SUPERCONDUCTOR-FERROMAGNET NANOSTRUCTURES

A. Buzdin

Institut Universitaire de France, Paris

and Condensed Matter Theory Group, University of Bordeaux

C.P.M.O.H.

UNIVERSITÉ BORDEAUX 1 Sciences Technologies

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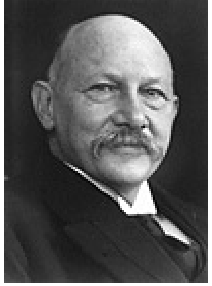
OUTLINE

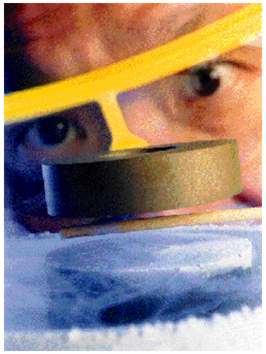
- Mechanisms of magnetism and superconductivity interaction.
- Electromagnetic interaction in S/F heterostructures.
- Proximity effect in superconductor-ferromagnet systems. Josephson π-junction.
- Spin-valve effet. Domain wall superconductivity.
- Coupling between magnetic moment and Josephson current in φ_0-junctions.
- The way to superconducting spintronics. Possible applications.

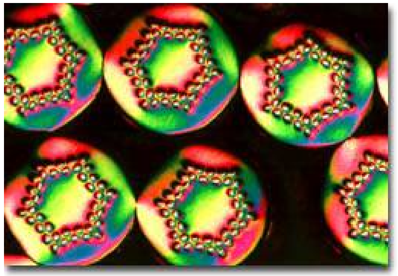
Supraconductivity



1913

Since the discovery by Heike Kamerlingh Onnes
6 Nobel Prizes.
Many important applications.

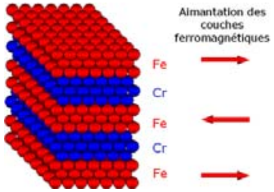




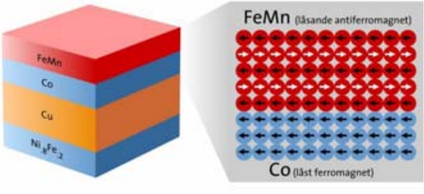
Magnetism

4 Nobel Prizes.

Recent Nobel Prize : A. Fert and P.Grunberg



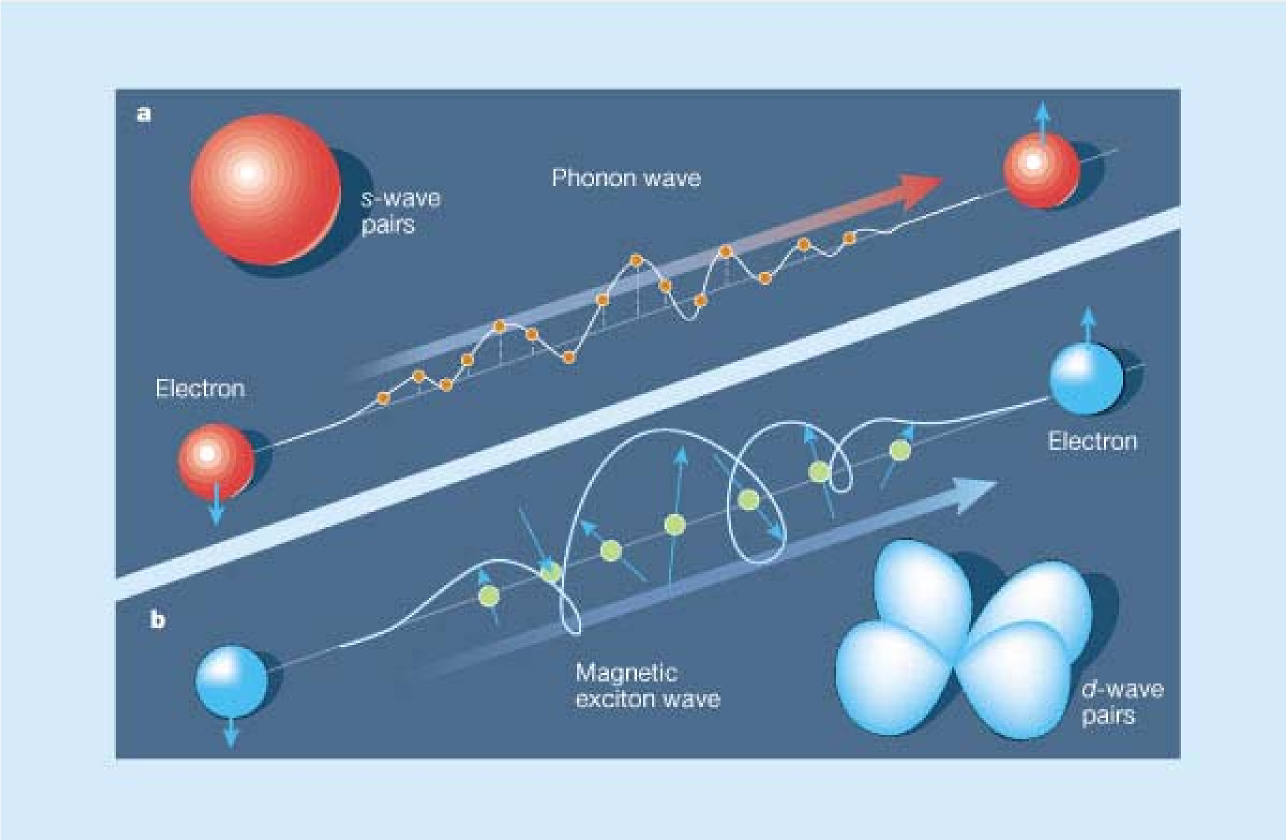
Spintronics



2007

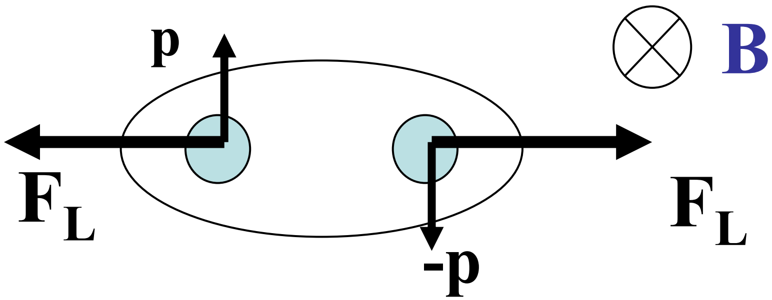
Is it possible to couple magnetism and superconductivity?

Superconducting Cooper pairs



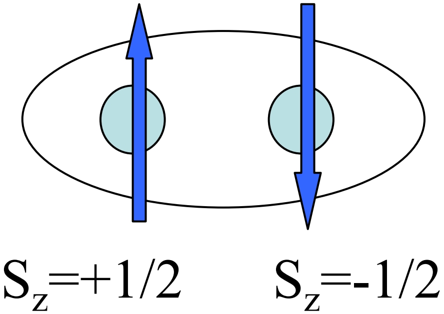
Antagonism of magnetism (ferromagnetism) and superconductivity

- Orbital effect (Lorentz force)



Electromagnetic mechanism (breakdown of Cooper pairs by magnetic field induced by magnetic moment)

- Paramagnetic effect (singlet pair)

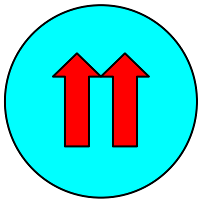


$\mu_B H \sim \Delta \sim T_c$

$$I\left(\vec{S}\cdot\vec{s}\right)\approx T_c$$

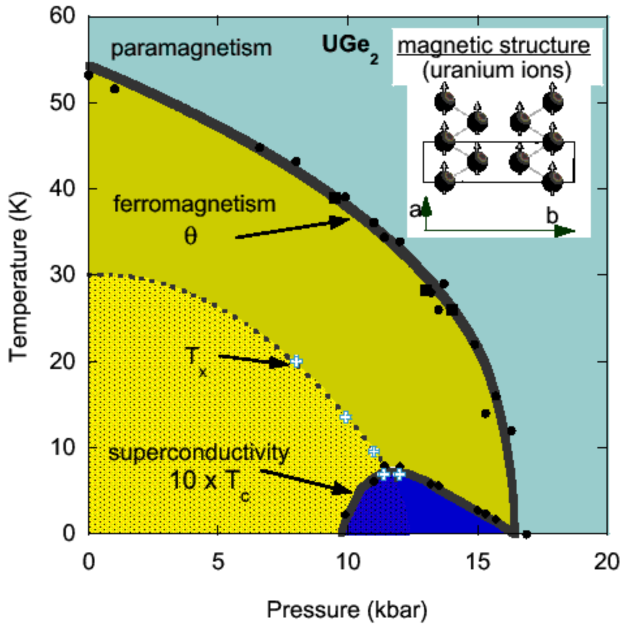
Exchange interaction

FERROMAGNETIC UNCONVENTIONAL (TRIPLET) SUPERCONDUCTORS



Triplet pairing

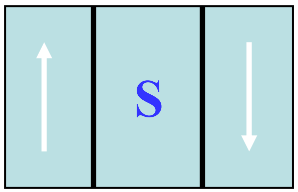
$\mathbf{UGe_2}$ **(Saxena *et al.*, 2000)**
and URhGe (Aoki *et al.*, 2001)

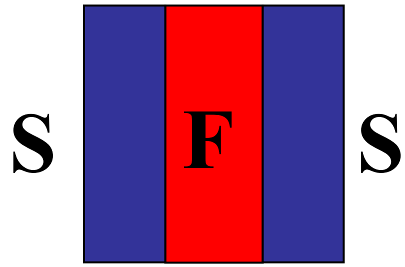


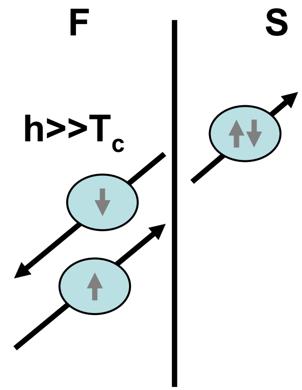
UGe_2

Very low T_c < 1 K, clean limit…

The coexistence of singlet superconductivity and ferromagnetism is basically impossible in the same compound but may be easily achieved in artificially fabricated superconductor/ferromagnet heterostructures.







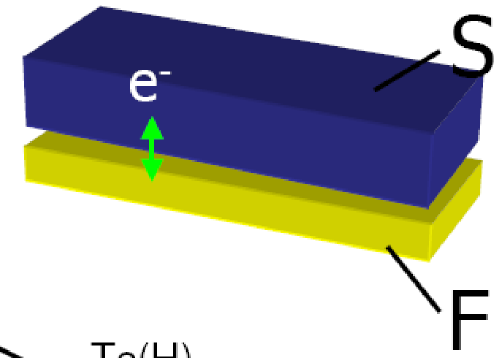
Due to the proximity effect, the Cooper pairs penetrate into the F layer and we have the unique possibility to study the properties of superconducting electrons under the influence of the huge exchange field.

The Josephson junctions with ferromagnetic layers reveal many unusual properties quite interesting for applications, in particular the so-called π-Josephson junction (with the π-phase difference in the ground state).

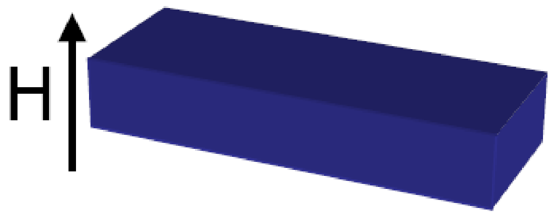
Superconductor-Ferromagnet hybrids

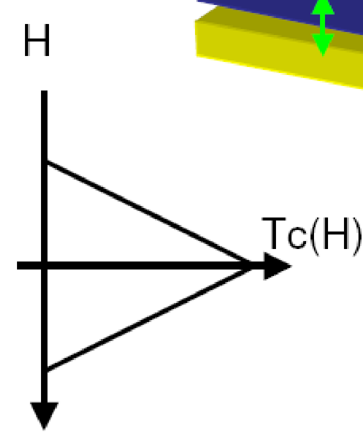
Interaction between superconductor (S) and ferromagnet (F):

1. Exchange interaction via the proximity effect (spin valve, π-junctions,...)



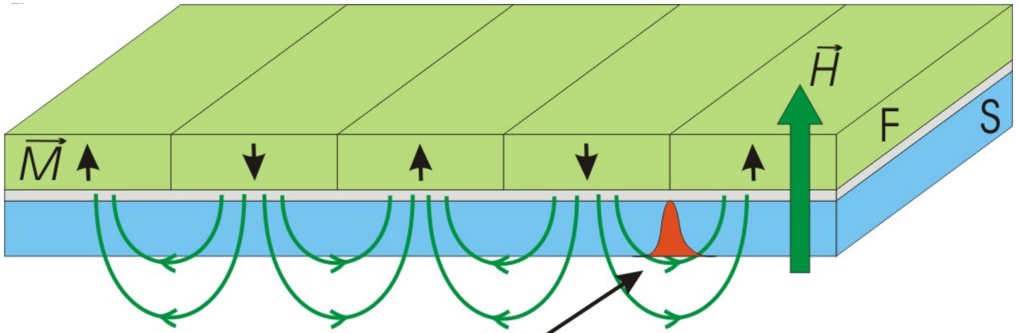
2. Electromagnetic interaction



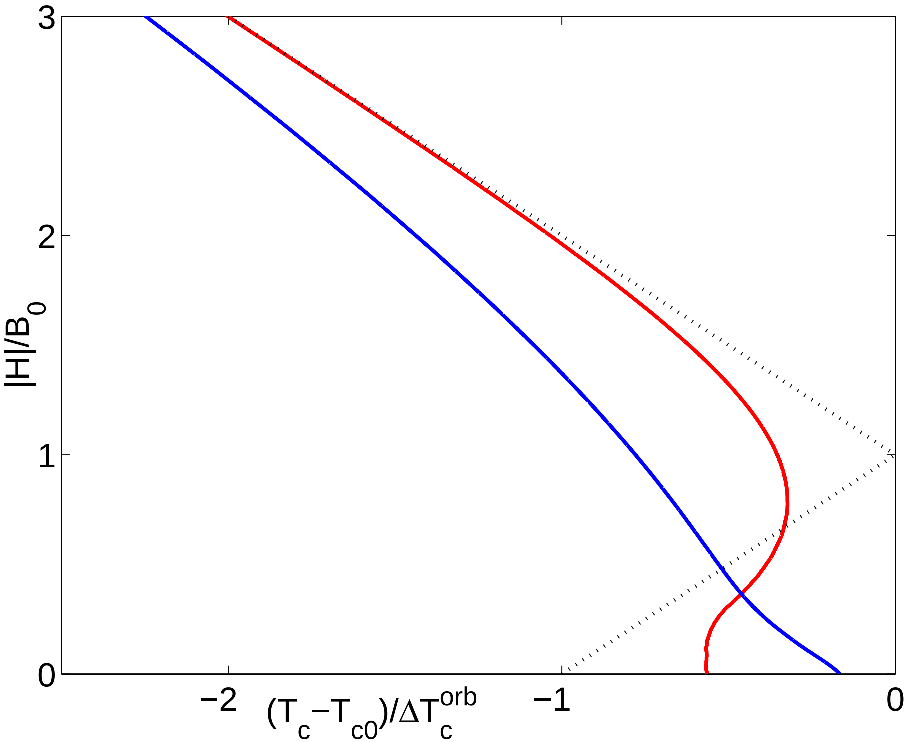


Varying in the controllable manner the thicknesses of the ferromagnetic and superconducting layers it is possible to change the relative strength of two competing ordering. Interesting effects at the nanoscopic scale.

Domain wall superconductivity in hybrid S/F systems or ferromagnetic superconductors



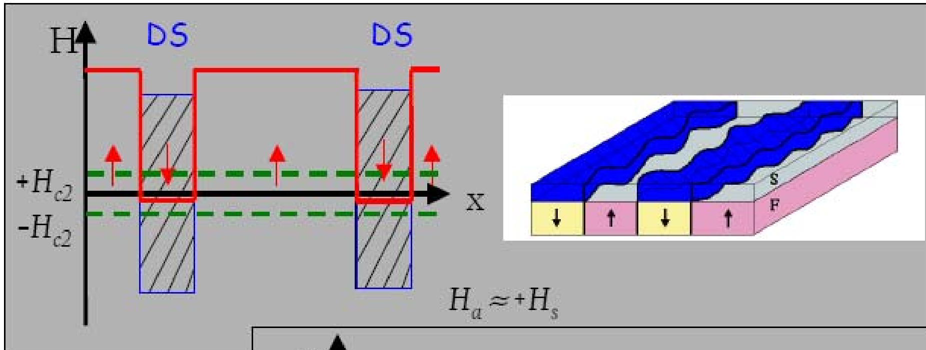
S/F bilayer with domain structure (Buzdin, Melnikov, PRB, 2002)



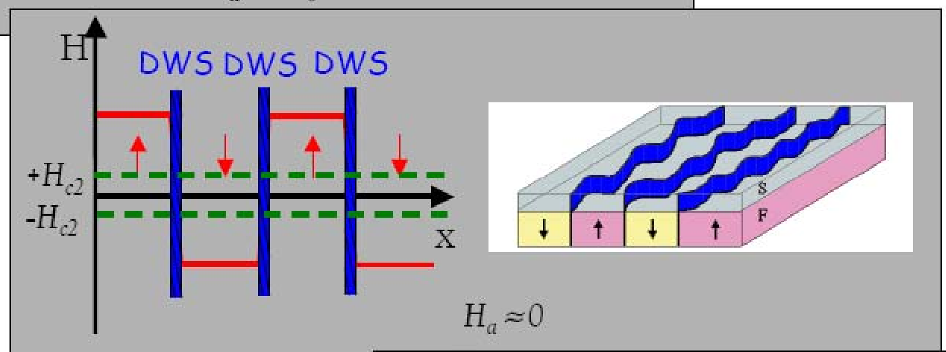
Phase diagrams of S/F systems with periodic domain structures

This domain wall superconductivity has been observed on experiment by Moschalkov et al. (Nature Material, 2005).

Domain wall superconductivity



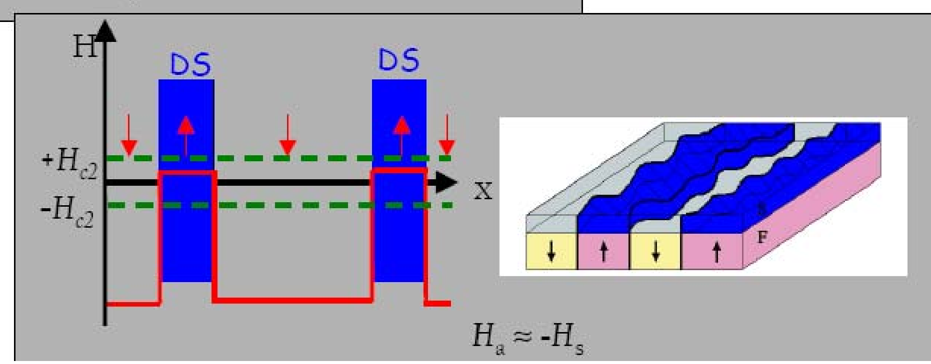
H > 0



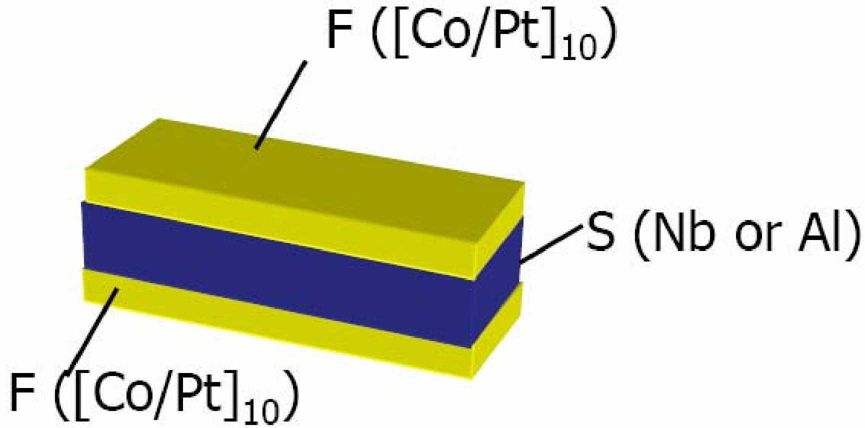
H = 0

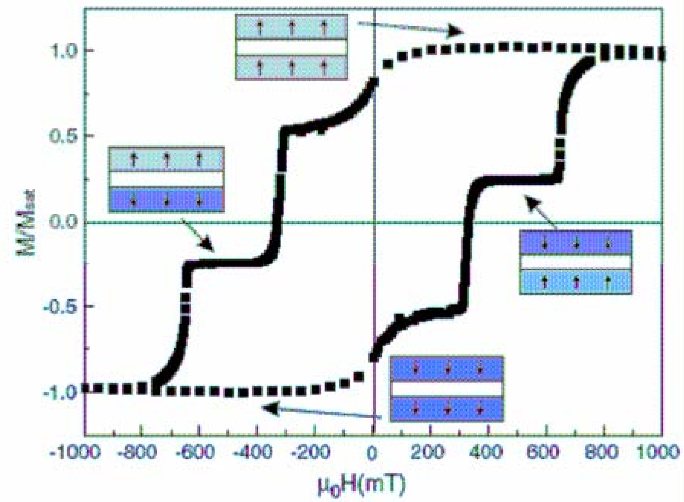
Z. Yang, . M. Lange, A. Volodin, R. Szymczak, V. V. Moshchalkov, *Nature Materials,* **3**, 793 (2004)

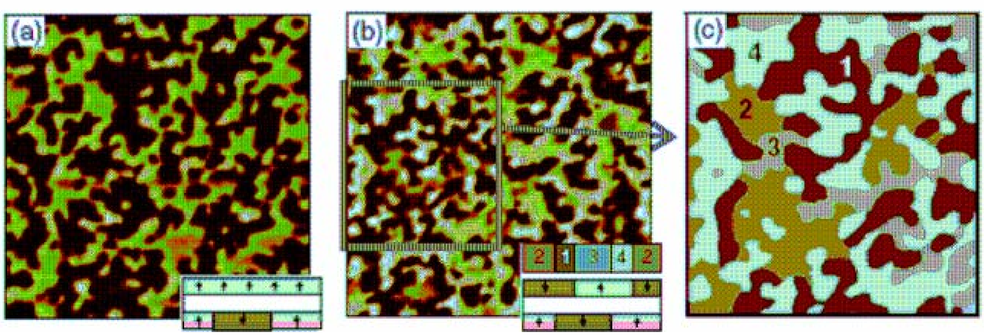
H < 0



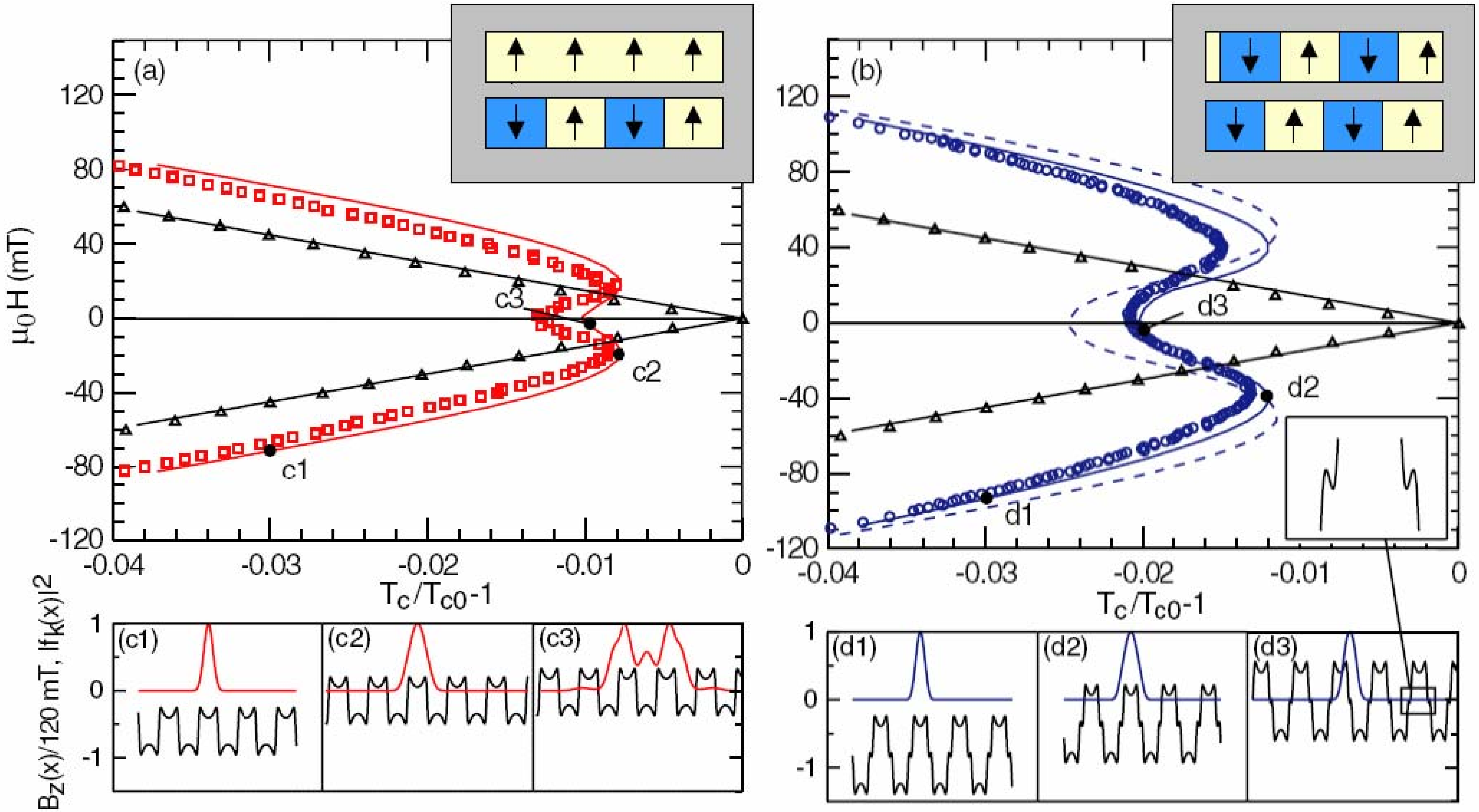
Sample characterization





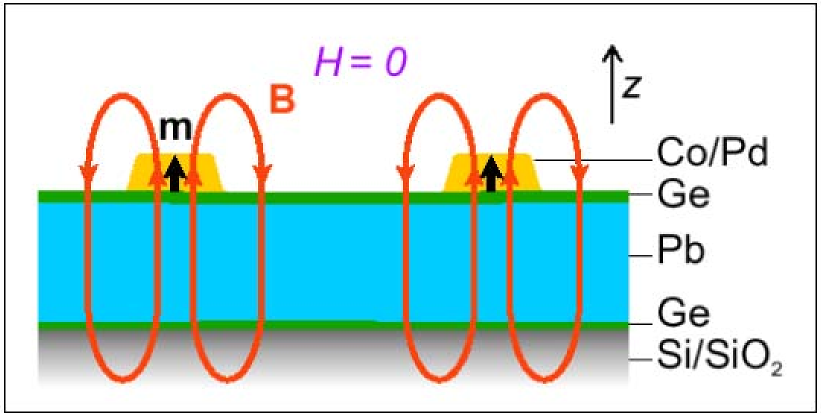


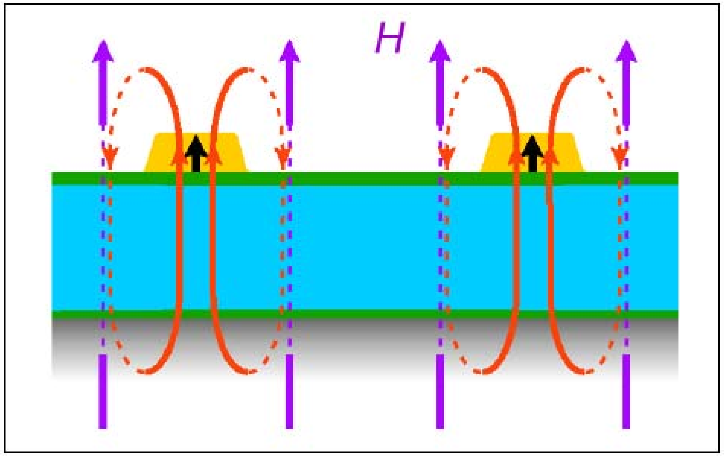
W. Gillijns et al.,
Phys. Rev. Lett. **95**, 227003 (2005)



W. Gillijns et al., *Phys. Rev. Lett.* **95**, 227003 (2005)

FIS in films with magnetic Co/Pd dots

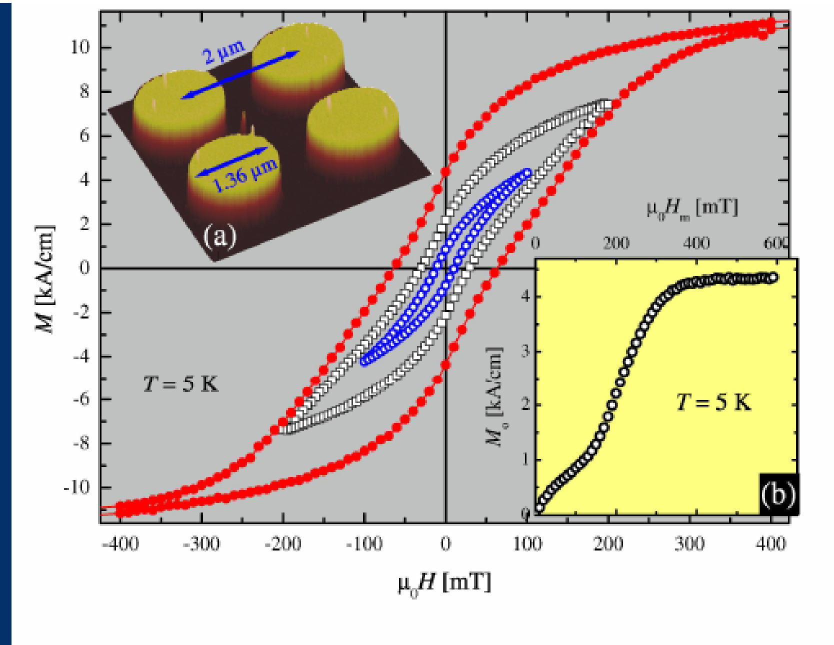


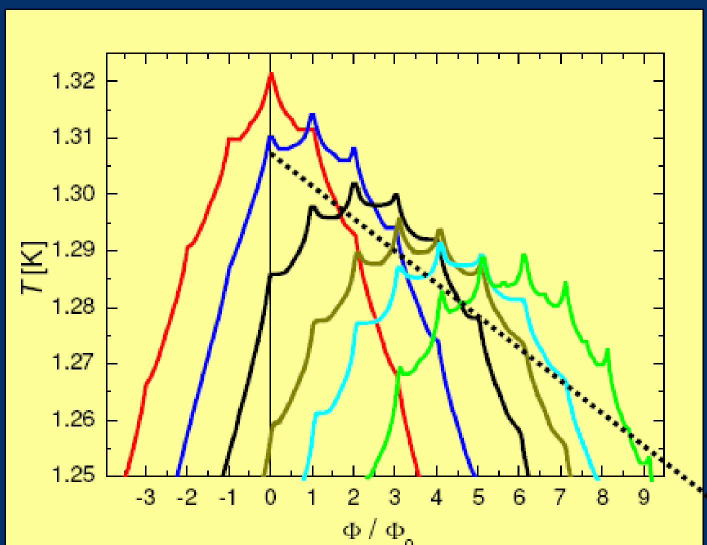


Nanoengineered magnetic-field-induced superconductivity,
PRL 90, 197006 (2003) + Focus

KATHOLIEKE UNIVERSITEIT LEUVEN

∞ possible states





TUNABLE FIELD INDUCED SUPERCONDUCTIVITY

Werner Gillijns, Alejandro V. Silhanek, Victor V. Moshchalkov, *Phys. Rev. B (Rapid. Comm.) 2006*

R(H) vs M

Superconducting order parameter behavior in ferromagnet

Standard Ginzburg-Landau functional:

$$F = a|\Psi|^2 + \frac{1}{4m}|\nabla\Psi|^2 + \frac{b}{2}|\Psi|^4$$

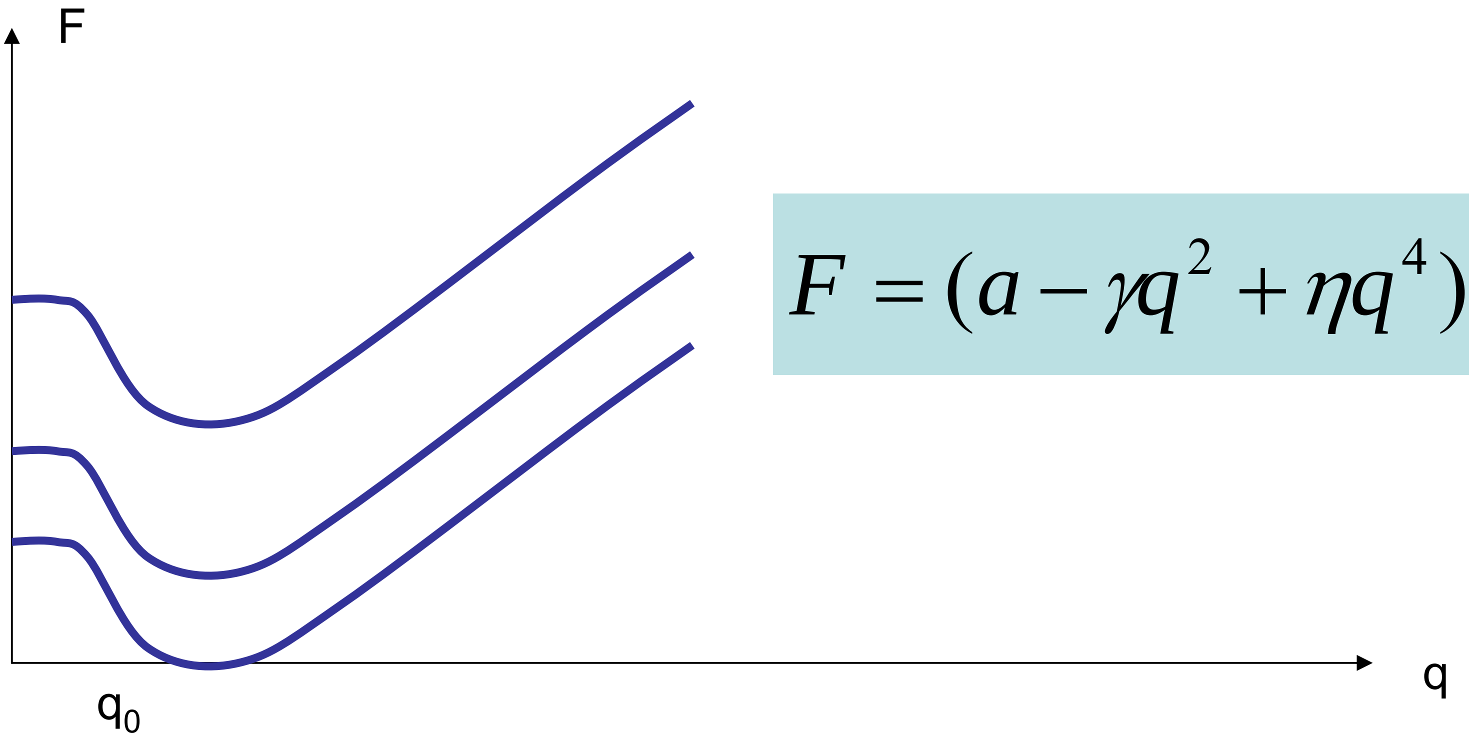
The minimum energy corresponds to Ψ=const

The coefficients of GL functional are functions of internal exchange field h !

Modified Ginzburg-Landau functional ! :

$$F = a|\Psi|^2 - \gamma|\nabla\Psi|^2 + \eta|\nabla^2\Psi|^2 + \ldots$$

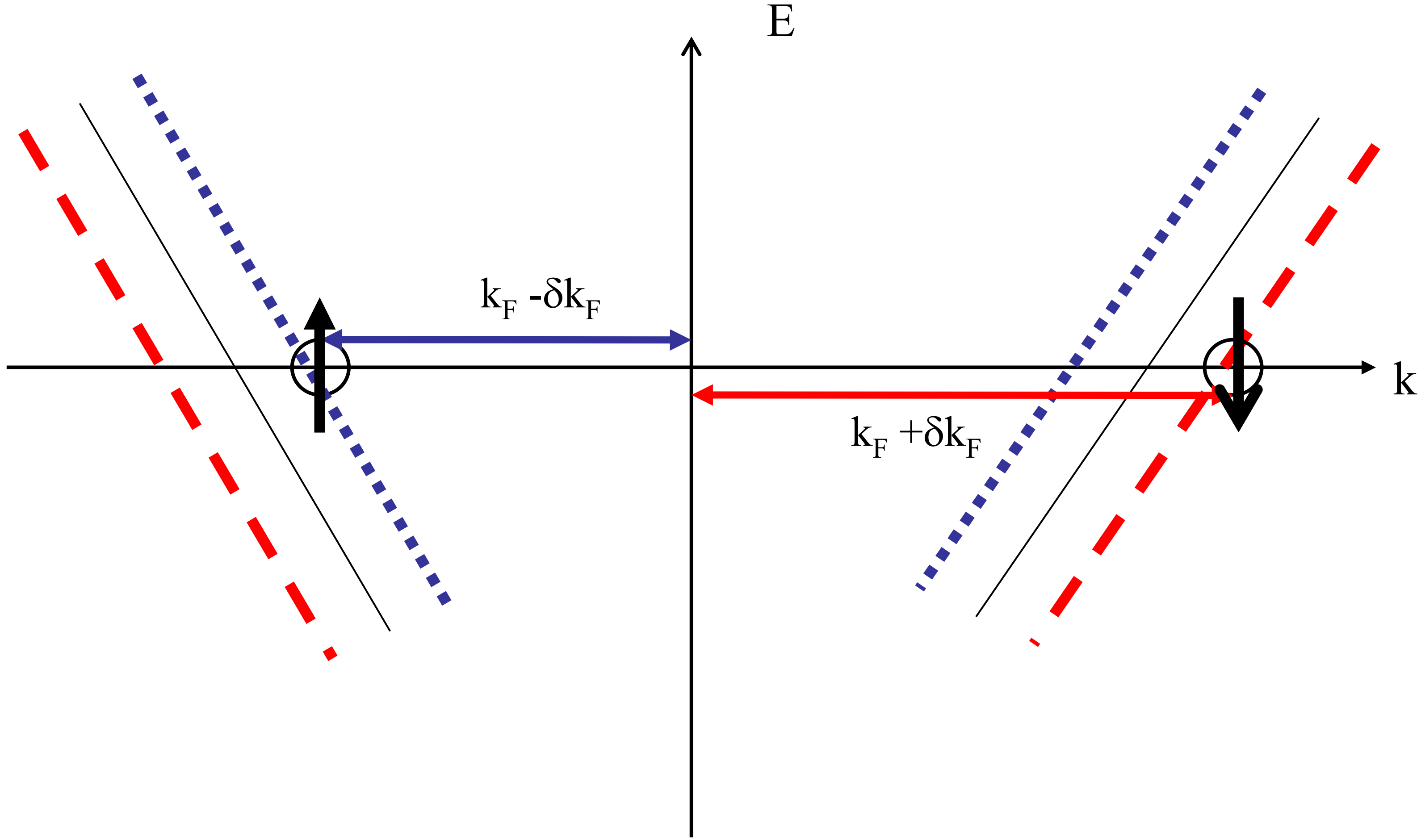
The **non-uniform** state $\Psi \sim \exp(iqr)$ will correspond to minimum energy and higher transition temperature



$$F = (a - \gamma q^2 + \eta q^4)\left|\Psi_q\right|^2$$

$\Psi \sim \exp(iqr)$ - **Fulde-Ferrell-Larkin-Ovchinnikov state (1964).**

Only in pure superconductors and in the very narrow region.



The total momentum of the Cooper pair is
$-(k_F - \delta k_F) + (k_F - \delta k_F) = 2\,\delta k_F$

Proximity effect in a ferromagnet ?

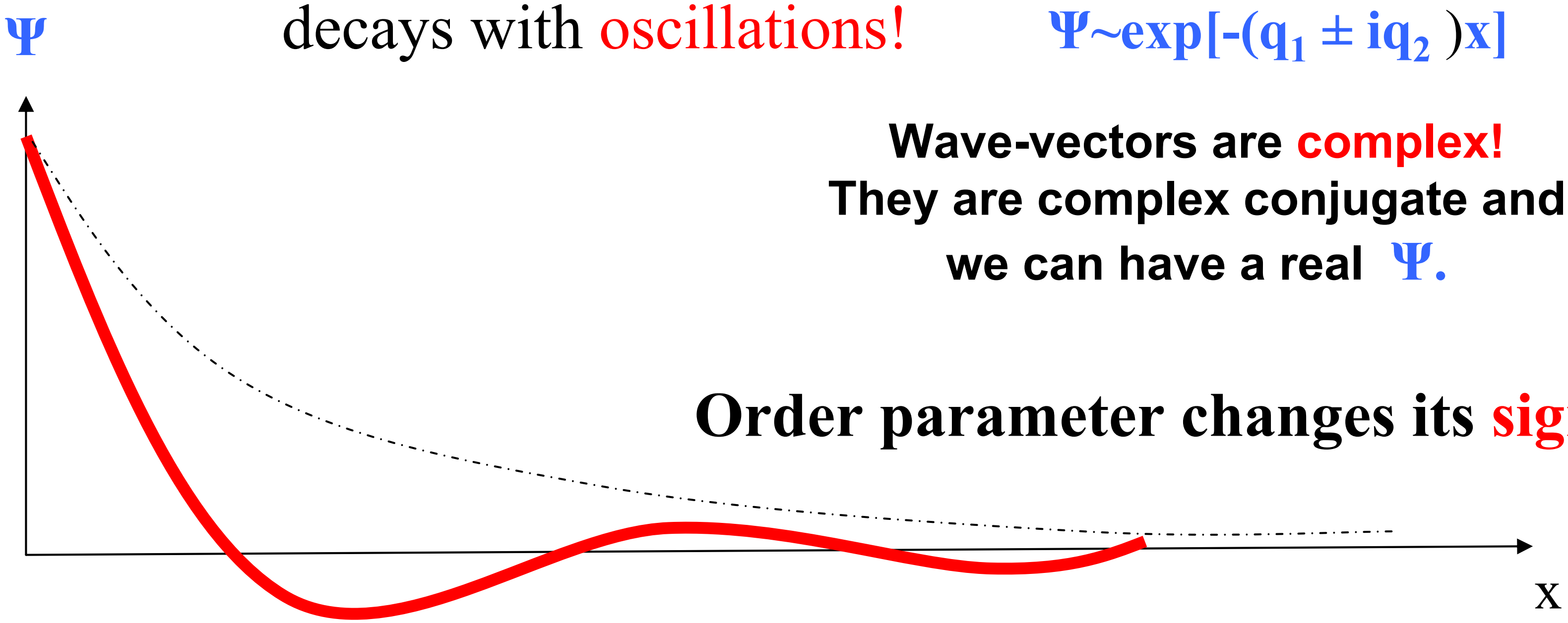
In the usual case (normal metal):

$$a\Psi - \frac{1}{4m}\nabla^2\Psi = 0, \text{ and solution for } T > T_c \text{ is } \Psi \propto e^{-qx}, \text{ where } q = \sqrt{4ma}$$

In **ferromagnet** (in presence of exchange field) the equation for superconducting order parameter is different

$$a\Psi + \gamma\nabla^2\Psi - \eta\nabla^4\Psi = 0$$

Its solution corresponds to the order parameter which decays with oscillations! **$\Psi \sim \exp[-(q_1 \pm iq_2)x]$**

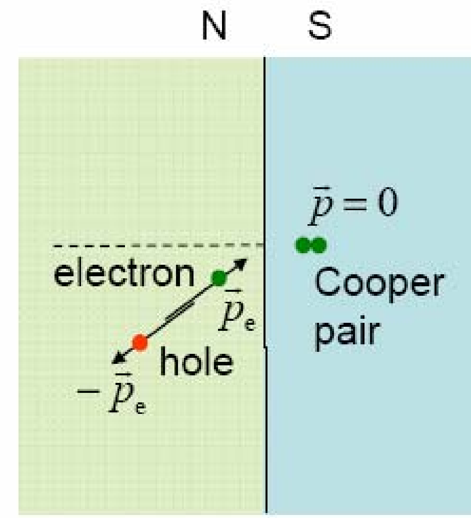


Wave-vectors are complex!
They are complex conjugate and we can have a real Ψ.

Order parameter changes its sign!

Proximity effect as Andreev reflection

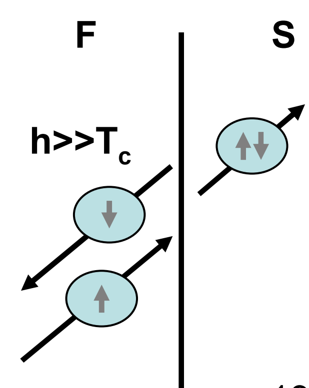
Classical Andreev reflection
(September, 2008, Miraflores, Spain)



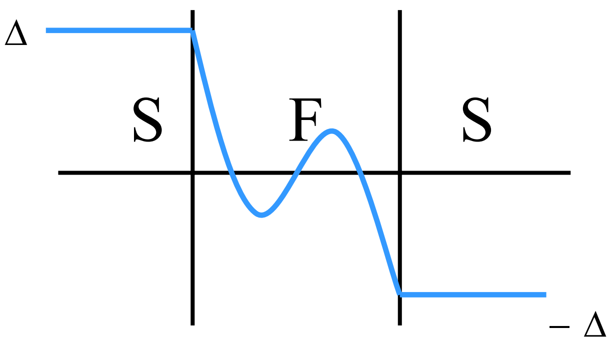
“retro”-reflection

Quantum Andreev reflection

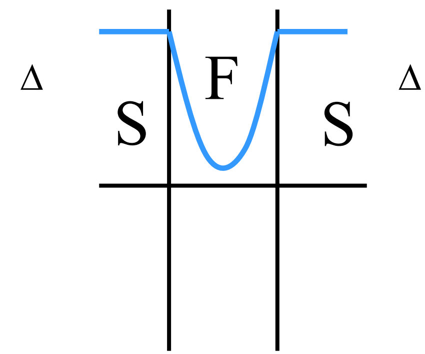
$$p_{F\uparrow} \neq p_{F\downarrow}$$



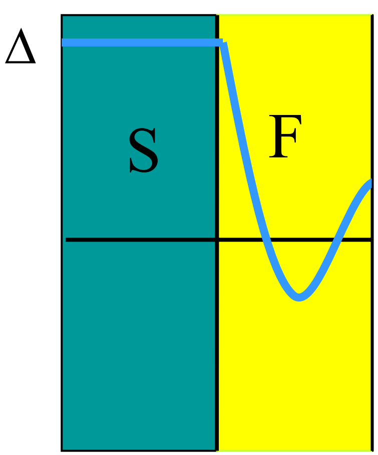
Remarkable effects come from the possible shift of sign of the wave function in the ferromagnet, allowing the possibility of a « π-coupling » between the two superconductors (π-phase difference instead of the usual zero-phase difference)



« π phase »



« 0 phase »



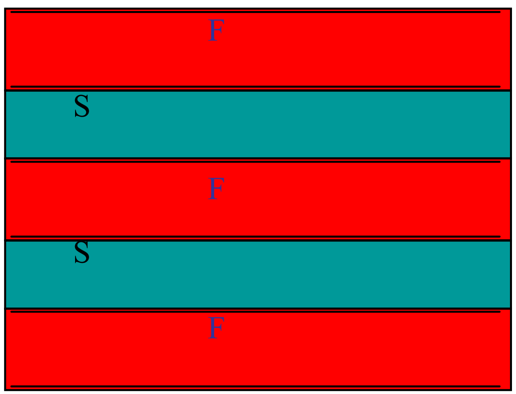
S/F bilayer

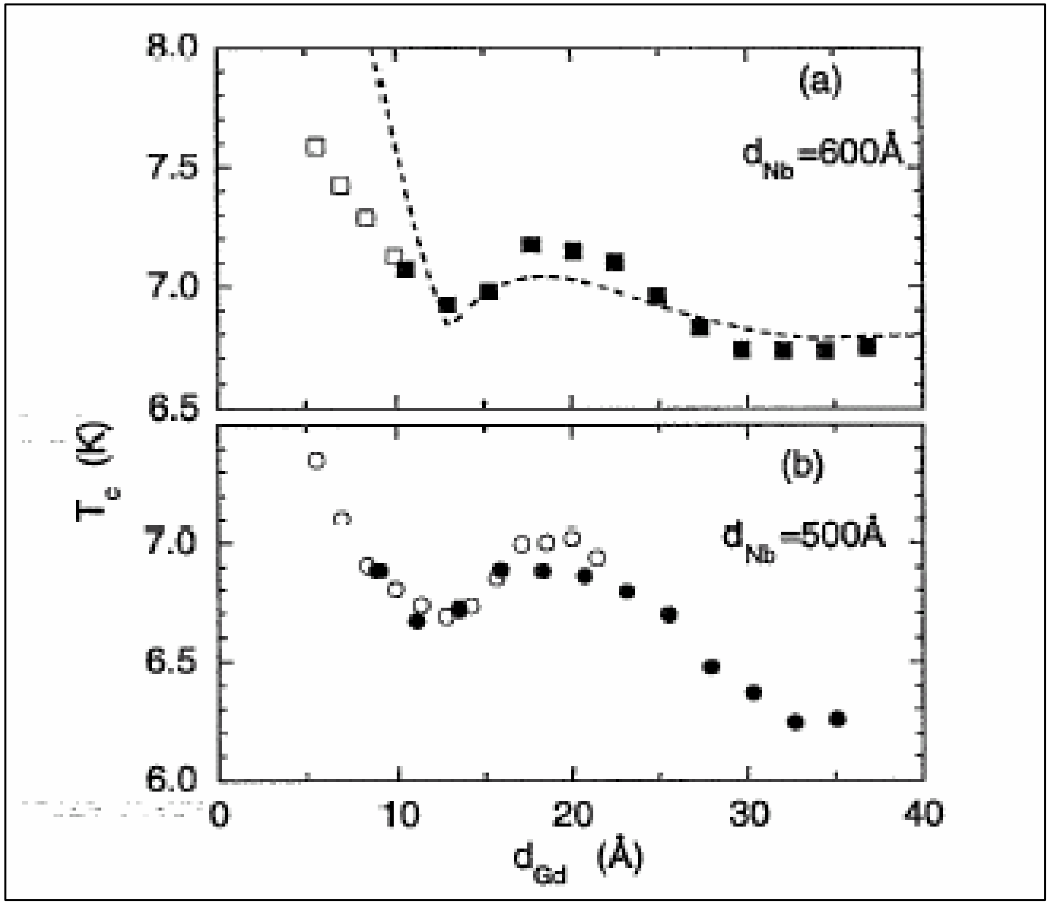
$$\xi_f = \sqrt{D_f / h} \propto (1-10)nm$$

h-exchange field,

D_f-diffusion constant

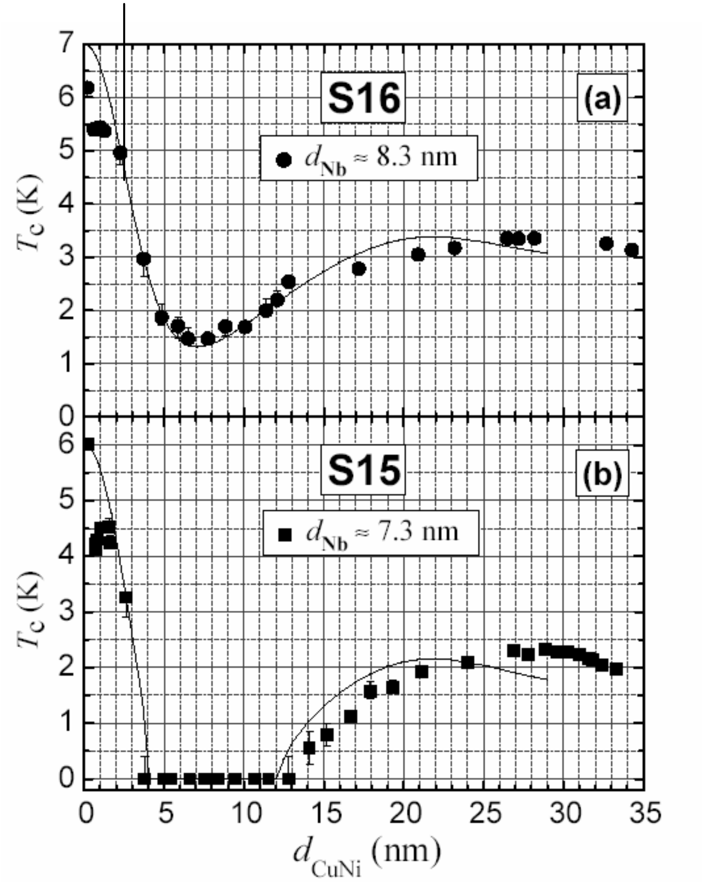
The oscillations of the critical temperature as a function of the thickness of the ferromagnetic layer in S/F multilayers has been predicted in 1990 and later observed on experiment by Jiang et al. PRL, **1995**, in Nb/Gd multilayers



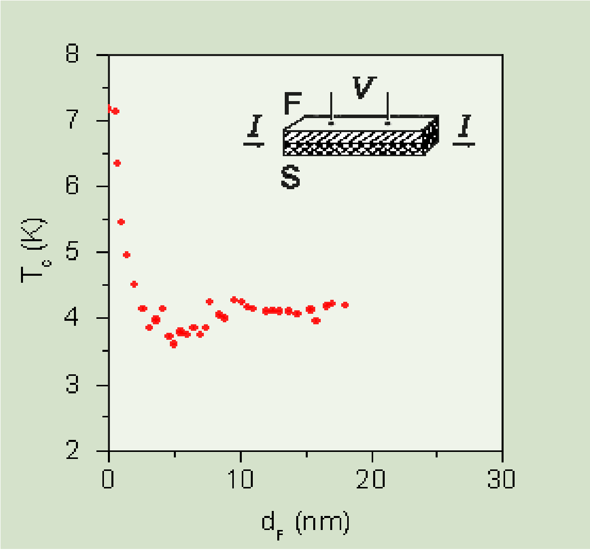


SF-bilayer T_c-oscillations

V. Zdravkov, A. Sidorenko et al
PRL (2007)
Nb-$Cu_{0.41}Ni_{0.59}$

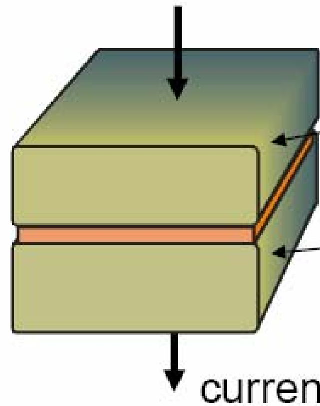


Ryazanov et al. JETP Lett. 77, 39 (2003) Nb-$Cu_{0.43}Ni_{0.57}$



d_{Fmin} =(1/4) λ_{ex} largest T_c-suppression

Josephson effect



superconductor

tunnel barrier

superconductor

current I

$$\Psi_1 = |\Psi_1| \exp(i\theta_1)$$

$$\Psi_2 = |\Psi_2| \exp(i\theta_2)$$

$$|\Psi_1| = |\Psi_2|$$

superconducting phase difference: $\varphi = \theta_1 - \theta_2$

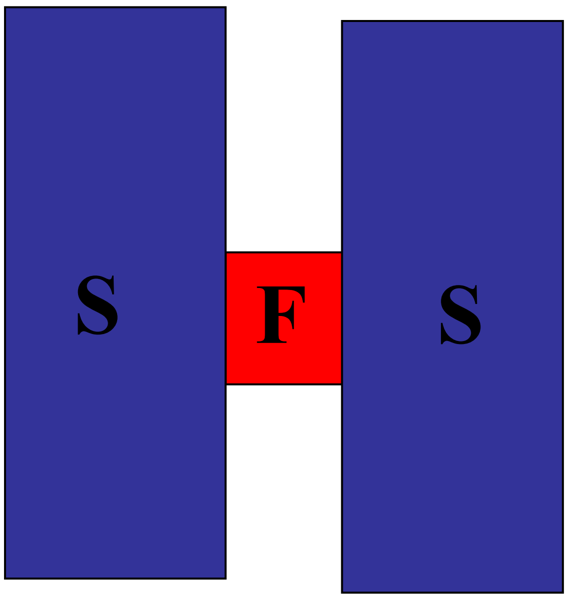
Josephson relations

$$\begin{cases} I_s = I_c \sin\varphi \\ V = \dfrac{\hbar}{2e}\dfrac{d\varphi}{dt} \end{cases}$$

Electromagnetic radiation at the frequency f

$$f = \frac{V}{\Phi_0}$$

S-F-S Josephson junction in the clean/dirty limit



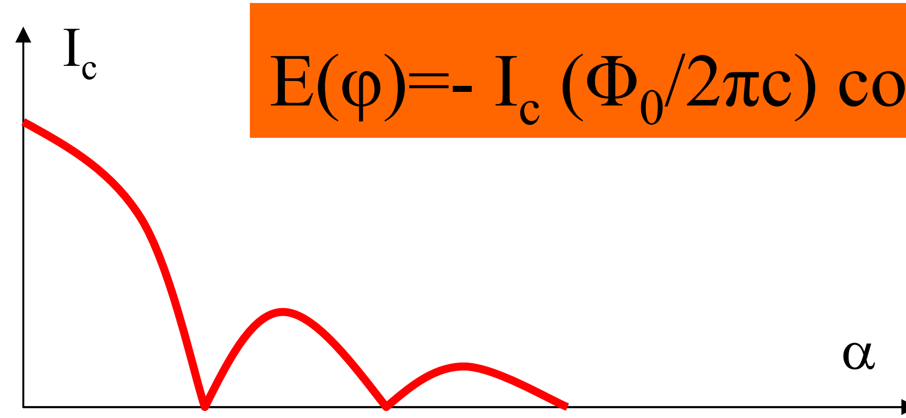
Damping oscillating dependence of the critical current I_c as the function of the parameter $\alpha = hd_F / v_F$ has been predicted.

(Buzdin, Bulaevskii and Panjukov, JETP Lett. 81)

h- exchange field in the ferromagnet,
d_F - its thickness

$$E(\varphi) = - I_c \, (\Phi_0/2\pi c) \cos\varphi$$

$$J(\varphi) = I_c \sin\varphi$$



Theory of S/F/S systems in dirty limit

Analysis on the basis of the Usadel equations

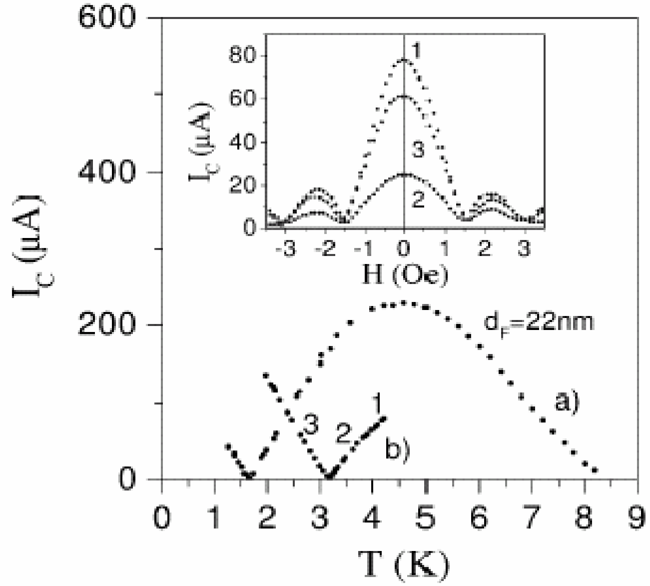
$$-\frac{D_f}{2}\vec{\nabla}^2 F_f(x,\omega,h) + (\omega + ih)F_f(x,\omega,h) = 0$$

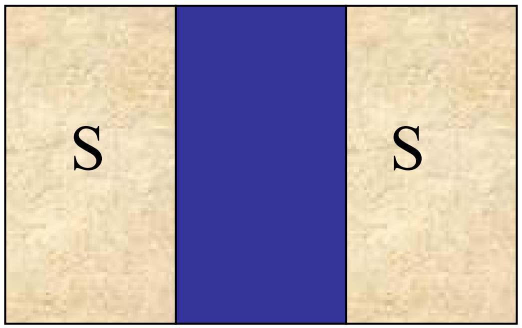
$$G_f^{\,2}(x,\omega,h) + F_f(x,\omega,h)F_f^{\,*}(x,\omega,-h) = 1$$

.

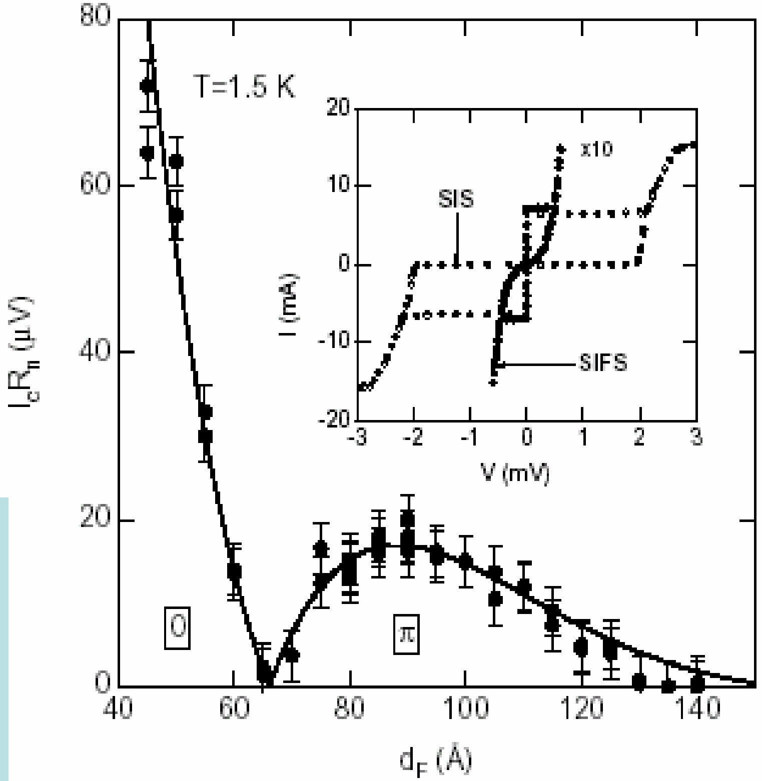
leads to the prediction of the oscillatory - like dependence of the critical current on the exchange field h and/or thickness of ferromagnetic layer. (Buzdin and Kuprianov, 1991)

The oscillations of the critical current as a function of temperature (for different thickness of the ferromagnet) in S/F/S trilayers have been observed on experiment by Ryazanov et al. 2000, PRL





F layer is CuNi alloys



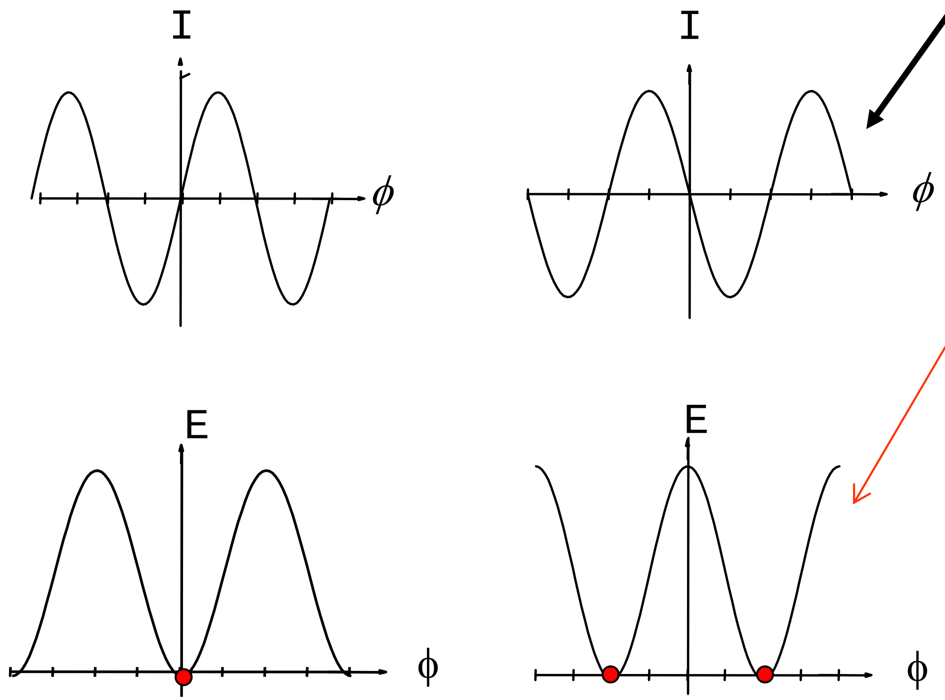
Later more S/F/S junctions has been observed, see for example a transition as a thickness of a ferromagnetic (NiPt) layer by Kontos et al. 2002, PRL

Phase-sensitive experiments

π-junction in one-contact interferometer

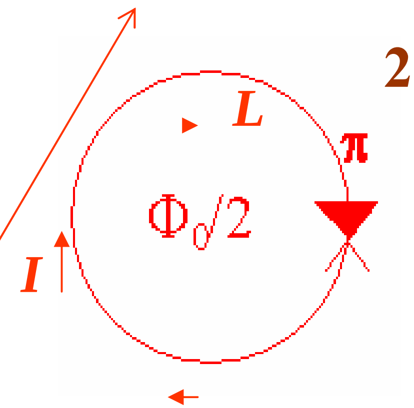
0-junction minimum energy at 0

π-junction minimum energy at π



$I = I_c \sin(\pi+\phi) = -I_c \sin\phi$

$E = E_J[1-\cos(\pi+\phi)] = E_J[1+\cos\phi]$



$2\pi L I_c > \Phi_0/2$

$\phi = \pi = (2\pi/\Phi_0)\int A dl = 2\pi\,\Phi/\Phi_0$

Spontaneous circulating current in a closed superconducting loop when $\beta_L>1$ with NO applied flux

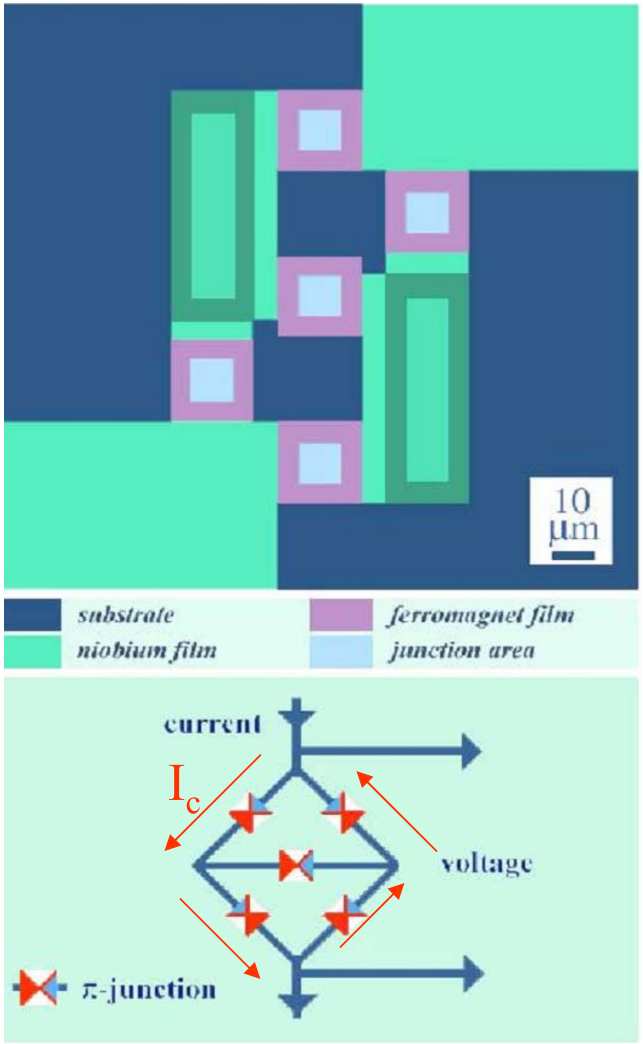
$\beta_L = \Phi_0/(4\pi L I_c)$

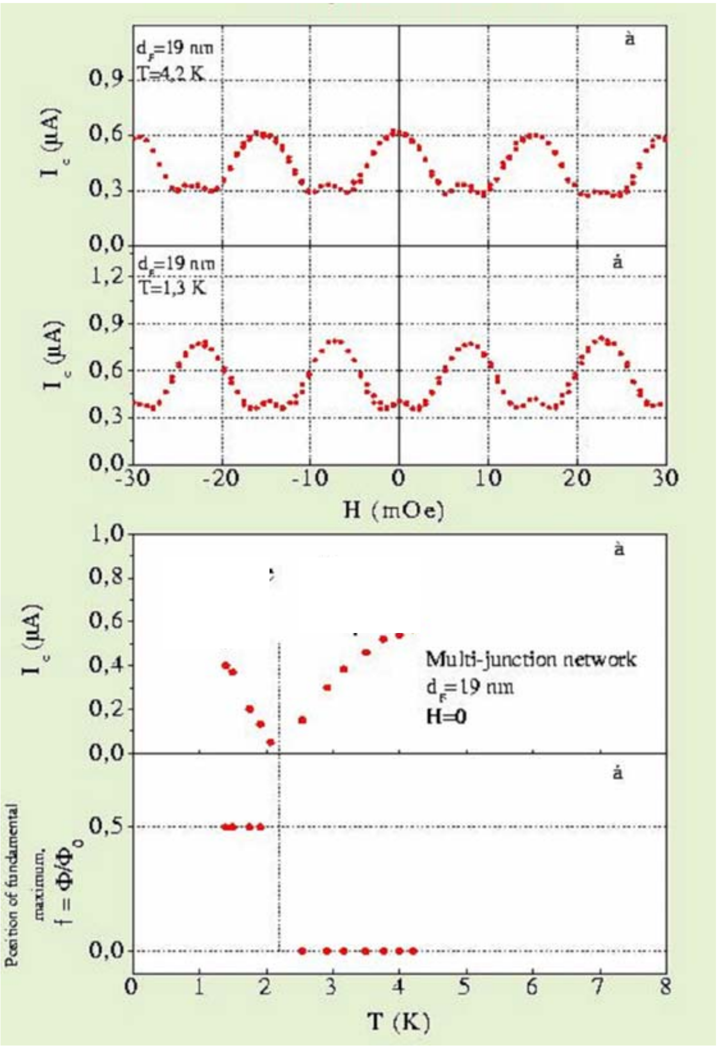
$\Phi = \Phi_0/2$

Bulaevsky, Kuzii, Sobyanin, JETP Lett. 1977

Current-phase experiment.

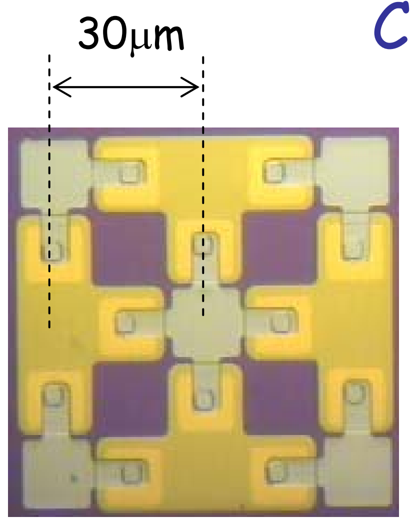
Two-cell interferometer



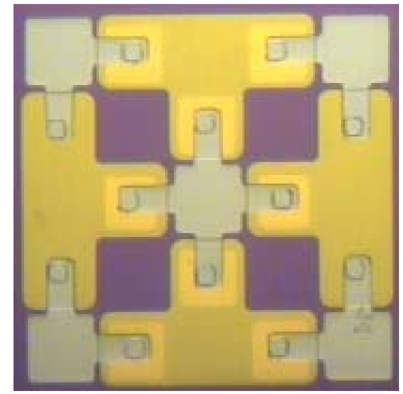


Cluster Designs (Ryazanov et al.)

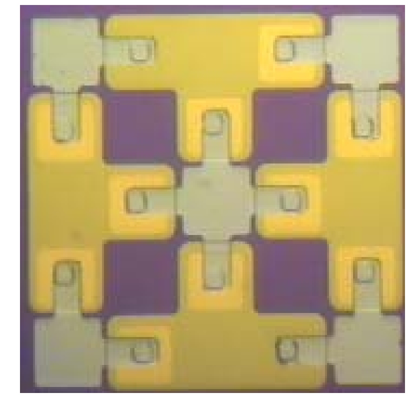
2 x 2



unfrustrated

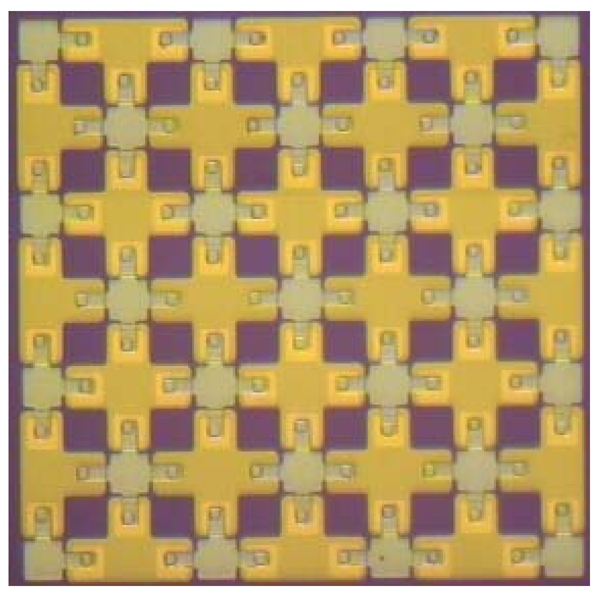


fully-frustrated

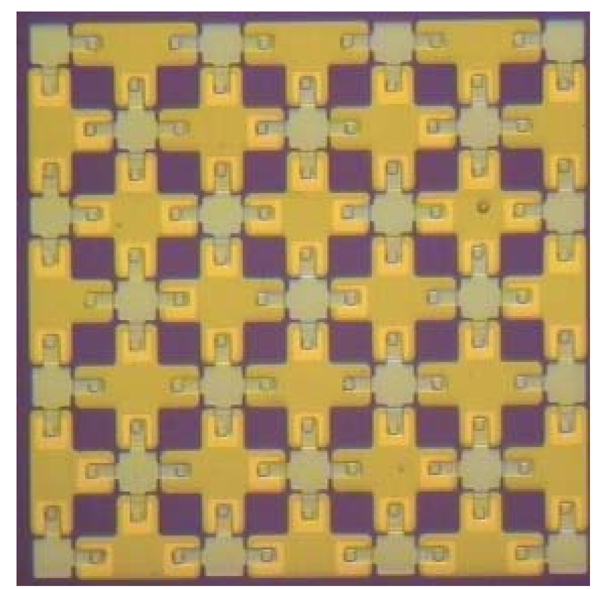


checkerboard-frustrated

6 x 6



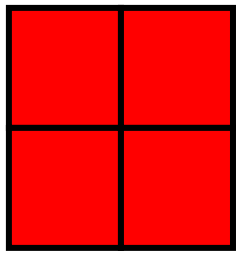
fully-frustrated

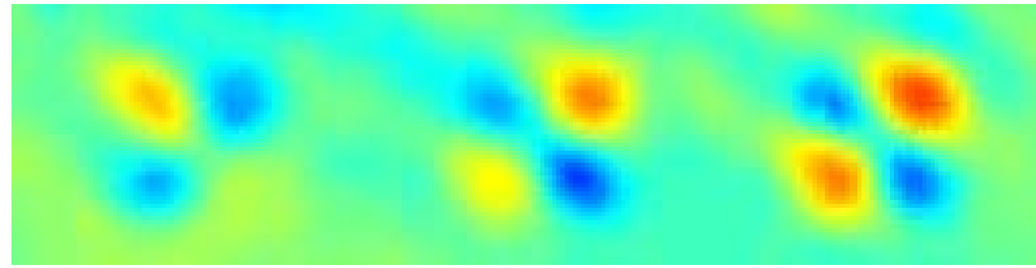


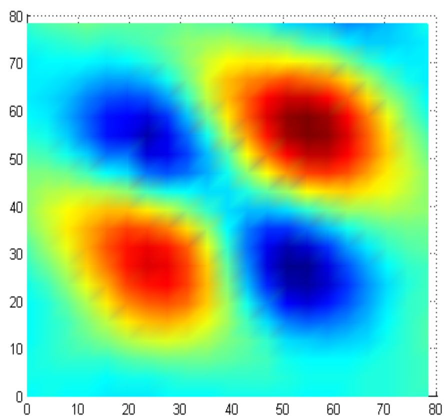
checkerboard-frustrated

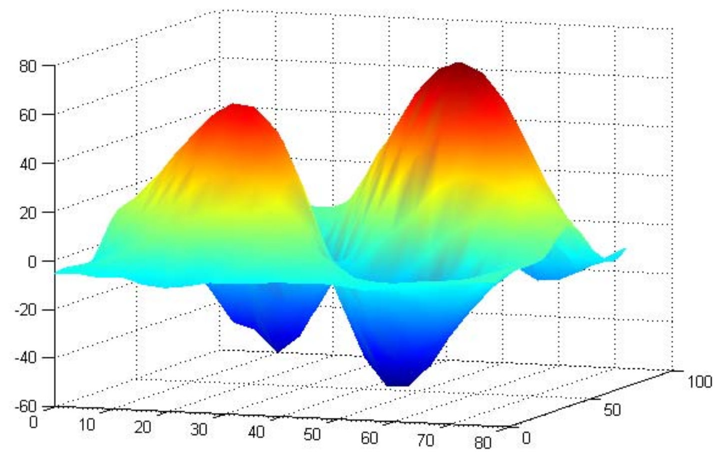
2 x 2 arrays: spontaneous vortices

Fully frustrated

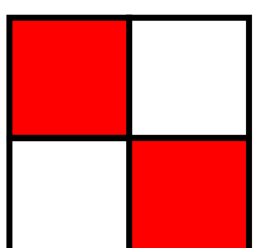


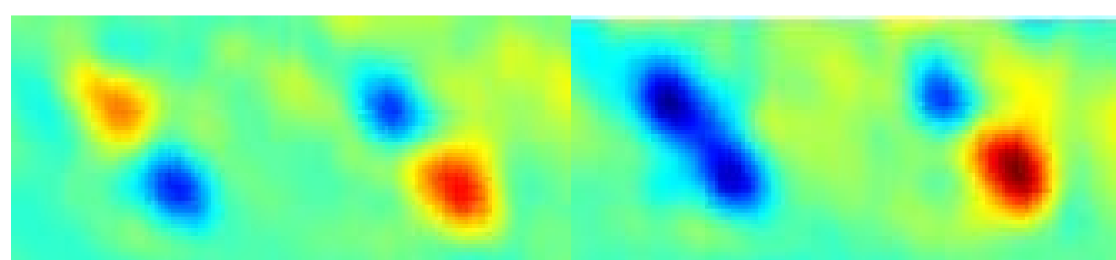






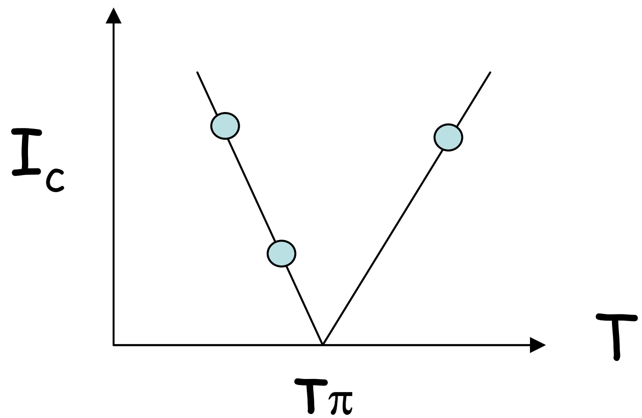
Checkerboard frustrated



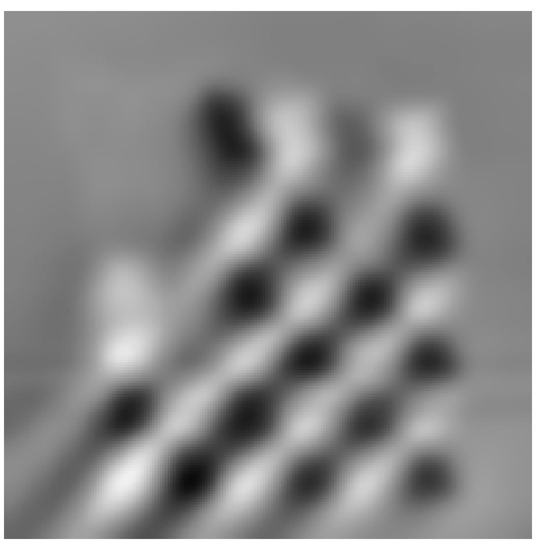


Scanning SQUID Microscope images

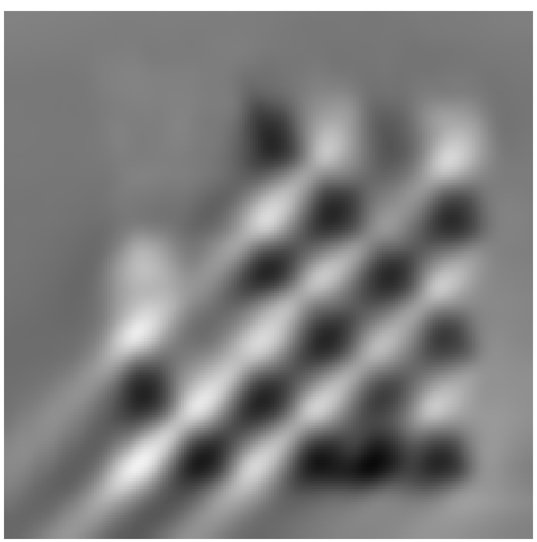
(Ryazanov et al.)



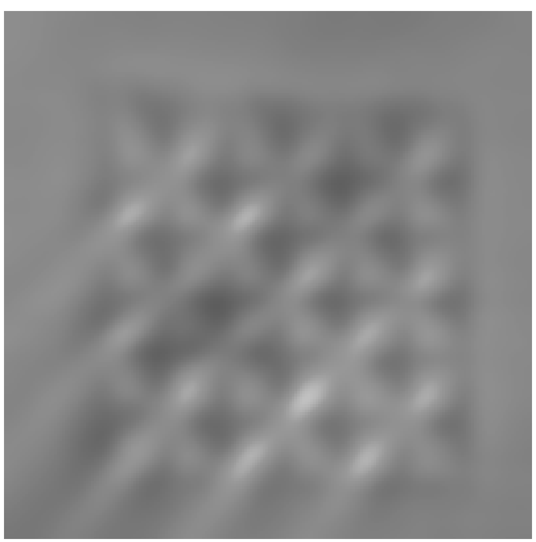
T = 1.7K



T = 2.75K

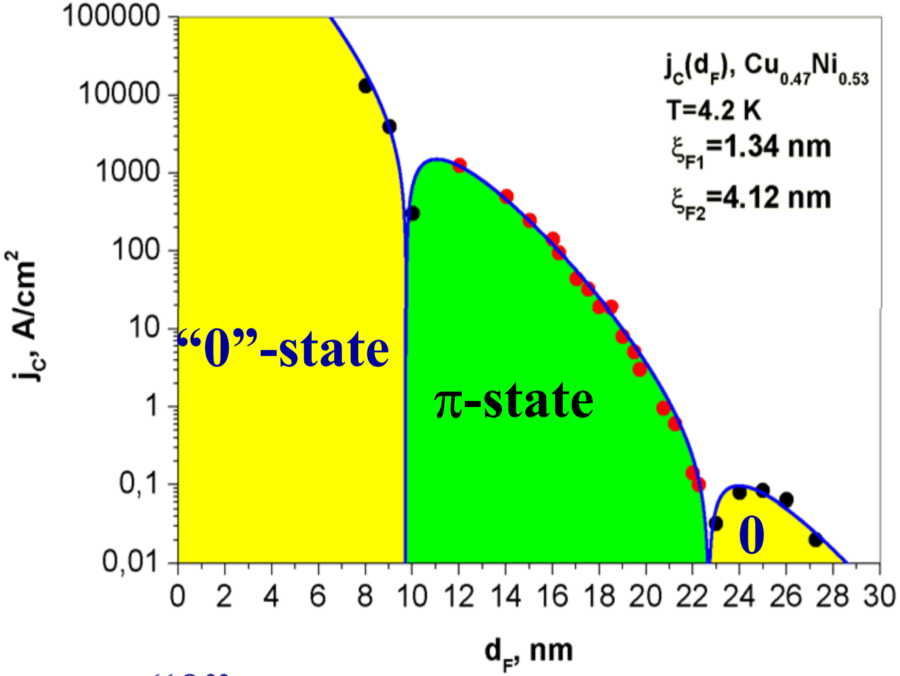


T = 4.2K



Critical current density vs. F- layer thickness (V.A.Oboznov et al., PRL, 2006)

$$I_c = I_{c0} \exp(-d_F/\xi_{F1}) \left|\cos(d_F/\xi_{F2}) + \sin(d_F/\xi_{F2})\right|$$



$d_F >> \xi_{F1}$

Spin-flip scattering decreases the decaying length and increases the oscillation period.

$\xi_{F2} > \xi_{F1}$

Nb-$Cu_{0.47}Ni_{0.53}$-Nb

"0"-state

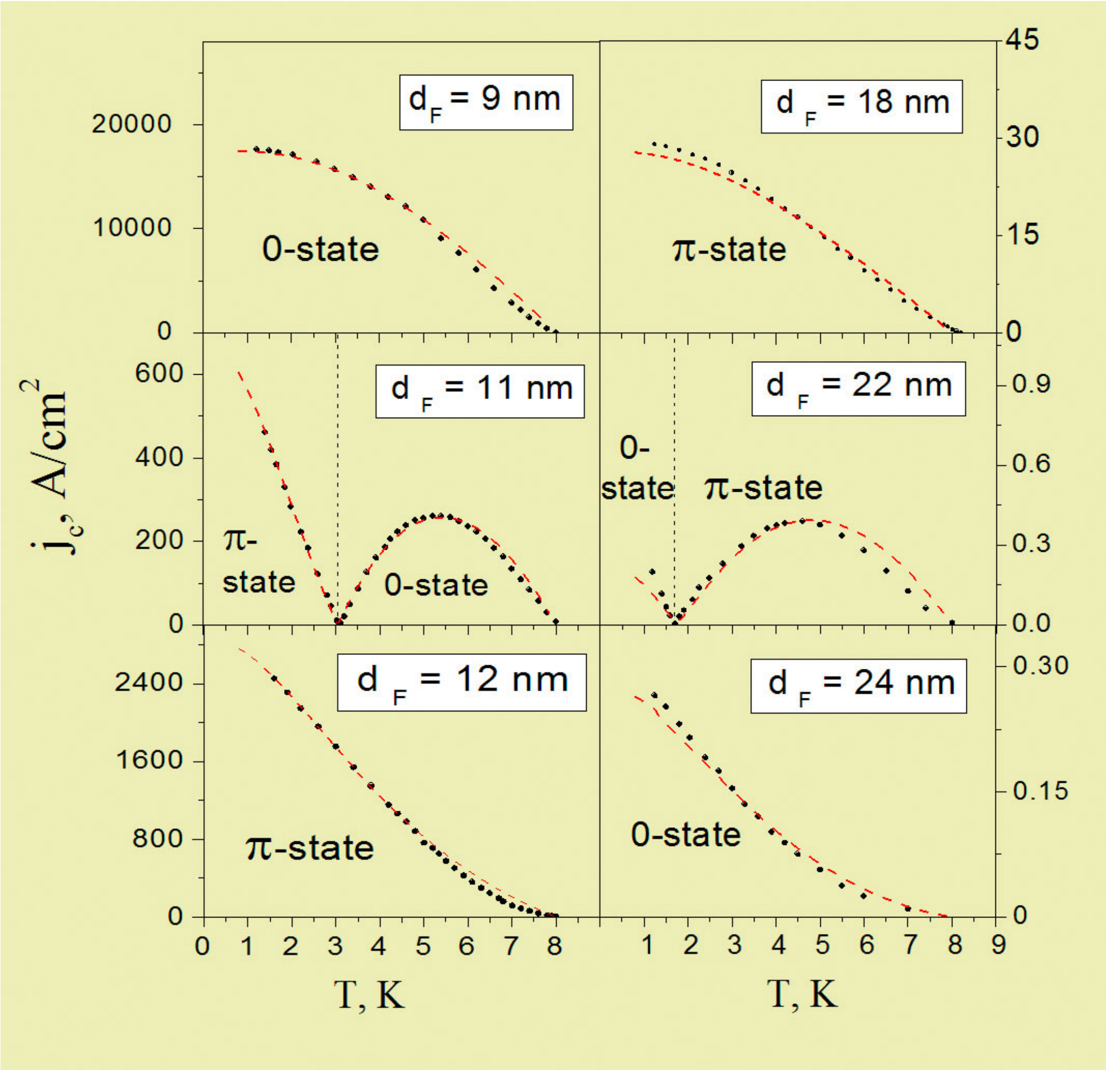
$I = I_c \sin\varphi$

π-state

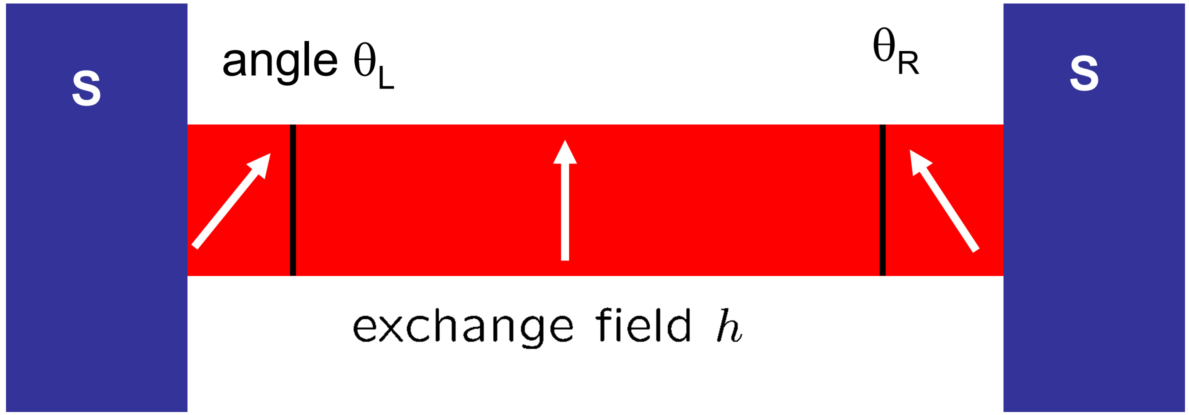
$I = I_c \sin(\varphi + \pi) = -I_c \sin(\varphi)$

Critical current vs. temperature (0-π- and π-0- transitions)

$Nb\text{-}Cu_{0.47}Ni_{0.53}\text{-}Nb$
d_{F1}=10-11 nm
d_{F2}=22 nm



(V.A.Oboznov et al., PRL, 2006)



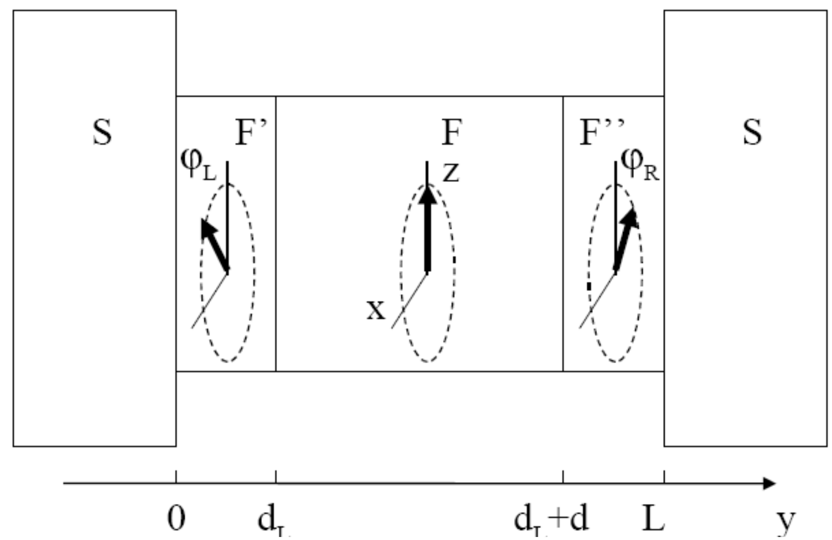


FIG. 1: Geometry of S/F'/F/F''/S junction. The arrows indicate non-colinear orientations of magnetizations in each layer with thickness d_L, d, d_R, respectively ($L = d_L + d + d_R$).

$\xi_f \ll L \ll \xi_0$

$$eR_F I_c = -\frac{2\Delta(T)^2 h_0^2}{\pi^3 T_c^3} \sin\theta_R \sin\theta_L$$

(+ small term)

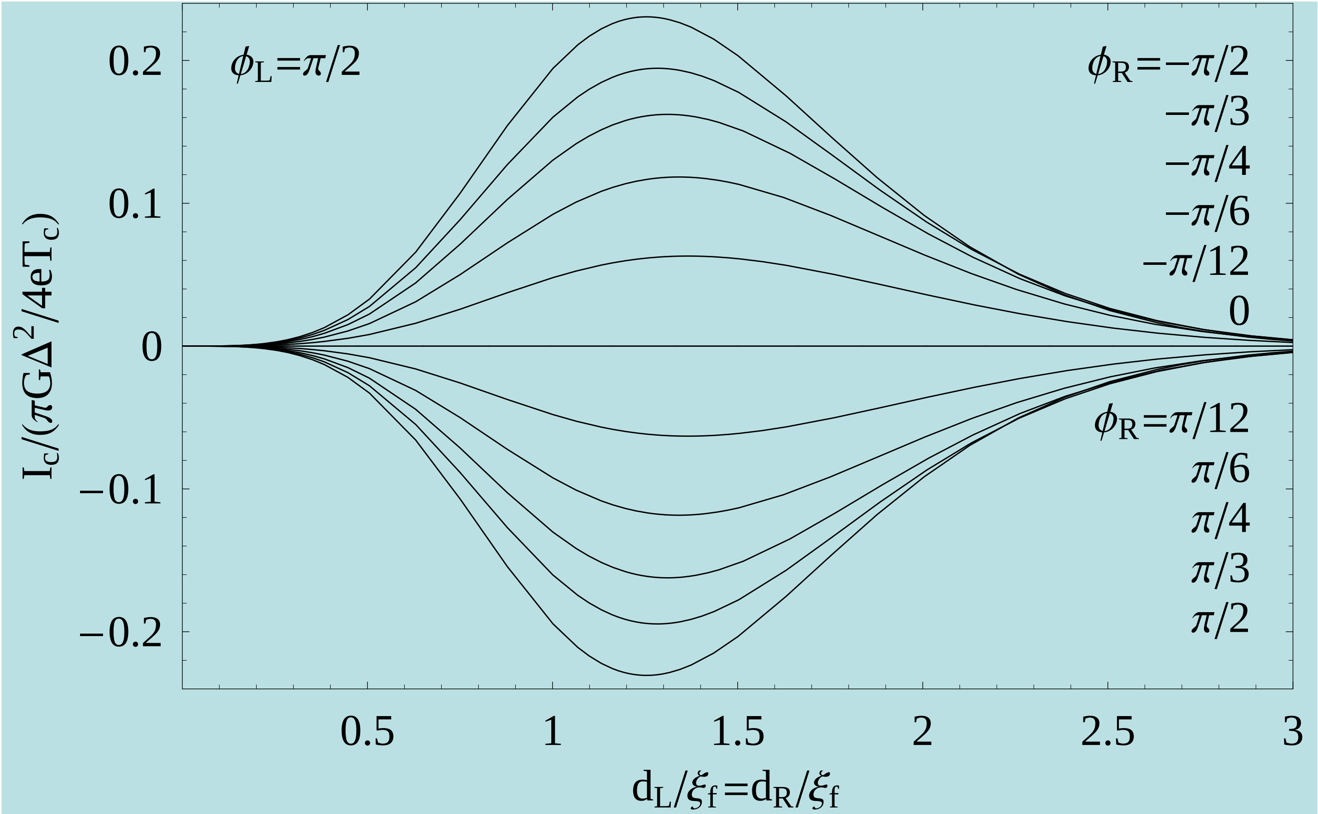


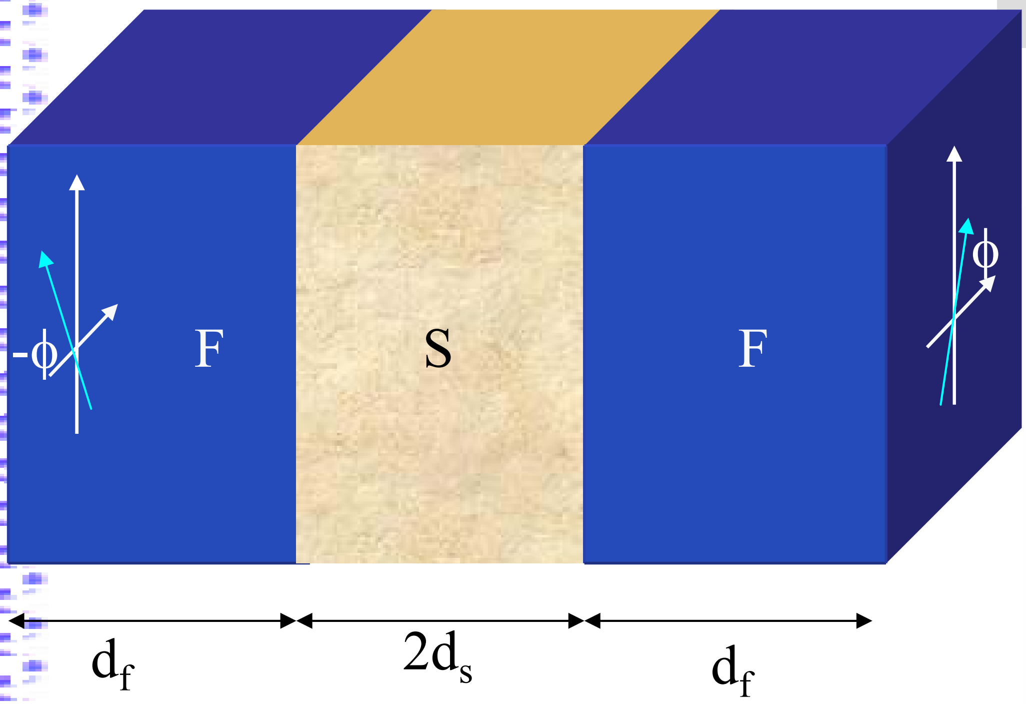
FIG. 2: Critical current induced by long range triplet proximity effect in S/F'/F/F''/S junction, in units of $(\pi G\Delta(T)^2/4eT_c)$, for varying length of F' and F'' layers, at $d_L = d_R \sim \xi_f \ll d \ll \xi_0$, and for different orientations of the magnetization in the layers.

Rather sharp maximum of the critical current at $d_L=d_R=\xi_f$

More details - M. Houzet and A. Buzdin « Long range triplet Josephson effect through a ferromagnetic trilayer », PRB, 2007.

F/S/F trilayers, spin-valve effect

If d_s is of the order of magnitude of ξ_s, the critical temperature is controlled by the proximity effect.



Firstly the FI/S/FI trilayers has been studied experimentally in 1968 by Deutscher et Meunier.
In this special case, we see that the critical temperature of the superconducting layers is reduced when the ferromagnets are polarized in the same direction

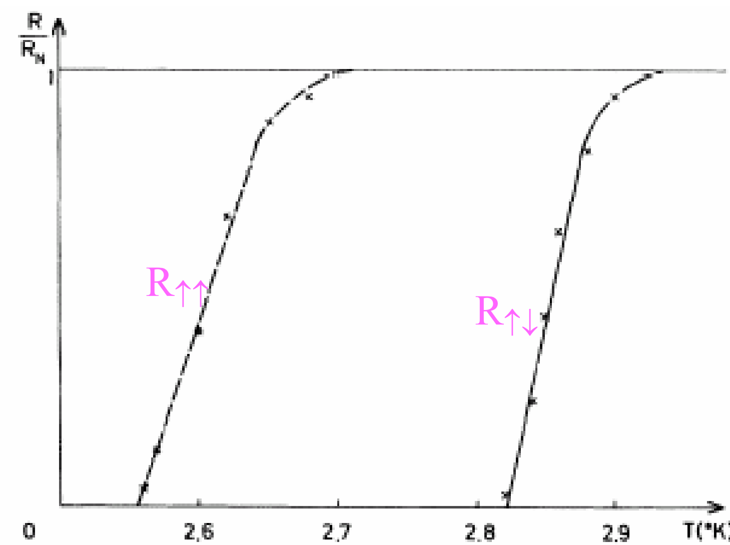


FIG. 1. Resistive measurements of the critical temperatures (R_N = resistance in the normal state) in zero field after the following: dashed line, application of 10 000 G ($T_{c\uparrow\uparrow}$) (all fields are applied parallel to the plane of the films); solid line, application of −10 000 G and subsequently +300 G to return the magnetization of the FeNi layer ($H_1 < 300$ G $< H_2$) ($T_{c\uparrow\downarrow}$).

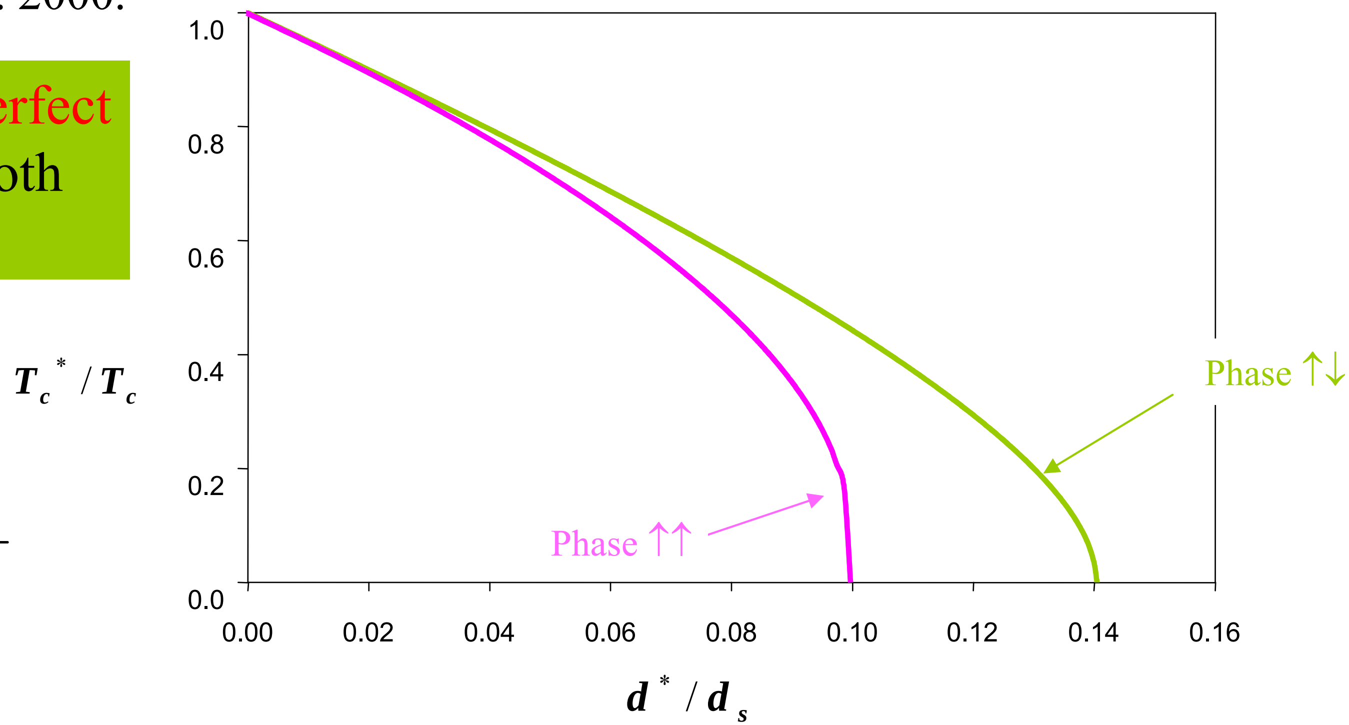
In the dirty limit, we used the quasiclassical Usadel equations to find the new critical temperature T^*_c.
We solved it self-consistently supposing that the order parameter can be taken as :

$$\Delta = \Delta_0\left(1-\frac{x^2}{L^2}\right)$$

with $L \gg d_S$

Buzdin, Vedyaev, Ryazhanova, Europhys Lett. 2000,
Tagirov, Phys. Rev. Let. 2000.

In the case of a perfect transparency of both interfaces

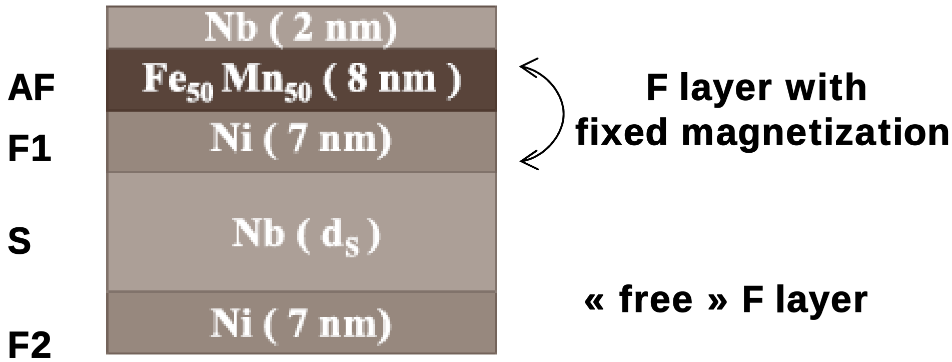


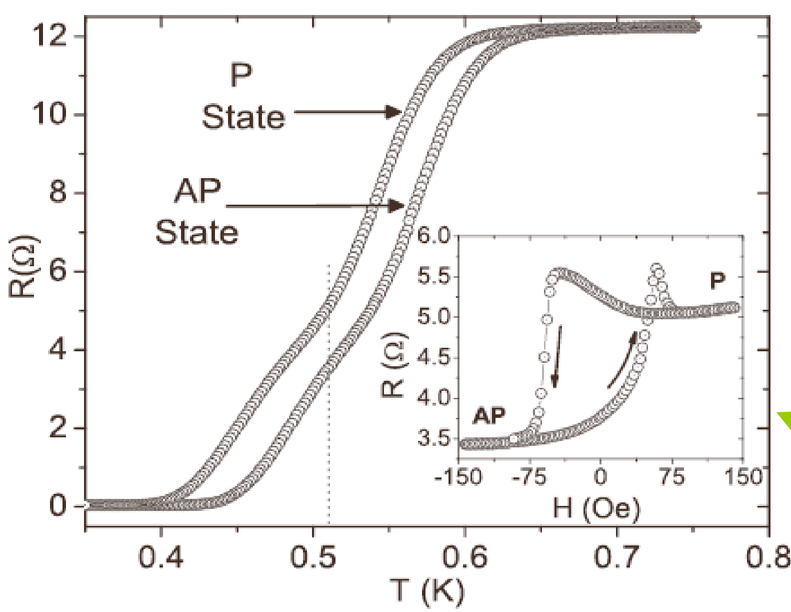
$$d^* = \gamma\sqrt{\frac{h}{D_n}\frac{D_s}{4\pi T_c}}$$

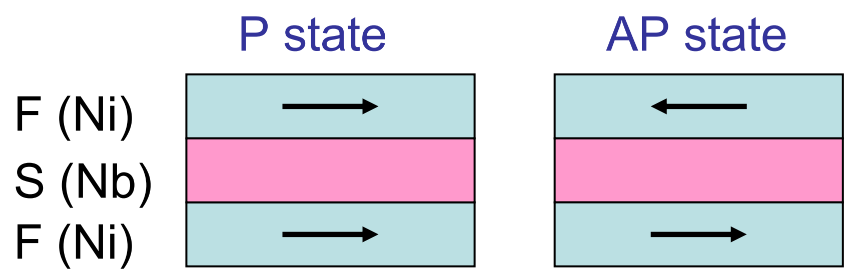
$$\ln\left(\frac{T^*_{c\uparrow\uparrow}}{T_c}\right) = \Psi\left(\frac{1}{2}\right) - \mathrm{Re}\,\Psi\left(\frac{1}{2}+\frac{d^*T_c}{d_sT^*_{c\uparrow\uparrow}}(1+i)\right)$$

$$\ln\left(\frac{T^*_{c\uparrow\downarrow}}{T_c}\right) = \Psi\left(\frac{1}{2}\right) - \Psi\left(\frac{1}{2}+\frac{d^*T_c}{d_sT^*_{c\uparrow\downarrow}}\right)$$

Recent experimental verifications







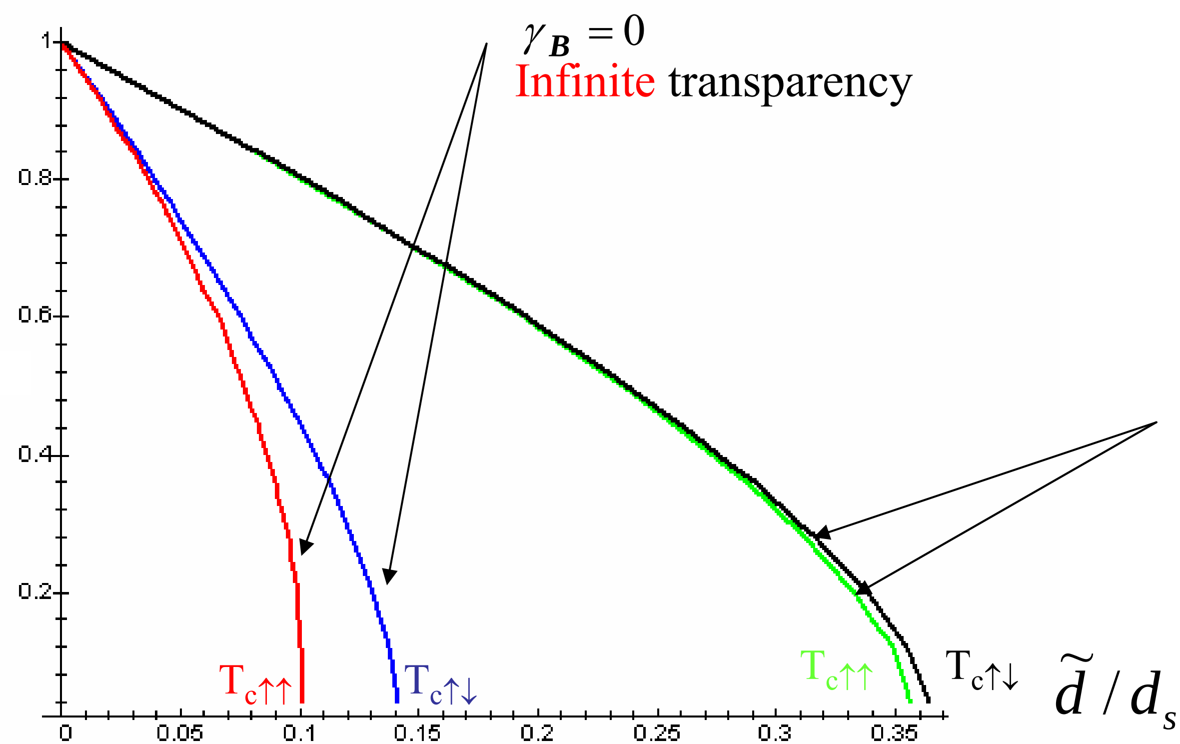
CuNi/Nb/CuNi

Gu, You, Jiang, Pearson, Bazaliy, Bader, 2002

Ni/Nb/Ni

Moraru, Pratt Jr, Birge, 2006

Evolution of the difference between the critical temperatures as a function of interfaces' transparency



$$\ln\left(\frac{T_{c\uparrow\uparrow}^*}{T_c}\right) = \Psi\left(\frac{1}{2}\right) - \mathrm{Re}\,\Psi\left(\frac{1}{2} + \frac{\tilde{d}T_c}{d_s T_{c\uparrow\uparrow}^*}(1+i)\right)$$

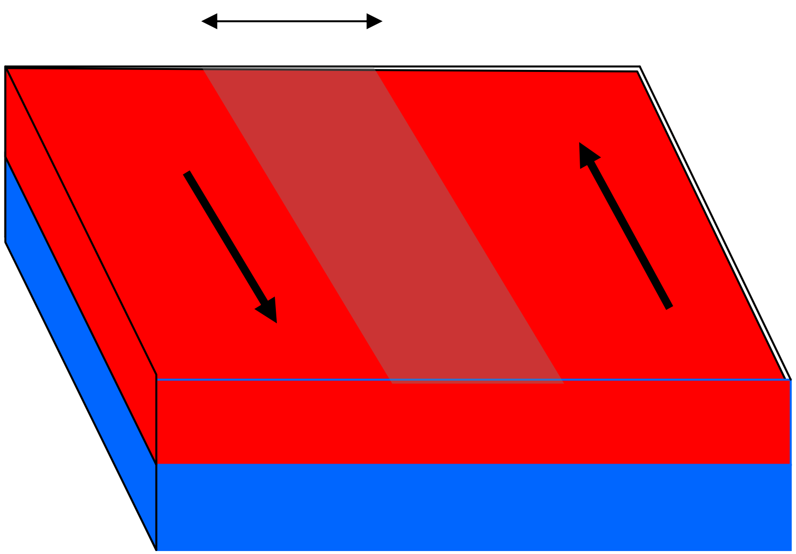
$$\ln\left(\frac{T_{c\uparrow\downarrow}^*}{T_c}\right) = \Psi\left(\frac{1}{2}\right) - \Psi\left(\frac{1}{2} + \left(\frac{\tilde{d}T_c}{d_s T_{c\uparrow\downarrow}^*}\right)\right)$$

$$\tilde{d} = \frac{D_s}{4\pi T_c} \frac{\gamma\sqrt{\frac{h}{D_n}}}{1+(1+i)\gamma_B\gamma\sqrt{\frac{h}{D_n}}}$$

Similar physics in F/S bilayers

In practice, magnetic domains appear quite easily in ferromagnets

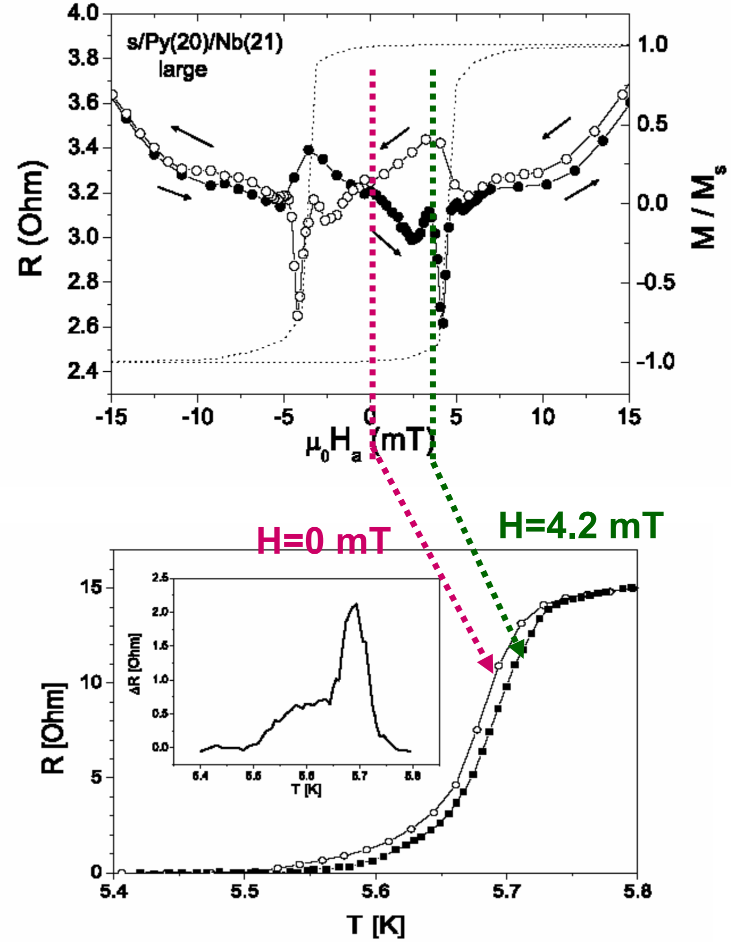
w: width of the domain wall



$Ni_{0.80}Fe_{0.20}$/Nb (20nm)

Thin films : Néel domains

Rusanov et al., PRL, 2004



Localized (domain wall) superconducting phase.

Theory - Houzet and Buzdin, Phys. Rev. B (2006).

Different mechanism for the φ_0 - Josephson junction realization.

Recently the broken inversion symmetry (BIS) superconductors (like $CePt_3Si$) have attracted a lot of interest.

Very special situation is possible when the weak link in Josephson junction is a non-centrosymmetric magnetic metal with broken inversion symmetry !

Suitable candidates : MnSi, FeGe.

Josephson junctions with time reversal symmetry: $j(-\varphi) = -j(\varphi)$;

i.e. higher harmonics can be observed $\sim j_n \sin(n\varphi)$ –the case the π junctions.

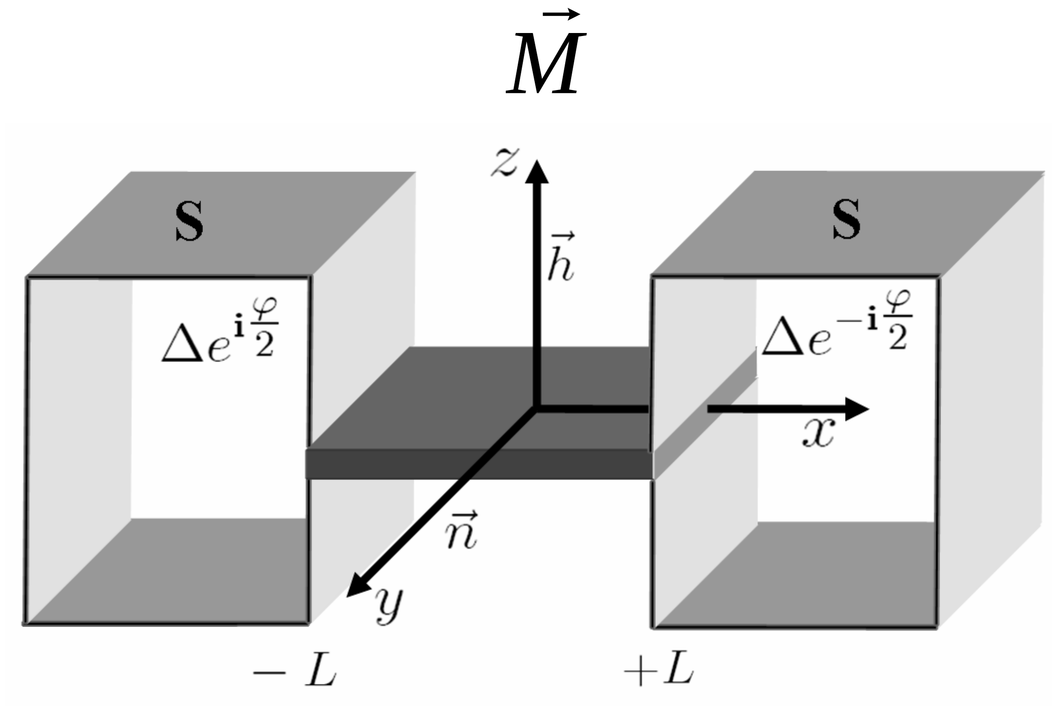
Without this restriction a more general dependence is possible

$$j(\varphi) = j_0 \sin(\varphi + \varphi_0).$$

Rashba-type spin-orbit coupling $\alpha(\vec{\sigma} \times \vec{p}) \cdot \vec{n}$

$\vec{n}$ is the unit vector along the asymmetric potential gradient.

Geometry of the junction with BIS magnetic metal



$$F = a|\Psi|^2 + \gamma|\vec{D}\Psi|^2 + \frac{b}{2}|\Psi|^4 - \varepsilon\vec{n}\left[\vec{h}\times\left(\Psi\left(\vec{D}\Psi\right)^* + \Psi^*\left(\vec{D}\Psi\right)\right)\right],$$

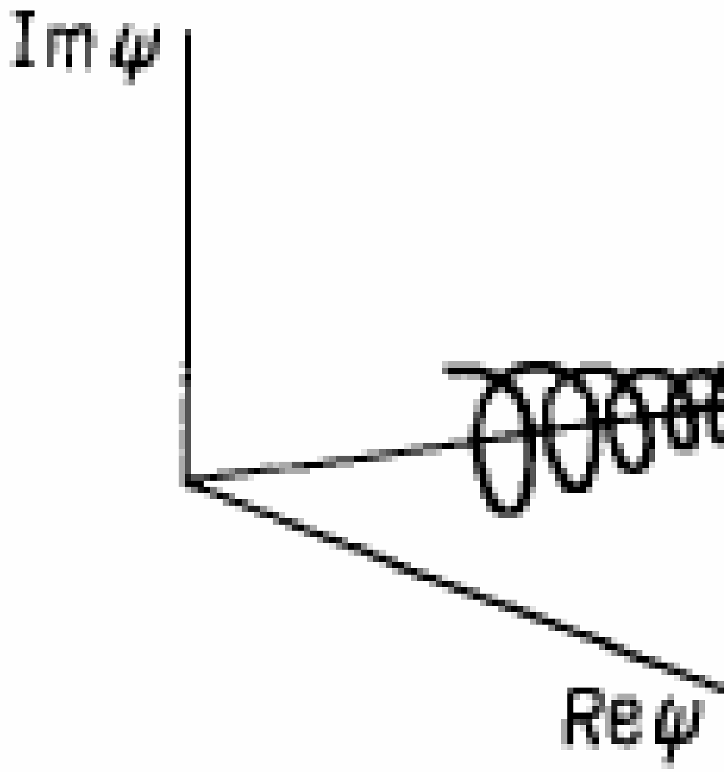
$$D_i = -i\partial_i - 2eA_i$$

$$a\Psi - \gamma\frac{\partial^2\Psi}{\partial x^2} + 2i\varepsilon h\frac{\partial\ \Psi}{\partial x} = 0,$$

$$\Psi \propto \exp(i\tilde{\varepsilon}x)\exp\left(-x\sqrt{\frac{a-a_c}{\gamma}}\right), \quad where\ \tilde{\varepsilon} = \frac{\varepsilon h}{\gamma}$$

φ_0 - Josephson junction (A. Buzdin, PRL, 2008).

$$\Psi \propto \exp(i\tilde{\varepsilon}x)\exp(-x\sqrt{\frac{a-a_c}{\gamma}}), \quad where\ \tilde{\varepsilon} = \frac{\varepsilon h}{\gamma}$$



In contrast with a π junction it is not possible to choose a real Ψ function !

φ_0 Josephson junction

$$j(\varphi) = j_c \sin(\varphi + \varphi_o)$$

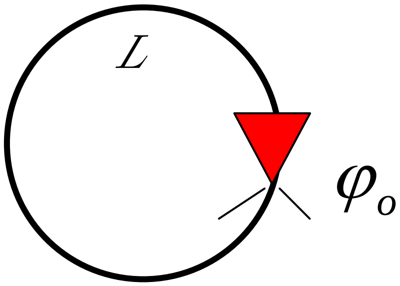
where $$\varphi_o = \frac{2\varepsilon hL}{\gamma}$$

The phase shift φ_0 is proportional to the length and the strength of the BIS magnetic interaction.

The φ_0 Junction is a natural phase shifter.

Energy $E_J(\varphi) \sim -j_c \cos(\varphi + \varphi_0)$

Spontaneous flux (current) in the superconducting ring with φ_0 - junction.



$$E(\varphi) = \frac{j_c}{2e}\left(-\cos(\varphi + \varphi_0) + \frac{k\varphi^2}{2} \right)$$

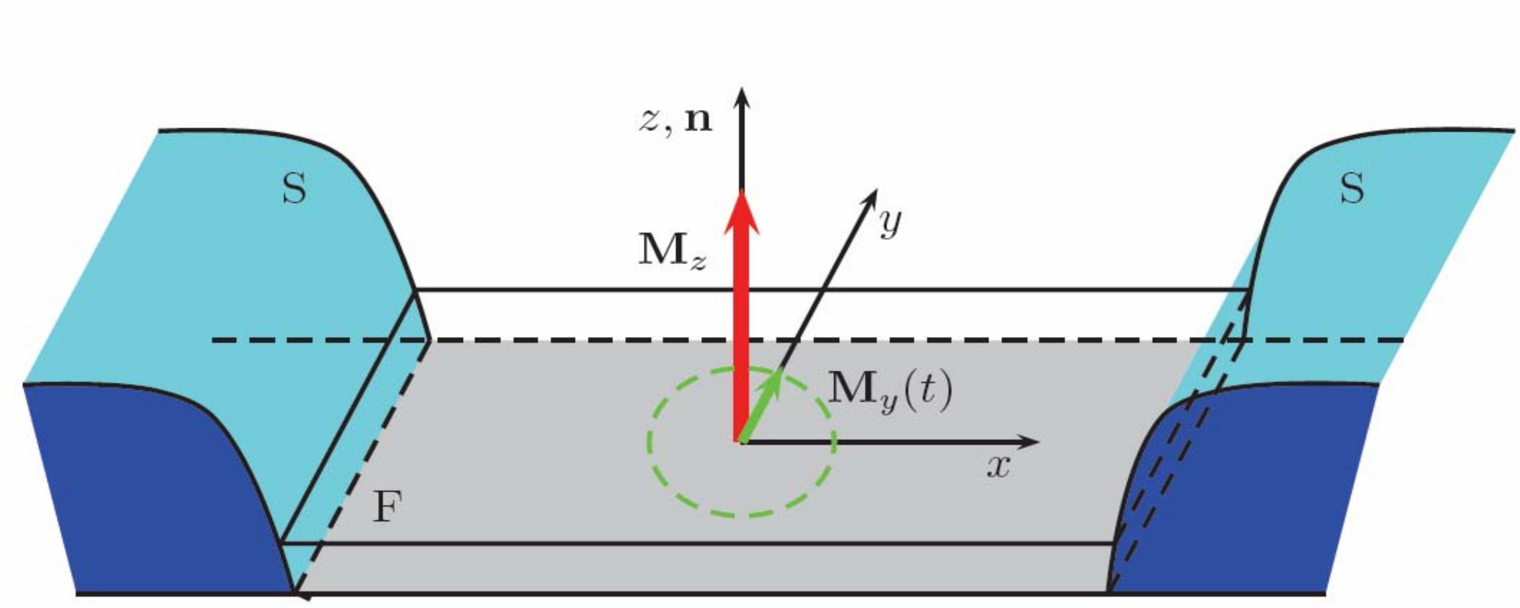
$$k = \frac{c\Phi_0}{2\pi L j_c}$$

In the k<<1 limit the junction generates the flux $\Phi = \Phi_0(\varphi_0/2\pi)$

$$\varphi_o = \frac{2\varepsilon h L}{\gamma}$$

Very important : The φ_0 junction provides a mechanism of a **direct coupling** between supercurrent (superconducting phase) and magnetic moment (z component).

Let us consider the following geometry :



$$\varphi_0 = x \frac{v_{so}}{v_F} \frac{M_y}{M_0}$$

$$\sin\theta = \frac{I}{I_c}\Gamma \quad \text{with } \Gamma = \frac{E_J}{K\mathcal{V}} x \frac{v_{so}}{v_F}$$

voltage-biased Josephson junction

$$\varphi(t) = \omega_J t$$

Magnetic anisotropy (easy z-axis) energy :

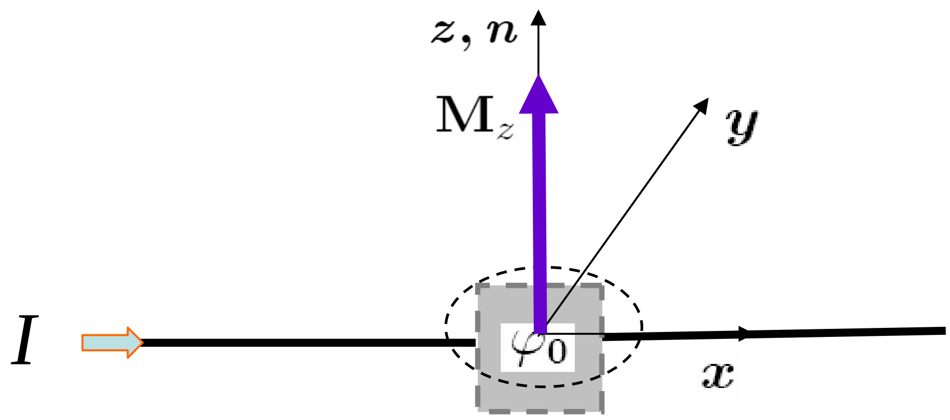
$$E_M = -\frac{K\mathcal{V}}{2}\left(\frac{M_z}{M_0}\right)^2$$

Coupling parameter :

$$\Gamma = \frac{E_J}{K\mathcal{V}} x \frac{v_{so}}{v_F}$$

Weak coupling regime : Γ<1.
Srong coupling regime : Γ>1.

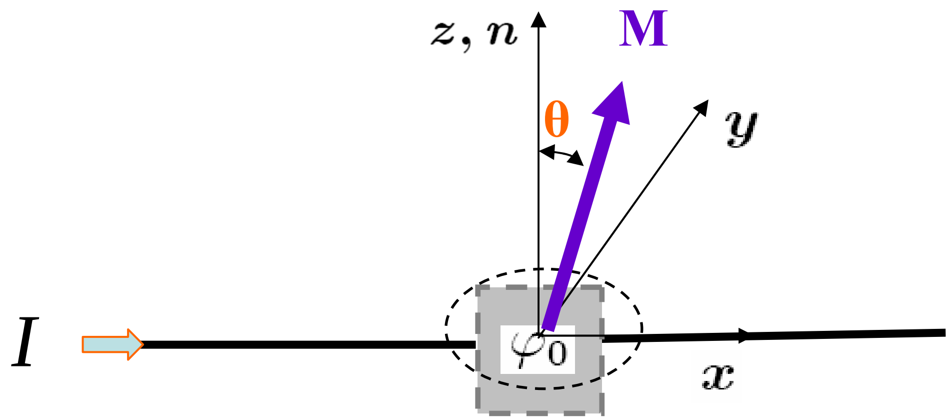
Let us consider first the φ_0 - junction when a constant current $I<I_c$ is applied :



$$\varphi_0 = x\frac{v_{so}}{v_F}\frac{M_y}{M_0}$$

$$E_{tot} = -\frac{\Phi_0}{2\pi}\varphi I + E_s(\varphi, \varphi_0) + E_M(\varphi_0)$$

Minimum energy condition: $\partial_\varphi E_{tot} = \partial_{\varphi_0} E_{tot.} = 0.$



The current provokes rotation of the magnetic moment :

$$\sin\theta = \frac{I}{I_c}\Gamma$$

$$M_y = M_0 \sin\theta$$

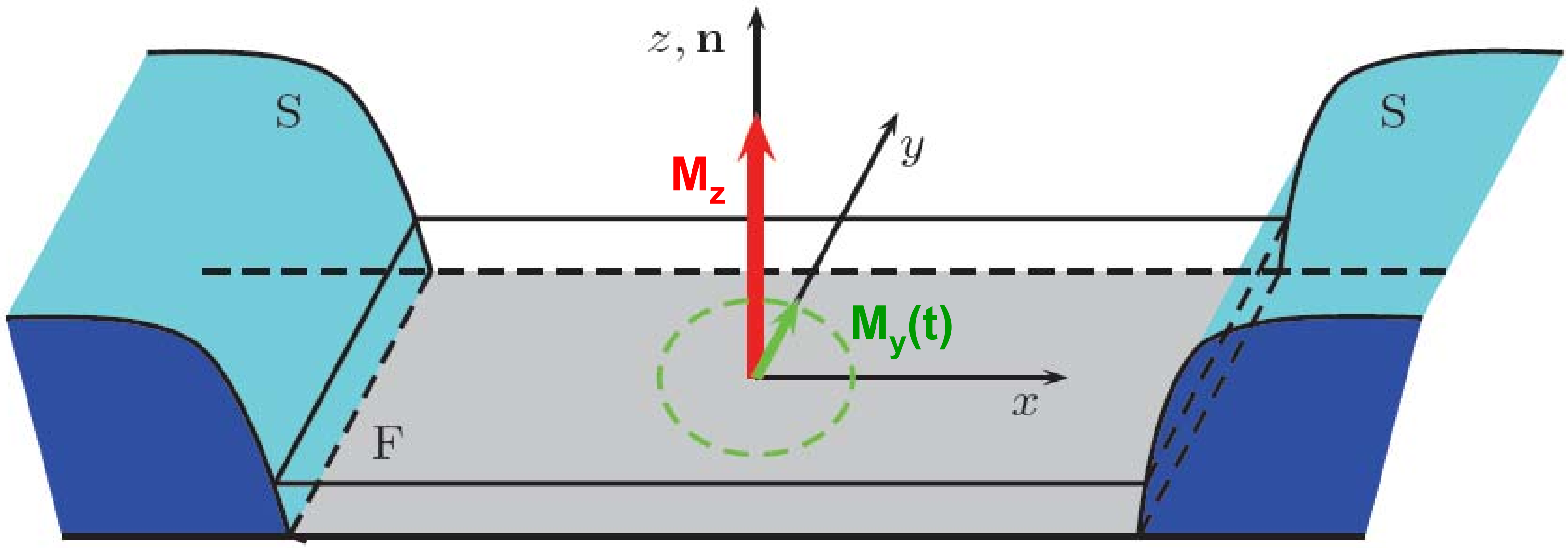
For the case $\Gamma>1$ when $I>I_c/\Gamma$ the moment will be oriented along the y-axis.

Applying to the φ_0 - junction a current (phase difference) we can generate the magnetic moment rotation.

a.c. current -> moment's precession!

Magnetic moment precession – voltage-biased φ_0- junction

$\varphi(t) = \omega_J t$



$$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \wedge \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_0}\left(\mathbf{M} \wedge \frac{d\mathbf{M}}{dt}\right),$$

where $\mathbf{H}_{\text{eff}} = -\delta F / \mathcal{V} \delta \mathbf{M}$ is the effective magnetic field

$$\mathbf{H}_{\text{eff}} = \frac{K}{M_0}\left[\Gamma \sin\left(\omega_J t - r\frac{M_y}{M_0}\right)\hat{\boldsymbol{y}} + \frac{M_z}{M_0}\hat{\boldsymbol{z}}\right]$$

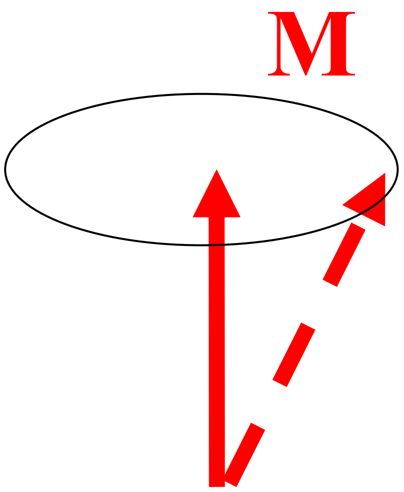
$r = x v_{\text{so}} / v_F$

Landau-Lifshitz equation :

$$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \wedge \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_0}\left(\mathbf{M} \wedge \frac{d\mathbf{M}}{dt}\right)$$

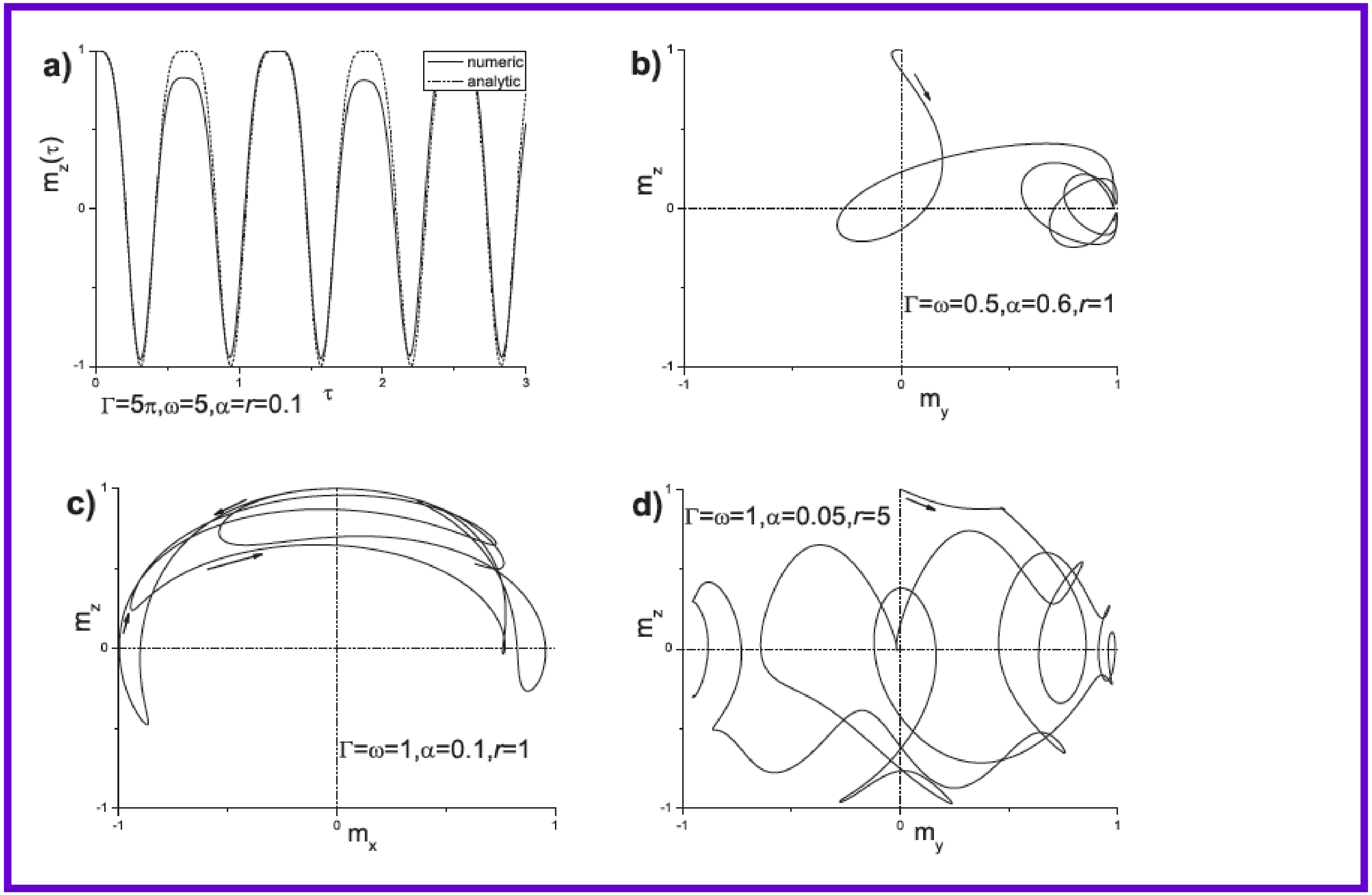
$$\mathbf{H}_{\text{eff}} = \frac{K}{M_0}\left[\Gamma \sin\left(\omega_J t - r\frac{M_y}{M_0}\right)\hat{\boldsymbol{y}} + \frac{M_z}{M_0}\hat{\boldsymbol{z}}\right]$$

Magnetic moment precession :



$$\frac{I}{I_c} = \sin \omega_J t + \frac{\Gamma r}{2}\frac{1}{\omega^2 - 1}\sin 2\omega_J t + \ldots,$$

Complicated regime of the magnetic dynamics :

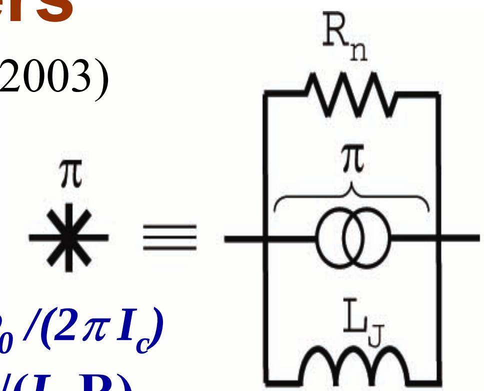


For more details – see (F. Konschelle and A. Buzdin, PRL, 2009).

Complementary Josephson logic

RSFQ-logic using π-shifters

A.V.Ustinov, V.K.Kaplunenko. Journ. Appl. Phys. **94**, 5405 (2003)

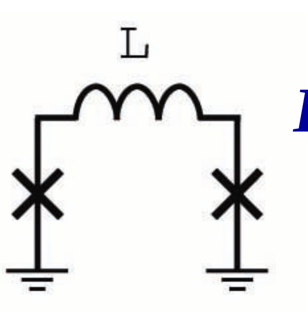


$L_J = \Phi_0 / (2\pi I_c)$

$\tau \sim 1/(I_c R)$

RSFQ- logic: Rapid Single Quantum logic

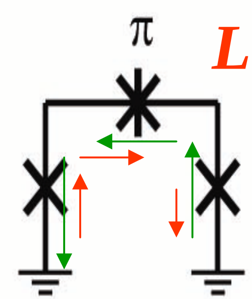
Conventional RSFQ-cell



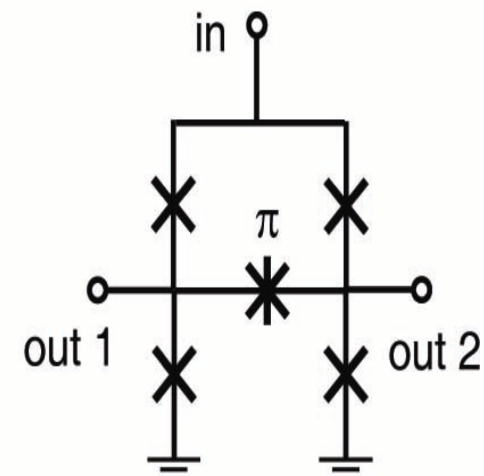
$LI_c > \Phi_0$

Fluxon memorizing cell

RSFQ -*π*– cell



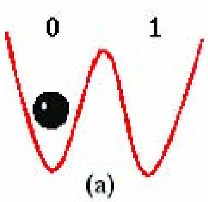
L → 0



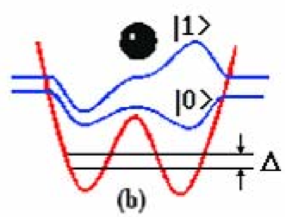
π-RSFQ –***Toggle Flip-Flop***

To operate at 20 GHz clock rate
$I_c R$~50 μV has to be
We have $I_c R$ > 0.1 μV for the present

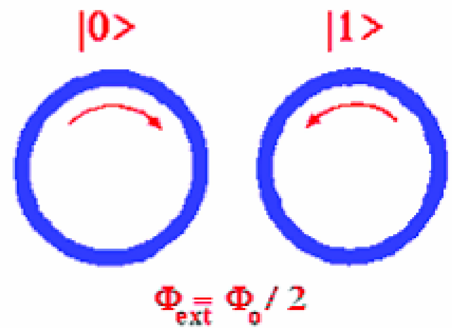
Superconducting phase qubit



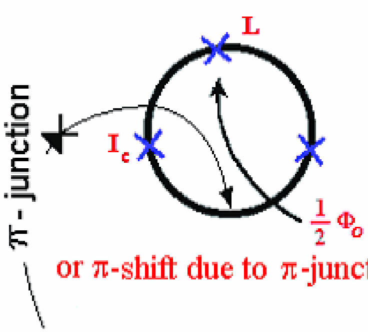
Digital bit



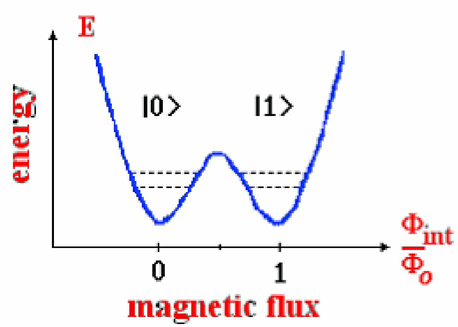
Quantum bit

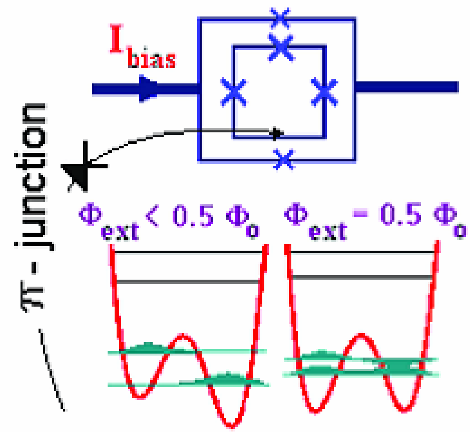


or π-shift due to π-junction



or π-shift due to π-junction





qubit operation

Conclusions

- **Superconductor-ferromagnet heterostructures permit to study superconductivity under huge exchange field ($h \gg T_c$).**

- **The π - junction realization in S/F/S structures is a quite general phenomenon.**

- **Domain wall superconductivity. Spin - valve effects.**

- **The BIS magnets provide a mechanism of the realization of the novel φ_0 - junctions with the very special properties.**

- **In these φ_0 - junctions a direct (linear) coupling between superconductivity and magnetism is realized. Seems to be ideal for superconducting spintronics.**

Some Refs.: **Magnetic superconductors-** M. Kulic and A. Buzdin in **Superconductivity,** Springer, 2008 (eds. Benneman and Ketterson).

S/F proximity effect - A. Buzdin, Rev. Mod. Phys. (2005).

φ_0 - junctions - A. Buzdin, PRL (2008), F. Konschelle and A. Buzdin, PRL (2009).