Ferromagnet/Superconductor hybrid systems, proximity effects

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Outline

1. Inhomogeneous superconductivity : gain & price of S/F nanostructures

2. Macroscopic and microscopic measurements

3. Josephson coupling in S/F/S (better S/F/I/S)

4. Macroscopic Quantum-Mechanics : π-SQUIDs and π-rings

Superconductivity

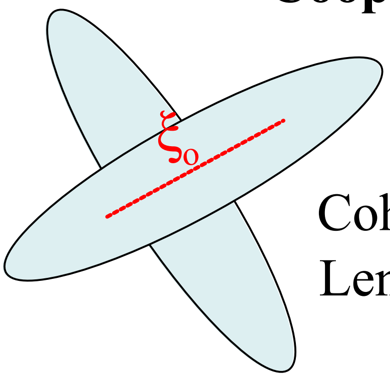
Order parameter

$$\Psi_{condensate} = e^{i\varphi}|\Psi_o|$$

Phase

Amplitude

Cooper pair

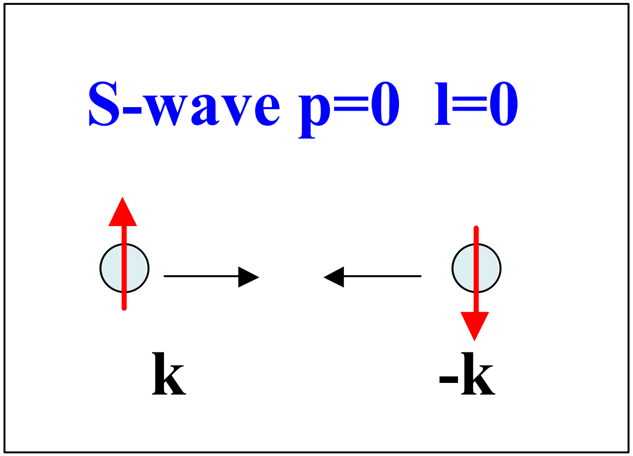


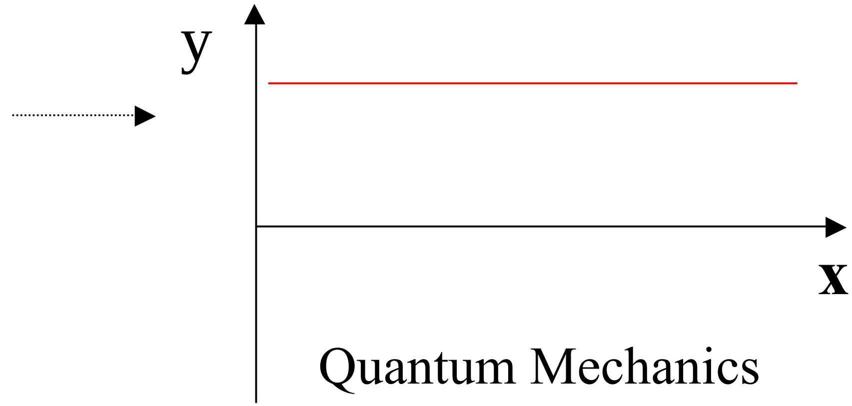
Coherence Length: ξ_o

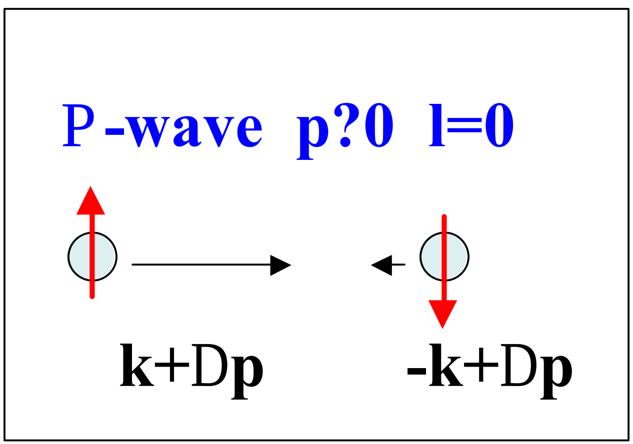
Below T_c the system condenses in a macroscopic number of Cooper pairs

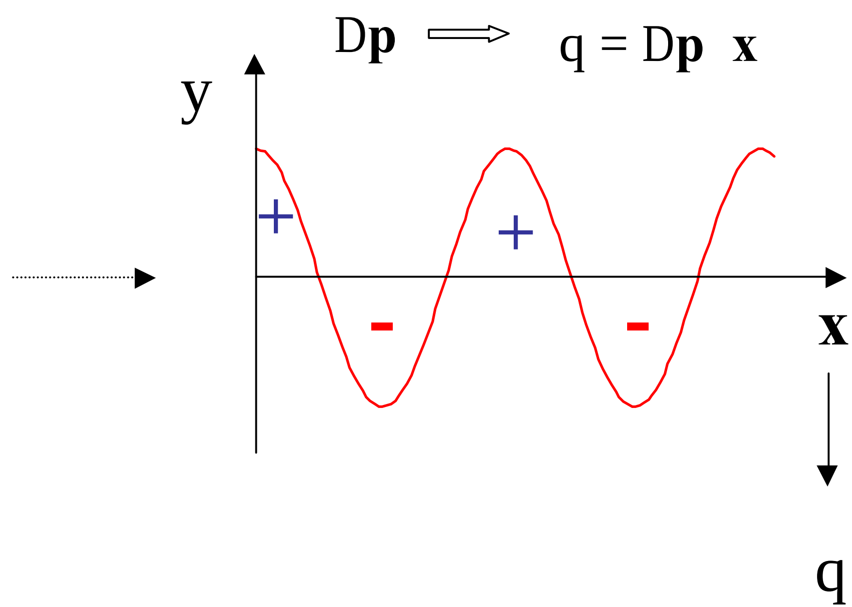
Cooper Pairs

Order parameter







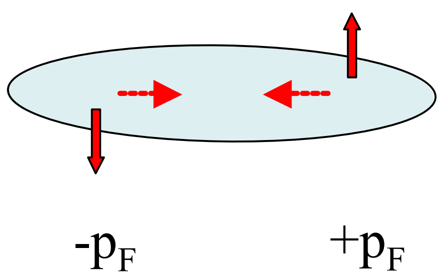


D-wave p=0 l=2

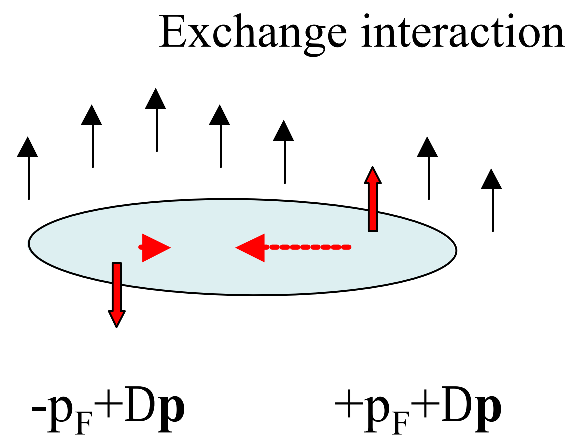
The Fulde-Ferrell-Larkin-Ovchinnikov state

Superconductor

Singlet state



Superconductor + Ferromagnet



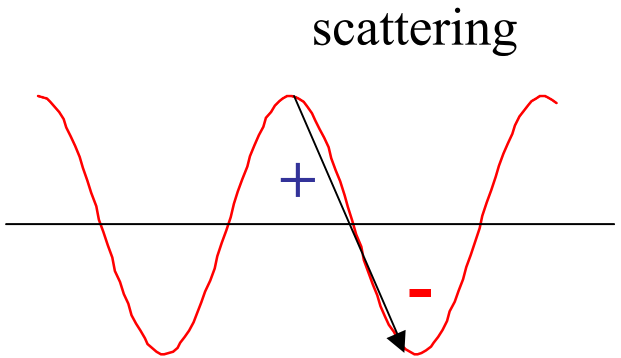
$$Dp = \frac{E_{ex}}{\hbar v_F}$$

Fulde and Ferrell PR 135, A550
Larkin and Ovchinnikov Sov.Phys. JETP 20, 762

Never found, why ?

1. Sensitivity to disorder :

$<\Delta>_{Fermi} = 0$

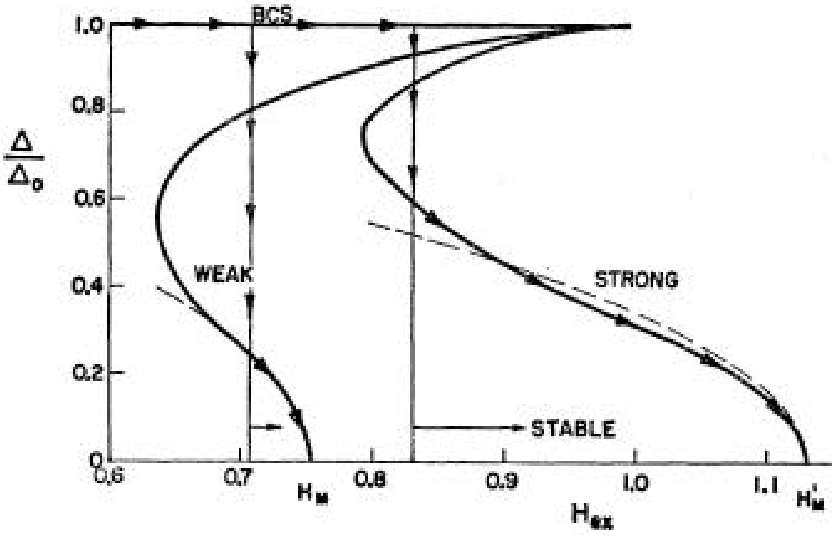


2. Phase diagram :

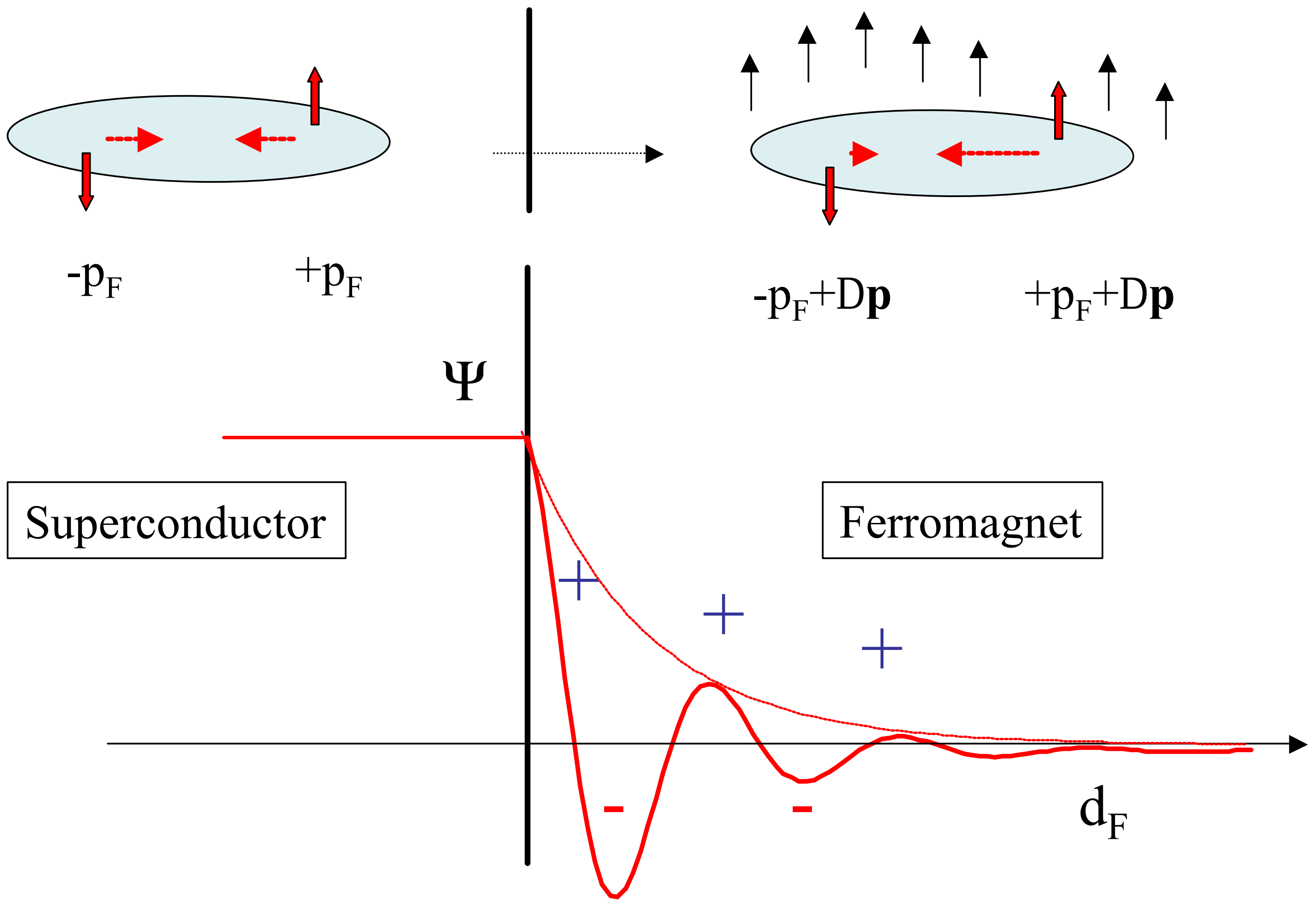
$E_{ex} \sim \Delta$

usually $E_{ex} \sim$ 0.1-1 eV

$\Delta \sim$ 1 meV



Ferromagnet/Superconductor proximity effect

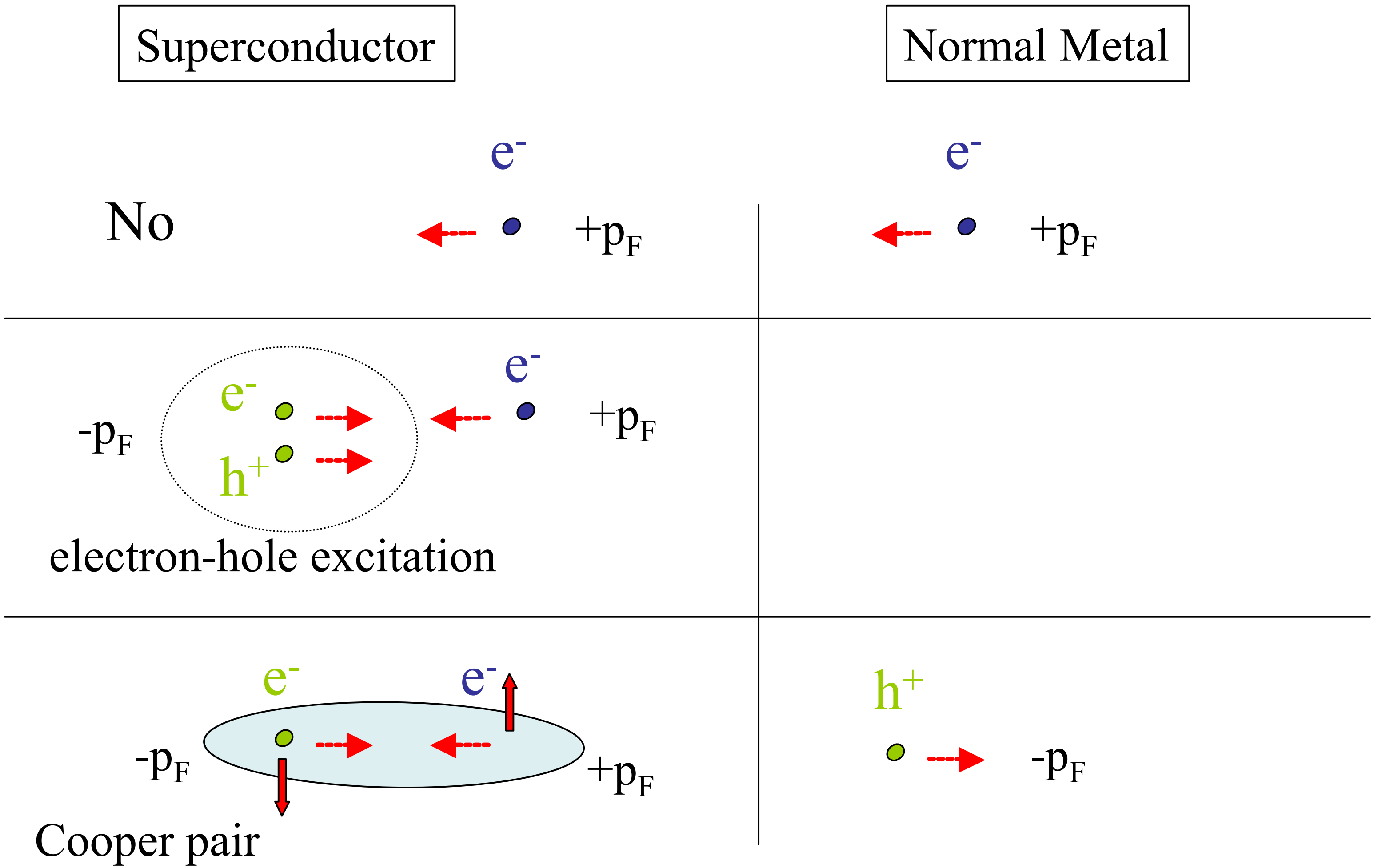


Question :

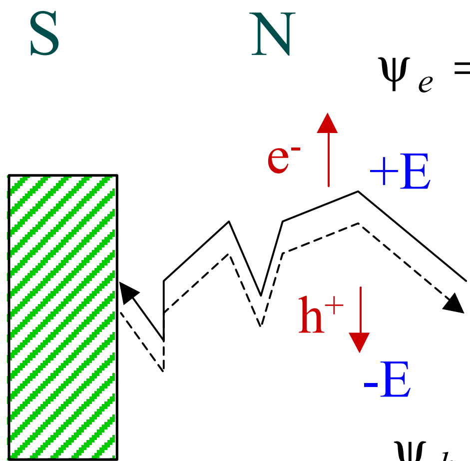
Where's the gain ?

Why S/F hybrid structures rather than bulk superconductors ?

Andreev Reflection

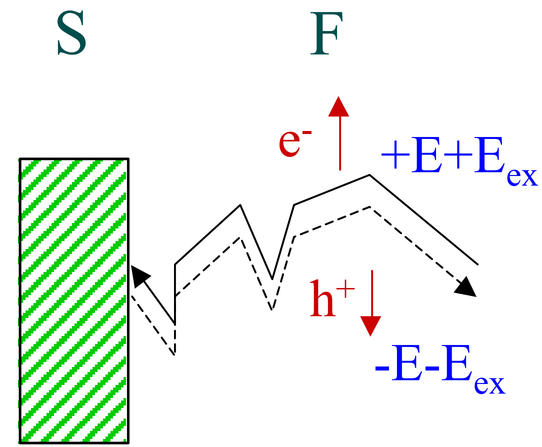


Superconducting Correlation Propagation



$$\psi_e = e^{-iEt/\hbar} \times \psi_0(x)$$

$$\psi_h = e^{iEt/\hbar} \times \psi_0(x)$$



No condensate $j(E,x) = Et/\hbar$

Phase coherence is lost when

$j(E,x) \sim 1 \longrightarrow\ ? \sim \hbar v_F/E$

As $E << E_{ex}$

$x \sim \hbar v_F/E_{ex} = \xi_F$

Coherent superposition of ψ_e and ψ_h

$$\psi = \psi_e + \psi_h \propto cos(E/E_{Th})$$

$E_{Th} = x/\hbar v_F$

$E \sim E_{ex}$

Answer

1. ξ_F does not depend on Δ.
   Superconducting correlations survive in F even if $E_{ex} \gg \Delta$

   Therefore S/F does not require comparable energy scales !!!

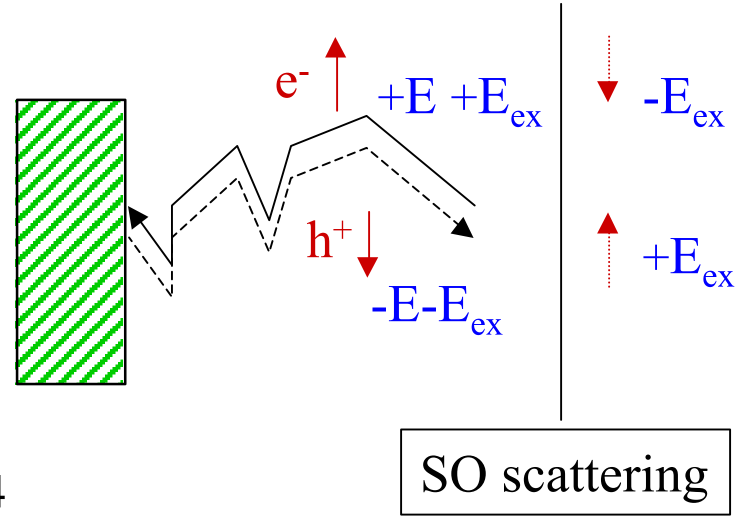
2. Only phase coherence is needed.
   No pairing equation in F.

   Therefore oscillations even in the dirty limit !!!

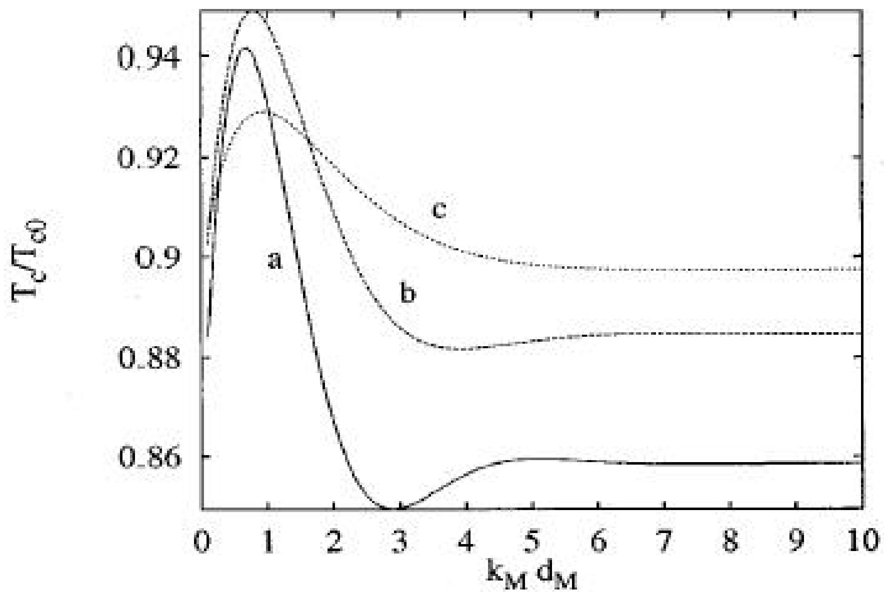
But...Spin must be a good Quantum Number

$$\psi = \psi_e + \psi_h \propto \cos\left(E_{ex}/E_{Th}\right)$$

is lost if Spin-Orbit scattering



Calculations by Demler et al. PRB 55, 15174



$1/\tau_{so} = 0.9\ E_{ex}$

$1/\tau_{so} = 0.5\ E_{ex}$

$1/\tau_{so} = 0.0$

Condition : $\tau_{so}\ v_F > \xi_F$

Therefore $1/\tau_{so} < E_{ex}$

The price to pay: Nanostructures !

$\xi_F = \hbar v_F / E_{ex}$ $E_{ex} \sim 0.1\text{-}1$ eV $\xi_F \sim 0.5\text{-}5$ nm

$\xi_N = \hbar v_F / K_B T$ $T \sim 1$ K $\xi_N \sim 1\ \mu m$

Reduced to 0.1-1 nm
in the dirty limit

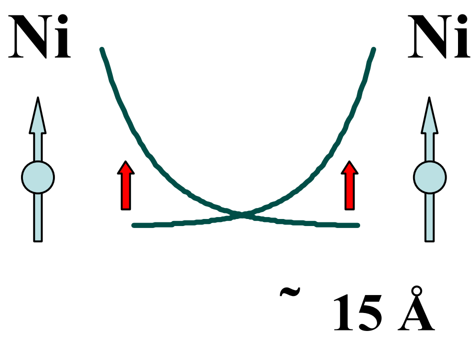
1. Deposition of thin films by e-gun and magnetron sputtering (thickness control down to 0.1 nm)

2. Materials : Nb (high T_c and H_{c2}, small coherence length)
   Ferromagnetic materials and alloys : Gd, CuNi and PdNi

$E_{ex} \sim 0.01$ eV $\xi_F \sim 10$ nm
homogeneous thin films

PdNi

(Orsay-group)



Indirect exchange

$m \sim 2.4\ m_B$ per Ni

$m_{Ni} = 0.6\ m_B$

Itinerant ferromagnetism

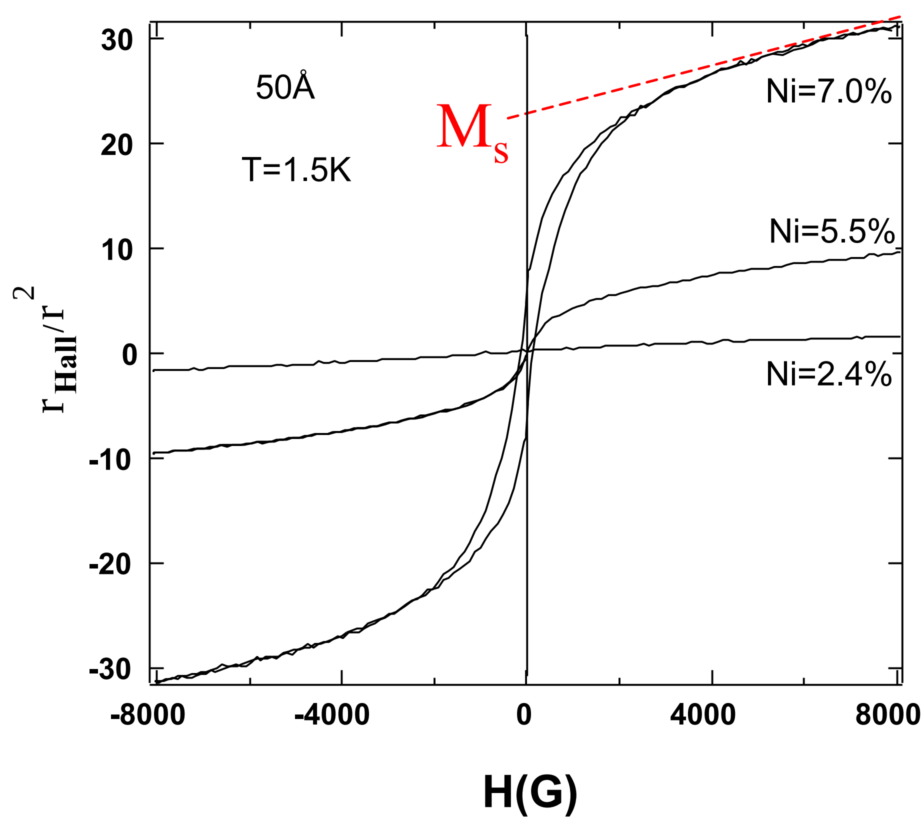
$$r_{Hall} = R_o B + R_s M_s$$

Hall resisitivity

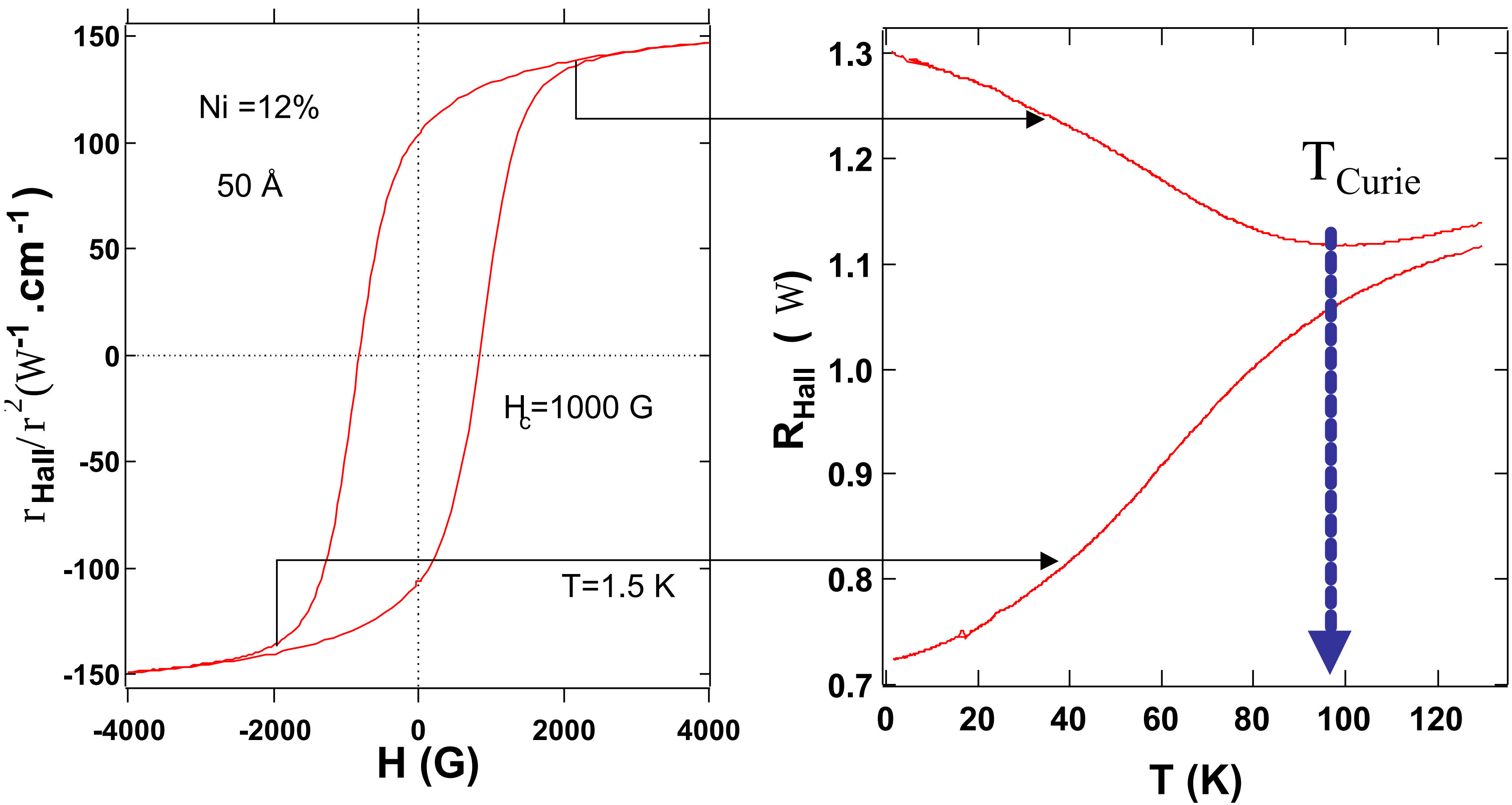
Normal

Anomalous

$R_s \sim r^2$



Curie's Temperature



T_c oscillations : Calculations

solving the Usadel eqs.

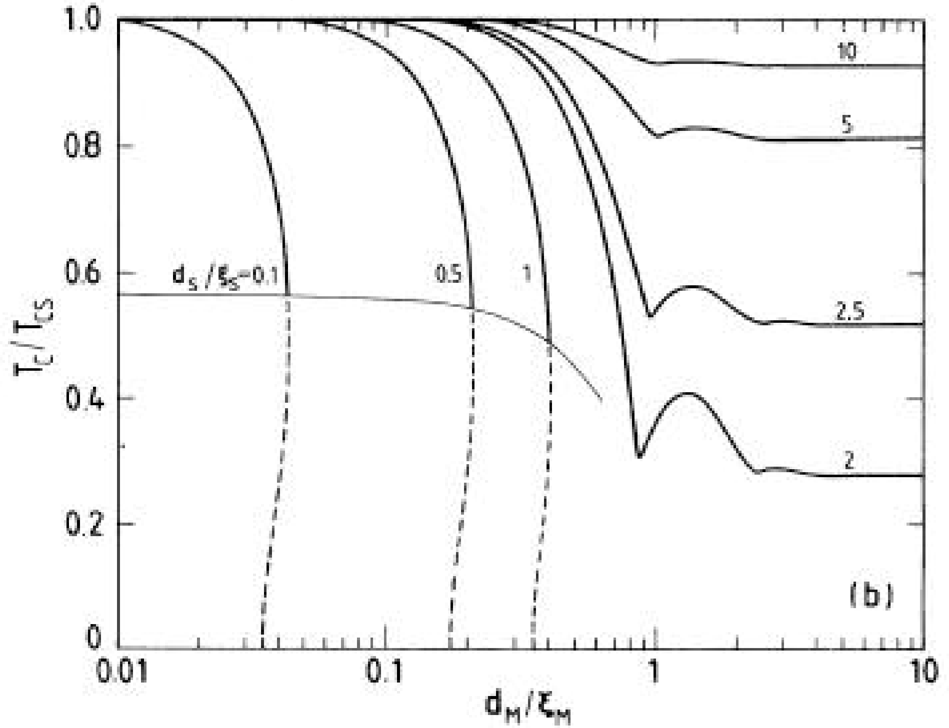
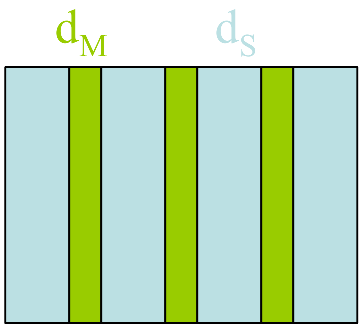


FIG. 1. The reduced transition temperature T_c/T_{cS} as a function of the reduced (a) S film thickness d_S/ξ_S, and (b) M film thickness d_M/ξ_M for $\epsilon = 10$ and $\Theta_D/T_{cS} = 200$. The tricritical points T^*/T_{cS} (thin curves) are also shown. Dashed curves show solutions that are physicaly unstable.

S/F Multilayer



Radovic et al. PRB 44, 759 see also Buzdin et al. Sov. Phys. JETP 74, 124

T_c oscillations : measures

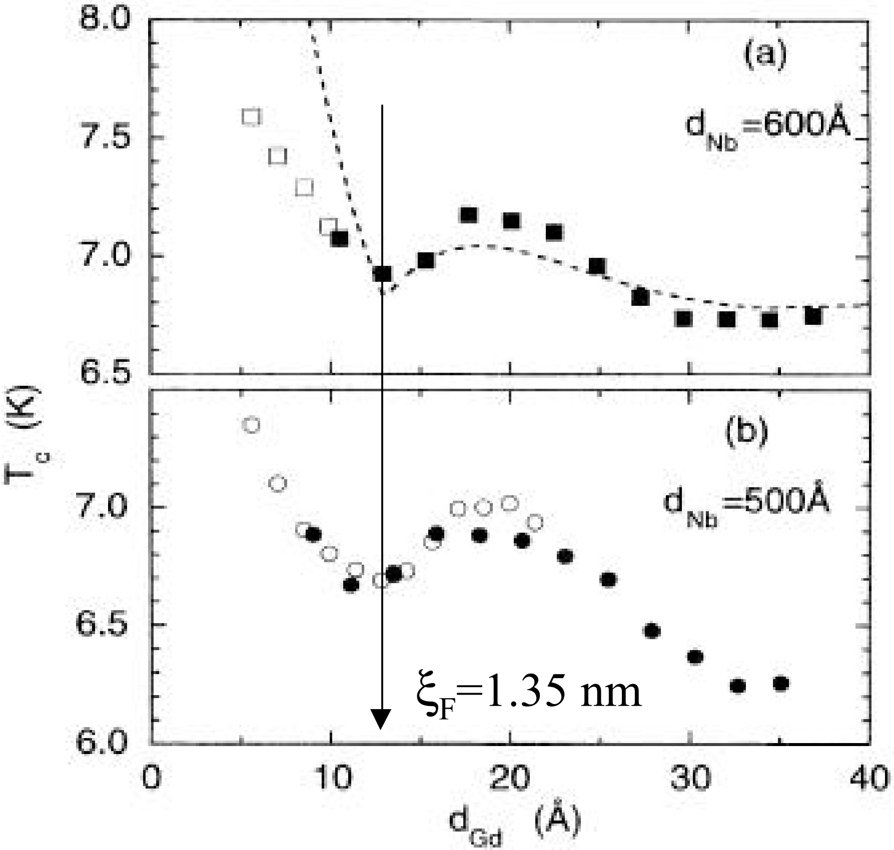
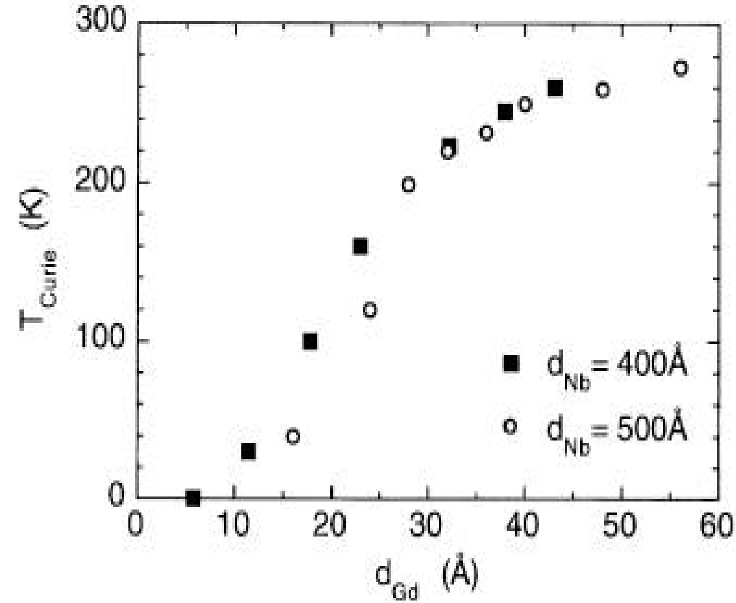


FIG. 4. Superconducting transition temperatures T_c vs d_{Gd} in Nb/Gd multilayers with (a) d_{Nb} = 600 Å and (b) 500 Å. Different symbols correspond to different sample series. Dashed line in (a) is a fit by the theory of Ref. [9]. A sputtered Nb film 0.5 μm thick has T_c = 8.8 K.

BUT

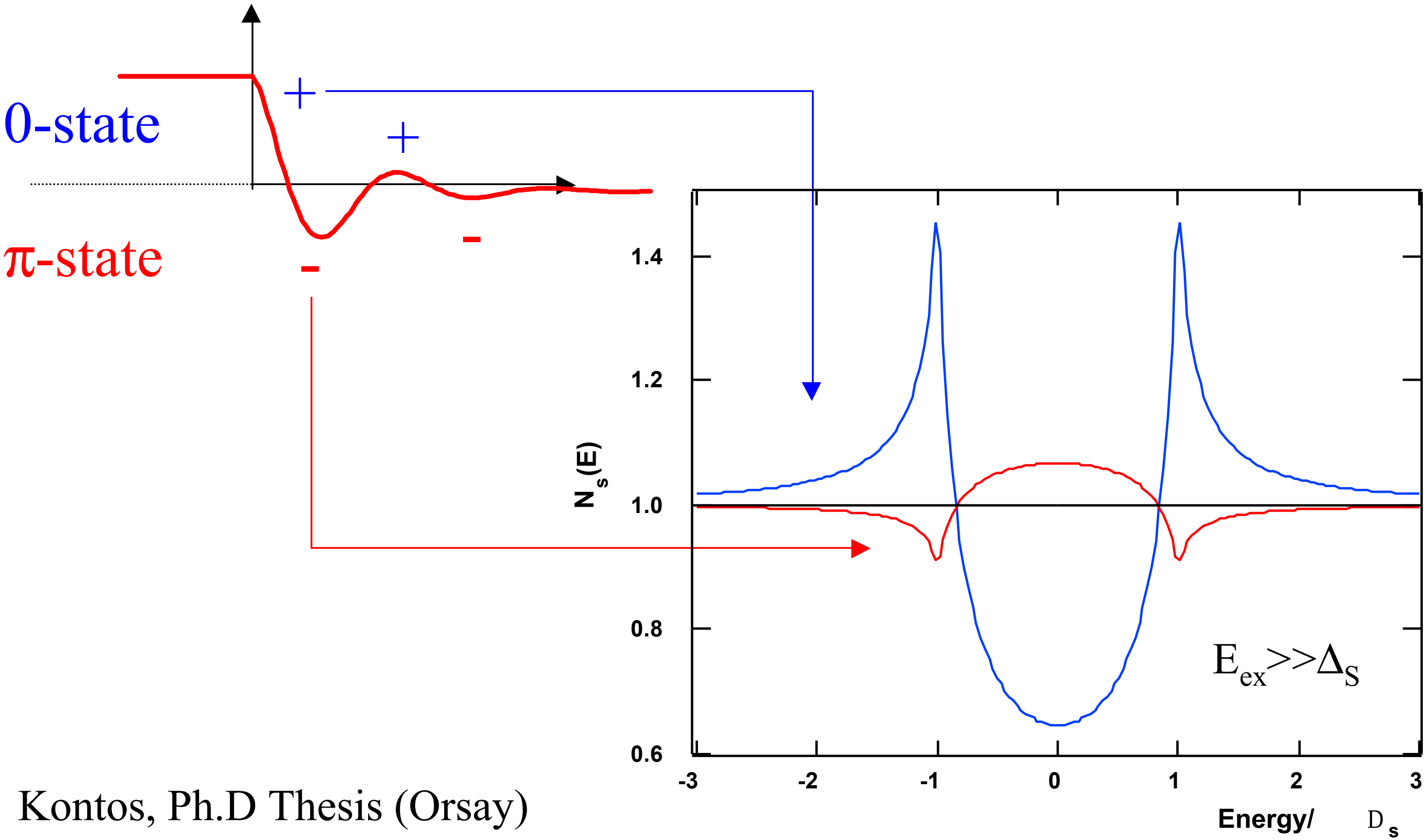


other pair breaking mechanism ?
dead layer ?

Jiang et al. PRL 74, 314

see also: Strunk et al. PRB 49, 4053
Aarts et al. PRB 44, 7745

The superconducting Density of States



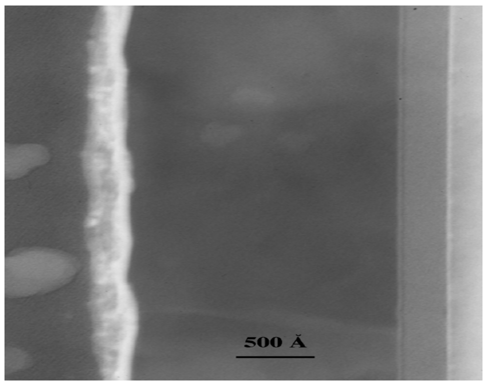
Kontos, Ph.D Thesis (Orsay)

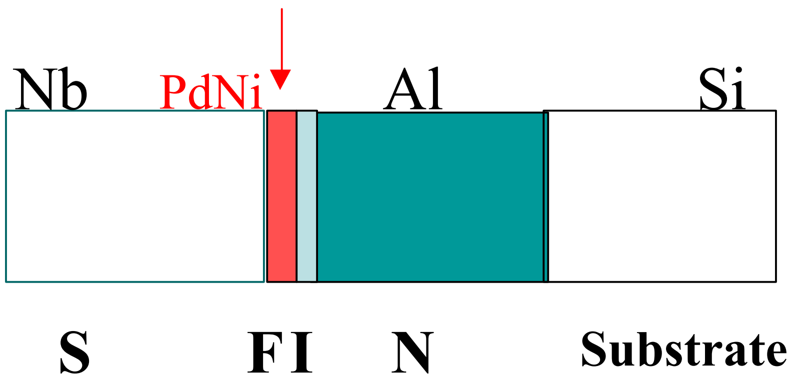
see also: Guoya Sun et al. PRB 65, 174508

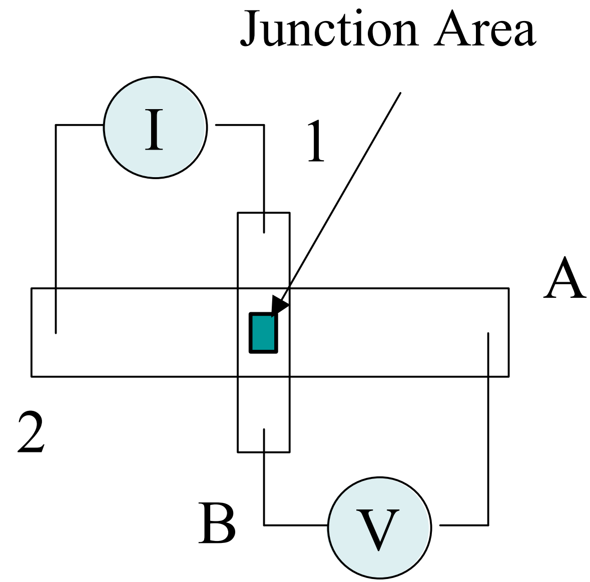
Buzdin PRB 62, 11377

Planar Tunnel Junctions

TEM



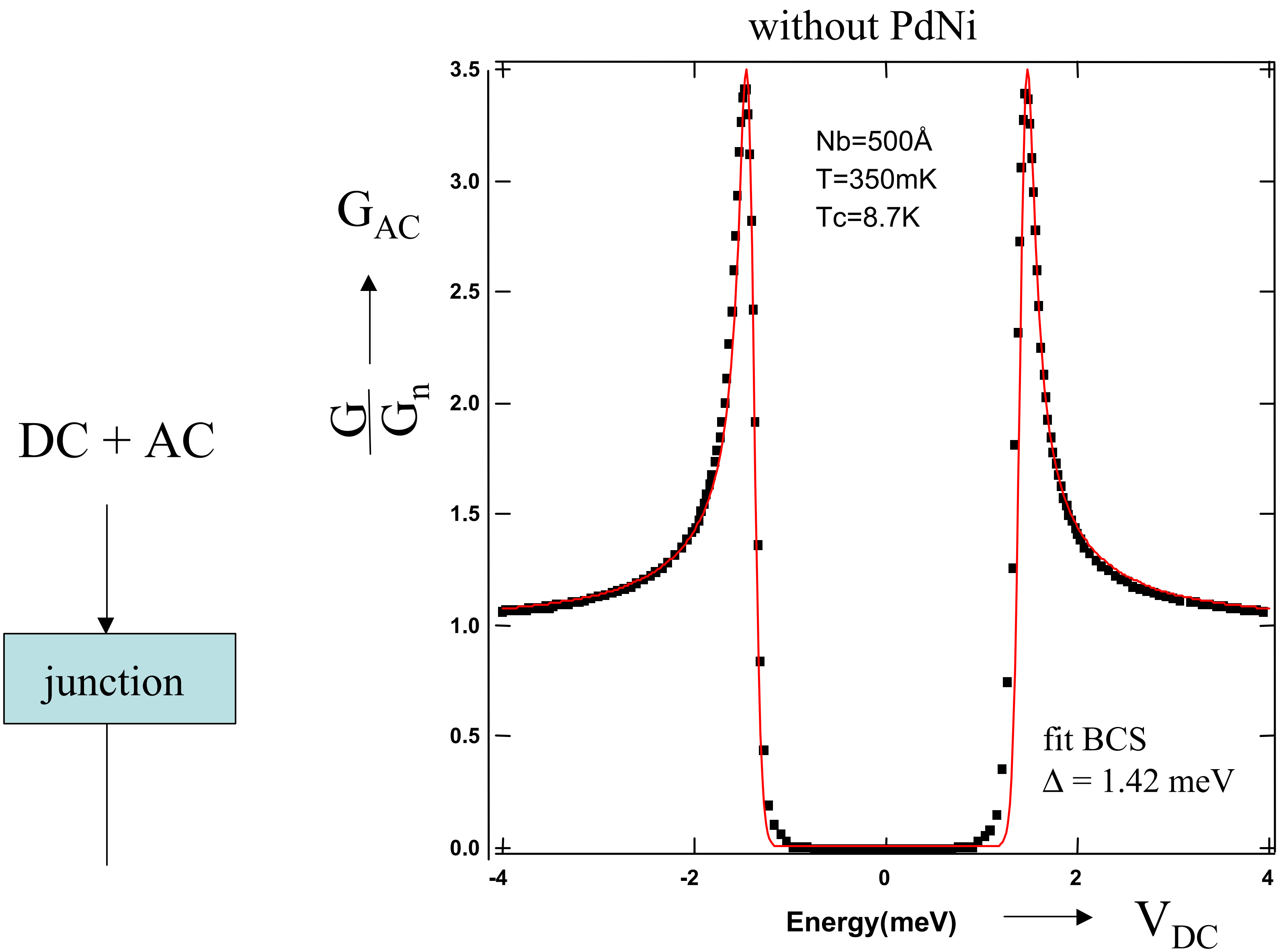




$$\frac{G}{G_n} = \int \frac{N_{PdNi}(E)}{N_{PdNi}(E_F)} \left[-\frac{\partial f}{\partial eV}\right]$$

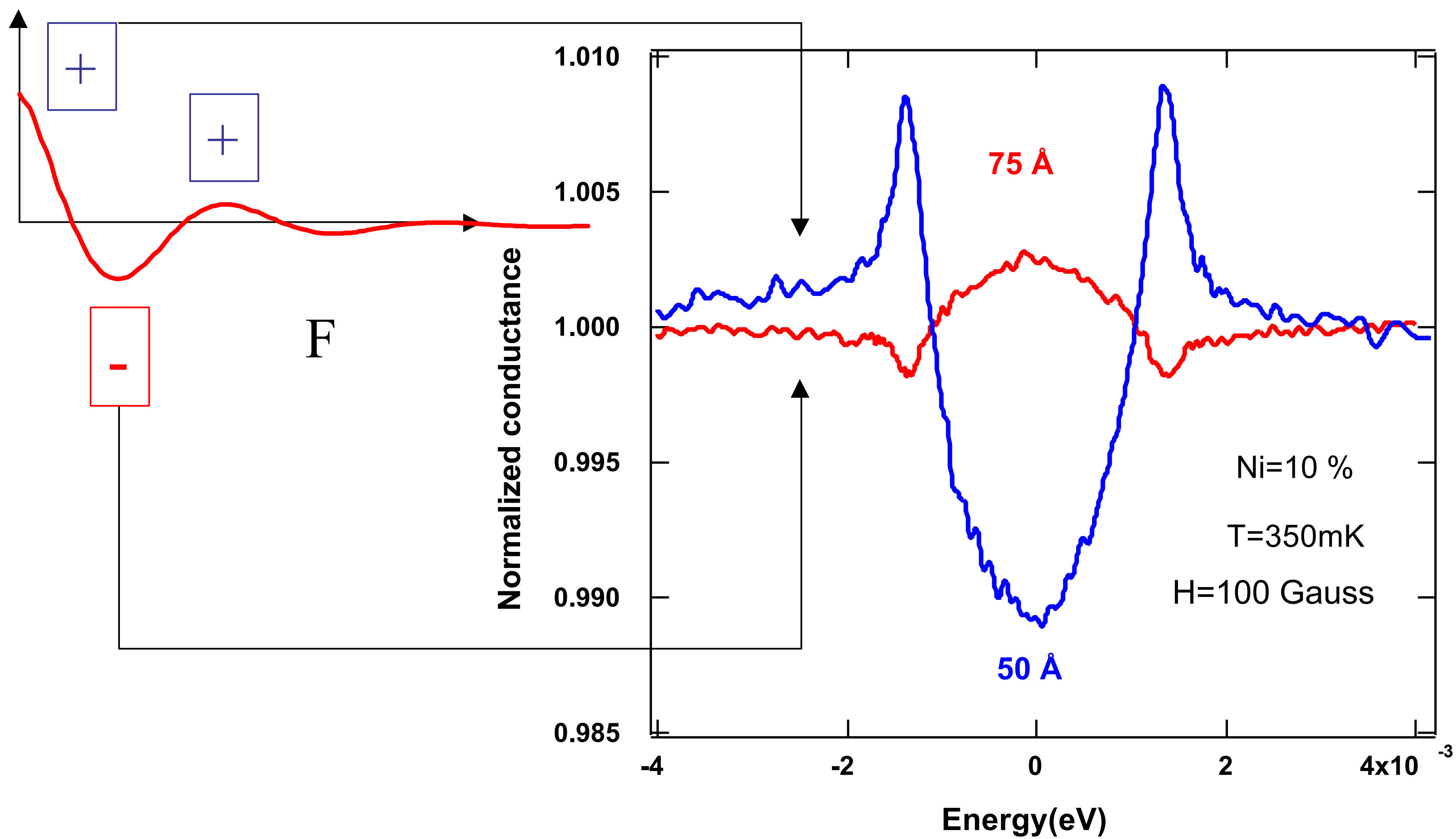
High energy and amplitude resolution

BCS Density of States

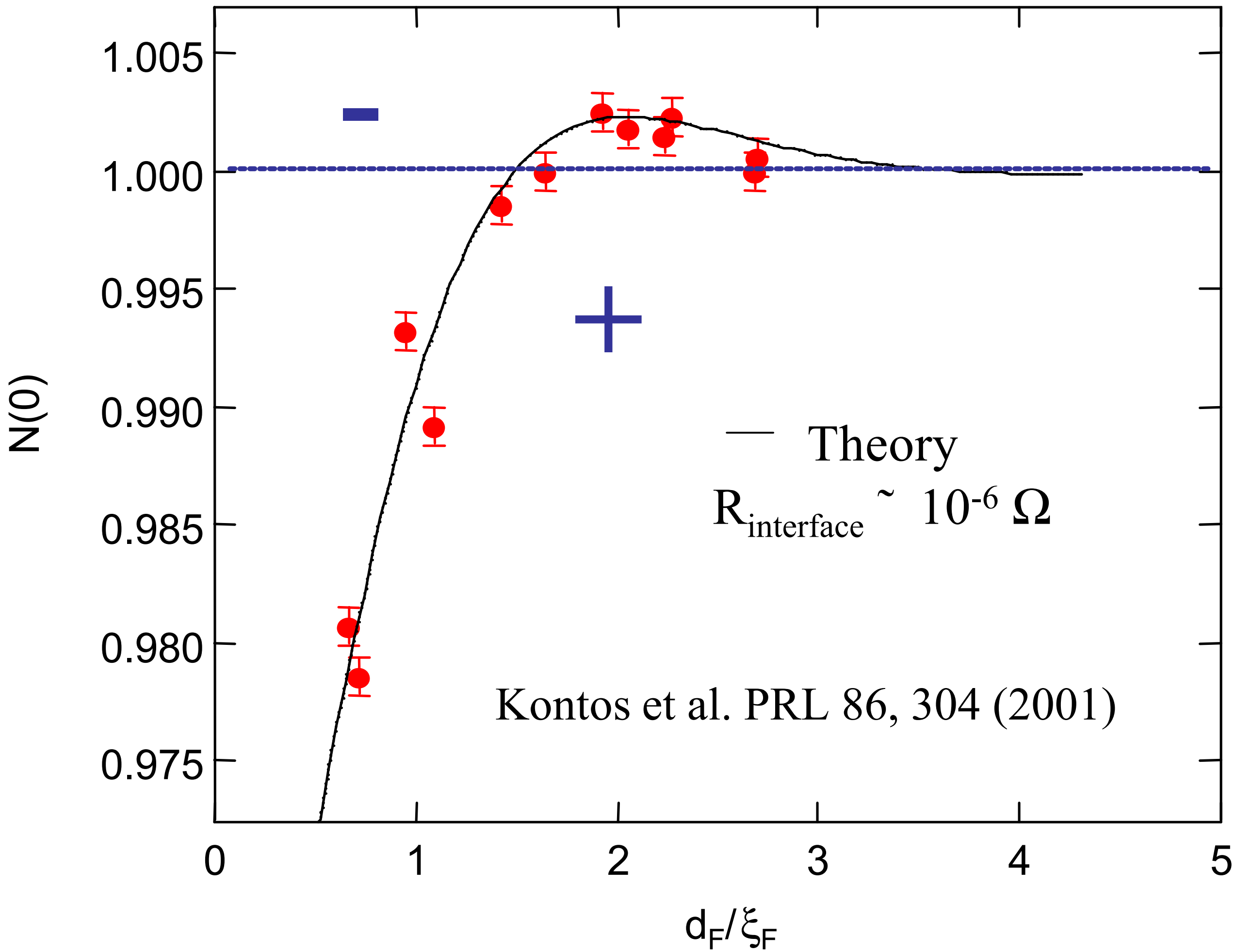


Tunneling Spectroscopy

$Pd_{1-x}Ni_x$ x ~ 10% T_c ~ 100 K E_{ex} ~ 10 meV ⟹ ξ_F ~ 50 Å

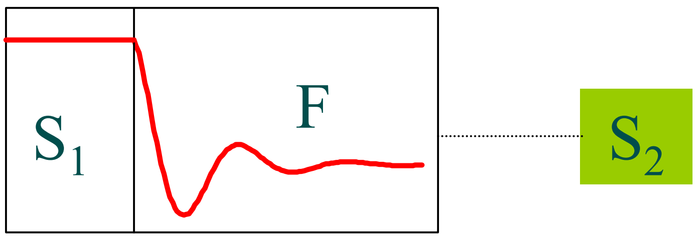


Density of States at Zero Energy

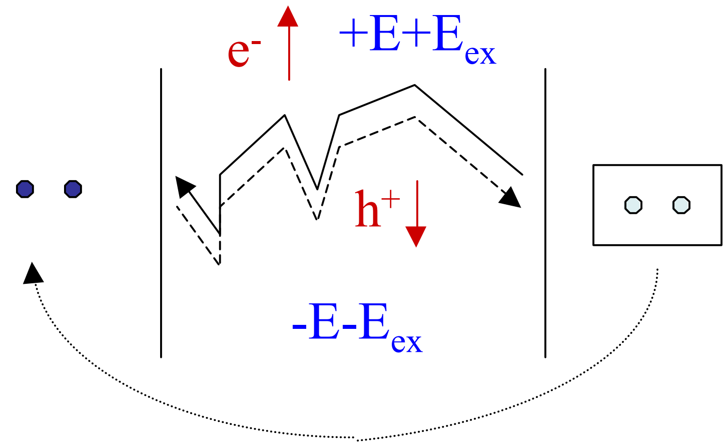


Josephson Coupling

Macroscopically



Microscopically



Current-phase relationship

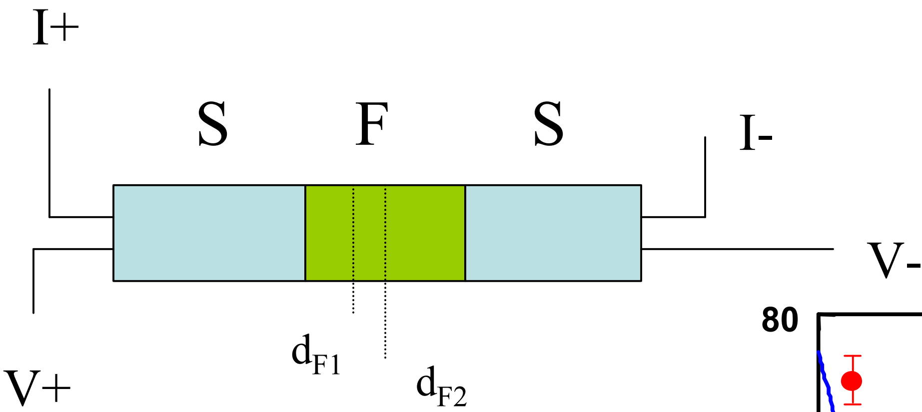
Cooper pair transfert

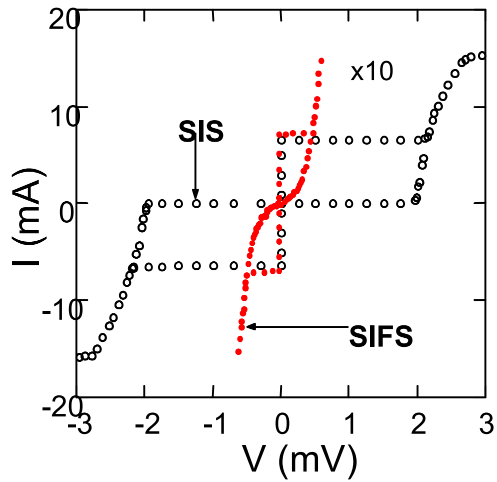
$I = I_c \sin\theta_{12}$? ? g? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?

→ $\sim \Psi$ → Oscillations

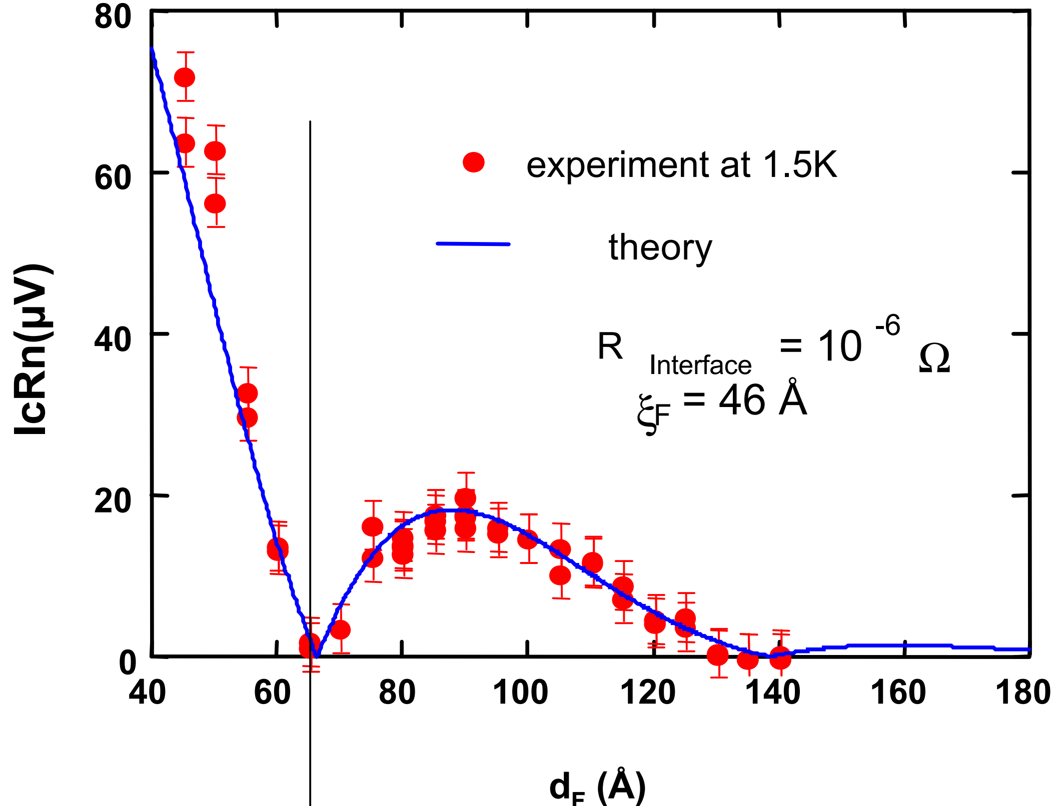
Josephson Coupling

Kontos et al. PRL 89, 137007 (**2002**)





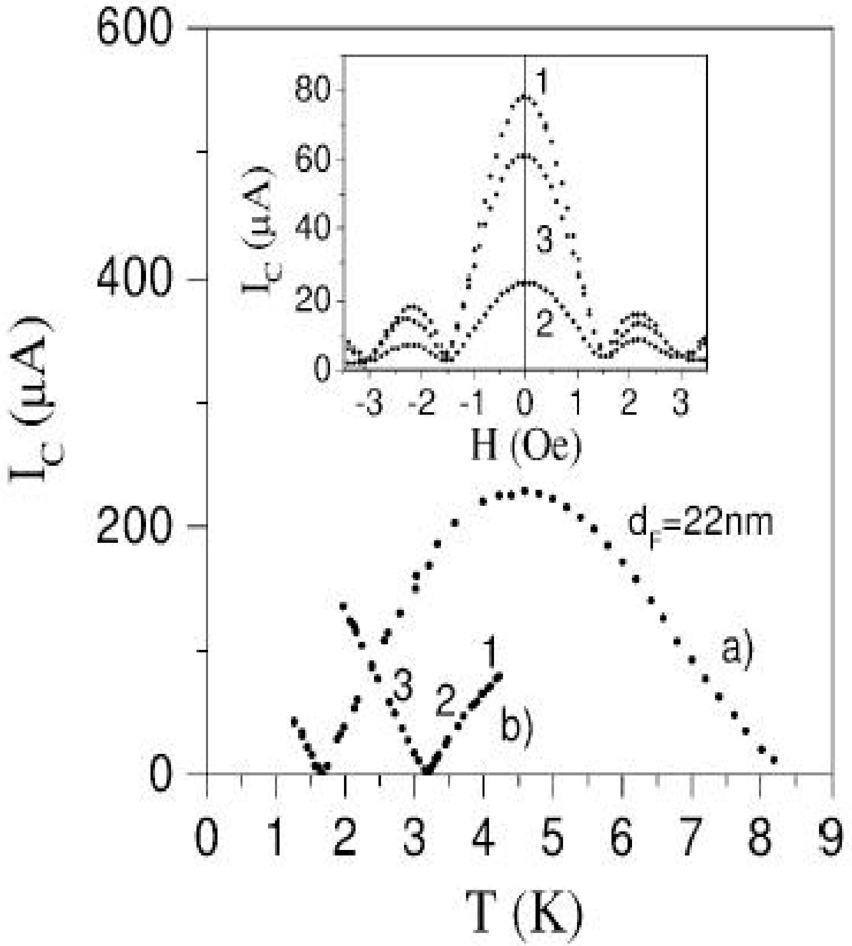
I-V characteristics



$I = I_c \sin\Delta\theta$ — 0-junction

$I = -I_c \sin\Delta\theta$ — π-junction

SFS

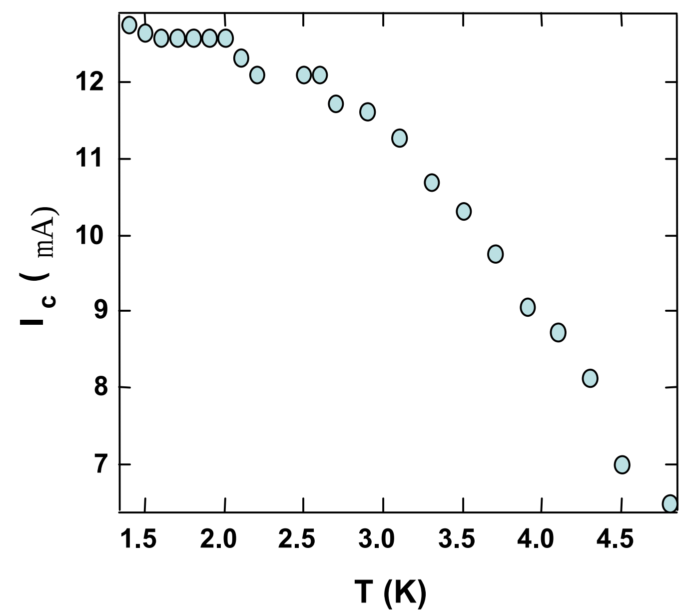


I_cR_n ~ 2nV

V. Ryazanov et al., PRL 86 2427 (2001)

Temperature dependence

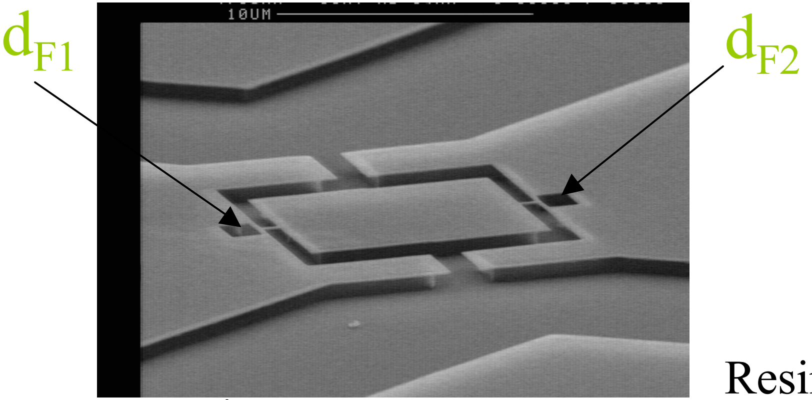
SFIS



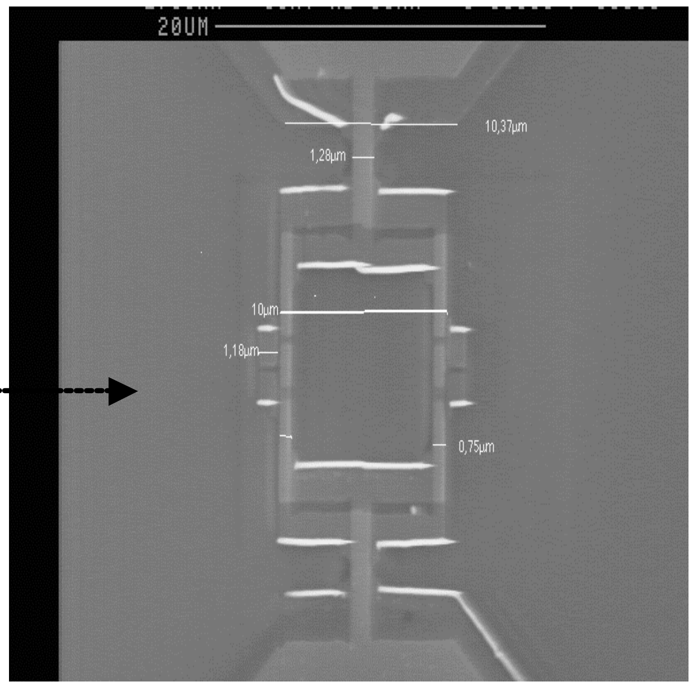
I_cR_n ~ 5μV

Kontos et al. PRL 89, 137007 (2002)

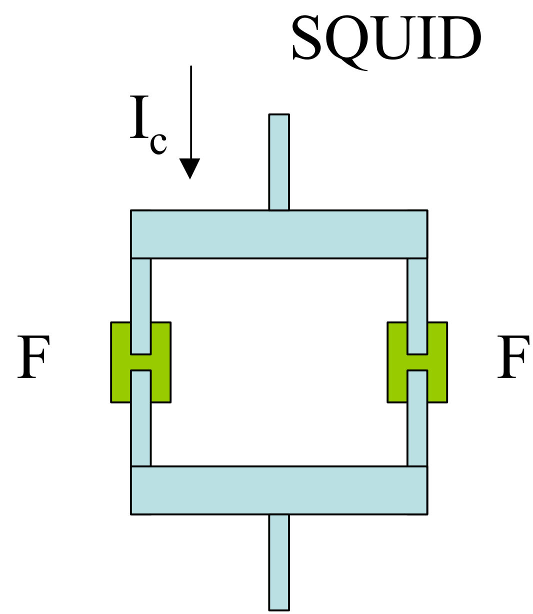
Quantum Interference Devices



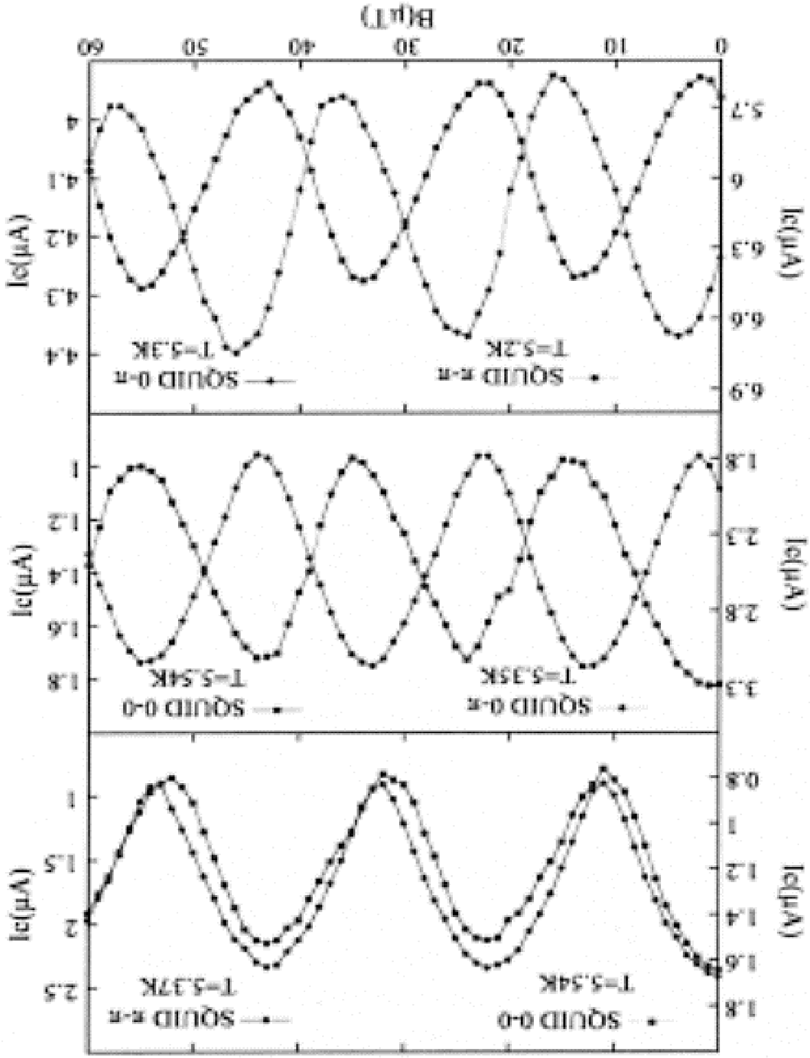
Resine mask



After deposition and lift-off



In collaboration with *W. Guichard, O. Bourgeois & P. Gandit*, CRTBT-Grenoble



Guichard et al. PRL 90, 167001 (2003)

Diffraction

Linearity : $I_c L \ll \Phi_o$

$$I = 2I_c \left| \cos(\pi\Phi/\Phi_o + \varphi/2) \right|$$

0 0

↓ ↓

0 π

↓ ↑

π π

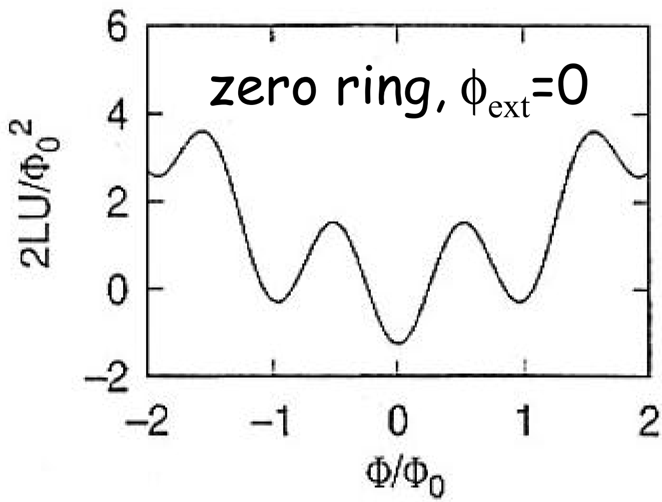
↑ ↑

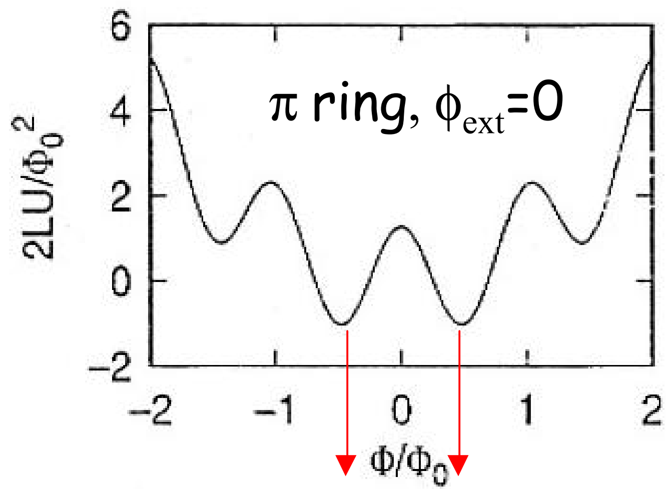
Sponteneous Supercurrents

Free energy:

$$U(\phi,\phi_{ext}) = \underbrace{\frac{LI^2}{2}}_{\text{magnetic term}} - \frac{\phi_0}{2\pi} \underbrace{I_c \cos\left(\frac{2\pi}{\phi_0}\phi + \varphi\right)}_{\text{Josephson term}}$$

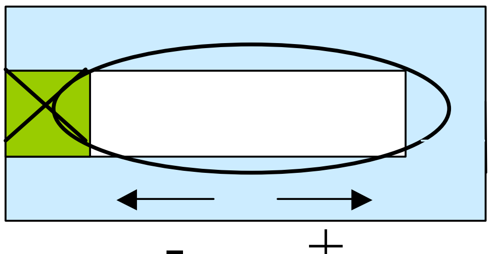
$\varphi=0$ zero ring
$\varphi=\pi$ π ring





Groundstate = +/- $\Phi_0/2$

π ring
$I_cL/\phi_0 \gg 1$



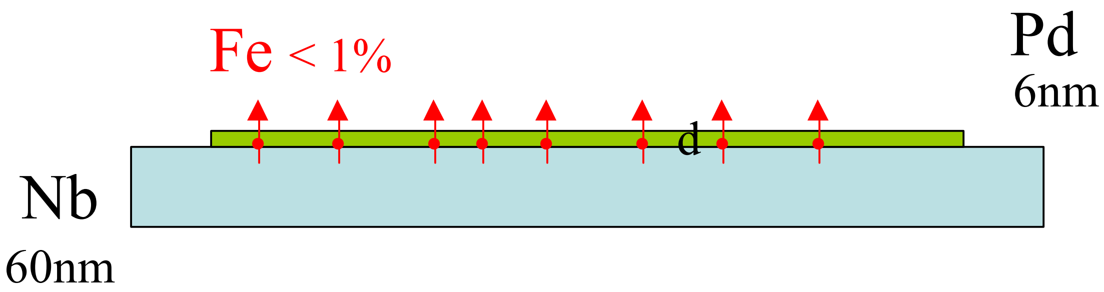
Question :

Can superconductivity be used to change the magnetic order ?

How nano-structures can help on that ?

Heterostructure

Tc=8.5K



Idea : χ_{Pd} is reduced by induced superconductivity

1. Why proximity effect ?

We do not need similar energy scales as in bulk superconductors.

Δ=1 meV E_{ex}=0.1-1 eV

2. Why dilute alloys ? $d>\xi_F$ = 2-20nm