# Observation of Spin-Triplet Superconductivity in Co-Based Josephson Junctions †

Team 1:
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† T. S. Khaire, M. A. Khasawneh, W. P. Pratt, Jr., N. O. Birge, *Phys. Rev. Lett.* 104, 137002 (2010)

# Triplet vs Singlet Superconductivity

**Order parameter** $\Delta_{\alpha\beta}(\boldsymbol{k}) \sim \langle C_\alpha(\boldsymbol{k})\, C_\beta(-\boldsymbol{k})\rangle$

$\alpha, \beta$ – *spin indeces*, $k$ – *momentum*

- No spin-orbit coupling ⇒ separation of spin a orbital degrees of freedom

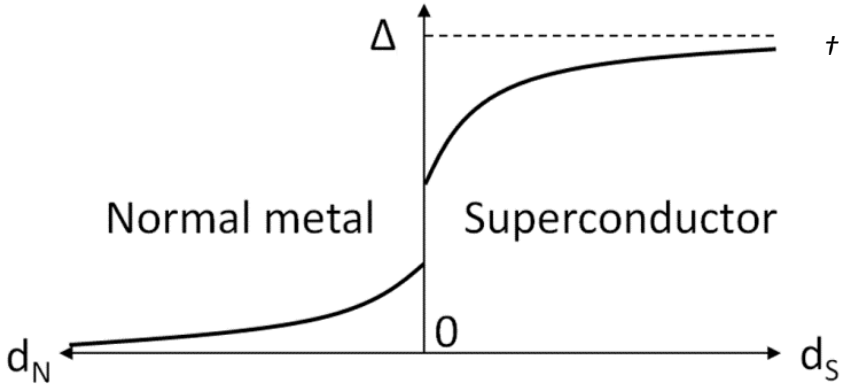
$$\Delta_{\alpha\beta}(\boldsymbol{k}) = \chi_{\alpha\beta}\Delta(\boldsymbol{k})$$

- Fermi statistics ⇒ $\Delta_{\alpha\beta}(\boldsymbol{k}) = -\Delta_{\beta\alpha}(-\boldsymbol{k})$

- Spin-singlet pairing $\chi_{\alpha\beta} = -\chi_{\beta\alpha} \Leftrightarrow \Delta(-\boldsymbol{k}) = \Delta(\boldsymbol{k})$

- Spin-triplet pairing $\chi_{\alpha\beta} = \chi_{\beta\alpha} \Leftrightarrow \Delta(-\boldsymbol{k}) = -\Delta(\boldsymbol{k})$

**Proximity effect**




- Rapid decay in a ferromagnetic material (few nm)
- *But not for triplet superconductors!*

⇒ *can be used to detect triplet Cooper pairing*

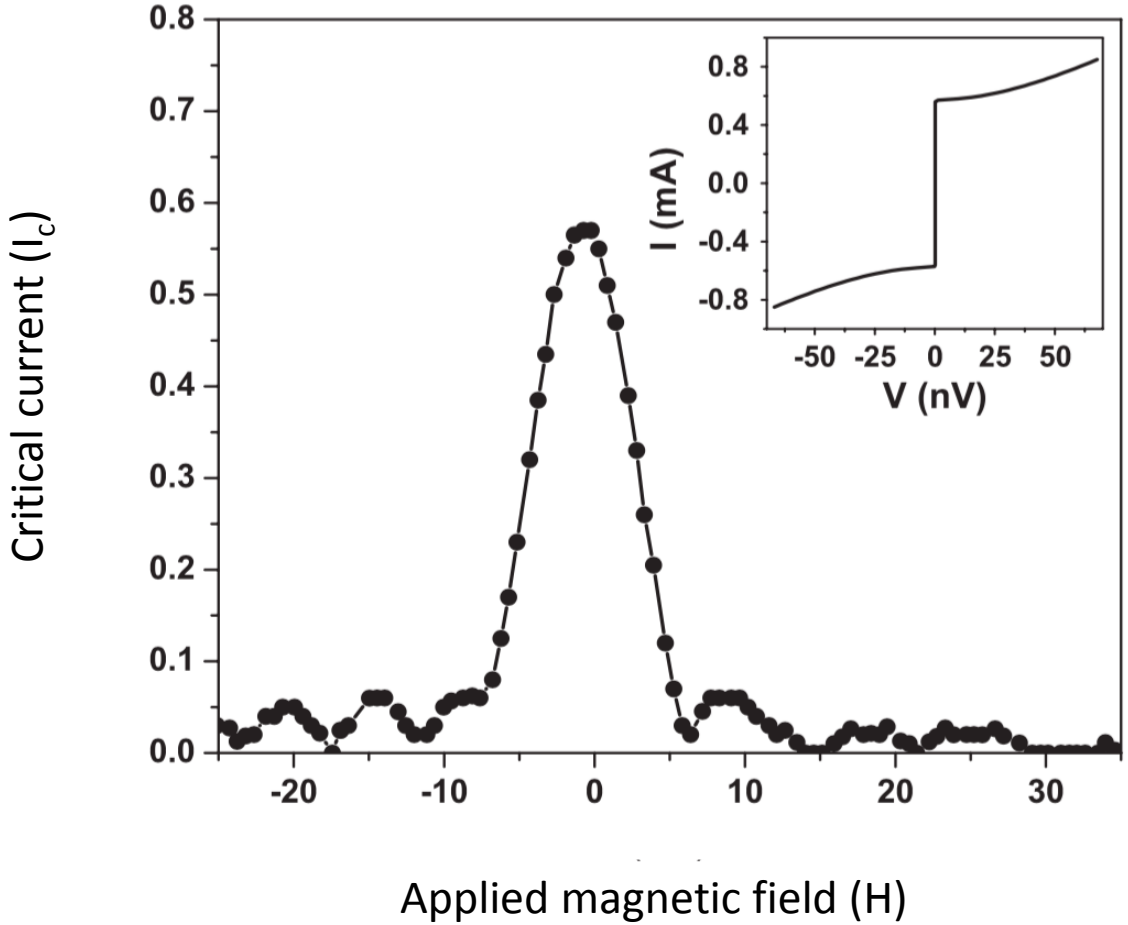
† http://www.intechopen.com

# Characterization Using Critical Current

**Critical current** - **maximum** super-current a superconducting device can carry

- $I > I_c$ leads to breaking of Cooper pairs
- Fraunhofer patterns allow for reliable critical current measurements

**Important phenomenological characteristic of superconducting phase!**



# Previous Work: Josephson Junctions with Ferromagnetic Barrier (early 2000s)

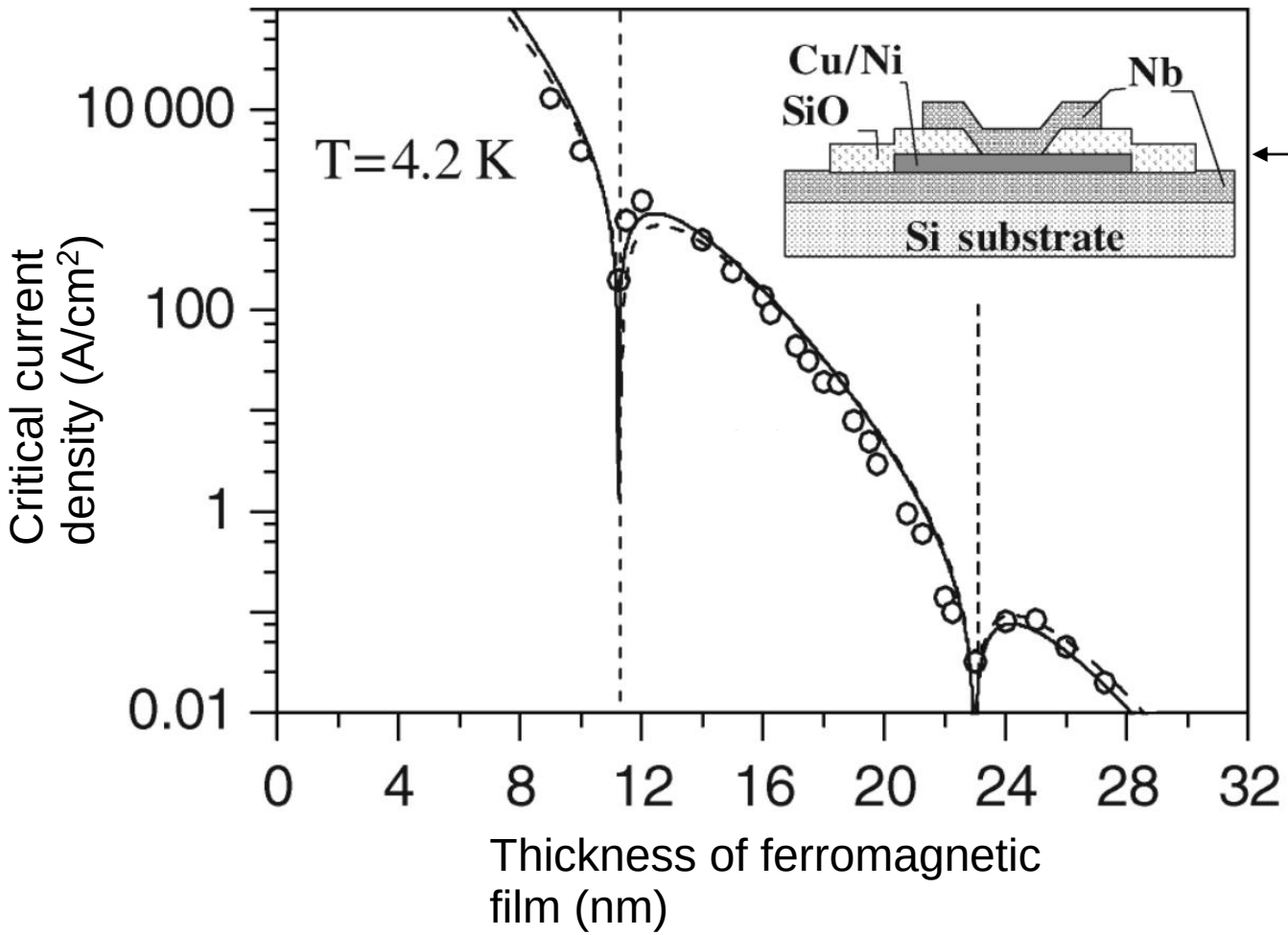
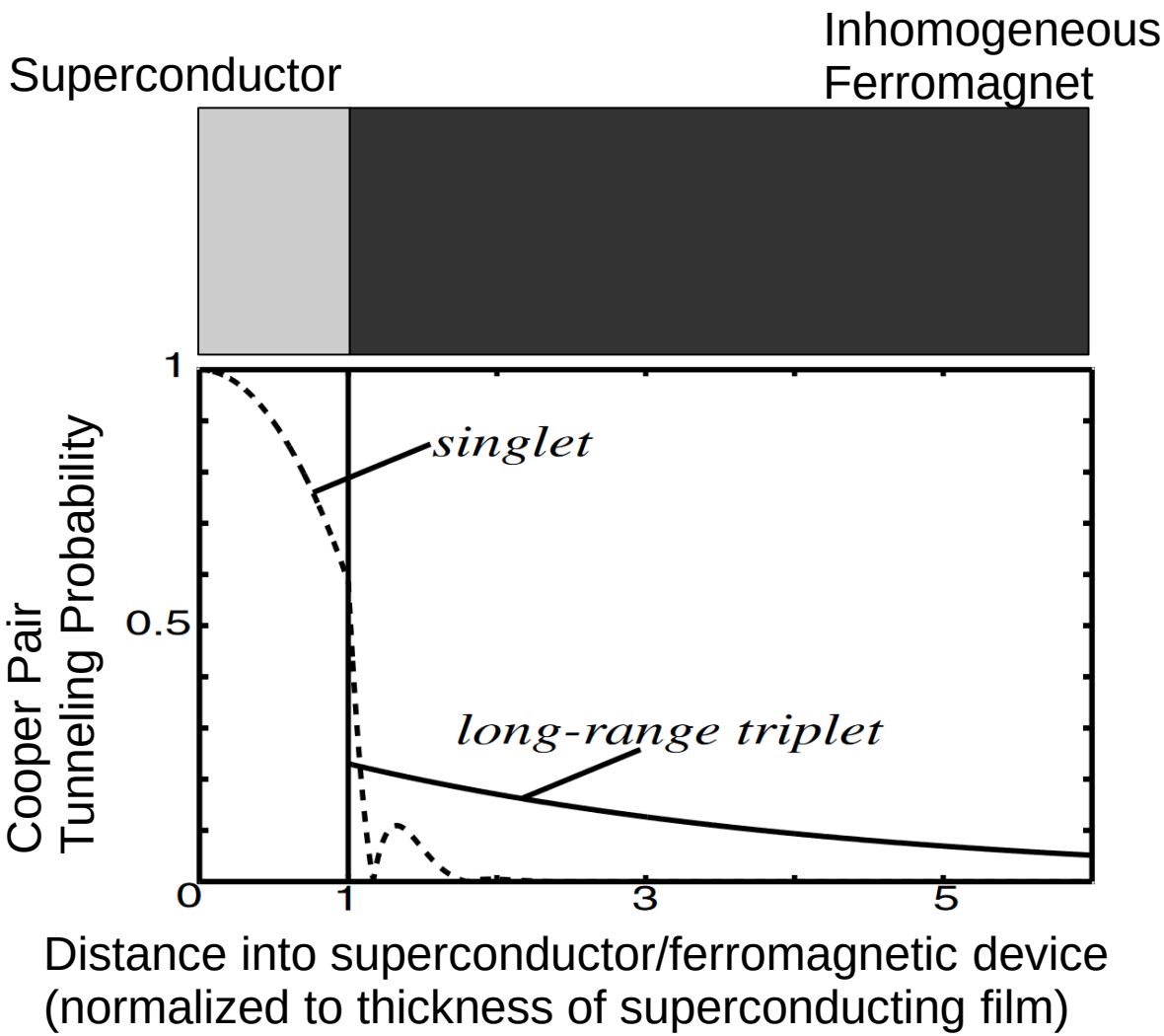



Diagram of device structure

- Supercurrent undergoes damped oscillations as the magnetic film thickness is increased
- Critical current is supressed by three orders of magnitude
  - Cooper pairs can tunnel ~100 nm in Josphson junctions that use normal metal as a barrier

Oboznov, V. A., et al. "*Thickness dependence of the Josephson ground states of superconductor-ferromagnet-superconductor junctions*." Physical review letters 96.19 (2006): 197003.

# Previous Work: Inhomogeneous Magnetization forms Triplet Cooper Pairs (2001)



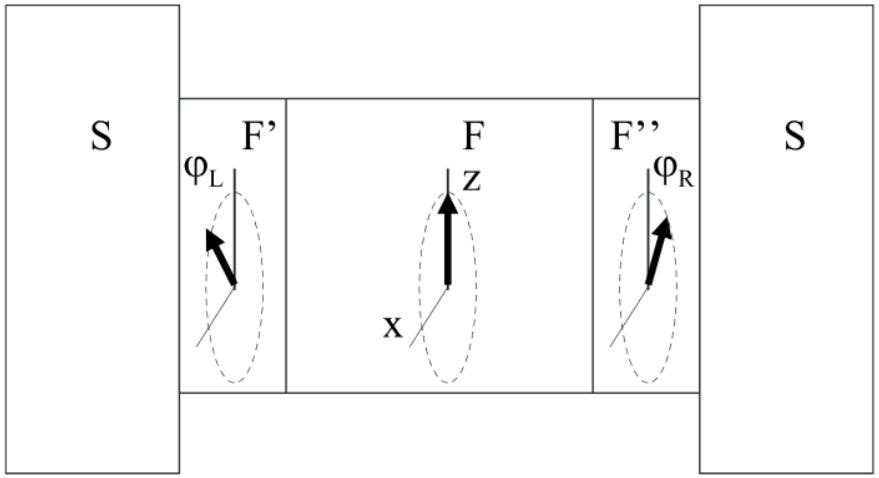

- Triplet superconductivity predicted to arise in inhomogeneous magnetization (2001)
- Triplet can tunnel much greater distance than singlet component

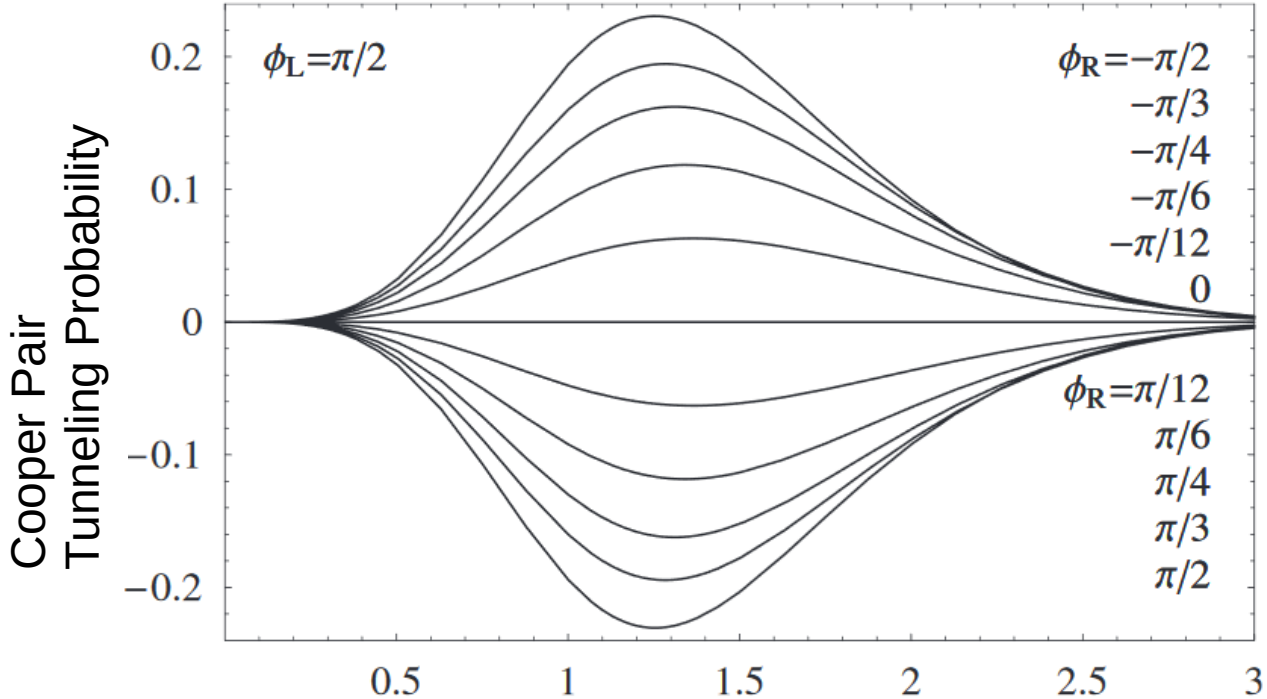
Volkov, A. F., F. S. Bergeret, and Konstantin B. Efetov. "*Odd triplet superconductivity in superconductor-ferromagnet multilayered structures.*" Physical review letters 90.11 (2003): 117006.

# Previous Work: Misaligned Magnetizations Form Triplet Pairs

- Predicted Triplet generation in magnetic film structure
  - Magnetizations of each film may point in different directions
- Various orientations of magnetizations were studied
  - Perpindicular magnetizations of all magnetic layers produces highest supercurrent
  - Supports Prediction that inhomogeneous magnetization generates triplet pairs

Josephson Junction structure



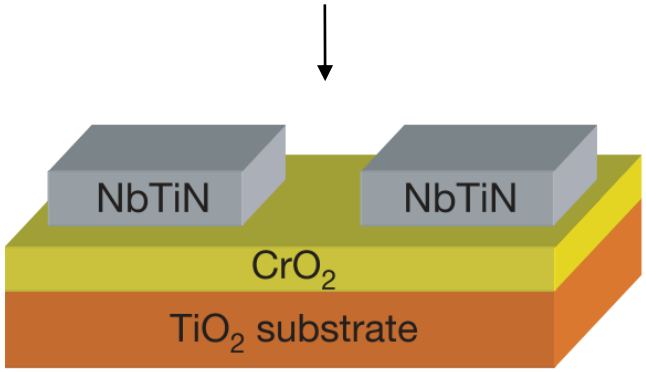



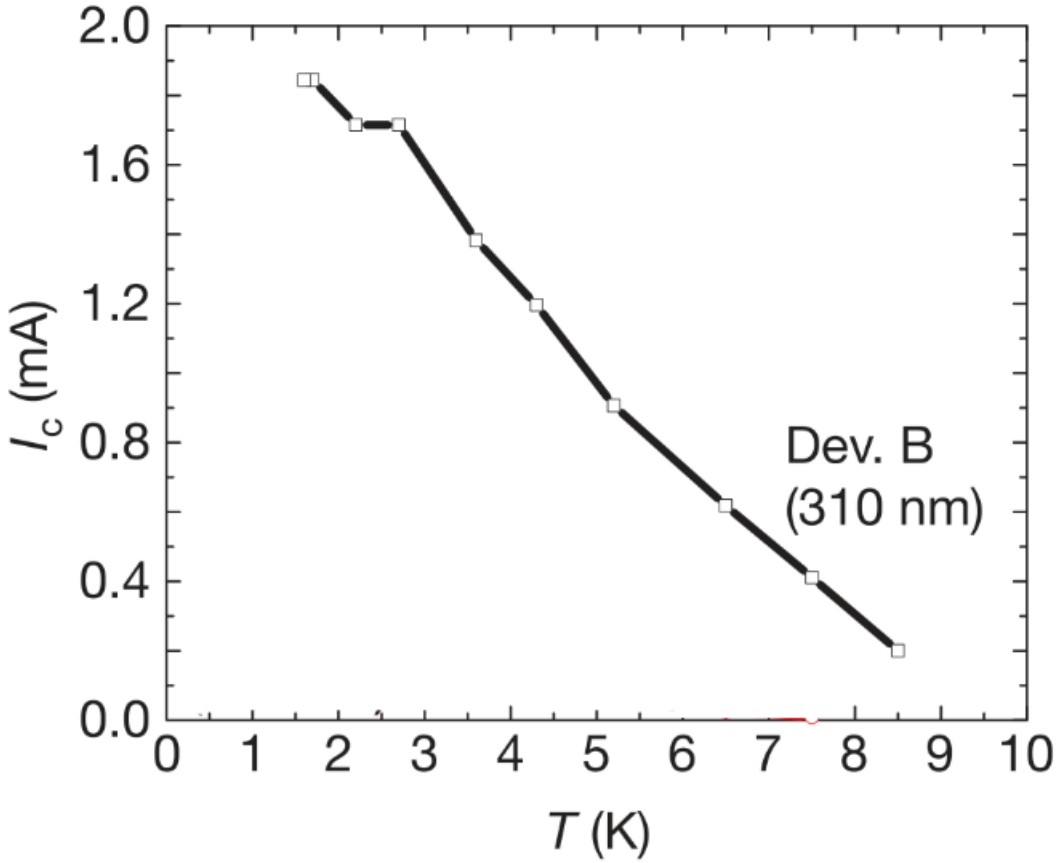

Distance into superconductor/ferromagnetic device (normalized to thickness of magnetic film)

Houzet, M., and Alexandre I. Buzdin. "*Long range triplet Josephson effect through a ferromagnetic trilayer*." Physical Review B 76.6 (2007): 060504

# Previous Work: Early Possible Experimental Observation of Triplet Pairs

Diagram of Josephson Junction Device

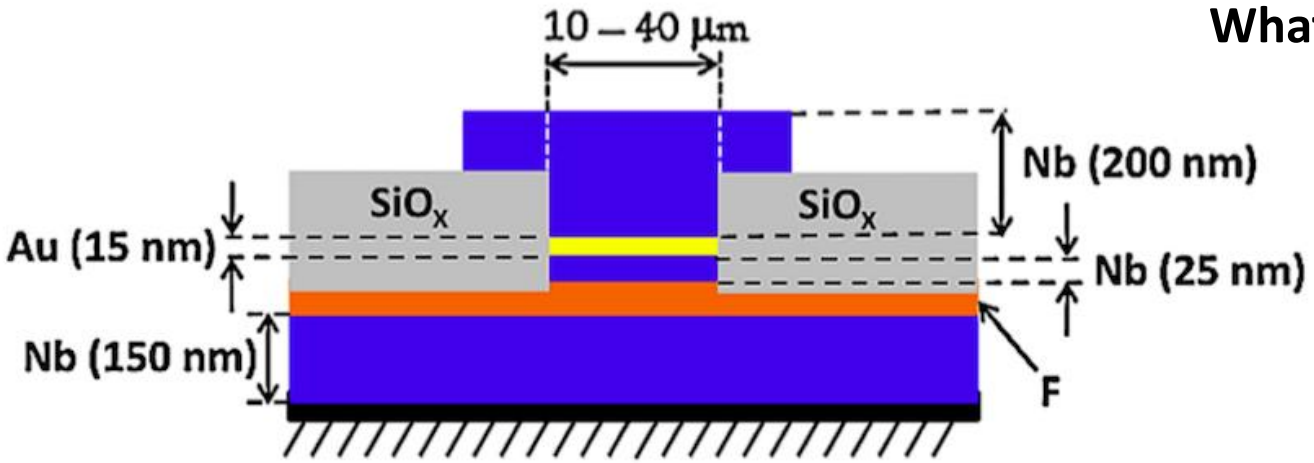


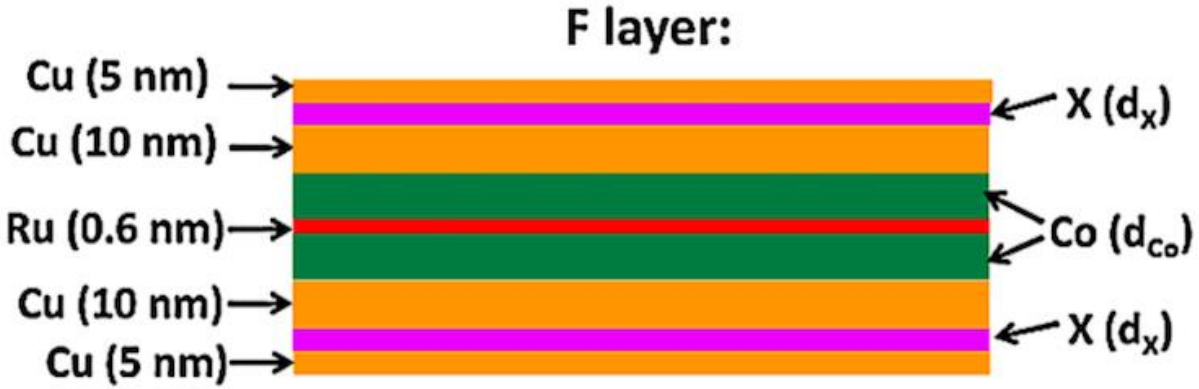




- Josephson Junctions with $CrO_2$ barrier produced critical current at thicknesses of 310 nm
  - $CrO_2$ is ferromagnetic, and tunneling in a Josephson junctions should vanish after a few nanometers
- This long range supercurrent is attributed to possible triplet pairs forming in the junction
  - Not enough conclusive data regarding the magnetic structure of $CrO_2$ means no conclusive triplet observation

Keizer, R. S., et al. "A *spin triplet supercurrent through the half-metallic ferromagnet CrO2."* Nature 439.7078 (2006): 825-827.

# Josephson Junction Devices




**What setup is used for triplet superconductivity generation?**

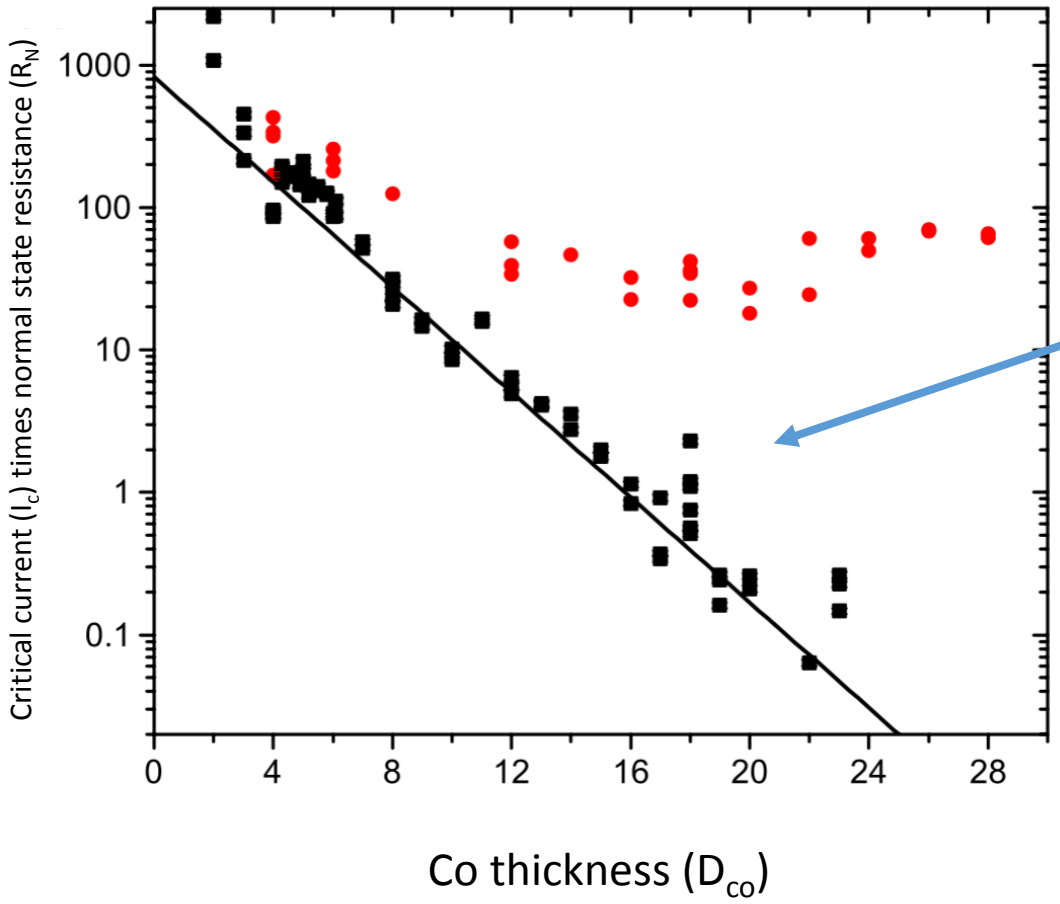
**Magnetic inhomogeneity plays a crucial role in triplet generation**

- Nb layers have a critical temperature 9K
- Au layer is fully superconducting due to proximity effect

- Co is used to suppress spin-singlet Josephson current
- Ru induces antiparallel exchange coupling between Co layers
- Cu serves as magnetic insulation

**X = $Pd_{0.88}Ni_{0.12}$ or $Cu_{0.48}Ni_{0.52}$ weakly ferromagnetic alloys**

# Thickness Dependent Study of Singlet Pairing Quenching



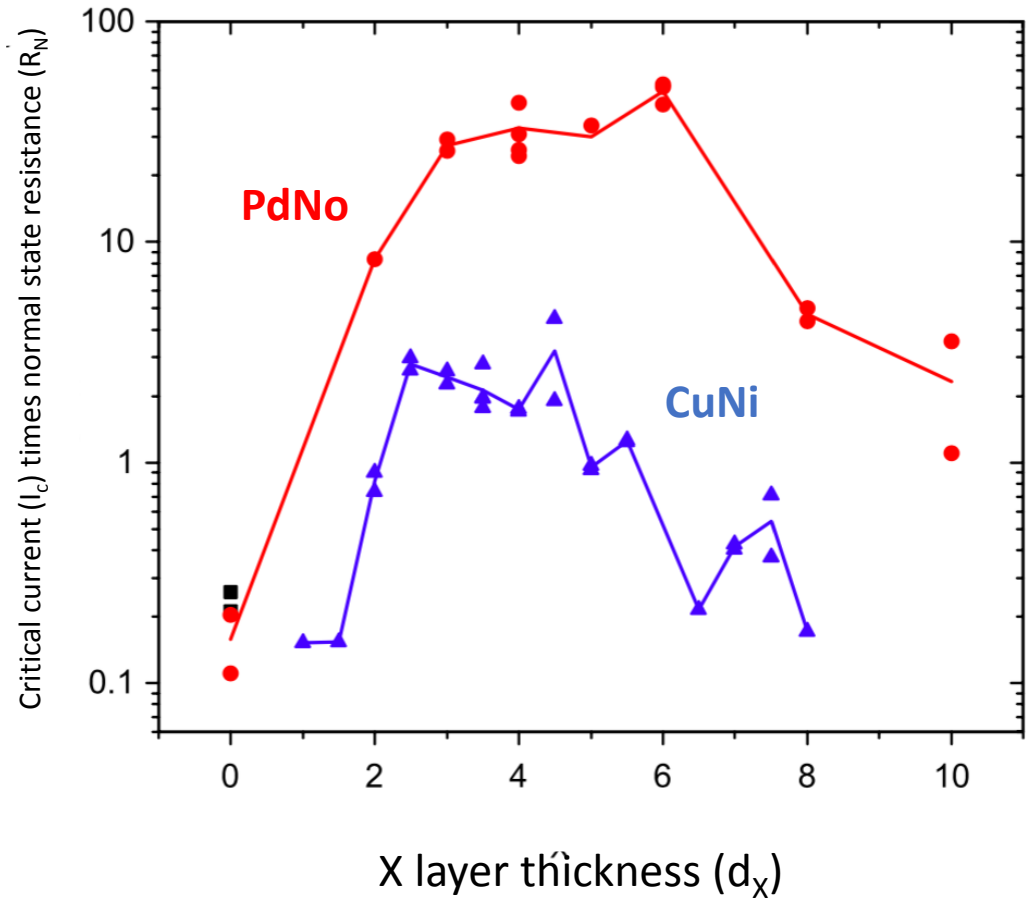

**What is the evidence of triplet pairing presence?**

- Red circles - fixed PdNi thickness (4 nm)
- Black squares - no X layer
- Varying Co layer thickness

- **Without X:** Rapid decay of $I_c$ with thickness
- **With X:** No decay of $I_cR_N$ for $D_{Co}$>12 nm

**Strong evidence of spin-triplet nature!**

# What is the role of X in enhancing the supercurrent?




- Fixed Co thickness (20 nm)
- Without X: small $I_cR_N$
- With X (few nm) : maximum $I_cR_N$
- Increasing thickness of X: decreases $I_cR_N$

*spin memory loss*

Possible sources of noncollinear magnetizaion:

i) Regions between adjecent X-layer domains

ii) Regions between X and Co layers

# Critical Analysis

- Overall a very important paper in the field- first direct observation of critical current in spin triplet superconductors
- "Comparison of our results with theory is problematic."
  - Issues comparing experimental results to theory: the theory can only calculate magnitude of supercurrent for idealized materials
  - Spin triplet decay lengths difficult to calculate- Length scale depends on $D_F$, the electron diffusion constant which is difficult to calculate for Co
  - Sample to sample fluctuations

# Critical Analysis

- Suggestions for improvement:
  - If possible try for a better experimental setup- smaller junctions, more consistent fabrication methods
  - Present a combined theory and experiment paper- a theoretical paper very close to this experiment was published around the same time

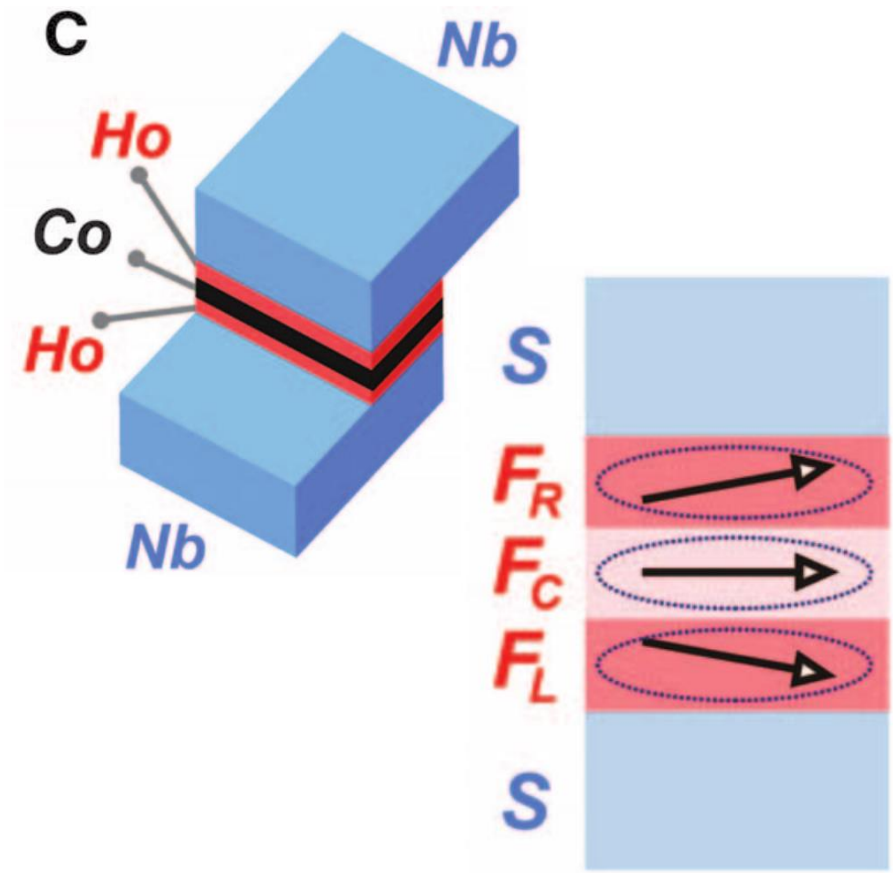
# Conclusions

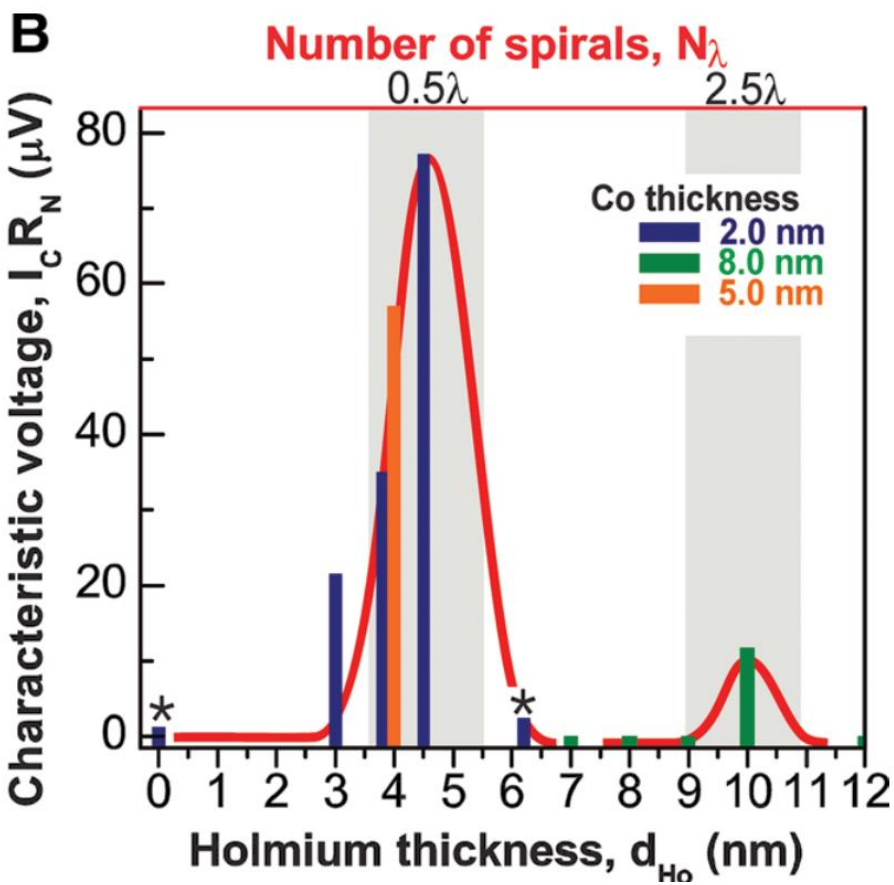
- Layer of weakly ferromagnetic material induced spin-triplet correlations
- Spin-triplet correlations allow superconducting current to persist for microns
- Even in orbital angular momentum, odd in frequency

# Citation Review

- 180 citations since 2010
- Continued research
  - Magnetic materials
  - Device structure
  - Control of LRTC generation

# Controlled LRTC with Holmium

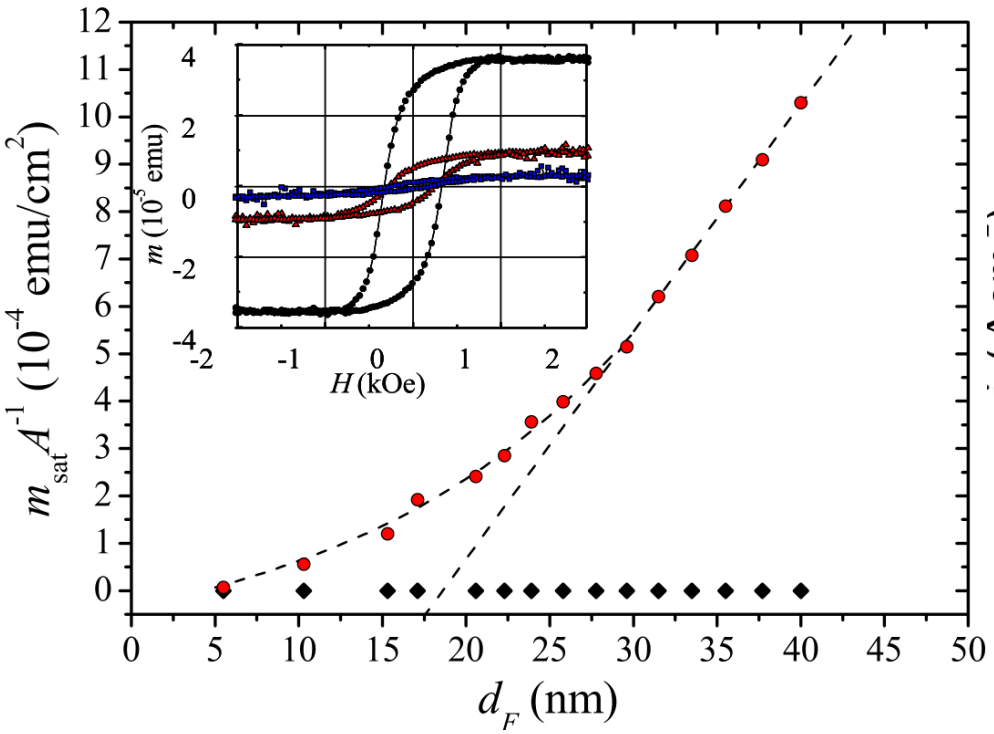


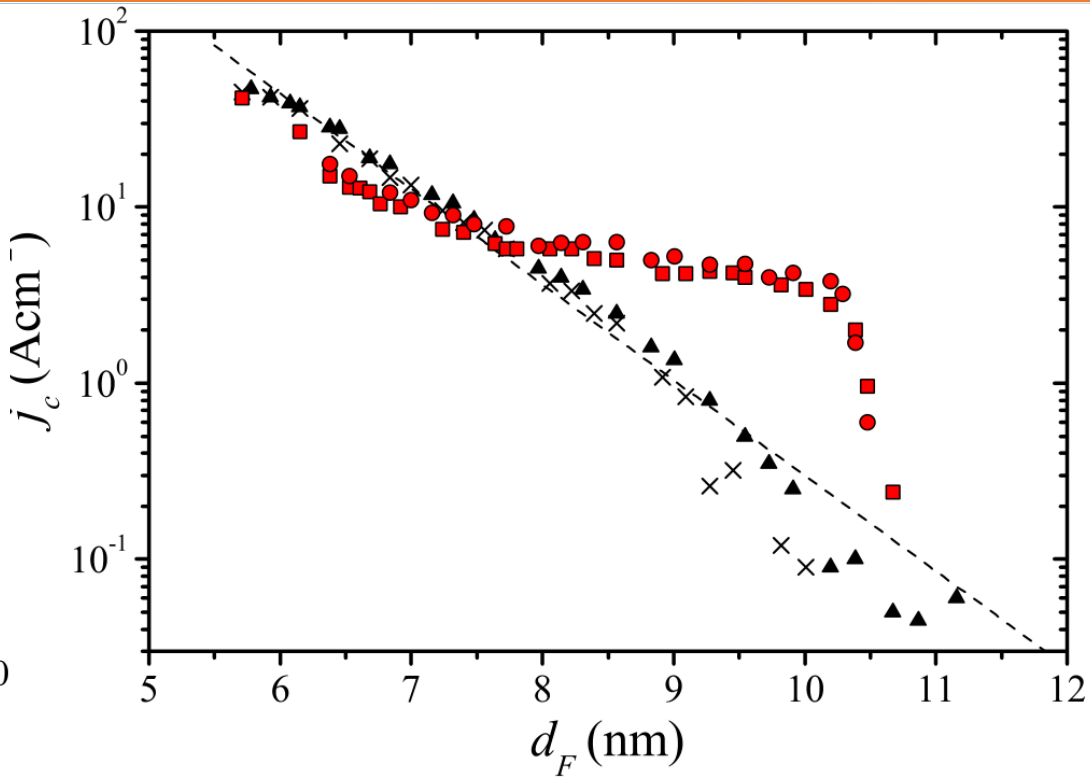




- Holmium rare earth magnet
  - Intrinsic inhomogeneity
- Presence of Ho increases $I_c$
  - Inidicates generation of LRTC from inhomogeneity

Robinson, J. W. A., J. D. S. Witt, and M. G. Blamire. "*Controlled injection of spin-triplet supercurrents into a strong ferromagnet*." Science 329.5987 (2010): 59-61.

# Heusler Alloy $Cu_2MnAl$

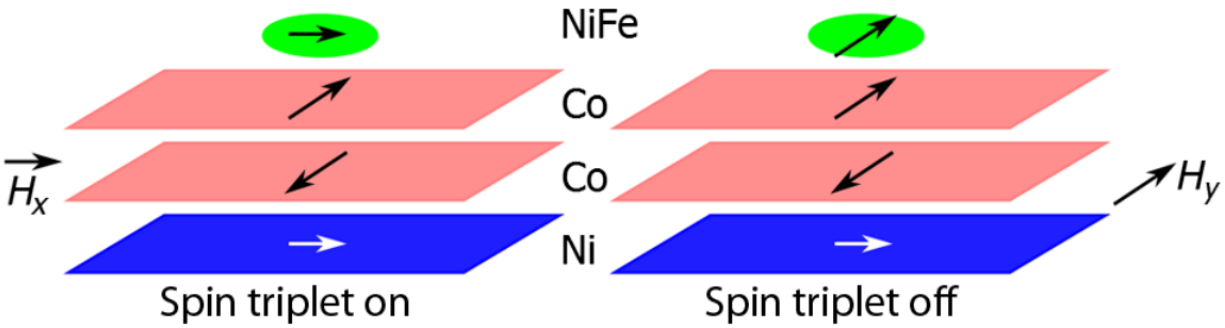


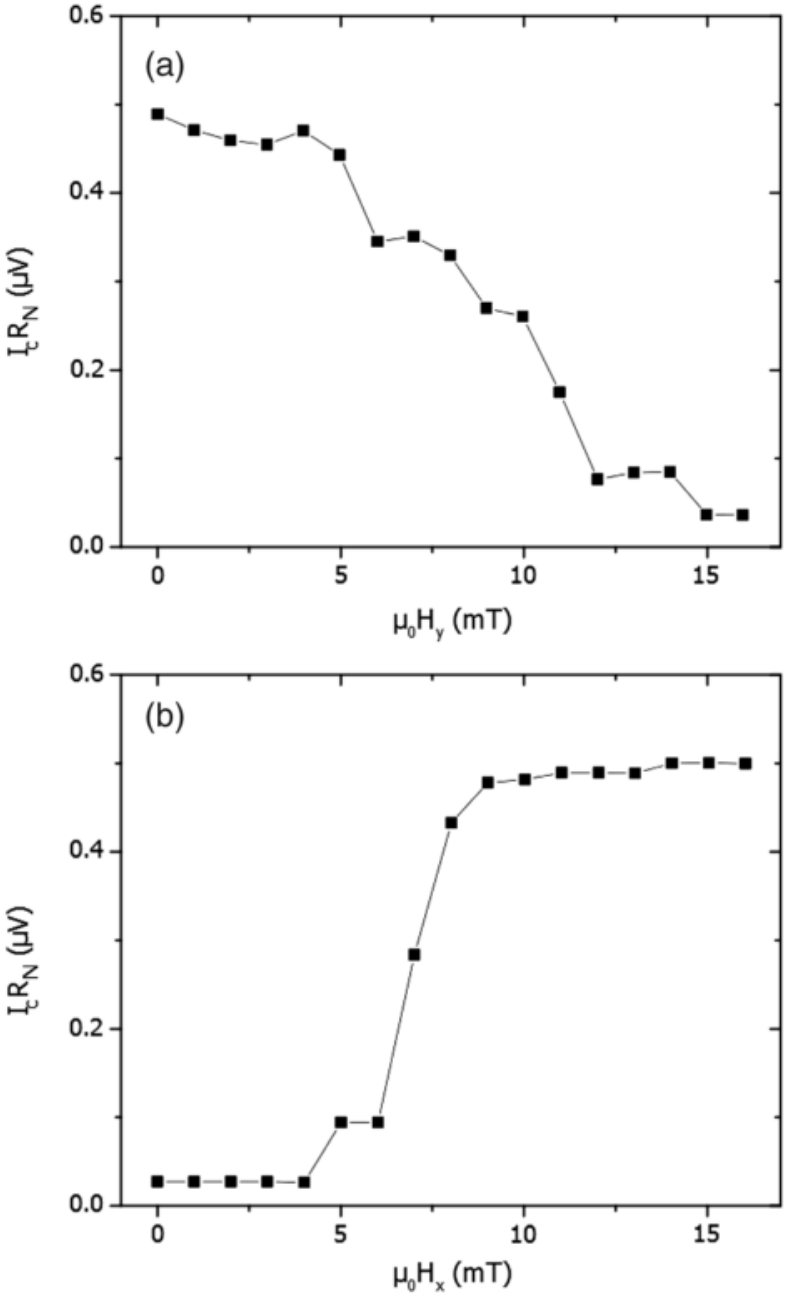

- Non-ferromagnetic in an “as prepared” state
- Ferromagnetism emerges after annealing
- Critical current increases in magnetic state
  - Indicates inhomogeneity and LRTC

Sprungmann, D., et al. "*Evidence for triplet superconductivity in Josephson junctions with barriers of the ferromagnetic Heusler alloy $Cu_2MnAl$*." Physical Review B 82.6 (2010): 060505.

# Control of Amplitude




Martinez, William M., W. P. Pratt Jr, and Norman O. Birge. "*Amplitude Control of the Spin-Triplet Supercurrent in S/F/S Josephson Junctions*." Physical review letters 116.7 (2016): 077001.




- NiFe alloy added to top
- Soft magnet
  - LRTC is turned off and on by $H_{ext}$