Magnetization-Dependent T_c Shift in F/S/F Trilayers with a Strong Ferromagnet

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Collaborators:

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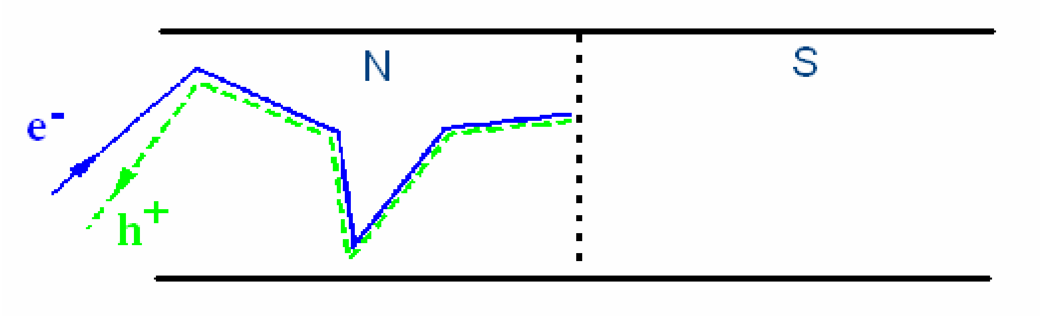
Work supported by NSF DMR

Andreev Reflection in N/S system



Coherence time

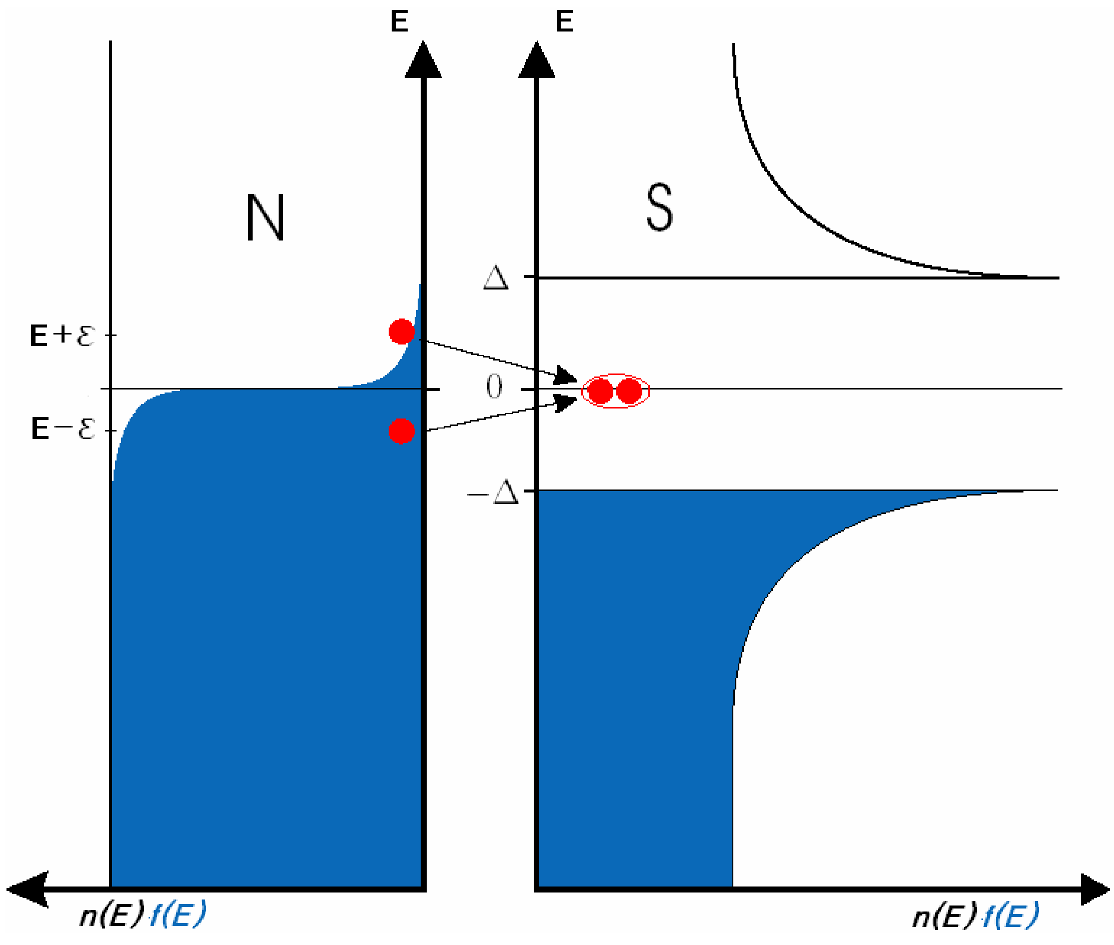
of electron and hole

$$\tau_\varepsilon = \hbar / 2\varepsilon$$

Distance traveled

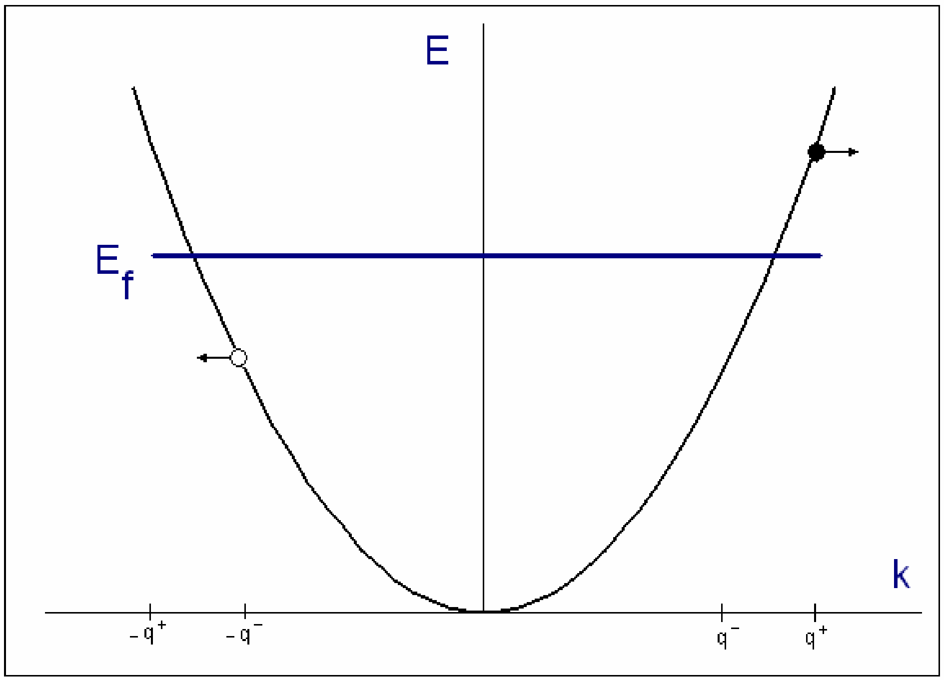
$$L_\varepsilon = \hbar v_F / \varepsilon$$ ballistic

$$L_\varepsilon = \sqrt{\hbar D / \varepsilon}$$ diffusive

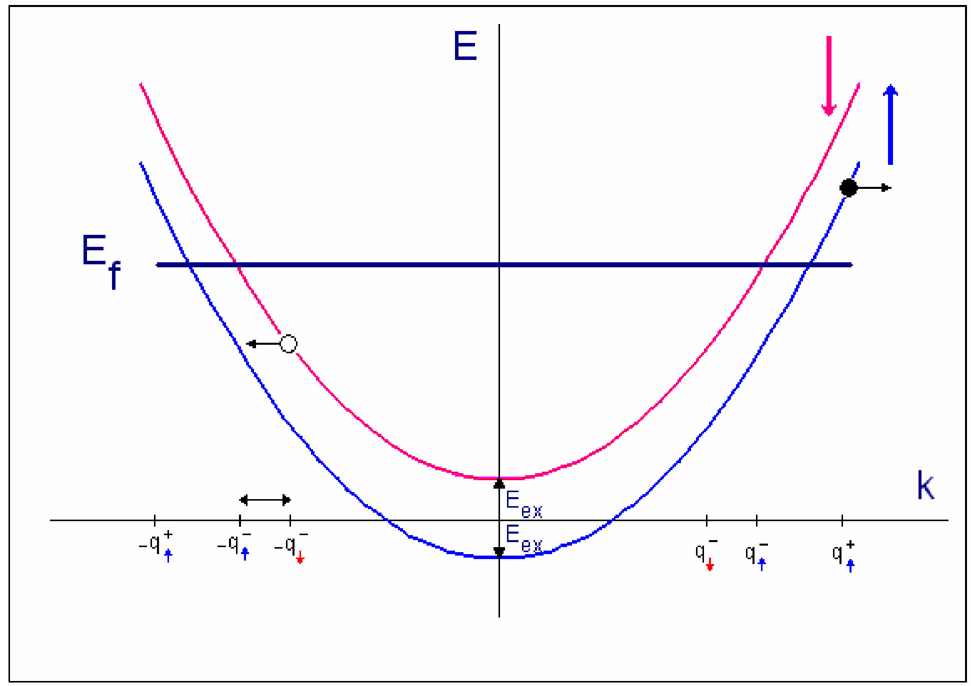


Andreev Reflection: N/S vs. F/S

N/S



F/S



$$k_F^{\uparrow} - k_F^{\downarrow} \equiv Q = 2\,E_{ex}/\eta v_F$$

Oscillation of order parameter in F on length scale:

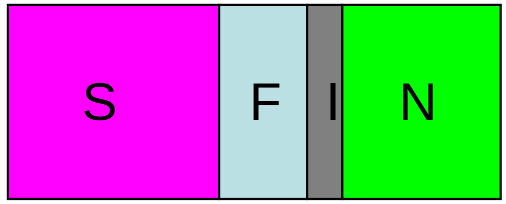
$$\xi_F = \frac{\eta v_F}{E_{ex}}$$

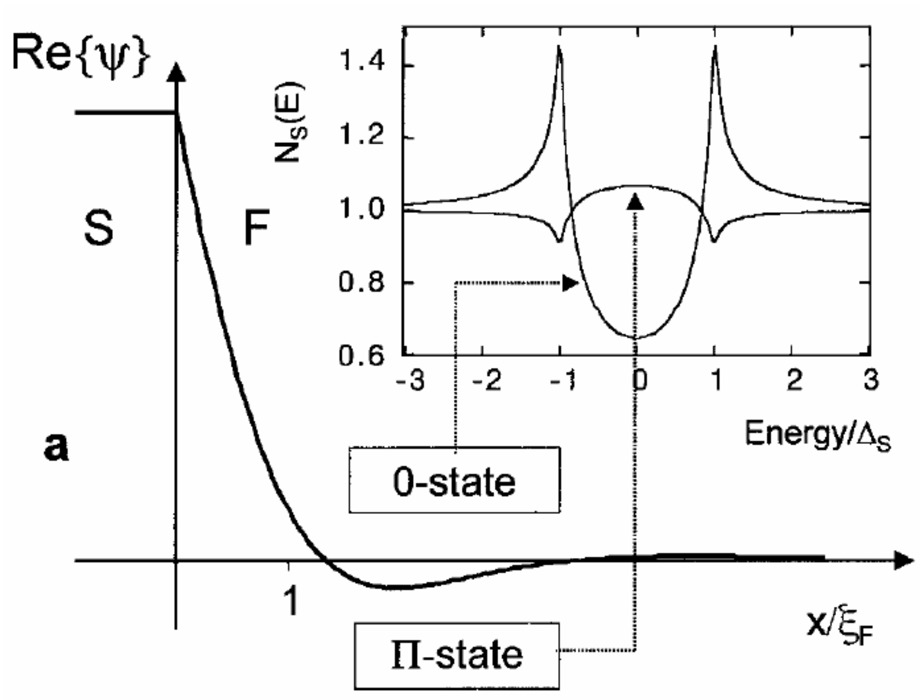
ballistic

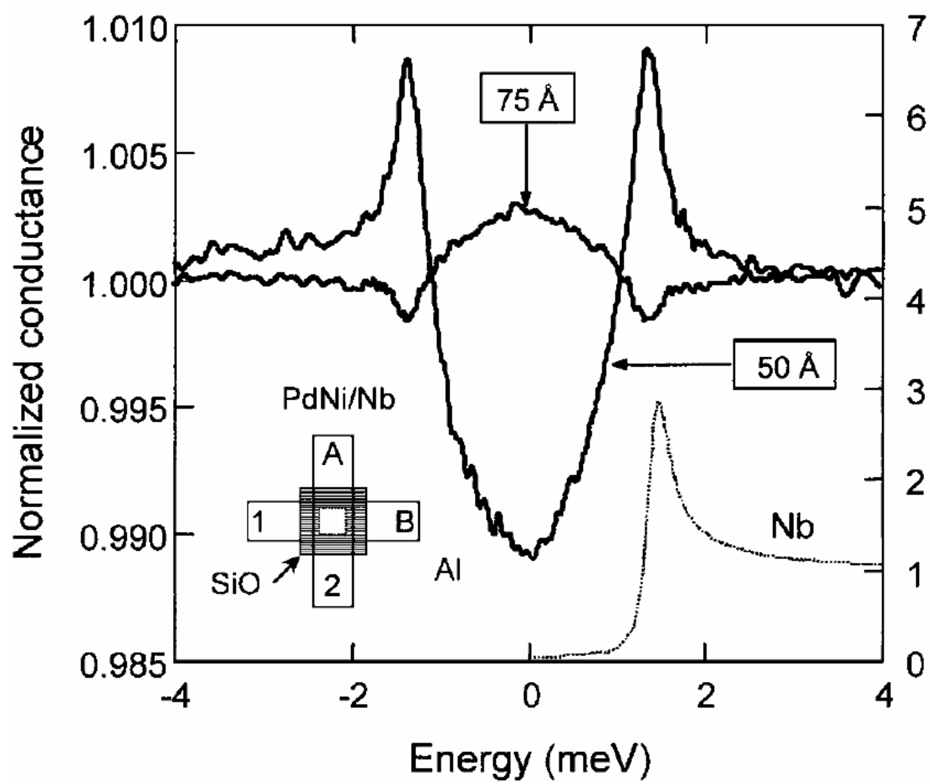
$$\xi_F = \sqrt{\frac{\eta D_F}{2\pi E_{ex}}}$$

diffusive

Density of states on F-side of S/F bilayer

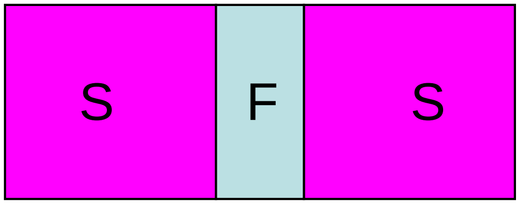


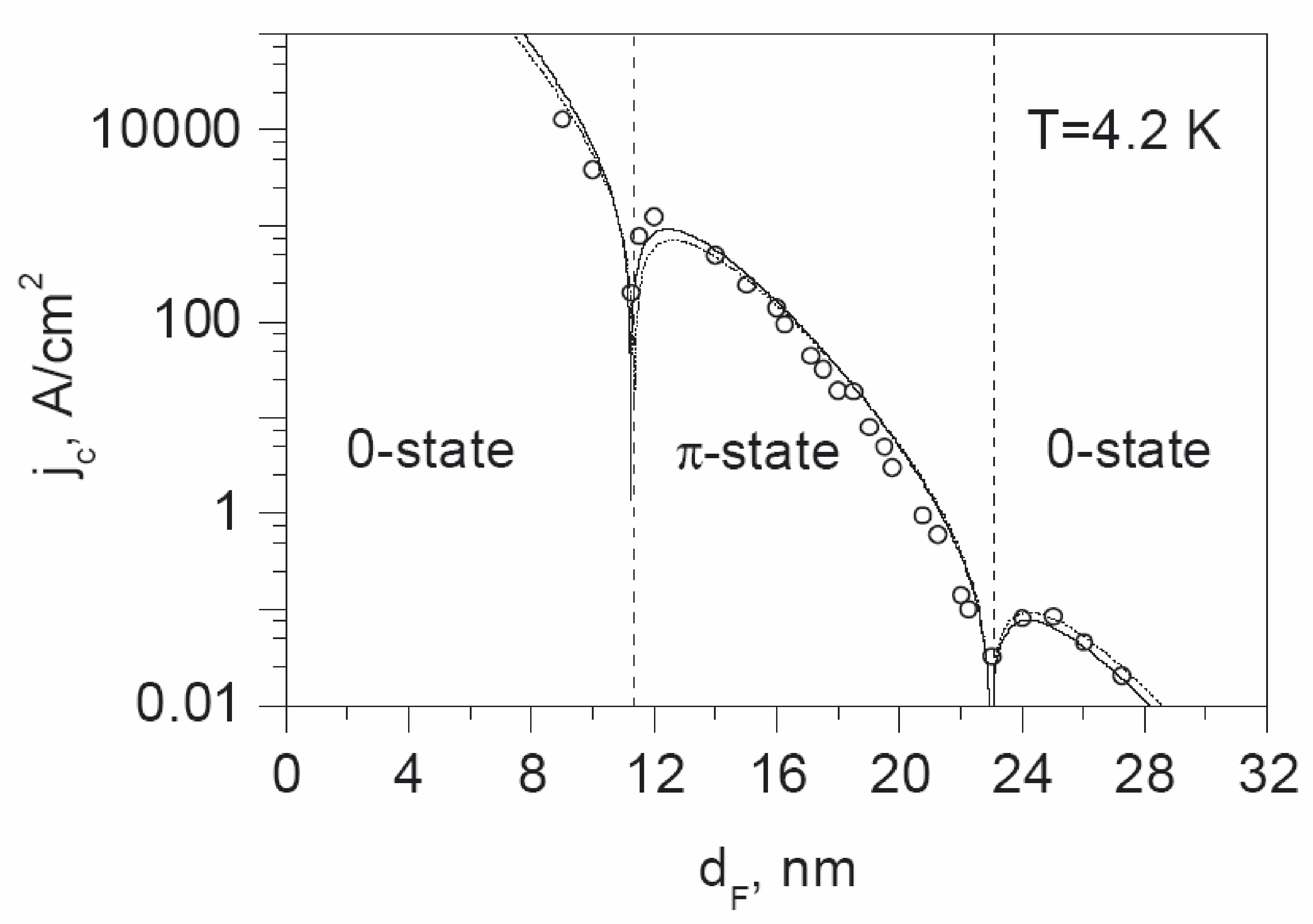




Kontos *et al.*, Phys. Rev. Lett. **86**, 304 (2001)

S/F/S π-junctions



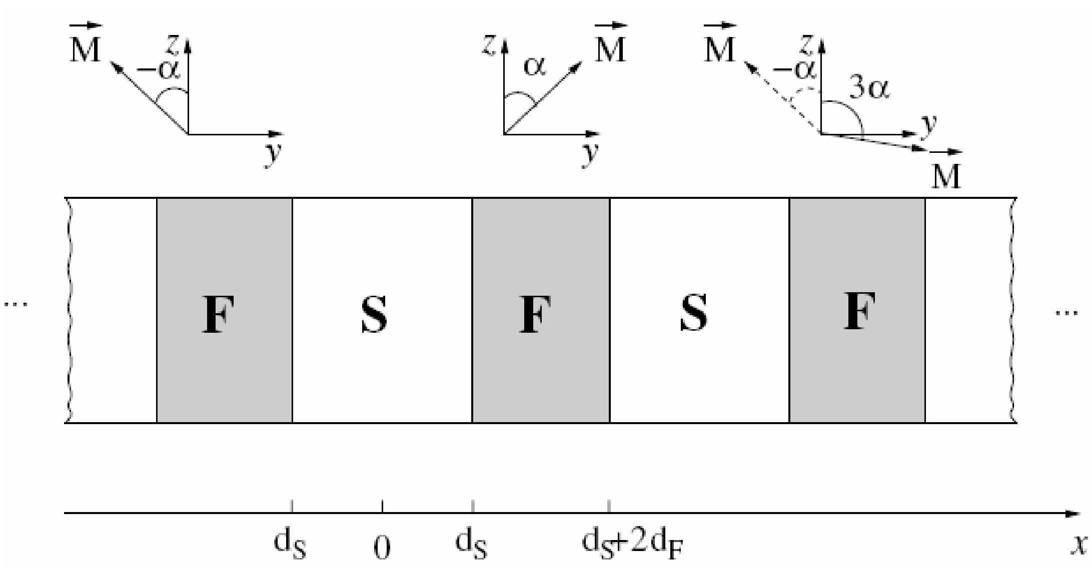


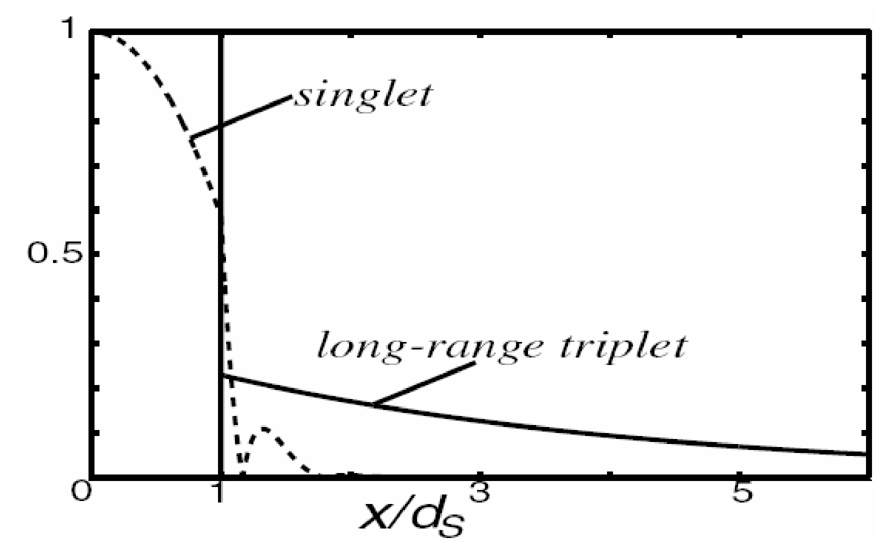
Ryazanov *et al.,* Phys. Rev. Lett. **86**, 2427 (2001)

Oboznov *et al.,* cond-mat/0508573

Prediction: induced triplet superconductivity in F/S/F with noncollinear magnetizations

Volkov, Bergeret, & Efetov, PRL 90, 117006 (2003); PRB 68, 064513 (2003)





Triplet: long-range proximity effect in F:

Singlet

$$\xi_F^{SC} = \sqrt{\frac{\hbar D_F}{2\pi E_{ex}}}$$

Triplet

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

$$\xi_F^{SC} << \xi_F^{TC}$$

Experimental requirements to observe induced triplet superconductivity

- $d_F >> \xi_F^{SC}$
  - singlet order parameter is suppressed
- $d_S \sim d_S^{cr}$
  - If d_S too small, $T_c = 0$
  - If d_S too large, no effect of ferromagnets
- $d_F << l_{sf}^F$
  - spin-flip or spin-orbit scattering in F kill triplet

Difficult!

Test options with preliminary experiment:

T_c of FSF Trilayers with P and AP Mutual Orientations

"superconducting spin switch"

Predicted by Tagirov; Buzdin, Vedyayev, & Ryzhanova (1999).

Observed by Gu *et al.* (2002) using dilute $Cu_{1-x}Ni_x$ alloy in CuNi/Nb/CuNi system

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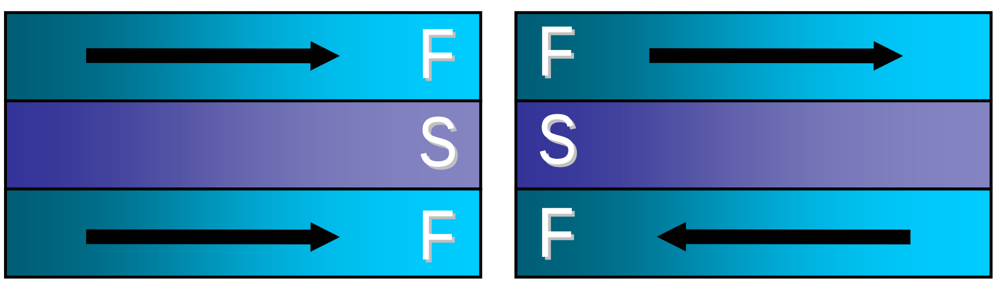
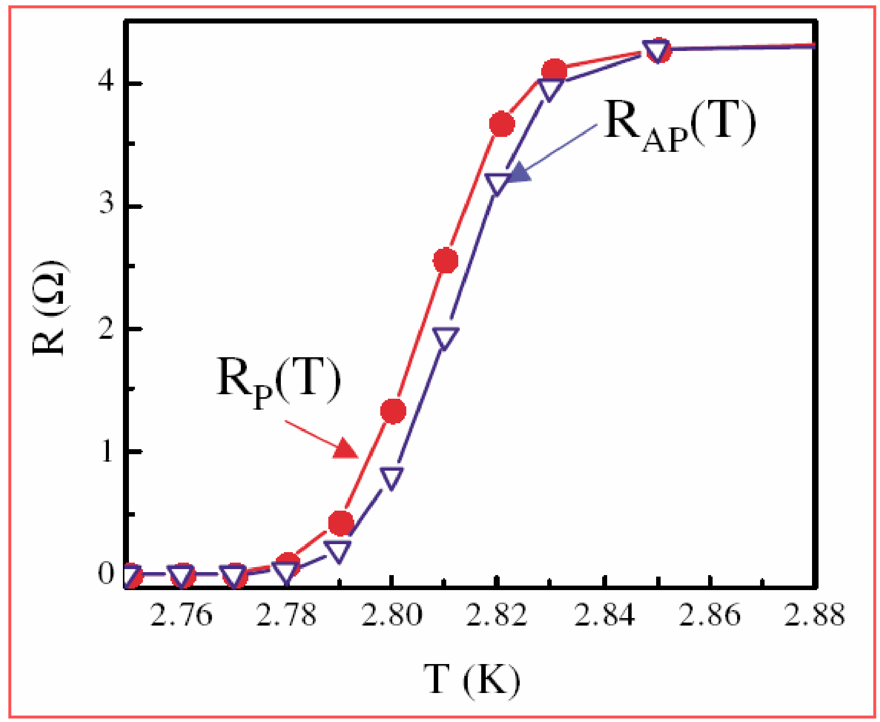


T_C (P) < T_C (AP)



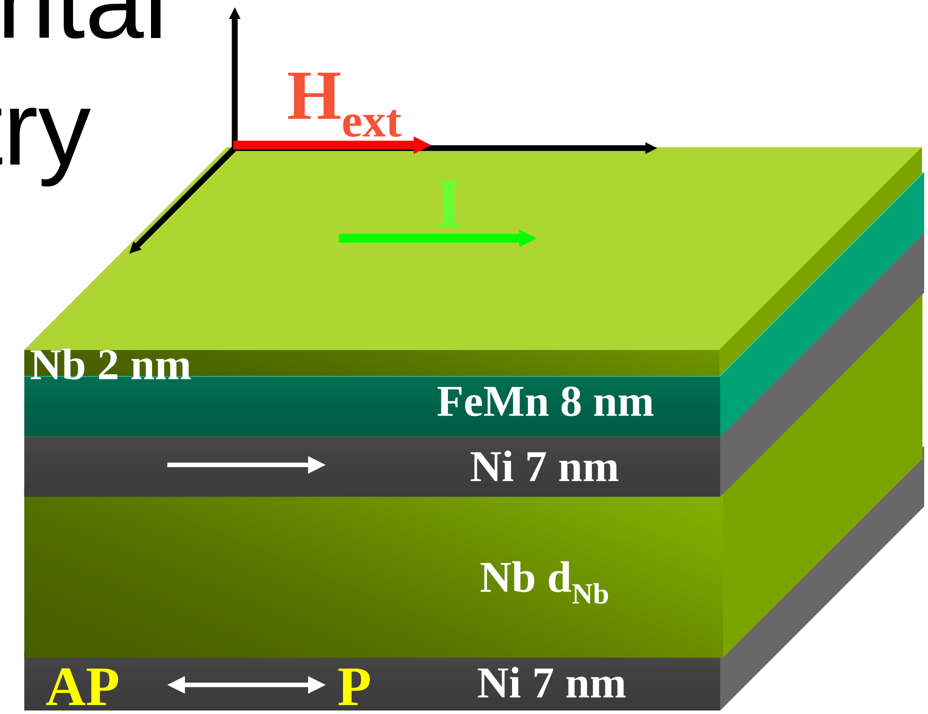
☟T_c = T_c^{AP} – T_c^{AP} 🕓 6 mK

Our approach

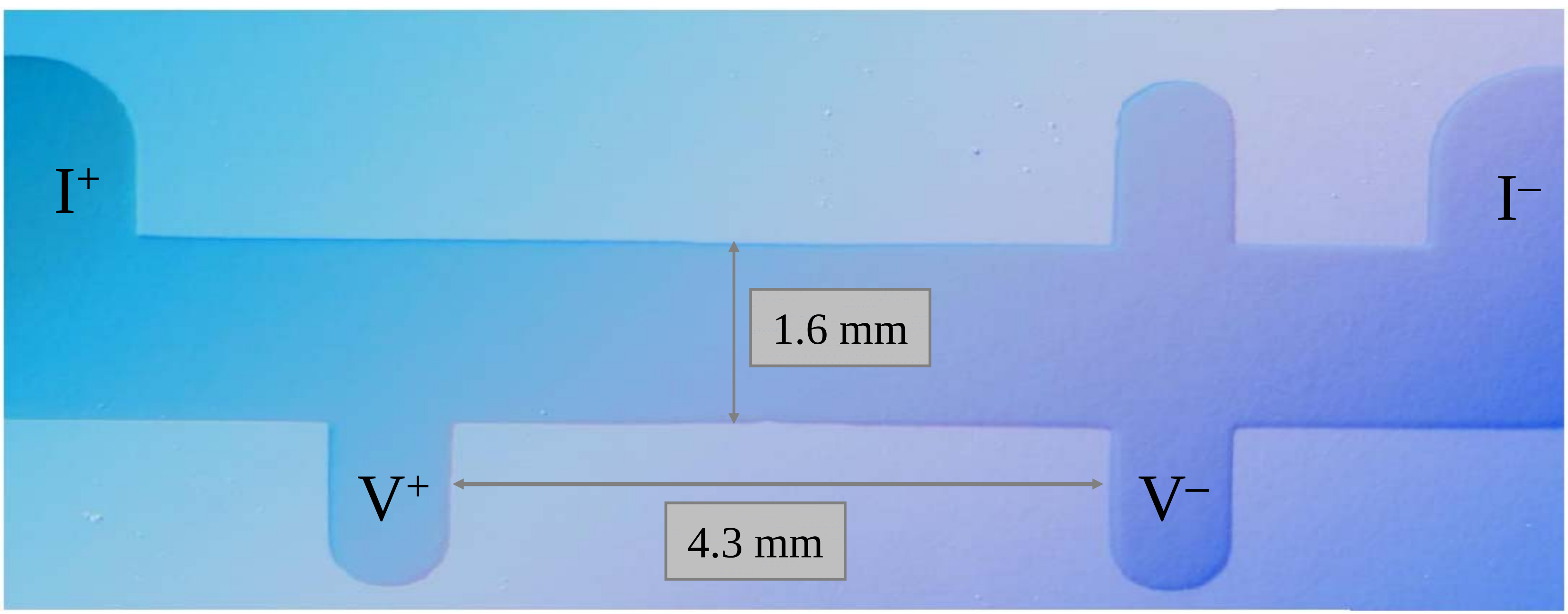
- Strong, Pure Ferromagnets
  - Less spin-flip and spin-orbit scattering than magnetic alloys?
  - Most pure ferromagnets are strong (Fe, Ni, Co)
  - Push theory to treat majority & minority spin bands: $n(E_F)$, v_F
  - Can we obtain large F/S effects?

- Thick Ferromagnet limit
  - Avoid difficulties with thin F (inhomogeneities, dead layer, lower Curie temperature)
  - Future: anticipate long-range proximity effect with triplet SC

Experimental Geometry

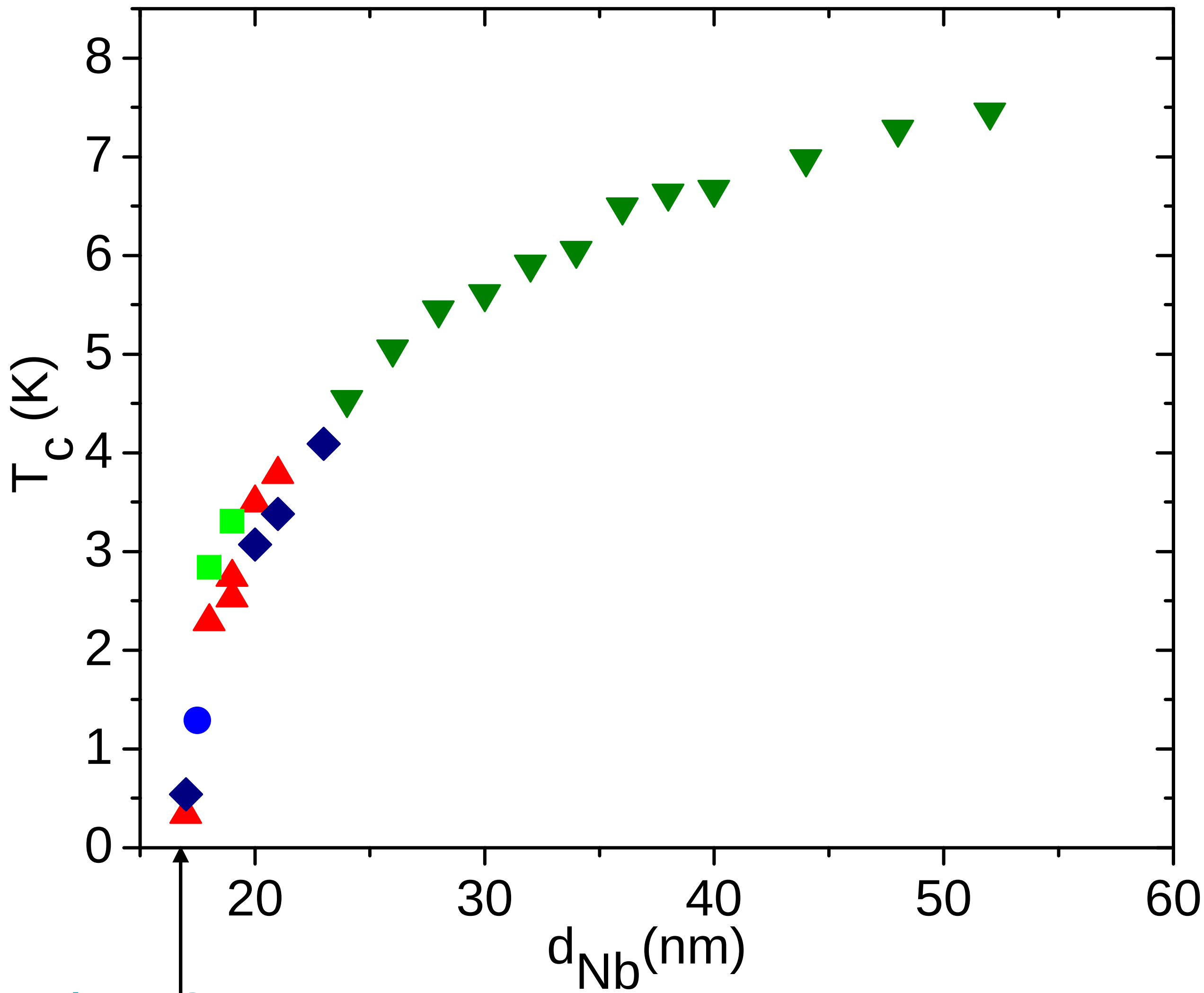


Current In Plane
4-Terminal Resistance
Measurement



T_C vs. d_{Nb}

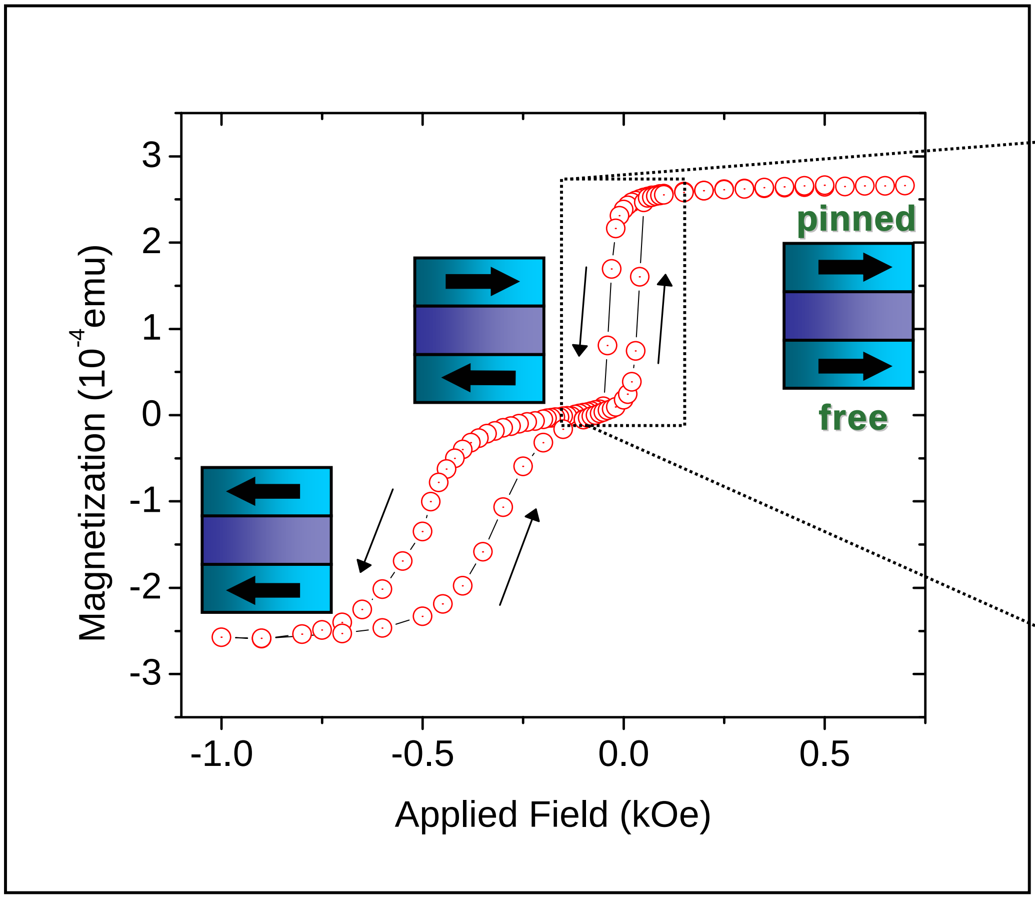
Ni(8)Nb(d_{Nb})Ni(8)FeMn(8)Nb(2)



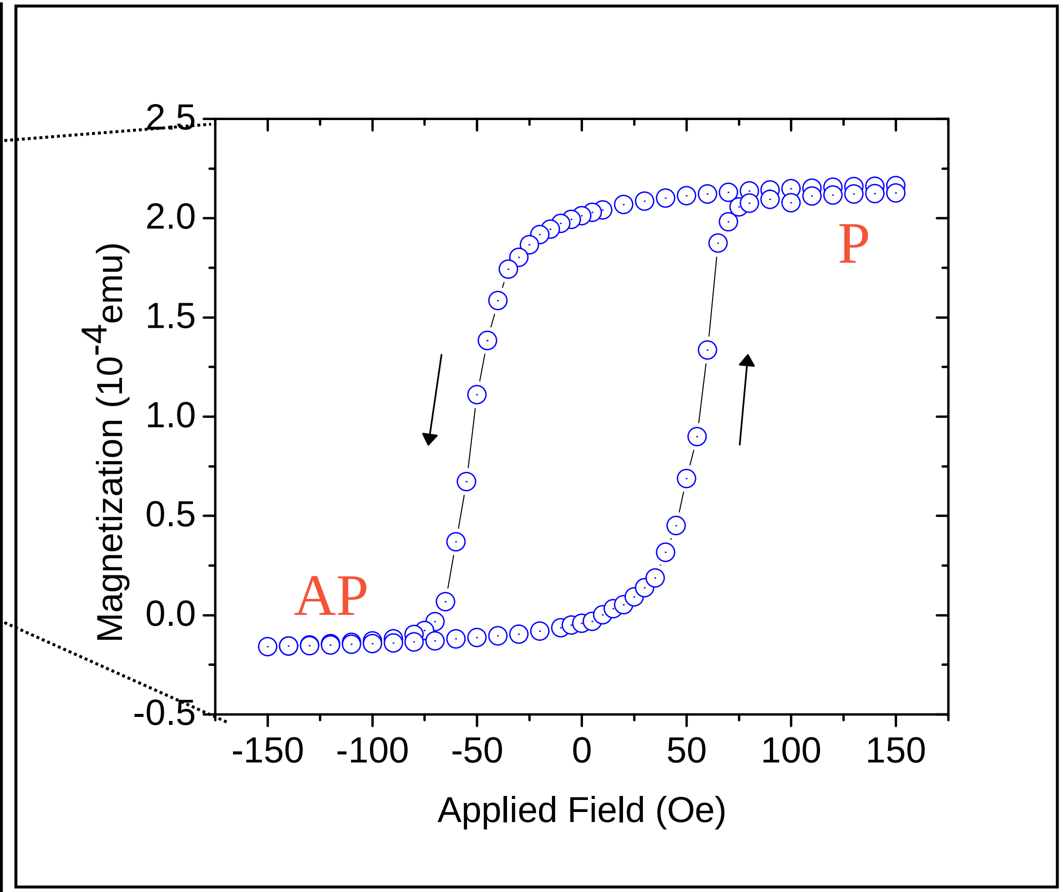
d_{Nb}^{cr} 🕔 16.5 nm

M vs. H

$d_{Nb} = 20$ nm

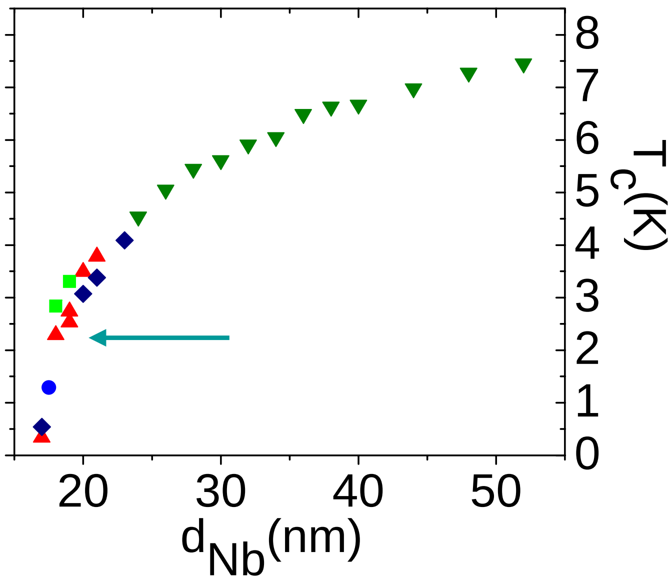


T = 100 K



T = 2.84 K

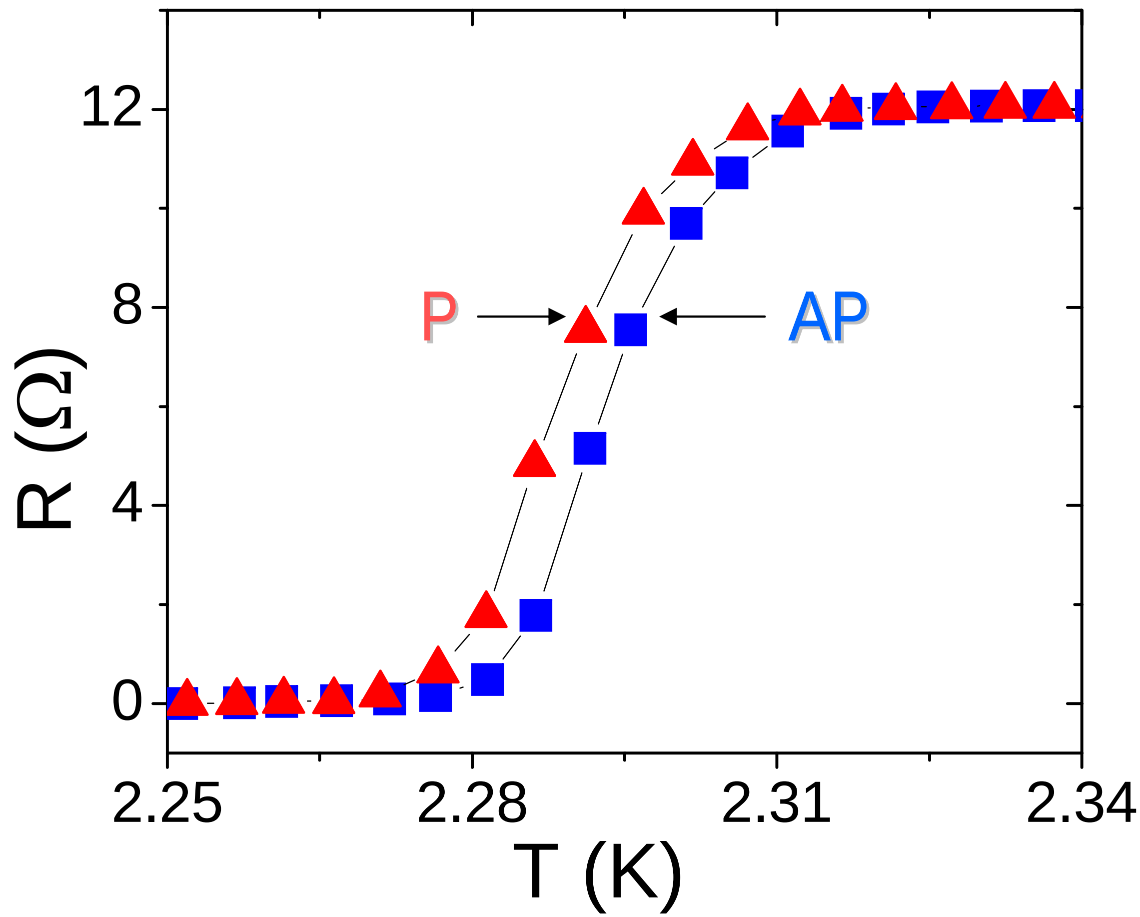
R vs. T



d_{Nb} = 18 nm

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

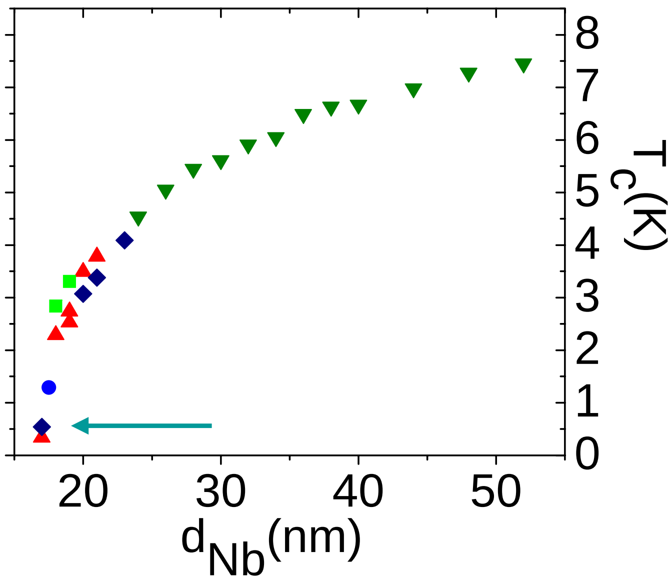
6 mK



T_C (P) < T_C (AP)

To get larger ΔT_c, make S layer thinner

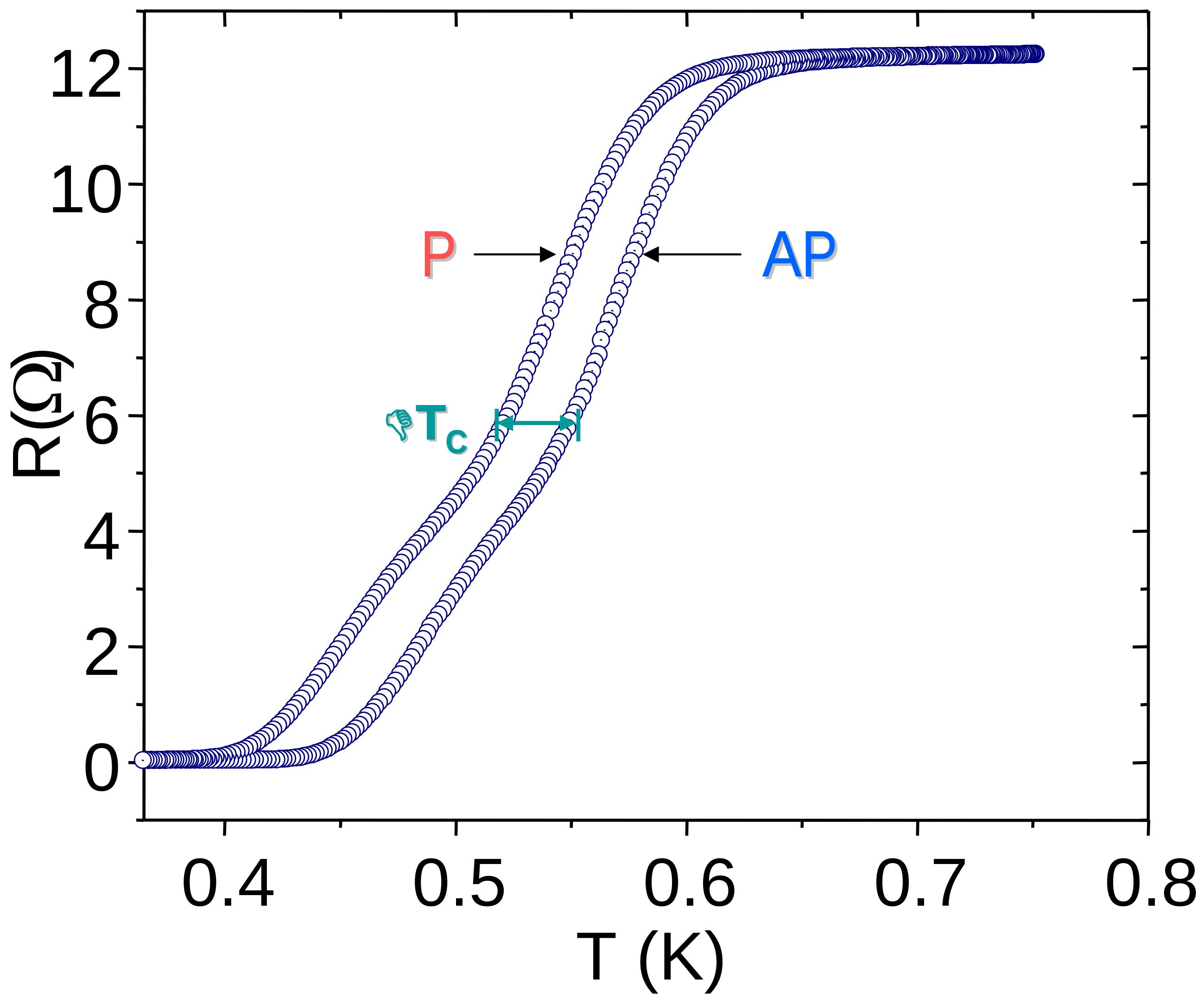
R vs. T



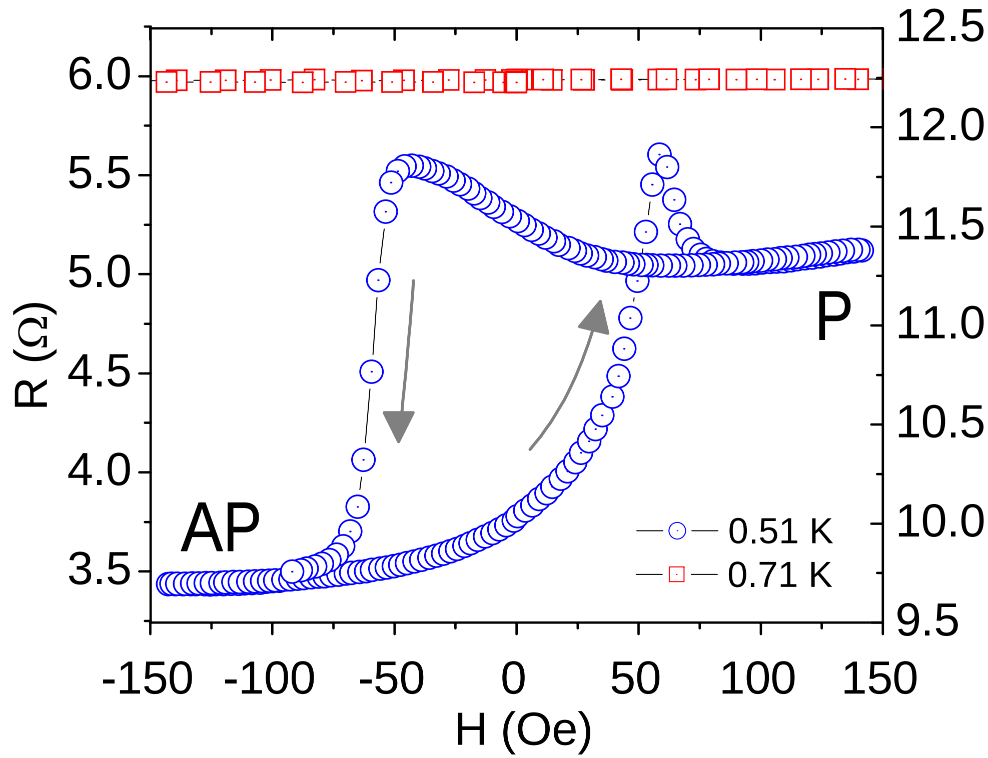
d_{Nb} = 17 nm

ΔT$_C$ = T$_C$^{AP} - T$_C$^{P}

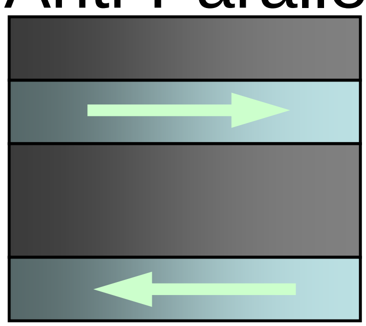
30 mK



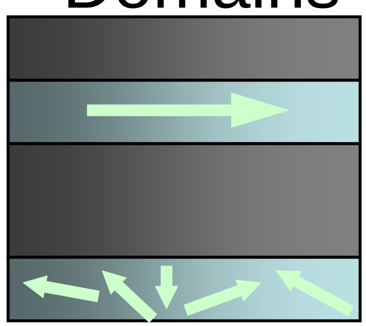
R vs. H



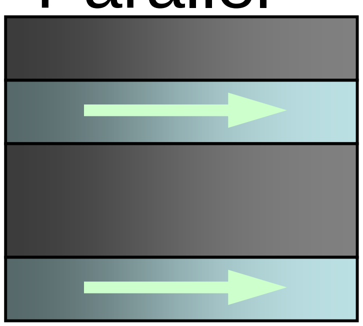
- Anti-Parallel



Domains



Parallel



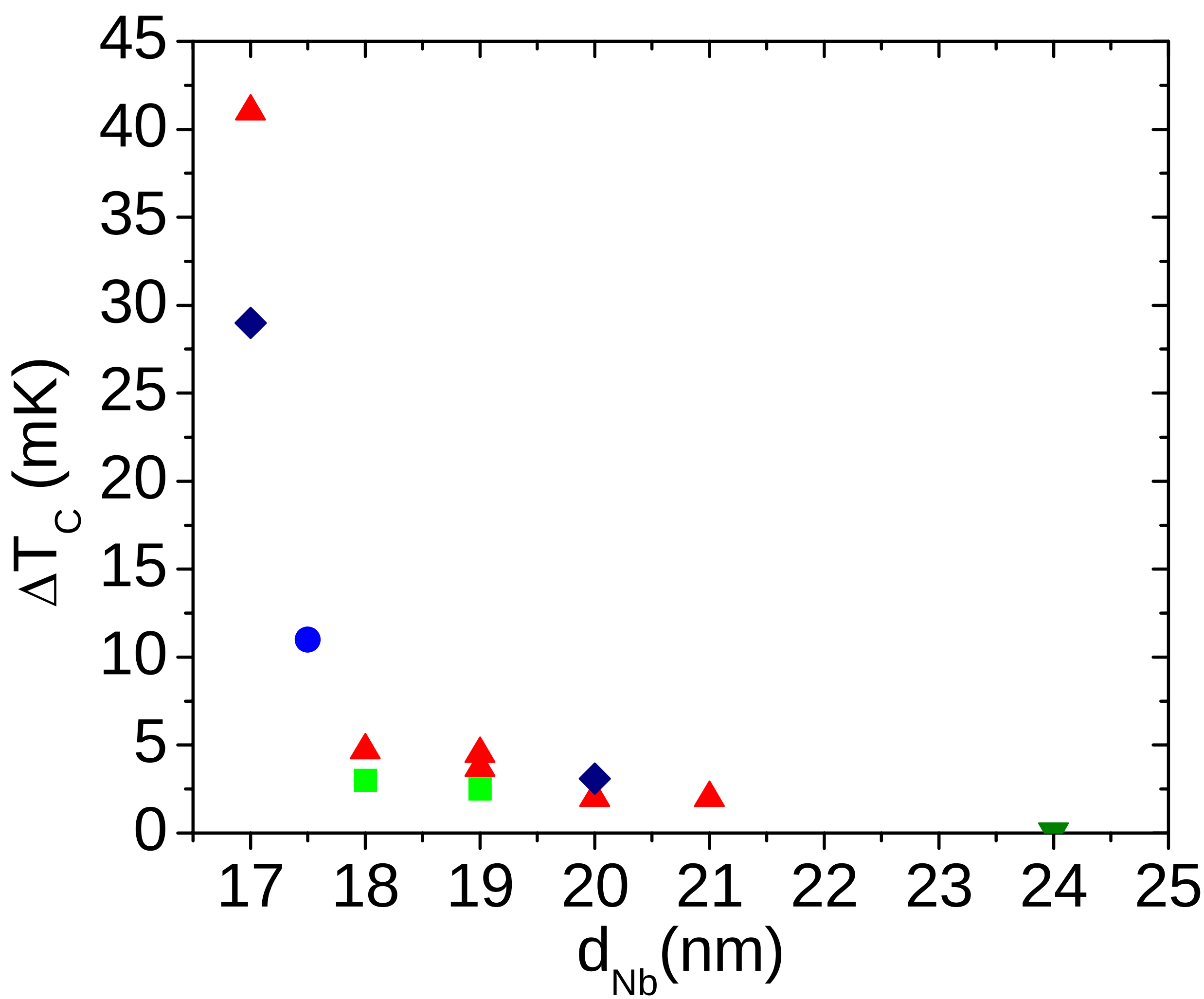
- H ~ -100 Oe

H ~ ± 10-50 Oe

H ~ +100 Oe

T_C vs. d_{Nb}

Ni(8)Nb(d_{Nb})Ni(8)FeMn(8)Nb(2)



Theory of T_c^P vs. T_c^{AP} in F/S/F

Tagirov, PRL 83, 2058 (1999); Physica C **307**,145 (1998)

Baladie & Buzdin, Phys. Rev. B 67 014523 (2003)

Fominov, Golubov & Kupriyanov, JETP Lett. 77, 510 (2003)

You *et al.*, Phys. Rev. B 70, 014505 (2004)

…

None of these treat strong ferromagnets with:

$$n^{\uparrow}(E_F) \neq n^{\downarrow}(E_F)$$

$$v_F^{\uparrow} \neq v_F^{\downarrow}$$

Try "clean limit" theory from

Tagirov, Physica C **307**,145 (1998)

FSF Critical Temperature

$$\ln t_C + \Re e \, \Psi\left(\frac{1}{2} + \frac{2\phi^2}{t_C (d_S / \xi_S)^2}\right) - \Psi\left(\frac{1}{2}\right) = 0$$

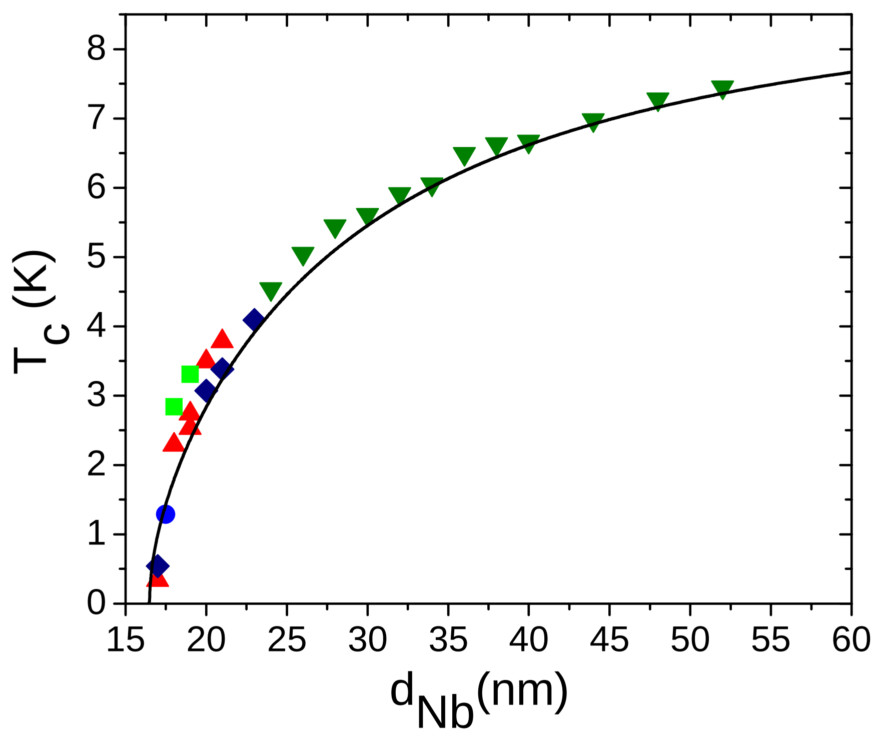
$$t_C \equiv T_C / T_{C0}$$

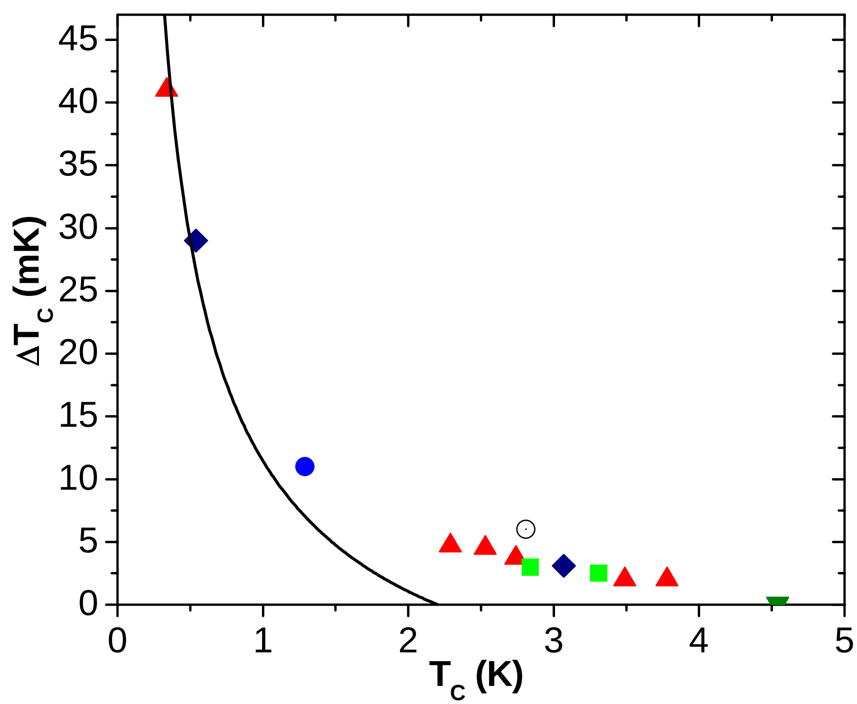
T_{C0}: Free Nb films

$$\phi^{P,\,AP} = \phi\left(\frac{d_S}{\xi_S}, \frac{\xi_F}{l_F}, \frac{N_F v_F \xi_S}{N_S D_S}, T\right)$$

- ξ_S: H_{C2} vs. T
- l_F: E_{ex}, ❒
- N_S: Literature
- T: Transparency constrained by d_S^{cr}

Theoretical Fits





$$\left(\frac{N_F v_F \xi_S}{N_S D_S (d_S^{cr})} \right) \Big/ (1 + 2/T) = const.$$

$$\xi_F / l_F = 0.7 \qquad T = 1.0$$

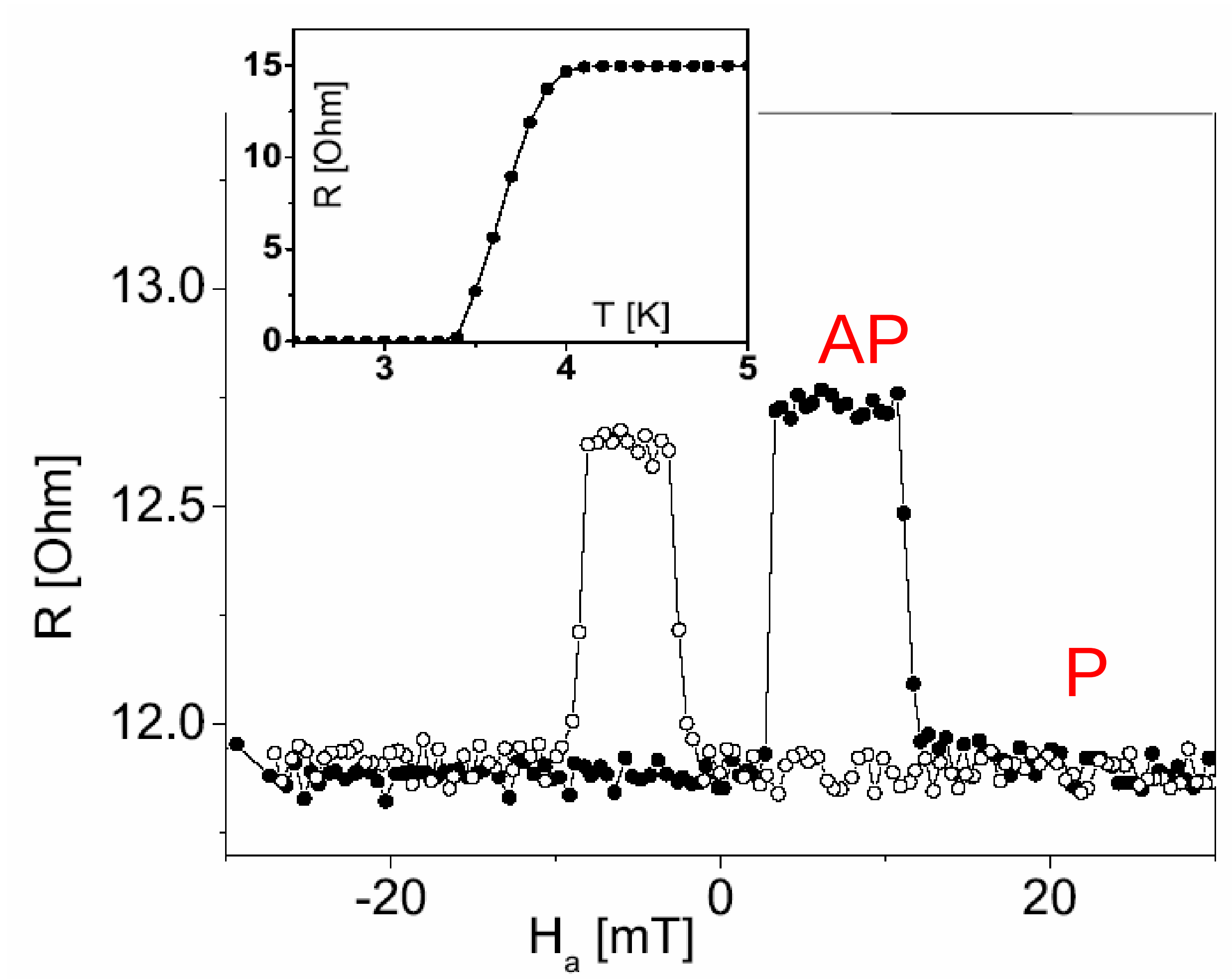
- Theory not suited for strong ferromagnets systems (majority and minority spin bands DOS and Fermi velocities)

Just when you thought everything was under control …

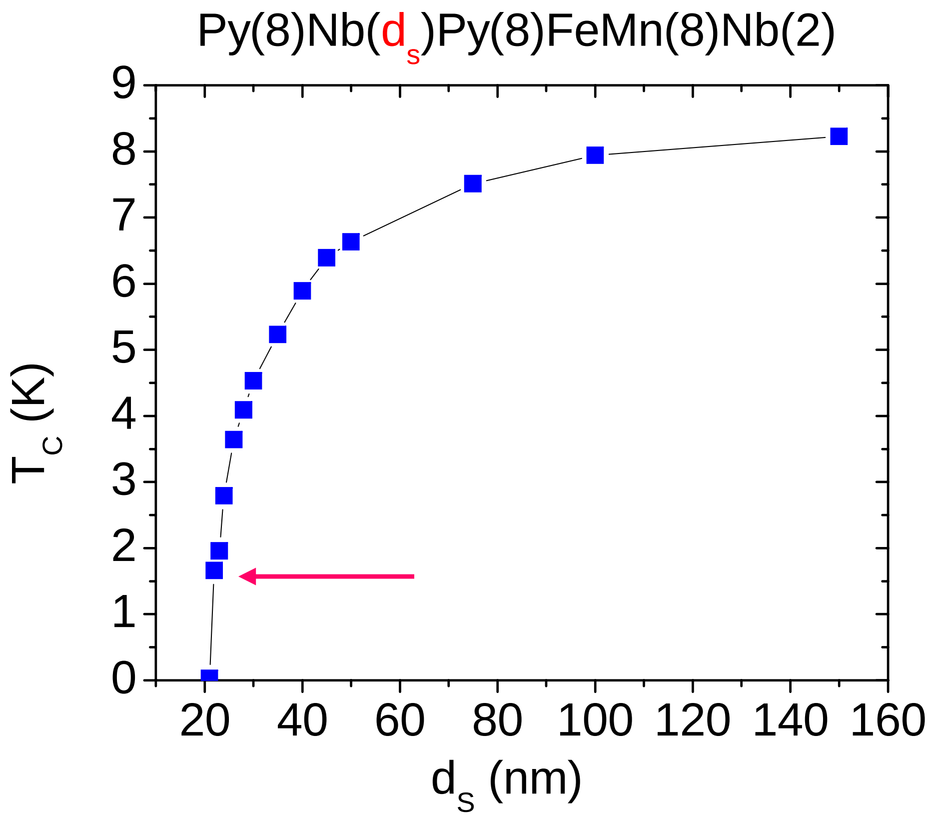
Rusanov, Habraken, & Aarts, cond-mat/0509156

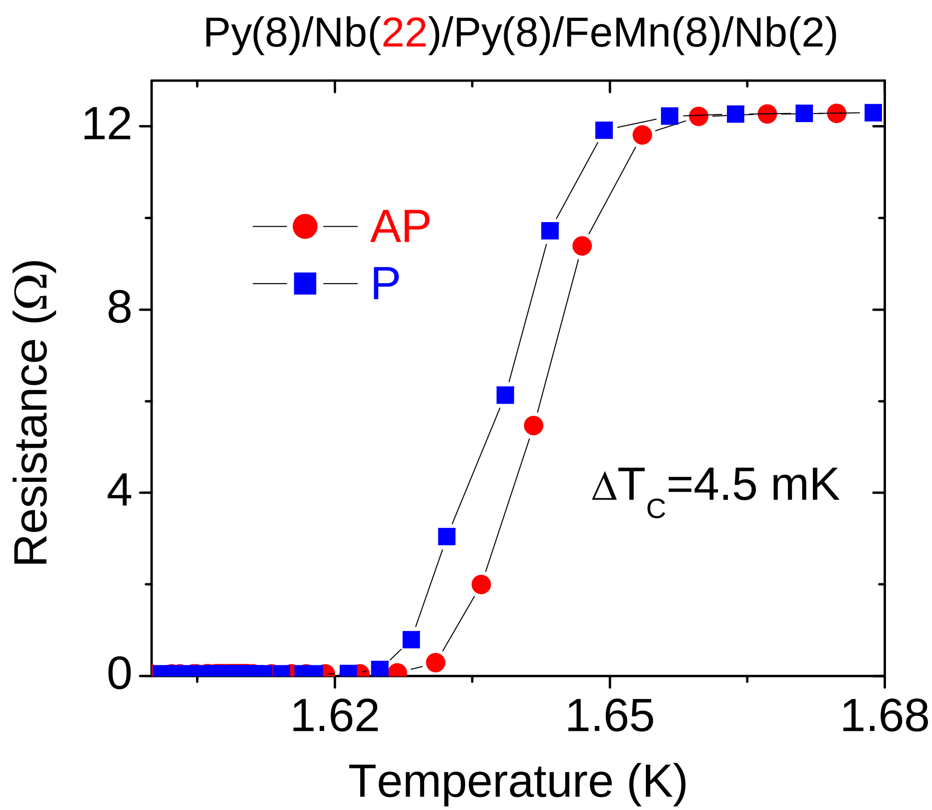
Py/Nb/Py trilayer

$T_c^P > T_c^{AP}$!!



Our preliminary data on Py/Nb/Py spin valves



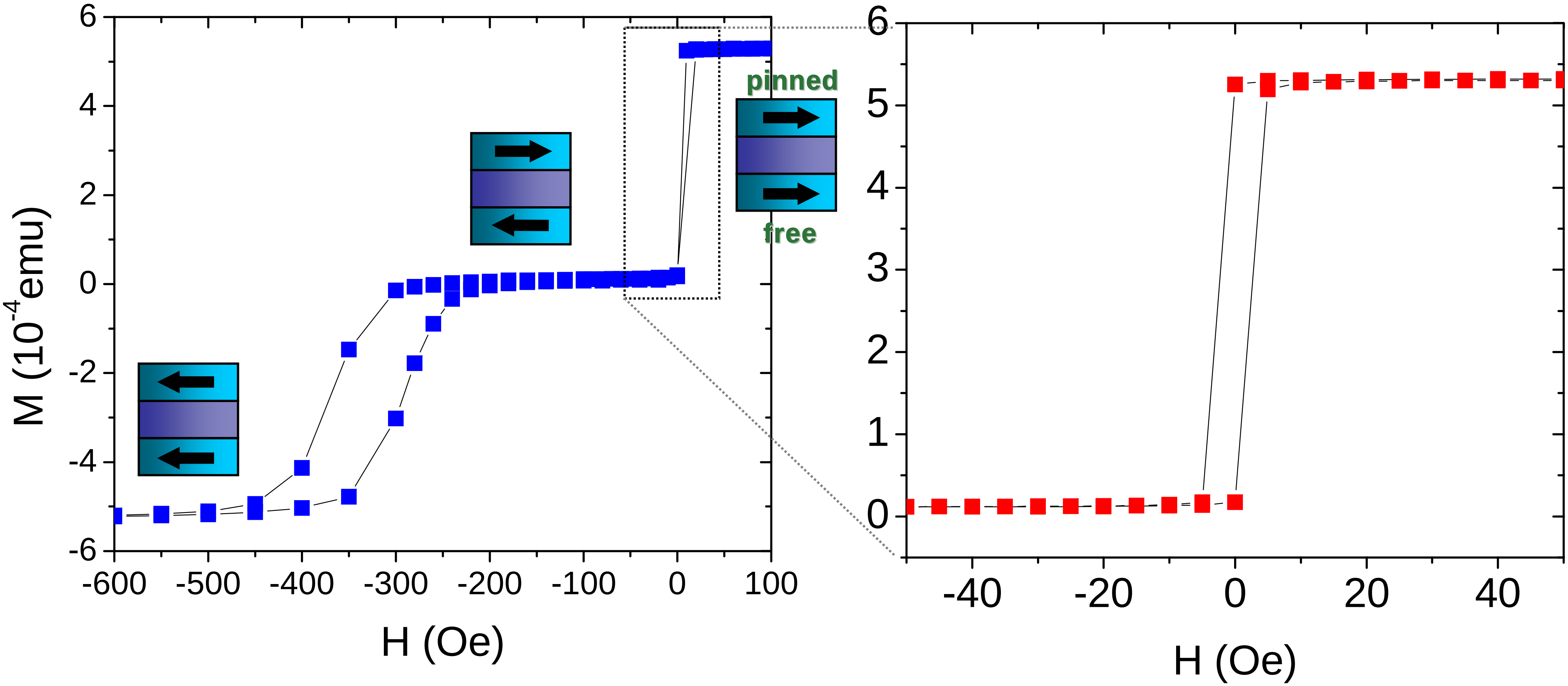


$T_c^P < T_c^{AP}$

Same as Ni/Nb/Ni spin valves

M vs. H

Py(8)Nb(28)Py(8)FeMn(8)Nb(2)



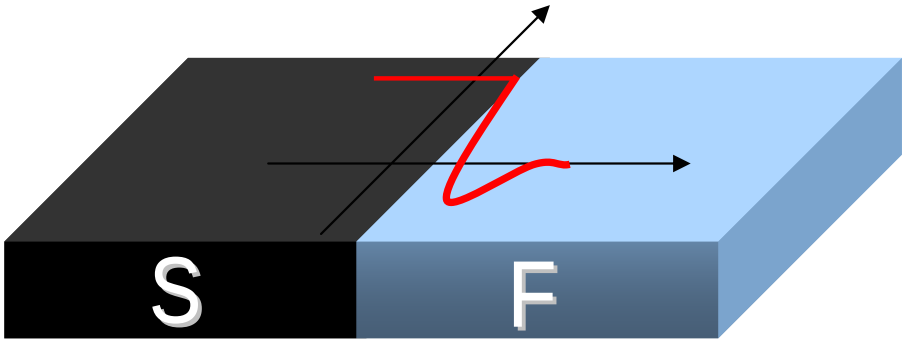
T = 100 K

T = 4.2 K

Summary

- 👎T_C in Ni/Nb/Ni system comparable to CuNi/Nb/CuNi
- Observe larger 👎T_C at lower T_C
- Strong ferromagnets are viable candidates for FS experiments, but need more complete theory
- We observe $T_c^P < T_c^{AP}$ in Py/Nb/Py, in contrast to recent preprint by Rusanov, Habraken & Aarts

Superconductor/ Ferromagnet



I. T_C oscillations Vs d_F in S/F bilayers and F/S/F trilayers

Strunk et al. (1994) in Nb/Gd/Nb trilayers & multilayers
Jiang et al. (1995) in Nb/Gd multilayers
Lazar et al. (2000) in Fe/Pb/Fe and Pb/Fe systems
Sidorenko et al. (2003) in Nb/Ni bilayers

II. Density of States measurements in F by proximity effect

Kontos et al. (2001) in a $Nb/Pd_{1-x}Ni_x/Al_2O_3/Al$ system

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III. □-State S/F/S Josephson Junction

Ryazanov et al. (2001) in a $Nb/Cu_{1-x}Ni_x/Nb$ system

IV. T_C Difference in FSF between Parallel (P) and Anti-Parallel (AP)

Gu *et al.* (2002), Potenza *et al.* (2005) in CuNi/Nb/CuNi system

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