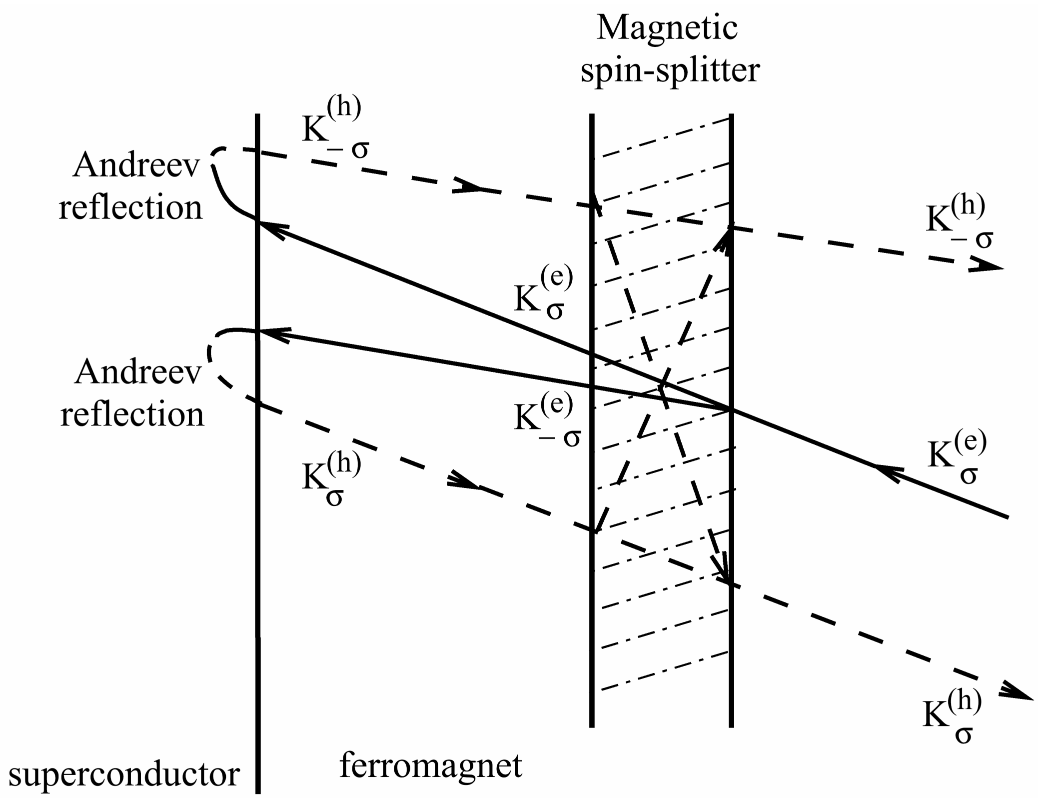
Total wave function $\Psi(t) = \left\langle \uparrow_{h_{ex}/2} \middle| \downarrow_{h_{ex}/2} \right\rangle e^{ith_{ex}/h} - \left\langle \downarrow_{-h_{ex}/2} \middle| \uparrow_{-h_{ex}/2} \right\rangle e^{-ith_{ex}/h}$

$$\Psi(t) = \Psi^S \cos(th_{ex}/h) + \Psi^T i \sin(th_{ex}/h)$$

Corresponding length in diffusive system $\lambda_F = \sqrt{DT} = \sqrt{2\pi Dh / h_{ex}} = 2\pi\xi_F$

Oscillation describes the conversion between singlet and odd triplet !!

How to get long-range triplets



Kadigrobov et al. (Europhys. Lett. 54(3) 2001)

back-scattered hole (spin down)

incident electron (spin up)

back-scattered hole (spin up)

Singlet (odd triplet)

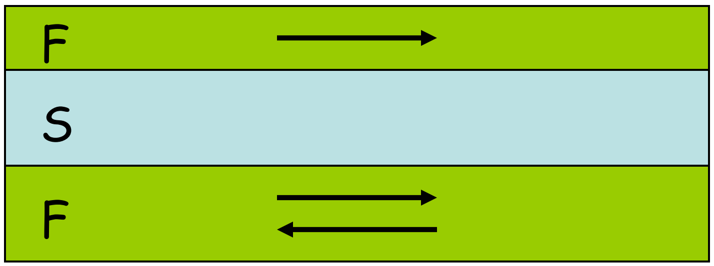
Triplet

The injected Cooper pairs must consist of singlet and triplet parts

Reducing the spin-splitter thickness towards an interface, we only need non-homogenous magnetization (ie. sampling non-co-linear magnetization directions)

FSF spin valve

Typical device layout



Theoretical model / prediction

- only co-linear magnetization
- identical spin-bands!! (no polarization)

- Parallel suppresses superconductor stronger than anti-parallel … but why ??

Comparing parallel and anti-parallel (within theoretical model)

- Normal reflections at the SF interfaces have become spin independent (no contribution of QPs, for them P and AP are identical)
- The proximity effect (AR) is only different for CPs using both F layers

parallel - always a strong de-phasing of pair
anti-parallel - possibility to avoid de-phasing by field

Difference between P and AP only due to de-phasing rates

stronger de-phasing leads to a more suppressed gap (superconductor)

What can we expect when non-identical spin bands are taken into account?

Cooper pair confinement strongest in Parallel - stronger gap
QP density in superconductor lowest in Parallel - stronger gap

Running experiments