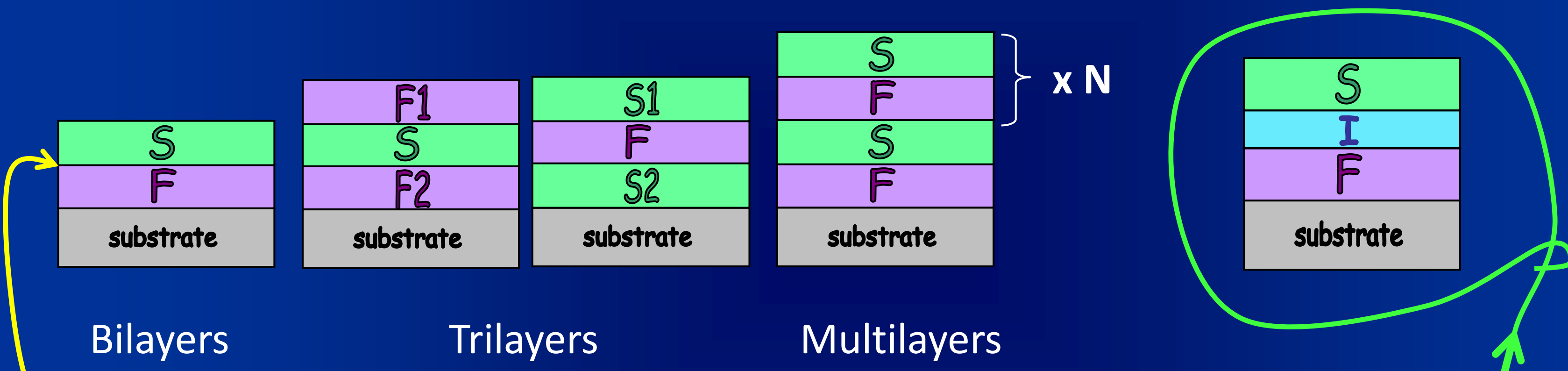
Superconducting - ferromagnetic heterostructures

- New technologies ⟾ films & structures with nanoscale range of layer thickness
- Close proximity of two long-range orders ⟾ new phenomena & potential applications



Exchange interactions

Interface: Cooper pairs penetrate inside the F layers (proximity effect)

Orbital effects

Long-range electromagnetic interactions of Cooper pairs with nonuniform magnetization due to magnetic texture

Outline

1. Introduction: symmetry of Cooper pairs

2. Proximity effect (exchange interactions)
   a) Proximity effect at S/F interface
   b) Singlet-triplet mixing and spin rotation
   c) Early experiments (multilayers)
   d) Josephson junction geometry
   e) Spin valve geometry

3. Orbital effects
   1) Phase transition line
   2) Vortex pinning

4. Summary

Symmetry of Cooper pairs

Spin singlet (S=0)

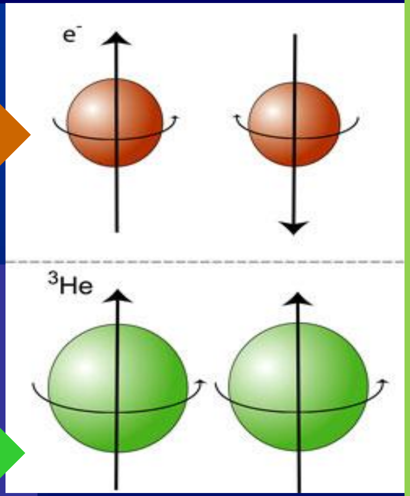
$$\frac{1}{\sqrt{2}}(|\uparrow,k\rangle\,|\downarrow,-k\rangle - |\downarrow,k\rangle\,|\uparrow,-k\rangle) \equiv (\uparrow\downarrow - \downarrow\uparrow)$$

Spin triplet (S=1)

$$S_z = 0 \quad \frac{1}{\sqrt{2}}(|\uparrow,k\rangle\,|\downarrow,-k\rangle + |\downarrow,k\rangle\,|\uparrow,-k\rangle) \equiv (\uparrow\downarrow + \downarrow\uparrow)$$

$$S_z = 1 \quad |\uparrow,k\rangle\,|\uparrow,-k\rangle \equiv \uparrow\uparrow$$

$$S_z = -1 \quad |\downarrow,k\rangle\,|\downarrow,-k\rangle \equiv \downarrow\downarrow$$



S/F structures

homogeneous magnetization — **singlet + S_z=0 triplet**

Condensate wave function (pair correlation function) must be even with respect to interchange of time coordinates

equal times correlations ≡ "even frequency pairing"

inhomogeneous magnetization — **$S_z = \pm 1$ triplet**

wave function must be odd with respect to interchange of time coordinates **"odd frequency pairing"**

Bergeret et al., Rev.Mod.Phys. 2005
Eschrig, Rep.Prog.Phys. 2015

Symmetry classification
(Pauli principle & Fermi statistics)

Spin	Frequency	Momentum	Overall	Type
Singlet (odd) ↑↓−↓↑	Even	Even (s, d)	Odd	A
	Odd	Odd (p, f)	Odd	B
Triplet (even) ↑↑ ↓↓ ↑↓+↓↑	Even	Odd (p, f)	Odd	C
	Odd	Even (s, d)	Odd	D

Conventional (s), high-Tc (d)

?

Superfluid ^{3}He-A, Sr_2RuO_4, Heavy fermion compounds (UGe_2, URhGe, UCoGe, UIr)

S/F interface (inhomogeneous) (s)

Proximity effect

Spin singlet (S=0)

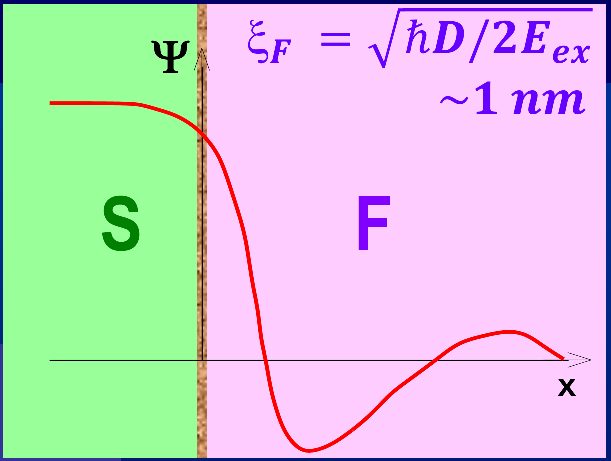
$$\frac{1}{\sqrt{2}}(|\uparrow, \mathrm{k}\rangle\,|\downarrow, -\mathrm{k}\rangle - |\downarrow, \mathrm{k}\rangle\,|\uparrow, -\mathrm{k}\rangle) \equiv (\uparrow\downarrow - \downarrow\uparrow)$$

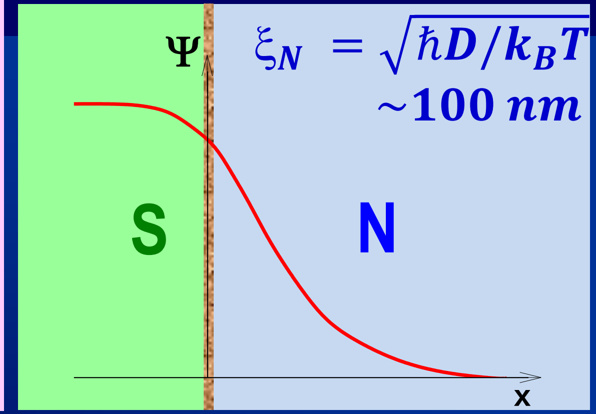
Spin triplet (S=1)

$S_z = 1$ $\quad |\uparrow, \mathrm{k}\rangle\,|\uparrow, -\mathrm{k}\rangle \equiv \uparrow\uparrow$

$S_z = 0$ $\quad \frac{1}{\sqrt{2}}(|\uparrow, \mathrm{k}\rangle\,|\downarrow, -\mathrm{k}\rangle + |\downarrow, \mathrm{k}\rangle\,|\uparrow, -\mathrm{k}\rangle) \equiv (\uparrow\downarrow + \downarrow\uparrow)$

$S_z = -1$ $\quad |\downarrow, \mathrm{k}\rangle\,|\downarrow, -\mathrm{k}\rangle \equiv \downarrow\downarrow$





Buzdin et al., JETP Lett. 1982; Buzdin&Kuprianov, JETP Lett. 1990; Radovic et al., PRB 1991

Demler et al., PRB 1997

$$k_{F\uparrow} = k + \frac{Q}{2} \qquad k_{F\downarrow} = k - \frac{Q}{2}$$

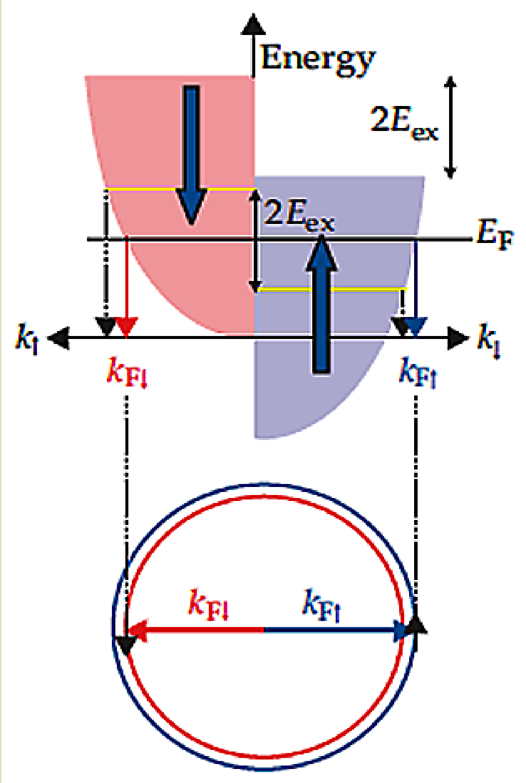
Cooper pair with center-of-mass momentum $\pm Q$

spin-dependent shift in the phase of the wavefunction:

$$(\uparrow\downarrow - \downarrow\uparrow) \Rightarrow (\uparrow\downarrow e^{iQR} - \downarrow\uparrow e^{-iQR}) = (\uparrow\downarrow - \downarrow\uparrow)\cos(QR) + i(\uparrow\downarrow + \downarrow\uparrow)\sin(QR)$$

⇨ **spatial modulation of the pair amplitude**

FFLO state (Fulde, Ferrel, Larkin, Ovchinnikov, 1964)



Proximity effect

Spin singlet (S=0)

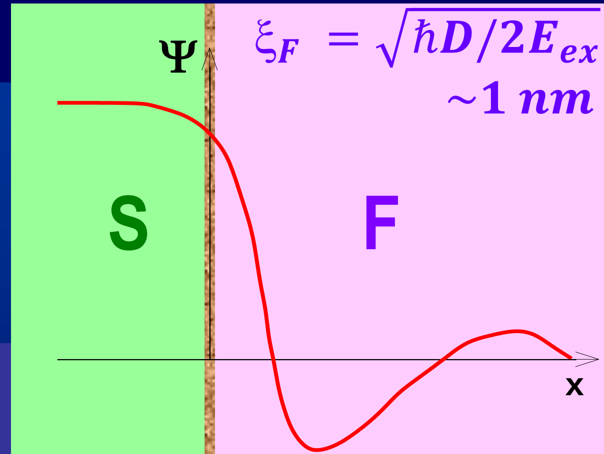
$$\frac{1}{\sqrt{2}}\left(|\uparrow,\mathrm{k}\rangle\,|\downarrow,-\mathrm{k}\rangle - |\downarrow,\mathrm{k}\rangle\,|\uparrow,-\mathrm{k}\rangle\right) \equiv (\uparrow\downarrow - \downarrow\uparrow)$$

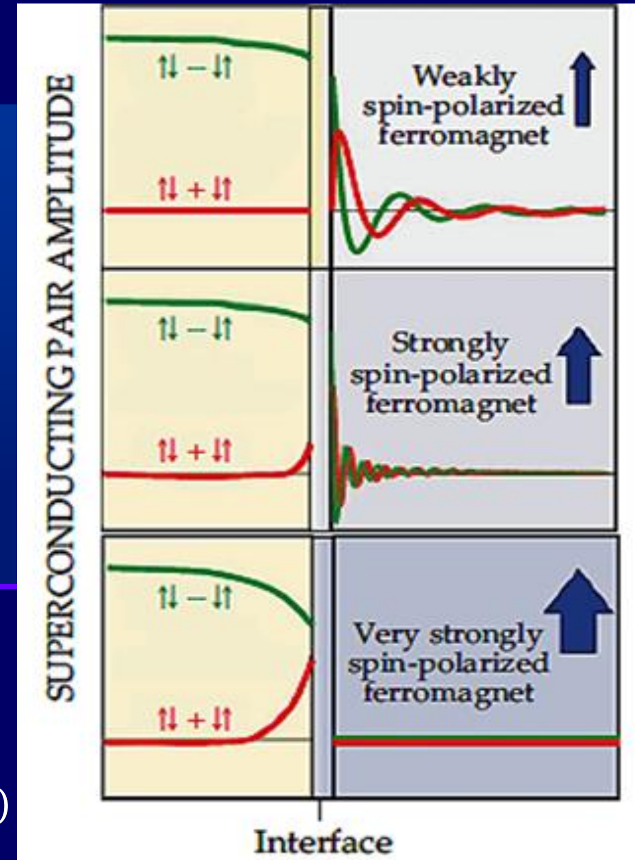
Spin triplet (S=1)

$S_z = 1$ $\quad |\uparrow,\mathrm{k}\rangle\,|\uparrow,-\mathrm{k}\rangle \equiv \uparrow\uparrow$

$S_z = 0$ $\quad \frac{1}{\sqrt{2}}\left(|\uparrow,\mathrm{k}\rangle\,|\downarrow,-\mathrm{k}\rangle + |\downarrow,\mathrm{k}\rangle\,|\uparrow,-\mathrm{k}\rangle\right) \equiv (\uparrow\downarrow + \downarrow\uparrow)$

$S_z = -1$ $\quad |\downarrow,\mathrm{k}\rangle\,|\downarrow,-\mathrm{k}\rangle \equiv \downarrow\downarrow$





Eschrig, Phys. Today 2011

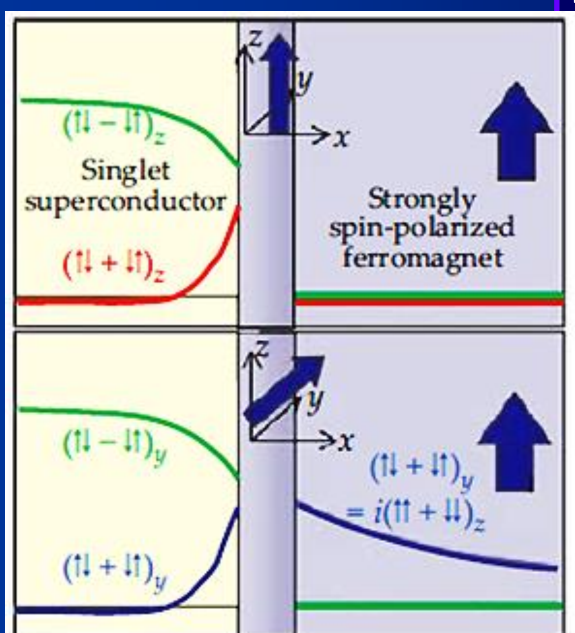
Singlet – triplet mixing

$(\uparrow\downarrow - \downarrow\uparrow)$

$\Rightarrow\ (\uparrow\downarrow e^{i\theta} - \downarrow\uparrow e^{-i\theta})$

$= (\uparrow\downarrow - \downarrow\uparrow)\cos(\theta) + i\,(\uparrow\downarrow + \downarrow\uparrow)\sin(\theta)$

singlet (S=0) triplet (S = 1, S_z= 0)



Spin rotation

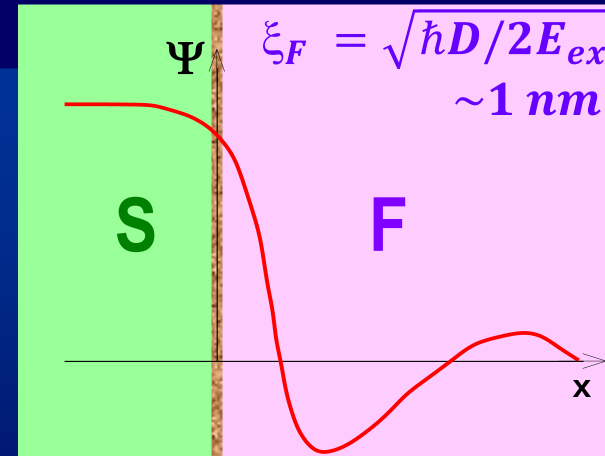
Bergeret et al., PRL (2001); Kadigrobov et al., Europhys. Lett. (2001); Eschrig et al., PRL (2003)

$(\uparrow\downarrow + \downarrow\uparrow)_y \ \Rightarrow\ i\,(\uparrow\uparrow + \downarrow\downarrow)_z$

S_z= 0 $\quad$ S_z= ±1

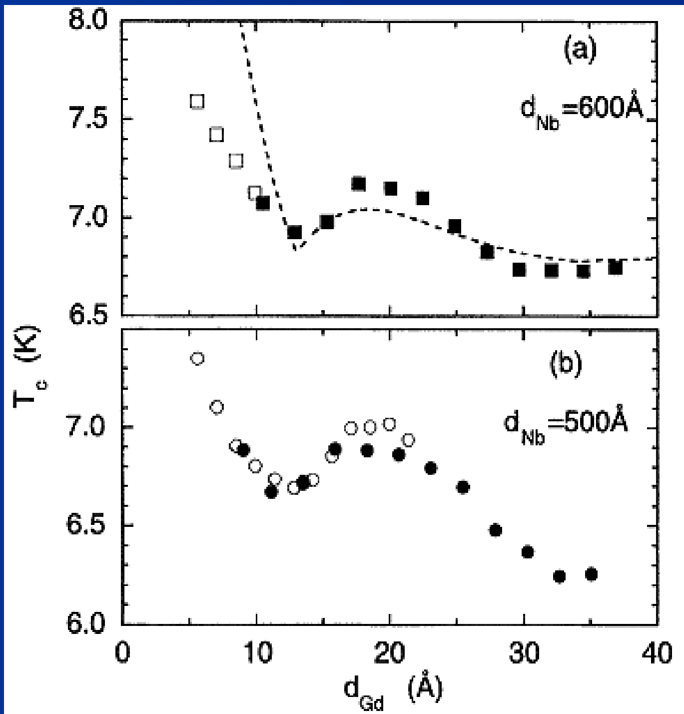
inhomogeneous non-collinear (to F) magnetization in the interface region → **Long-range triplet supercurrent**

Early experiments

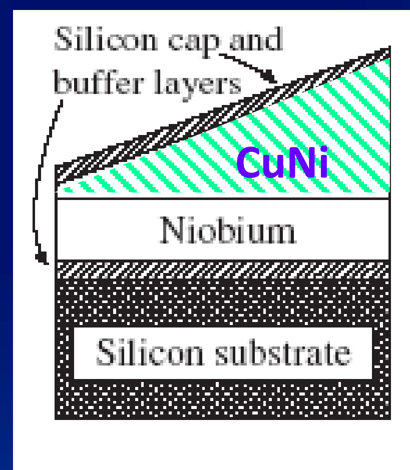


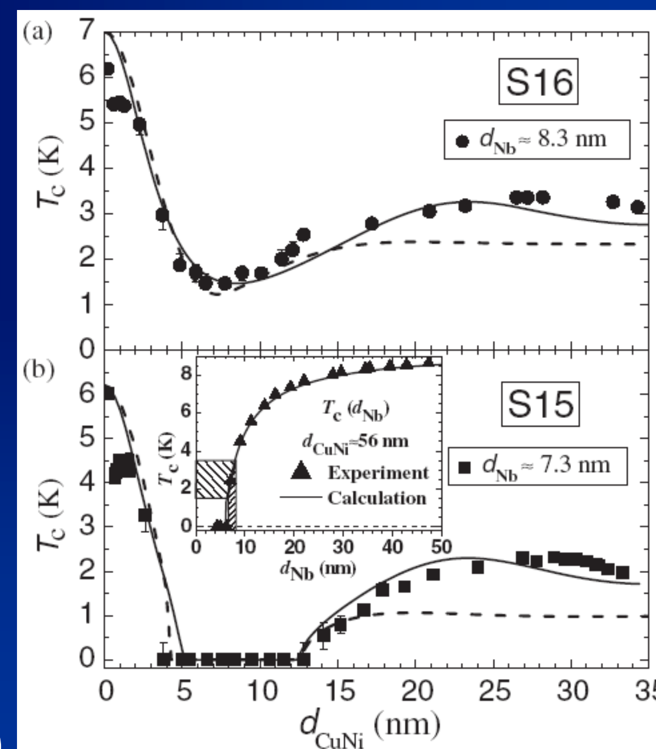
Oscillatory $T_c(d_F)$ – Nb/Gd multilayers

Jing et al., PRL (1995)



Reentrant $T_c(d_F)$ – bilayers *Zdravkov et al., PRL(2006)*



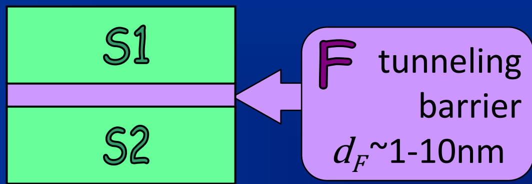


mK measurements

wedge sample of CuNi on Nb (grown by magnetron sputtering)

Early experiments

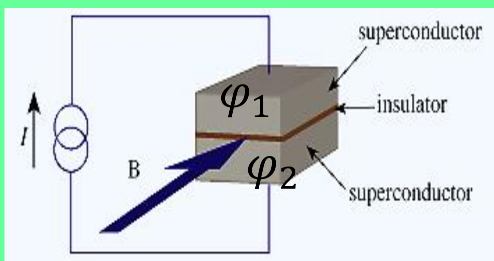
Josephson junction geometry



- $\Delta\varphi(d_F) \implies I_c(d_F)$
- Large d_F $\implies$ sc triplet current

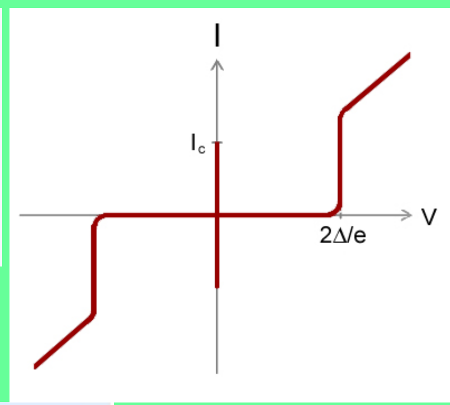
SIS (or SNS) junction

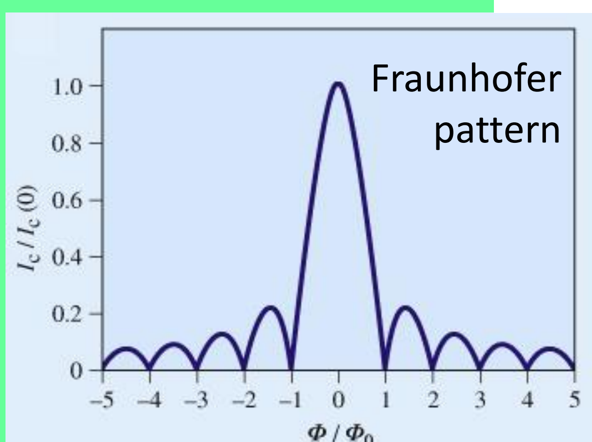
B.D. Josephson,1962



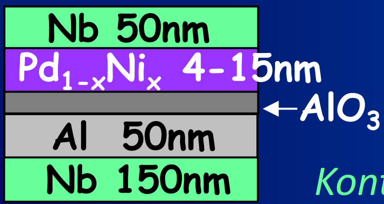
$$I = I_c \sin\Delta\varphi$$

$$\Delta\varphi = \varphi_1 - \varphi_2$$



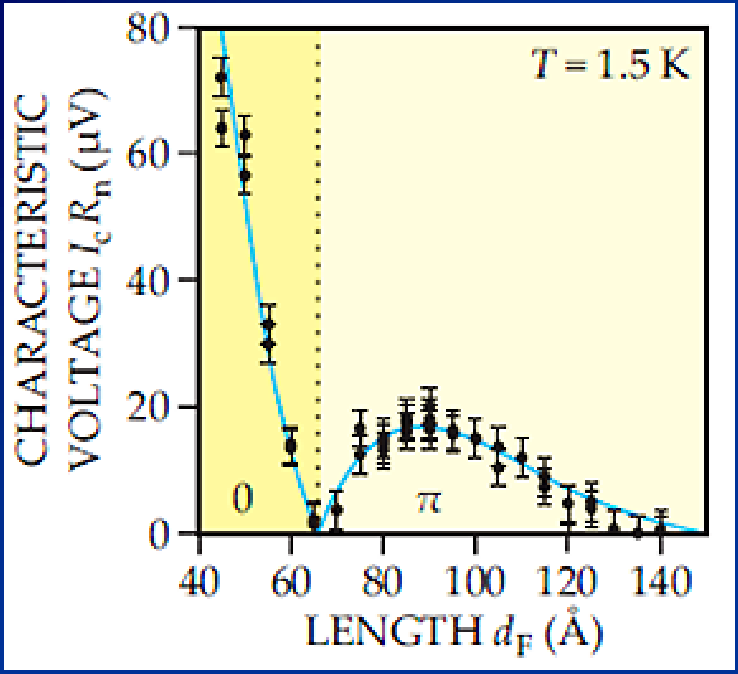


$$I \sim \frac{\sin(\pi\Phi/\Phi_0)}{\pi\Phi/\Phi_0}$$



π-junction

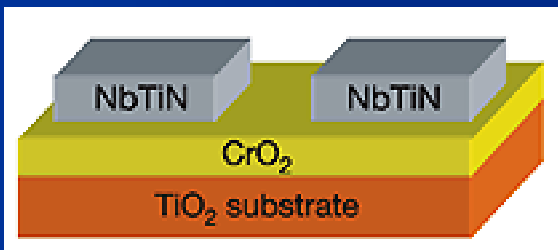
Kontos at al., PRL (2002)



Josephson junction experiments

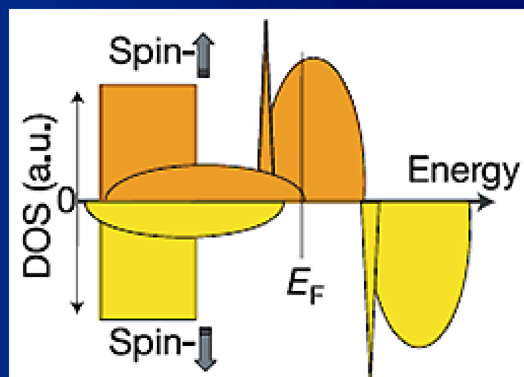
Spin triplet supercurrent

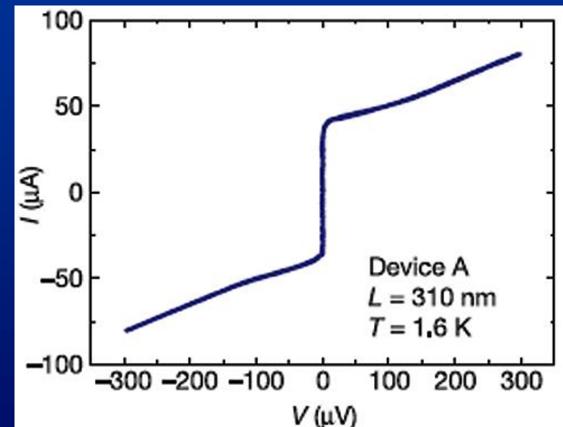
Keizer at al., Nature (2006)

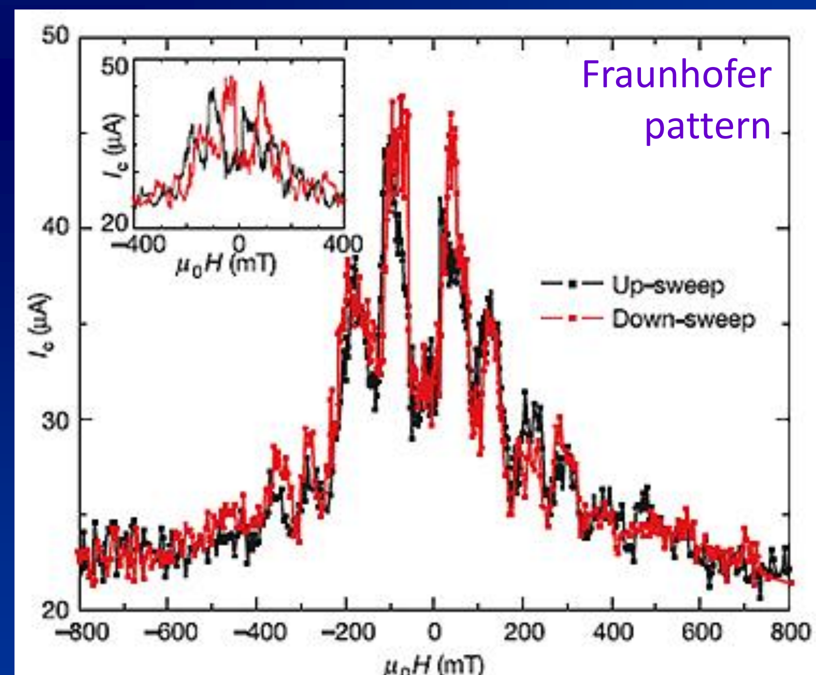


CrO_2: half-metallic ferromagnet – no singlet supercurrent:

d_F = 0.3-1μm

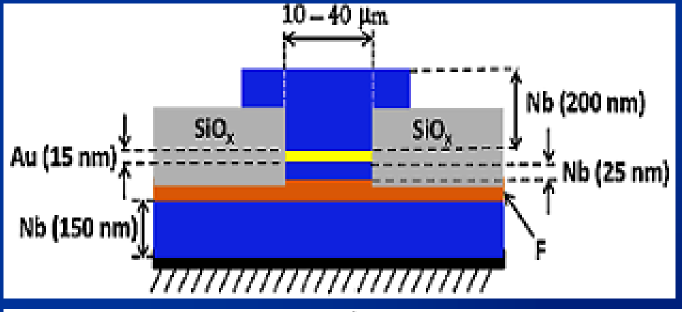


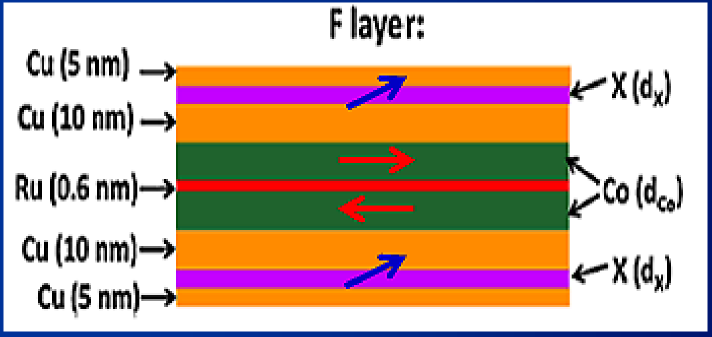




The origin of inhomogeneous field: unclear

Josephson junction experiments





Long range triplet supercurrent

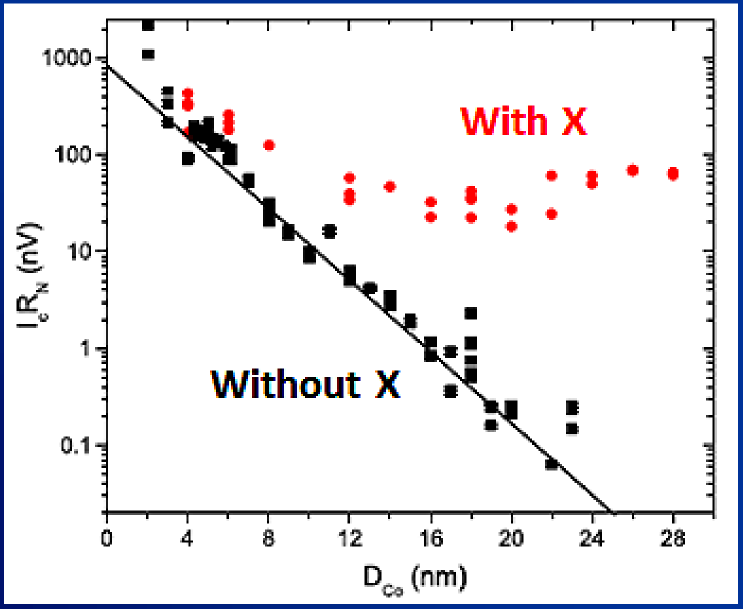
Ru - exchange coupling of Co-layers (total M=0)

Co - suppresses spin singlet current

X=$Pd_{0.88}Ni_{0.12}$ provides noncolinear M

Cu decouples X & Co layers

Khaire at al., PRL (2010)

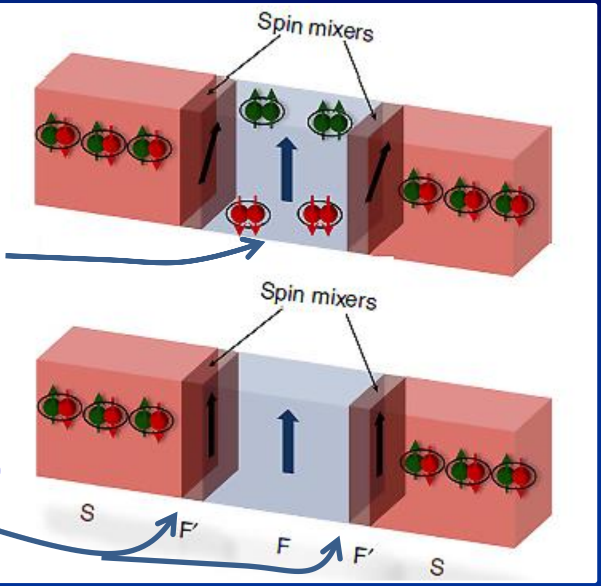


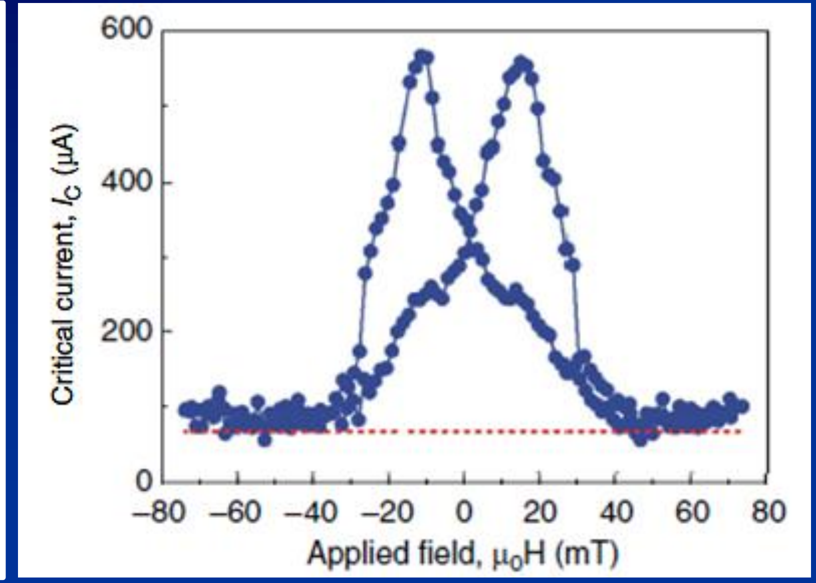
Banerjee at al., Nature Commun. 2014

Control of the amplitude of triplet current

F=Co

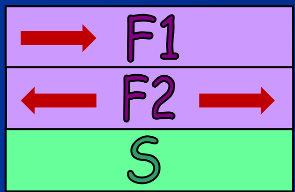
F'=$Ni_{80}Fe_{20}$ (Permalloy, Py)



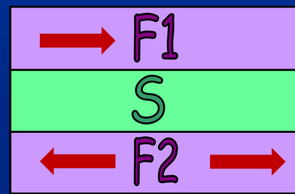


Spin valve geometry

Oh et al., 1997



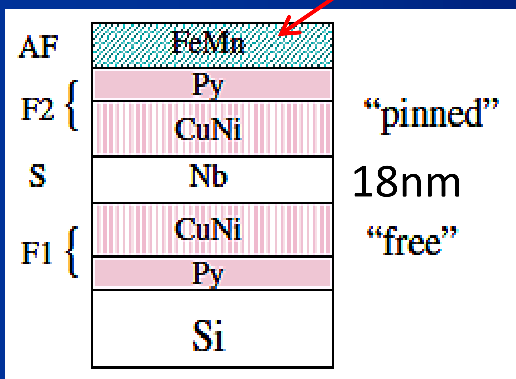
Tagirov, 1999; Buzdin et al., Europhys. Lett. 1999

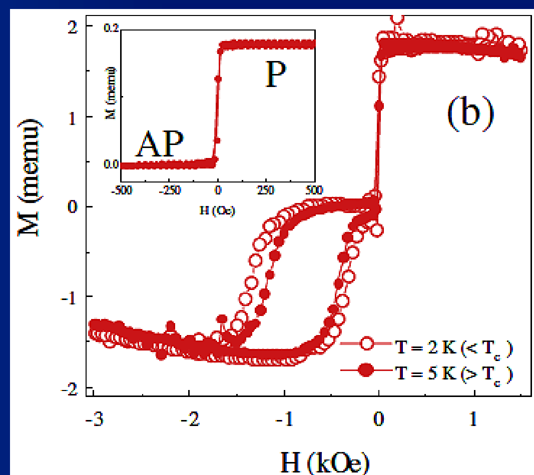


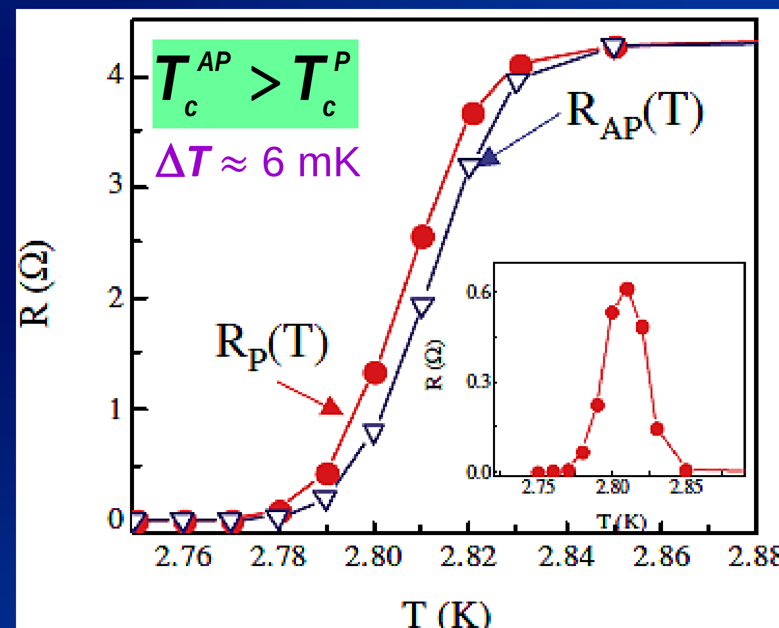
Weaker pair-breaking in AP configuration ⇒ $T_c^{AP} > T_c^{P}$

Gu et al., 2002

Provides exchange bias







Rusanov et al., PRB 2006 $T_c^{AP} < T_c^{P}$

Moraru et al., PRB 2006 $T_c^{AP} > T_c^{P}$

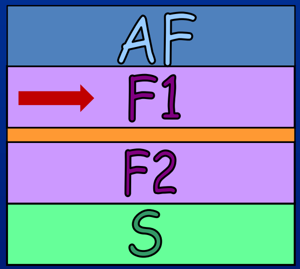
Py/Nb/Py

Spin valve experiments

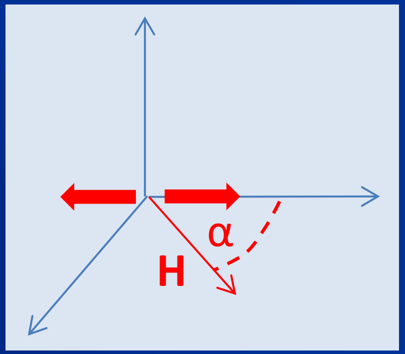
Triplet spin valve

Theory: Fominov at al., JETP Lett. (2010)

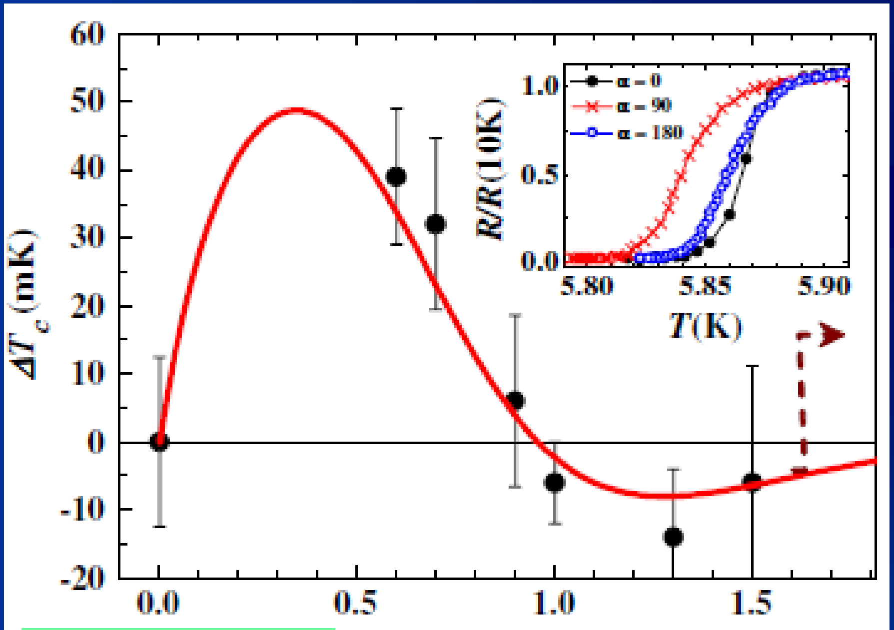
Main origin of the T_c change :
drainage of singlets into the triplet channel



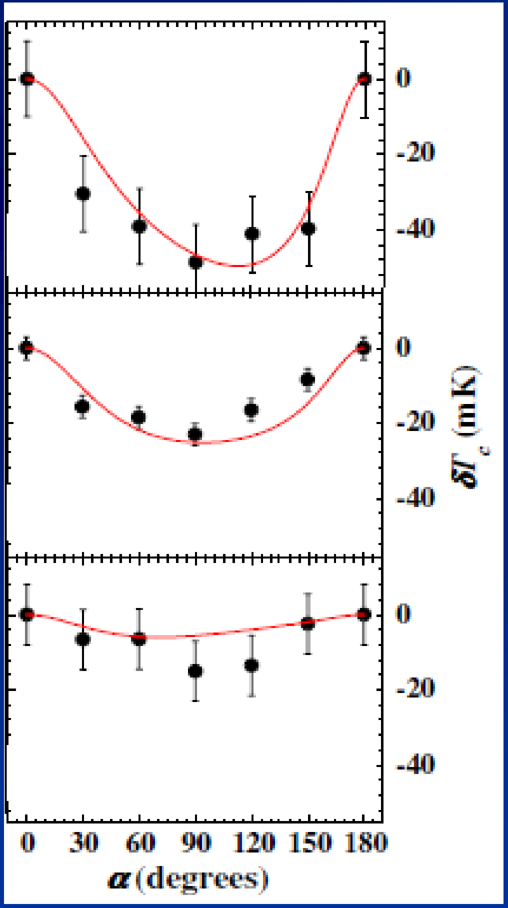
CoO_x
Fe
Cu
Fe (d_F)
Pb(35nm)



Leksin at al., PRL (2012)



$$\Delta T_c = T_c^{AP} - T_c^{P}$$



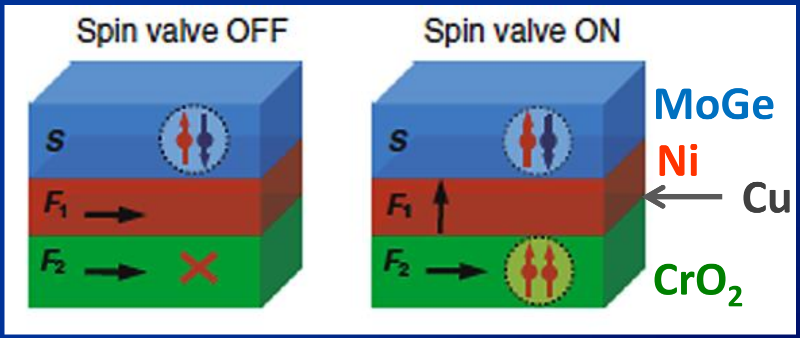
ΔT_c is the largest for α=90°

Sign of ΔT_c depends on d_F

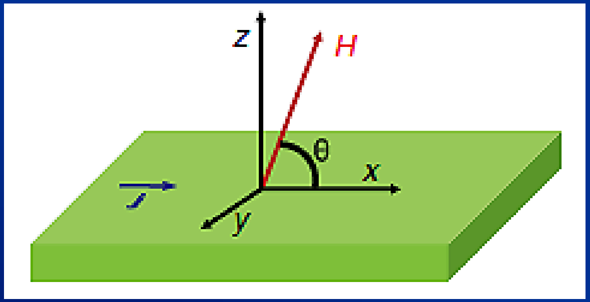
Spin valve experiments

Colossal proximity effect

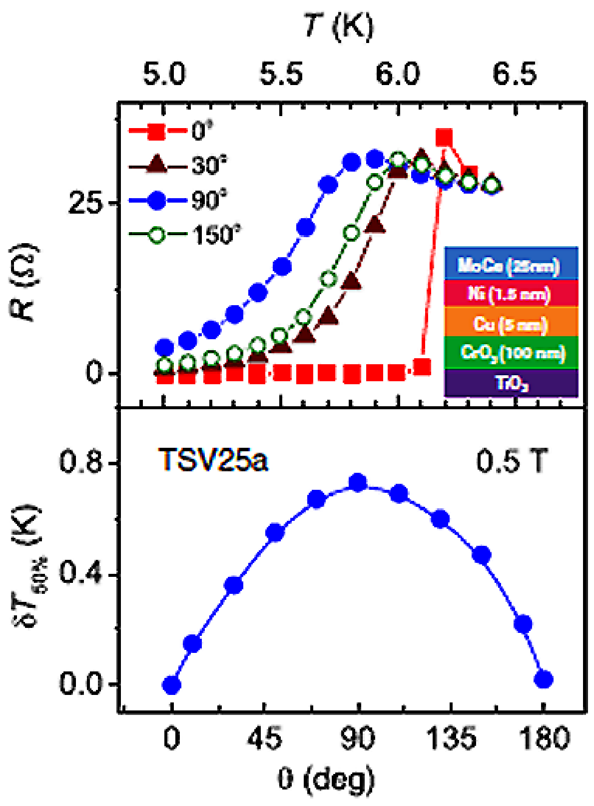
Singh at al., PRX (2015)

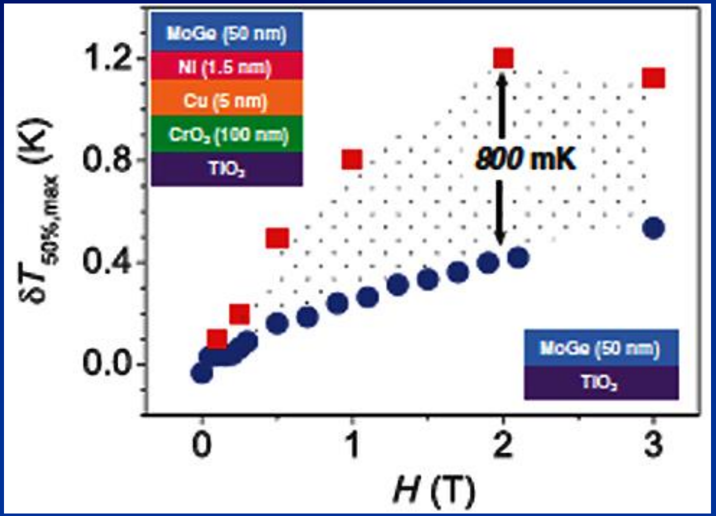


25-50nm

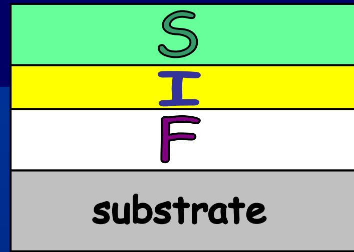


- ❑ Half-metallic ferromagnet
- ❑ Out-of-plane rotation





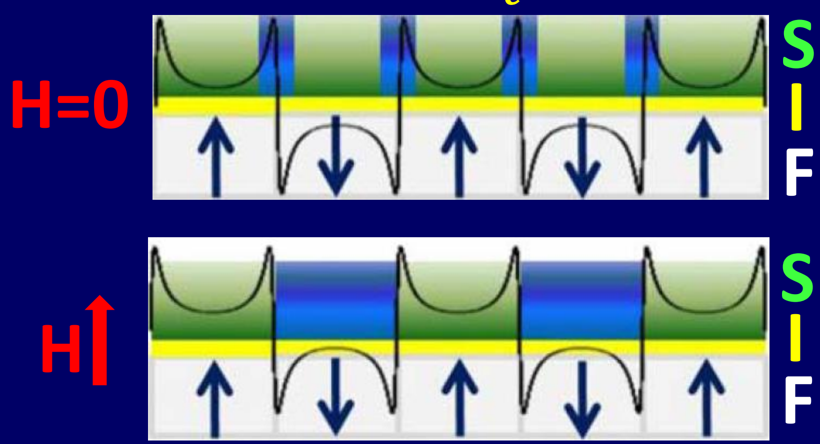
Orbital effects



Long-range electromagnetic interactions of Cooper pairs with the magnetic moment of the magnetic texture

Phase transition line: $T_c(H)$

$T \sim T_c$



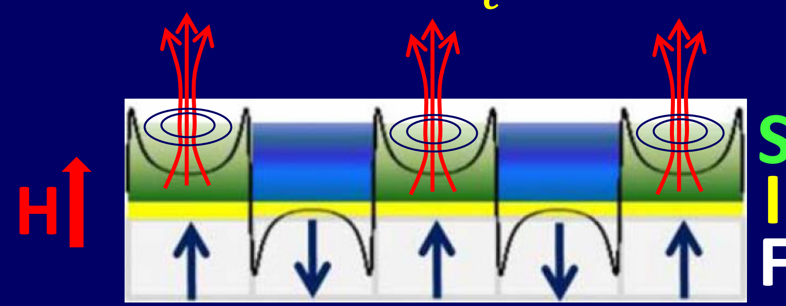
Nucleation of superconductivity:
where **H_{loc} = H + H_{domain}** is the lowest

H=0 → above domain walls (DWS)
H>0 → above negative domains
H<0 → above positive domains

nonlinear $T_c(H)$

Vortex pinning

$T < T_c$



Vortex-domain interaction:

$$U = -\overrightarrow{h_v} \cdot \overrightarrow{m}$$

vortex magnetic field + screening currents generated in S by $\overrightarrow{m}$

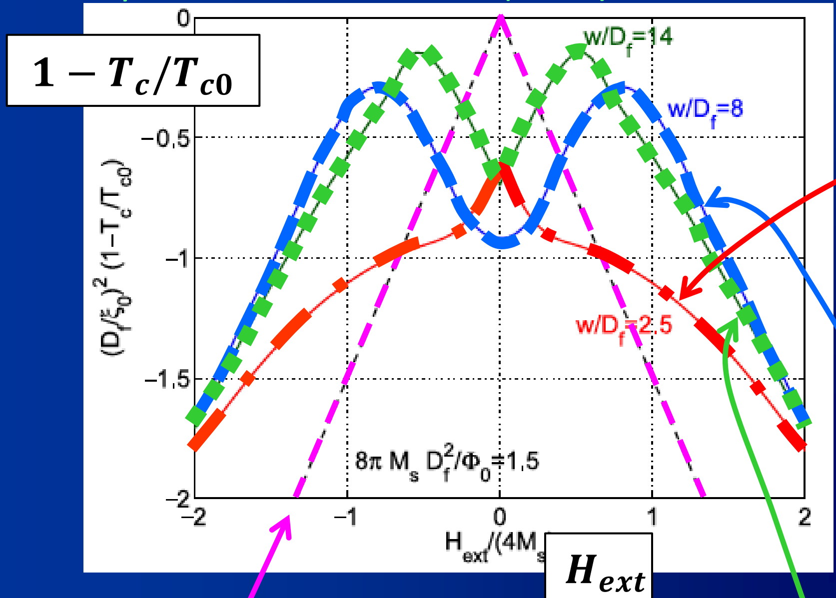
magnetic moment of the domain $\overrightarrow{m}$

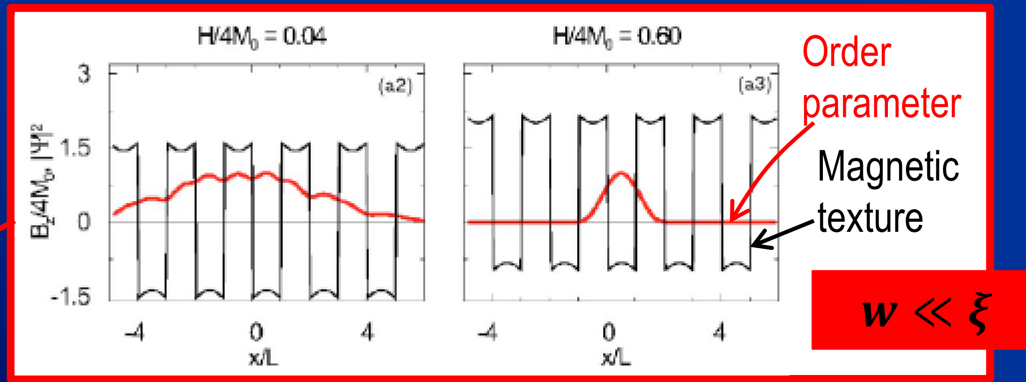
enhanced vortex pinning ⇒ enhanced critical current density at high T

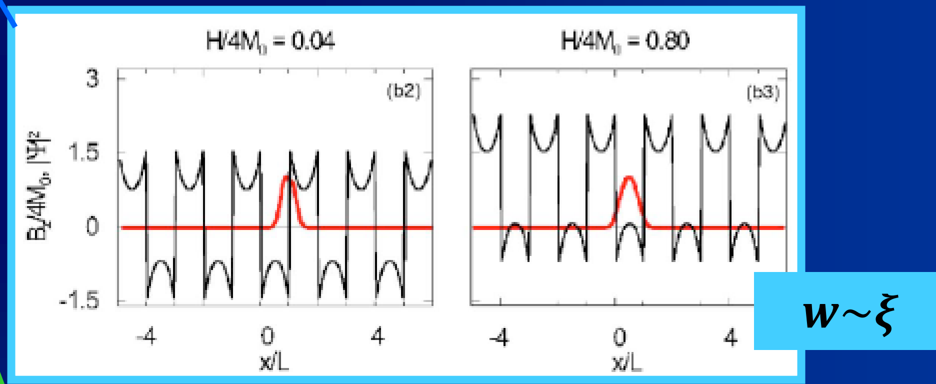
Phase transition line

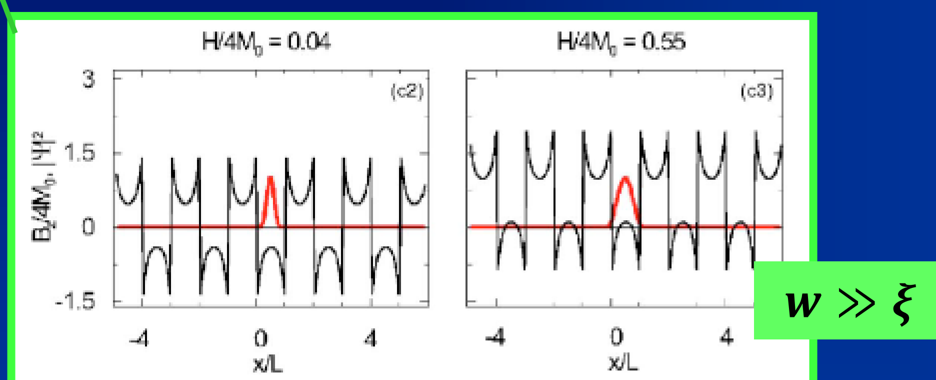
Buzdin & Mel'nikov, PRB (2003); Aladyshkin, et al., PRB (2003); Lyuksyutov & Pokrovsky, Adv. Phys. (2004); Milosevic & Peeters, PRL (2004), PRL (2005); Aladyshkin & Moshchalkov, PRB (2006)

Aladyshkin et al., Supercond. Sci. Technol. (2009)









Ginzburg-Landau equations ⇒ linear dependence

$$\frac{T_c}{T_{c0}} = 1 - \frac{|H_{ext}|}{H_{c2}(0)}$$

$$H_{c2}(0)=\Phi_0/(2\pi\xi_0)$$

Magnetic texture ➡ nonlinear modifications at small H_{ext}

Two maxima of T_c away from $H = 0$

Phase transition line

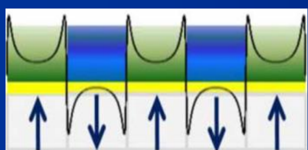
Yang et al., Nat. Mater. (2004) $Nb/BaFe_{12}O_{19}$ (monocrystals)

Gillijns et al., PRL (2005) F/S/F trilayer, S=Nb (d=35nm, $T_c \sim$ 3K), F=Co/Pd

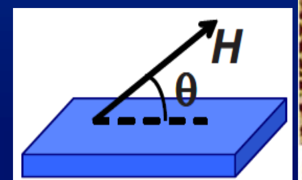
dependence on w?

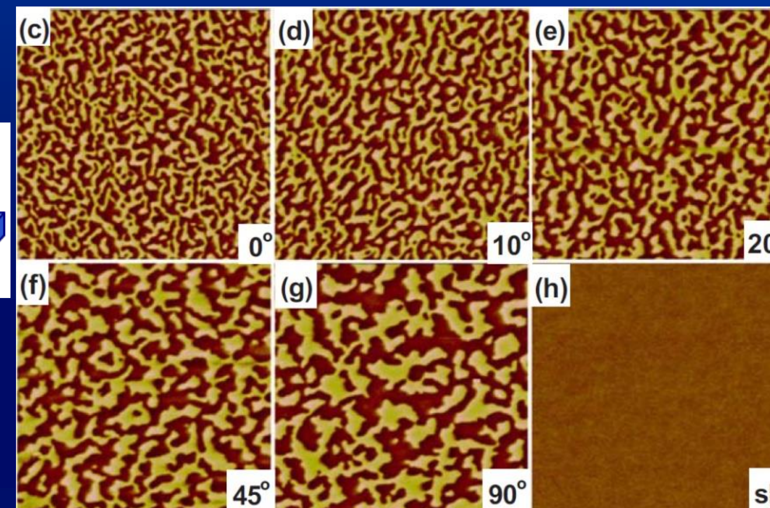
Tunable bilayer Nb/[Co,Pt]

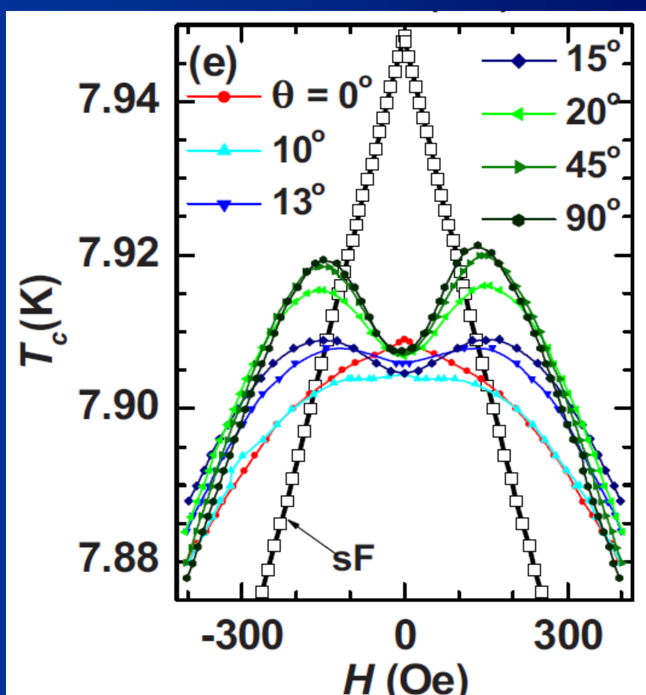
Zhu, Cieplak & Chien, PRB(2010)

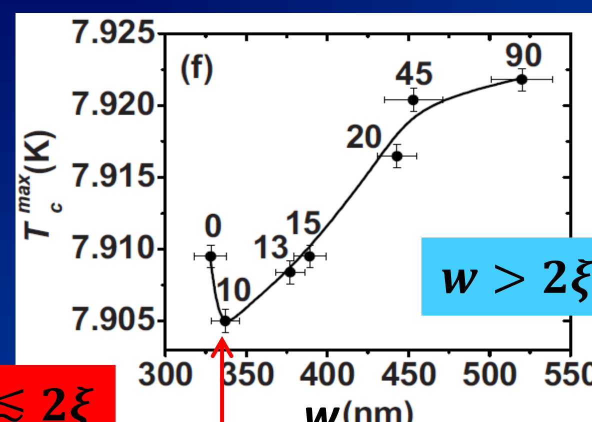


Nb (20nm)
Si
$[Co(0.6)/Pt(0.3)]_8$









single maximum

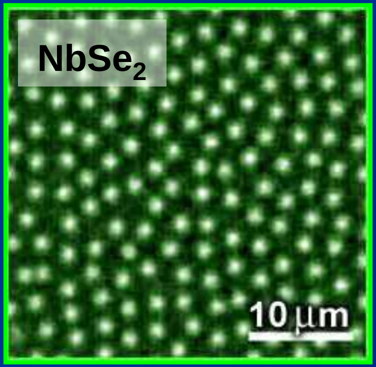
$w \lesssim 2\xi$

$w > 2\xi$ bimodal

$w = 337nm \sim 2\xi$

Vortex pinning

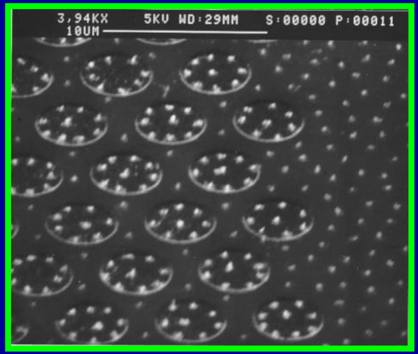
Abrikosov vortex lattice



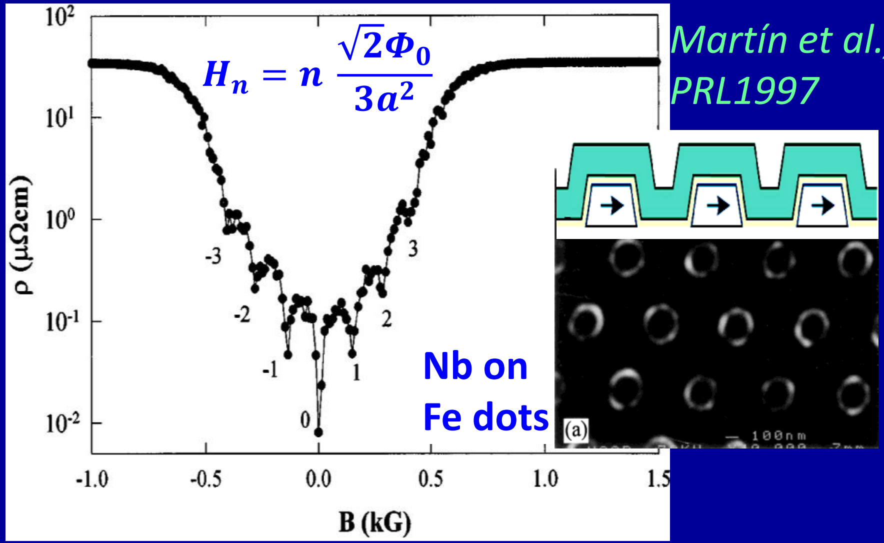
Goa et al., Supercond. Sci. Technol. 2001

Pinning potentials ⤇ commensurability effects

Bezryadin et al., PRB 1996



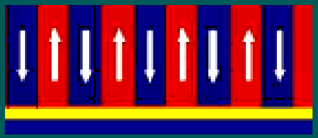
Nb with perforated microholes

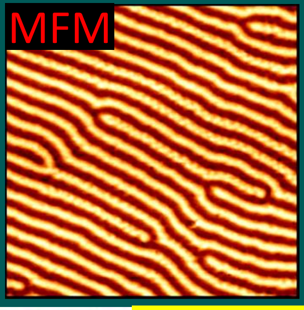


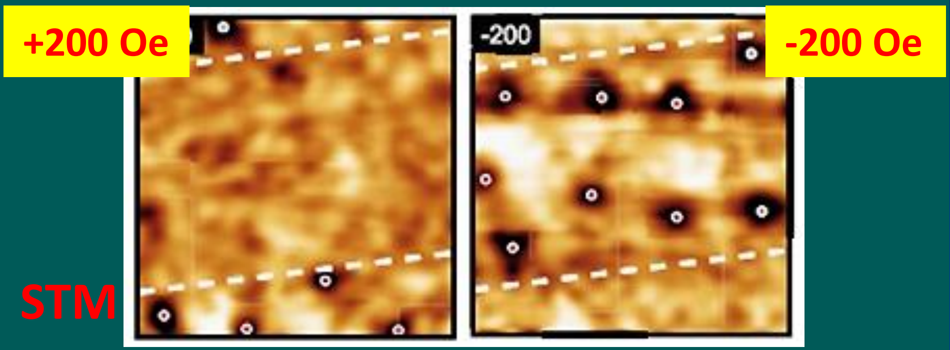
Martín et al., PRL1997

Vortex chains in S/F bilayer

Karapetrov et al., PRB (2009)







Search for pinning enhancement in S/F bilayers

Bulaevskii et al., APL (2000)

Magnetic pinning ⤇ enhancement of the critical current density in S/F multilayers at high temperatures

S = $YBa_2Cu_3O_7$ F = $BaFe_{17}O_{19}$, PrSrMnO, $SrRuO_3$, LaCaMnO, LaSrMnO, Co/Pt

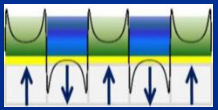
Pb/(Co/Pt), Nb/(Co/Pt), Nb/Cu/$SrRuO_3$

enhancement × 1.5 - 3

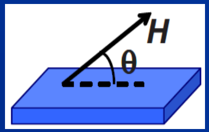
Vortex pinning

Zhu et al., PRB 2010; Cieplak et al., PRB 2011 & 2013; Adamus et al., PRB 2016

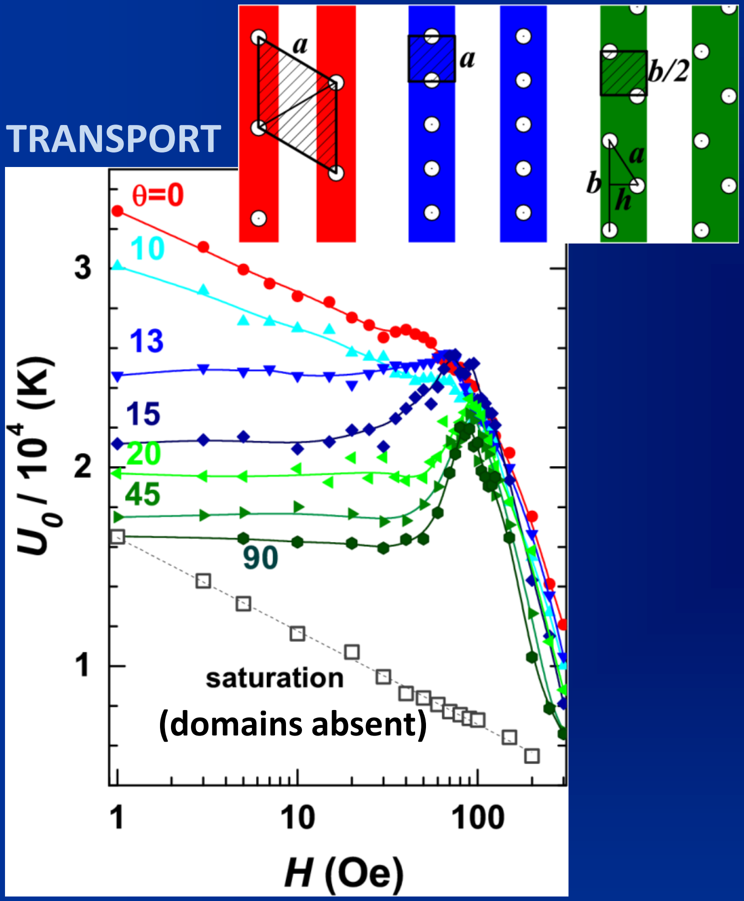
Commensurability effects in the vortex activation energy

Si  Nb (20nm) and (76nm)

$[Co(0.6)/Pt(0.3)]_8$

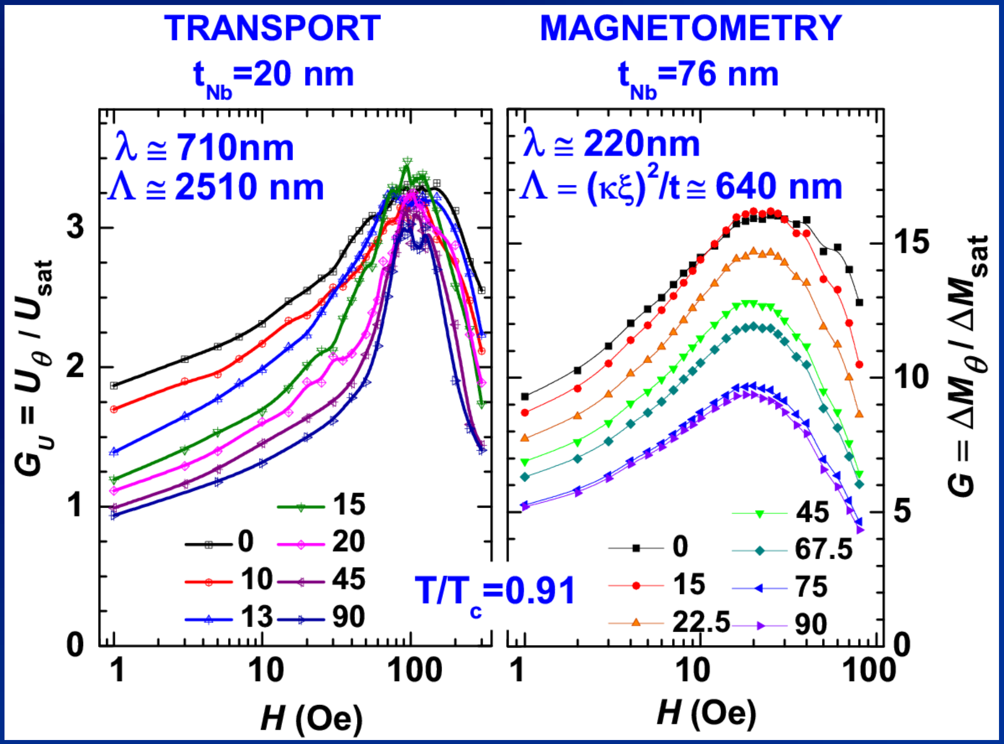


TRANSPORT



Narrow domains - single vortex chains
wide domains - double vortex chains

Pinning enhancement



Largest (to-date) and tunable pinning enhancement:
most effective for $\lambda \sim w$

Summary

1. Proximity effect at S/F interface $\rightarrow$
   long-range, spin triplet supercurrent

2. Orbital interactions $\rightarrow$
   modification of phase transition line &
   enhancement of vortex pinning

- Potential applications:
  superconducting spintronic devices
- Near future:
  development of the control of
  these effects

Other experiments:

- high-T_c materials (oxide interfaces)
  Dybko & Przyslupski (2015)
- mesoscopic systems
  (vortex rachet effects, etc.)
- Topological insulators
  (spin-orbit $\Rightarrow$ unusual sc states?)
- .....