Probing Anomalous Field-Expulsion in Superconductor/Ferromagnetic Thin Films

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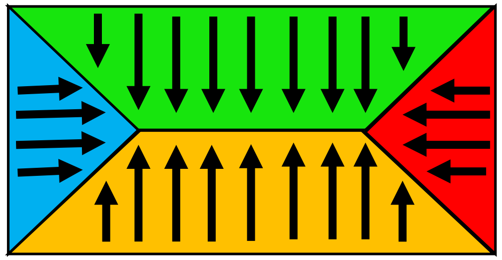
August 6th, 2019

Outline

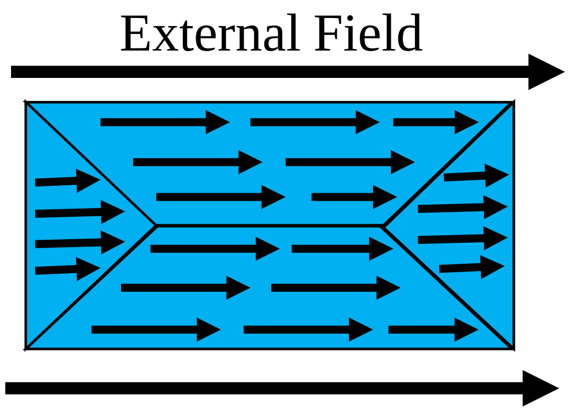
1. Background
   - What is a Ferromagnet?
   - What is a Superconductor?
   - S/F Heterostructure Proximity Effects
   - Introduction to Reflectometry
2. Experimental Methods
   - Polarized Neutron Beam
   - Closed Cycle Cryostat
3. Results
   - Collected X-Ray/PNR Data
   - Finding Structures of Samples
4. Final Thoughts
   - What We Learned
   - If I had More Time

What is a Ferromagnet?

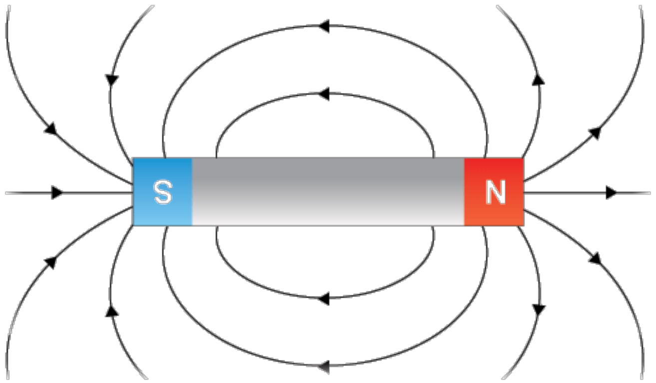
- Has a net dipole moment from electron spins



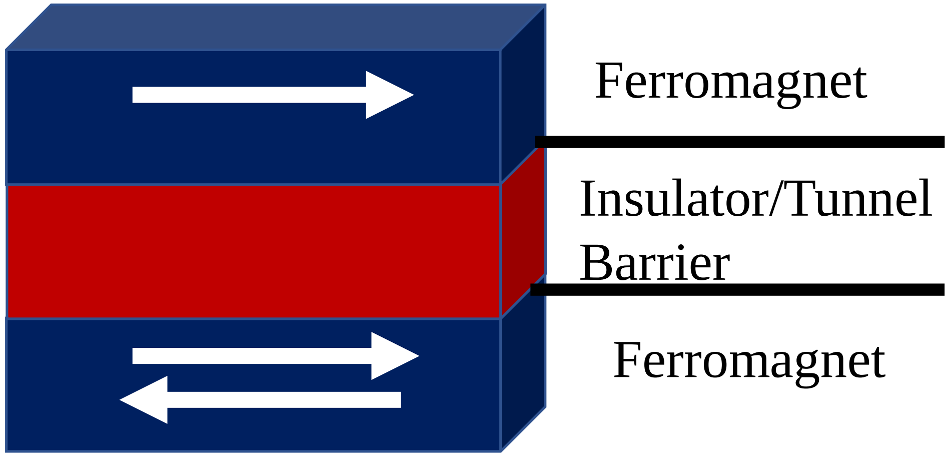
- Magnetic domains align in the presence of external magnetic field



- The material is magnetized, allowing it to create a magnetic field



Ferromagnets are subject to intense study once again, due to their uses in non-volatile memory storage devices. i.e. MRAM



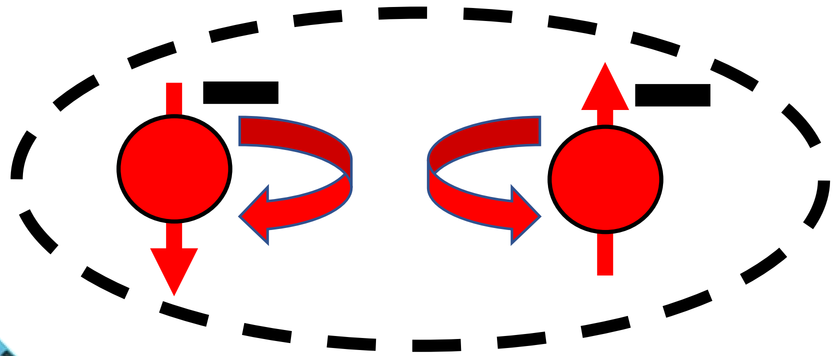
This low resistance reads as a 0

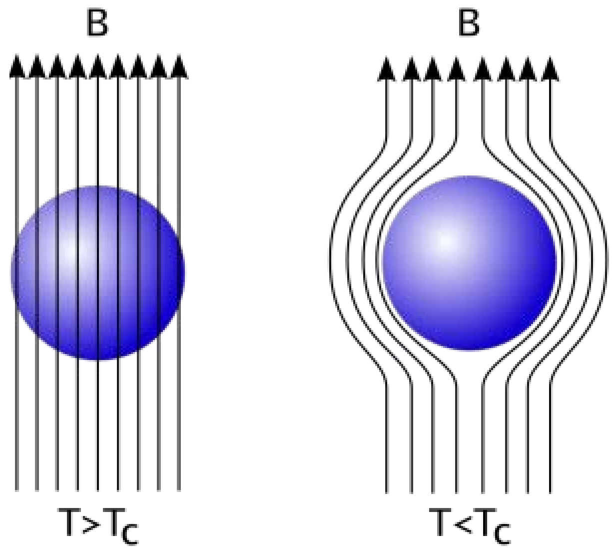
This high resistance reads as a 1

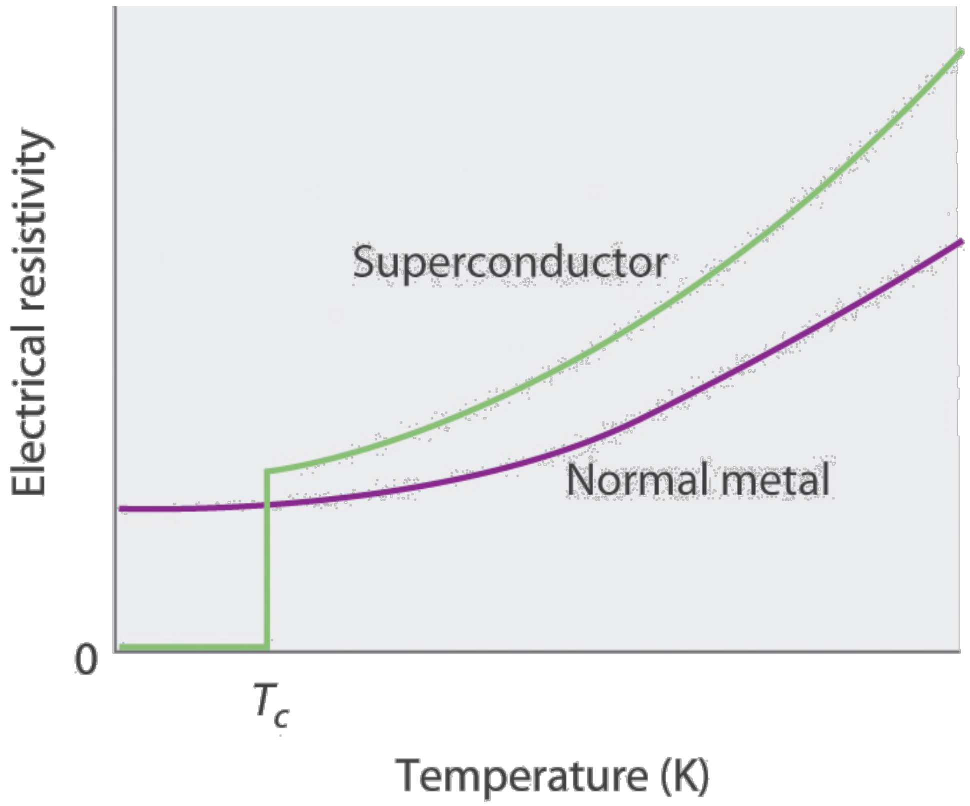
https://www.askiitians.com/iit-jee-magnetism/magnetic-field/

What is a Superconductor?

- Electrons pair up into Cooper pairs creating the superconducting state
- The material must be cooled to a critical superconducting temperature
- Lets the material have zero electrical resistance and expels external magnetic field



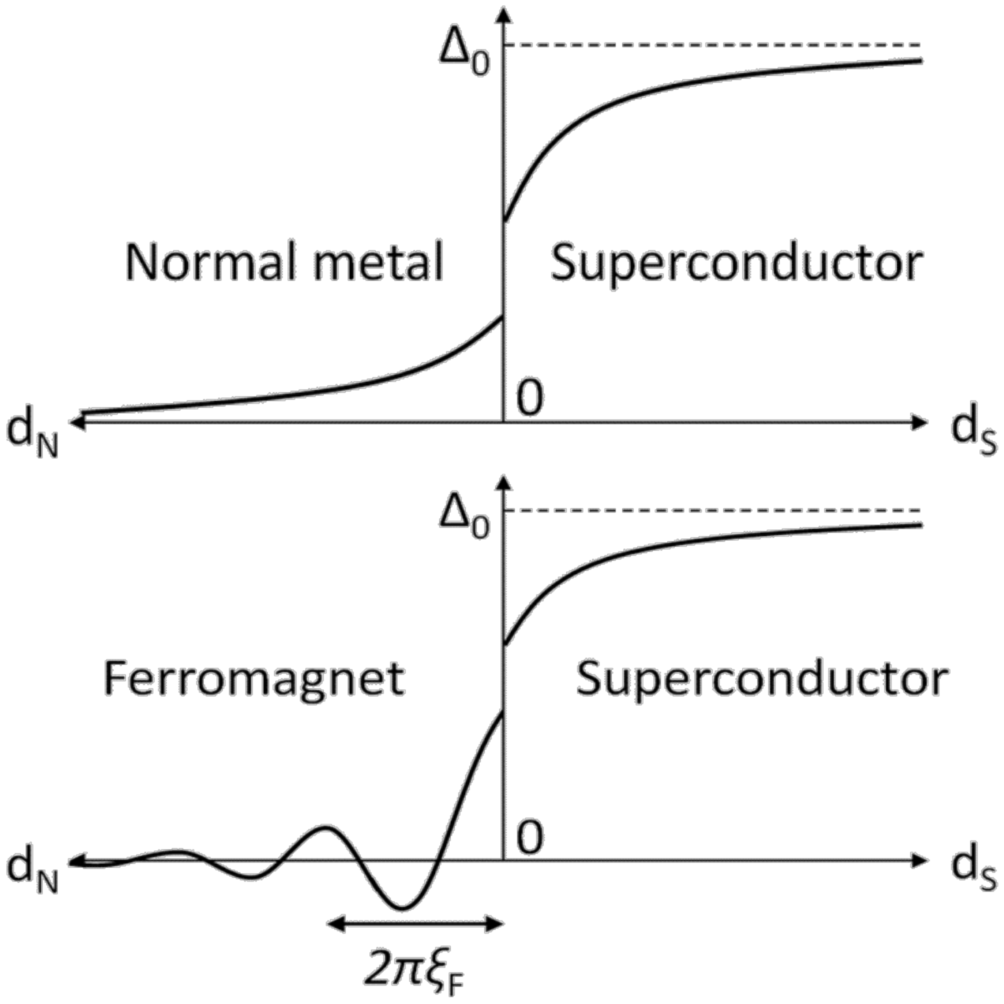




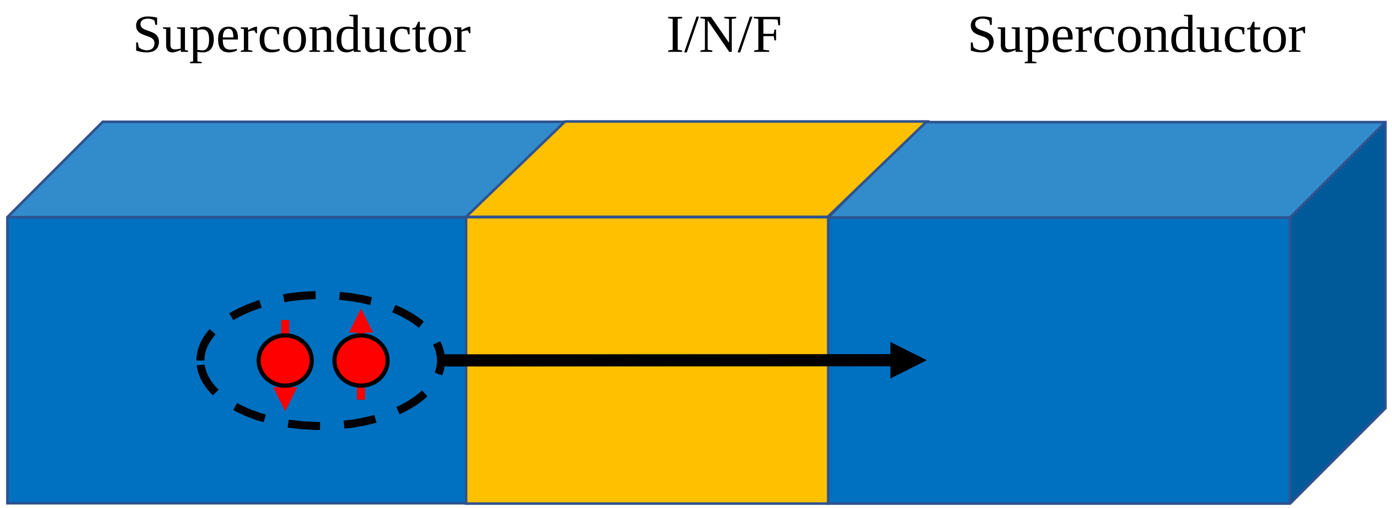
https://www.globalspec.com/learnmore/materials_chemicals_adhesives/electrical_optical_specialty_materials/superconductors_superconducting_materials
https://chem.libretexts.org/Bookshelves/General_Chemistry/Map%3A_General_Chemistry_(Petrucci_et_al.)/23%3A_The_Transition_Elements/23.9%3A_High_Temperature_Superconductors
https://www.shutterstock.com/search/thermometer+cold

Proximity Effects in S/F Thin Films

Superconducting Proximity Effect



- Superconductivity leaks into the normal metal (N) and ferromagnet (F)
- Superconducting hetero-structures make Josephson junctions



https://www.intechopen.com/books/superconductors-new-developments/spintronics-driven-by-superconducting-proximity-effect

Proximity Effects in S/F Thin Films

Superconductor-ferromagnet structures

A. I. Buzdin, B. Bujicic,[1] and M. Yu. Kupriyanov

L. M. Lomonosov Moscow State University

(Submitted 6 June 1991)

Zh. Eksp. Teor. Fiz. **101**, 231–240 (January 1992)

Interplay of superconductivity and magnetism in superconductor/ferromagnet structures

I. Baladié, A. Buzdin, N. Ryzhanova, and A. Vedyayev

Phys. Rev. B **63**, 054518 – Published 12 January 2001

Remotely induced magnetism in a normal metal using a superconducting spin-valve

M. G. Flokstra, N. Satchell, J. Kim, G. Burnell, P. J. Curran, S. J. Bending, J. F. K. Cooper, C. J. Kinane, S. Langridge, A. Isidori, N. Pugach, M. Eschrig, H. Luetkens, A. Suter, T. Prokscha & S. L. Lee

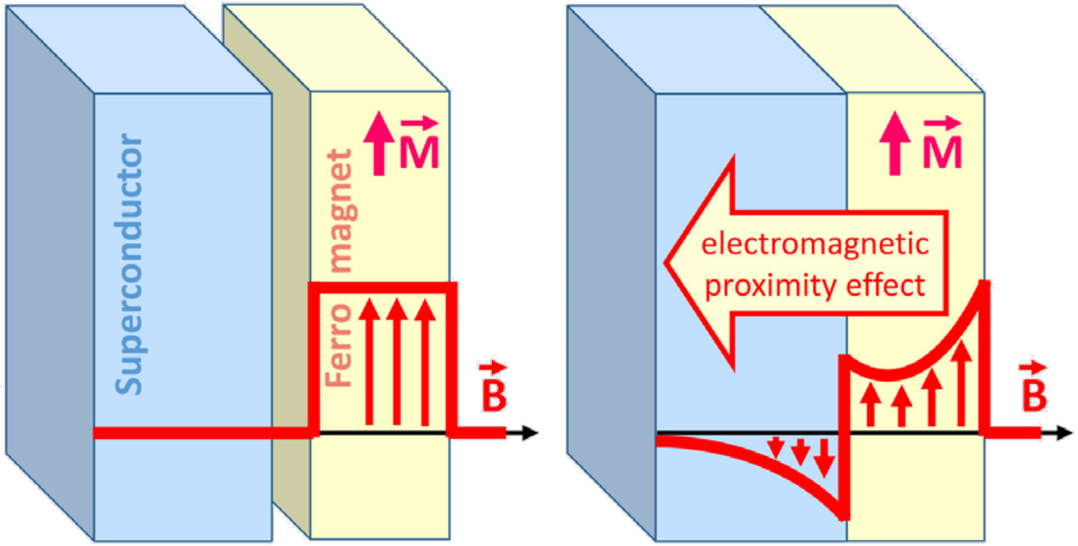
Nature Physics **12**, 57–61 (2016) | Download Citation

APPLIED PHYSICS LETTERS **113**, 022601 (2018)

Electromagnetic proximity effect in planar superconductor-ferromagnet structures

S. Mironov,[1] A. S. Mel'nikov,[1,2] and A. Buzdin[3,4,5]

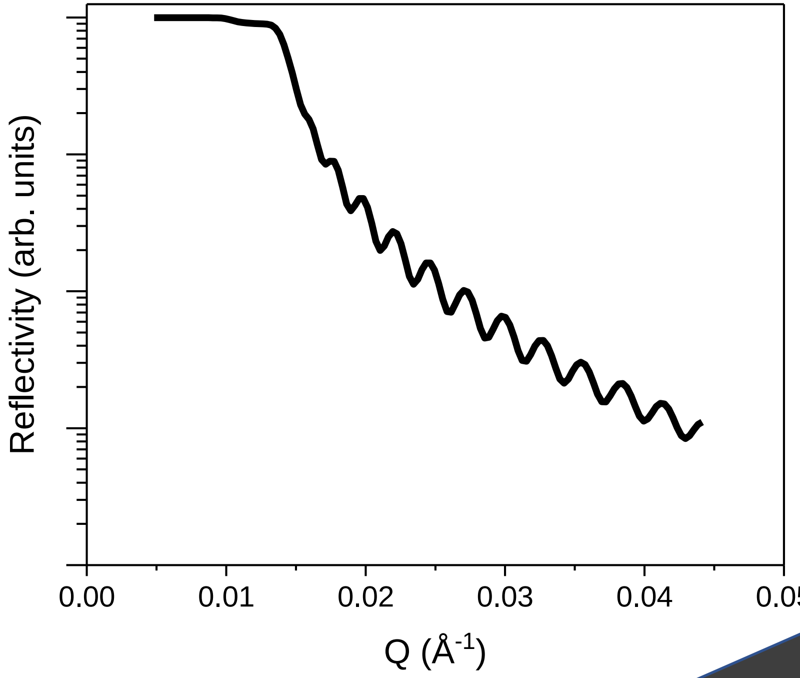
- Started by calculating the superconducting proximity effect
- Previously unexplained experimental results occur
- Theorists predict the electromagnetic proximity effect

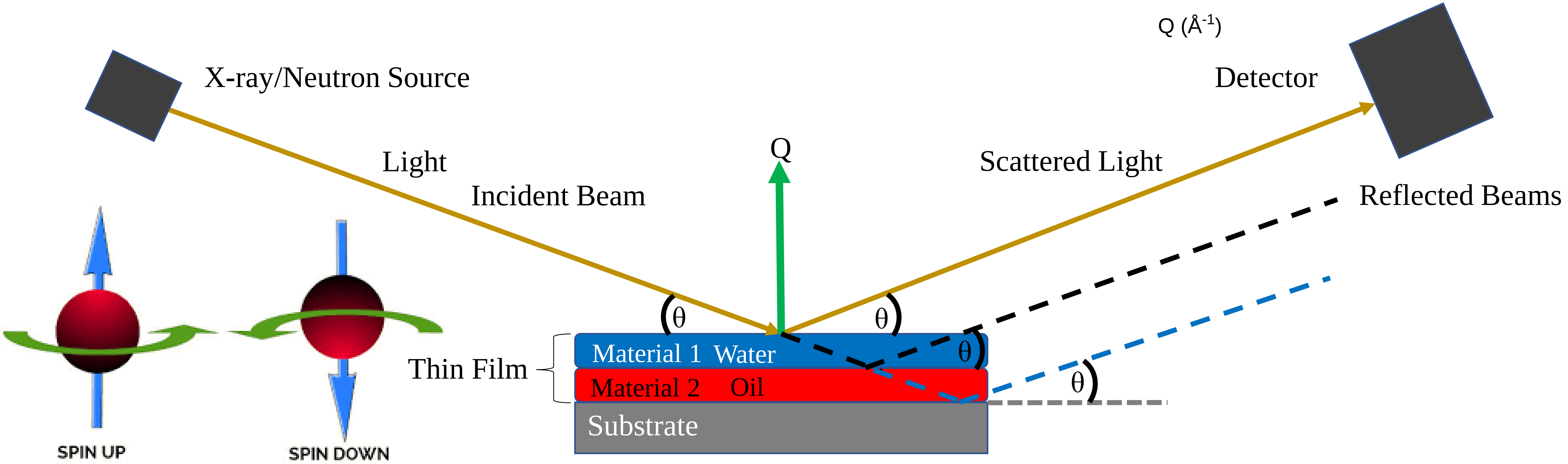


https://phys.org/news/2018-07-underlying-mechanism-magnetic-effect-superconducting.html

Reflectometry Explained

- Gives us the depth profile of the thin film
- Constructive (peaks) $2\sin(\theta) = n\lambda$
- Destructive (valleys) $2\sin(\theta) = (n+\frac{1}{2})\lambda$
- PNR can directly detect magnetization

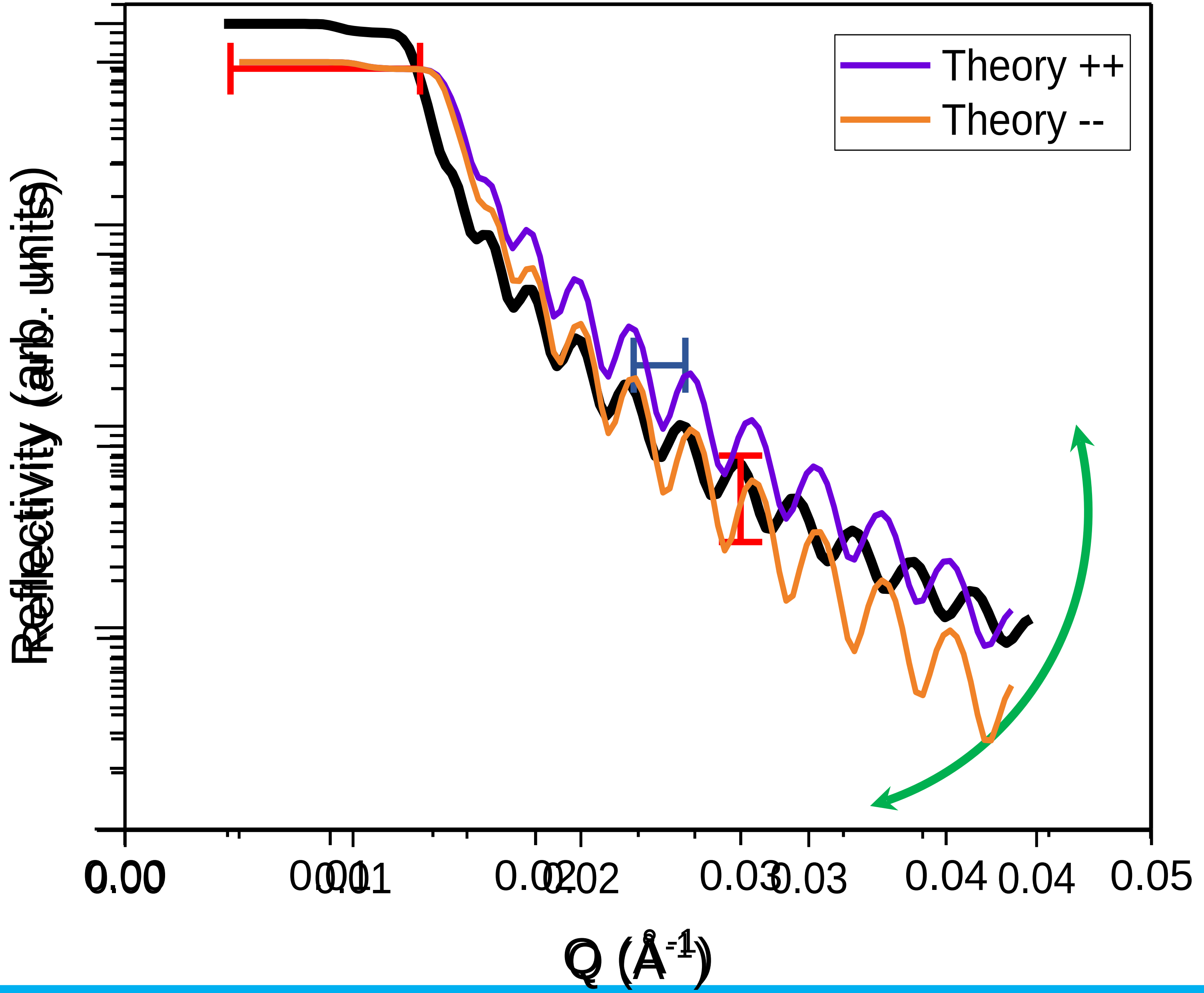




https://alunosonline.uol.com.br/fisica/spin.html

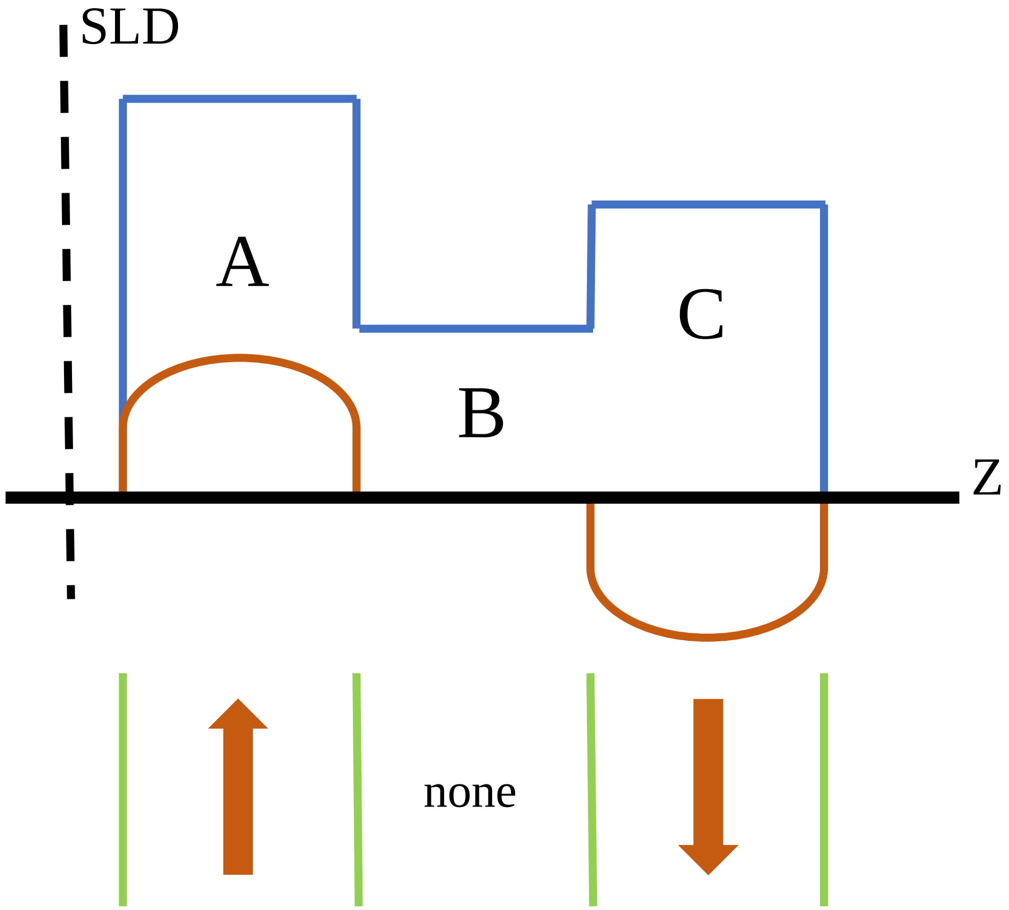
Reading Reflectivity Data

- Scattering Length Density
  - Critical edge length
  - Height of peaks
  - Often abbreviated SLD
- Roughness
  - Fall off rate
  - Usable data before background
- Thickness
  - Space between peaks
  - 2π/d
- Magnetic Component

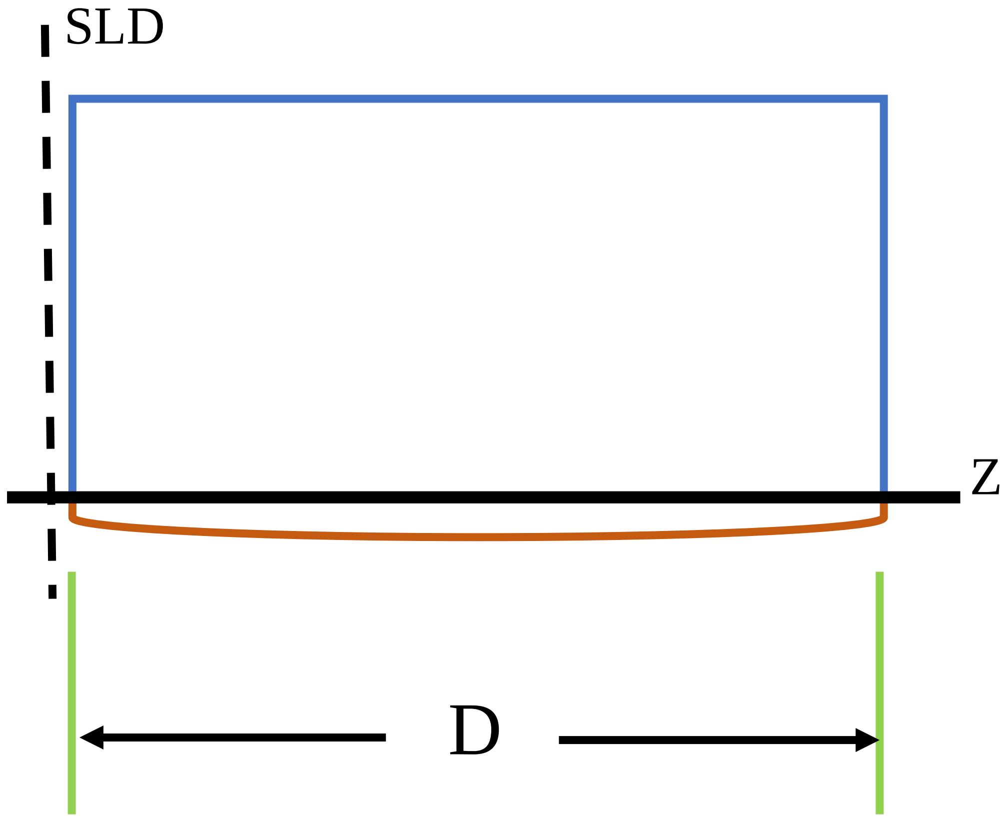


Nuclear/Magnetic Depth Profile Examples

- Nuclear SLD
- Magnetization



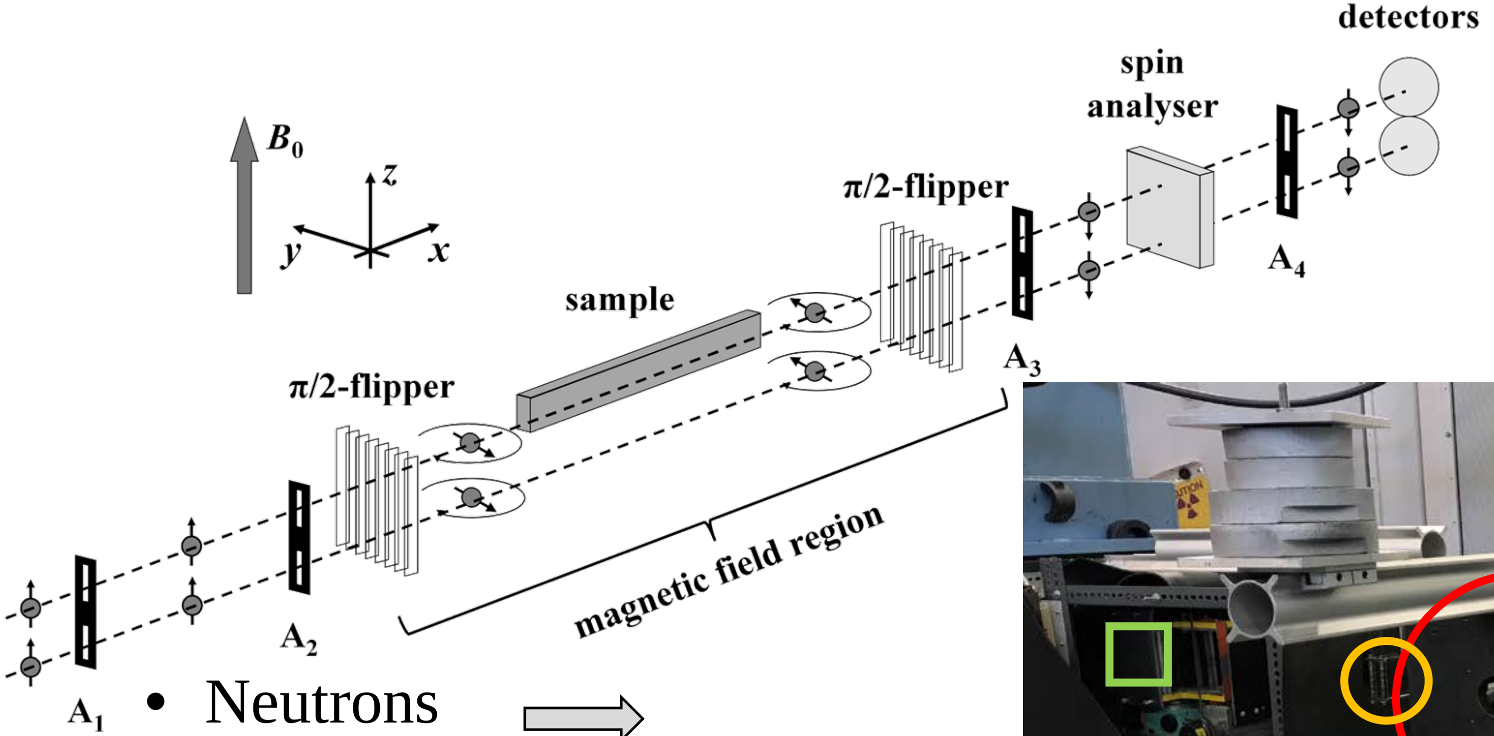
Magnetization Direction

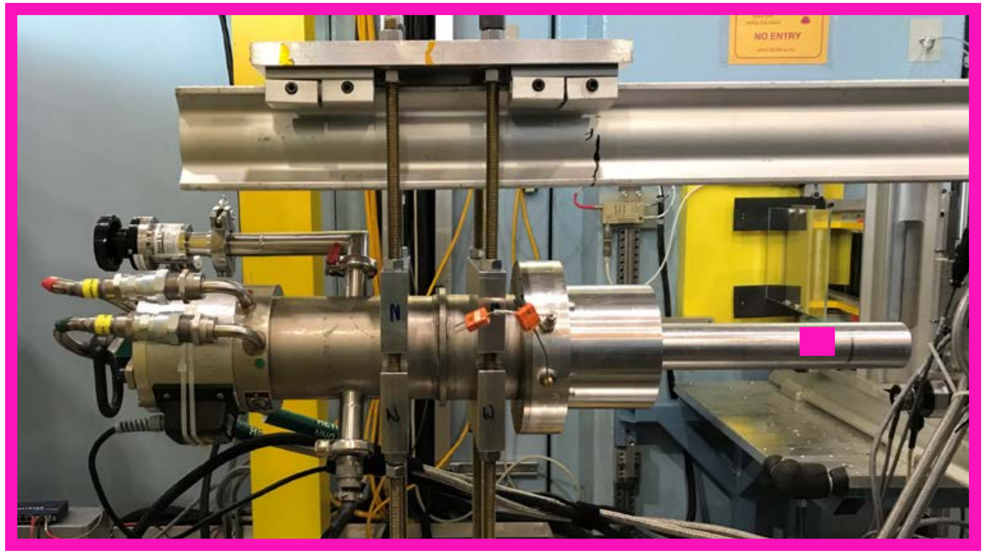


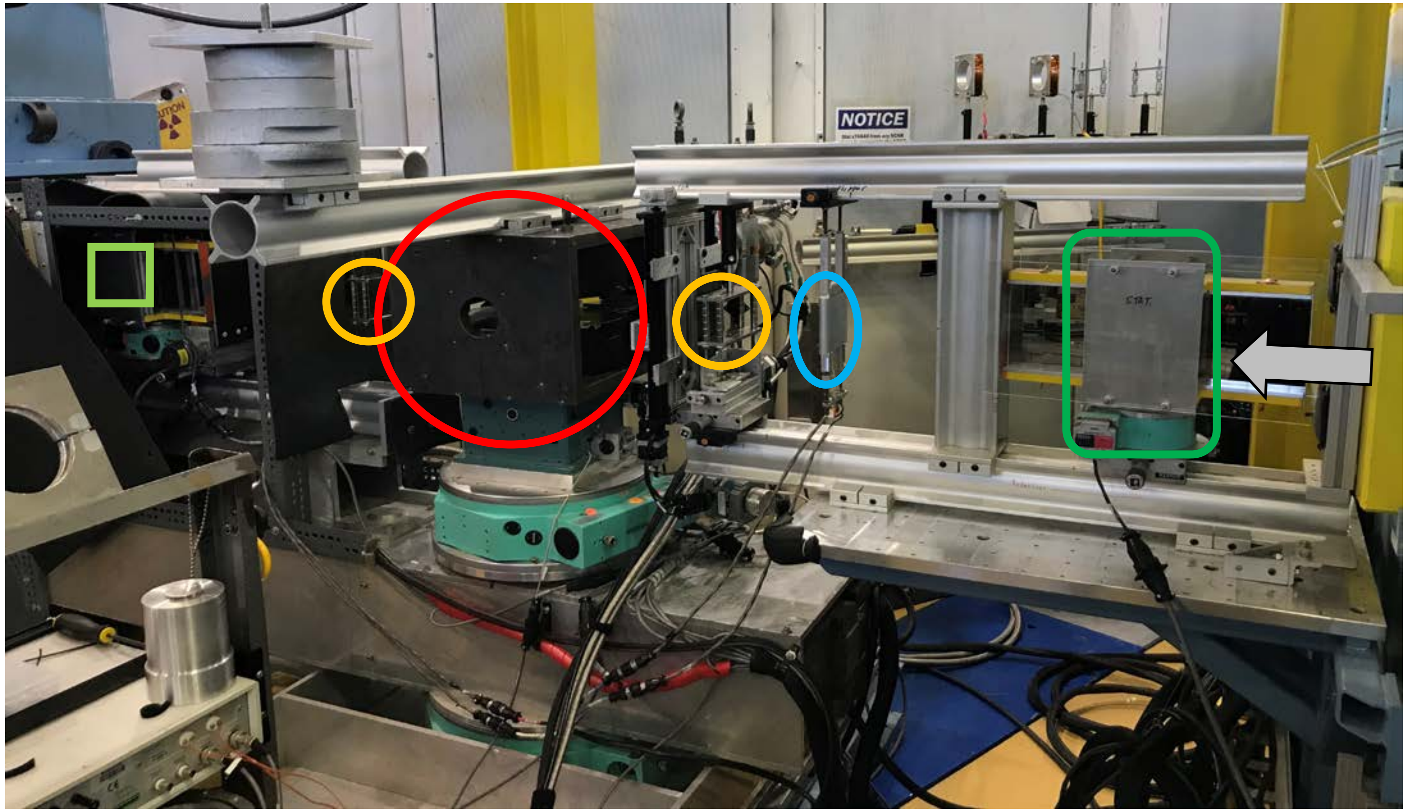
London Penetration Equation

$$B(x) = B_0 \cosh\left(\frac{x}{\lambda} - \frac{d_s}{2\lambda}\right) / \cosh\left(\frac{d_s}{2\lambda}\right)$$

PBR, a Polarized Neutron Beam





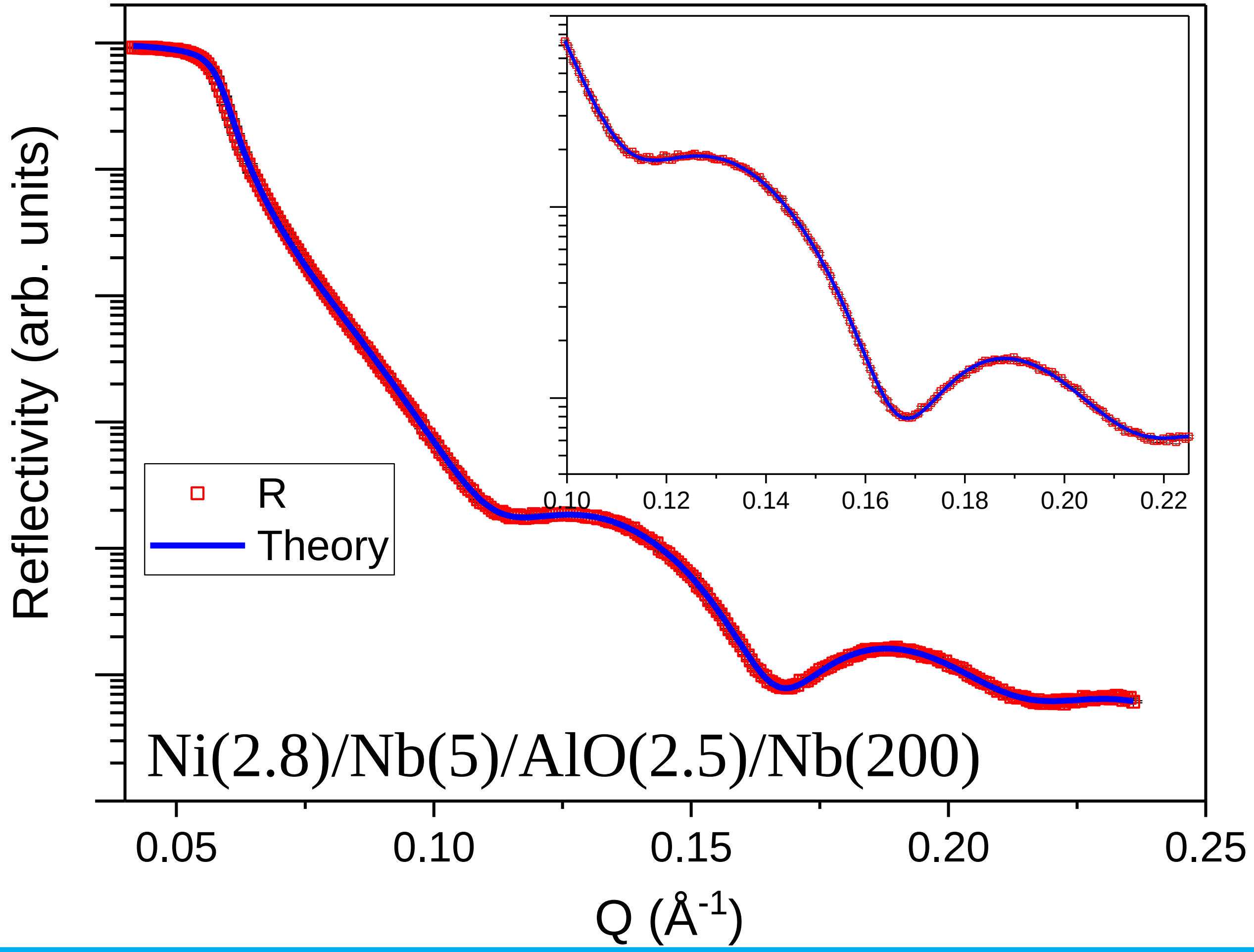


- Neutrons
- Spin Polarized Mirror
- Spin Flippers
- Electromagnet (0.7 T)
- Guide Fields
- Detector
- Closed Cycle Cryostat

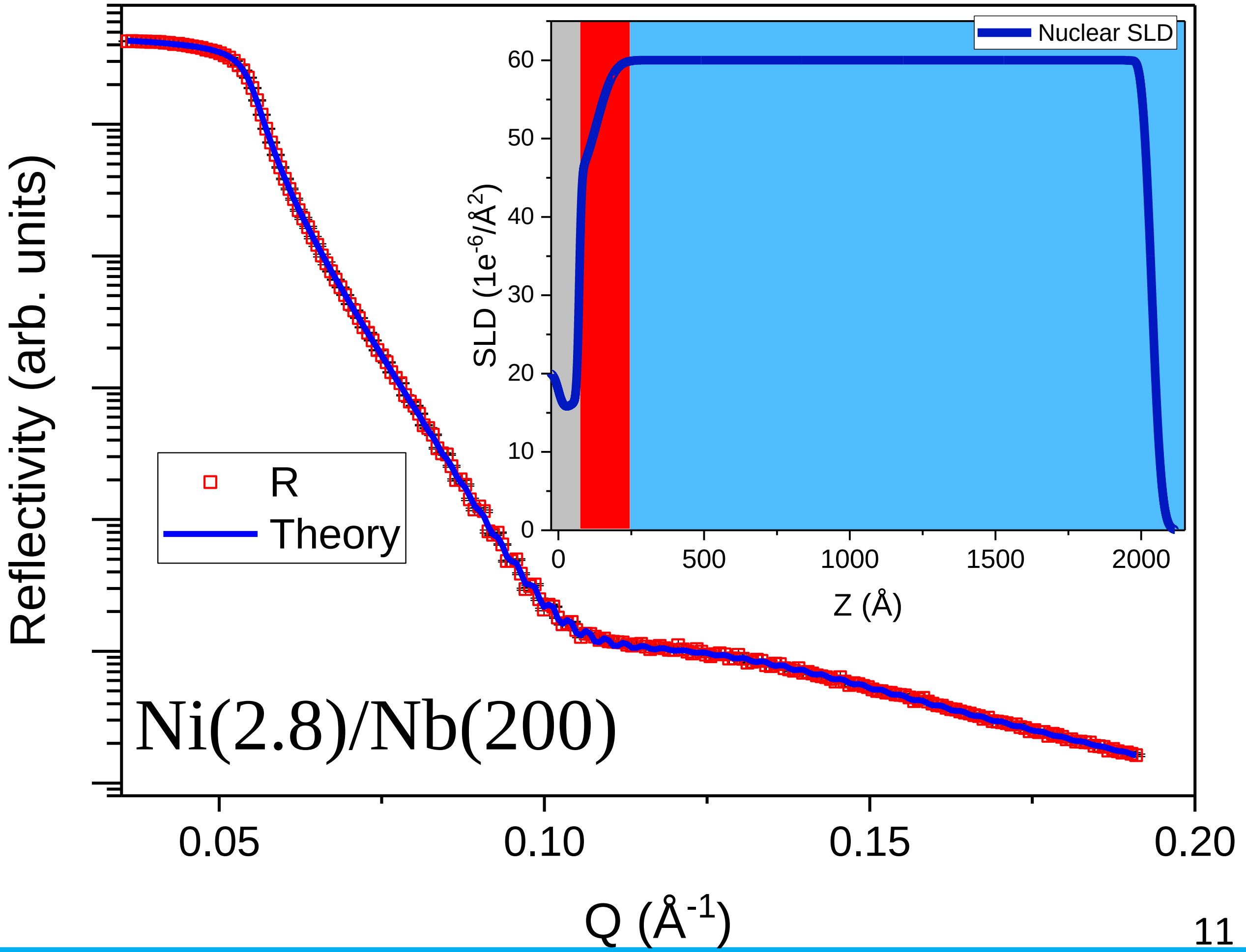
http://inspirehep.net/record/1113311/plots

From Data to Knowing Structure

- Thin layer oscillations are prevalent
- Roughness smears out Nb oscillations

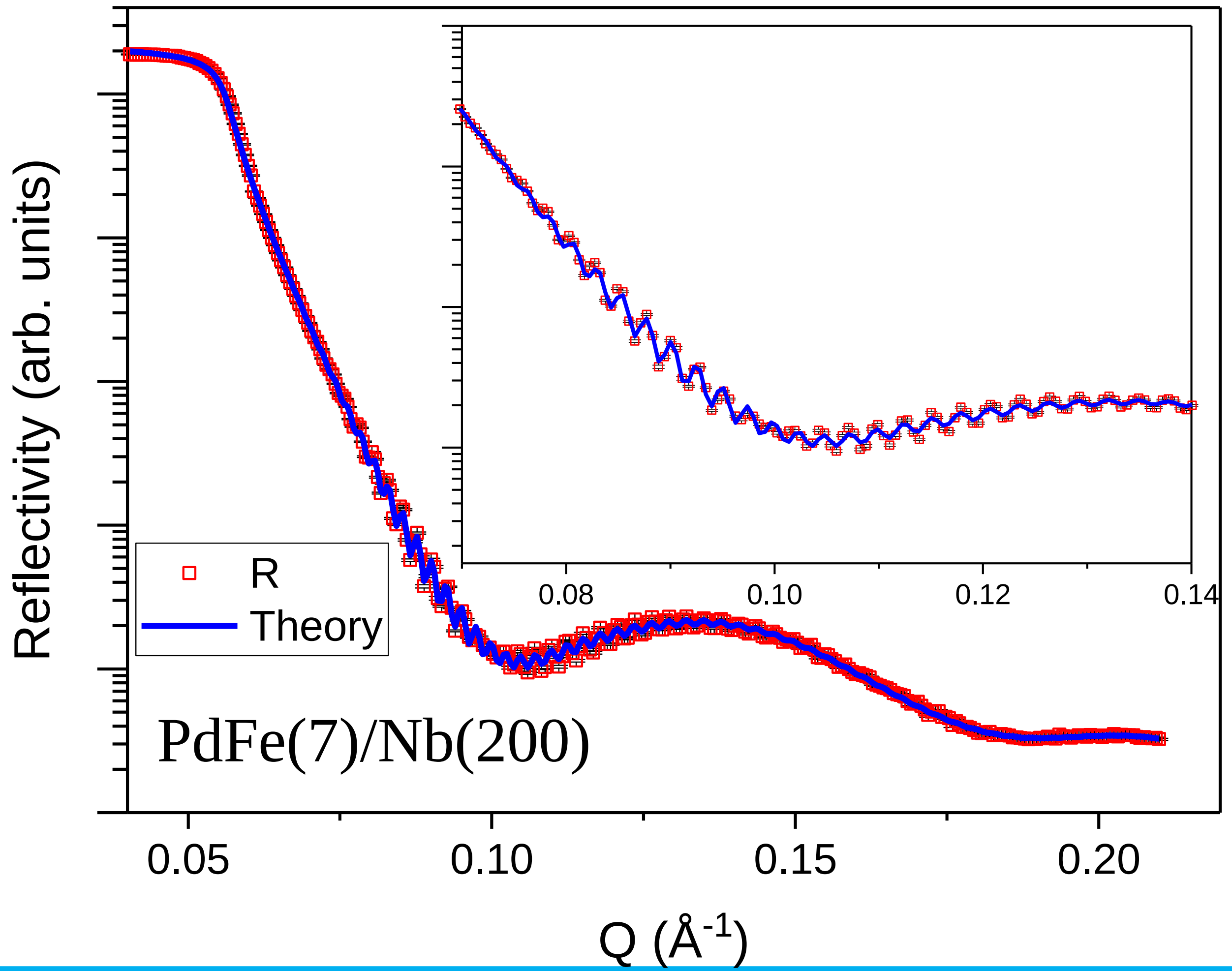


- Compact Nb oscillations
- Thin Ni layer smeared out by roughness

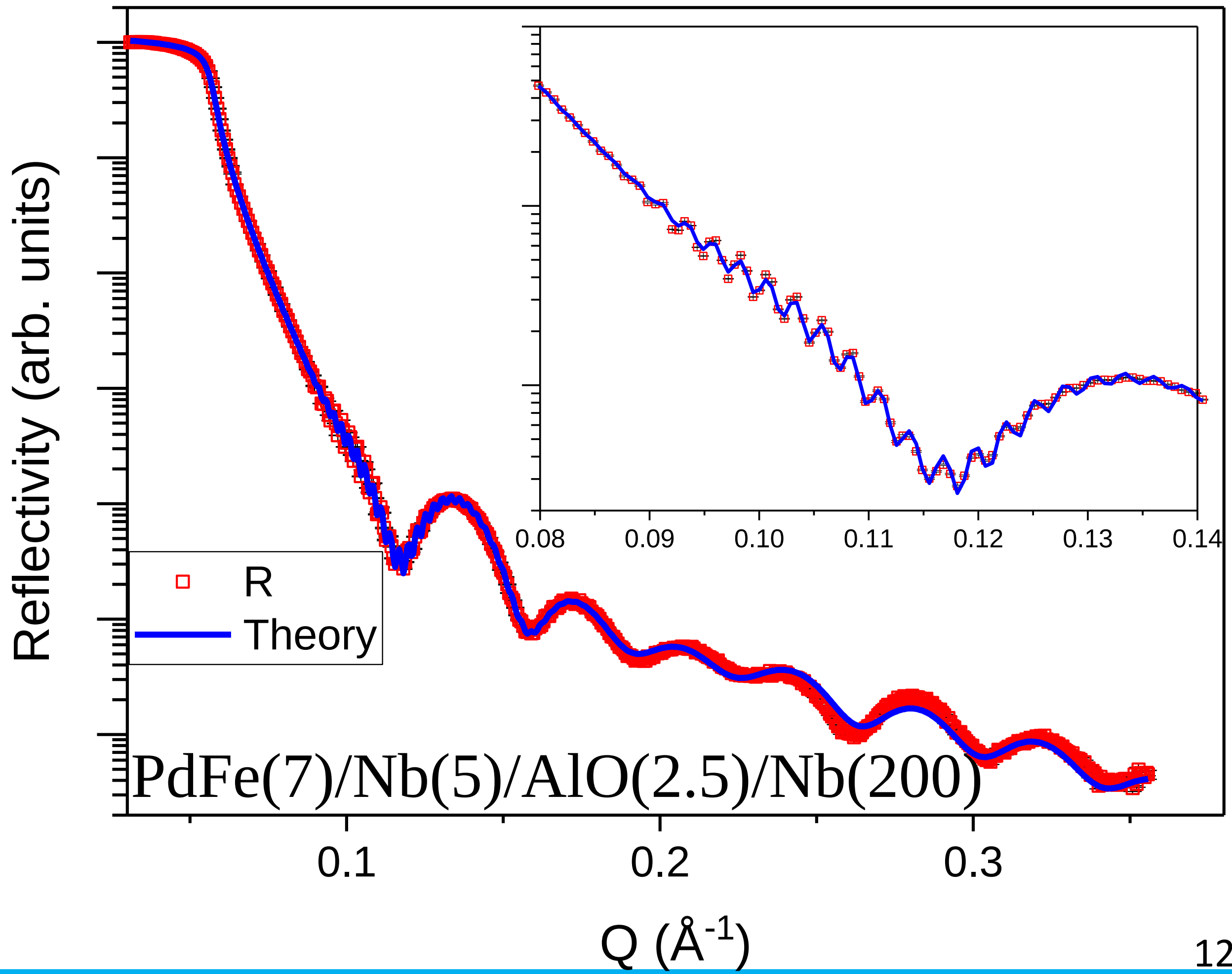


From Data to Knowing Structure

- Clearly see compact Nb oscillations on the long PdFe oscillation

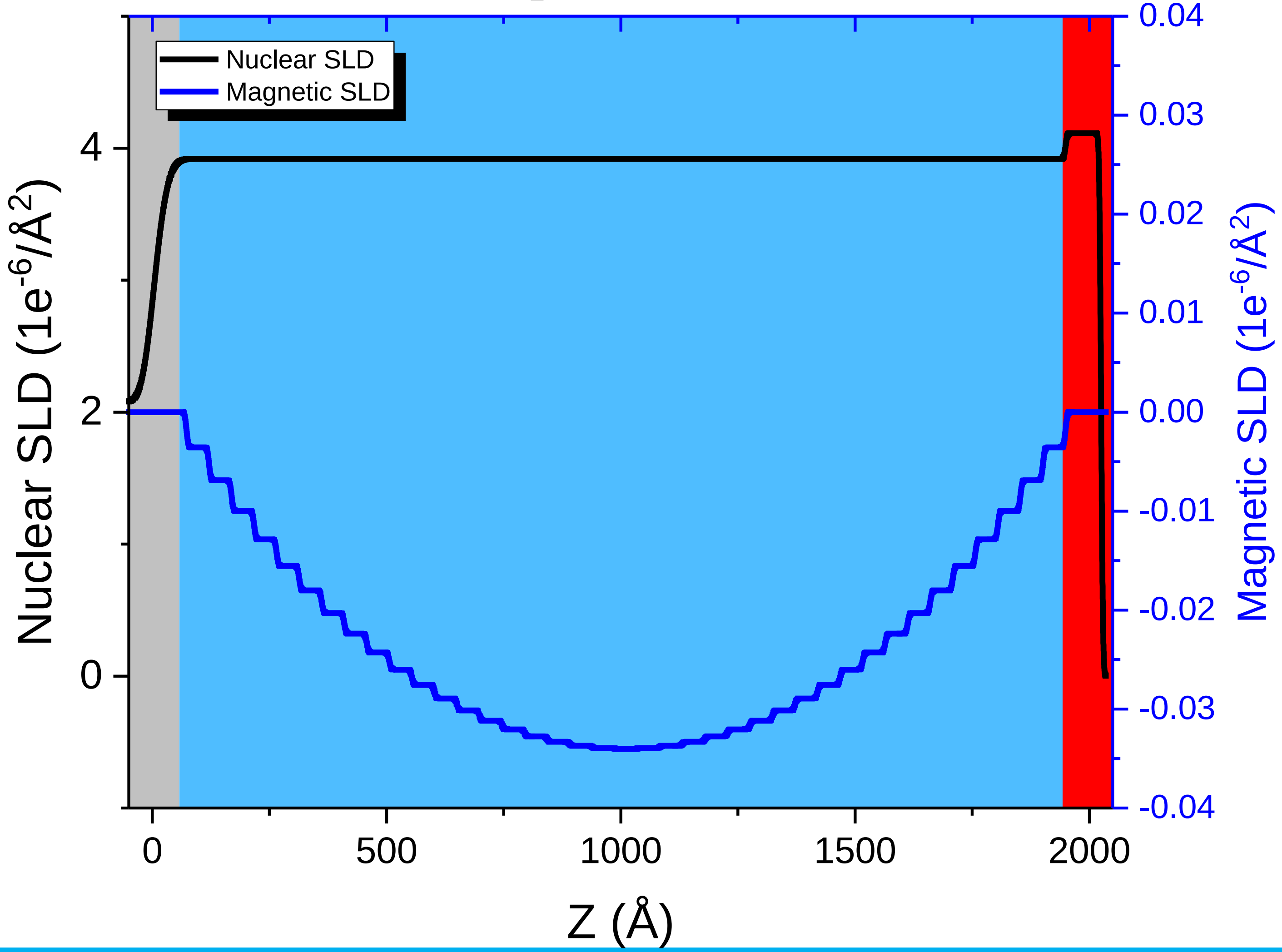


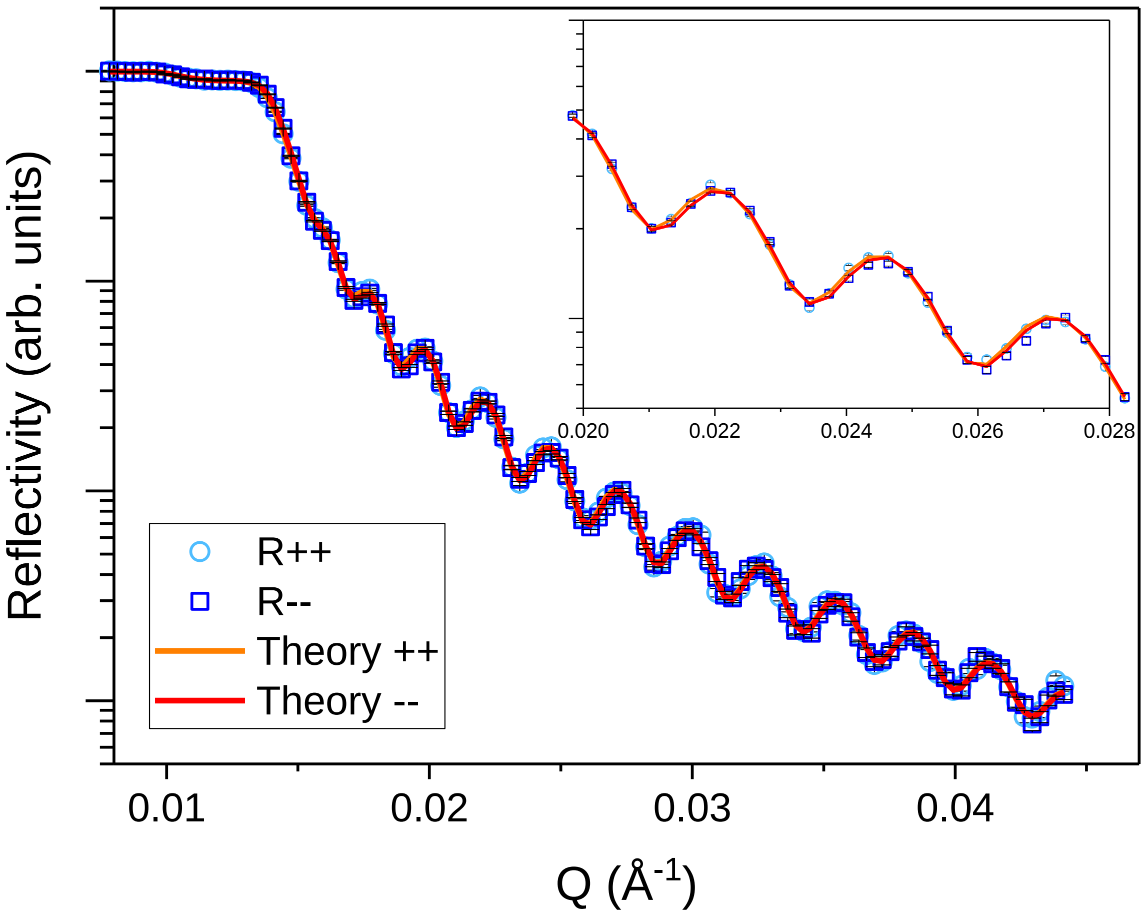
- Can really see all the different lengths of oscillations from each layer



200 nm Nb at 3 K, PNR Data

Depth Profile

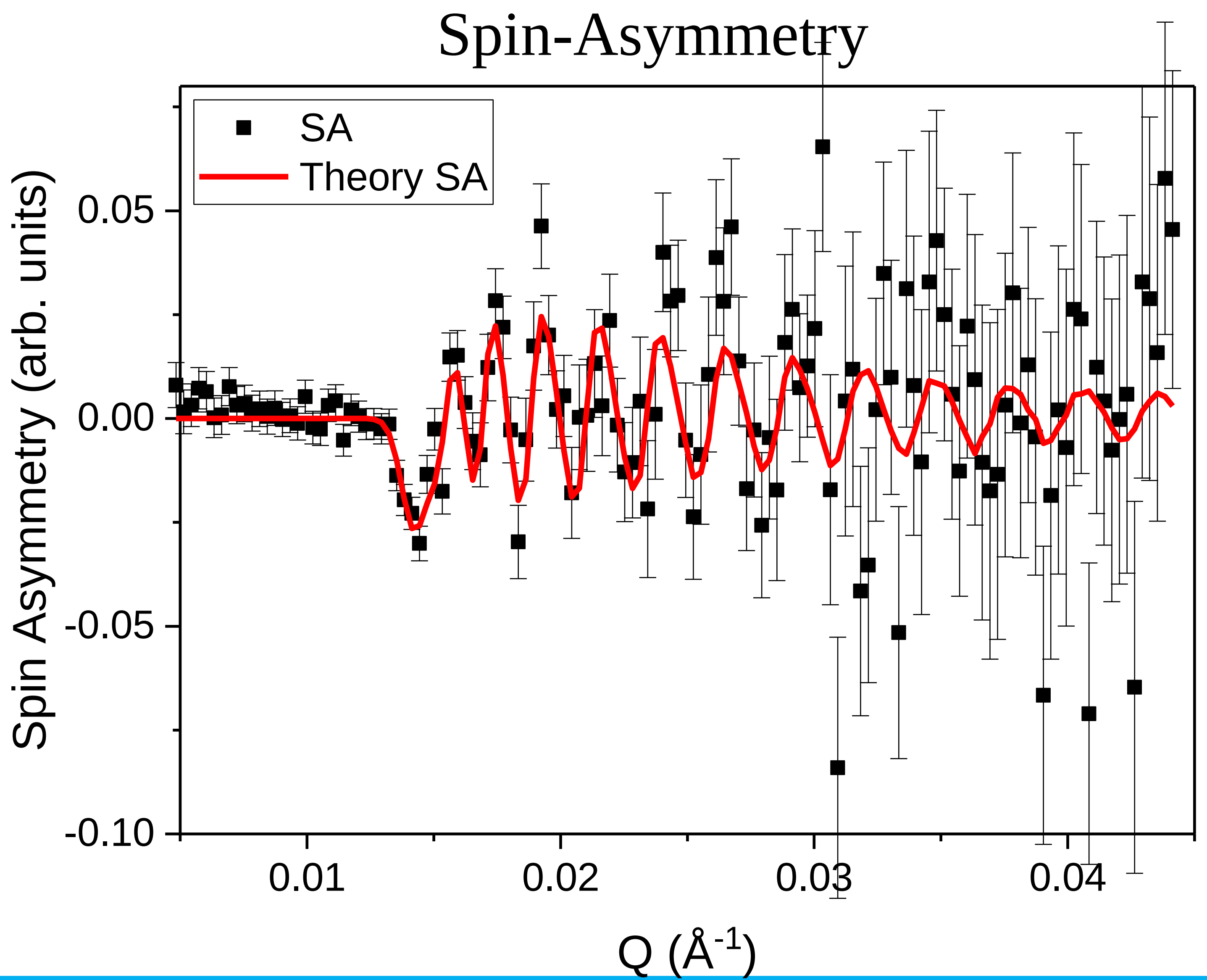




$$B(x) = B_0 \cosh\left(\frac{x}{\lambda} - \frac{d_s}{2\lambda}\right) / \cosh\left(\frac{d_s}{2\lambda}\right)$$

- $Chi^2 = 1.44$
- Exp. λ = 1009 ±50 Å
- Theor. λ = 820 Å

200 nm Nb at 3 K, PNR Data

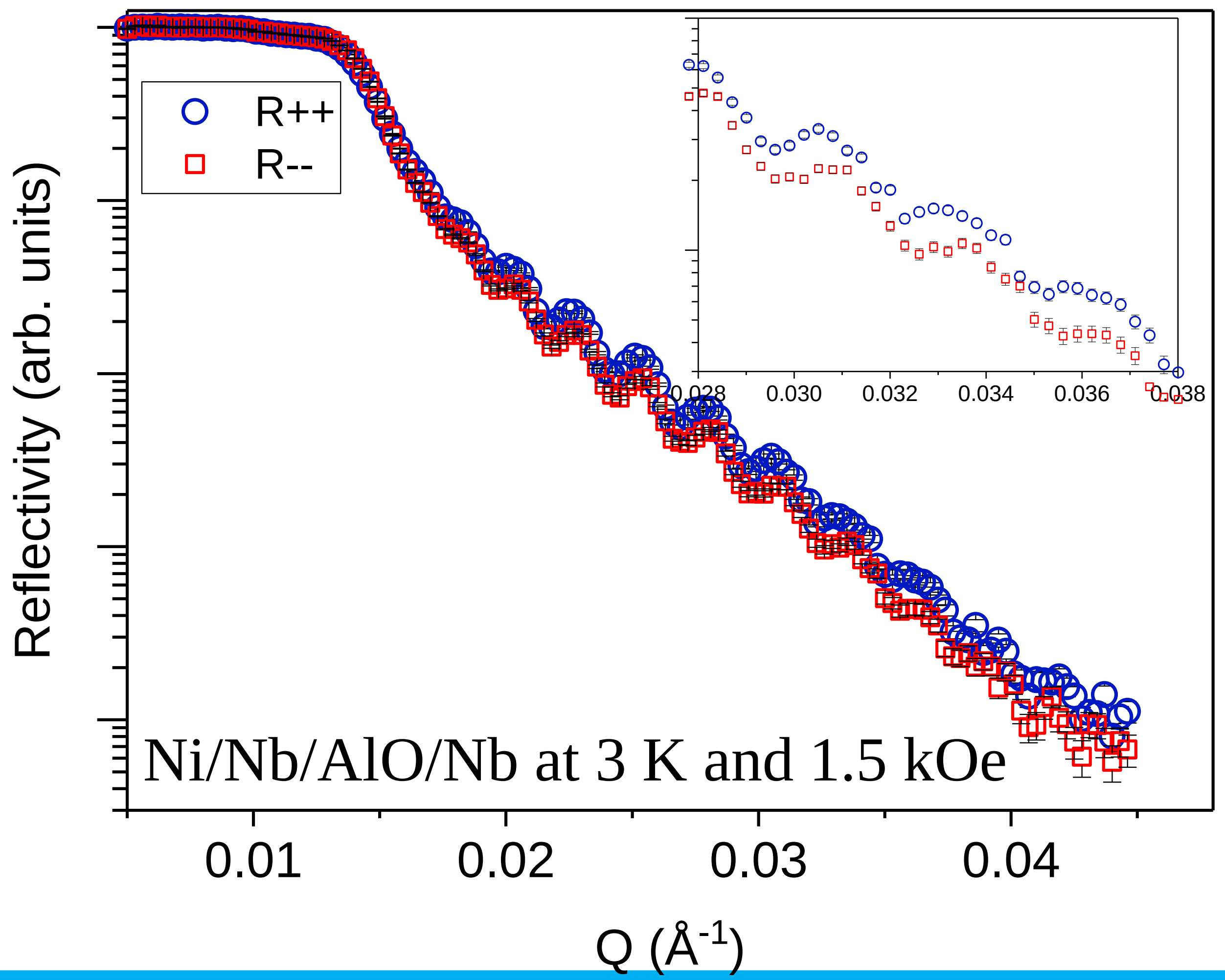


$$SA = \frac{(\uparrow\uparrow - \downarrow\downarrow)}{(\uparrow\uparrow + \downarrow\downarrow)}$$

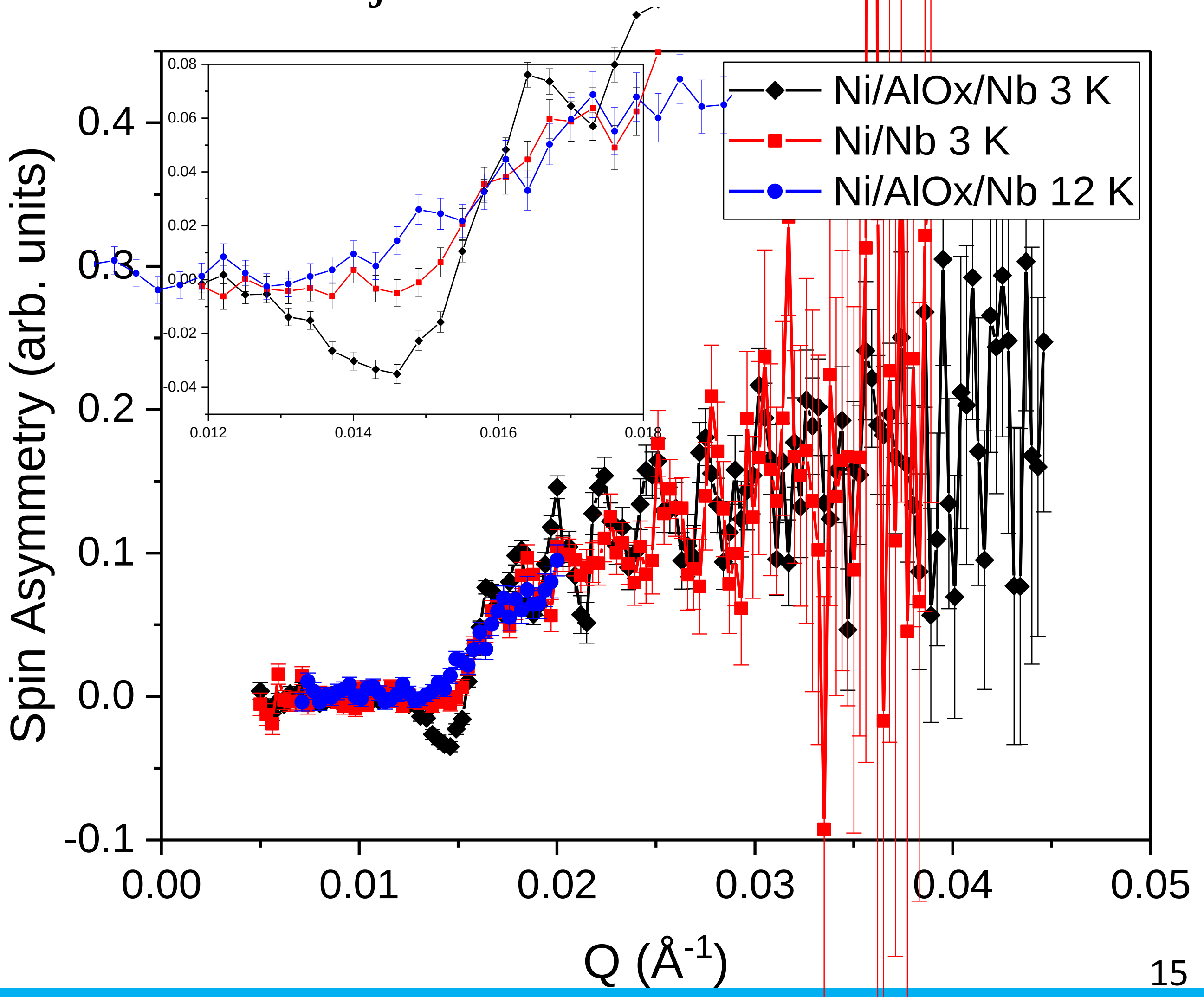
- What is Spin Asymmetry?
- Notice the oscillations of superconducting Nb's SA
- Another way PNR allows us to view magnetic components of materials

On-Going PNR Data Collected

- The ferromagnetic Ni causes the two oscillations to split



- We see a distinct and separate feature from just the Meissner effect



What We Learned From Our Experiments

- Details of samples
  - X-ray data showed Si-wafers are extremely rough
  - Determined the structures of S/F samples
- Understanding important data
  - Found Nb’s London penetration depth
  - Captured abnormal feature in SA plot
- Continued analysis required
  - Attempt to describe abnormal feature
  - Analysis of other sample structures required

If I was a SURF student for…

- Another month
  - Finish collecting x-ray data
  - Fit structures of each sample
- Another year
  - Fit structures of PNR data with the help of x-ray fits
  - Continue analysis of PNR fits to investigate electromagnetic proximity effect
- Life
  - Consider other field geometries to study
  - Test non-colinear magnetization in adjacent materials
  - Publish paper on findings

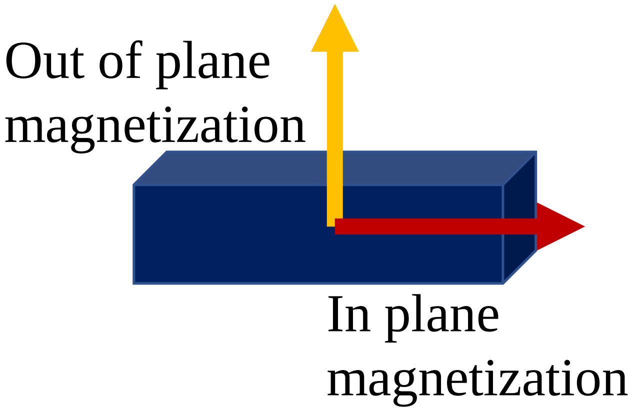
Thank You!

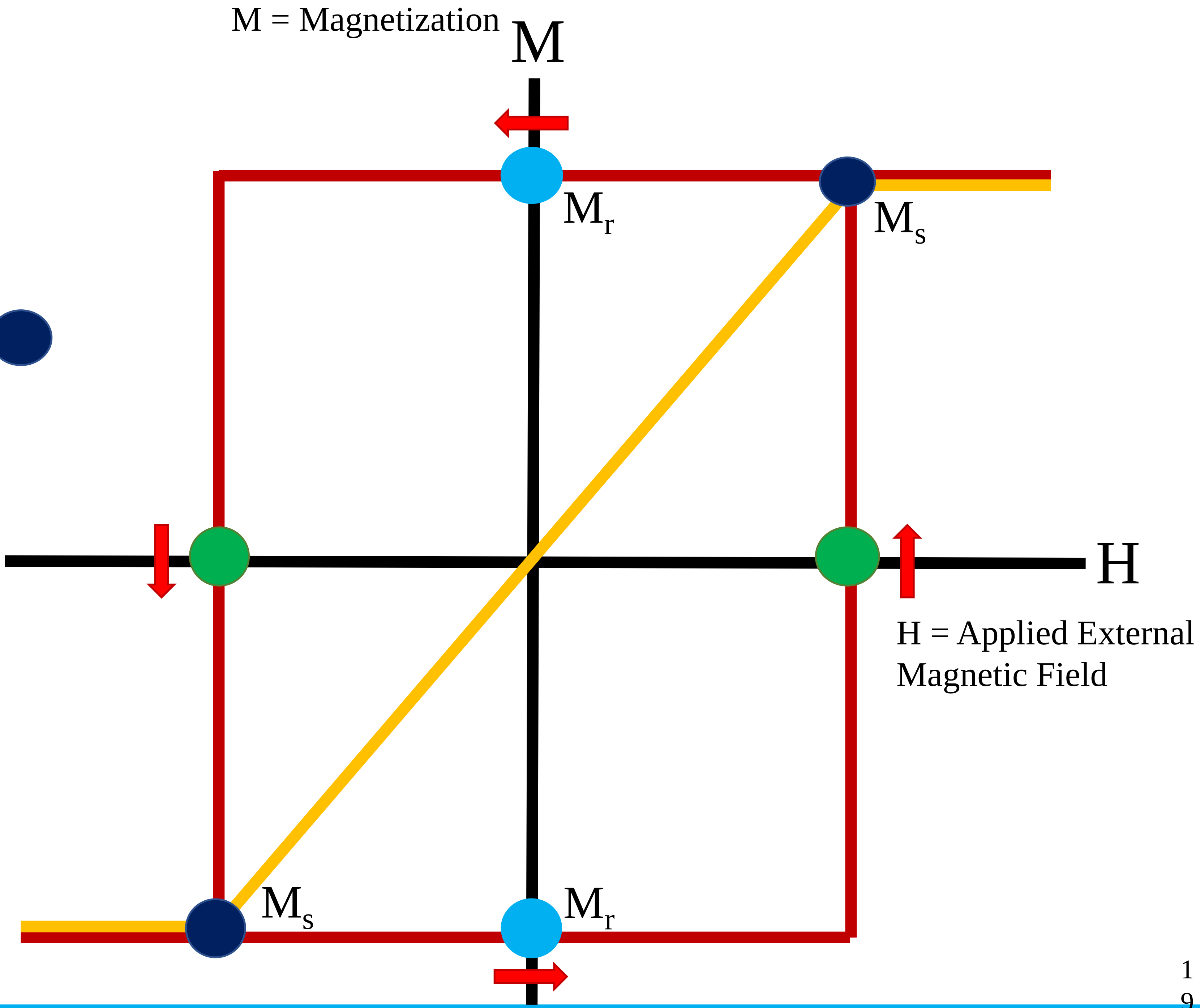
- Acknowledgments: Patrick Quarterman
  Alex Grutter
  Julie Borchers
  Joe Dura
  NCNR Softball Team

Hysteresis Curves

- Easy Axis
- Hard Axis
- Magnetization Saturation
- Coercivity
- Remnant Field

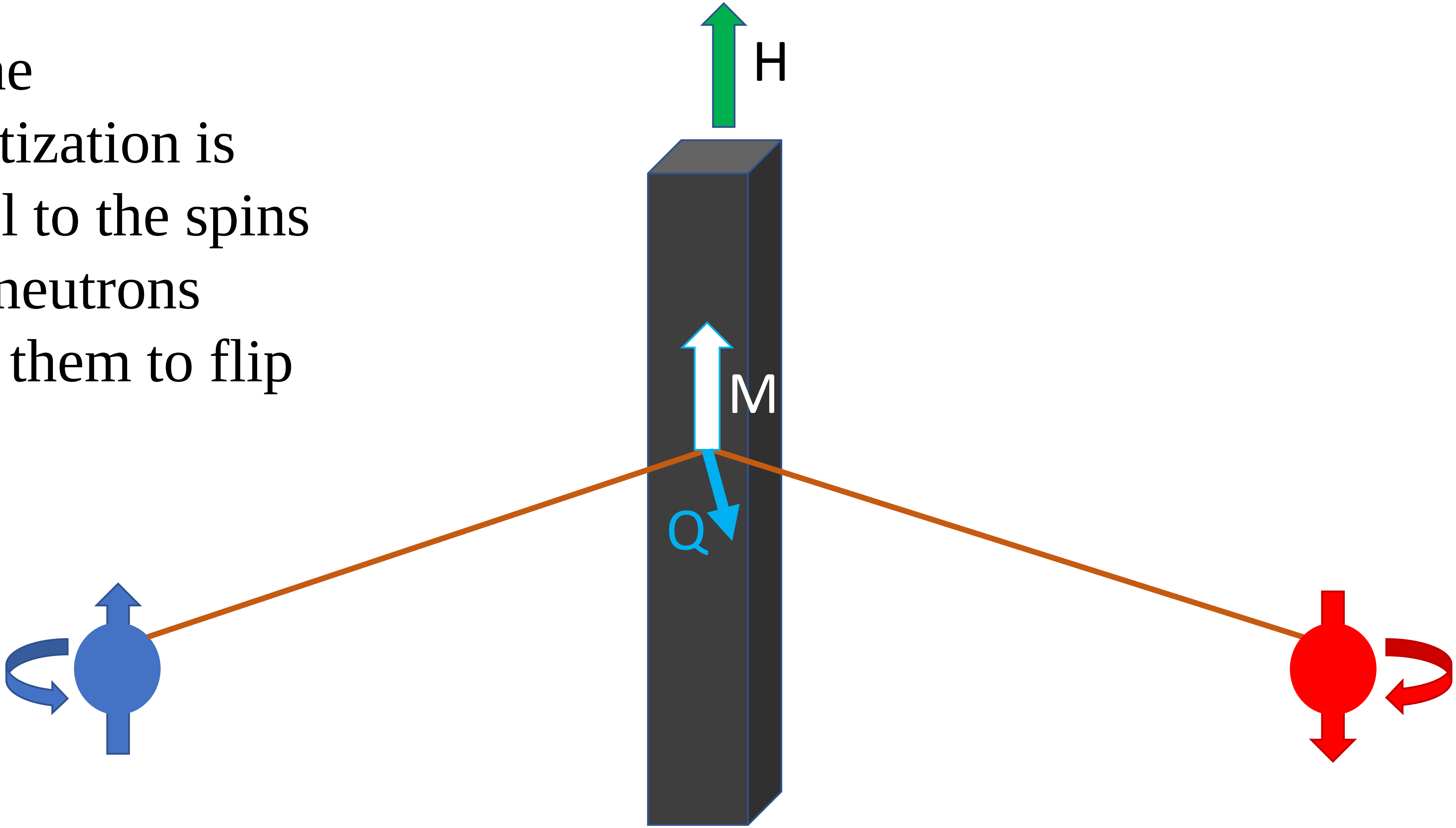
Ex.





How PNR Directly Detects Magnitization

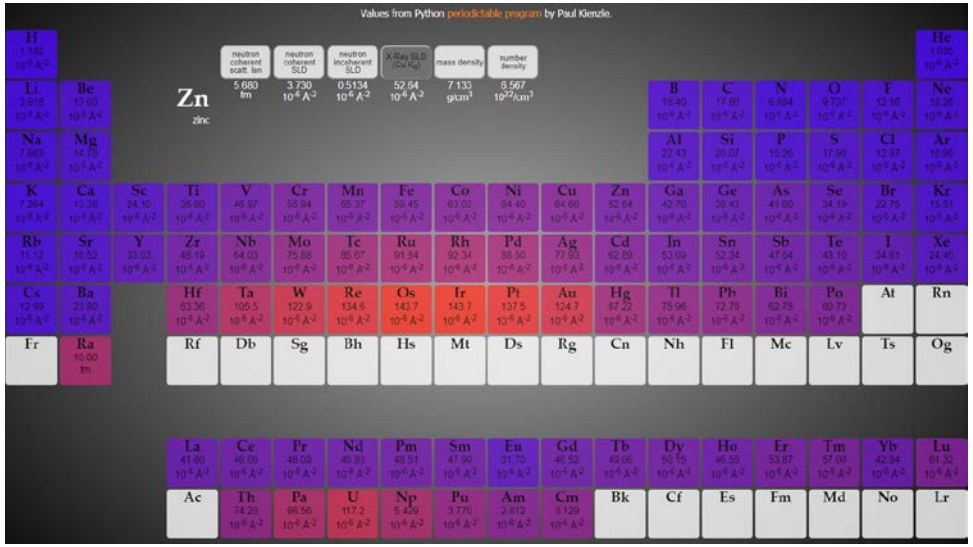
- In plane magnetization is parallel to the spins of the neutrons causes them to flip



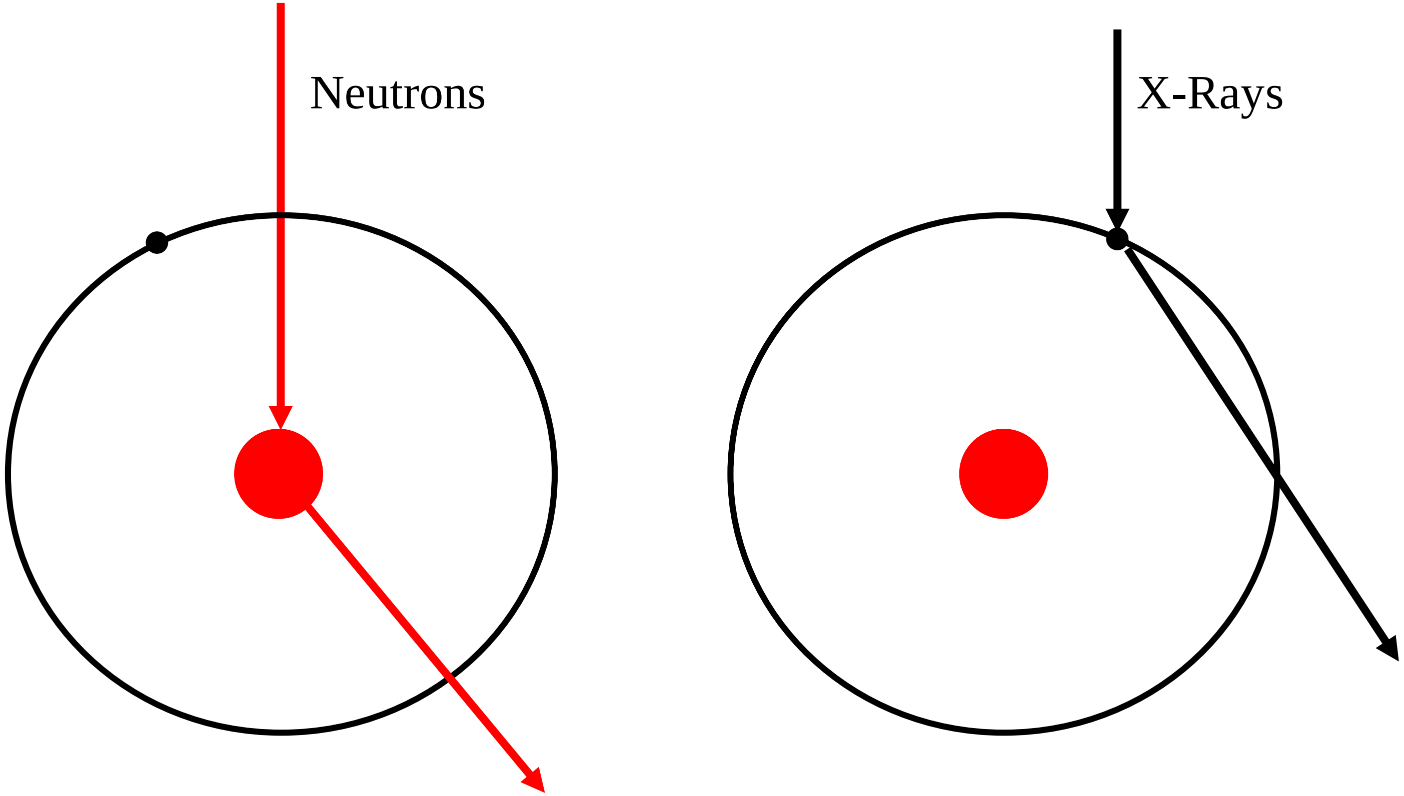
https://alunosonline.uol.com.br/fisica/spin.html

Why We Do PNR and XRR

- Neutron SLD



- X-Ray SLD

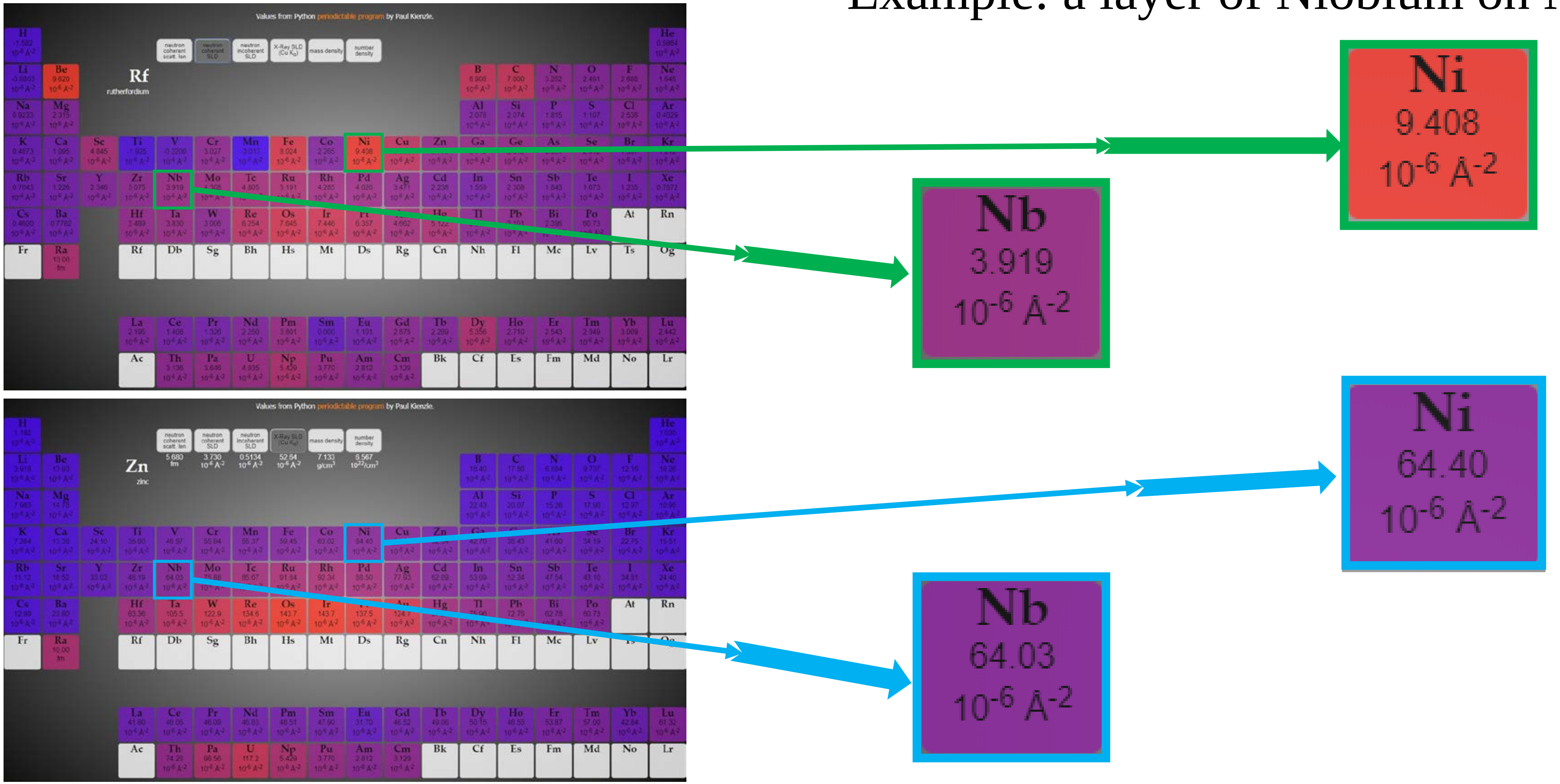


https://ncnr.nist.gov/instruments/magik/Periodic.html

Neutrons Advantage

- Neutron SLD

- Example: a layer of Niobium on Nickel

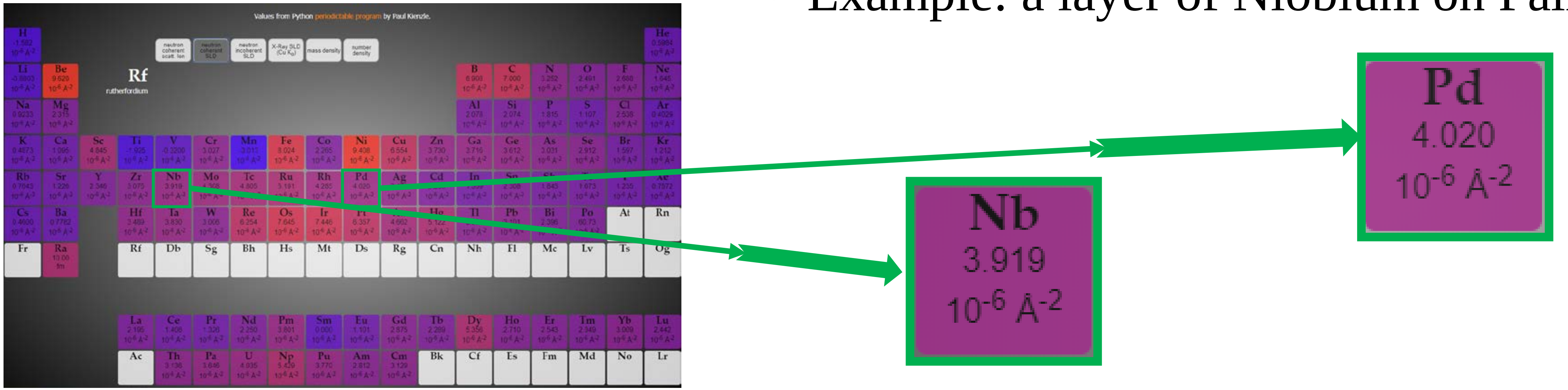


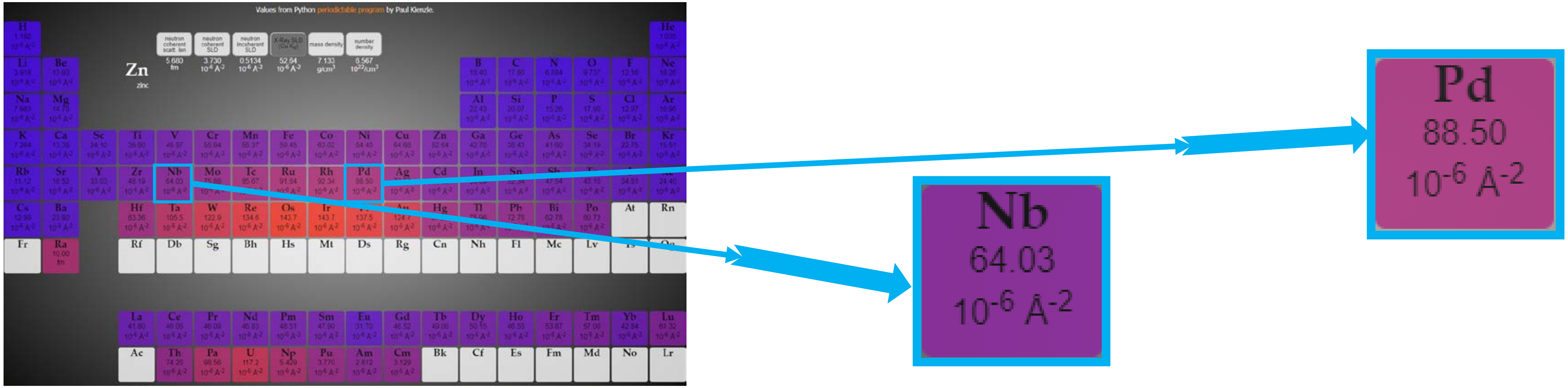
- X-Ray

X-Ray Advantage

- Neutron SLD

- Example: a layer of Niobium on Palladium

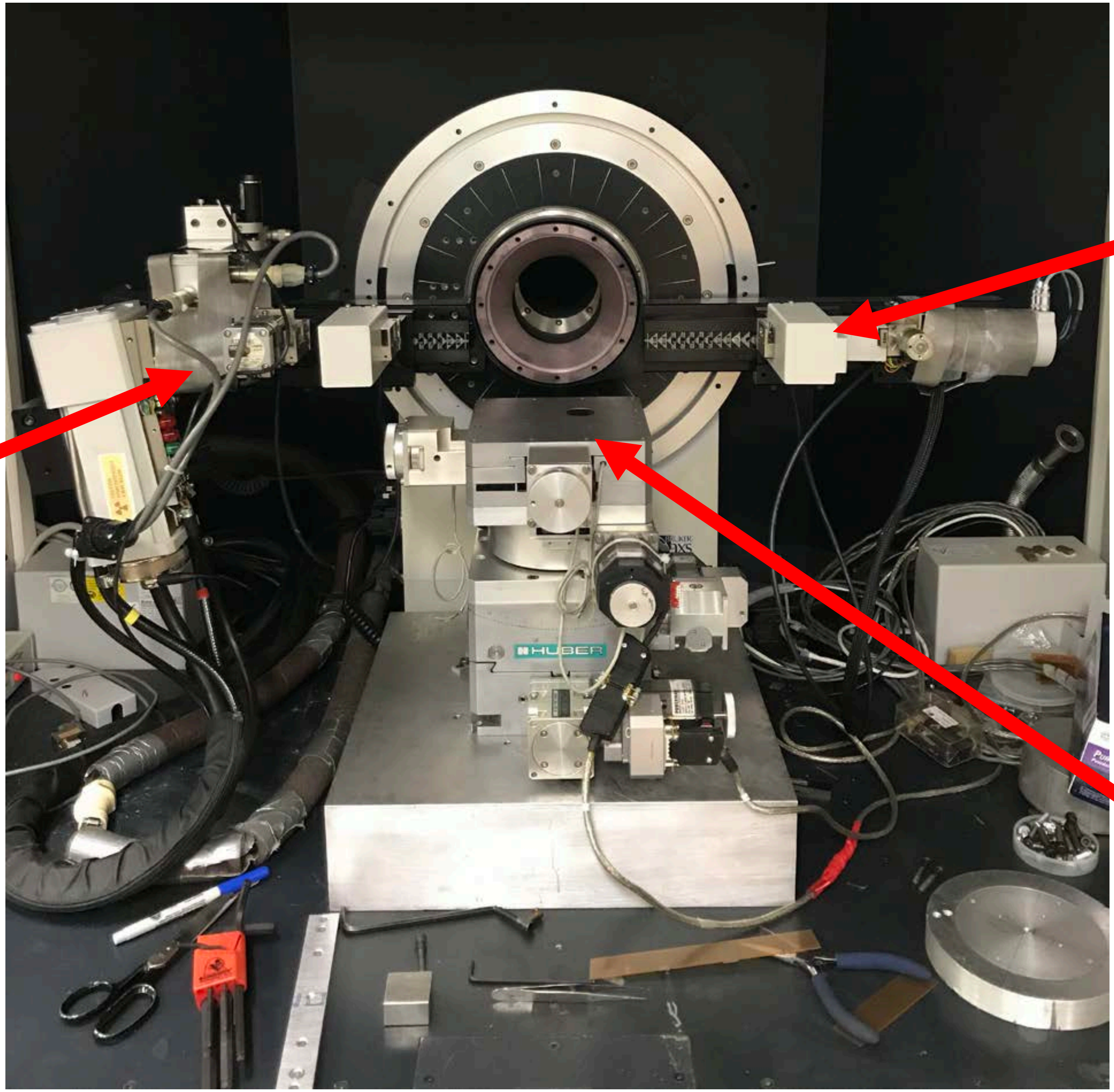




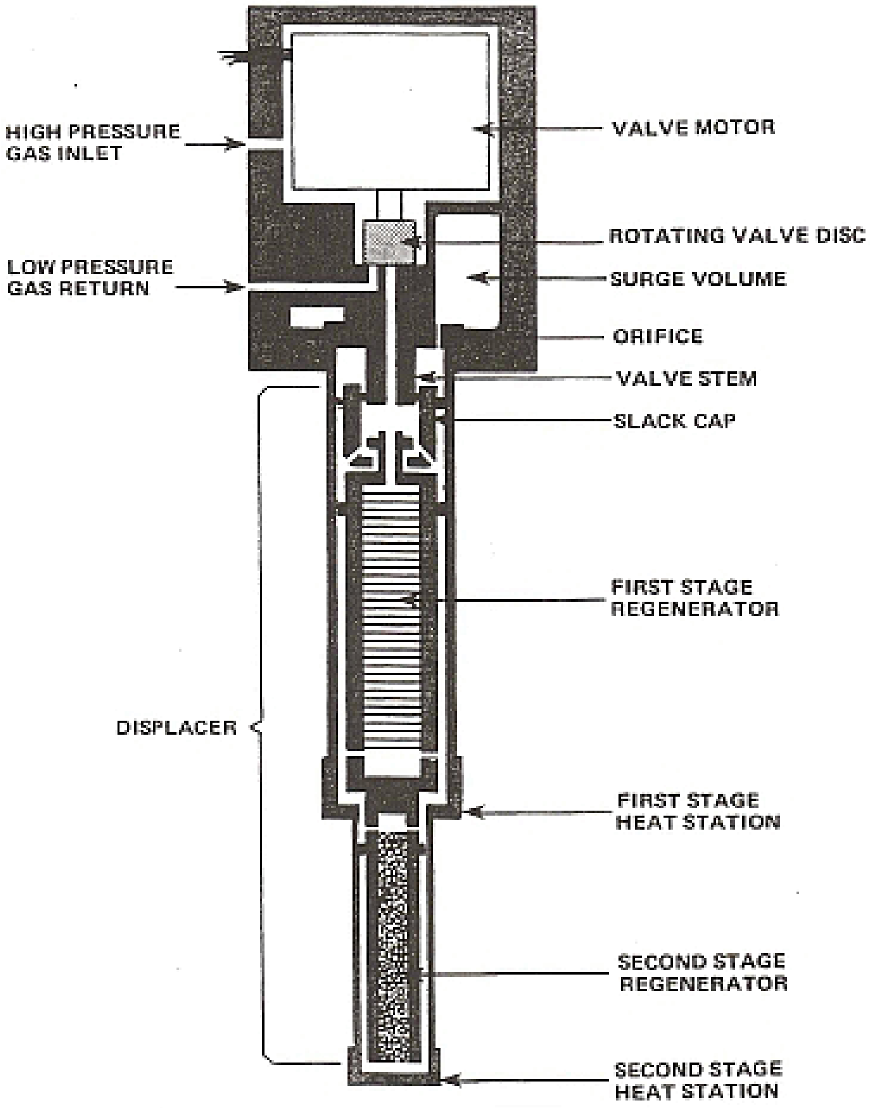
- X-Ray SLD

https://ncnr.nist.gov/instruments/magik/Periodic.html

Bruker XRR



Closed Cycle Cryostat



https://www.arscryo.com/cryocooler-principles-of-operation

(Back-up Fits for Possible Questions)