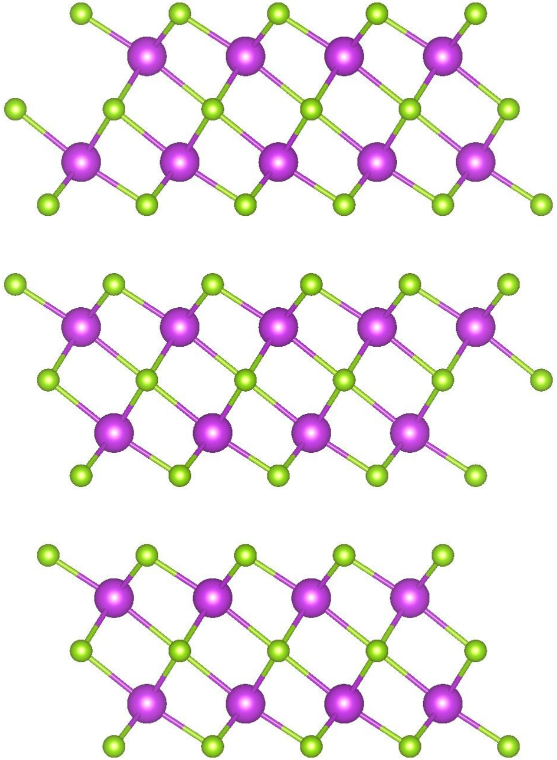
Understanding Length Scales for Magnetic Coupling in Thin Film Topological Insulators

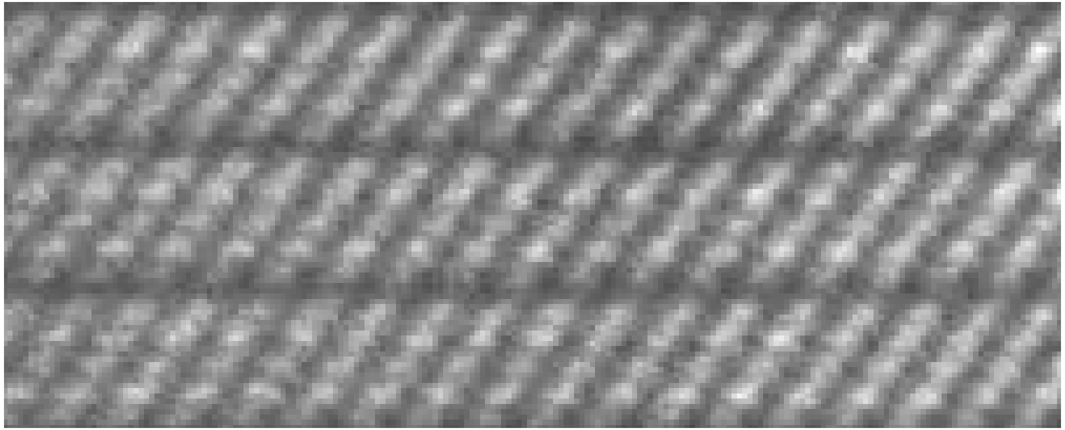
Jyotsna Rao
Montgomery Blair High School

Mentor: Alexander Grutter
NIST Center for Neutron Research

Thin Film Topological Insulators

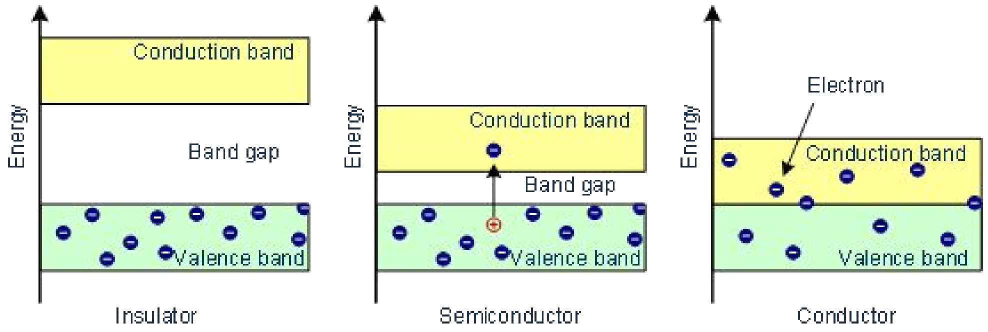
- Insulators in interior
- Metallic and conductive surface state
- Layered structure
    - $(Bi\text{-}Sb)_2Te_3$

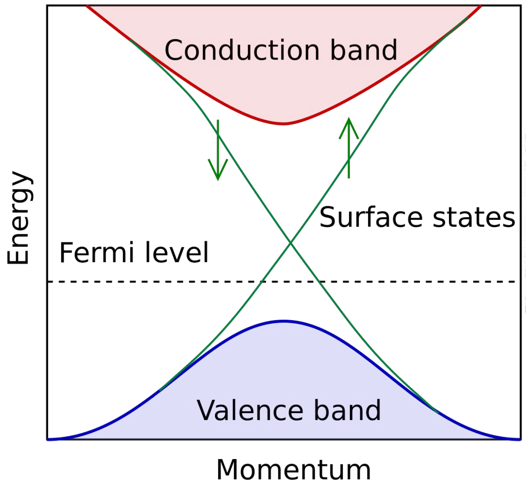


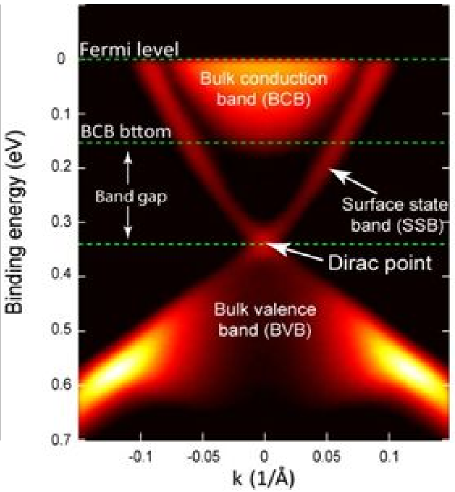


Band Structure

- Combining of orbitals in bonding creates molecular orbitals with many different energy levels
- When electrons can move around, there is conduction
- Topological insulators have surface states for electrons to move through

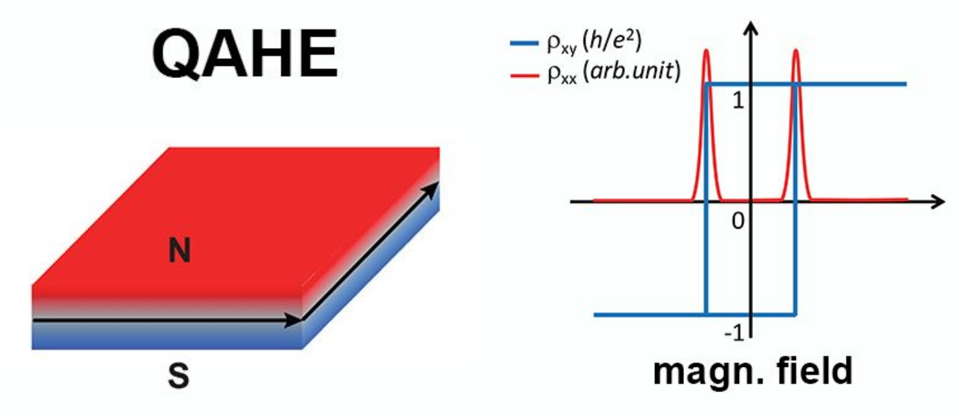






Quantum Anomalous Hall Effect

- **Quantum Anomalous Hall Effect:** Quantized edge conduction
  - 2D electronic material
  - Magnetic
  - Topological
- QAHE allows dissipationless transport
  - Around edge of material
- Applications in low power devices

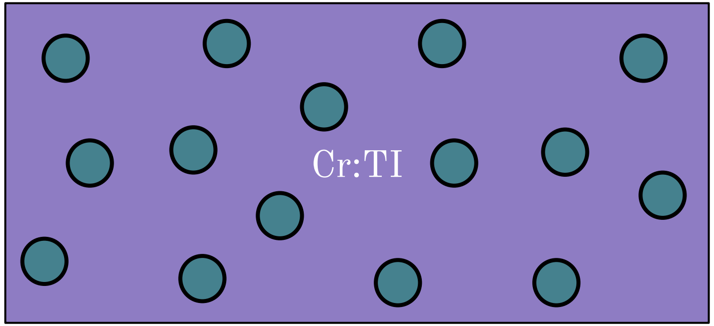


Why does raising magnetic ordering temperature not raise QAHE temperature?

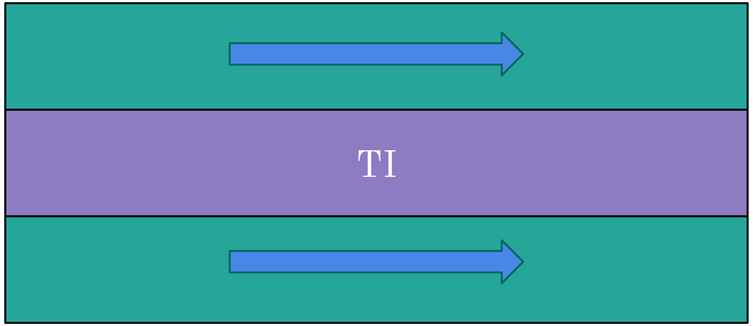
- QAHE disappears at less than 1K
- Magnetization seen at up to 400K
- Theory: QAHE very sensitive to defects and inhomogeneity
- Goal: Magnetize TI while minimizing defects
  - High quality interfaces
  - Separate dopants from surface state
  - Raise QAHE temperature?

How can we magnetize?

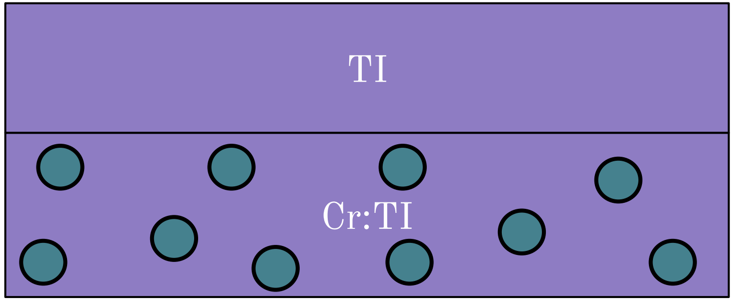
- Doping with chromium



- Grow TI on magnet



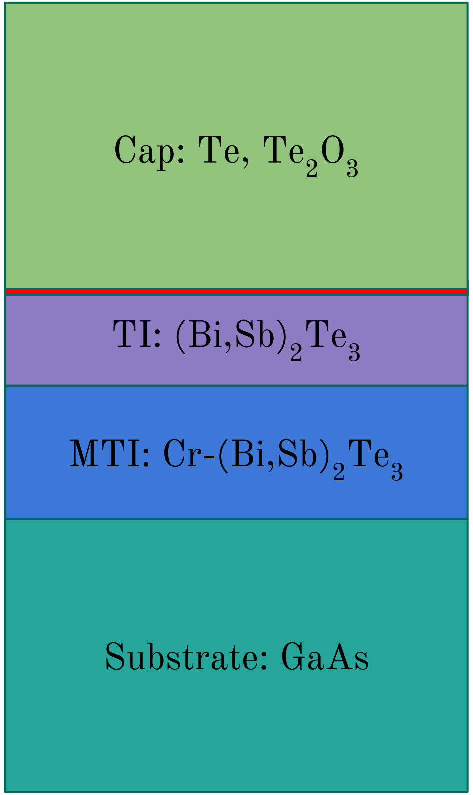
- Grow TI on MTI

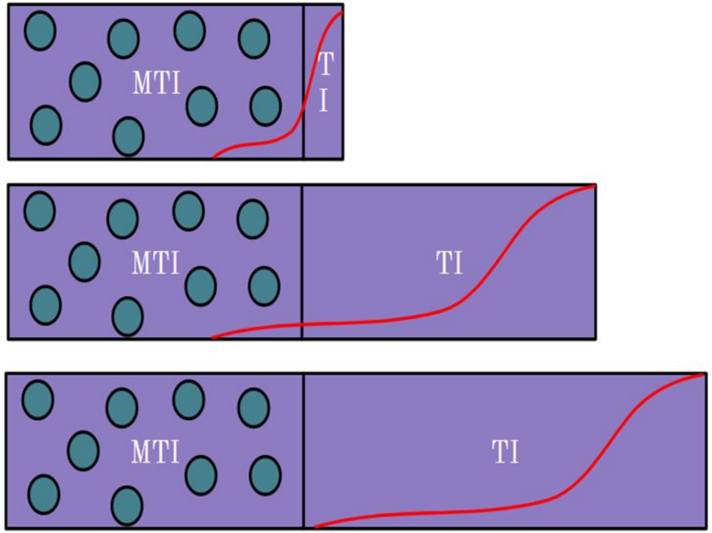


- TI on MTI reduces defects
  - No dopants in TI
  - No rough interface

Samples

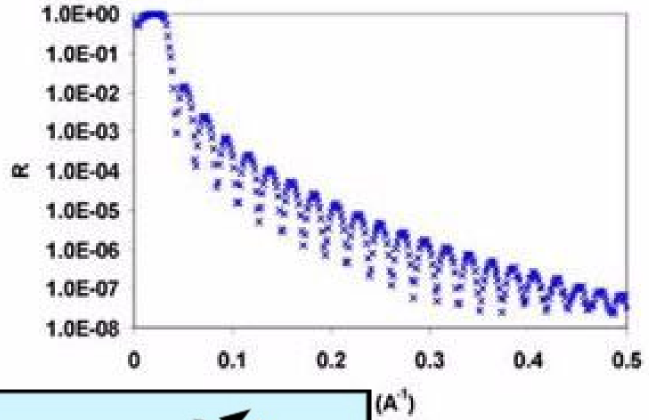
- Grown on substrate
  - Easier to handle
  - Fewer defects
- TI layer adjacent to MTI layer
  - MTI layer magnetism affects TI
- Thickness range for TI
  - 1 nm
  - 3 nm
  - 6 nm

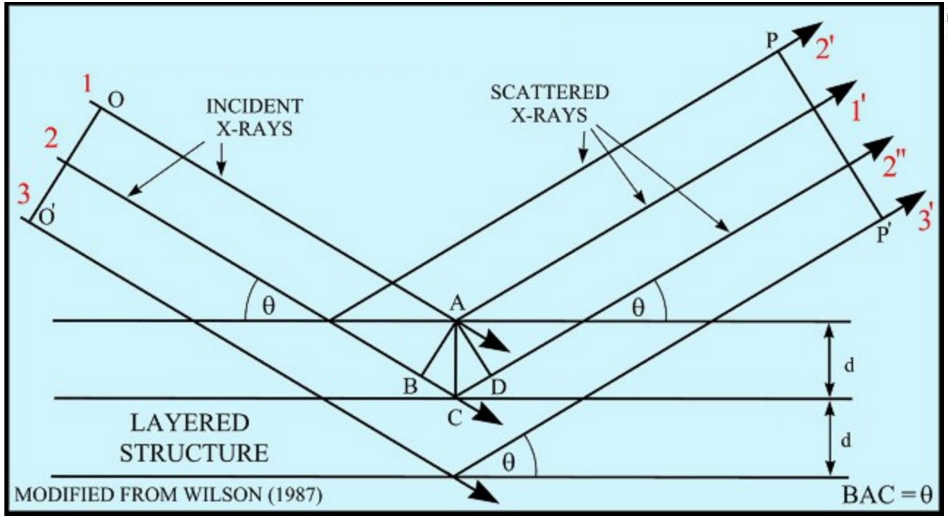




X-Ray Reflectometry

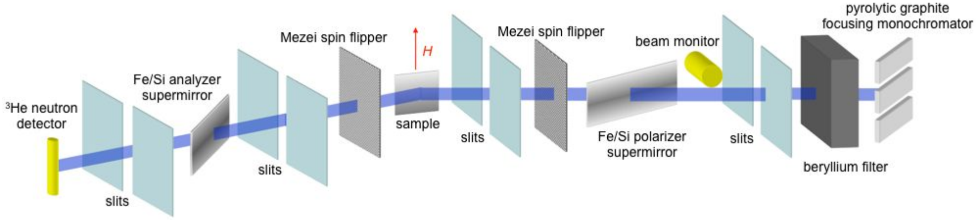
- Beam of X-rays shot at sample
- Measure intensity of reflected beam
- Fit resulting data
- X-rays interact with electrons in sample

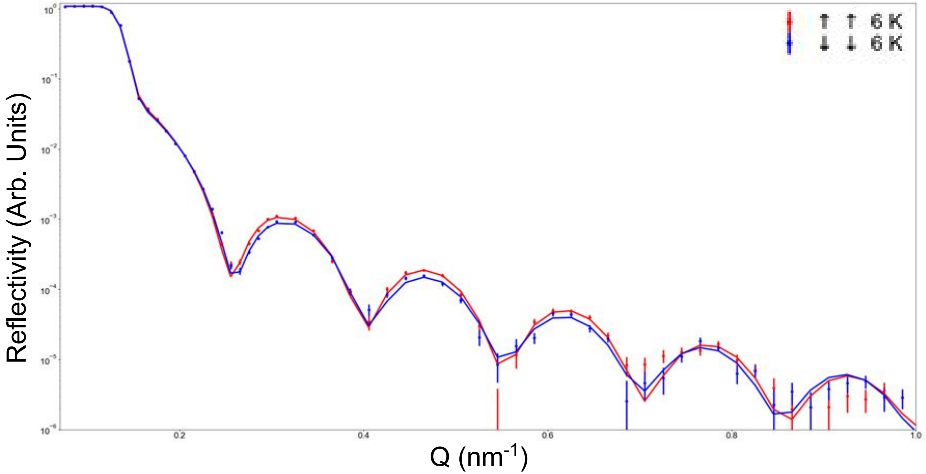




Polarized Neutron Reflectometry

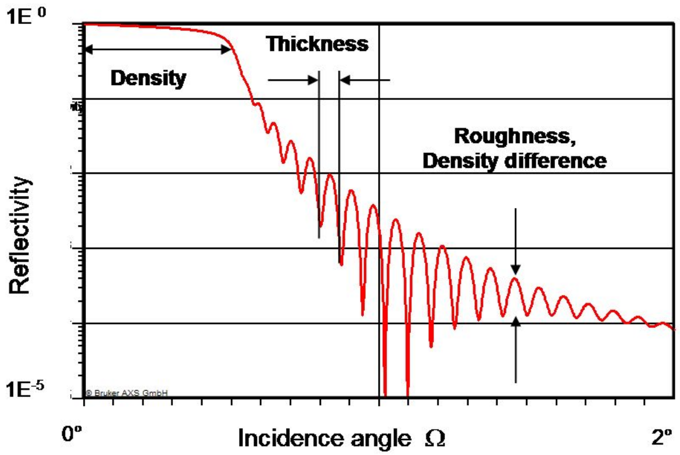
- Similar to X-ray reflectometry
  - Neutrons are also waves
- Neutrons interact with nucleus
- Neutrons give information about magnetism in sample
  - Spin up and down neutrons interact slightly differently

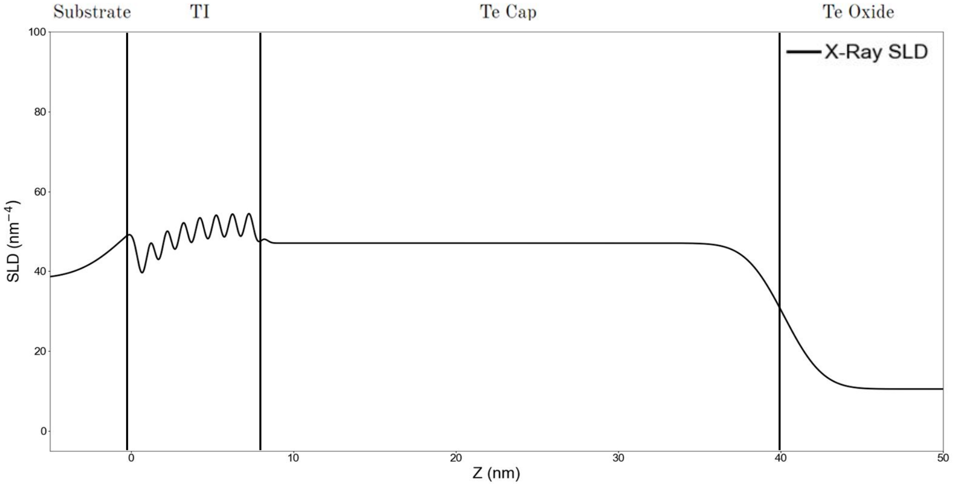




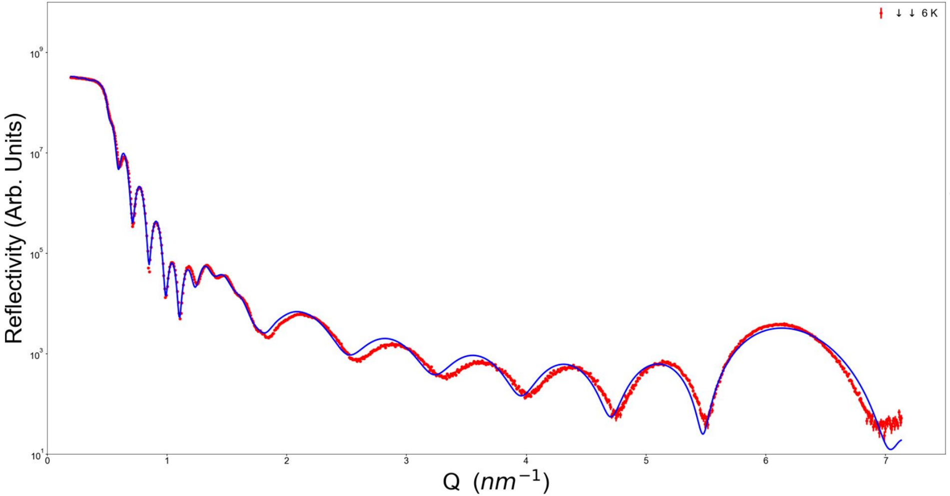
Fitting

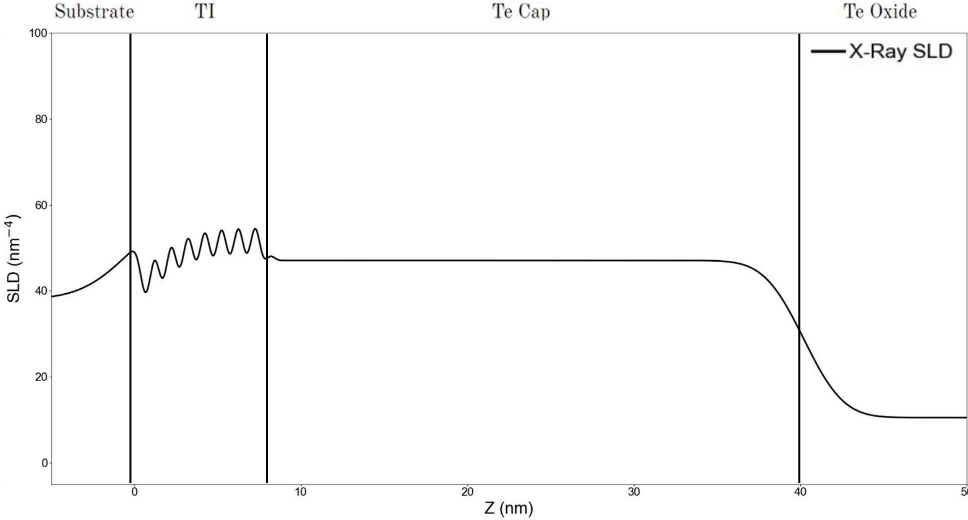
- Vary parameters for each layer of sample
  - Thickness
  - Roughness
  - SLD
- Gives depth and magnetic profiles

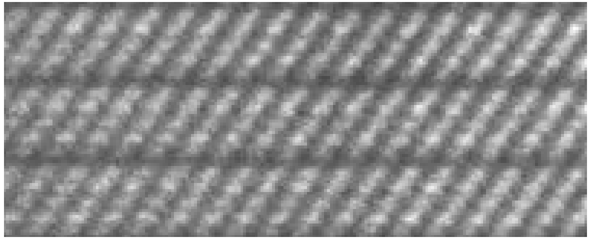




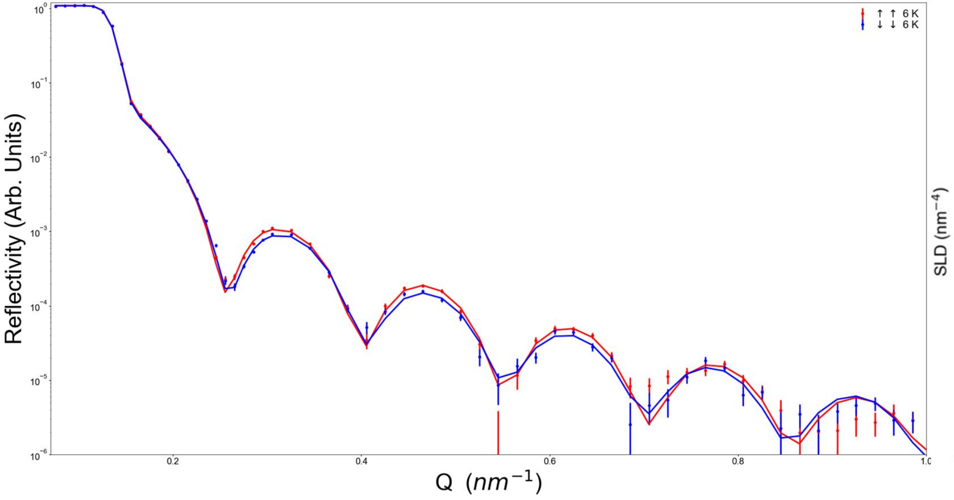
X-Ray Results

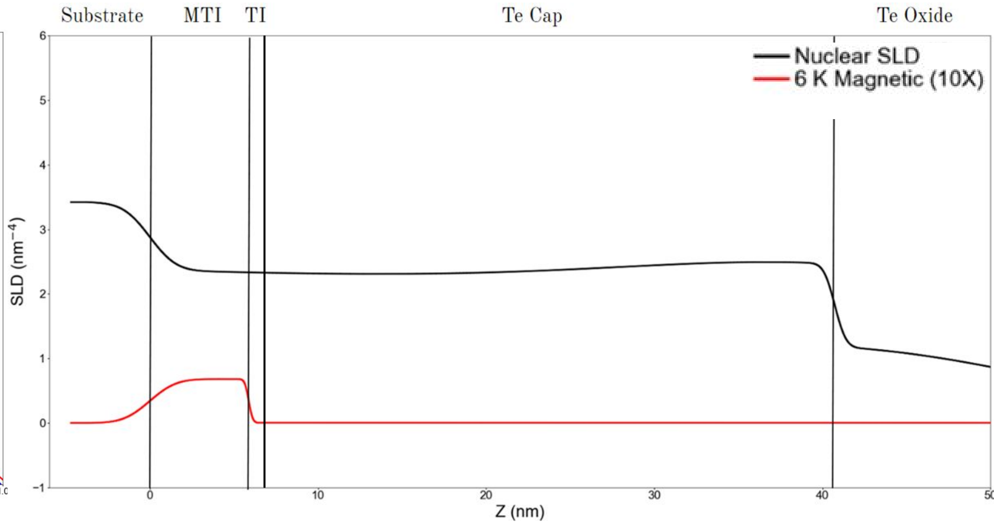




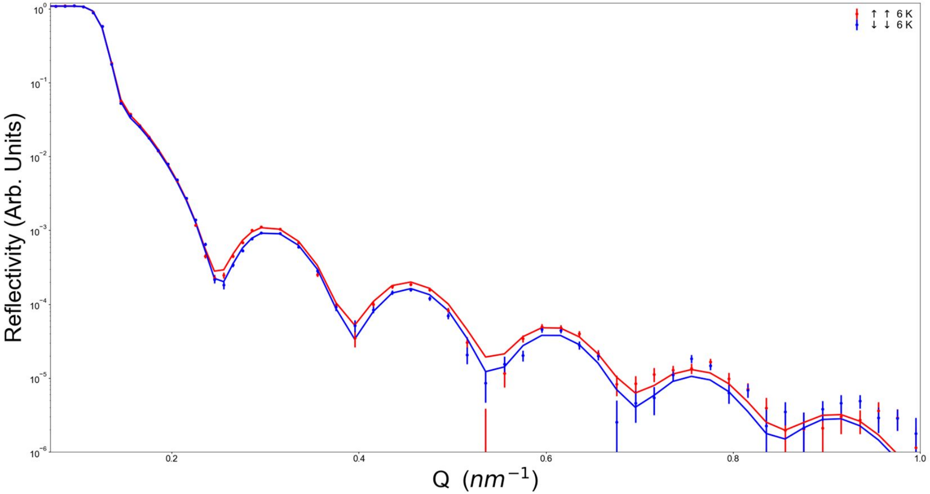


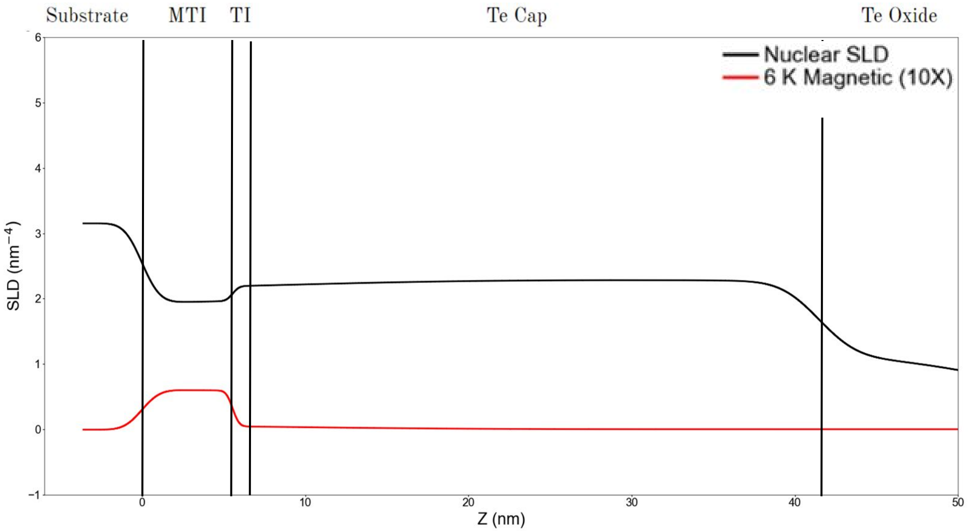
Neutron Results



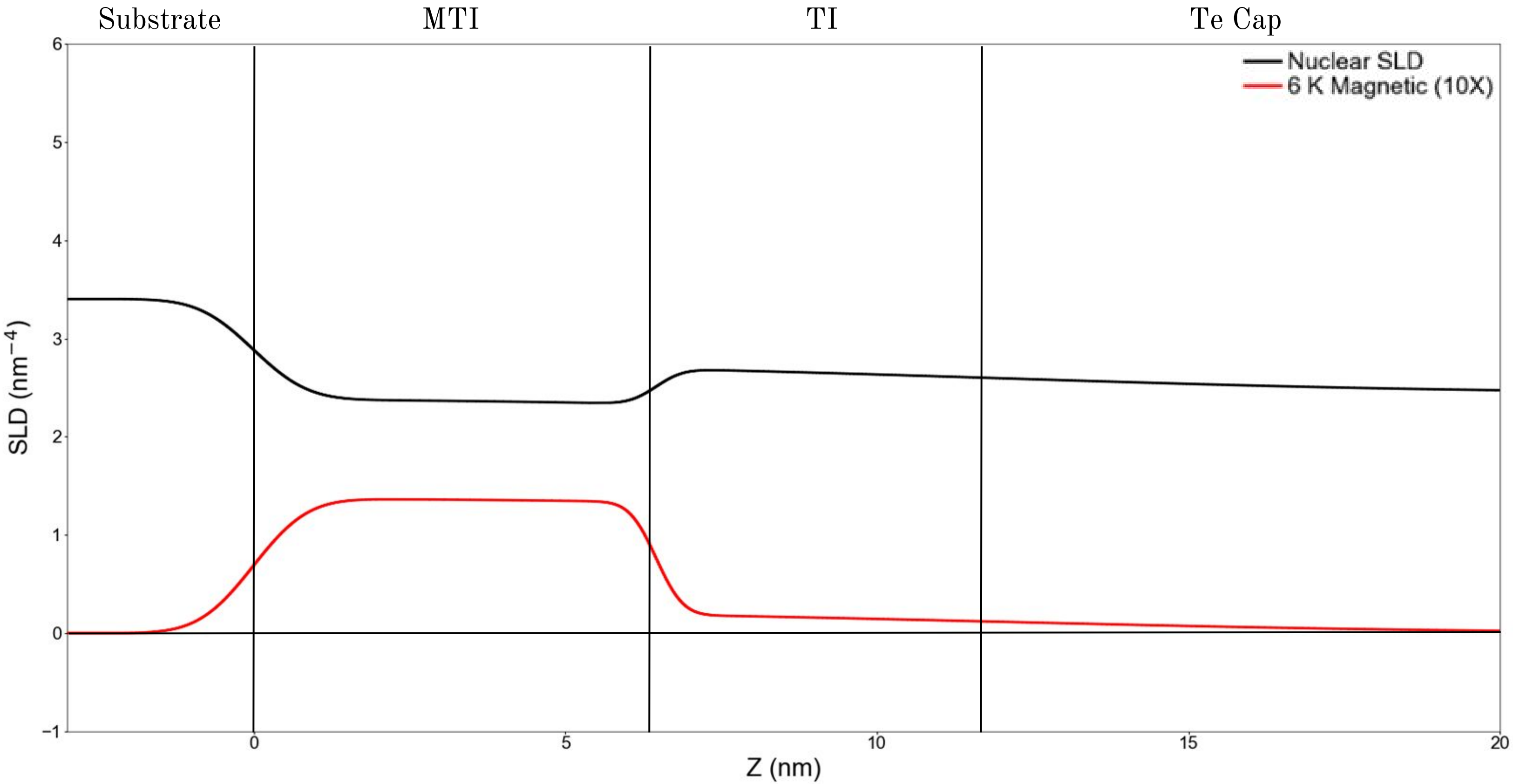


Alternative Fit



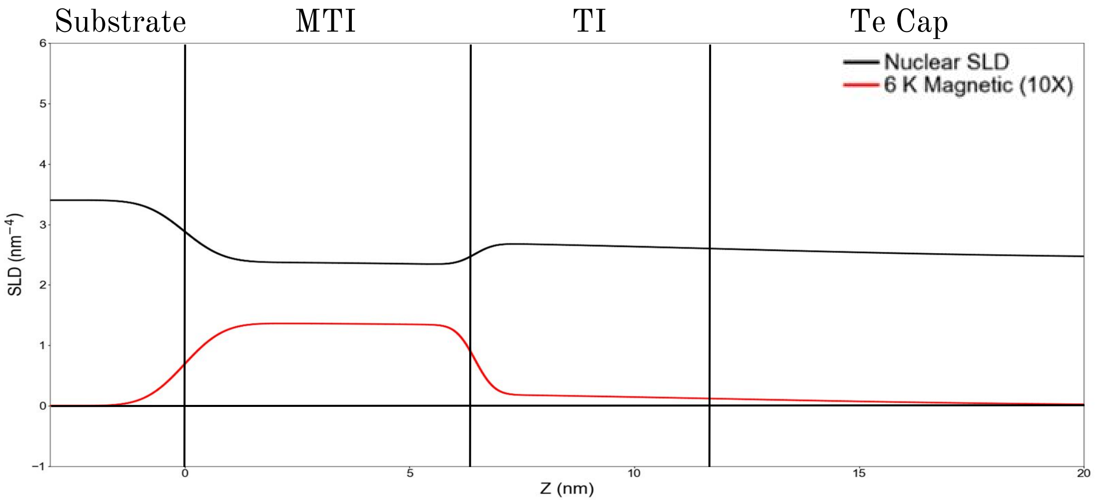


Another Sample



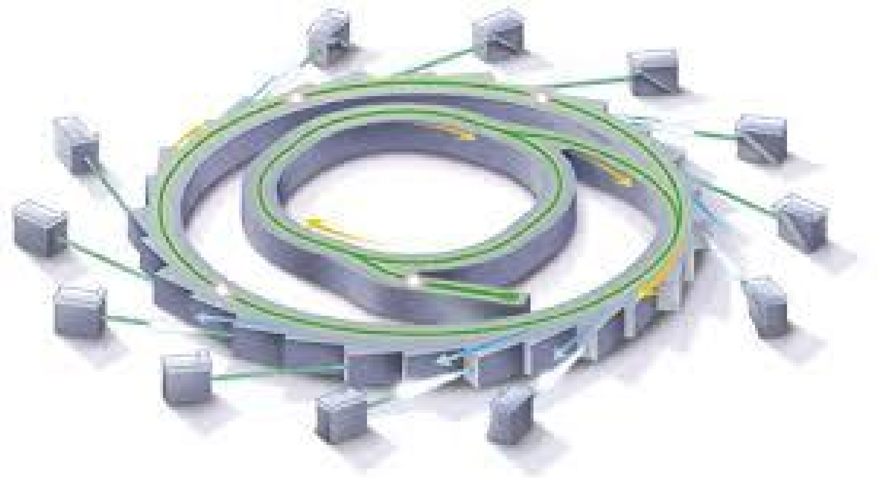
Conclusions

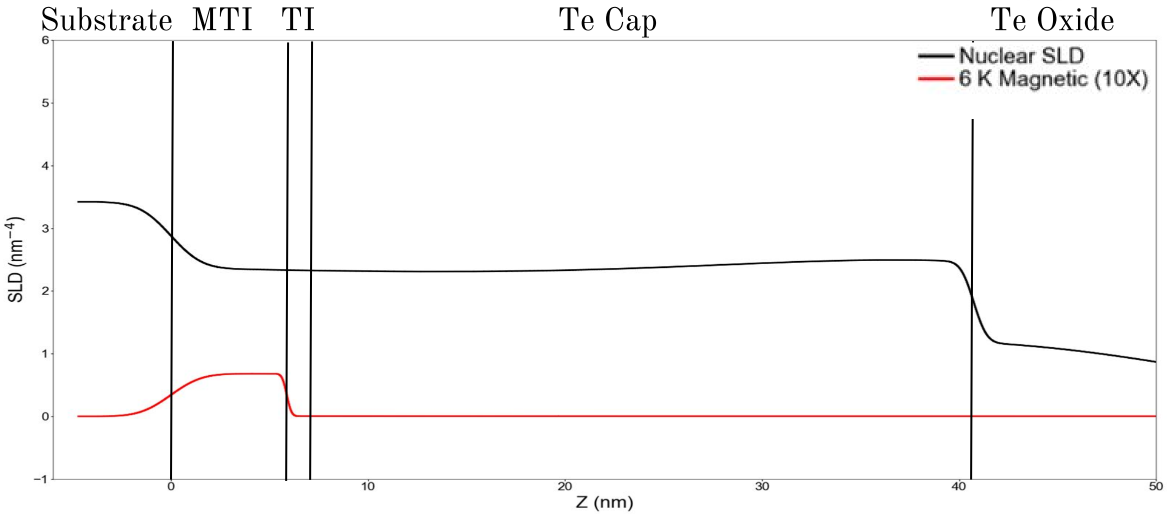
- Structural depth profiles ✔
- Magnetic depth profiles ✔
- Chrome dopant locations ??
- Some evidence of magnetized undoped TI layer
  - Need more statistical analysis
- X-ray reflectometry so far not sensitive enough to detect chromium dopants
- Neutrons may be able to differentiate between Cr:TI and TI



Next Steps

- Probe chrome dopants with synchrotron
- More chrome dopants?
- Different capping material





Acknowledgements

- Alexander Grutter
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- Julie Borchers
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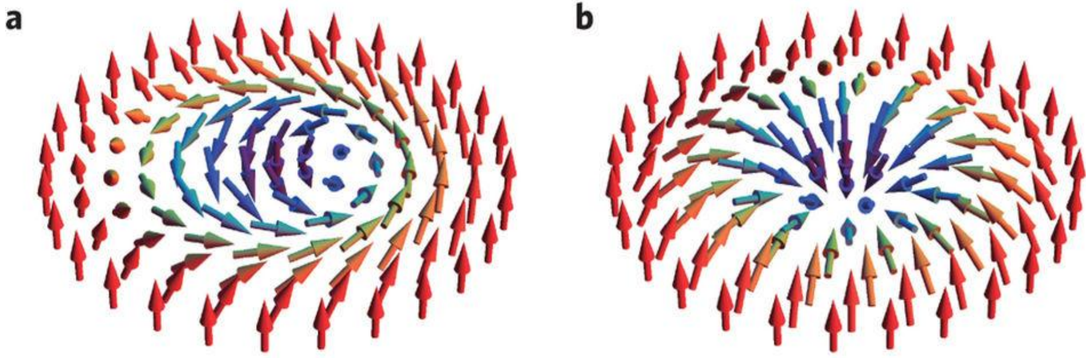
- NCNR
- CHRNS

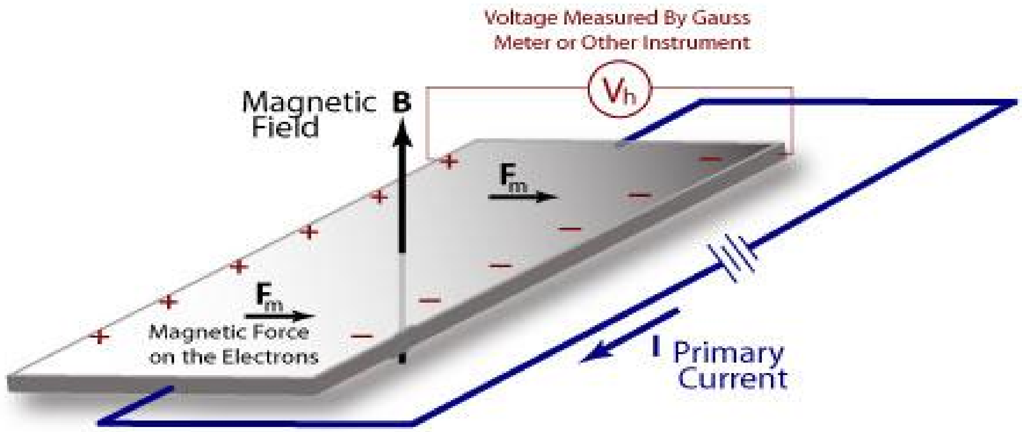
Topological Order

- Topological invariant: Property of an object which remains invariant regardless of transformations
- TI have topological invariants
  - Invariants not change as long as material is an insulator
  - Invariant broken at surface boundary → metallic surface state
  - Topological invariant caused by electrons' wavefunctions



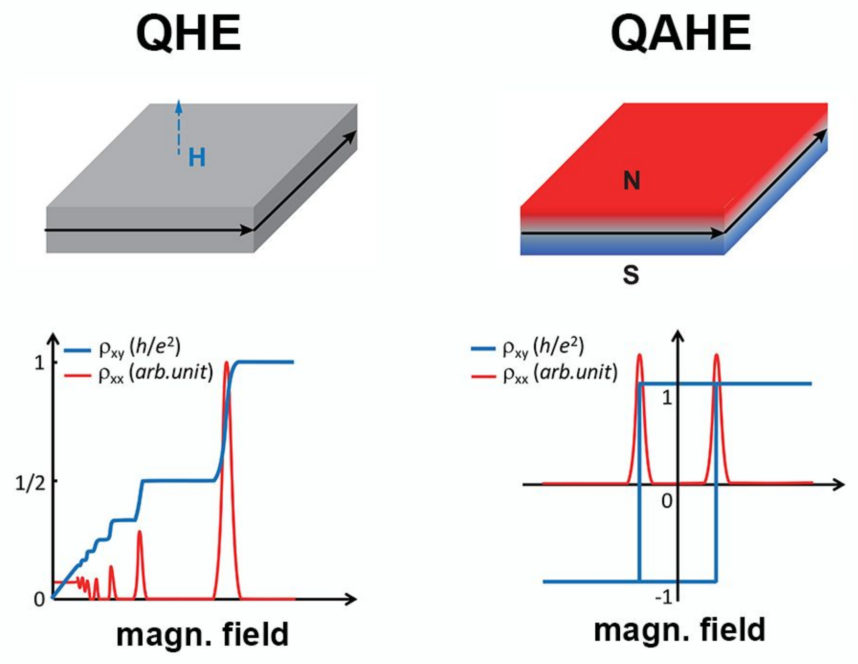
Hall Effect

- **Hall Effect:** Voltage transverse to current in applied magnetic field
- **Anomalous Hall Effect:** Hall effect is much stronger in ferromagnetic materials
  - Voltage w



Quantum Anomalous Hall Effect

- **Quantum Hall Effect:** Quantized values of Hall conductance
  - Low temperatures (~0K)
  - Strong magnetic field
  - 2D electronic materials
- **Quantum Anomalous Hall Effect:** Quantized values of Hall conductance
  - Low temperatures (~0K)
  - 2D electronic materials
  - Magnetic
  - Topological
- QAHE allows dissipationless transport



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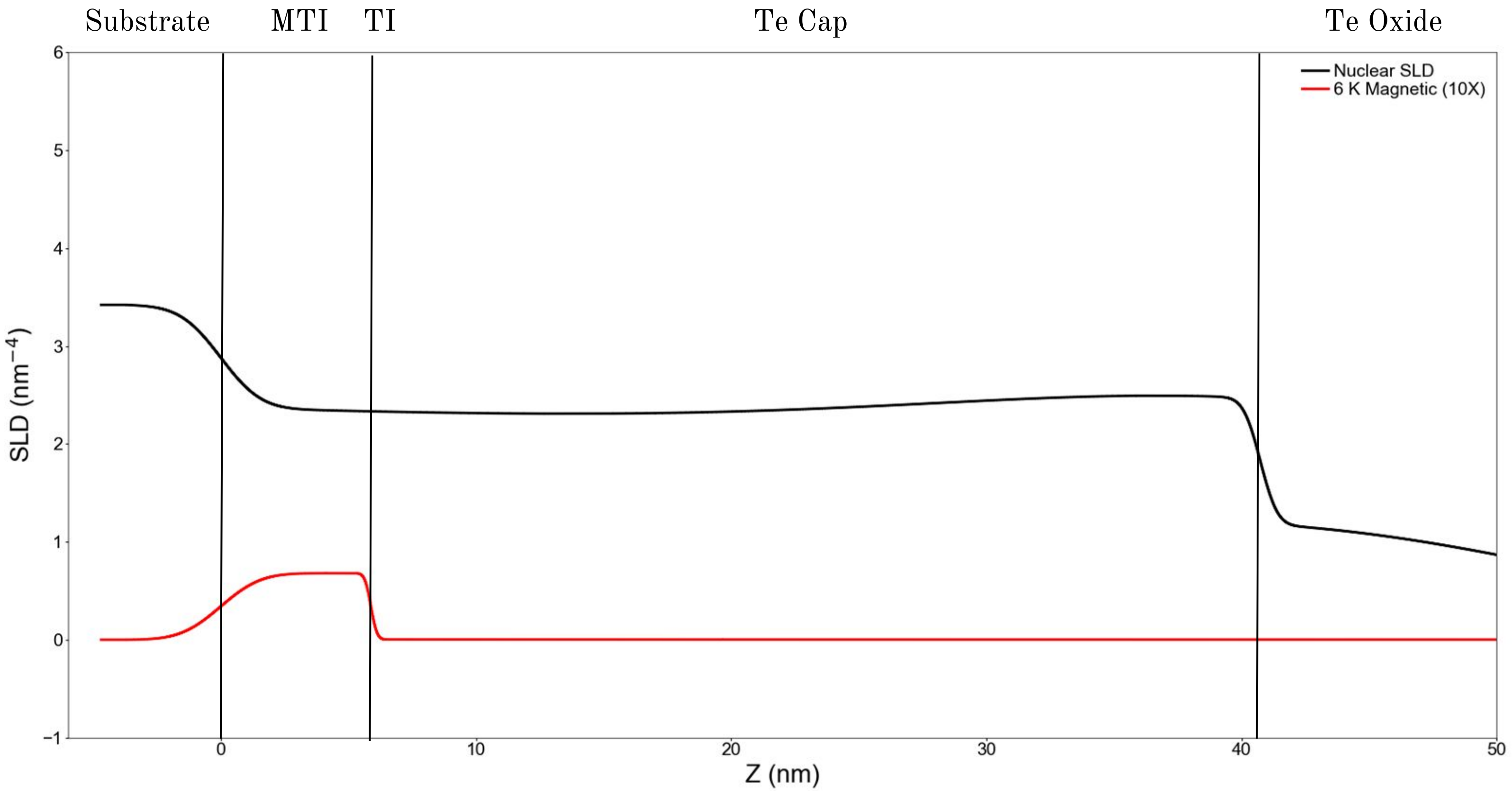
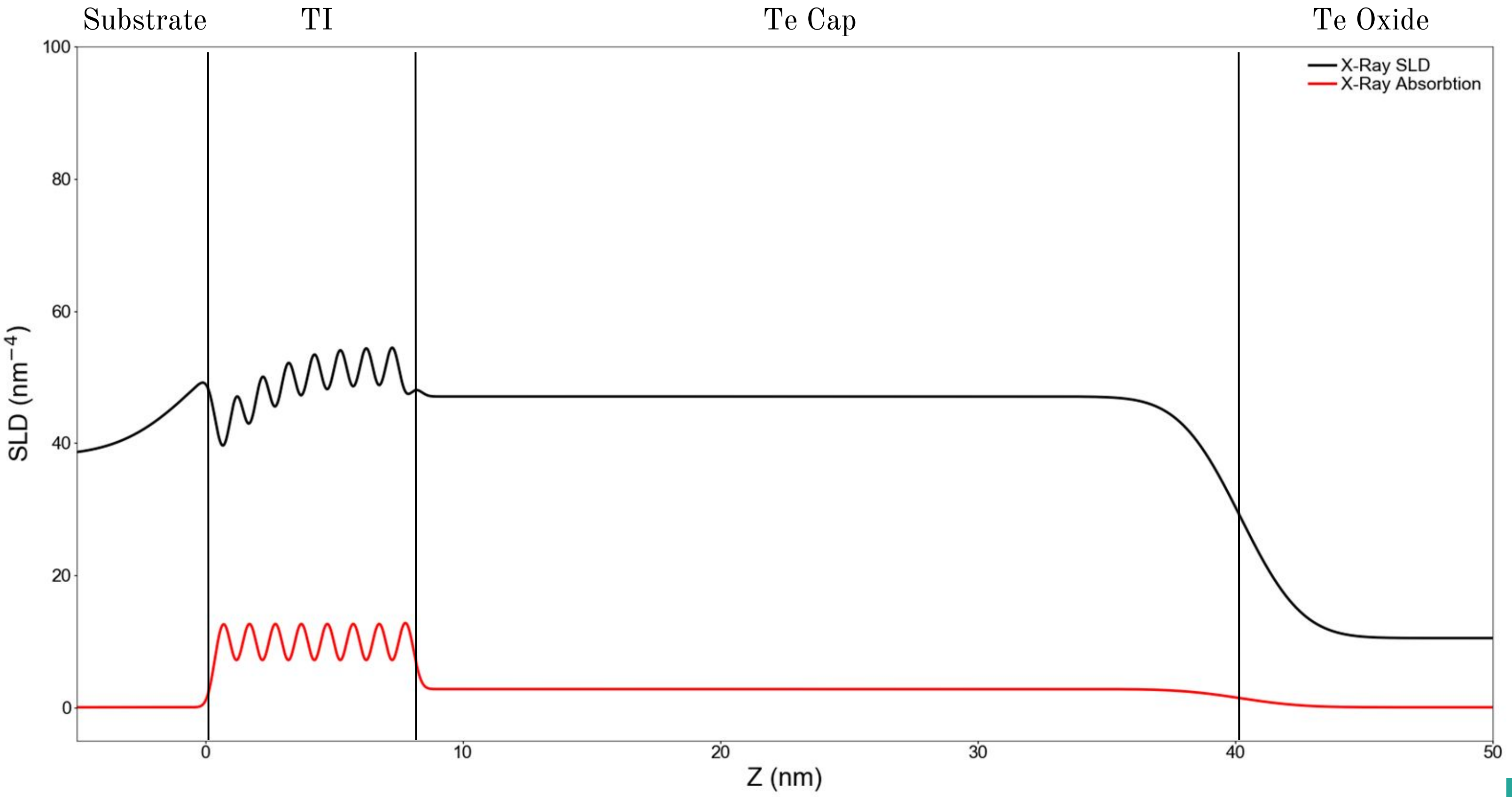
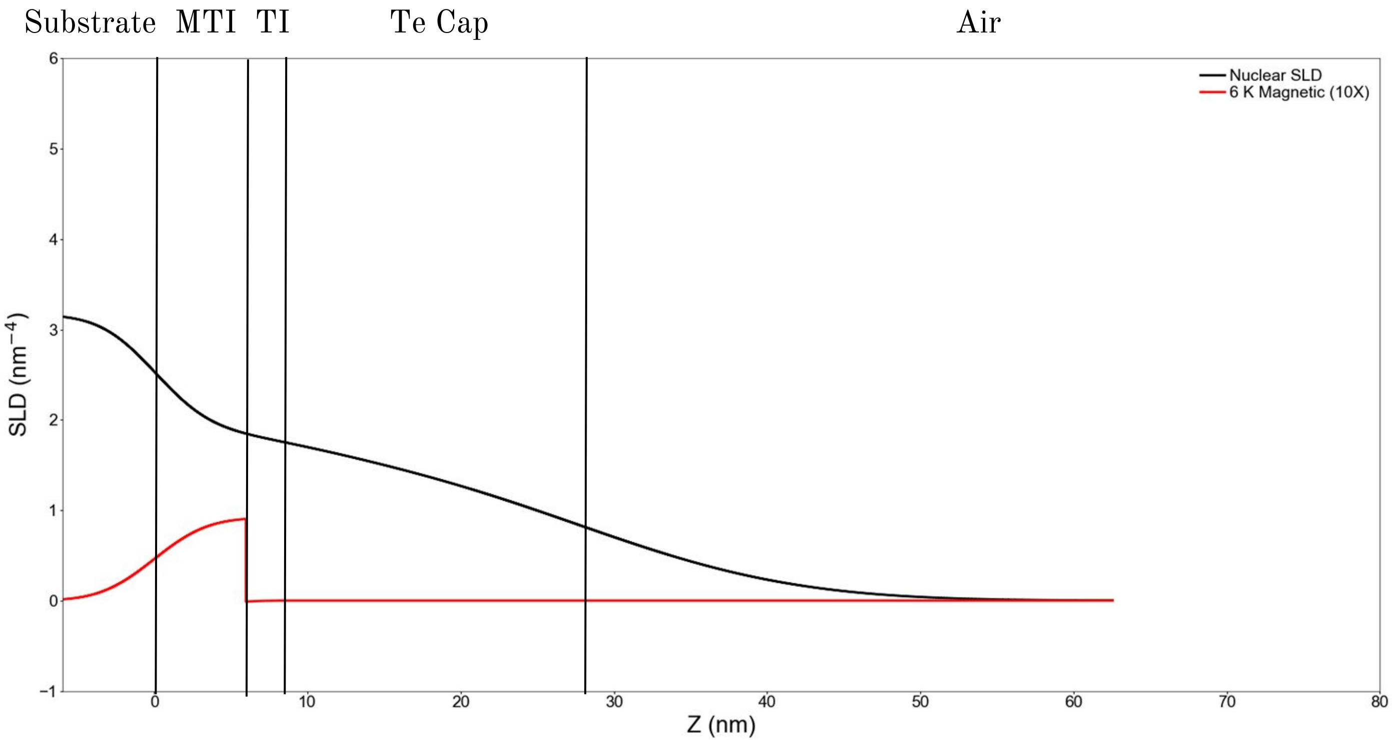

Substrate
MTI
TI
Te Cap
Te Oxide
Nuclear SLD
6 K Magnetic (10X)
SLD (nm^{-4})
Z (nm)
6
5
4
3
2
1
0
−1
0
10
20
30
40
50

LP2984

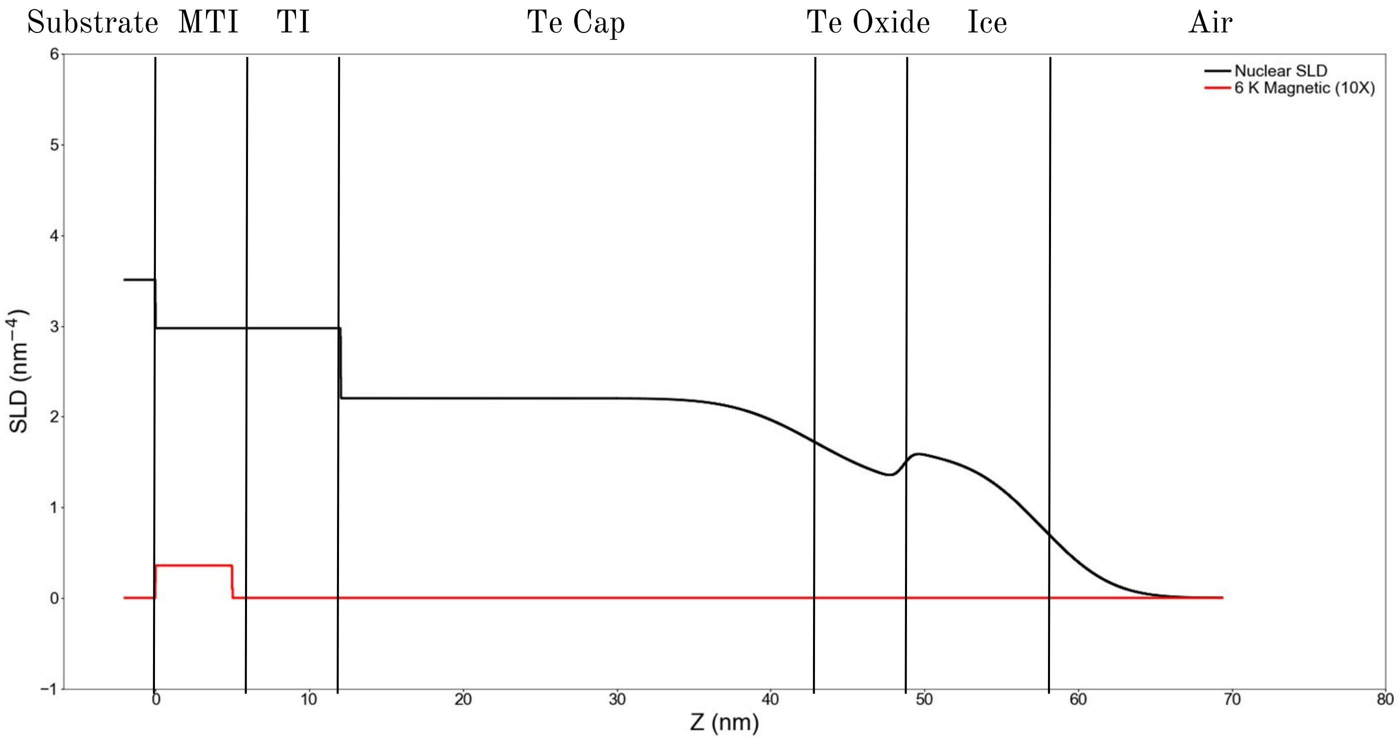


Substrate
TI
Te Cap
Te Oxide
X-Ray SLD
X-Ray Absorbtion
SLD (nm^{-4})
Z (nm)
0
20
40
60
80
100
0
10
20
30
40
50

LP2985

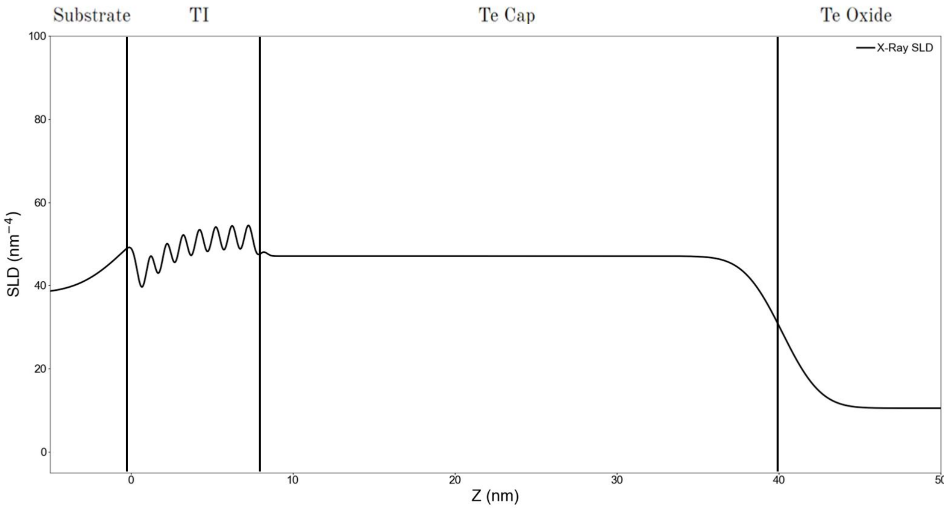

Substrate
MTI
TI
Te Cap
Air
Nuclear SLD
6 K Magnetic (10X)
SLD (nm^{-4})
Z (nm)
6
5
4
3
2
1
0
−1
0
10
20
30
40
50
60
70
80

LP2985

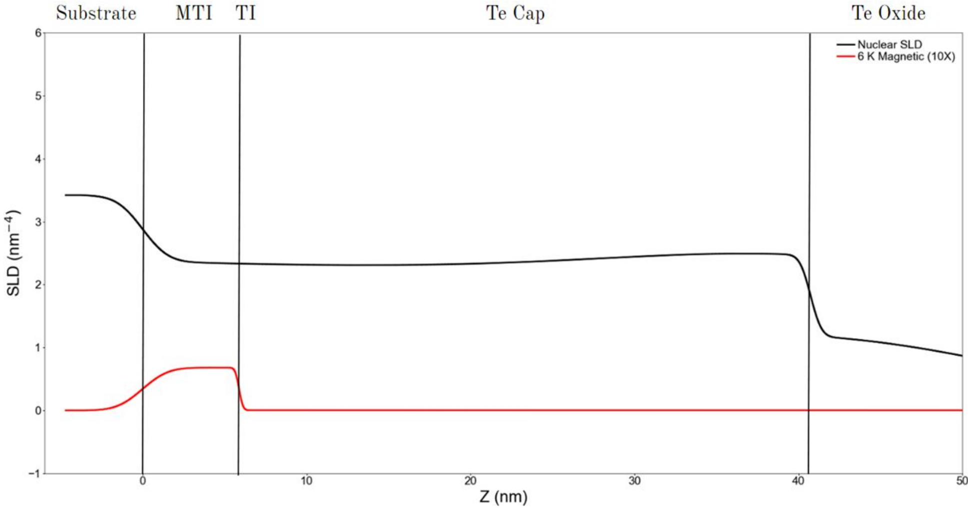


Substrate
MTI
TI
Te Cap
Te Oxide
Ice
Air
Nuclear SLD
6 K Magnetic (10X)
SLD (nm^{-4})
Z (nm)
6
5
4
3
2
1
0
−1
0
10
20
30
40
50
60
70
80

Profiles



Substrate
TI
Te Cap
Te Oxide
X-Ray SLD
SLD (nm^{-4})
Z (nm)



Substrate
MTI
TI
Te Cap
Te Oxide
Nuclear SLD
6 K Magnetic (10X)
SLD (nm^{-4})
Z (nm)