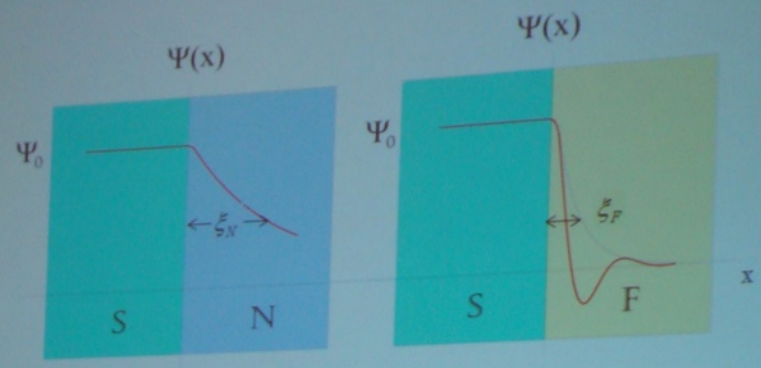
Proximity effect: S/N vs. S/F



$$\xi_N = \sqrt{\frac{\hbar D_N}{2\pi k_B T}} \approx few\ \mu m$$

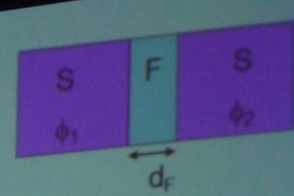
$$\xi_F \sim \sqrt{\frac{\hbar D_F}{E_{ex}}} \approx few\ nm$$

$$\Psi(x) = \Psi_0 \exp(-x/\xi_N)$$

$$\Psi(x) = \Psi_0 \cos(x/\xi_F)\exp(-x/\xi_F)$$

S/F/S Josephson junctions:

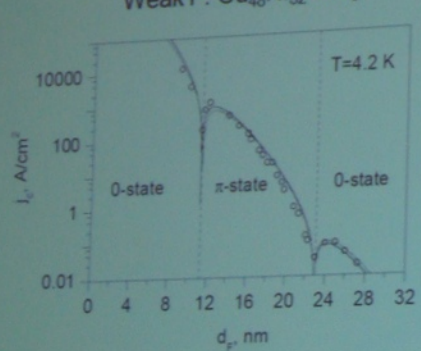
oscillations cause π-junctions:



0-state: $I_s = I_c \sin(\phi_2-\phi_1)$

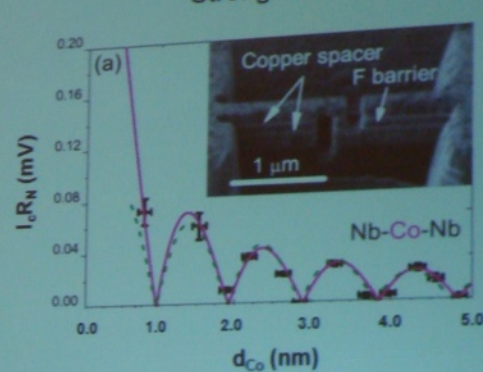
π-state: $I_s = I_c \sin(\phi_2-\phi_1+\pi)$

Weak F: $Cu_{48}Ni_{52}$ alloy



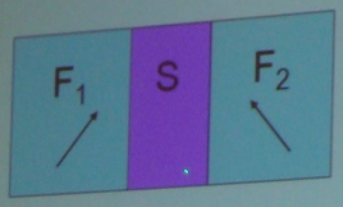
Ryazanov *et al.*, PRL **86**, 2427 (2001); **96**, 197003 (2006).

Strong F: Co

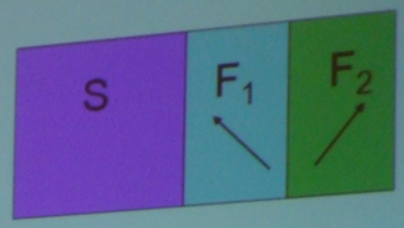


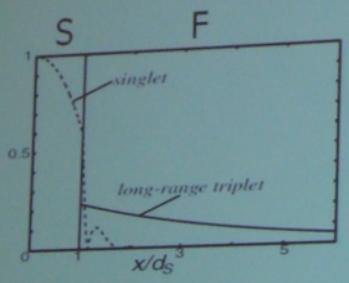
Robinson, Piano, Burnell, Bell, Blamire, PRL **97**, 177003 (2005)

Prediction: long-range spin-triplet pair correlations induced by noncollinear magnetization



or





Singlet

$$\xi_F^{\,S} = \sqrt{\frac{\hbar D_F}{E_{ex}}}$$

Triplet

$$\xi_F^{\,T} = \sqrt{\frac{\hbar D_F}{2\pi k_B T}}$$

$$\xi_F^{\,S} << \xi_F^{\,T}$$

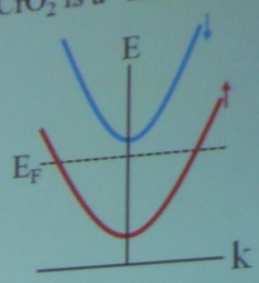
Bergeret, Volkov & Efetov, Phys. Rev. B 64, 134506 (2001); PRL **90**, 117006 (2003)

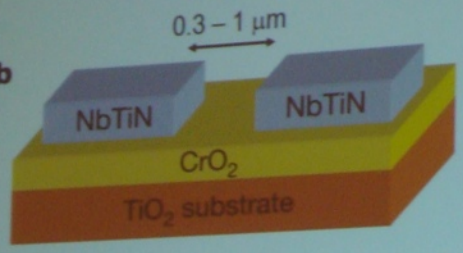
Kadrigrobov, Shekhter & Jonson, Europhys. Lett. **54**, 394 (2001)

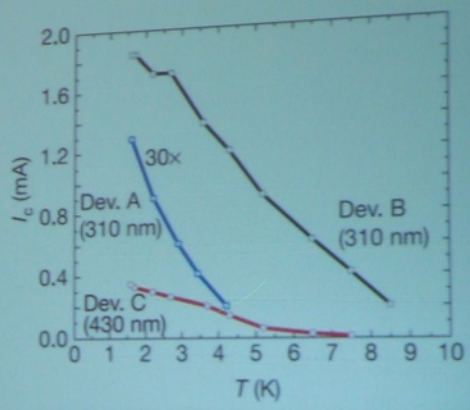
Possible observation of triplet:

Keizer, Goennenwein, Klapwijk, Miao, Xiao, Gupta, Nature **439**, 825 (2006)

CrO_2 is a "half metal"



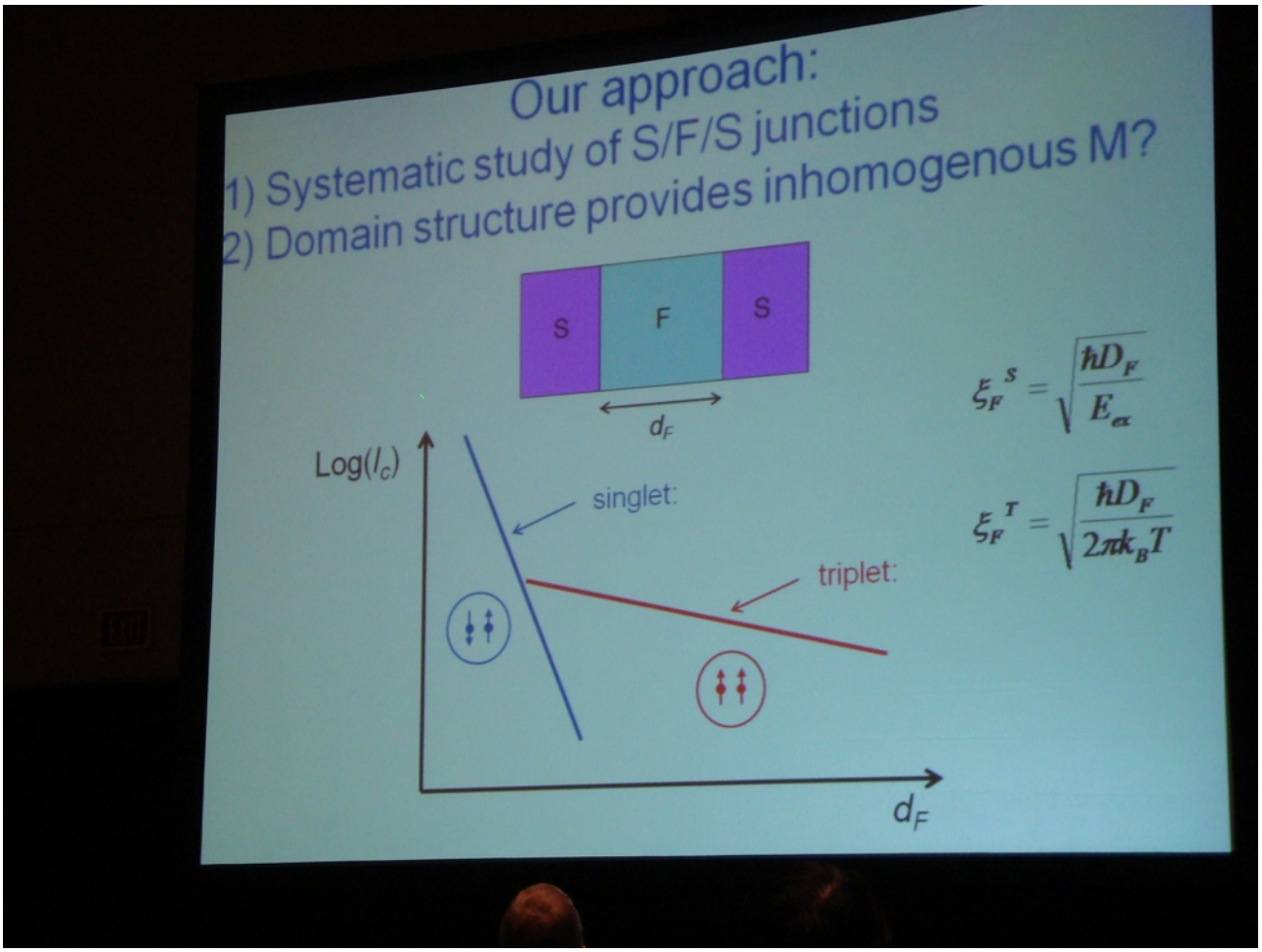


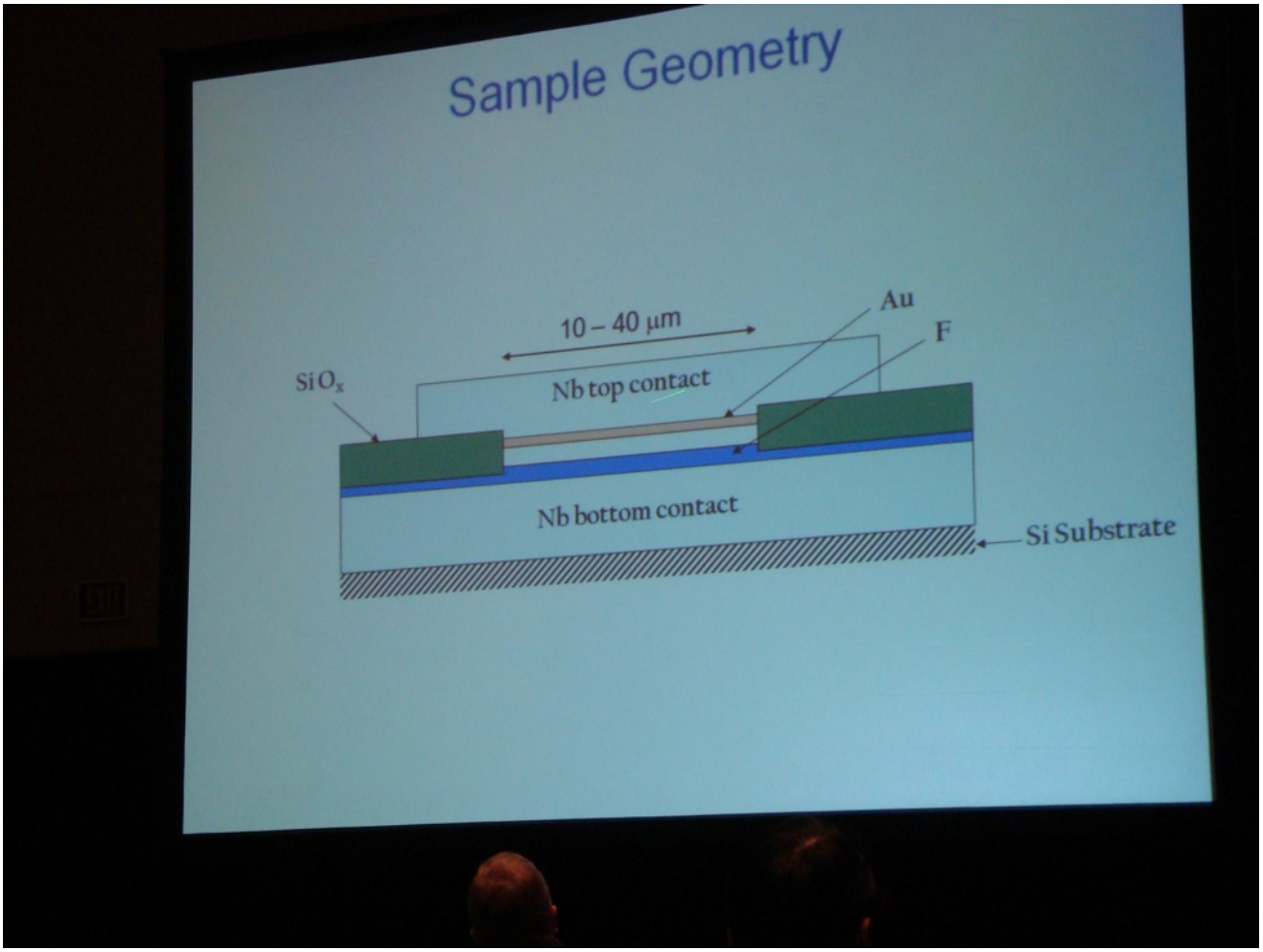


Long-range propagation of supercurrent,

but large sample-to-sample variations in I_c.

Reproduced last year by J. Aarts


Our approach:
1) Systematic study of S/F/S junctions
2) Domain structure provides inhomogenous M?
S
F
S
d_F
$\xi_F^S = \sqrt{\frac{\hbar D_F}{E_{ex}}}$
$\xi_F^T = \sqrt{\frac{\hbar D_F}{2\pi k_B T}}$
Log(I_c)
singlet:
triplet:
d_F


Sample Geometry
10 – 40 μm
Au
F
Si O_x
Nb top contact
Nb bottom contact
Si Substrate

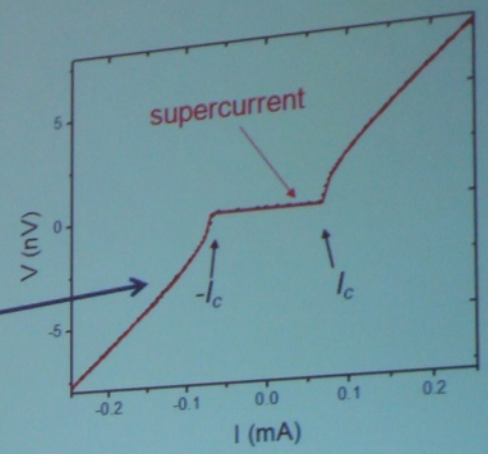
Measurement

Low sample resistance (7 – 100 μΩ)

→ Measure with SQUID-based current comparator circuit

I-V characteristic of overdamped Josephson junctions

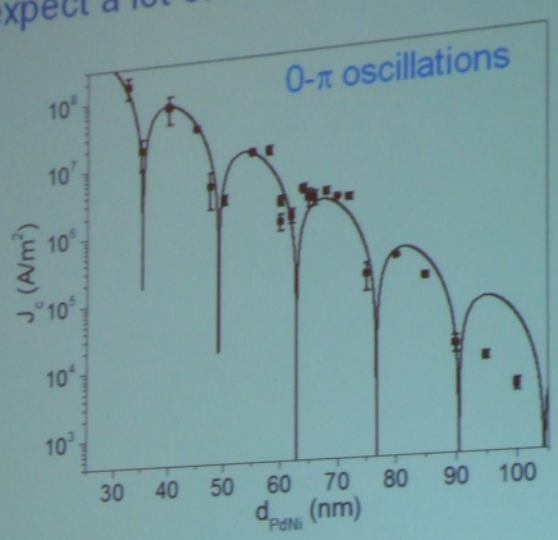
Measure at T = 4.2 K in "quick-dipper" cryostat in helium storage dewar

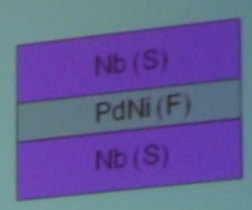


$I_c \equiv$ critical current

S/F/S junctions with a weak F: $Pd_{88}Ni_{12}$ alloy

(expect a lot of magnetic inhomogeneity)





Khaire, Pratt, and Birge, Phys. Rev. B 79, 094523 (2009)

Why don't we see spin-triplet supercurrent in S/F/S Josephson junctions with PdNi?

Too much spin-flip and/or spin-orbit scattering

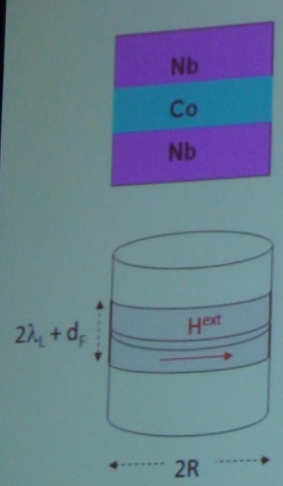
measured using Giant Magnetoresistance techniques

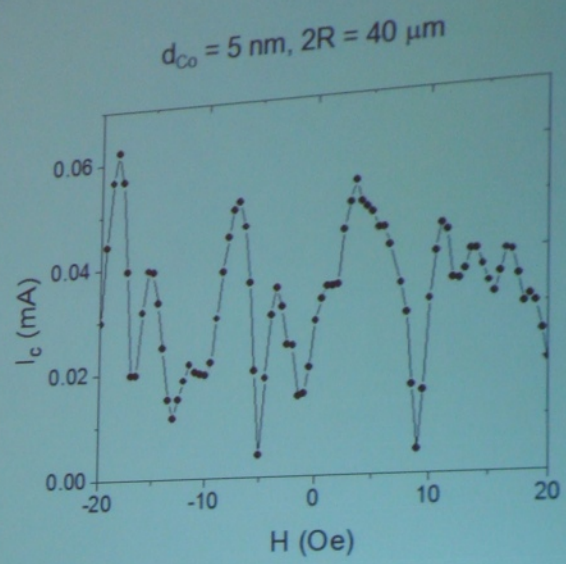
Arham, Khaire, Loloee, Pratt, & Birge, PRB 80, 174515 (2009)

Try a different approach:

Use a strong F with long spin-memory length: Co

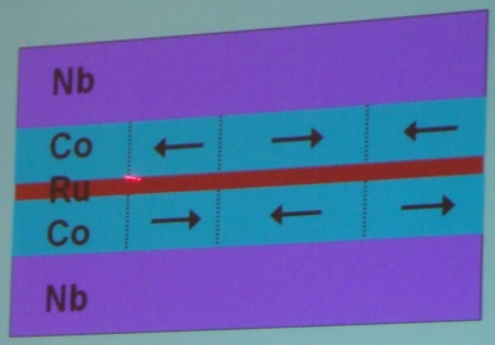
Large-area Nb/Co/Nb junctions





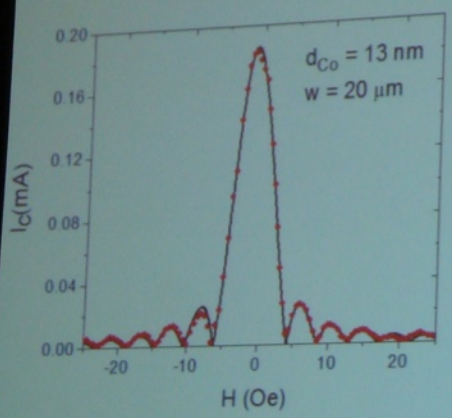
Random Fraunhofer pattern due to complex domain configuration

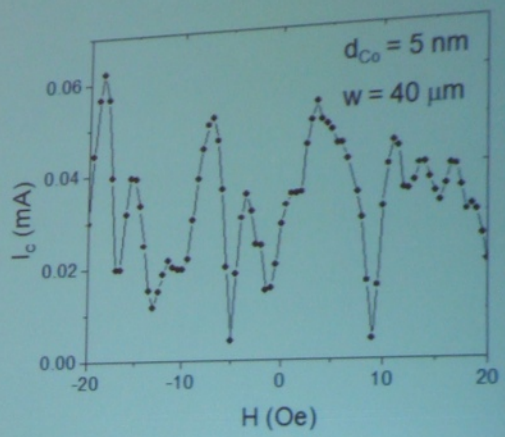
Trick: achieve flux cancellation with Co/Ru/Co synthetic antiferromagnet



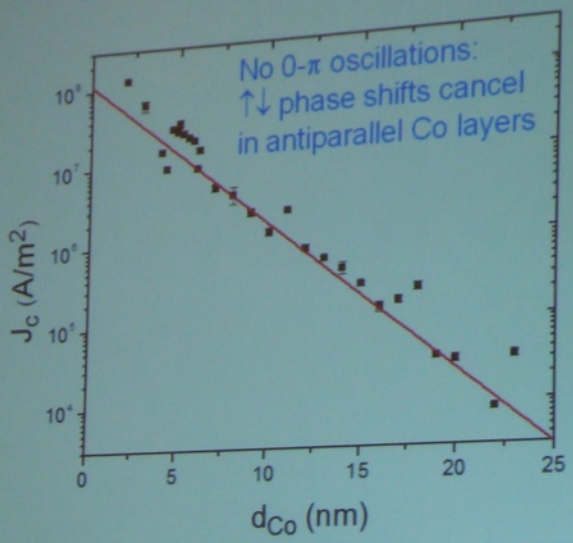
H.A.M. vandenBerg *et al.*, J. Mag. Magn. Mat. 165, 524 (1997).

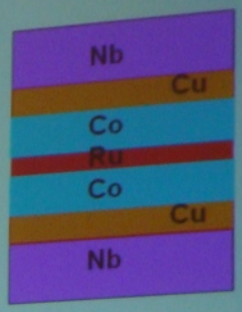
Co/Ru/Co synthetic antiferromagnet restores Fraunhofer pattern!





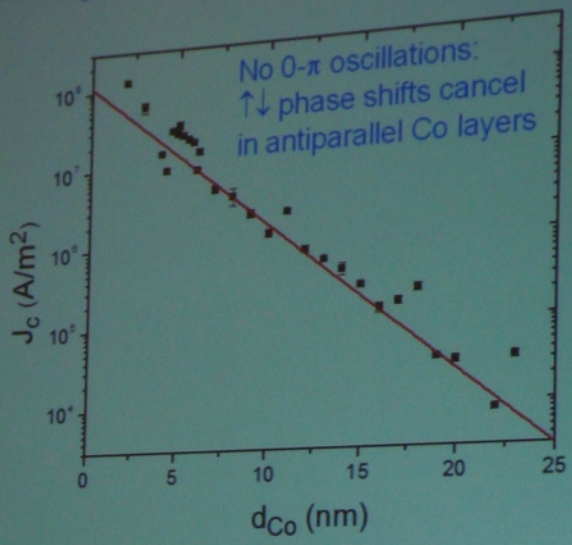
S/F/S junction with a strong F: Co

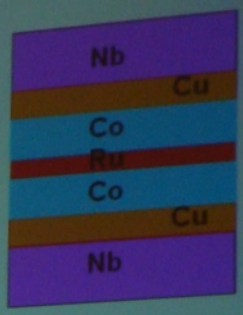




Khasawneh, Pratt, and Birge, Phys. Rev. B 80, 020506(R) (2009)

S/F/S junction with a strong F: Co





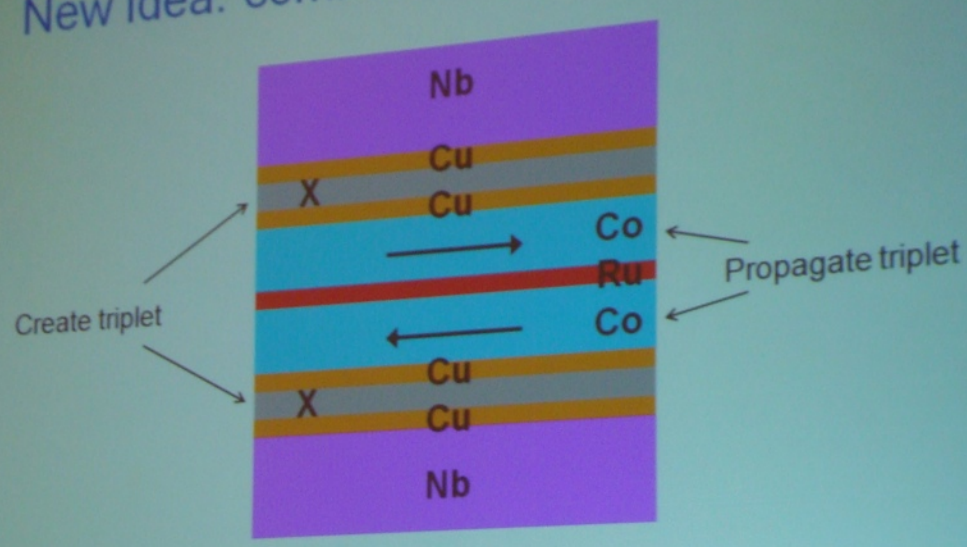
No sign of spin-triplet supercurrent!

Khasawneh, Pratt, and Birge, Phys. Rev. B 80, 020506(R) (2009)

Why haven't we seen spin-triplet correlations?

- PdNi
  - Inhomogeneous M ⇒ short spin memory length
  - Bad for propagation of triplet
  - Good for generation of triplet
- Co/Ru/Co
  - Homogeneous M
  - Bad for generation of triplet
  - Good for propagation of triplet

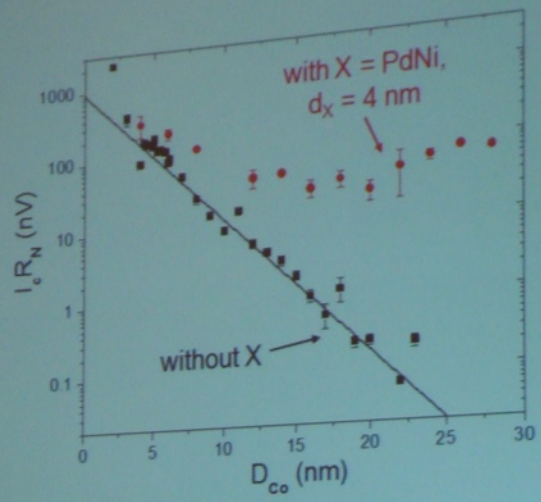
New Idea: combine best of two materials

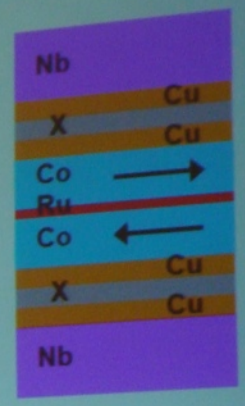


X = PdNi or CuNi alloy

(Cu buffer layers magnetically isolate X from Co)

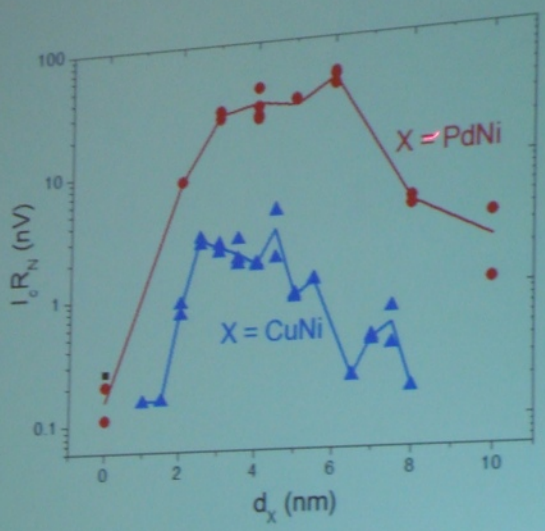
Finally, the triplet appears!

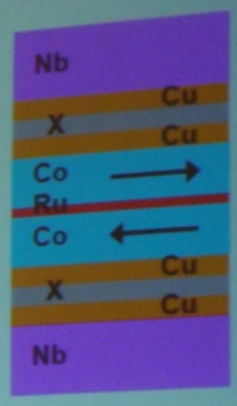




Khaire, Khasawneh, Pratt, & Birge, Phys. Rev. Lett. **104**, 137002 (2010)

Control amplitude of triplet with d_X

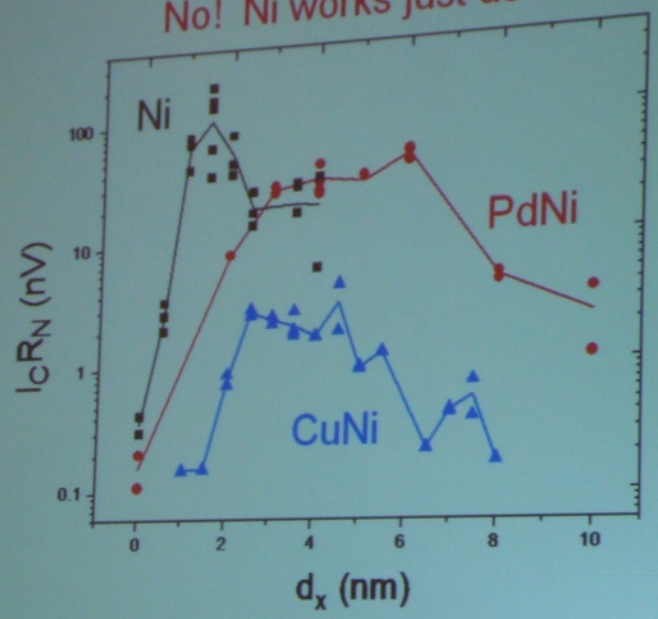




Khaire, Khasawneh, Pratt, & Birge, Phys. Rev. Lett. **104**, 137002 (2010)

Is it crucial to have inhomogeneous X layer?

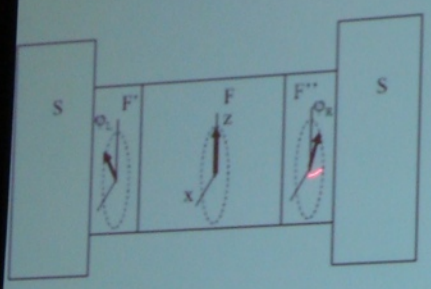
No! Ni works just as well.

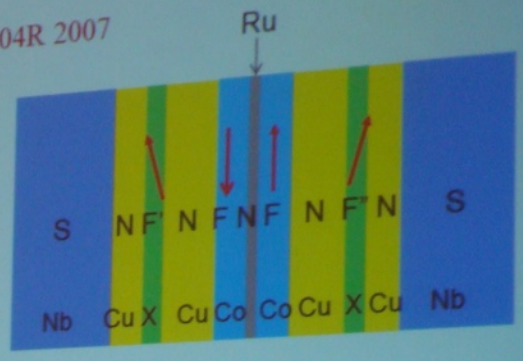


Khasawneh, Khaire, Klose, Pratt, & Birge, Supercond. Sci. Technol. **24**, 024005 (2011).

Mechanism for generating triplet

M. Houzet and A. I. Buzdin, PRB **76**, 060504R 2007



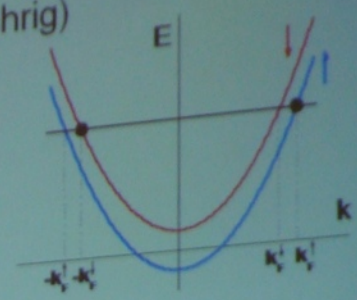


X = PdNi, CuNi, or Ni

F' and F" are <u>not</u> required to be inhomogeneous

Microscopic mechanism for triplet generation

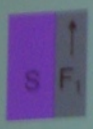
(from discussion with M. Eschrig)



$$|\psi\rangle = |0,0\rangle_z = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle e^{iQx} - |\downarrow\uparrow\rangle e^{-iQx}\right)$$

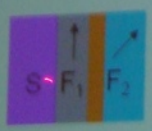
$$Q = k_F^{\uparrow} - k_F^{\downarrow}$$



$$= \frac{1}{\sqrt{2}}\left[\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)\cos(Qx) + i\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)\sin(Qx)\right]$$

$$= |0,0\rangle\cos(Qx) + |1,0\rangle_z \sin(Qx)$$

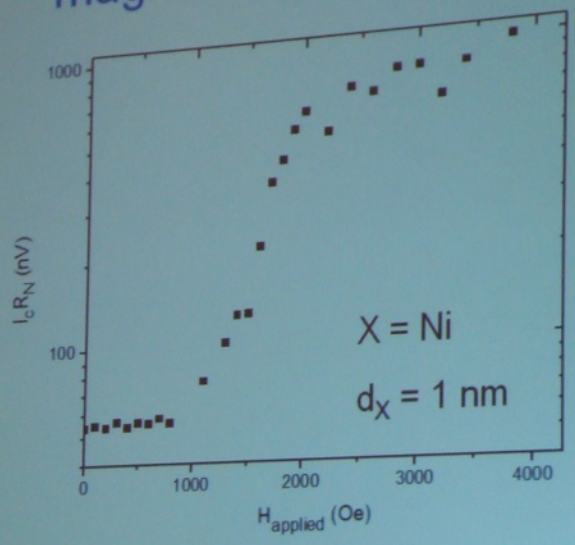
short-range triplet component



$$|1,0\rangle_z \rightarrow \begin{cases} |1,1\rangle_\theta = |\uparrow\uparrow\rangle_\theta \\ |1,0\rangle_\theta = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\uparrow\downarrow\rangle\right) \\ |1,-1\rangle_\theta = |\downarrow\downarrow\rangle_\theta \end{cases}$$

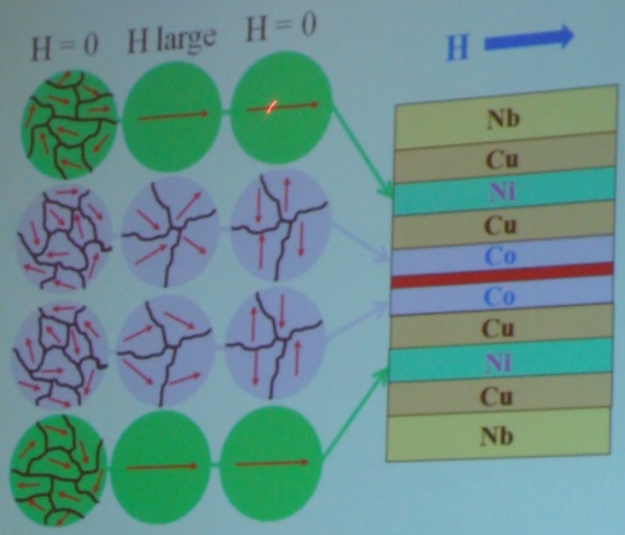
long-range triplet components

Does triplet disappear after we magnetize the samples?



No!!!

Co/Ru/Co undergoes "spin-flop" transition



Peculiar feature: these spin-triplet pair correlations are odd in frequency!

(idea of Berezinski in 1974)

	s=0	s=1
ℓ=0	BCS	S/F
ℓ=1	S/F	Sr_2RuO_4
ℓ=2	high-T_c	S/F

- s=1: pairs not subject to E_{ex}
  $\Rightarrow$ long-range penetration in F
- ℓ=0: insensitive to disorder

Bergeret, Volkov & Efetov, Rev. Mod. Phys. **77**, 1321 (2005)

Summary

- Experimental search for long-range supercurrent in S/F/S Josephson junctions:
  - F = PdNi: no triplet (too much spin-memory loss)
  - F = Co/Ru/Co: no triplet (not enough magnetic inhomogeneity)
  - F = X/Cu/Co/Ru/Co/Cu/X: clear signature of triplet
  - other options for F: see next talk
- New type of Fermion pairing occurs in S/F systems: odd-frequency, spin-triplet, s-wave.

Conclusions

- S/I_F/S strongly filters out singlet current
  - Singlet pairs have low tunneling probability
  - Domain walls seem to provide enhanced supercurrent
  - Mixers to create triplet currents => spin-polarised triplet current
- SFS triplet junction can be reliably created with Ho mixer layers
- Nb/Ho/Co/Al/Co/Ho/Nb junctions have relatively large triplet current
  - No mixer between Co and Al – therefore triplet pairs propagating in Al
  - Triplet pairs can extracted from ferromagnets – to be used to do spintronics
  - Suggestion that I_cR_n decreases at T_{cAl} but further research needed