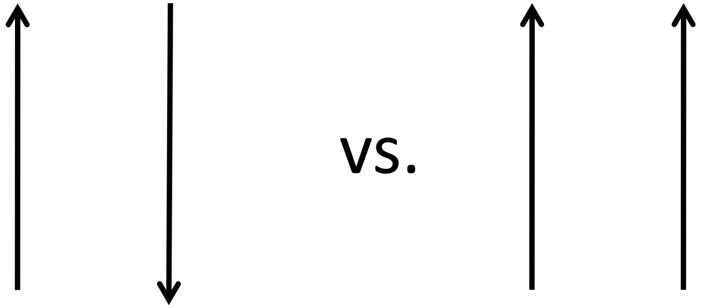
Superconductor/Ferromagnet Hybrid (Quantum) Systems

Reinhold Kleiner
Summer School 2010, Blaubeuren



vs.

= something new (?)

Outline

- Cooper Pairs vs. Ferromagnets – the problems

- Coexistence in bulk materials

- Layered Systems
  - S-I-F bilayers: Domain wall superconductivity and other effects
  - Proximity effect in SF bilayers

  - Trilayers and multilayers
  - why?

  - SFS structures: the Josephson effect
  - …SFSFS… multilayers

  - FSF structures: magnetoresistive effects

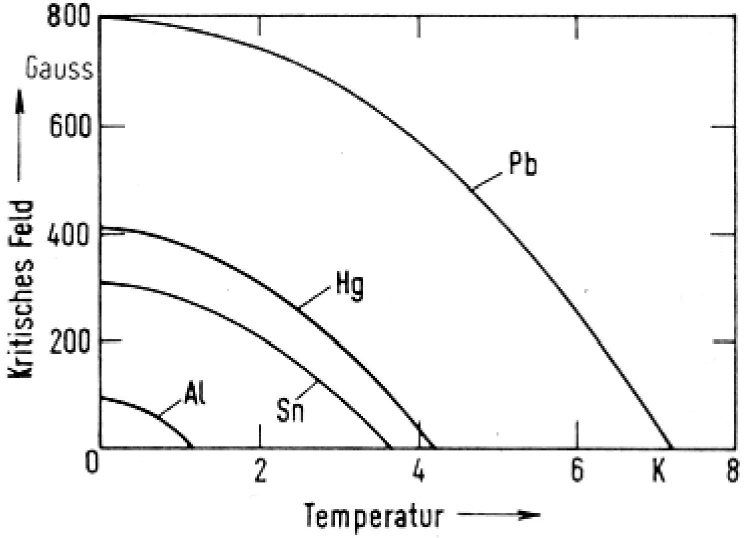
Some Basics

Superconductor	Ferromagnet
Interaction	
(mostly) Electron-Phonon Long range, weak Itinerant electrons, (mostly)Spin-Singulett Cooper-Pairing	Exchange interaction Short range, strong Localized or itinerant electrons
Ordered state	
Macroscopic wave function, s-Wave („Conventional“) d-wave (e. g. Cuprates)	Parallel spin alignment within domain
Critical temperature T_c 1 K-100 K	Curie temperature T_C (100 K-1000 K)
Characteristic length scales:	
Cooper pair density: Coherence length ξ (1-1000 nm)	Exchange interaction: few nm Magnetic domain size: nm..µm
Supercurrents, magnetic field London penetration depth λ_L(50-500 nm)	Domain walls: some nm

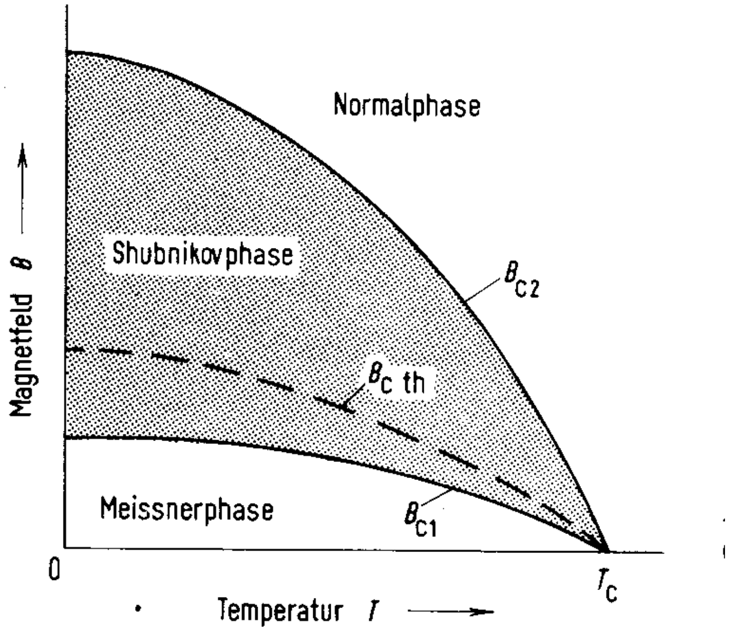
Some Basics

Superconductor phase diagrams

Type I :
Meissner state and normal state
Critical field B_c



Type II:
Meissner state, vortex state, normal state
Lower critical field B_{c1}
Upper critical field B_{c2}



Cooper Pairs vs. Ferromagnets – the Problems

Early experiments : Magnetic impurities harmful for superconductivity

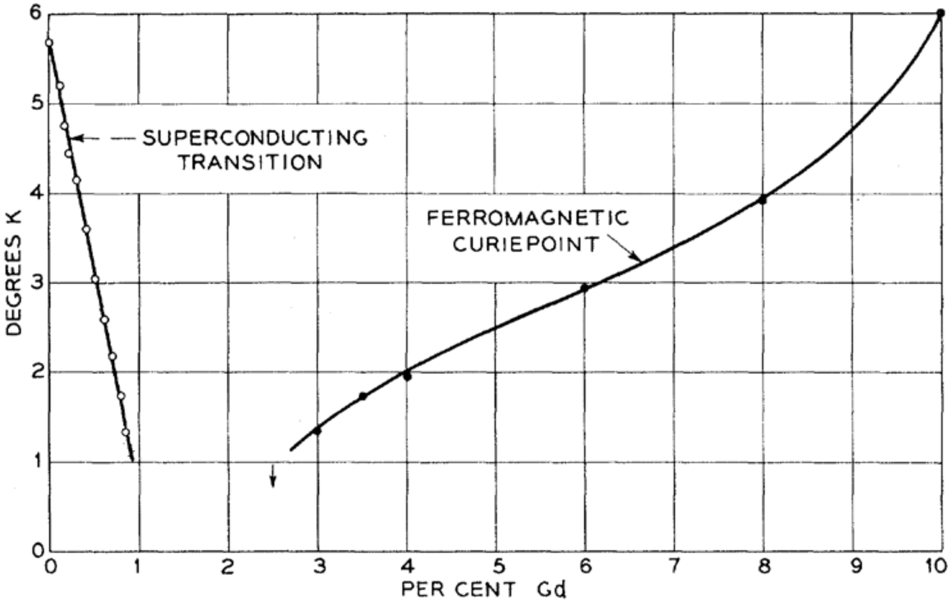


FIG. 3. Ferromagnetic and superconducting transition temperatures of solid solutions of gadolinium in lanthanum.

B. Matthias et al, Phys. Rev. Lett. **1**, 92 (1958)

Cooper Pairs vs. Ferromagnets – the Problems

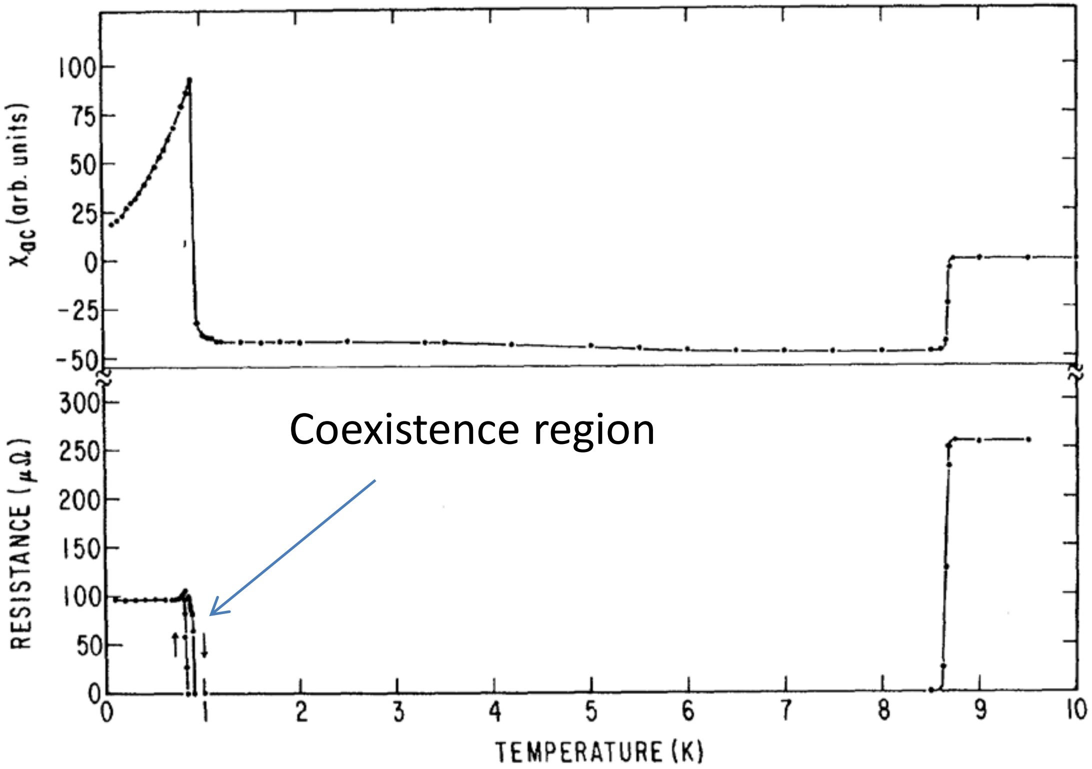
-Orbital effect (Lorentz force):
Cooper pairs get destroyed by
magnetic field induced by magnetic moment

-Paramagnetic effect:
exchange interaction favors parallel spin orientation
-> destroys spin singulett Cooper pairs

Note: No big problem in case of Antiferromagnets (AF).
AF properties must be averaged over SC coherence length

S-F coexistence in bulk materials
-
the more exotic effects

Reentrance and S-F coexistence in bulk materials



Coexistence region

FIG. 1. ac magnetic susceptibility χ_{ac} and ac electrical resistnace vs temperature for $ErRh_4B_4$ in zero applied magnetic field.

W. A. Fertig et al., Phys. Rev. Lett. **38**, 987 (1977)

Reentrance and S-F coexistence in bulk materials

early prediction for Coexistence Region:
Very narrow FM domains develop: „Crypto-Ferromagnetism“
(Anderson & Suhl, Phys. Rev. **116**, 898 (1959)

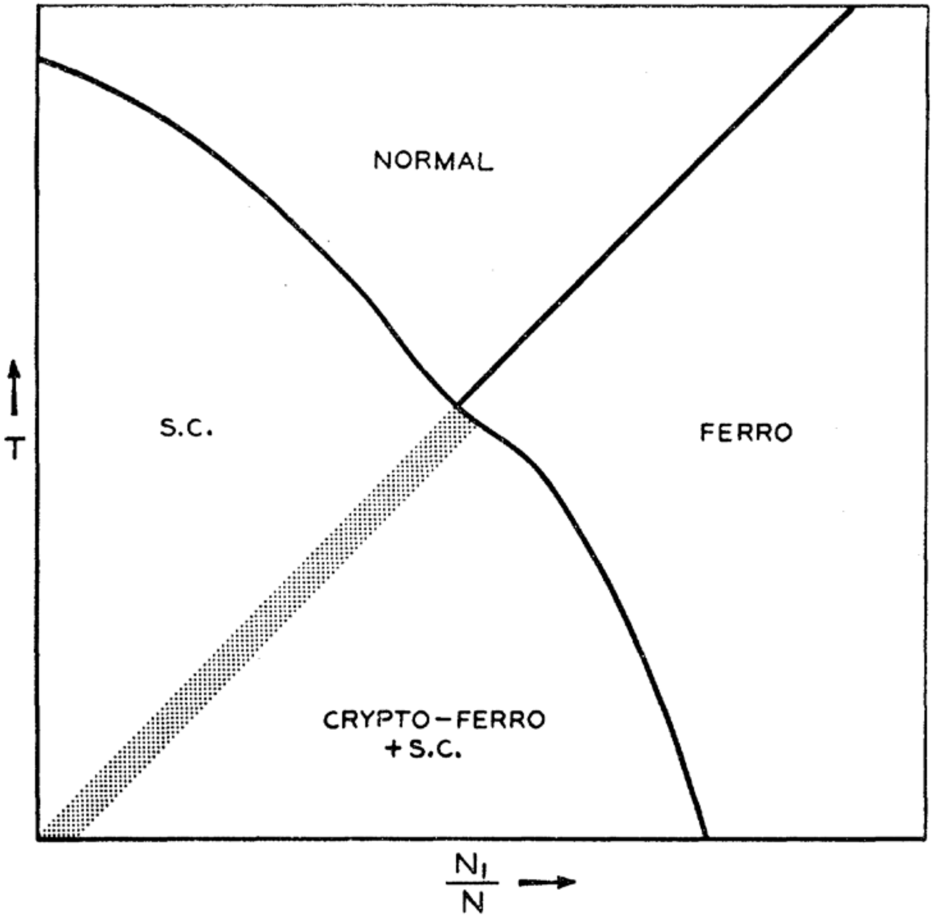


FIG. 2. Phase diagram for ferromagnetism, superconductivity, and cryptoferromagnetism.

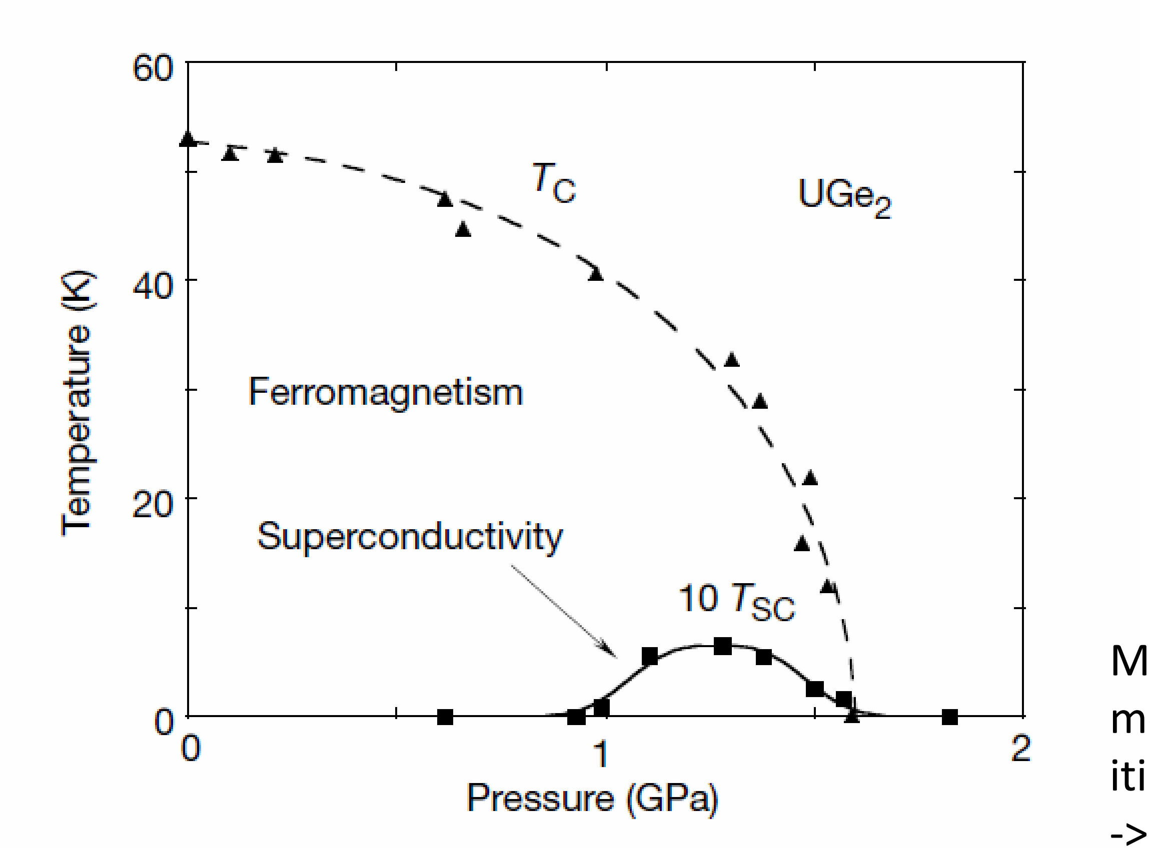
Observation
via neutron stattering
[Sinha et al, PRL **48**, 950 (1982)]

Wavelength ≈ 100 nm

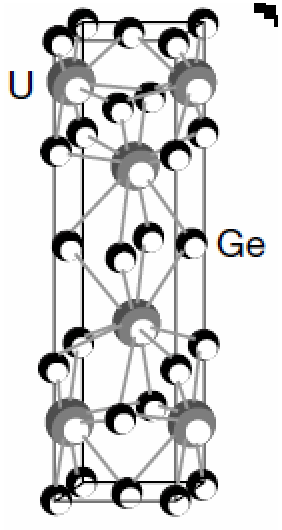
Comments:
-rare case of SC state affecting ferromagnet
-confirmation took *long* time!

Spin-Triplett Superconductivity (?)

Coexistence under pressure: Heavy Fermion Compound UGe_2



Saxena et al., Nature **406**, 587 (2000)

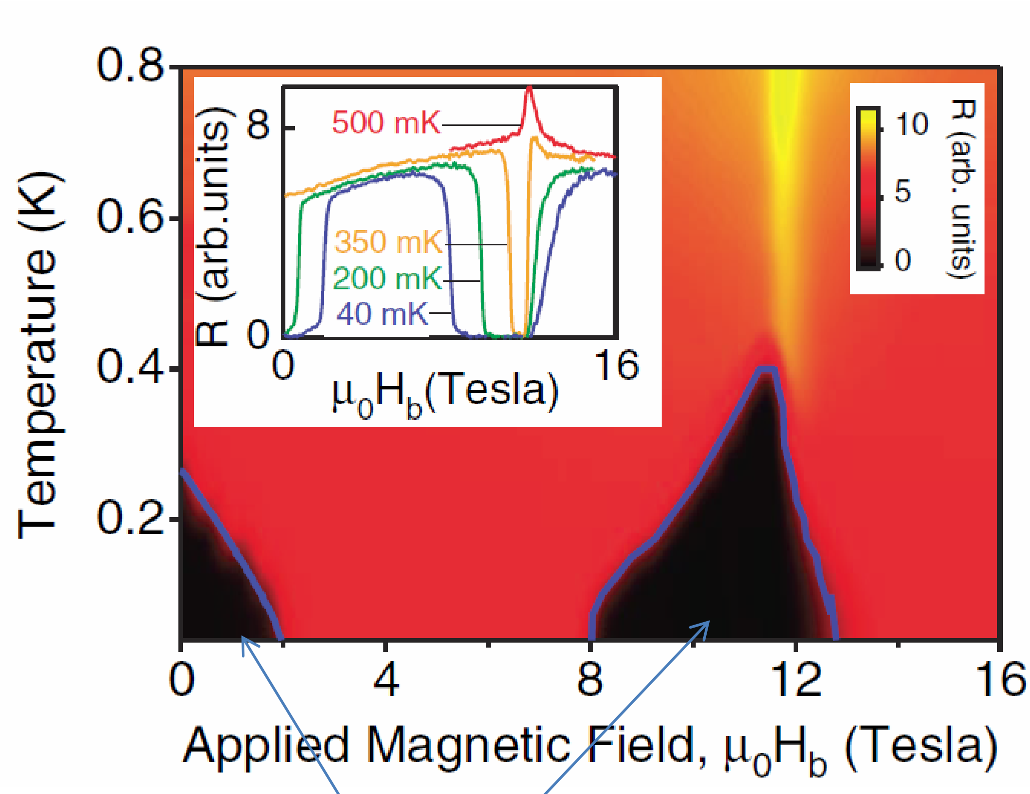


Magnetization / susceptibility measurements ->
itinerant electrons produce FM **and** SC
-> spin triplett pairing
via magnon exchange?

Note: Supercond. *confined* to FM phase

Spin-Triplett Superconductivity (?)

Field induced superconductivity in URhGe



Superconducting regions

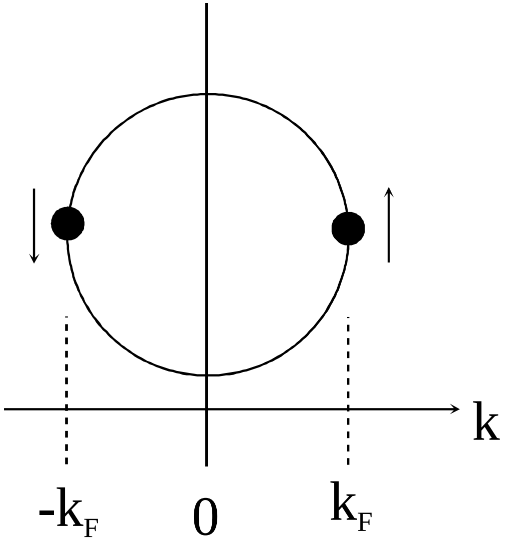
F. Lévy et al.,
Science **309**, 1343 (2005)

$T_{Curie} = 9.5$ K

The FFLO state

(Fulde-Ferrell-Larkin-Ovchinnikov; prediction, 1964)

Cooper pair in conventional superconductor



(-k,k) pairing
$E \approx 2\ E_{Fermi}$

Cooper pair in ferromagnet

↑ electron gains exchange energy E_{ex}

↓ electron looses exchange energy E_{ex}

Center of mass momentum of pair ↓↑ shifts by amount $Q=E_{ex}/v_F$

P. Fulde , R. A. Ferrell, Phys. Rev. 135, A550 (1964).
A. I. Larkin, Yu. N. Ovchinnikov, Zh. Eksp. Teor. Fiz. **47,** 1136 (1964)
[Sov. Phys. JETP **20** (1965) 762]

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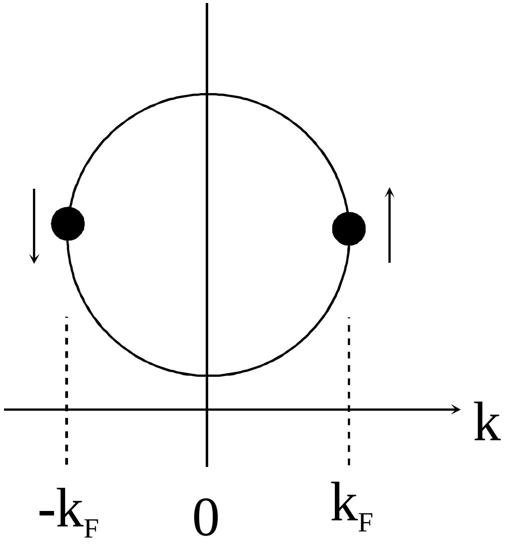

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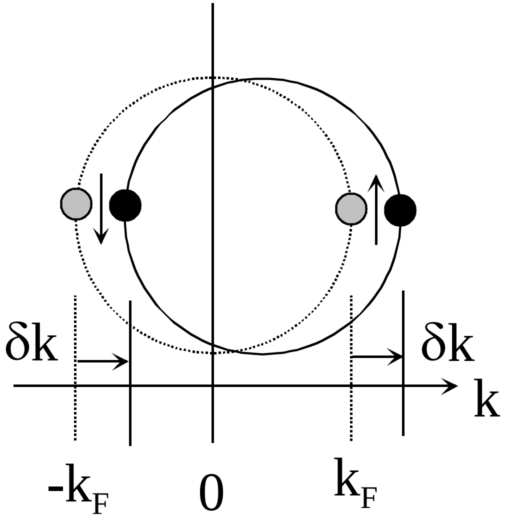

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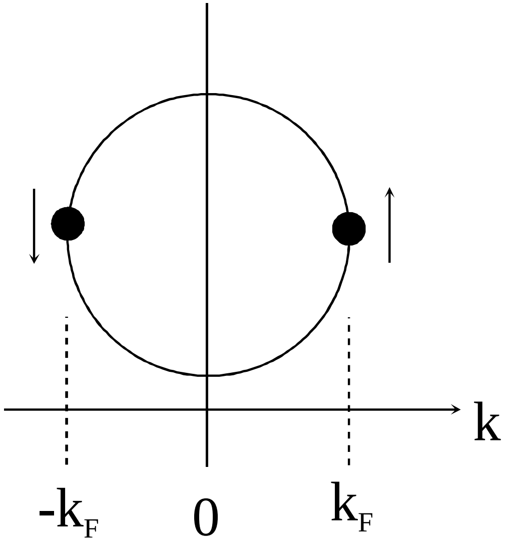
The FFLO state

Cooper pair in conventional superconductor



(-k,k) pairing
$E \approx 2\, E_{Fermi}$

Cooper pair in ferromagnet

↑ electron gains exchange energy E_{ex}

↓ electron looses exchange energy E_{ex}

Center of mass momentum of pair ↓↑ shifts
by amount $Q=E_{ex}/v_{Fermi}$

Analog: ↑↓ shifts by $Q=-E_{ex}/v_{Fermi}$

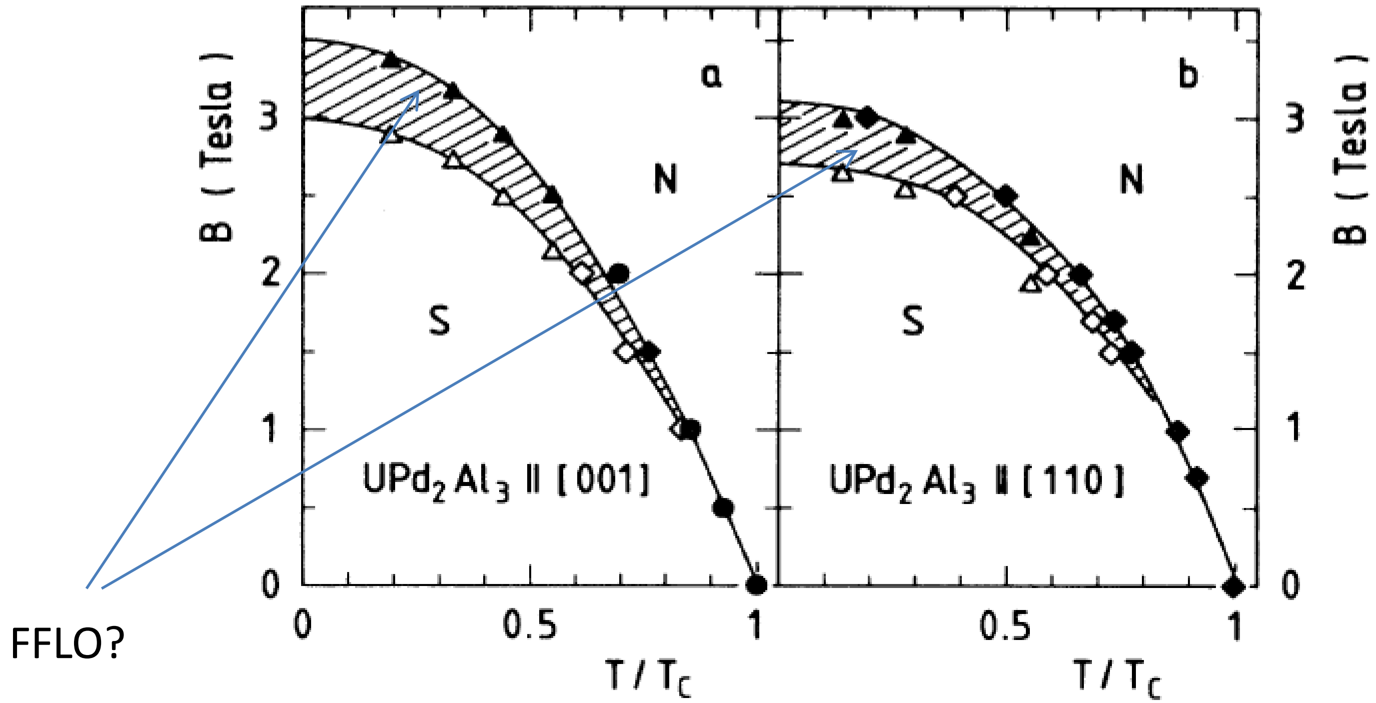
Symmetrize
⇒ *Oscillating* macroscopic wave function

$$\Psi \propto e^{iQz/\hbar} + e^{-iQz/\hbar} \propto \cos Qz/\hbar$$

P. Fulde , R. A. Ferrell, Phys. Rev. 135, A550 (1964).
A. I. Larkin, Yu. N. Ovchinnikov, Zh. Eksp. Teor. Fiz. **47,** 1136 (1964)
[Sov. Phys. JETP **20** (1965) 762]

The FFLO state

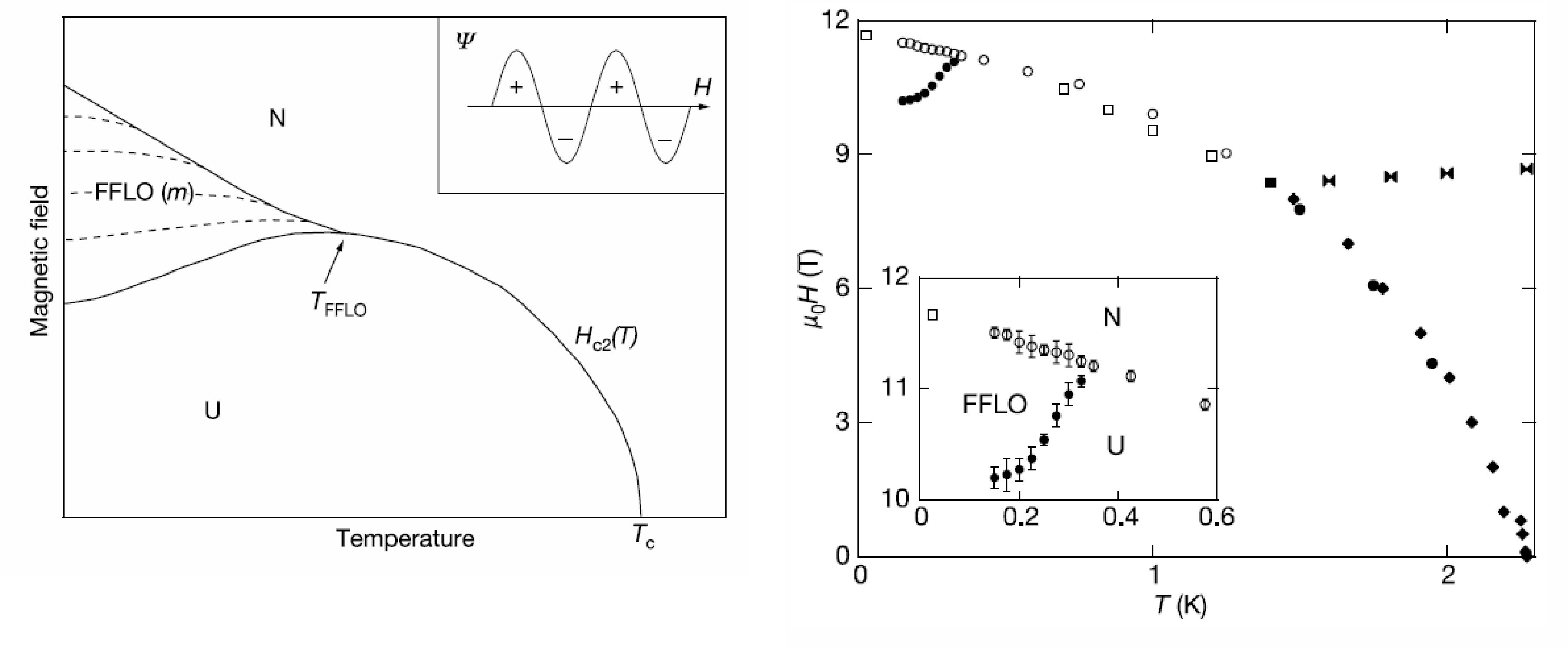
Experimental evidence
(Heavy fermion UPd_2Al_3)
(thermal expansion, magnetostriction measurements)



K.Gloos et al., Phys. Rev. Lett. **70**, 501 (1993)

The FFLO state

Experimental evidence
(Heavy fermion $CeCoIn_5$ in high fields)
(Heat capacitance and magnetization measurements)



H.A. Radovan et al., Nature **425**, 51 (2003)

Other candidate: Organic superconductor κ -BEDT-TTF_2CuNCS_2

Towards more robust effects: Interacting S-F multilayers

„Domain Wall Superconductivity“ and related effects

Idea:

take multidomain-magnet with magnetization perpendicular to surface ($BaFe_{12}O_{19}$)

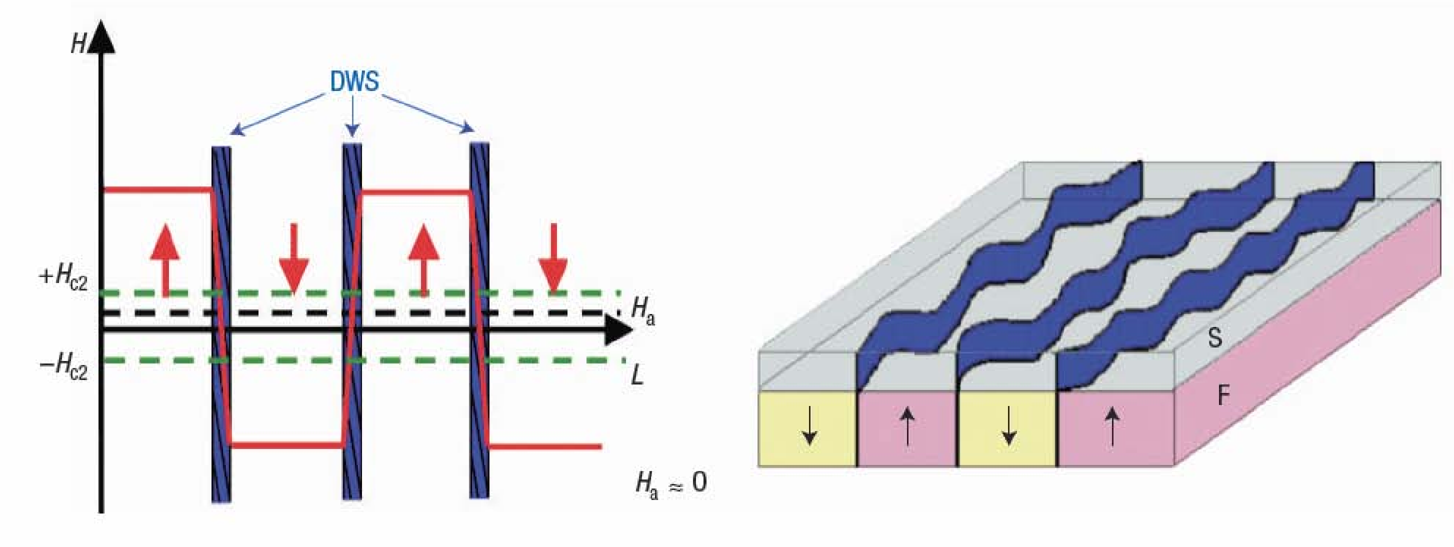
put insulating layer + superconducting layer (Nb) on top

Magnet affects superconductor by stray fields

Sufficiently close to (but below) T_c of bare Nb film:

stray field H_s above domains > H_{c2}, no superconductivity here

But: $H_s < H_{c2}$ above domain walls, filamentary „Domain Wall Superconductivity“

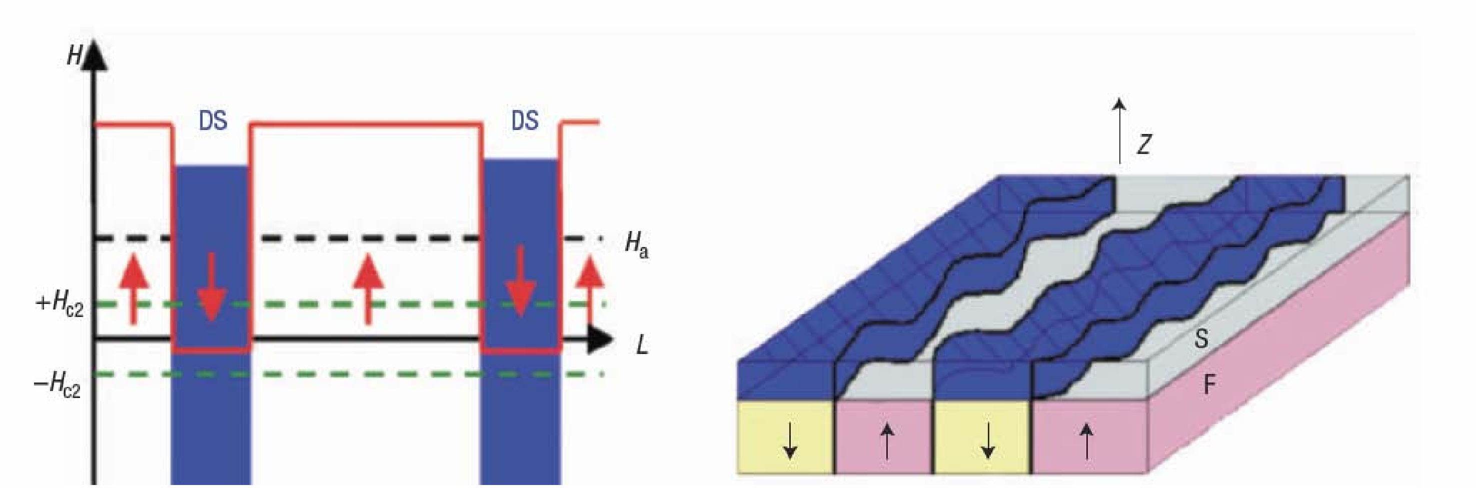


Z. Yang et al., Nature Materials **3**, 793 (2004)

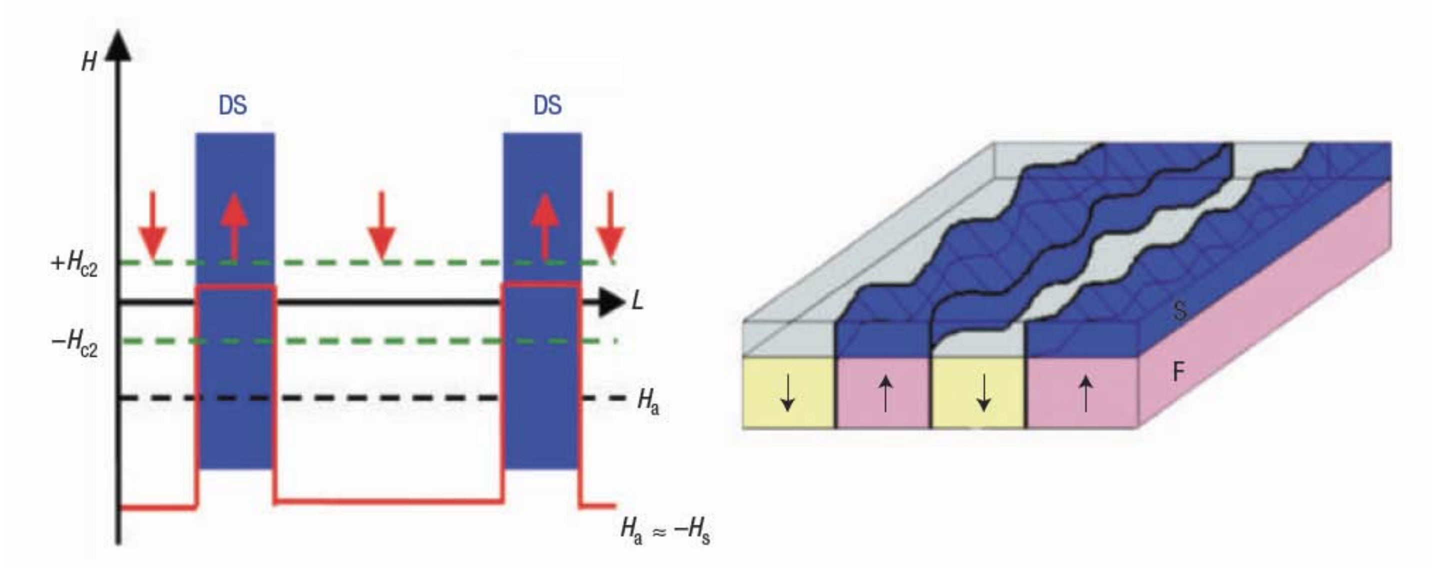
„Domain Wall Superconductivity“ and related effects

Apply perpendicular field H ≈ stray field H_s :
total field H > H_{c2} above „reverse domains“ „ Reverse Domain Superconductivty“

H „up“



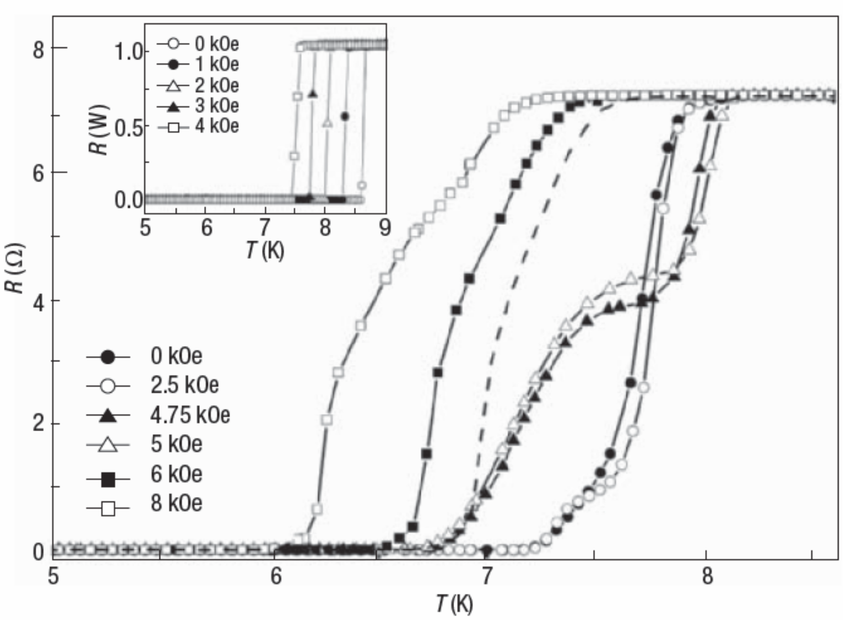
H „down“

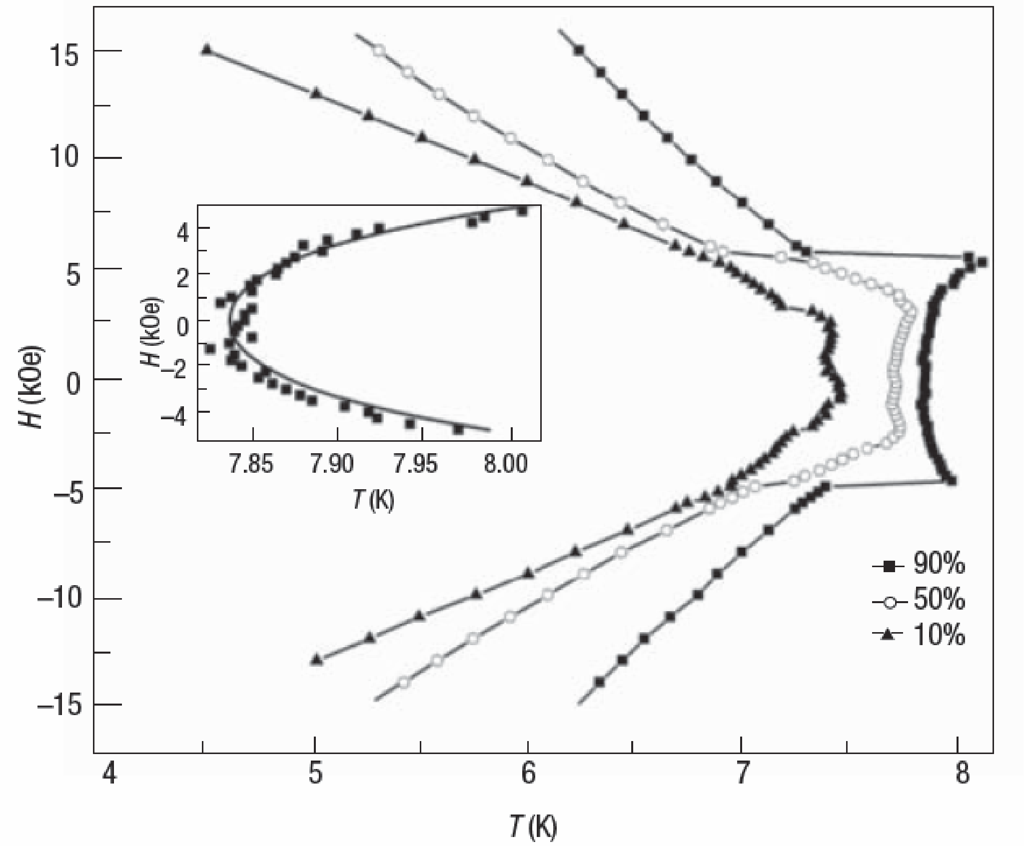


Z. Yang et al., Nature Materials **3**, 793 (2004)

„Domain Wall Superconductivity“ and related effects

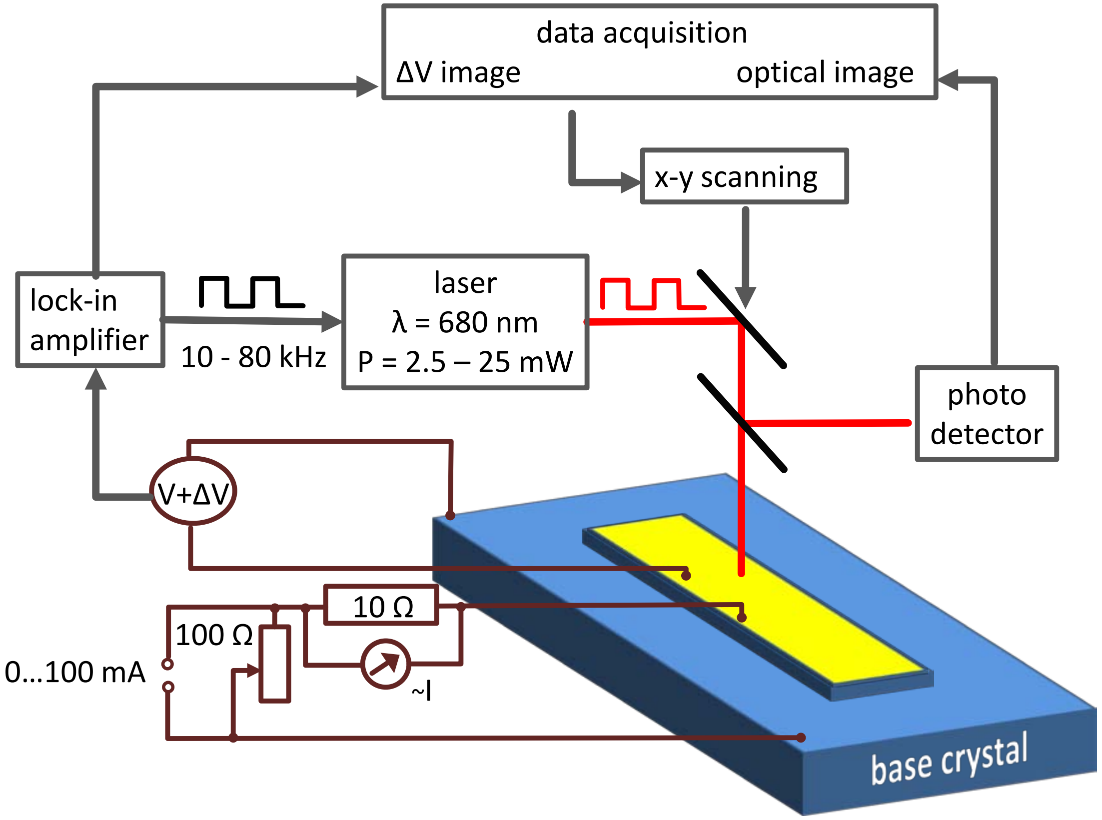
R vs. T and Phase Diagram





Z. Yang et al., Nature Materials **3**, 793 (2004)

Low Temperature Scanning Laser Imaging



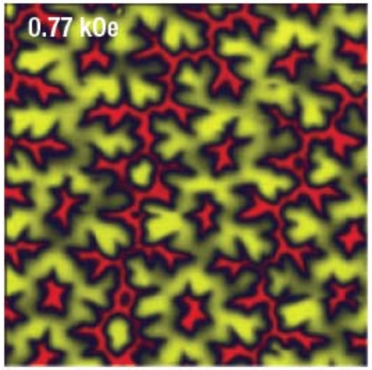
2-5 K temperature rise in laser spot

-> change of j_c, resistivity

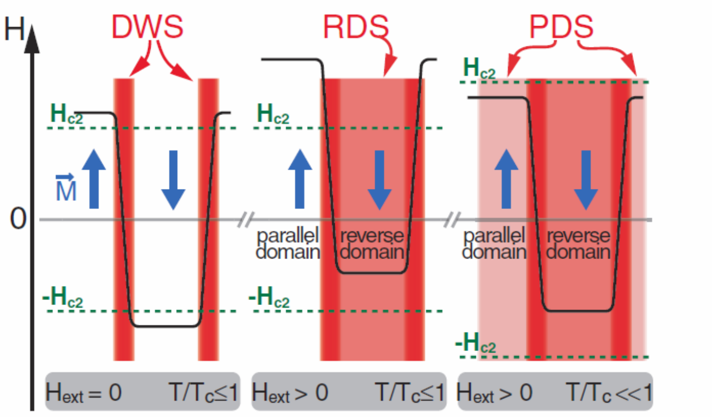
-> change in global voltage

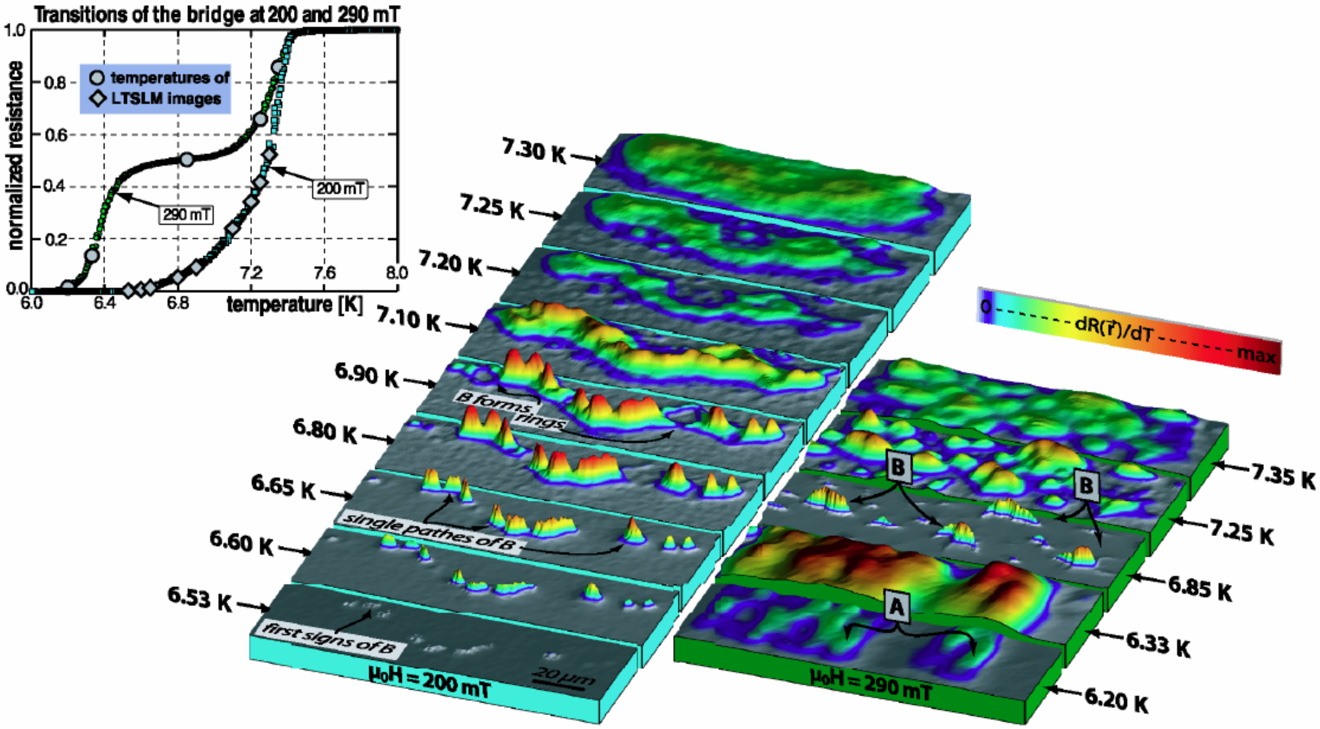
-> contrast for LTSLM image

„Domain Wall Superconductivity“ and related effects



MFM image, 300K

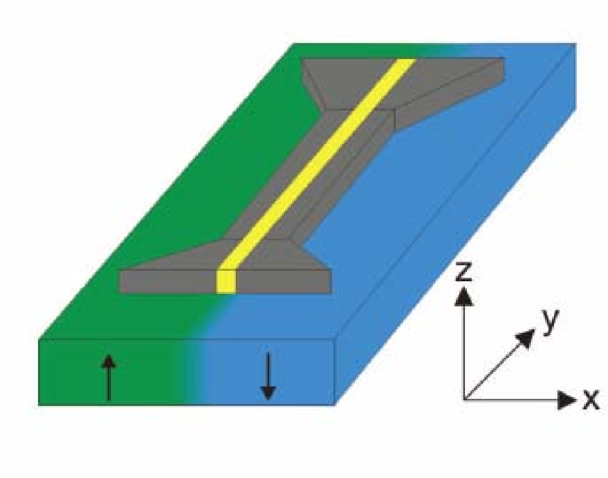


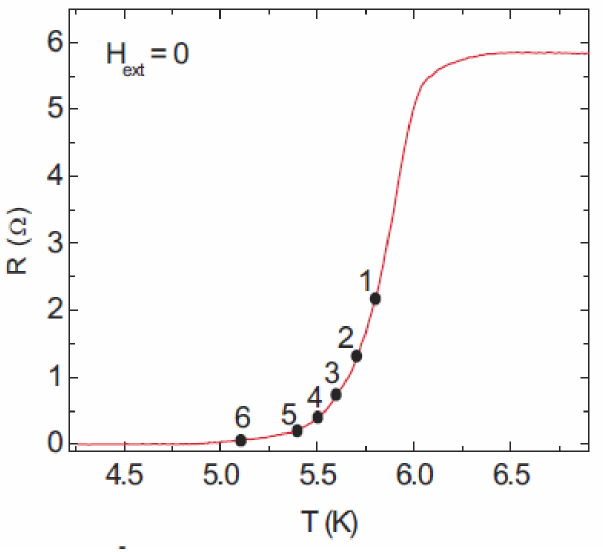


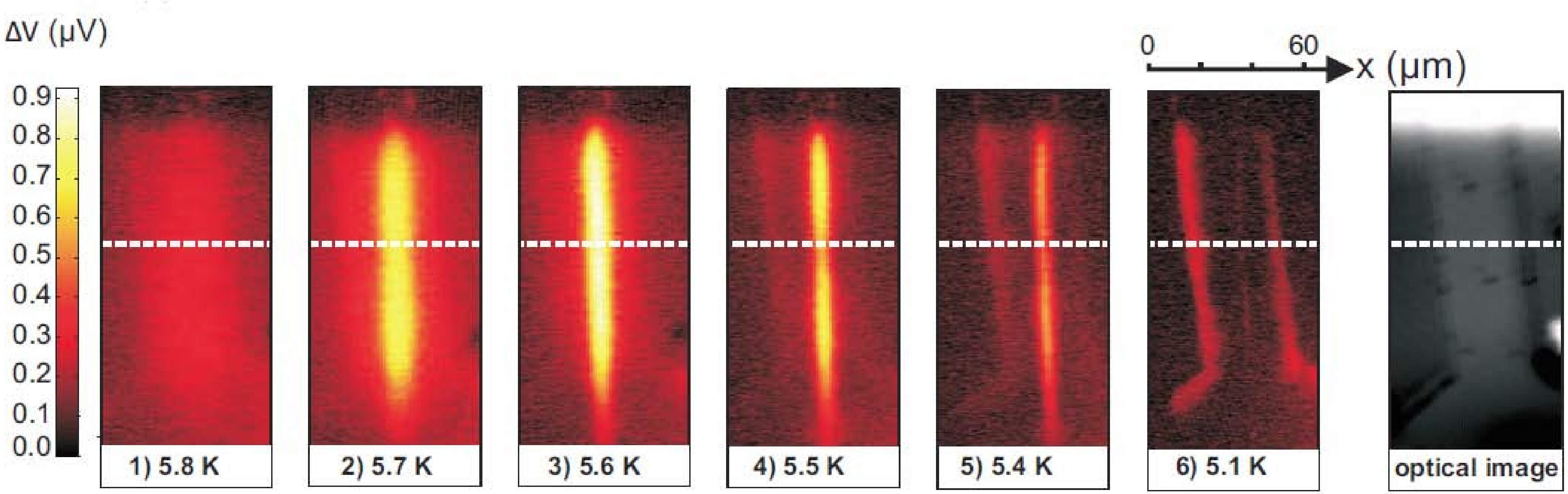
LTSLM data

J. Fritzsche, et al., Phys. Rev. Lett. **96**, 247003 (2006)

„Domain Wall Superconductivity“ and related effects







R. Werner, et al., in preparation (2010)

Transparent S/F interfaces

First: Superconductor/Normal metal interface

- free e^- in both N and S regions
- pair correlations partially remain in N (length scale ξ_N)
- pair correlation in S weakened near NS boundary (length scale ξ_S)

= proximity effect

ξ_N: coherence length in N

ξ_S: (BCS) coherence length in S

$\xi_N \approx \frac{\hbar v_F}{2\pi k_B T}$ in „clean limit“, i. e. mean free path l >> ξ_S

$\xi_N \approx \sqrt{\frac{\hbar v_F l}{6\pi k_B T}} = \sqrt{\frac{\hbar D}{2\pi k_B T}}$ (D: diffusion constant)

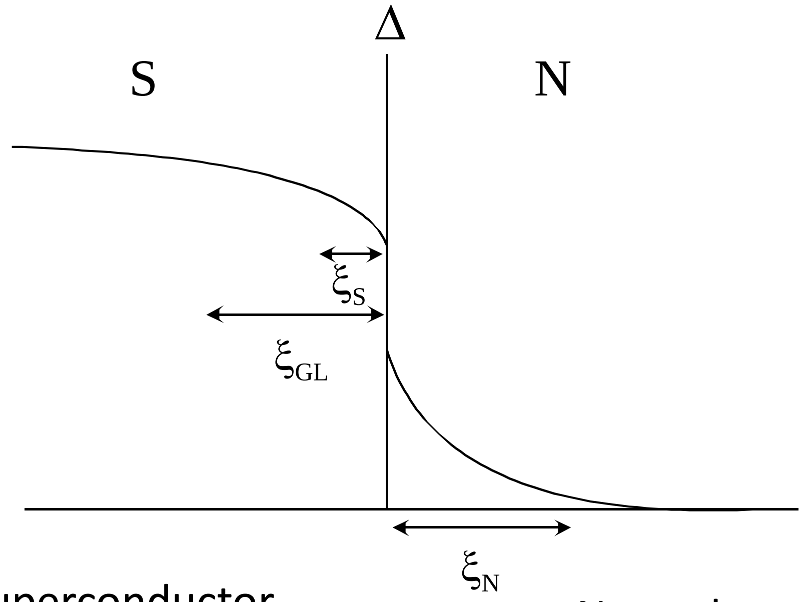
in „dirty limit“, i. e. mean free path l << size of Cooper pair

Note: ξ_N diverges for T -> 0

Transparent S/F interfaces

First: Superconductor/**Normal metal** interface

Superconducting order parameter @ interface: Proximity effect



Superconductor,
suppressed gap

Normal conductor, exp. decay

Often jump @ interface

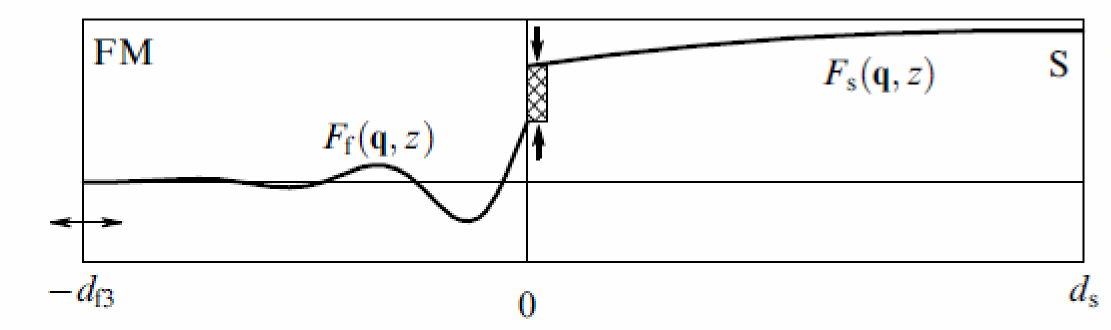
Also T_c suppressed by proximity effect

Transparent S/F interfaces

Now: Superconductor/**Ferromagnet** interface

As for FFLO state: Order parameter oscillates in F-Layer

In addition: exponential decay due to proximity effect



Y. A. Izyumov et al.,
Physics Uspekhi **45**, 109 (2002).

$$\Psi(z) \propto e^{-z/\xi_{m1}} \cos z/\xi_{F2}$$

$$\xi_{F1,2} = \sqrt{\frac{\hbar D}{\sqrt{E_{ex}^2 + (\pi k_B T)^2} \pm \pi k_B T}}$$ in „dirty limit“

Theoretical Calculations: „Usadel equations“ (Quasiclassial Theory)

Typical length scales: ξ_{F1} and ξ_{F2} of order 5-10 nm

Transparent S/F interfaces

Consequence: T_c vs. thickness of F layer oscillates in SF multilayers

Theory:

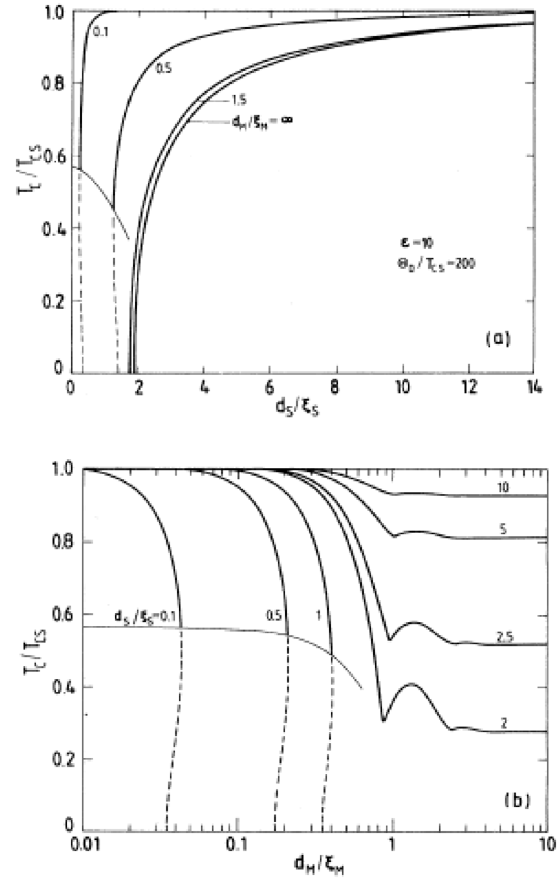


FIG. 1. The reduced transition temperature T_c/T_{cS} as a function of the reduced (a) S film thickness d_S/ξ_S, and (b) M film thickness d_M/ξ_M for $\varepsilon = 10$ and $\Theta_D/T_{cS} = 200$. The tricritical points T^*/T_{cS} (thin curves) are also shown. Dashed curves show solutions that are physicaly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

Z. Radovic et al., Phys. Rev. B **44**, 759 (1991)

Experiment

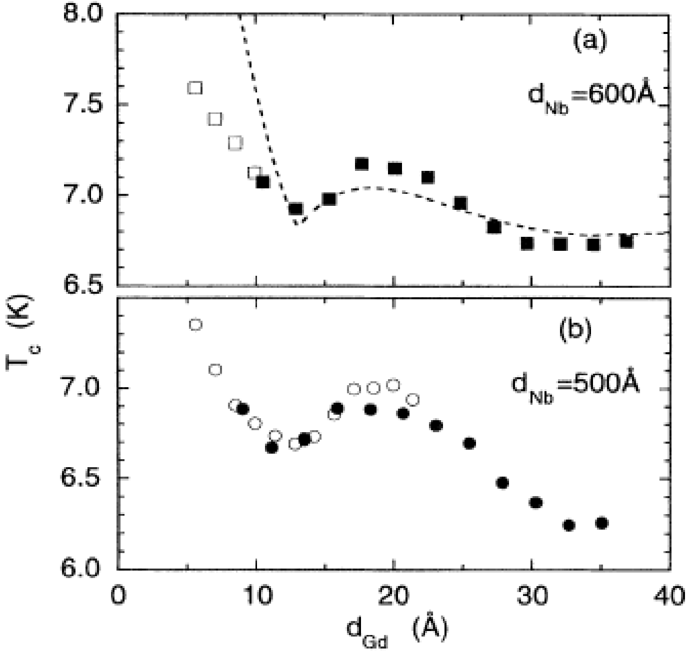


FIG. 4. Superconducting transition temperatures T_c vs d_{Gd} in Nb/Gd multilayers with (a) $d_{Nb} = 600$ Å and (b) 500 Å. Different symbols correspond to different sample series. Dashed line in (a) is a fit by the theory of Ref. [9]. A sputtered Nb film 0.5 μm thick has $T_c = 8.8$ K.

J. S. Jiang et al., Phys. Rev. Lett. **74**, 315 (1995)

But: alternative explanations possible, experiment controversial

More complex structures (trilayers, multilayers)

Why?

Trilayers:

S-F-S: Josephson junction
…but with very low resistance

S-I-F-S, S-I-F-N-S: improved Josephson junctions

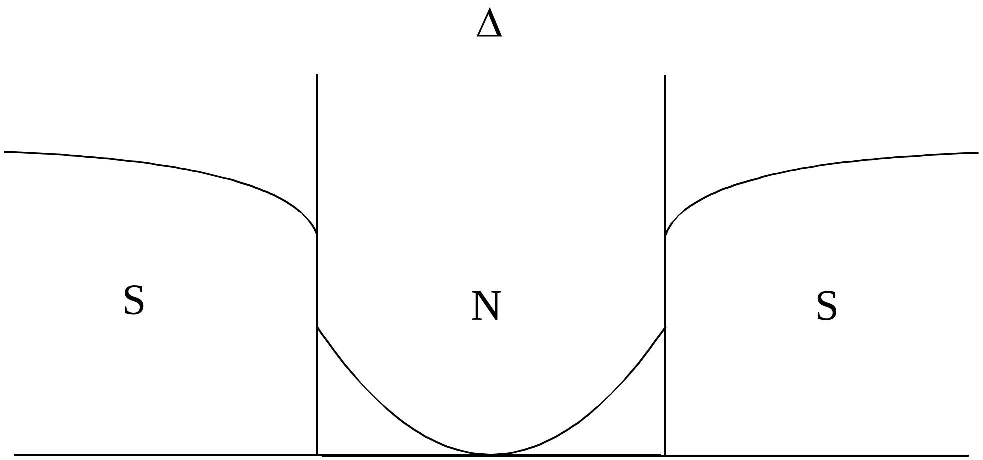
F-S-F: magnetoresistive devices, spin valve structures

Multilayers (…..S-F-S-F-S-……,… S-I-F-I-S-I-F-I-S….)

Superconducting and/or magnetic effects become more pronounced, partially new effects

Superconductor/Normal metal/Superconductor junctions

Order parameter:



System acts as Josephson junction

Supercurrent across N layer: $I_s = I_c \sin(\varphi_2 - \varphi_1)$

φ_2, φ_1 : Phases of order parameter in S layers 2 and 1

Superconductor/Ferromagnetic metal /Superconductor junctions

-Order parameter oscillates in F layer

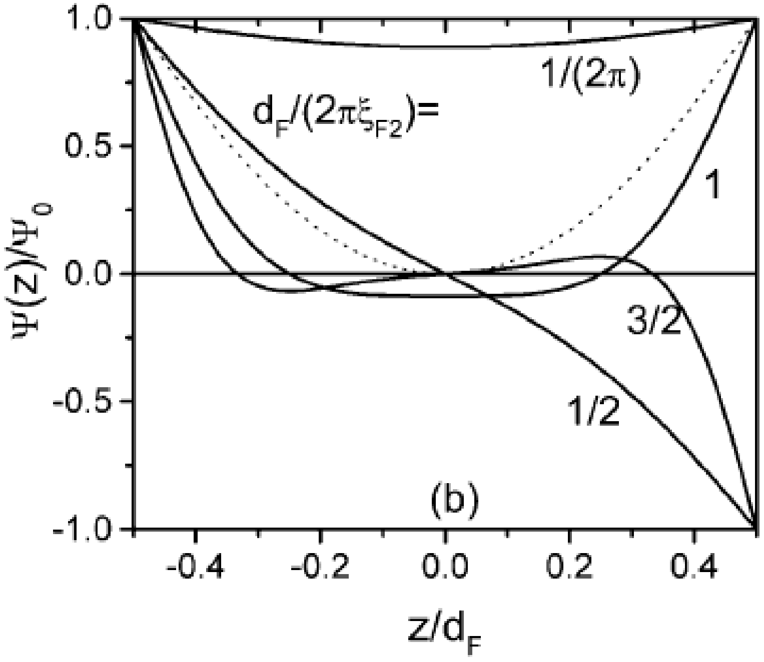
-has same or different sign in the S layers depending on F layer thickness

- if sign change :

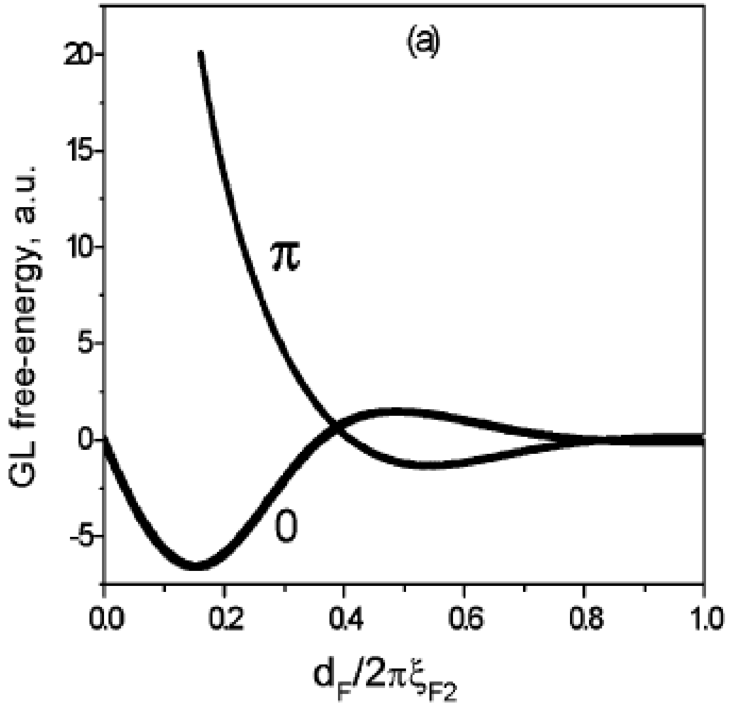
$$I_s = I_c \sin(\varphi_2 - \varphi_1 + \pi) = -I_c \sin(\varphi_2 - \varphi_1)$$

π Josephson junction

Order parameter



Free energy

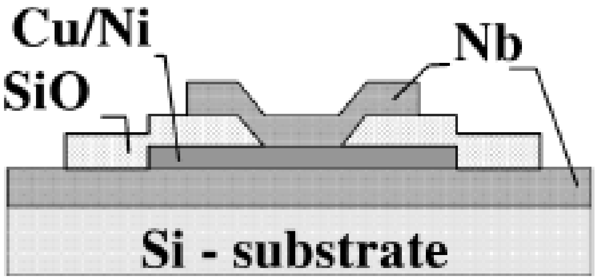


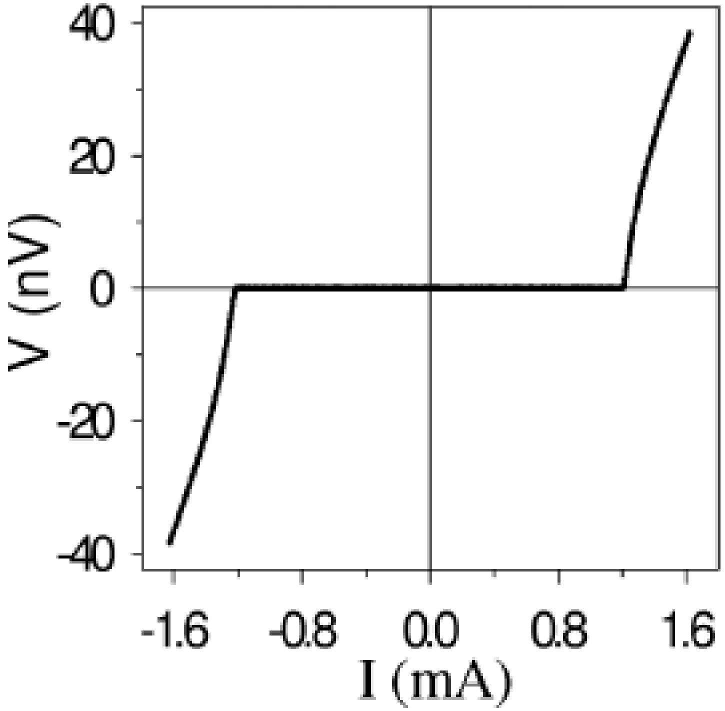
V. V. Ryazanov et al., Phys. Rev. Lett. **86**, 2427 (2001)

π Josephson junctions

First realization: Nb – $Cu_{0.5}Ni_{0.5}$ – Nb

Weak ferromagnet





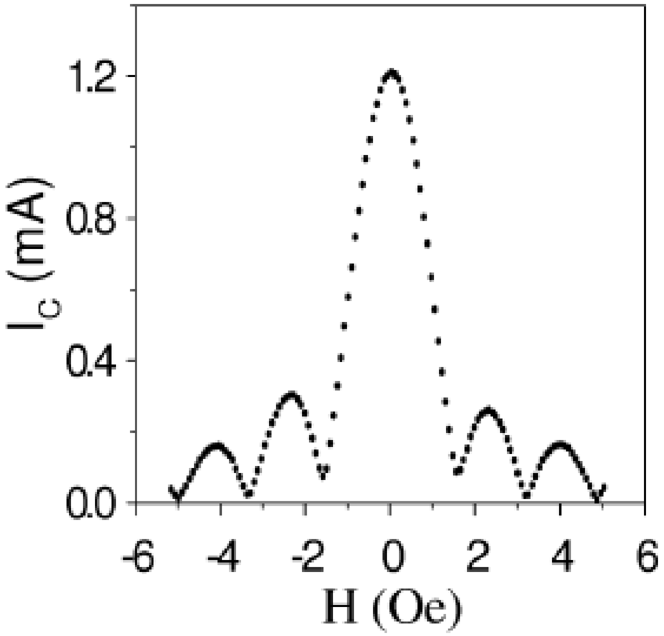
V. V. Ryazanov et al., Phys. Rev. Lett. **86**, 2427 (2001)

π Josephson junctions

What to measure?

Critical current vs magnetic field, (Fraunhofer pattern):

observes $|I_c|$ only, cannot distinguish 0 und π



V. V. Ryazanov et al., Phys. Rev. Lett. **86**, 2427 (2001)

π Josephson junctions

What to measure?

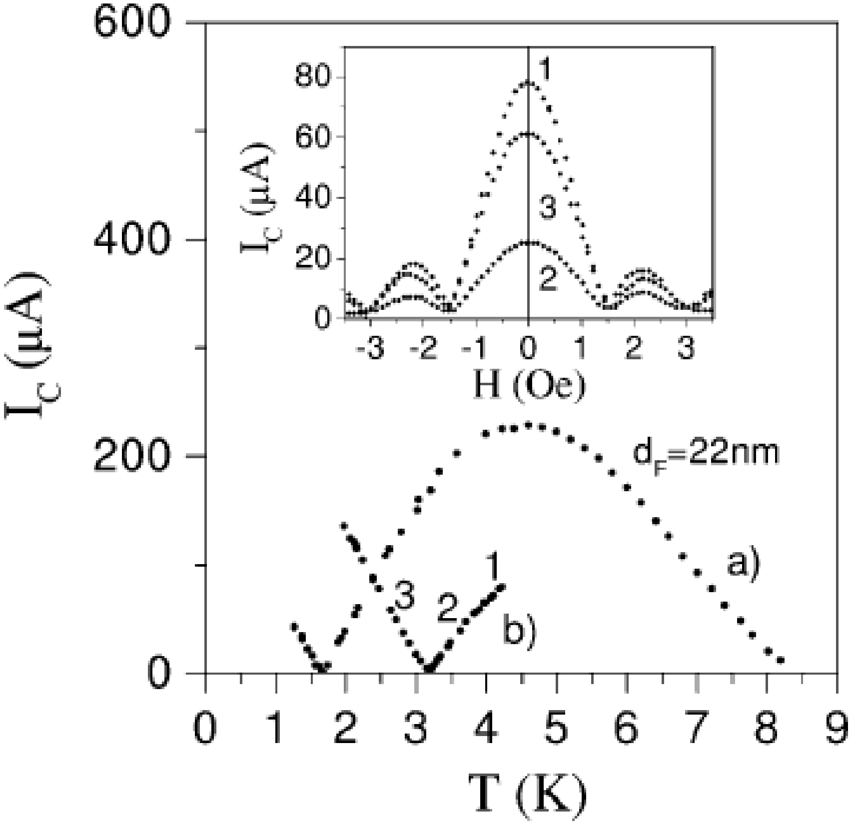
However: Oscillation length ξ_{F2} and thus ratio d_F/ξ_{F2} is temperature dependent

$$\xi_{F2} = \sqrt{\frac{\hbar D}{\sqrt{E_{ex}^2 + (\pi k_B T)^2} - \pi k_B T}}$$

⇒

Transition between 0 junction and
0 and π junction as function of temperature
I_c vs. T has a zero

⇒ Good indication for π junction, however no proof!



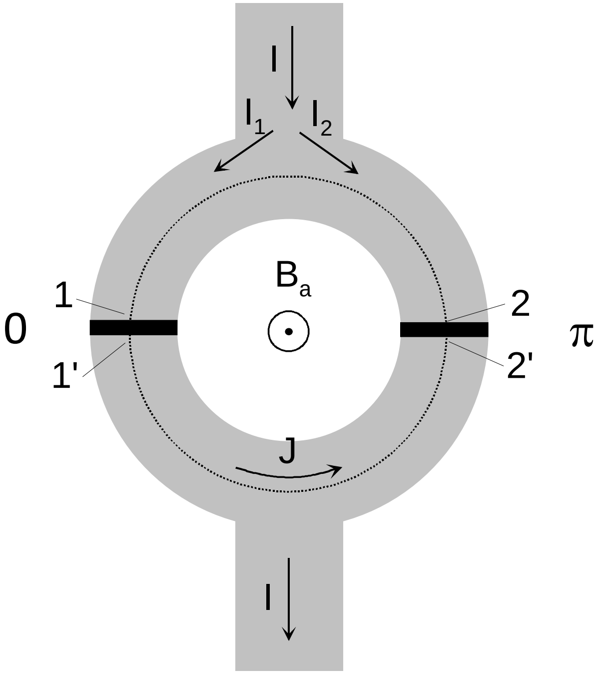
V. V. Ryazanov et al., Phys. Rev. Lett. **86**, 2427 (2001)

π Josephson junctions

What to measure?

0-π-dc SQUID:

Assume $LI_c \ll \Phi_0/2\pi$



$$I = I_c \sin\gamma_1 + I_c \sin(\gamma_2 + \pi) =$$

$$= I_c[\sin\gamma_1 + \sin(\gamma_1 + 2\pi\frac{\Phi}{\Phi_0} + \pi)] =$$

$$= I_c[\sin\gamma_1 + \sin(\gamma_1 + 2\pi(\frac{\Phi}{\Phi_0} + \frac{1}{2})]$$

Choose γ_1 to maximize [….] $\Rightarrow$

$$I_c(\Phi) = 2I_c\,|\cos\pi\Phi/\Phi_0\,|$$ for 0-0 or π-π

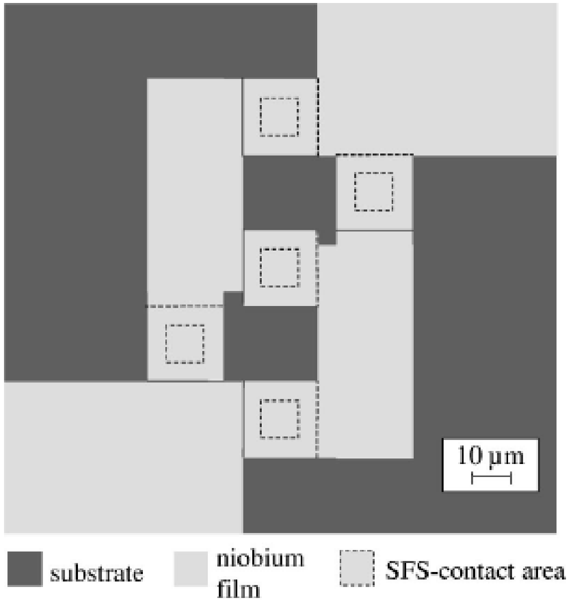
$$I_c(\Phi) = 2I_c\,|\cos\pi(\Phi/\Phi_0 + 1/2)\,|$$ for π-0 or 0-π

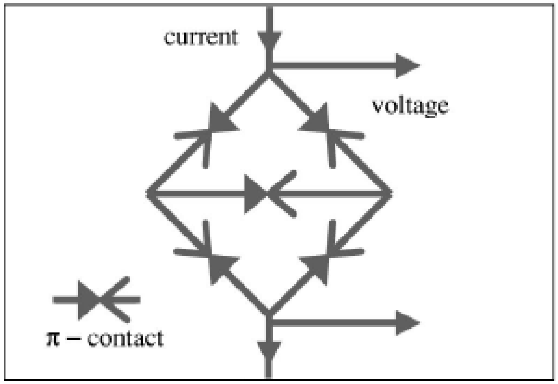
π Josephson junctions

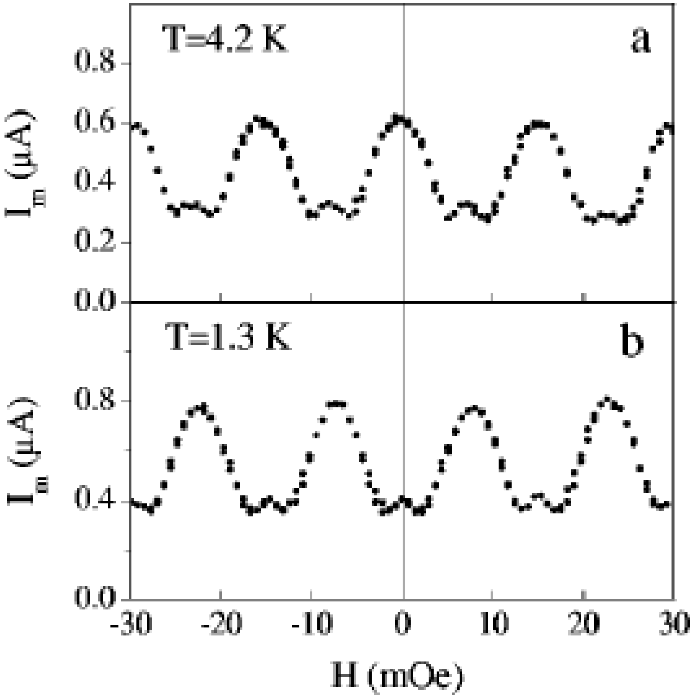
What to measure?

Actual interferometer: **5 junction**

(works similar as 0-π dc SQUID)







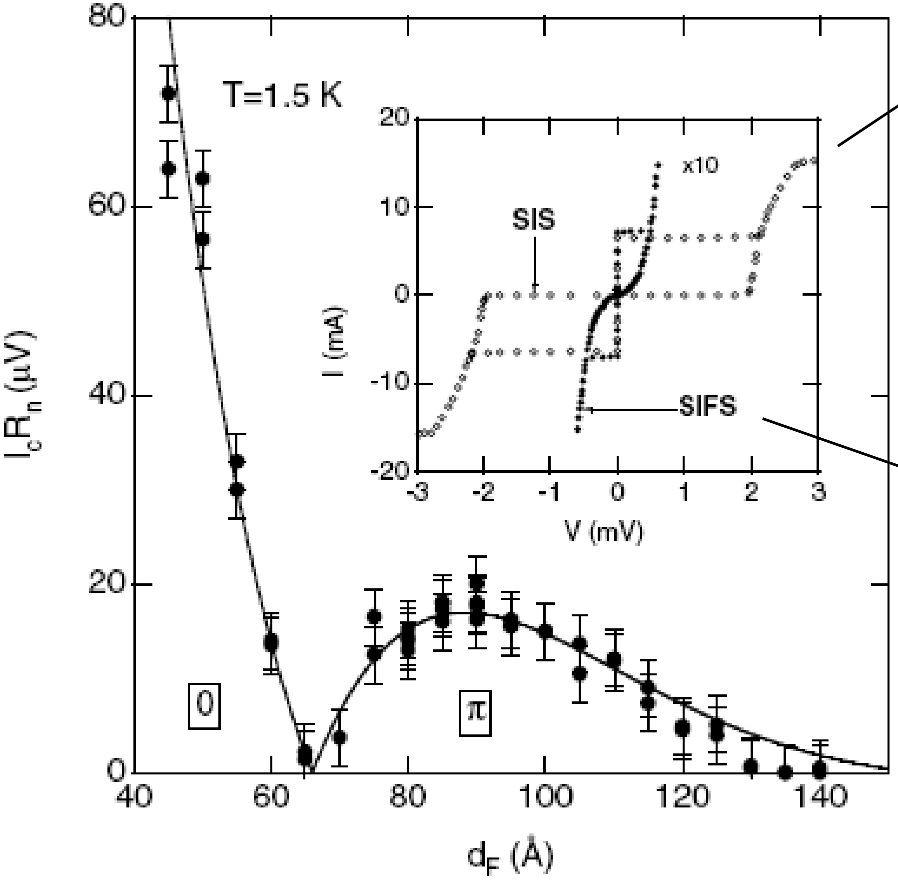
V. V. Ryazanov et al., Phys. Rev B **65**, 020501 (2001)

π Josephson junctions

Nb/Al/AlO$_x$/PdNi/Nb

S S (proximity) I F S

Effect of F layer thickness



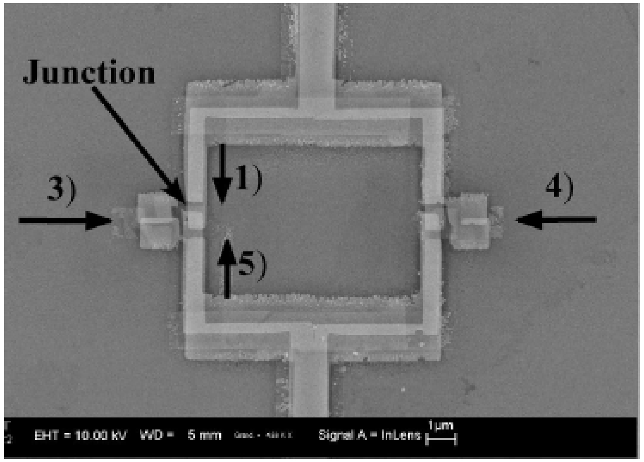
without PdNi

with PdNi

T. Kontos et al.,
Phys. Rev. Lett. **89**, 137007 (2002)

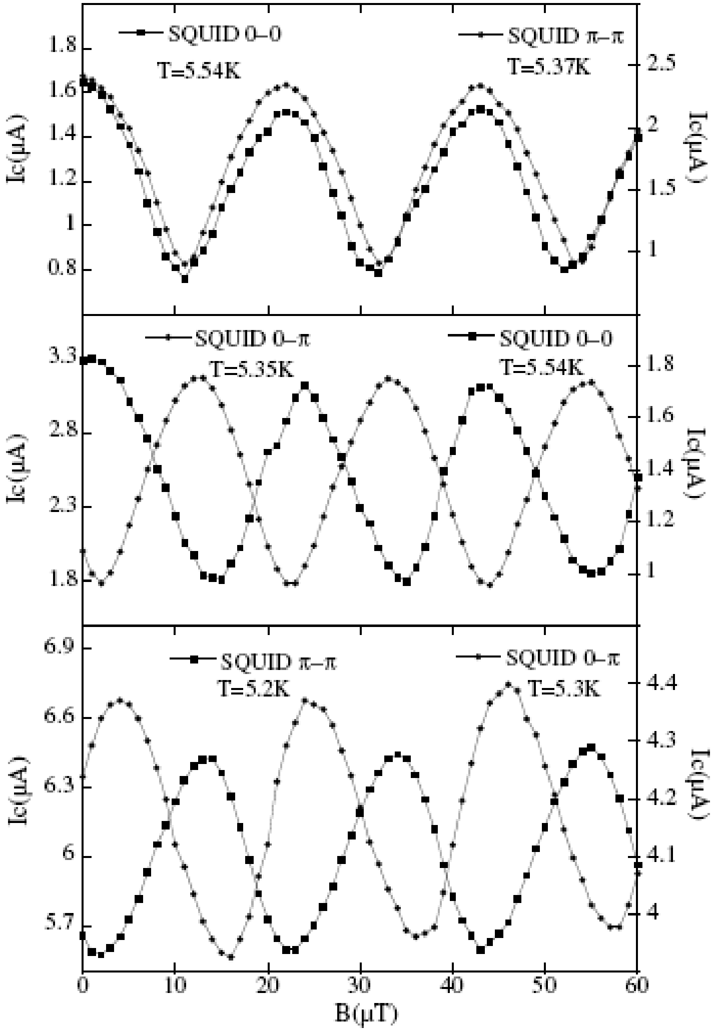
π Josephson junctions

Nb/Al/AlO$_x$/PdNi/Nb junctions – realization of 0-π ring



Various thicknesses $d_{F1,2}$
of the two junctions

⇒ 0-π, ππ, 00 possible

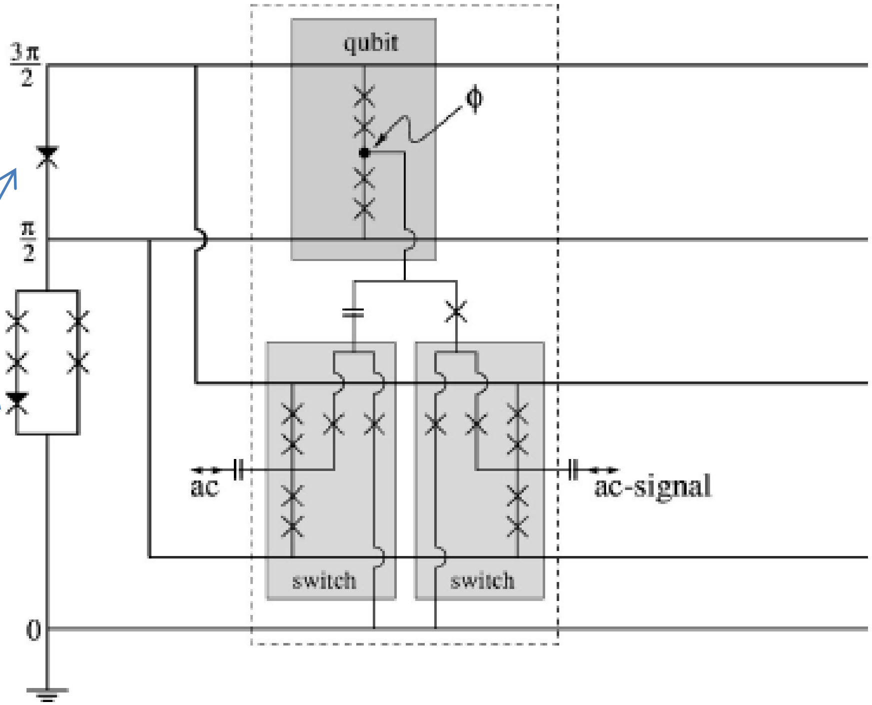


W. Guichard et al., Phys. Rev. Lett. **90**, 167001 (2003)

π junctions and qubits

π junctions as phase shifters; simplify circuits, less bias lines

Example: Proposal of „quiet“ 5 junction phase qubit



π junctions

FIG. 8. In a quantum computer the superconducting phase qubits can be operated with three phase buses providing the phases 0, $\pi/2$, and $3\pi/2$. The π junctions needed in producing the appropriate phase reservoirs are large classical junctions. Only the qubit requires nanoengineered mesoscopic junctions performing quantum dynamics.

G. Blatter, V. B. Geshkenbein,
L. B. Ioffe,
Phys. Rev. B **63**, 174511

π junctions and qubits

Experimental demonstration:

A.K. Feofanov et al., Nature Physics **6**, 593 (2010)

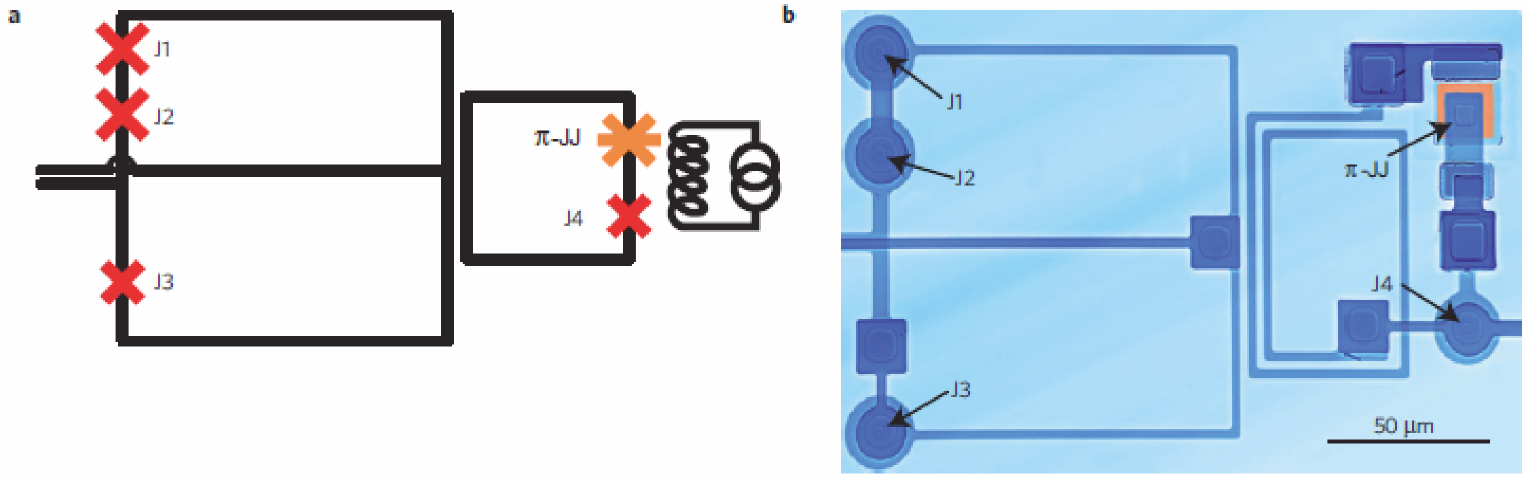


Figure 3 | Self-biased phase qubit. a, Schematic of a phase qubit circuit used to test the decoherence properties of the π-junction. The qubit is realized by the central loop with embedded conventional and π-Josephson junctions. The larger loop to its left is a d.c.-SQUID for qubit readout. To the right of the qubit is a weakly coupled flux bias coil. **b**, Scanning electron microscope picture of the realized phase qubit employing a π-junction in the qubit loop. The flux bias coil is not shown.

π junctions and qubits

Experimental demonstration:

A.K. Feofanov et al., Nature Physics **6**, 593 (2010)

Rabi oscillations

Self biased phase qubit

Conventional phase qubit, on same chip

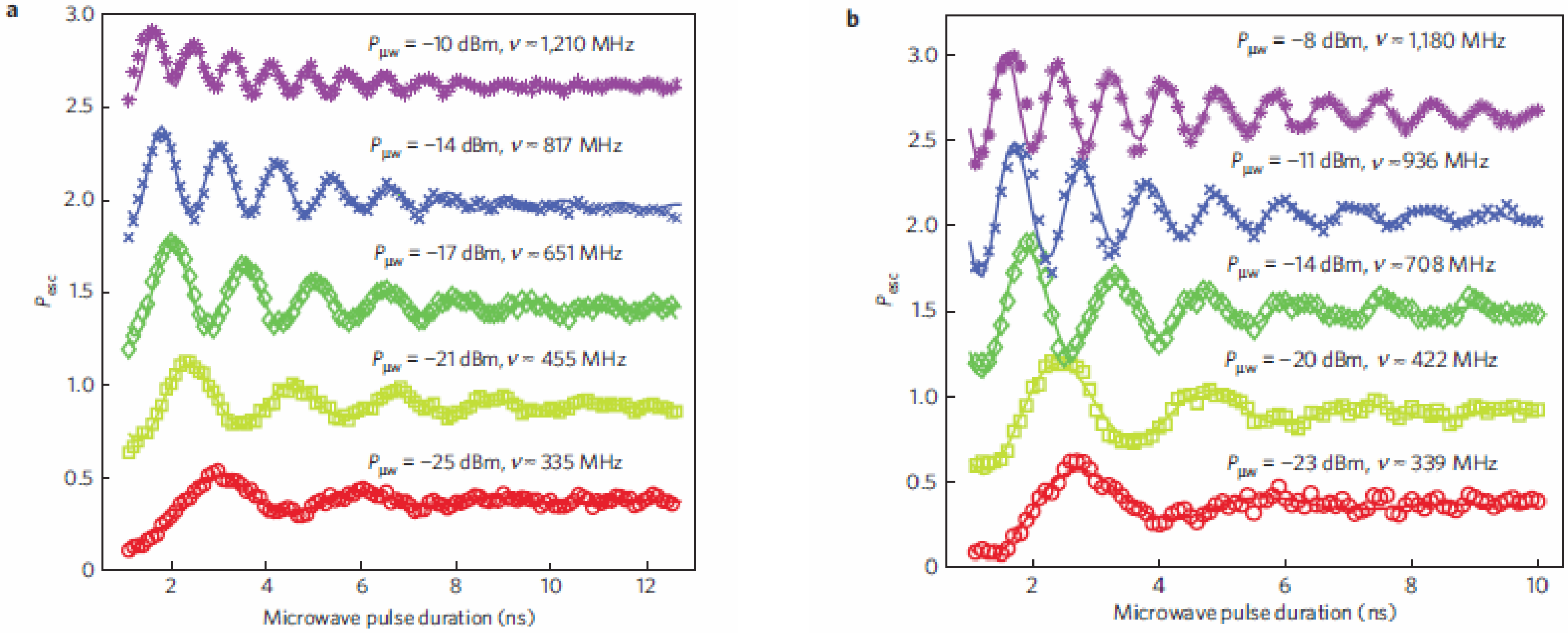


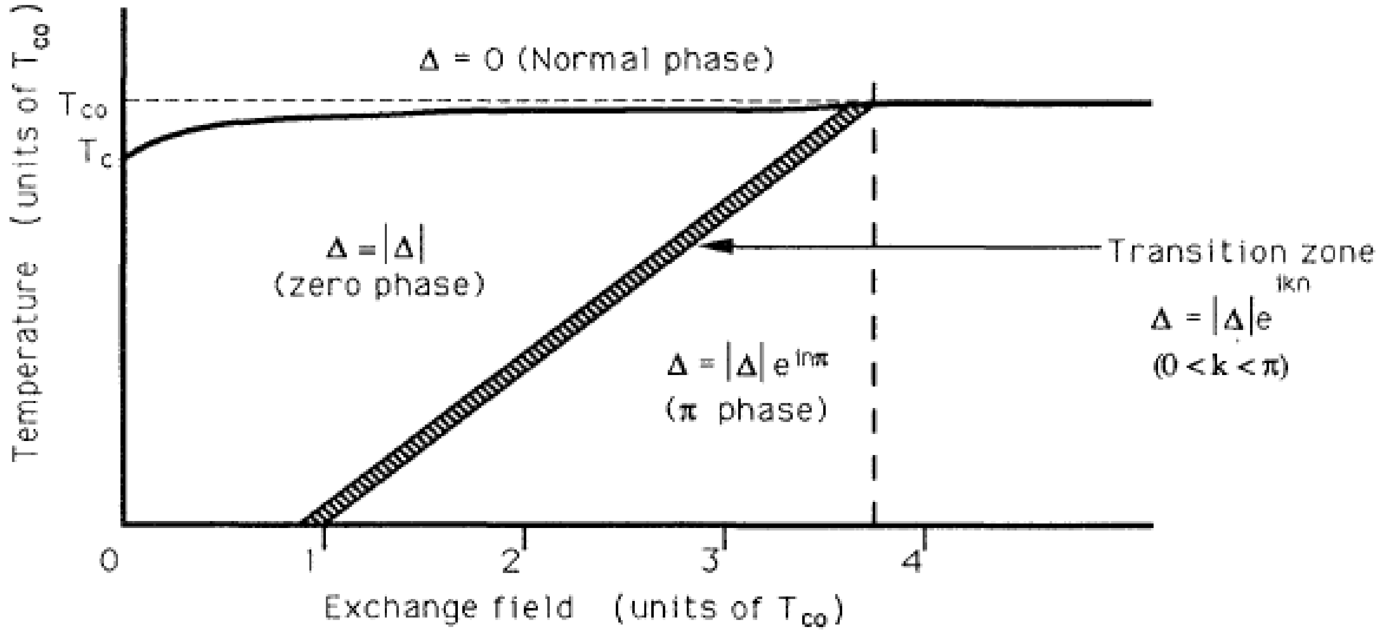
Figure 4 | Rabi oscillations between the ground and the excited qubit states resulted from resonant microwave driving. a,b, Rabi oscillations observed in the phase qubit with an embedded π-junction (**a**) and a conventional phase qubit made on the same wafer as a reference (**b**). Each data set was taken using the indicated microwave power as delivered by the generator, giving rise to a change in the coherent oscillation frequency as expected for Rabi oscillation.

More details on π Junctions: -> Tutorial Edward Goldobin

π Phases in SFSF.. multilayers

0 phase: same sign of order parameter in each layer

π phase: order parameter changes sign between adjacent layers



A. V. Andreev et al., Phys. Rev. B **43**, 10124 (1991)

π Phases in SFSF.. multilayers

Special Interest:

New combined S-F quantum states,
new devices

Example: Interplay between
-superconducting 0 and π phases
-FM/AM arrrangement of magnetization in F layers

--> 4 logic states

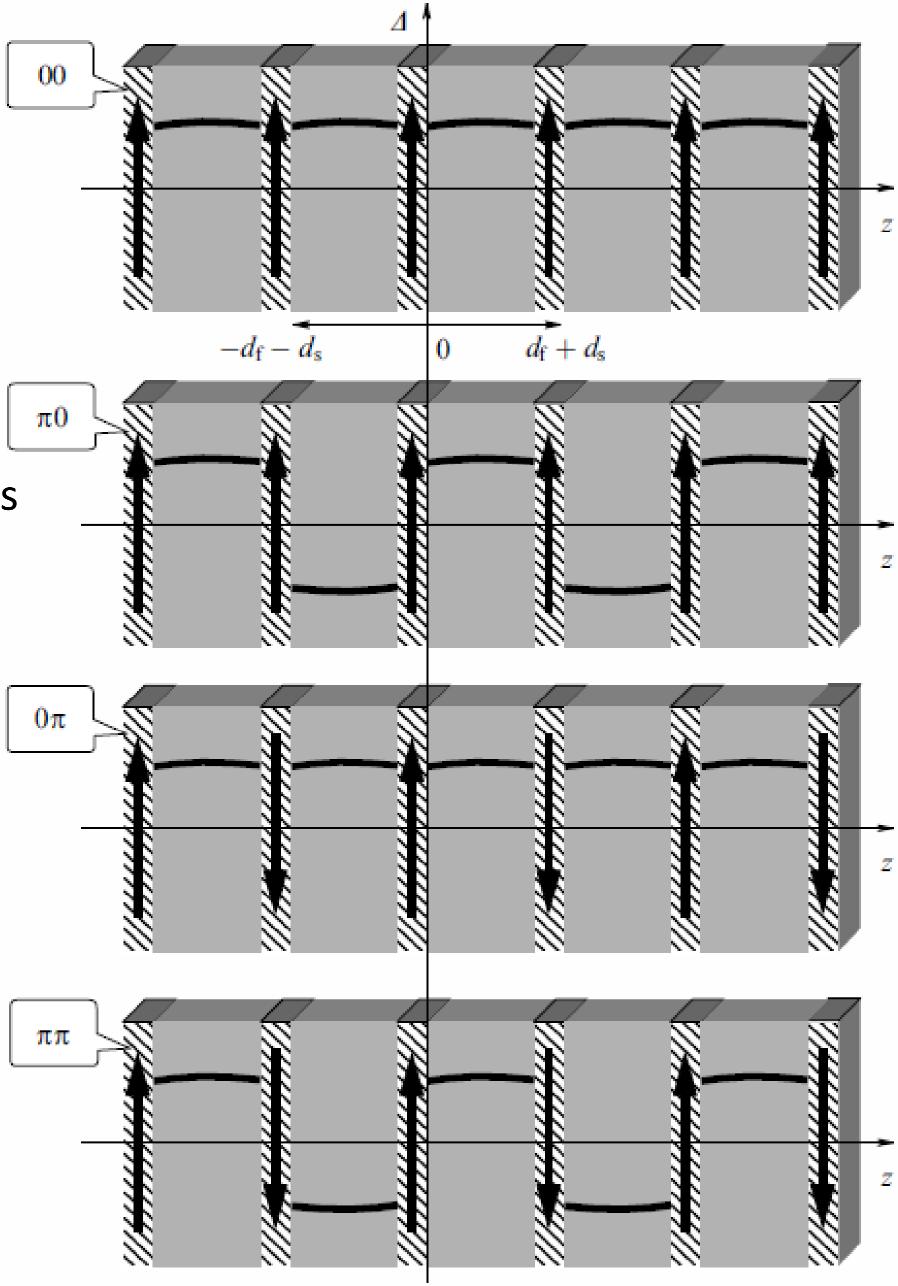


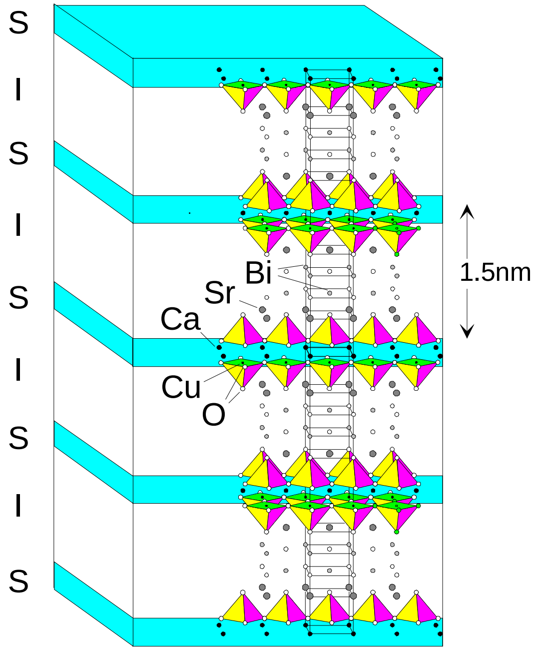
Figure 6. Four possible states of the FM/S superlattice. Horizontal arrows show the unit cell of the superlattice. Solid lines show the behavior of the superconducting order parameter (OP) $\Delta(z)$ in the S layers. In the FM layers, thick solid arrows show the direction of magnetizations, which plays the role of the magnetic OP.

Review: Y. A. Izyumov et al.,
Physics Uspekhi **45**, 109 (2002).

π Phases in SFSF.. multilayers

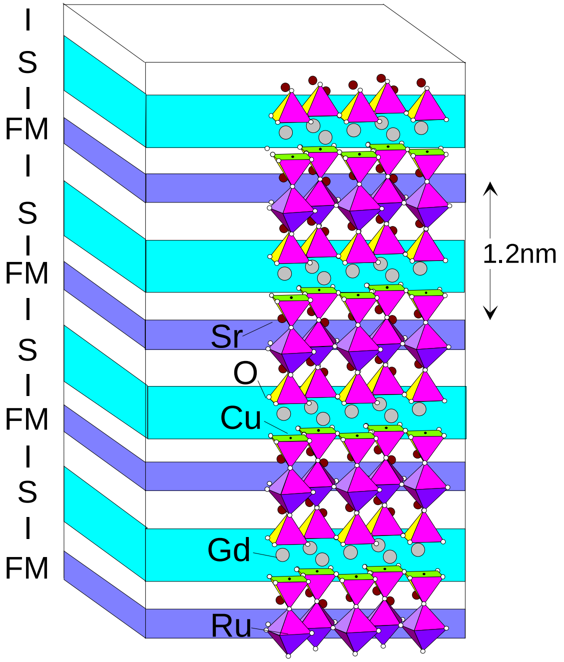
Candidate: Ruthenocuprate $RuSr_2GdCu_2O_8$

$T_c \approx 90K$



$Bi_2Sr_2CaCu_2O_8$

$T_c \approx 55K$



$RuSr_2GdCu_2O_8$

Cuprate $Bi_2Sr_2CaCu_2O_8$:
Natural SISIS…Multilayer;
Josephson effect between CuO_2 layers

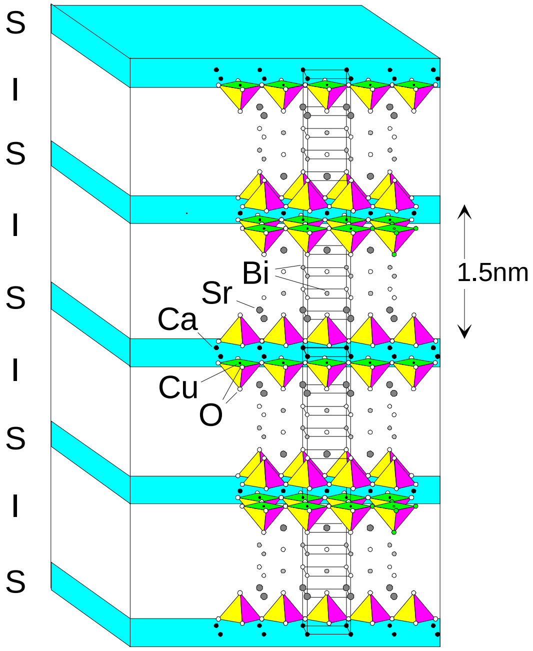
R. Kleiner et al., Phys.Rev. Lett. **68** 2394(1992)

$RuSr_2GdCu_2O_8$:
Natural SIFISIF…-Multilayer
π-Phases between CuO_2 layers?
Josephson effect between CuO_2 layers?

π Phases in SFSF.. multilayers

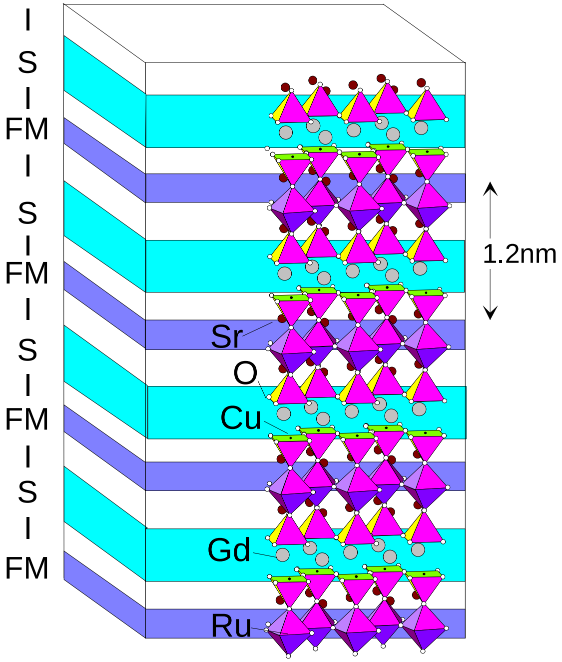
Candidate: Ruthenocuprate $RuSr_2GdCu_2O_8$

$T_c \approx 90K$



$Bi_2Sr_2CaCu_2O_8$

$T_c \approx 55K$



$RuSr_2GdCu_2O_8$

$RuSr_2GdCu_2O_8$, Experiment: Natural SIFISIF… Structure: **yes**

Josephson effect between CuO_2 layers: **yes**

π-Phases between CuO_2 layers: **no evidence!**

T. Nachtrab et al., Phys. Rev. Lett. **92,** 11700 (2004); T. Nachtrab et al., Comptes Rendus Physique **7**, 68 (2006).

π Phases in SFSF.. multilayers

$YBa_2Cu_3O_7$/ $La_{2/3}Ca_{1/3}MnO_3$

High-T_c superconductor Colossal Magnetoresistance

Strongly correlated electrons in both cases
-> new + unexpected physics?

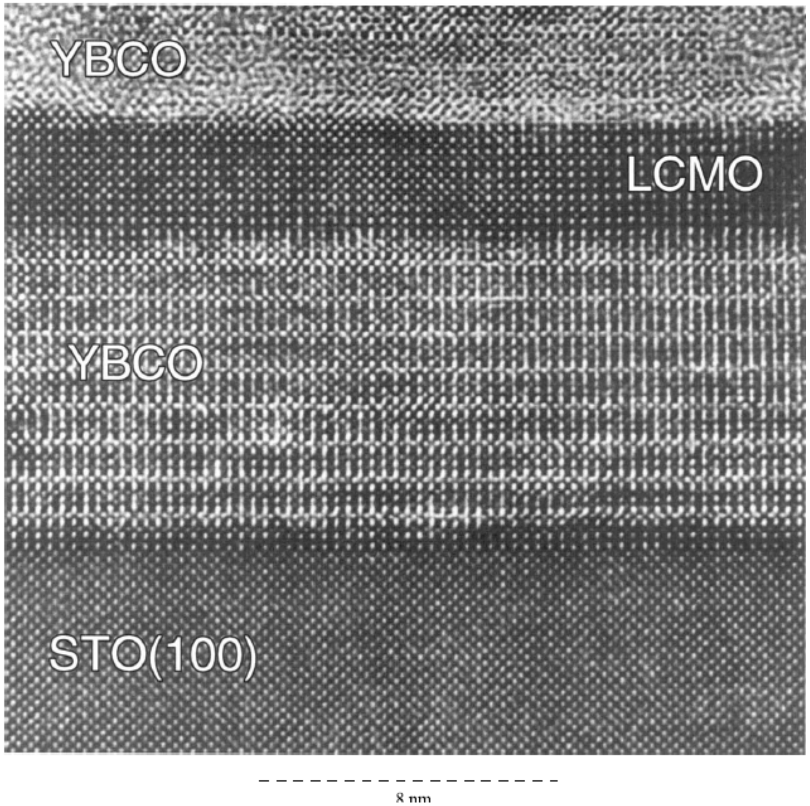


Fig. 1. High resolution cross-sectional TEM of a YBCO/LCMO [8 nm/4 nm]$_{20}$ SL.

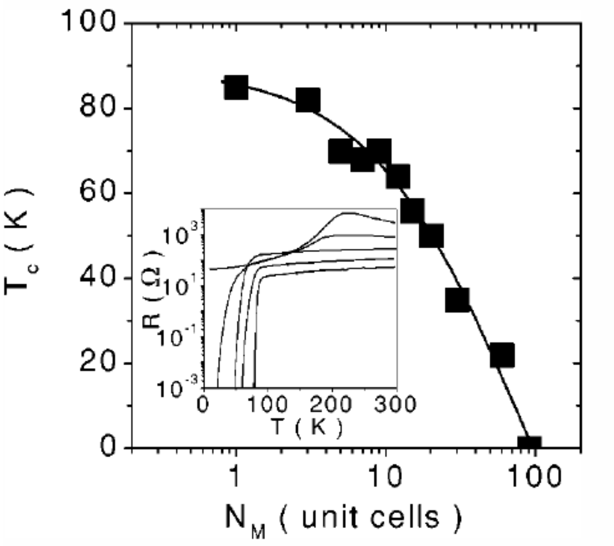
H.-U. Habermeier et al. / Physica C 364–365 (2001) 298–304

SFSF.. multilayers

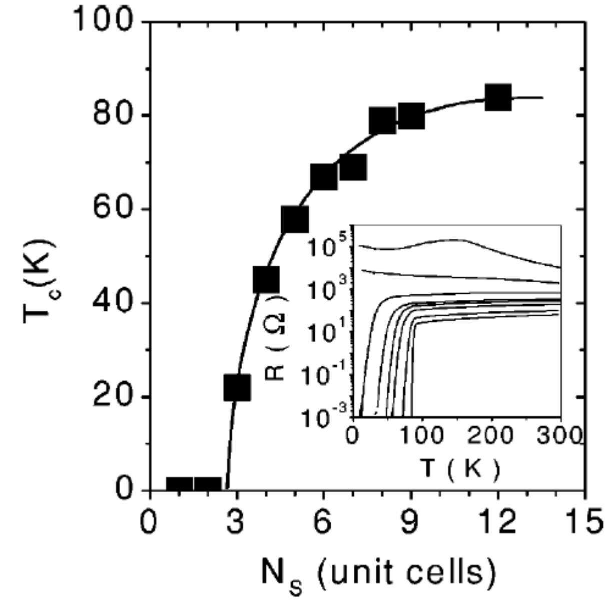
$YBa_2Cu_3O_7/ La_{2/3}Ca_{1/3}MnO_3$

Proximity induced supression of superconductivity

T_c vs LCMO thickness; YBCO: 5 unit cells



T_c vs YBCO thickness ;LCMO: 5 unit cells



Z. Sefriui et al., Phys. Rev. B **67**, 214511 (2003).

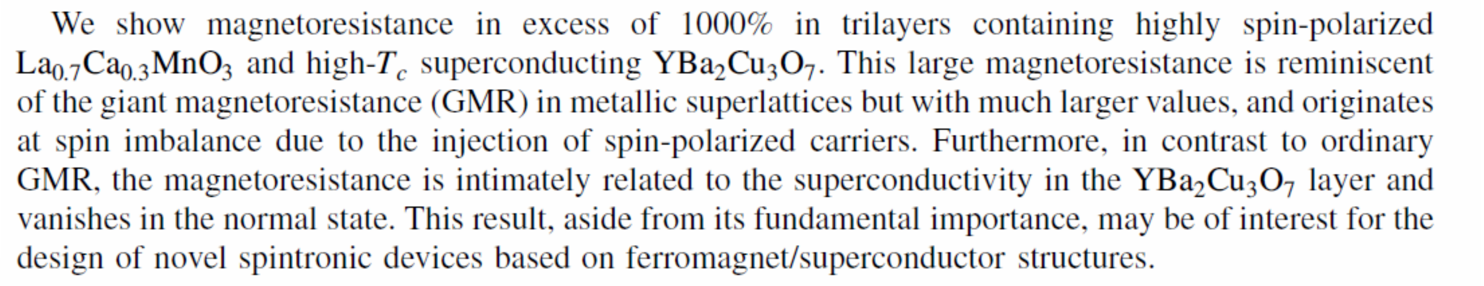
Proximity induced metal to isulator transition in LCMO/YBCO/LCMO

T. Holden et al., Phys. Rev. B **69**, 064505 (2004)

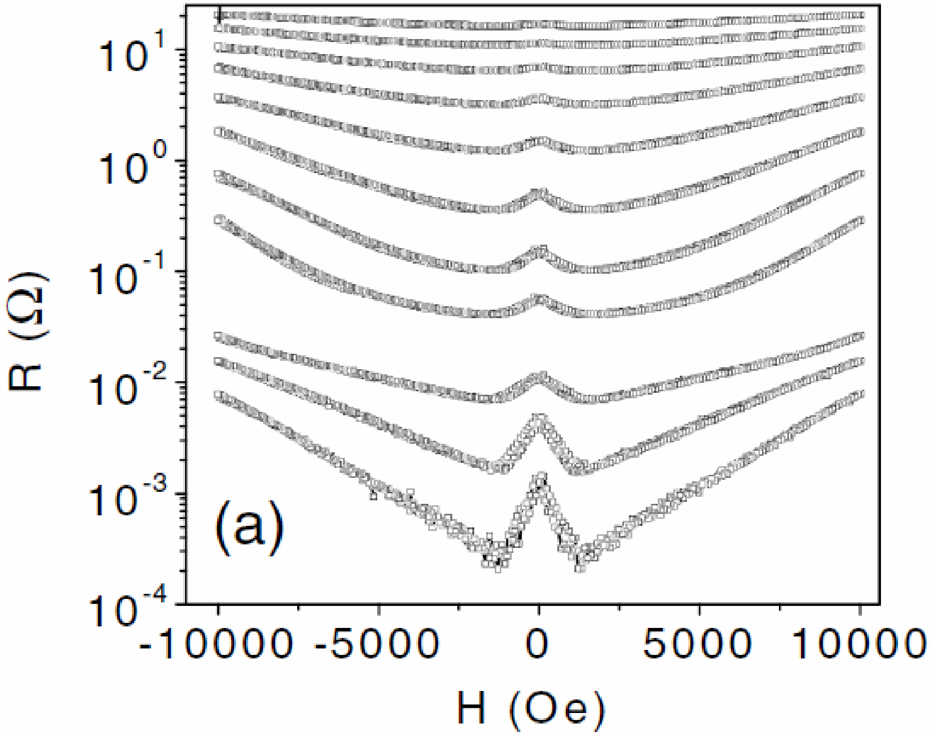
SFSF.. multilayers

$YBa_2Cu_3O_7$/ $La_{2/3}Ca_{1/3}MnO_3$

Giant magnetoresistance   in LCMO/YBCO/LCMO trilayer



We show magnetoresistance in excess of 1000% in trilayers containing highly spin-polarized $La_{0.7}Ca_{0.3}MnO_3$ and high-T_c superconducting $YBa_2Cu_3O_7$. This large magnetoresistance is reminiscent of the giant magnetoresistance (GMR) in metallic superlattices but with much larger values, and originates at spin imbalance due to the injection of spin-polarized carriers. Furthermore, in contrast to ordinary GMR, the magnetoresistance is intimately related to the superconductivity in the $YBa_2Cu_3O_7$ layer and vanishes in the normal state. This result, aside from its fundamental importance, may be of interest for the design of novel spintronic devices based on ferromagnet/superconductor structures.



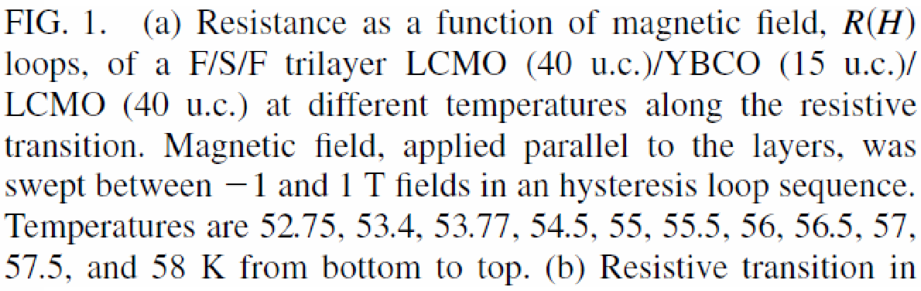


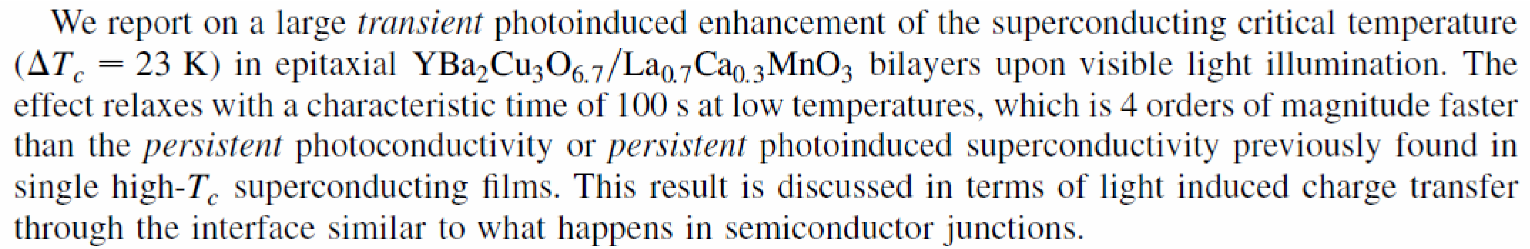
FIG. 1. (a) Resistance as a function of magnetic field, $R(H)$ loops, of a F/S/F trilayer LCMO (40 u.c.)/YBCO (15 u.c.)/ LCMO (40 u.c.) at different temperatures along the resistive transition. Magnetic field, applied parallel to the layers, was swept between −1 and 1 T fields in an hysteresis loop sequence. Temperatures are 52.75, 53.4, 53.77, 54.5, 55, 55.5, 56, 56.5, 57, 57.5, and 58 K from bottom to top. (b) Resistive transition in

V. Pena et al., Phys. Rev. Lett. **94**, 057002 (2005)

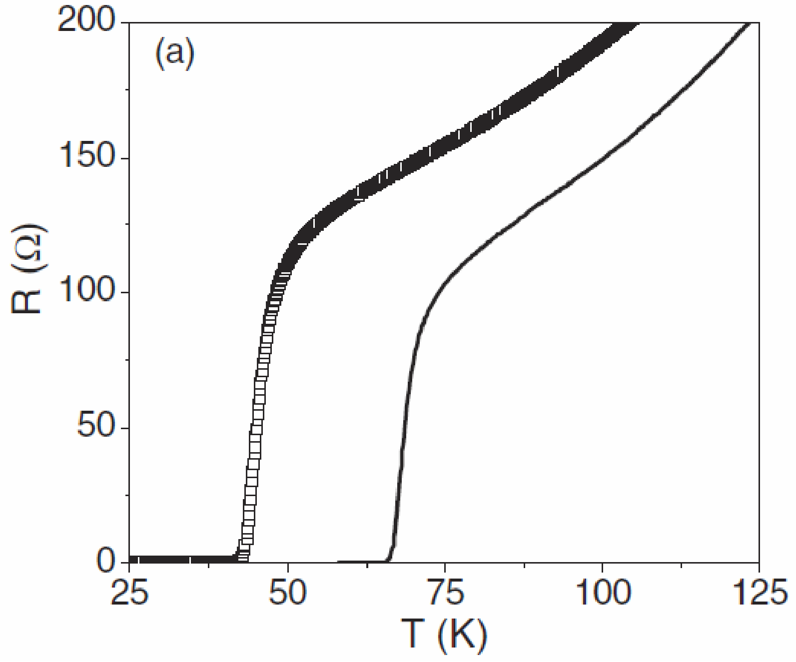
SFSF.. multilayers

$YBa_2Cu_3O_7$/ $La_{2/3}Ca_{1/3}MnO_3$

Giant photodoping effect in YBCO/LCMO bilayer



We report on a large *transient* photoinduced enhancement of the superconducting critical temperature ($\Delta T_c = 23$ K) in epitaxial $YBa_2Cu_3O_{6.7}/La_{0.7}Ca_{0.3}MnO_3$ bilayers upon visible light illumination. The effect relaxes with a characteristic time of 100 s at low temperatures, which is 4 orders of magnitude faster than the *persistent* photoconductivity or *persistent* photoinduced superconductivity previously found in single high-T_c superconducting films. This result is discussed in terms of light induced charge transfer through the interface similar to what happens in semiconductor junctions.



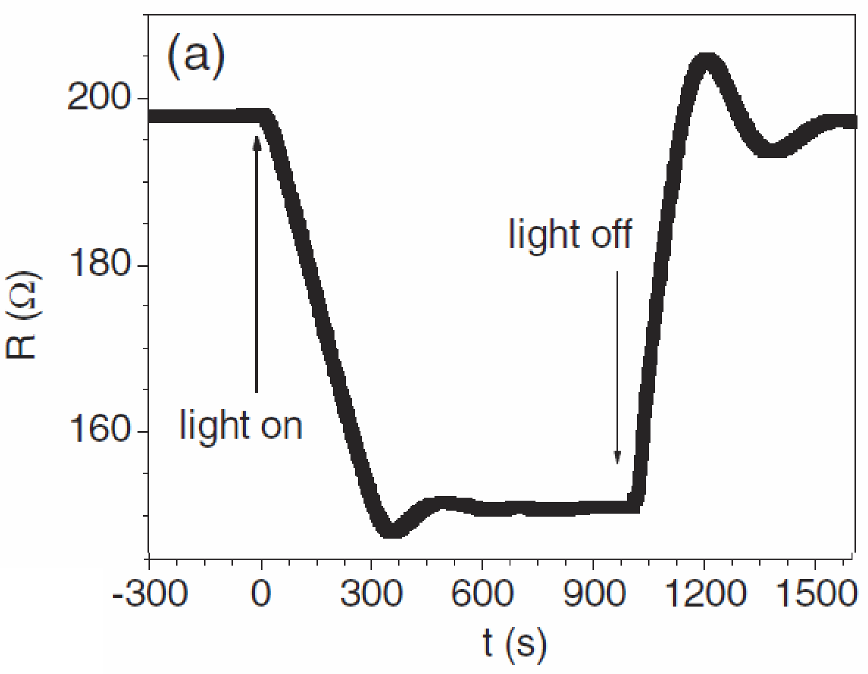
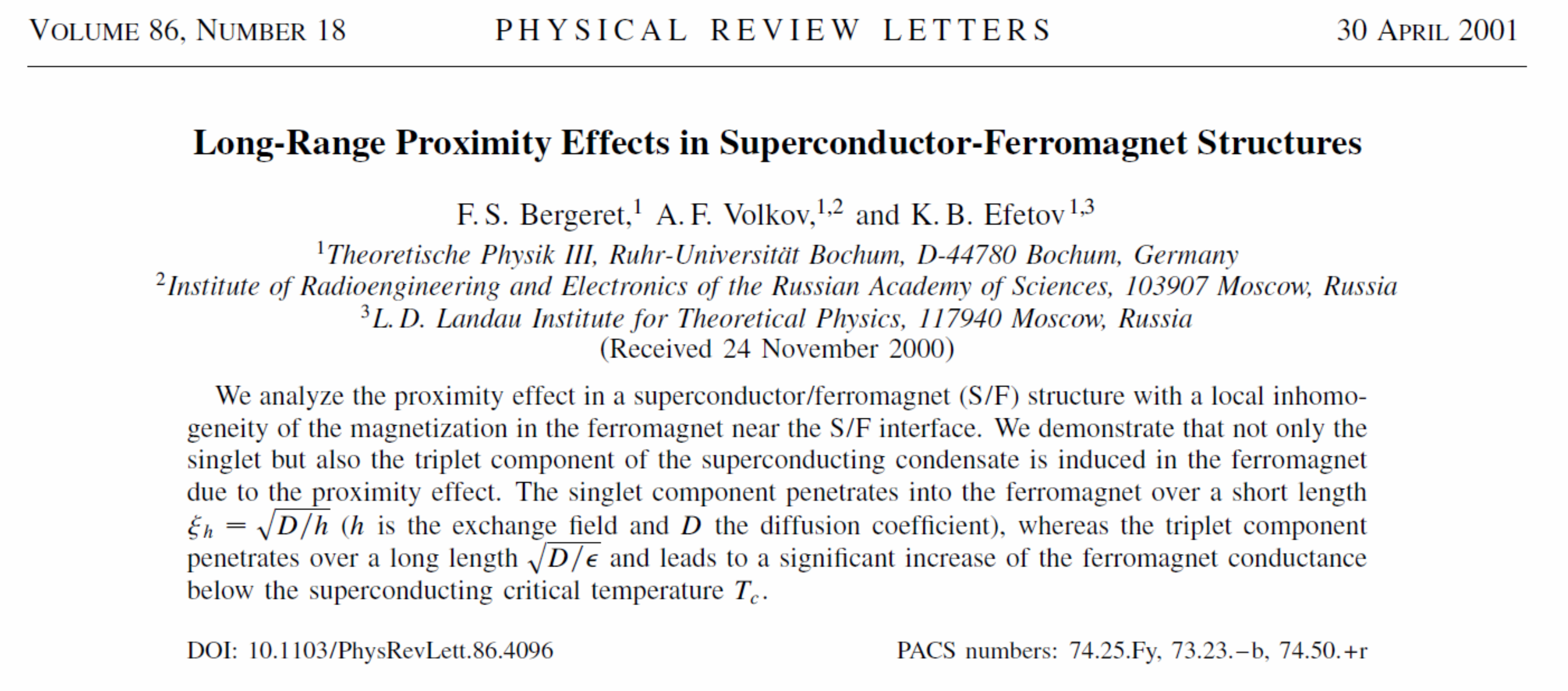


FIG. 1. (a) Resistance curves vs temperature for a bilayer with 12 u.c.$YBCO_{6.7}$/40 u.c.LCMO, in the dark (open symbols) with $T_c = 43$ K, and under illumination (solid line). The change in the critical temperature is $\Delta T_c = 23$ K. (b) Resistance curves for

V. Pena et al., Phys. Rev. Lett. **97**, 177005 (2006)

What about triplet superconductivity in SFS?



VOLUME 86, NUMBER 18 PHYSICAL REVIEW LETTERS 30 APRIL 2001

Long-Range Proximity Effects in Superconductor-Ferromagnet Structures

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[2]*Institute of Radioengineering and Electronics of the Russian Academy of Sciences, 103907 Moscow, Russia*
[3]*L. D. Landau Institute for Theoretical Physics, 117940 Moscow, Russia*

(Received 24 November 2000)

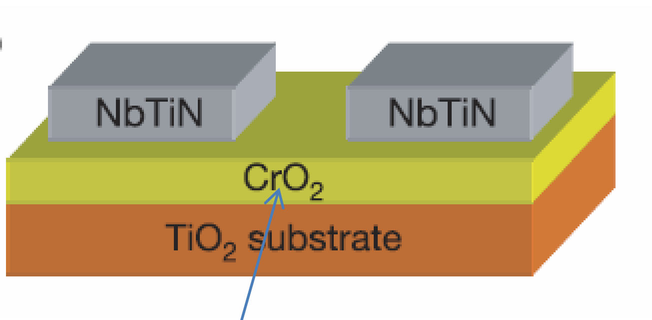
We analyze the proximity effect in a superconductor/ferromagnet (S/F) structure with a local inhomogeneity of the magnetization in the ferromagnet near the S/F interface. We demonstrate that not only the singlet but also the triplet component of the superconducting condensate is induced in the ferromagnet due to the proximity effect. The singlet component penetrates into the ferromagnet over a short length $\xi_h = \sqrt{D/h}$ (h is the exchange field and D the diffusion coefficient), whereas the triplet component penetrates over a long length $\sqrt{D/\epsilon}$ and leads to a significant increase of the ferromagnet conductance below the superconducting critical temperature T_c.

DOI: 10.1103/PhysRevLett.86.4096 PACS numbers: 74.25.Fy, 73.23.–b, 74.50.+r

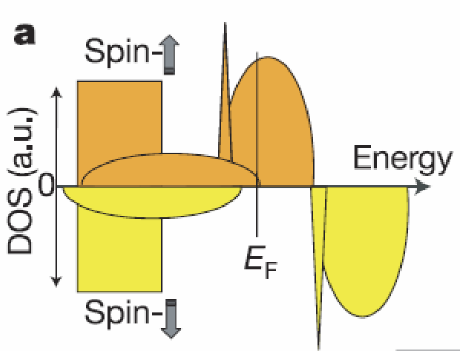
Spin triplet component predicted to penetrate into F layer over long distance;
Inhomogeneous magnetization of F layer required

Long range proximity effect

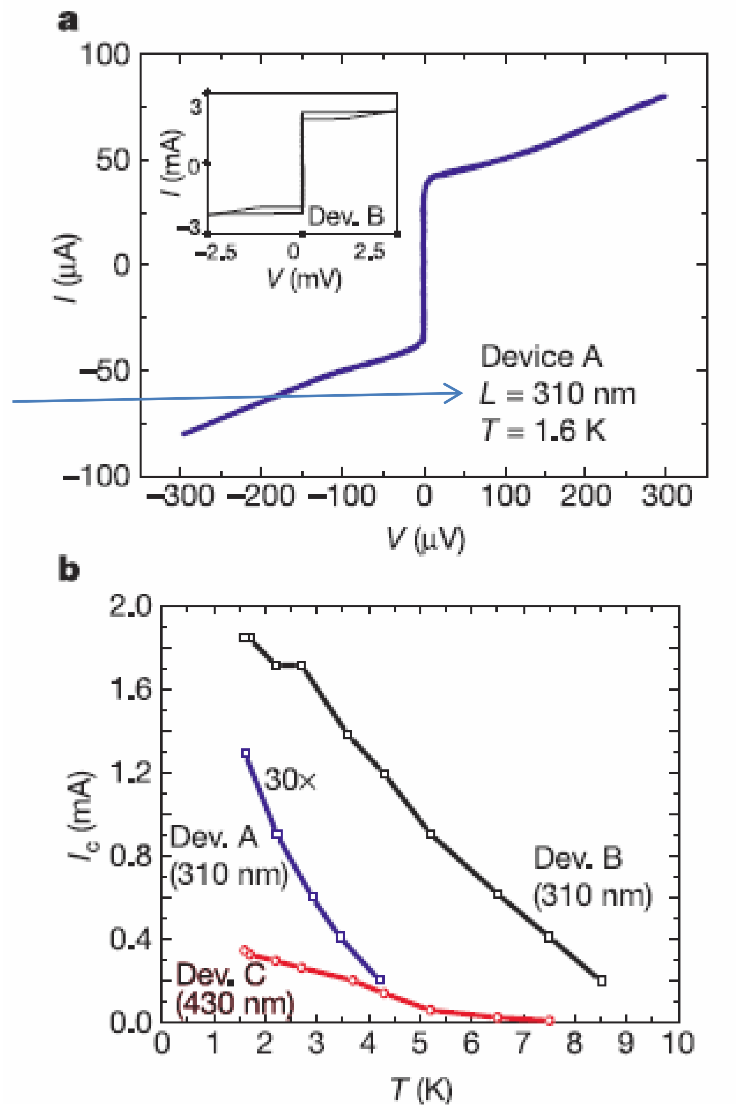
Experimental observation: R. S. Keizer et al., Nature **439**, 825 (2006).



Half metal

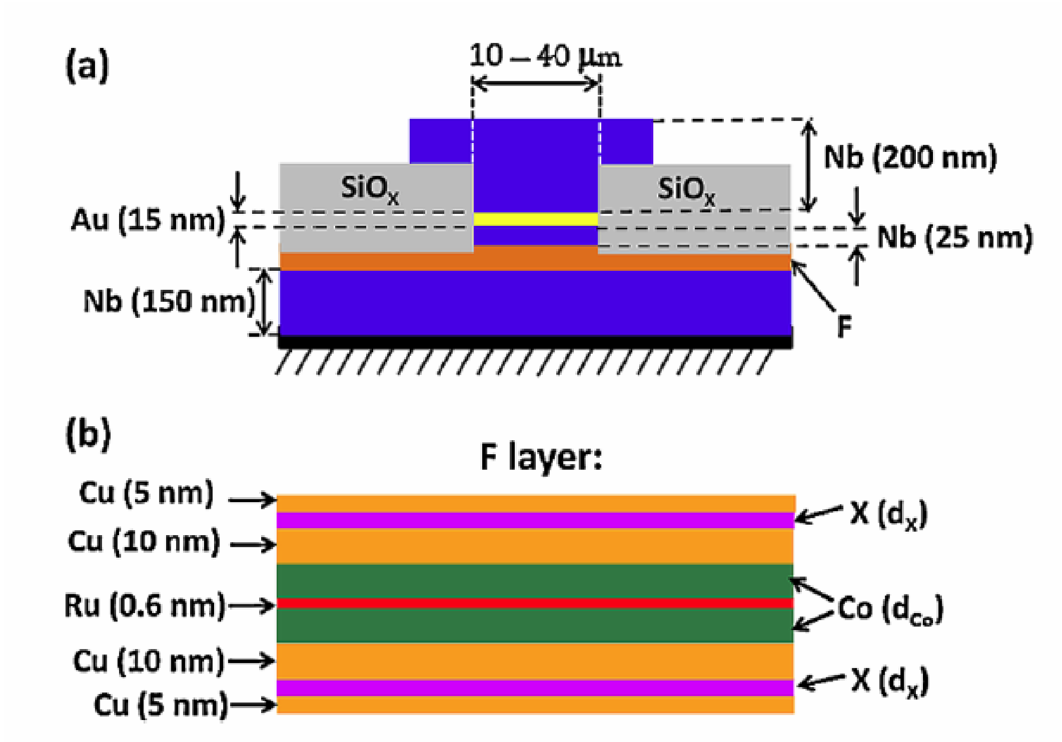


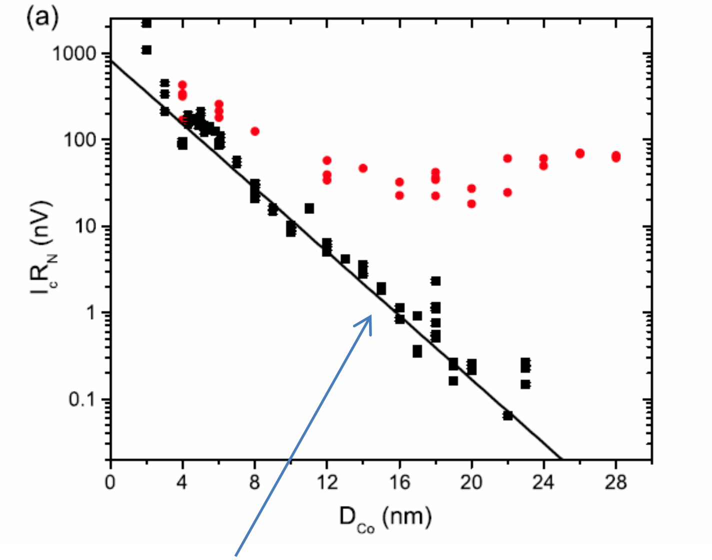
Length of CrO_2 channel



Long range proximity effect

Experimental observation: T. S. Khaire et al., Phys. Rev. Lett. **104**, 137002 (2010)





No X layer

X: PdNi or CuNi (weak ferromagnets)
Co: Strong ferromagnet, suppresses singulett pairs
Ru: induces antiferromagnetic exchange coupling
Cu decouples X and Co; improves interface quality

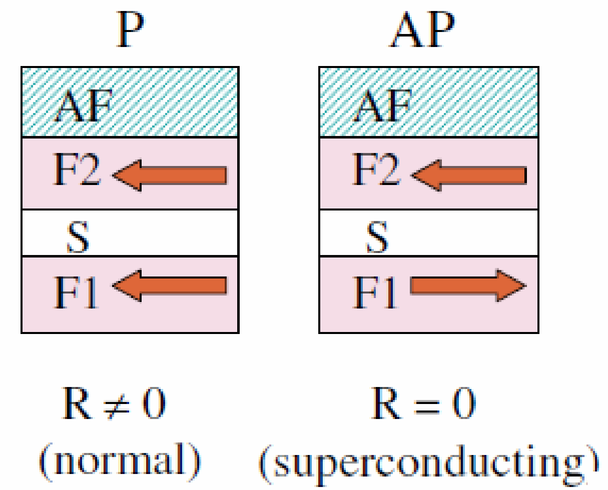
Finally, an example for a FSF structure….

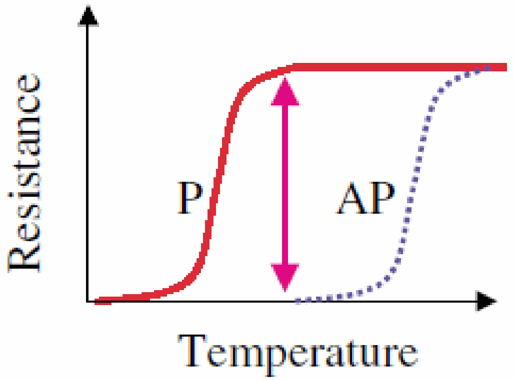
T_c depends on orientation of magnetization in F layer (parallel vs. antiparallel)

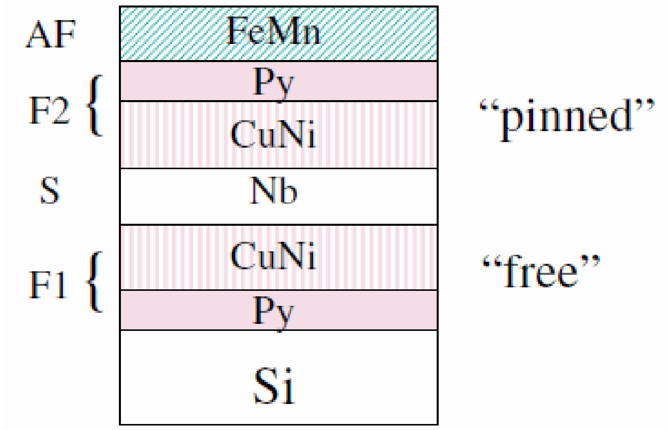
-> strong magnetoresistance near T_c; analog to spin valve

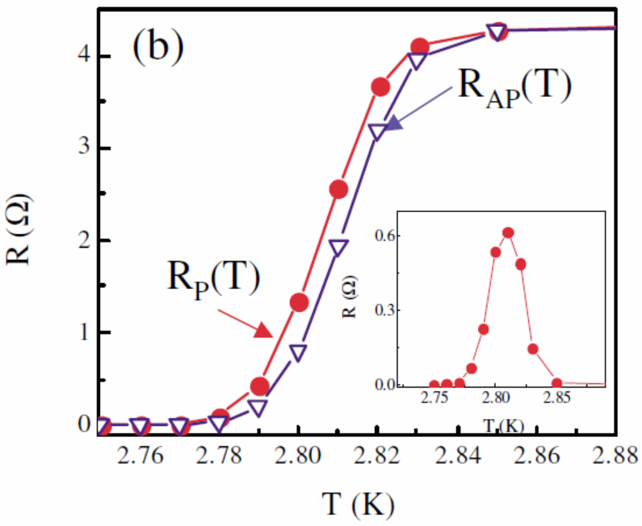
-> Theory: L. R. Tagirov, Phys. Rev. Lett. **83**, 2058 (1999)

-> Experiment: J. Y. Gu et al, Phys. Rev. Lett. **89**, 267001 (2002)









Summary

- Cooper Pairs vs. Ferromagnets – the problems

- Coexistence in bulk materials

- Layered Systems
  - S-I-F bilayers: Domain wall superconductivity
  - SF bilayers:
    - Oscillating order parameter (spin singlet Cooper pairs)
    - long range proximity effect (spin triplet component)

  - Trilayers and multilayers
    - SFS, SIFS: π Josephson junctions
    - FSF : magnetoresistive effects
    - …SFSFS… multilayers

  -> potential devices for classical and quantum circuits

Thank you!