Ground State of Ferromagnetic Josephson Jonctions

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Meso 2003

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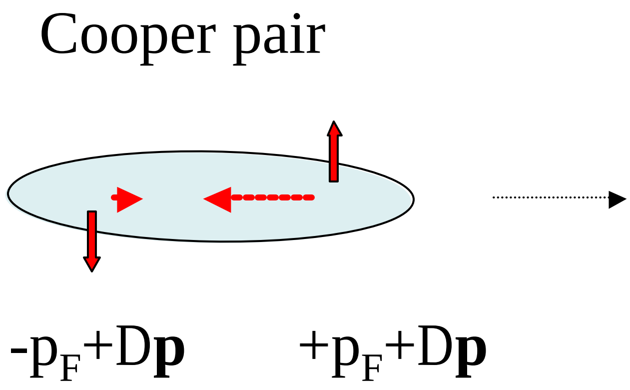
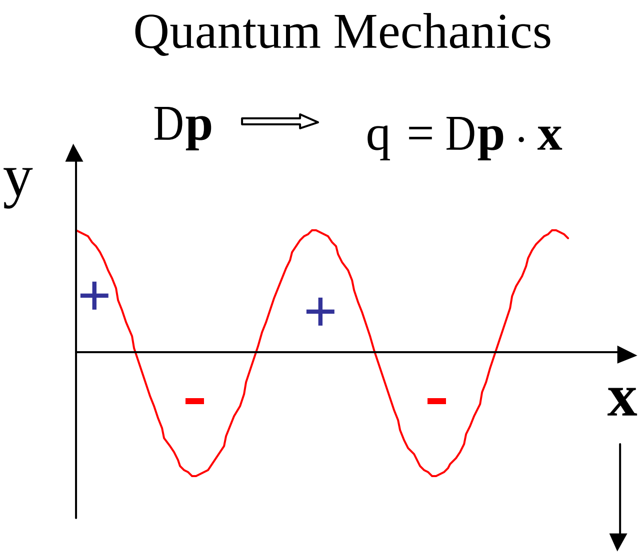
Many Thanks to: D. Estève, H. Poitier, W. Belzig, Y. Nazarov, A. Golubov, P.Monod, J. Ferré, V. Ryazanov,
J. Aarts, C. Stunk, B. Leridon, L. Dumoulin, A. Leggett, D. Van Harlingen, M. Salez, T. Carrington, H. Sellier, H. Bernas, A. Buzdin

Motivation

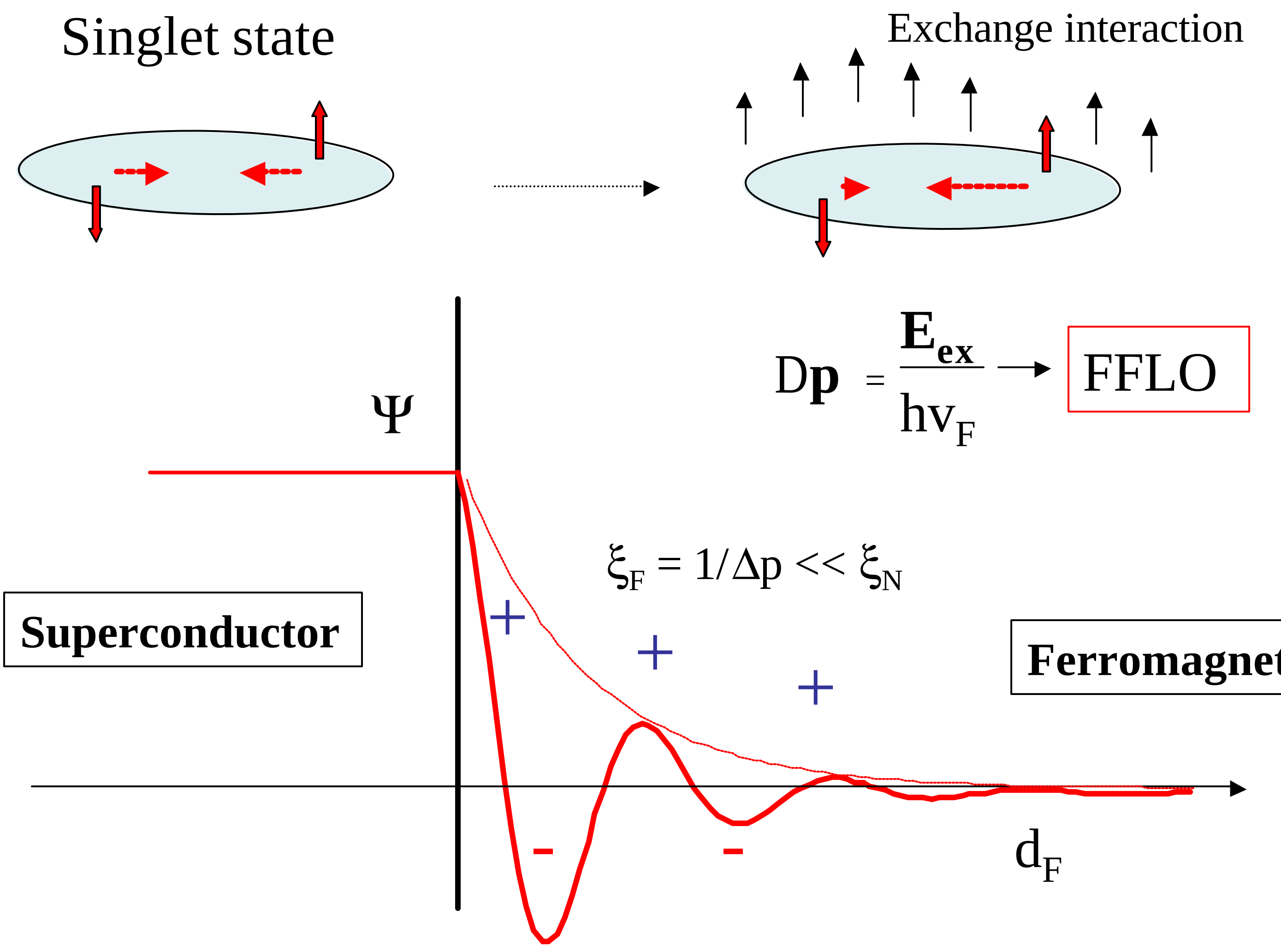
Superconductivity **p?0 l=0**





Analogy : D-wave p=0 l=2 q

Ferromagnetic proximity effect



Gain

Since only phase coherence is required in F :

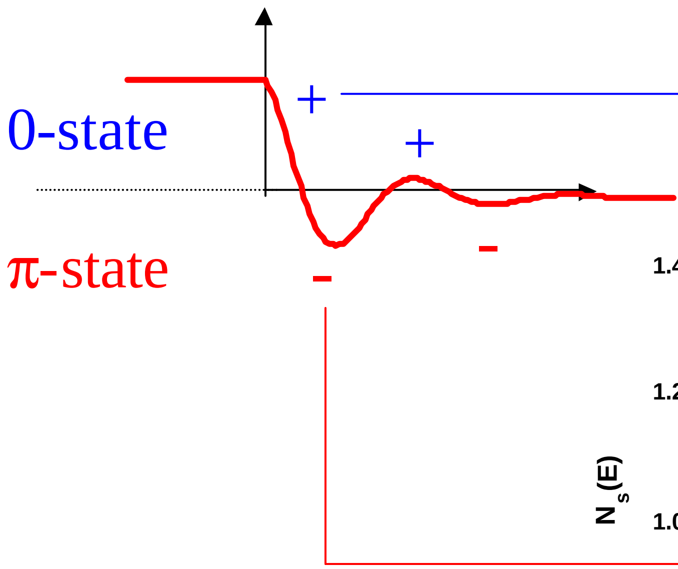
1. $E_{ex} \sim \Delta$
2. clean limit

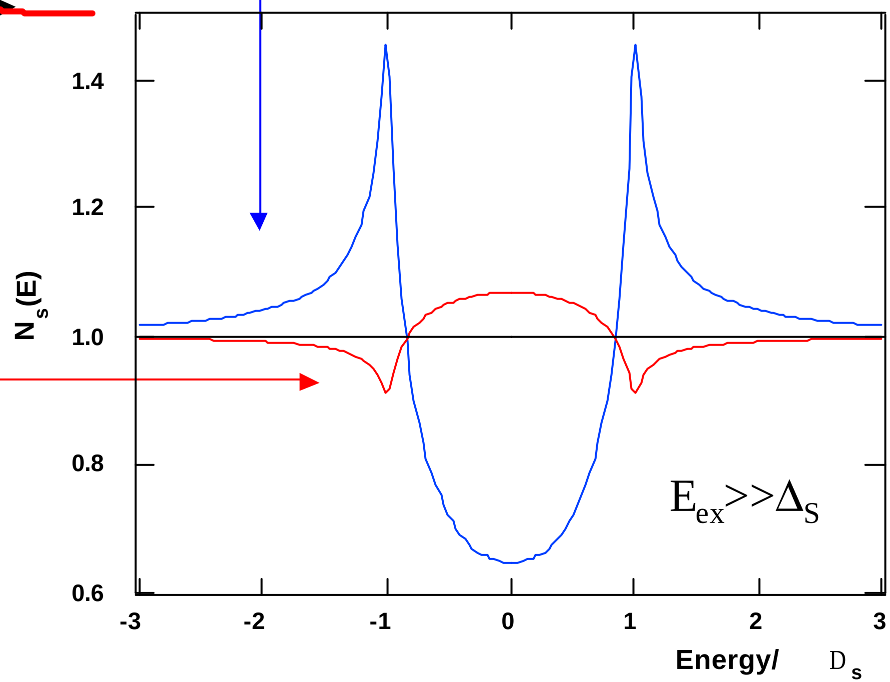
But

We need the spin to be a good quantum number :

1. ξ_F < domain size
2. $h/\tau_{so} \ll E_{ex}$

The superconducting Density of States





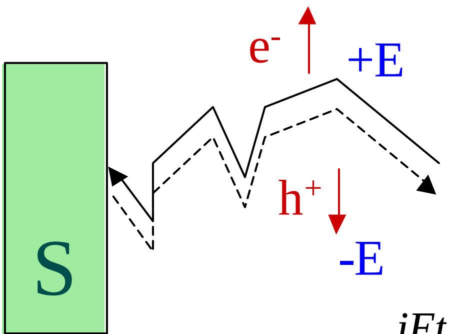
Usadel equations :

$$\frac{\hbar D}{2}\frac{\partial^2 \theta}{\partial x^2} + i\left(E + E_{ex}\right)\sin\theta = 0$$

$$N(E) = \Re e\{\cos\theta\}$$

Andreev Reflections

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



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

Coherent superposition

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

For $E << E_{ex}$ $\quad$ $\boldsymbol{E_{ex}}$

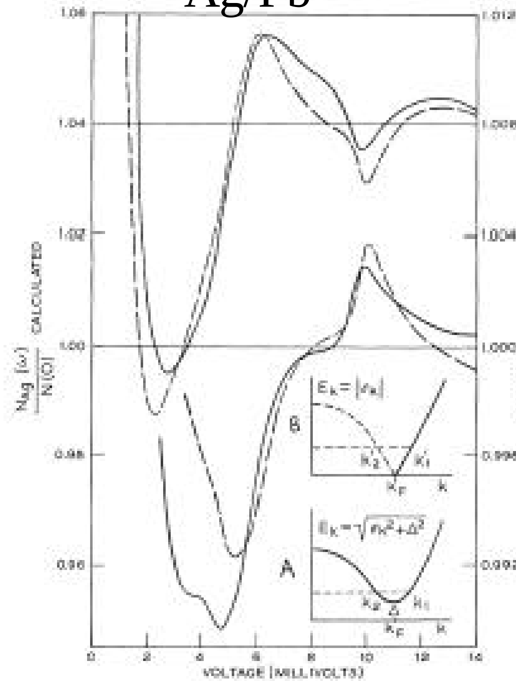
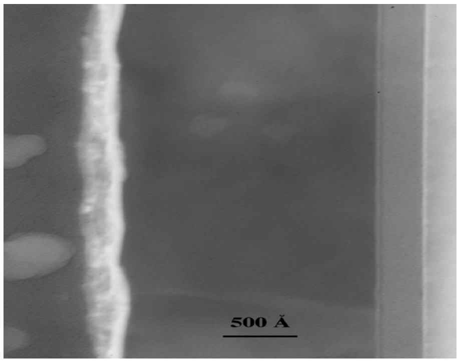


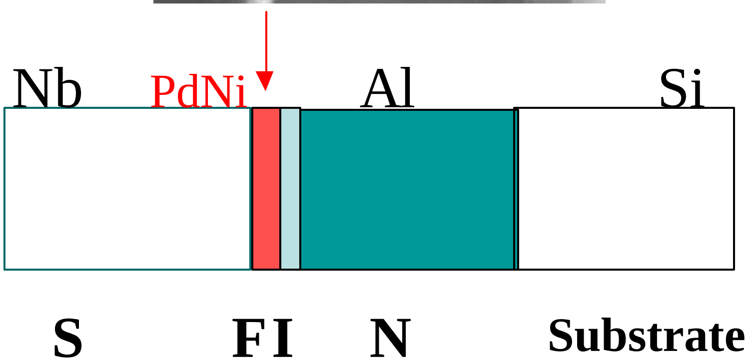
FIG. 1. Solid lines show measured densities of states for two junctions with silver film thicknesses of 1000 Å (upper) and 470 Å (lower) and lead thickness of 850 Å. Dashed lines show the calculated variation of density of states. The value $N_{Ag}(\omega)/N(0) - 1$ has been shifted vertically by 0.04 (left-hand scale) for the upper curves. Inserts (a) and (b) show the E_k-vs-k diagrams for a superconducting and normal metal, respectively.

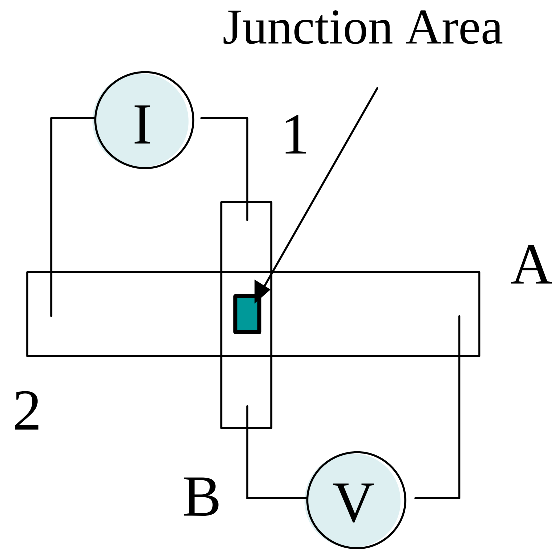
Rowell & MacMillan PRL 16, 453 (1966)

Planar Tunnel Junctions

TEM







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

$Pd_{1-x}Ni_x$ $x \sim 10\%$ $T_c \sim 100$ K

Small exchange energy ~ 10 meV

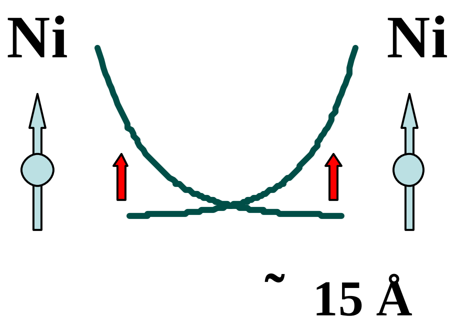
High energy and amplitude resolution

PdNi

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

Hall resisitivity — Normal — Anomalous

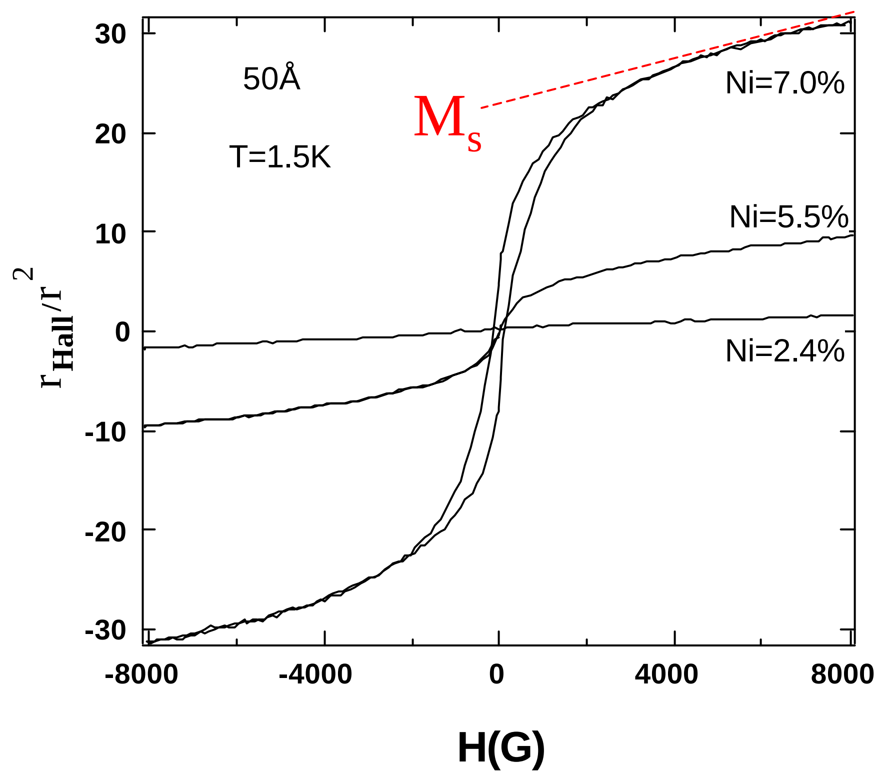
$R_s \sim r^2$



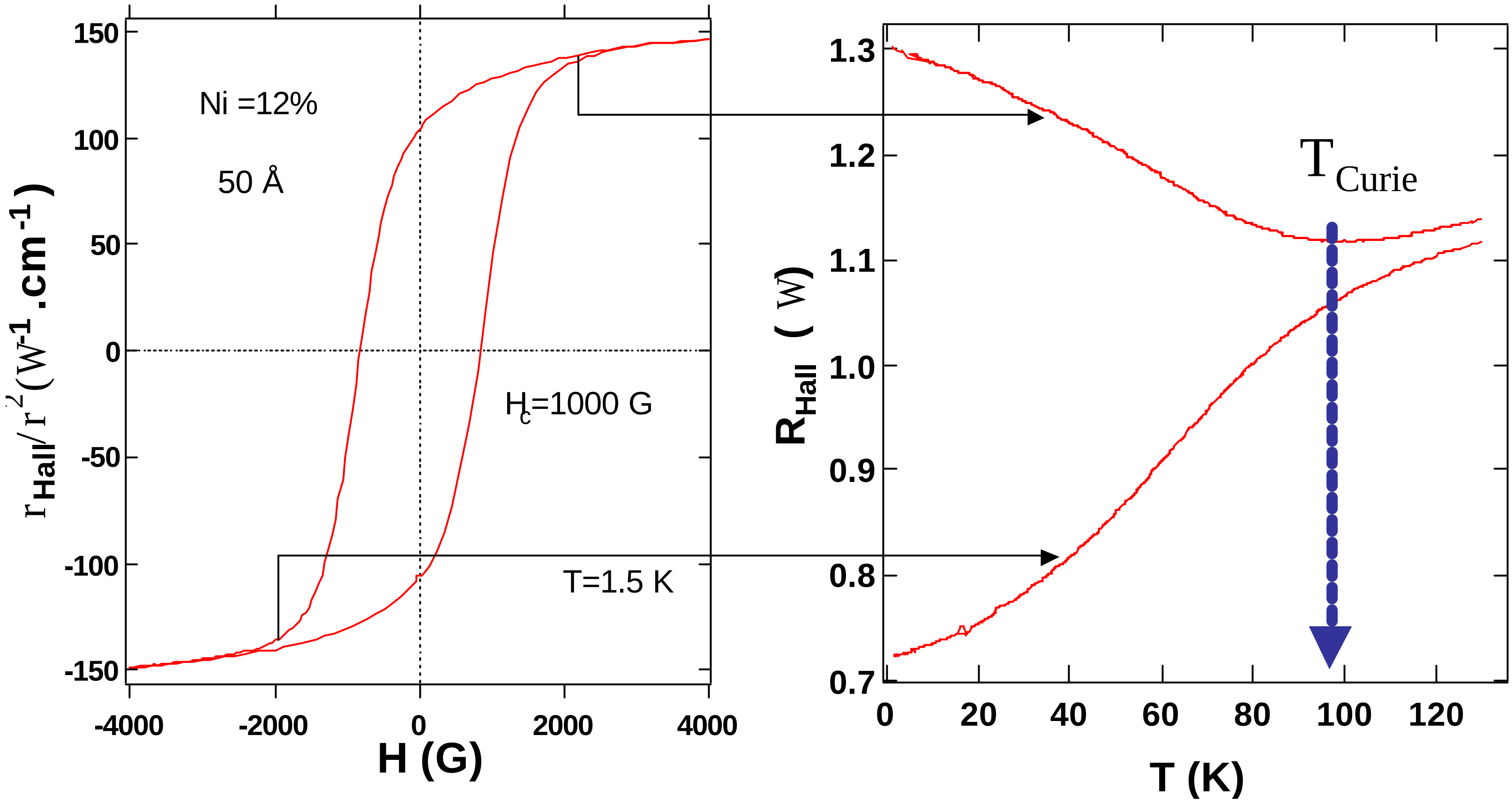
Indirect exchange

$m \sim 2.4\ m_B$ per Ni
$m_{Ni} = 0.6\ m_B$

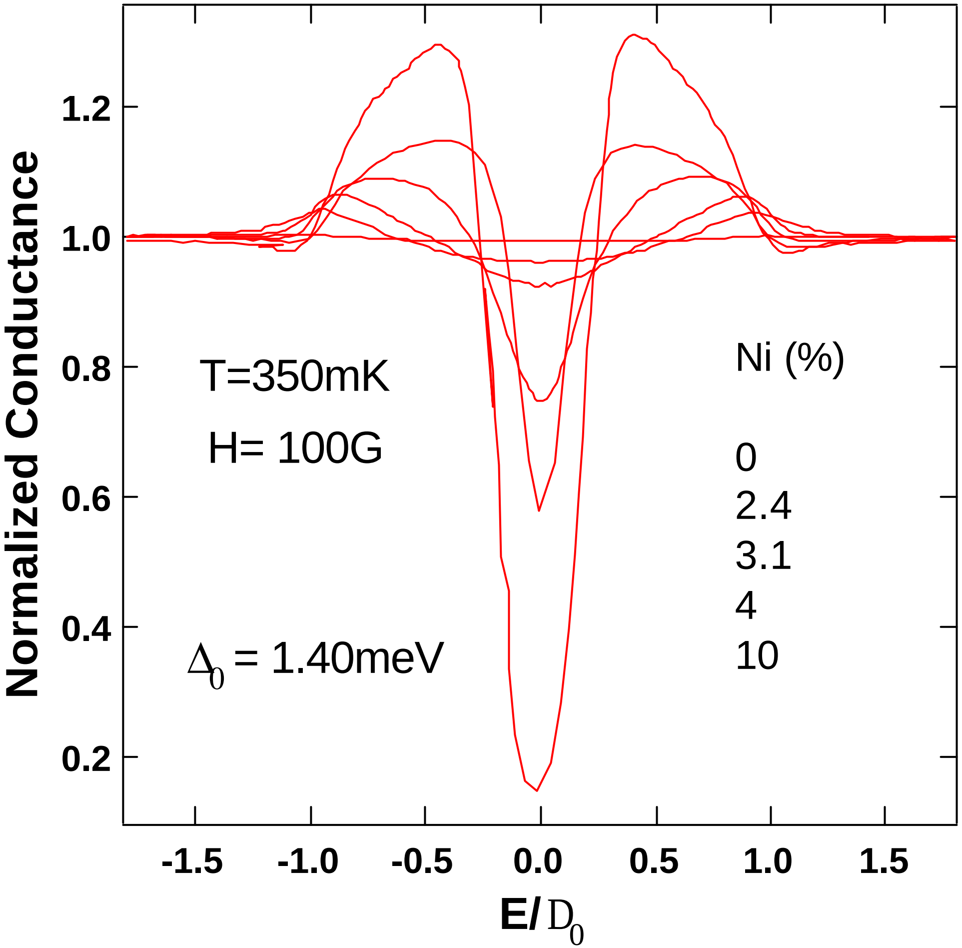
Itinerant ferromagnetism

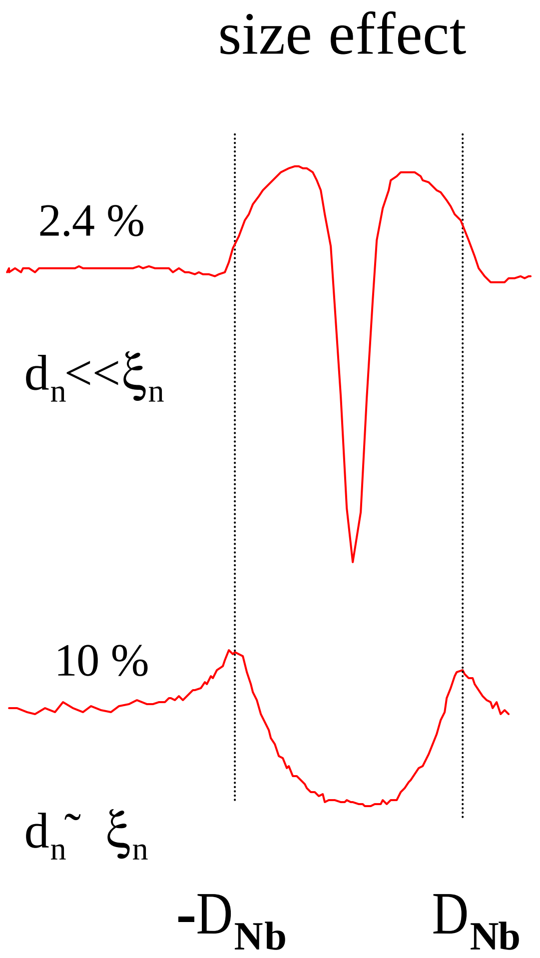


Curie's Temperature

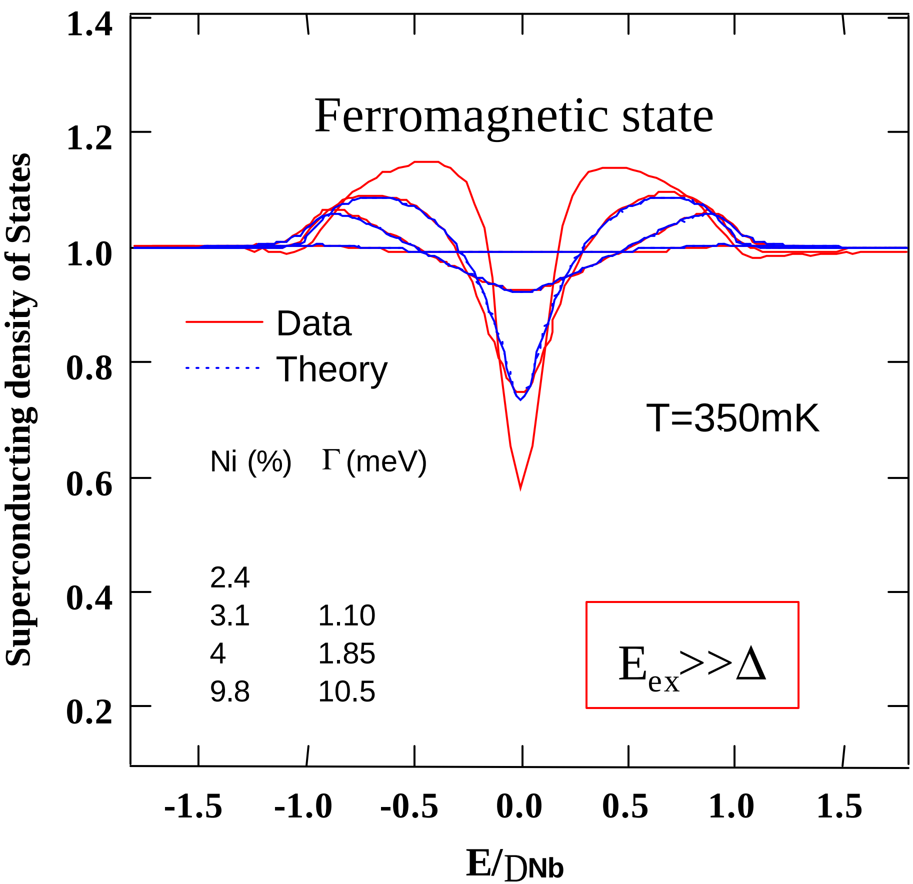


Tunneling Spectroscopy

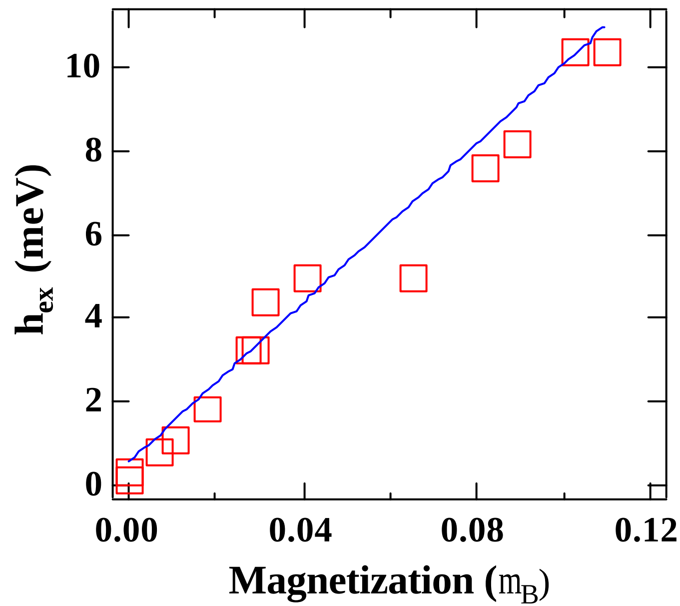




Measure of the exchange energy



$G = E_{ex}$



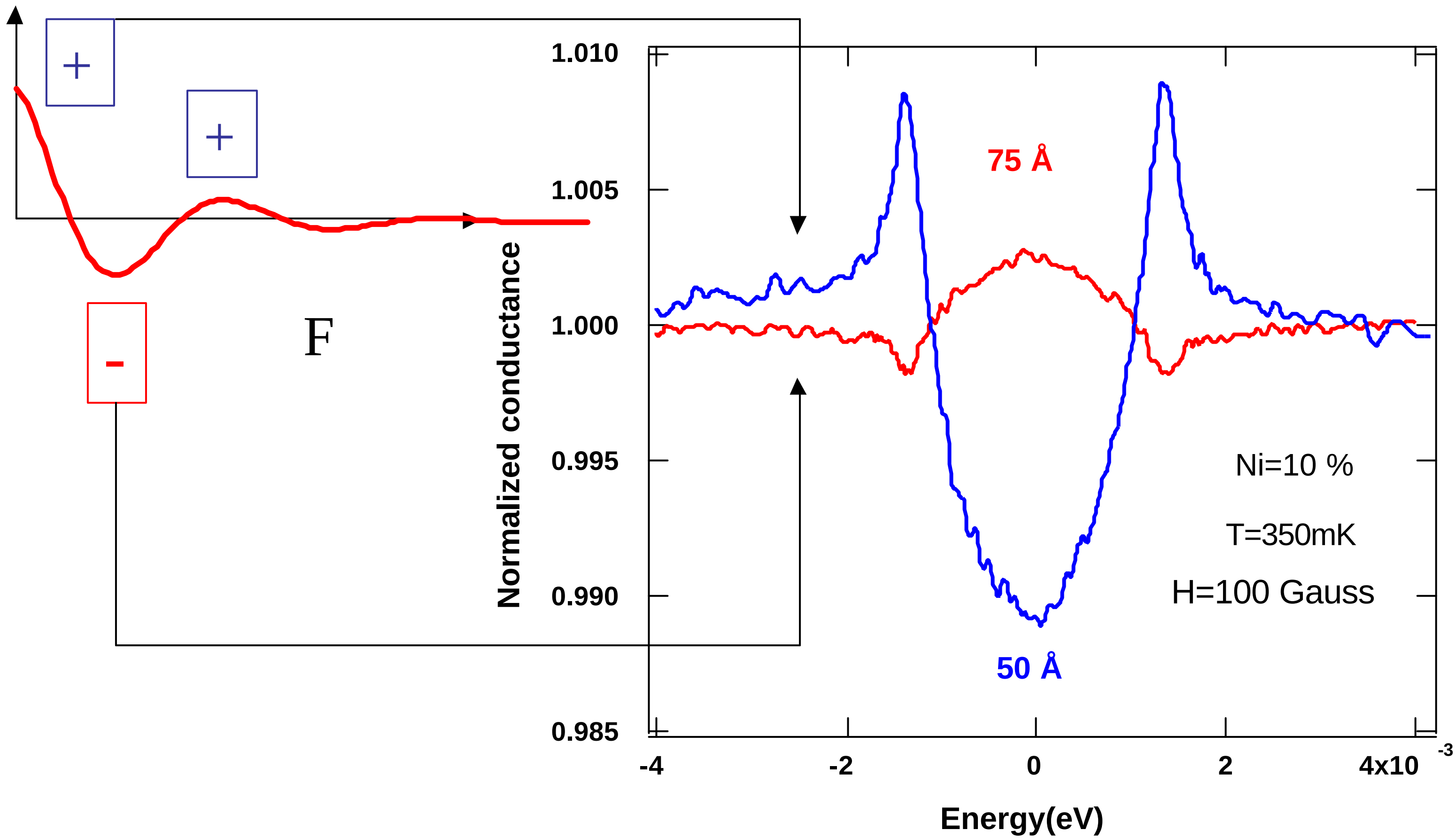
$$M = m_B E_{ex} N(E_F) I_{Stoner}$$

We get $M \sim 0.1 m_B$ for $E_{ex} \sim 10 meV$

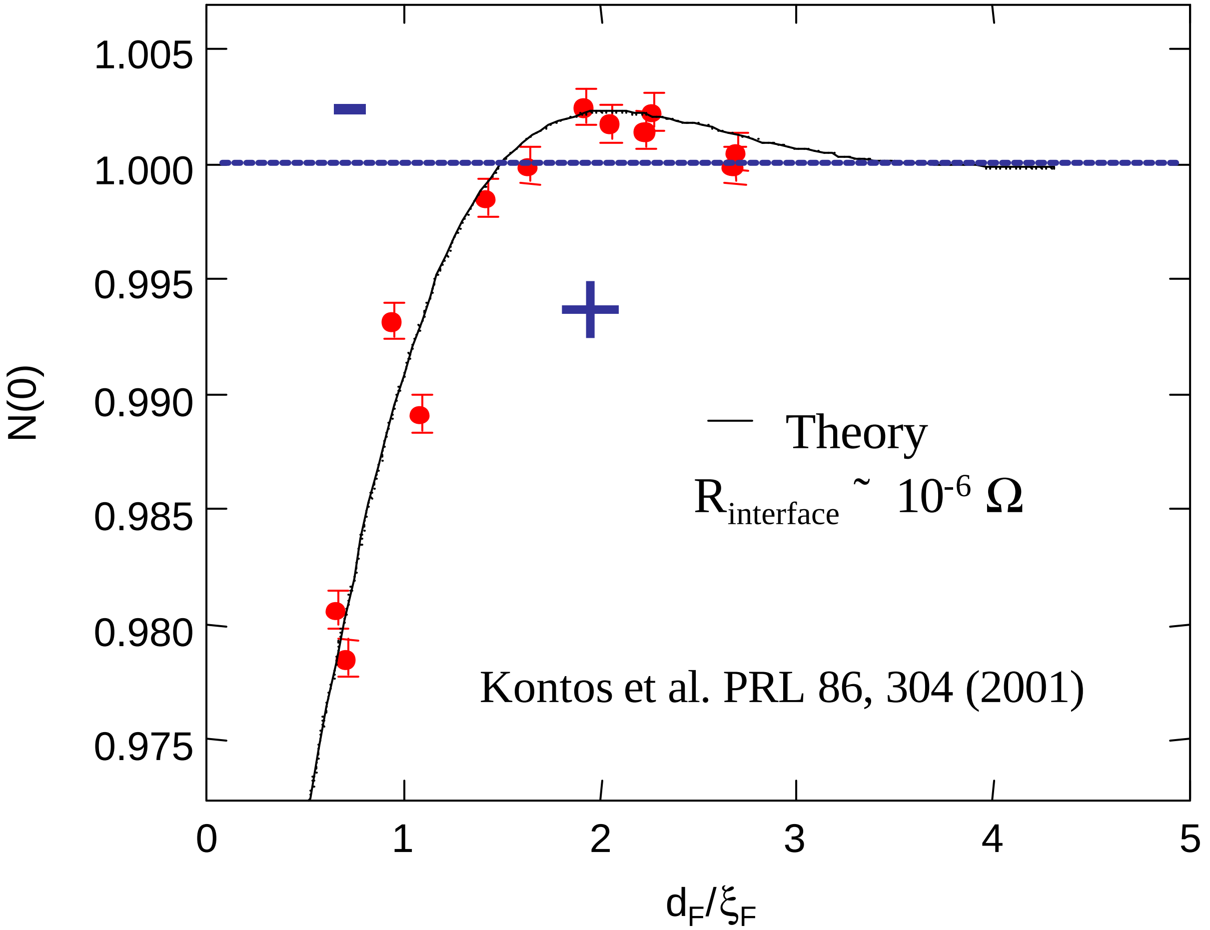
Kontos et al. preprint

Tunneling Spectroscopy

$E_{ex} \sim 10$ meV $\Longrightarrow$ $\xi_F \sim 50$ Å

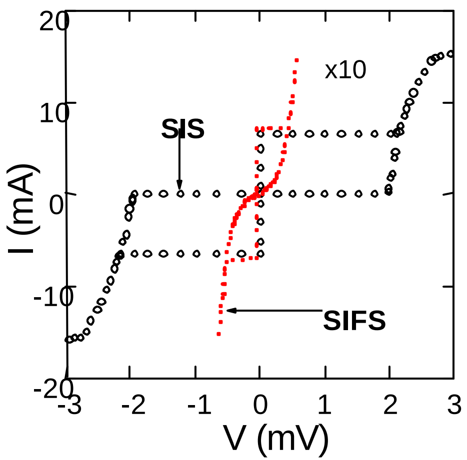


Density of States at Zero Energy

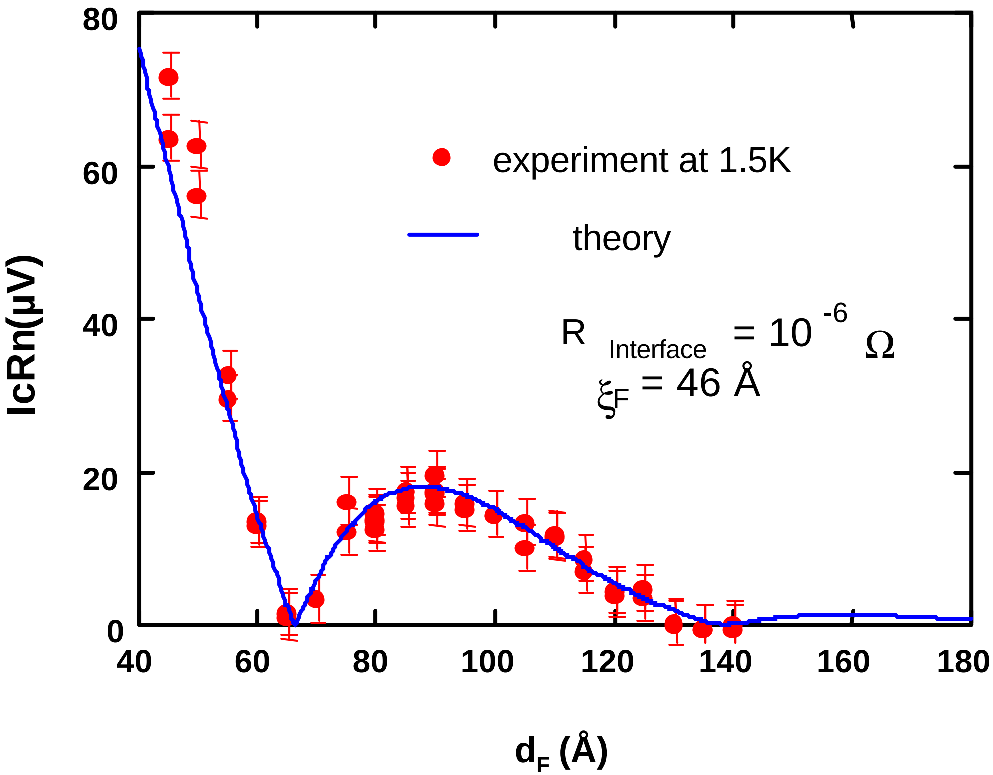


Josephson Coupling

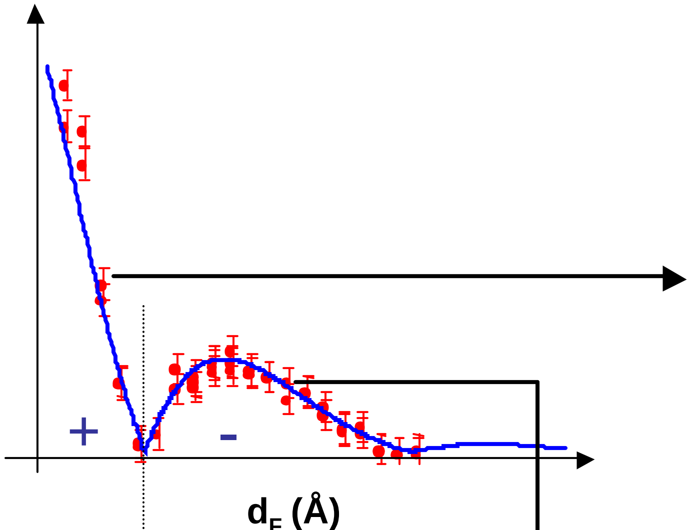
Density of States	$N(0) \sim R_B^2$	Smaller effect
Josephson coupling	$I_c R_n \sim R_B$	Larger effect

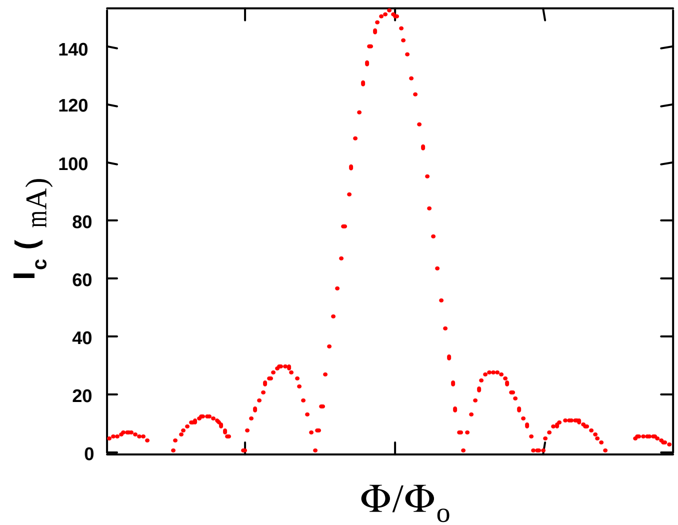


I-V characteristics



? ? ? ? ? ? ? ? ? ? Pattern



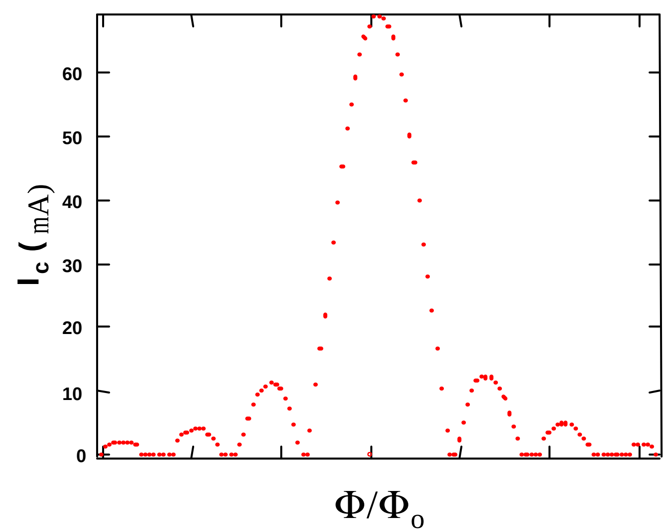


$I = I_c \sin\Delta\phi$

0-junction

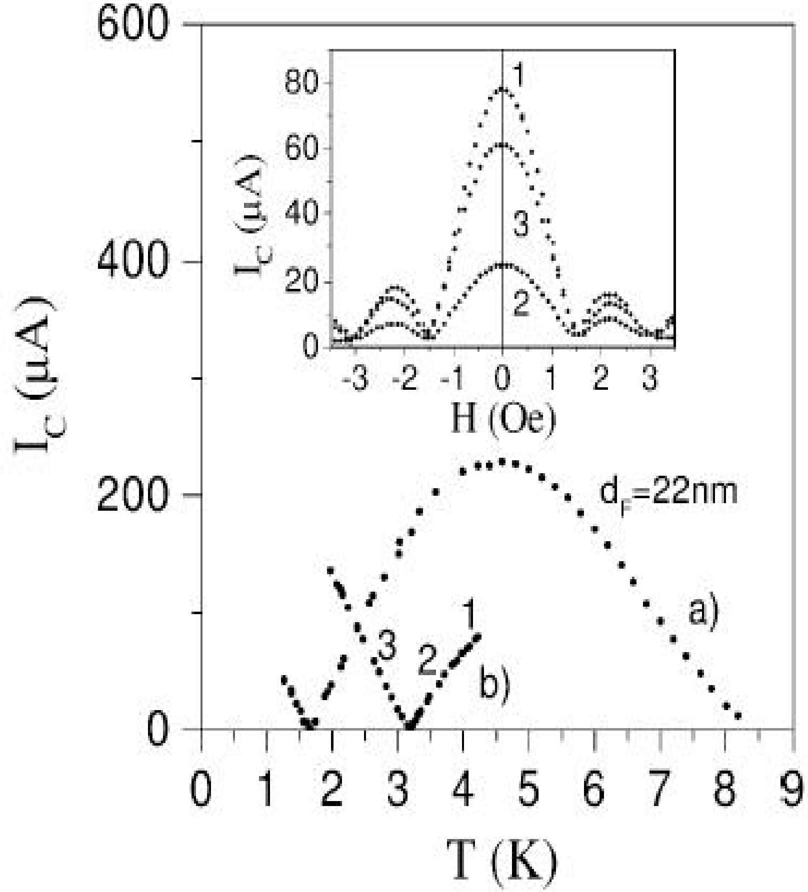
$I = -I_c \sin\Delta\phi$

π-junction



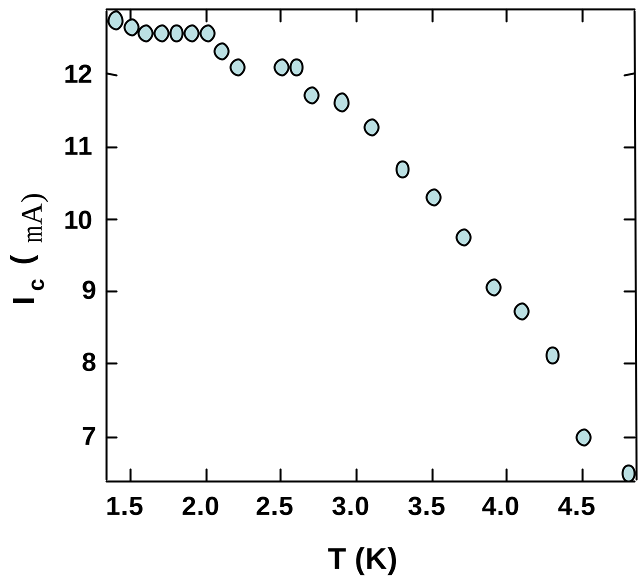
Kontos et al. PRL 89, 137007 (**2002**)

SFS



Temperature dependence

SFIS



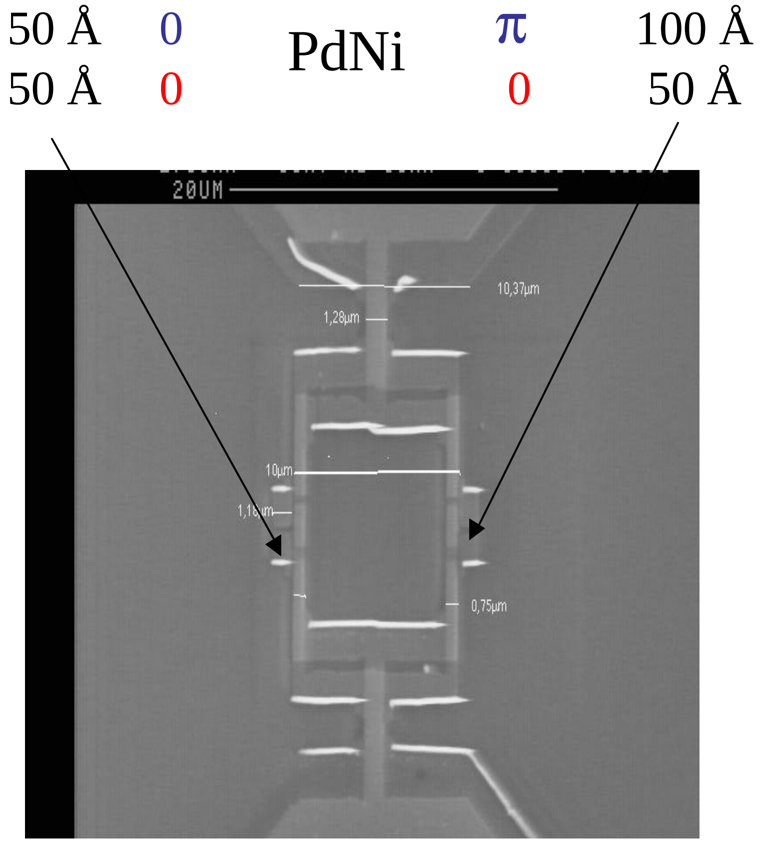
I_cR_n ~ 2nV

I_cR_n ~ 5μV

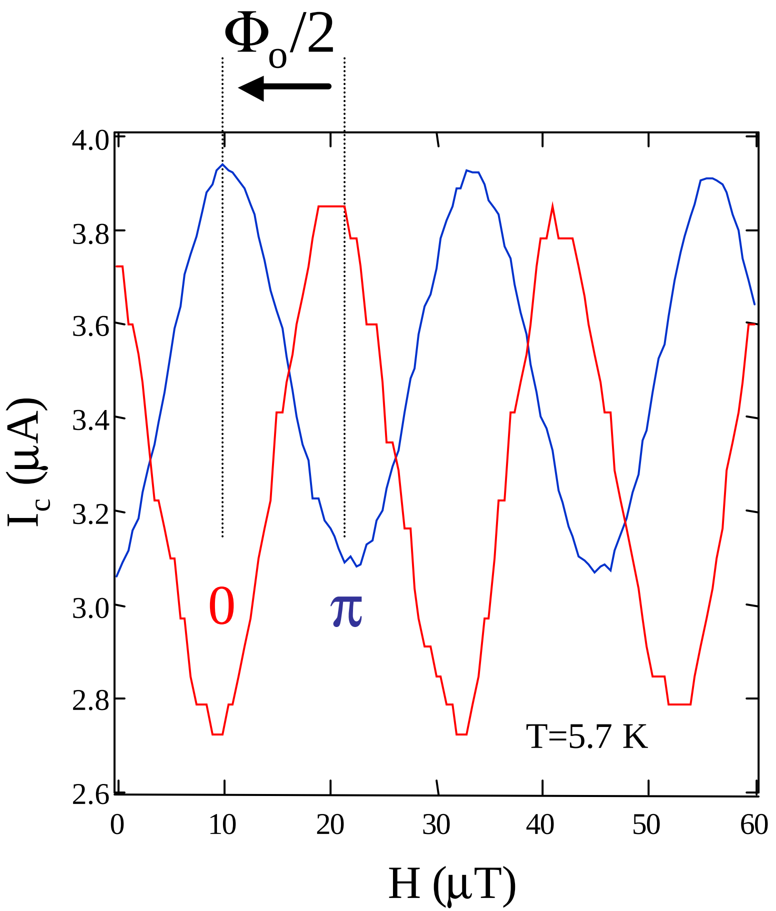
V. Ryazanov et al., PRL 86 2427 (2001)

Kontos et al. PRL 89, 137007 (2002)

p-SQUIDs

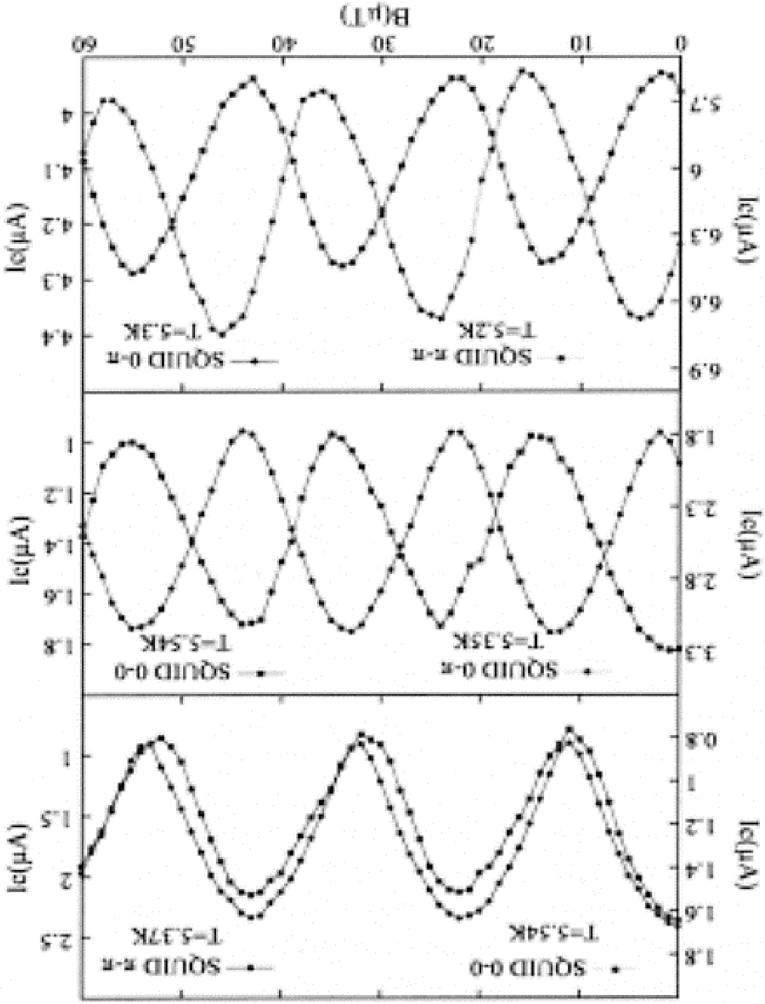


Electron lithography

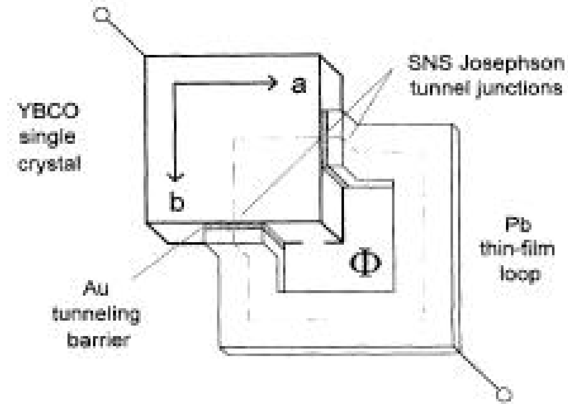


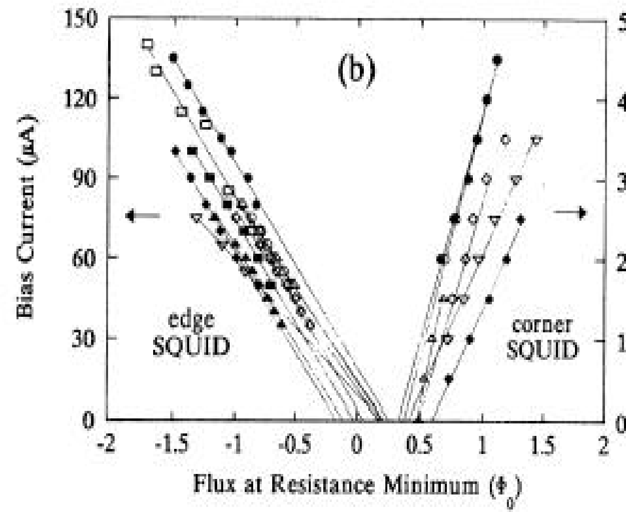
Linearity :$I_cL << \Phi_o$

In collaboration with *W. Guichard & P. Gandit*, CRTBT-Grenoble, Diffraction : $I=2I_c\left|\cos(\pi\Phi/\Phi_o+\delta_{ab}/2)\right|$



W. Guichard et al. PRL (2003)

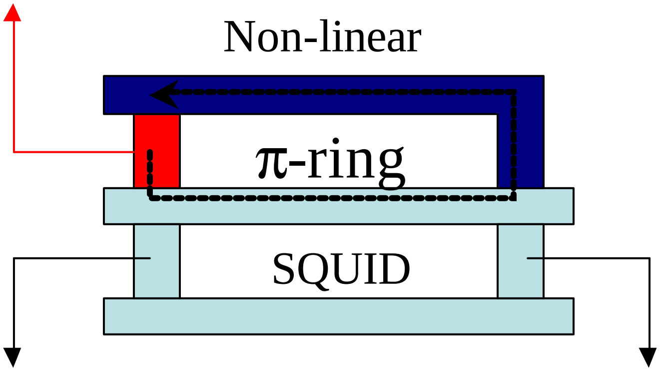




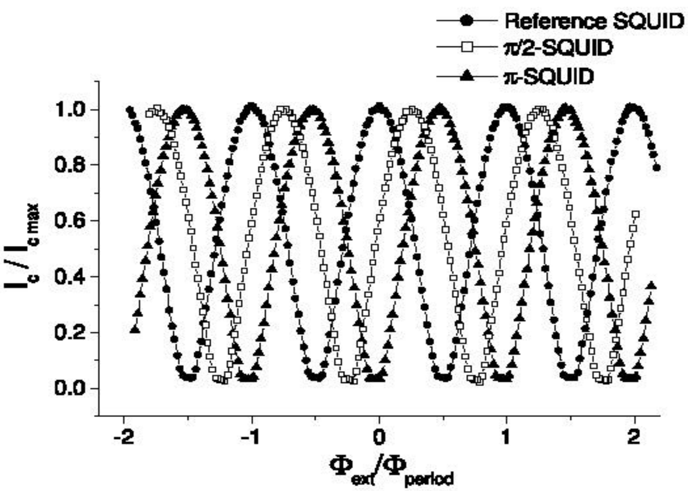
D. Van Harlingen Rev. Mod. Phys. 67, 515 (1995)

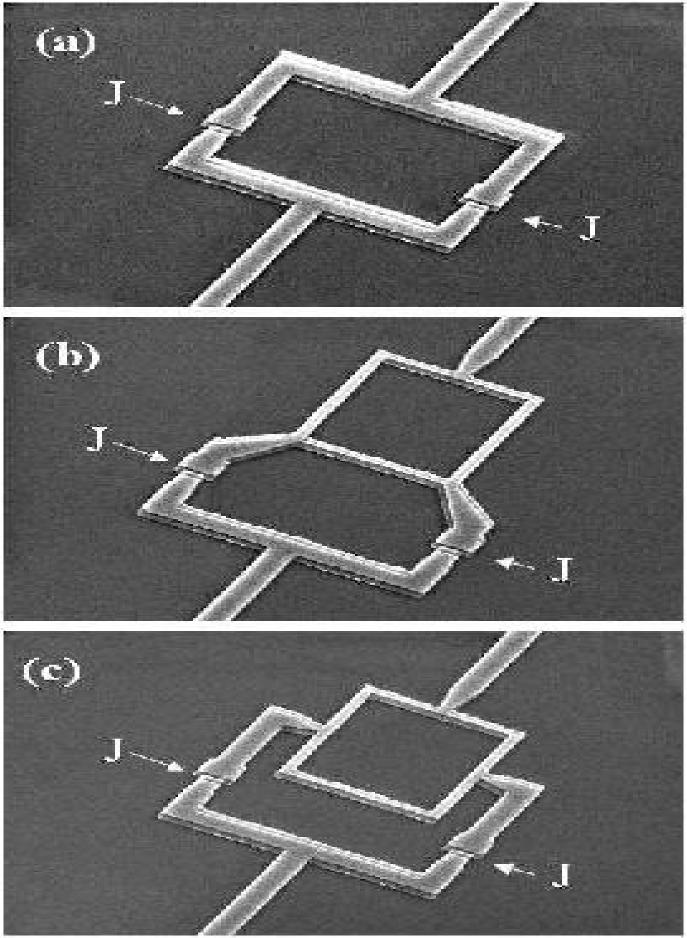
p-Rings

π-Junction



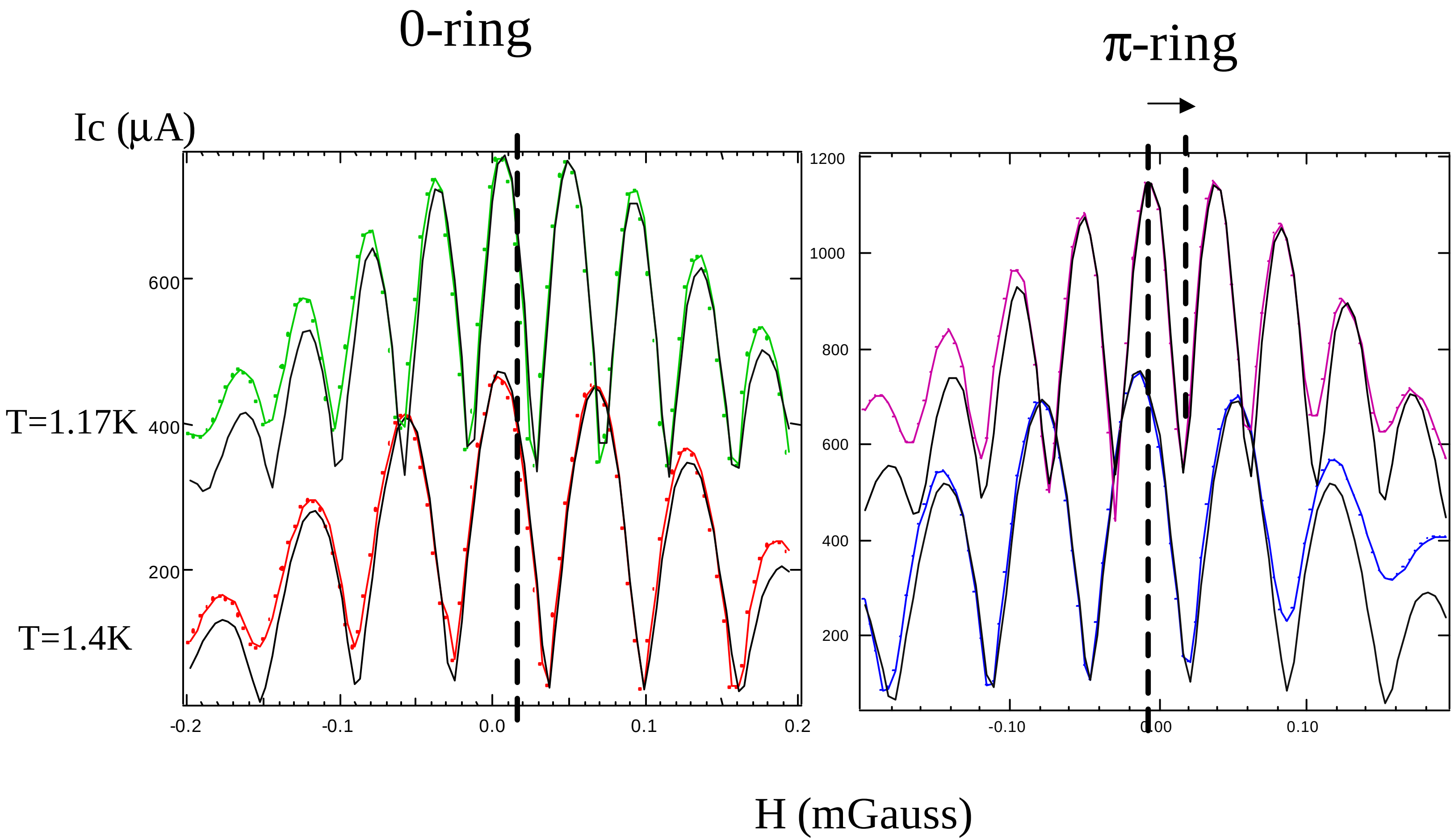
Josephson Junctions





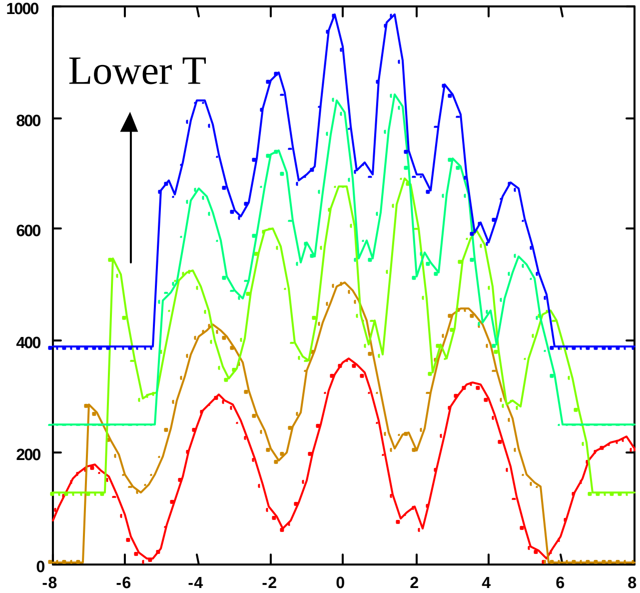
Majer et al. Submitted APL

Spontaneous currents

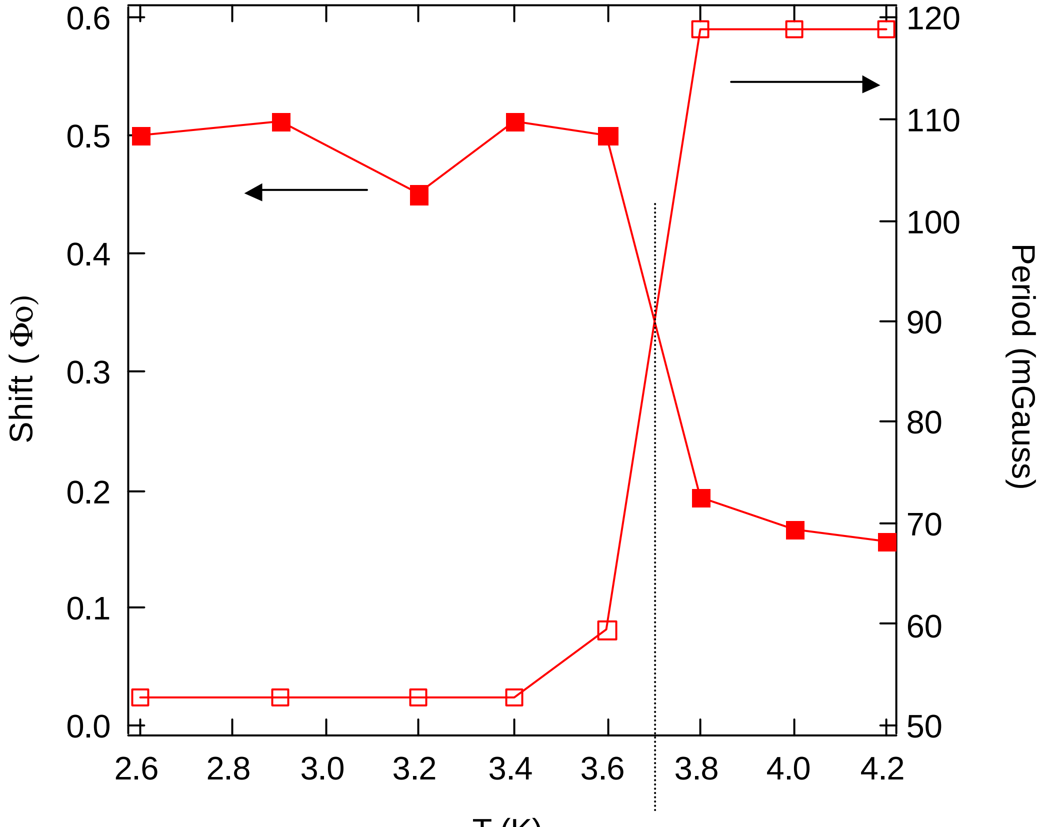


Shift in the detection SQUID

No shift in the envelop !



I_{bobine} (mA)



T_c ring

Conclusions

The exchange field modifies the superconducting wave function :

i) Spectroscopy of a oscillating Order Parameter (“0-state” and “π-state”).

ii) Negative Josephson coupling: π-Junctions.

iii) π-SQUIDs.

iv) π-rings and spontenous supercurrents.

Direct measurement of the exchange energy.