The attraction of magnetic scattering

NIST Center for Neutron Research Summer School 2008

Gaithersburg, MD

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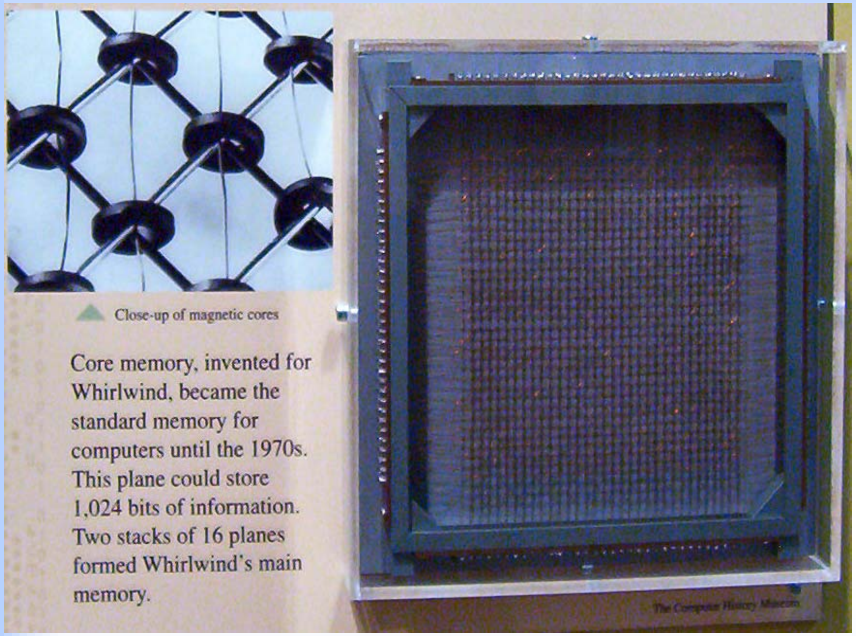
Agenda

Part I. Demonstrate how neutrons can be used to study magnetism (reflectivity example from patterned array).

Part II. Apply polarization analysis to obtain 3-dimesional magnetic information (SANS example from nanosphere ensemble).

Motivation: Miniaturize Magnetic Memory

1950's ~8 bytes / in^2



Close-up of magnetic cores

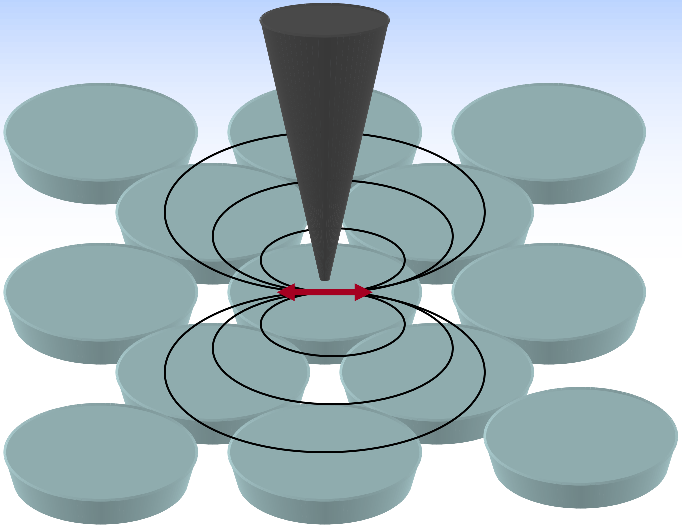
Core memory, invented for Whirlwind, became the standard memory for computers until the 1970s. This plane could store 1,024 bits of information. Two stacks of 16 planes formed Whirlwind's main memory.

The Computer History Museum

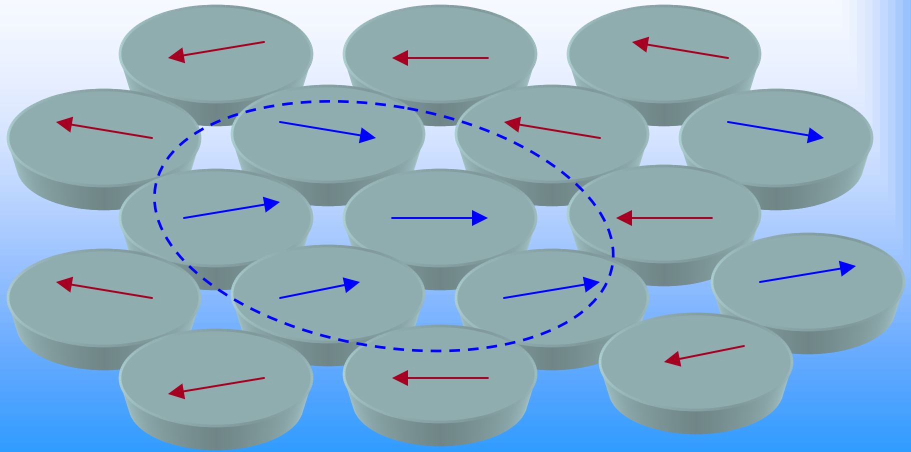
All the essential ingredients:

- o Addressability
- o Switch single bit (write 0 or 1)
- o Store (durability)
- o Read (sensing line)

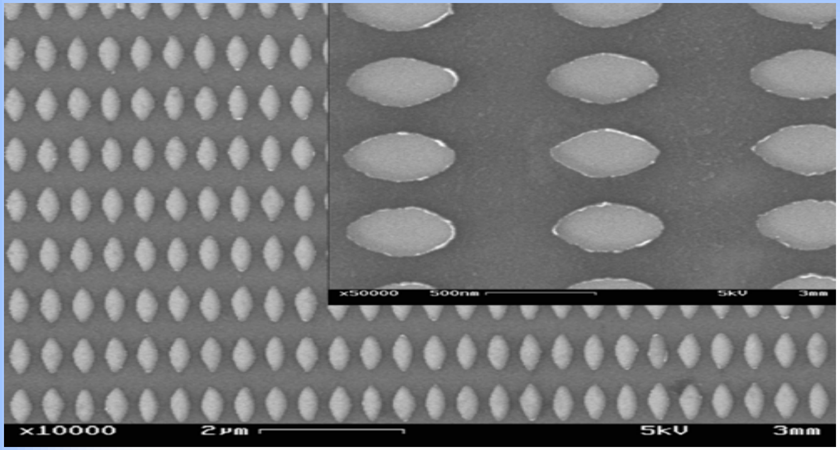
To achieve goal of TB / in^2 we turn to nano-patterning



To characterize magnetic interaction, we look for domain formation…



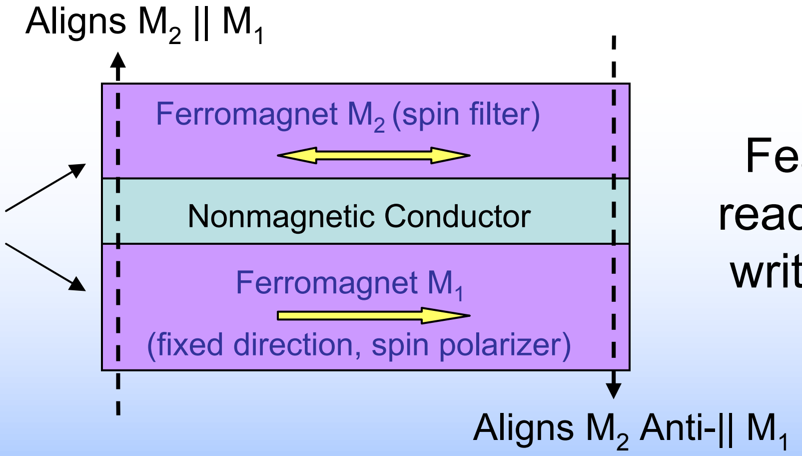
Example I: Magnetic coupling within a nanopillar array



Direction	Dimensions	Measurements
Long	Length	550 nm
	Period	900 nm
	Spacing	350 nm
Short	Length	350 nm
	Period	450 nm
	Spacing	100 nm

NiFe(4nm)/**Cu(4nm)**/Co(6nm)/IrMn(4nm)/Au(4nm)

Electronics +
Spin Sensitivity =
Spintronics


Aligns $M_2 \parallel M_1$

Ferromagnet M_2 (spin filter)

Nonmagnetic Conductor

Ferromagnet M_1

(fixed direction, spin polarizer)

Aligns M_2 Anti-|| M_1

Features fully *electronic* reading (Δ resistance) and writing (reverse magnetic direction) of bits.

Questions:

1) How do the top and bottom ferromagnetic layers interact?

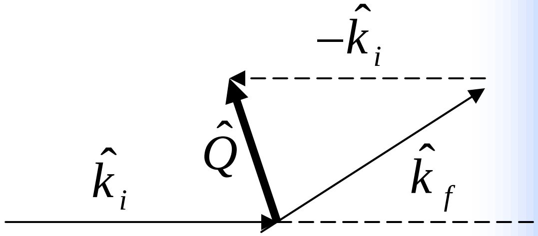
2) What is the magnetic distribution within each nanopillar?

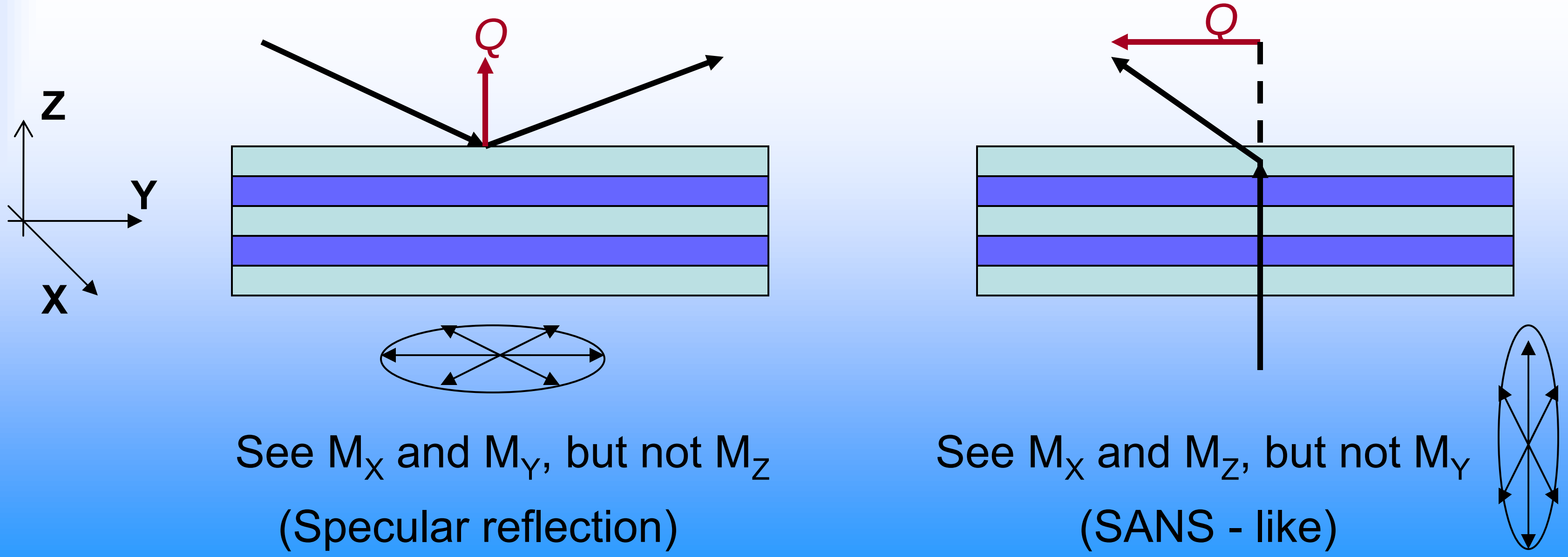
3) What are the size(s) of the in-plane magnetic domains?

Why use neutrons for magnetic analysis?

- Neutrons probe deeply and are not surface limited
- Neutrons measure length scales from atomic distances, to single nanoparticles, and to domains
- Neutrons see all magnetic moments
- *Neutrons only sense magnetism perpendicular to Q*

Recall that $\hat{Q} = \hat{k}_f - \hat{k}_i$





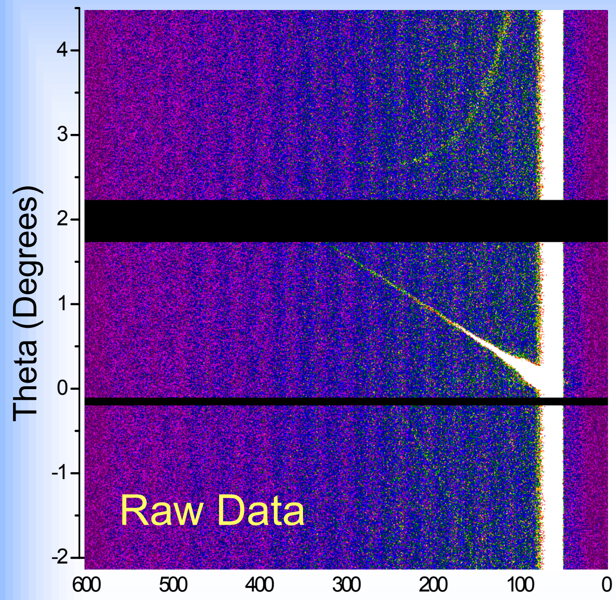
See M_X and M_Y, but not M_Z

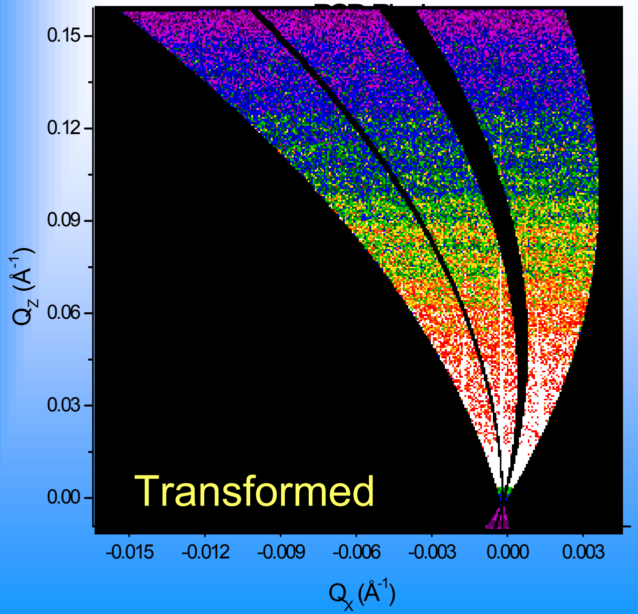
(Specular reflection)

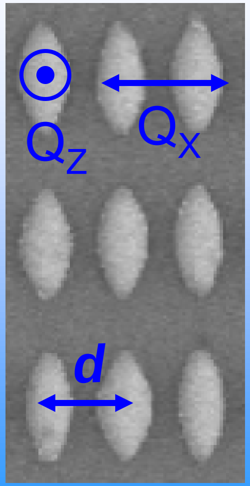
See M_X and M_Z, but not M_Y

(SANS - like)

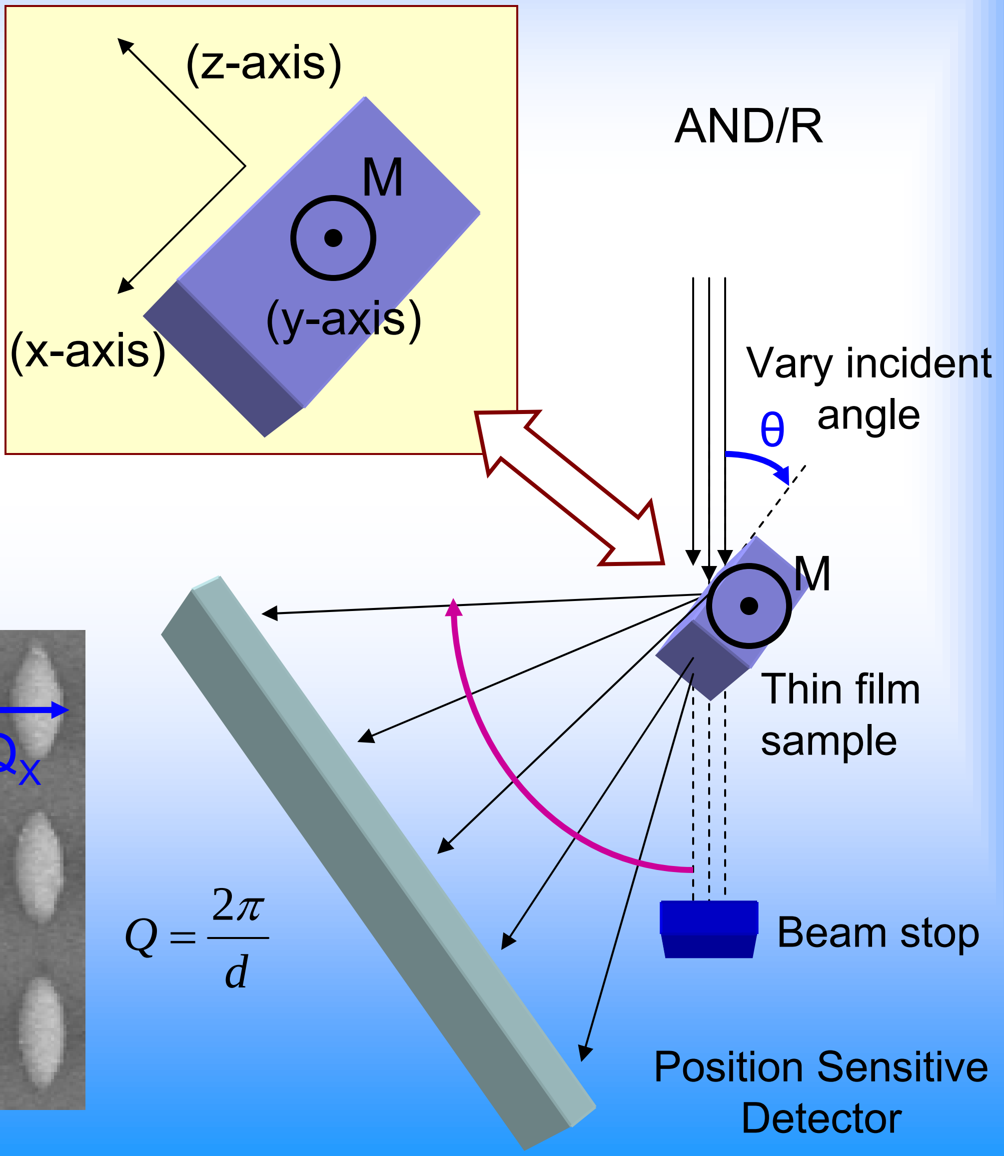
Reflection from magnetic nanopillar array



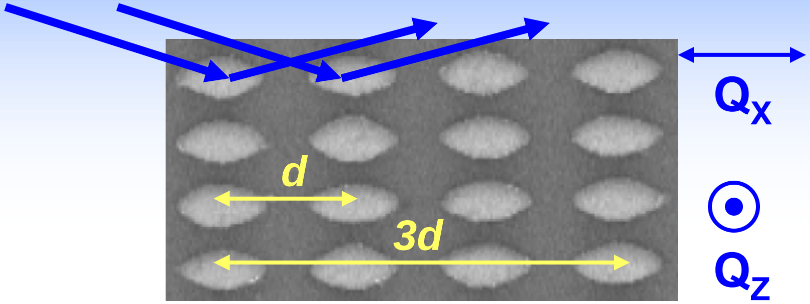


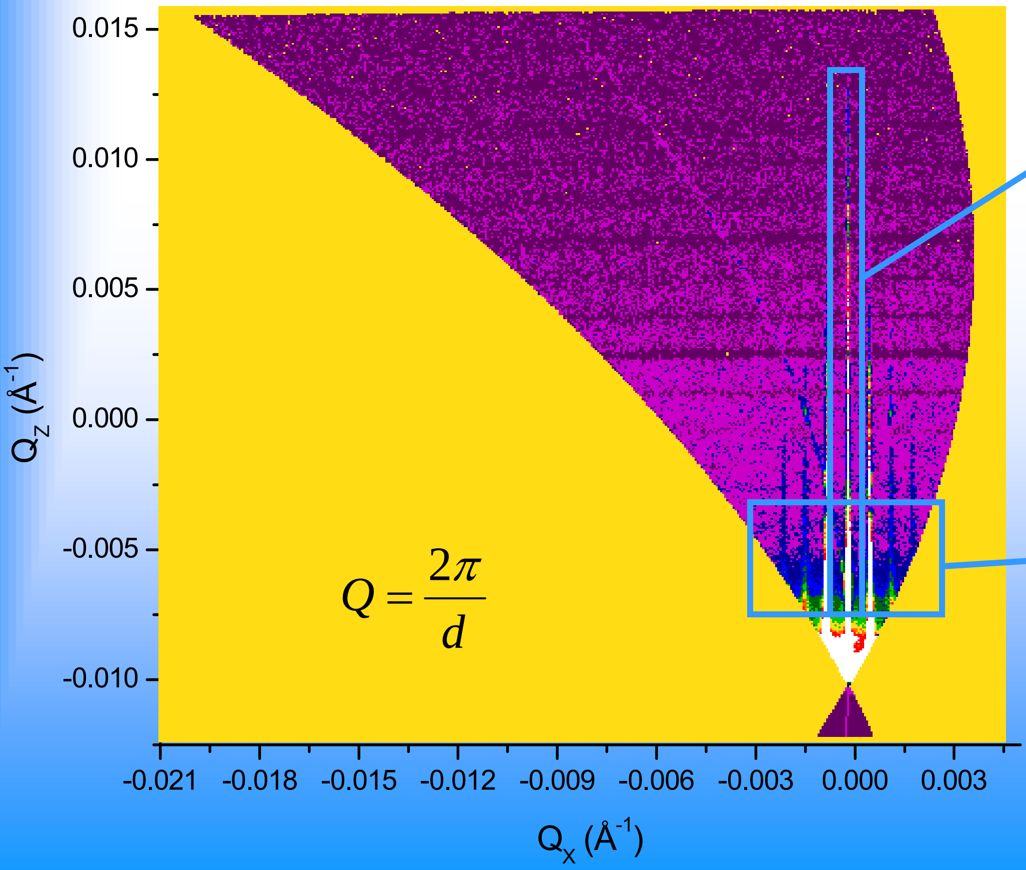


$$Q = \frac{2\pi}{d}$$



Diffuse scattering and reciprocal space (Specular Plus!)





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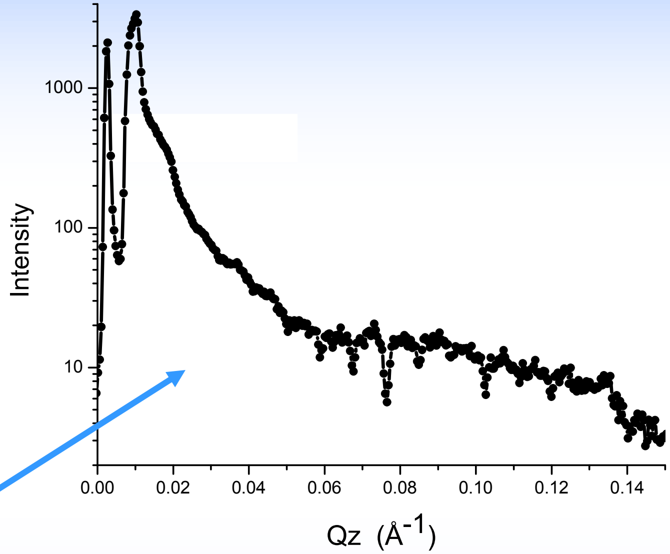
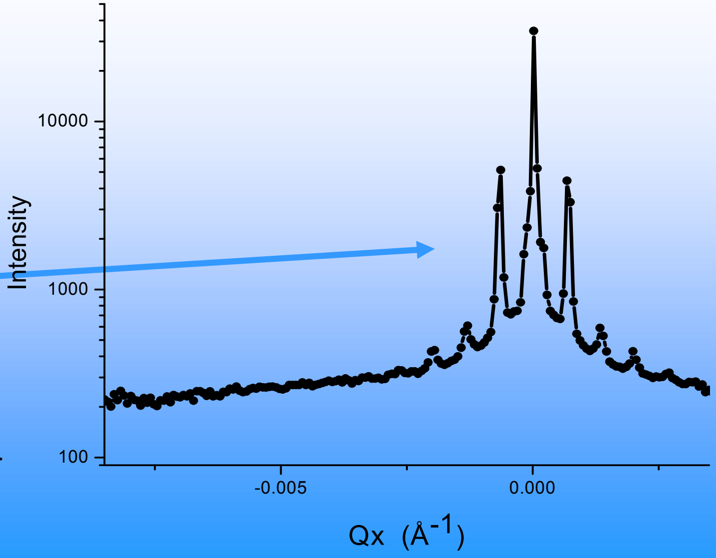
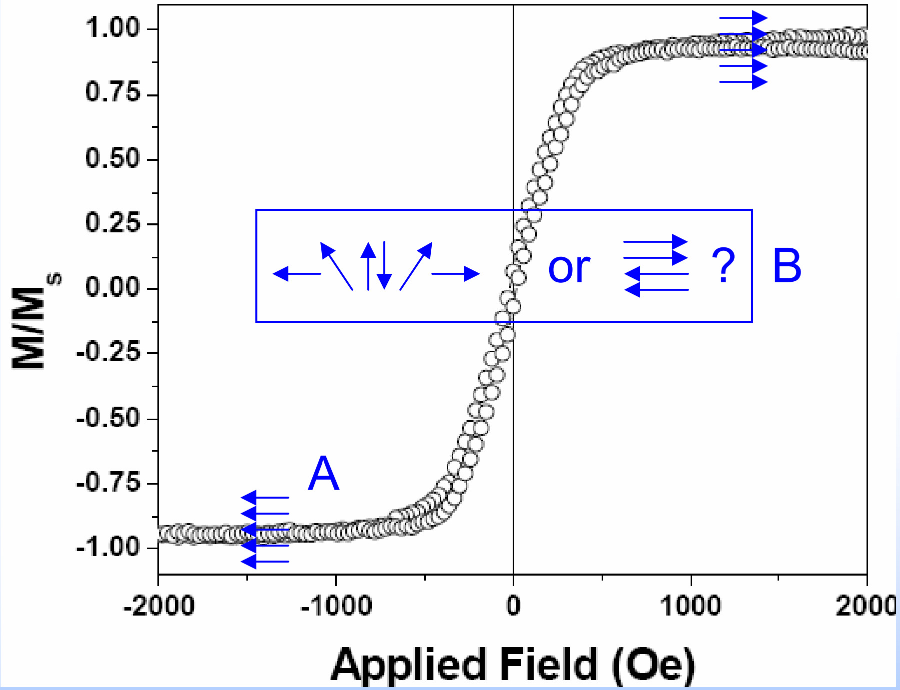
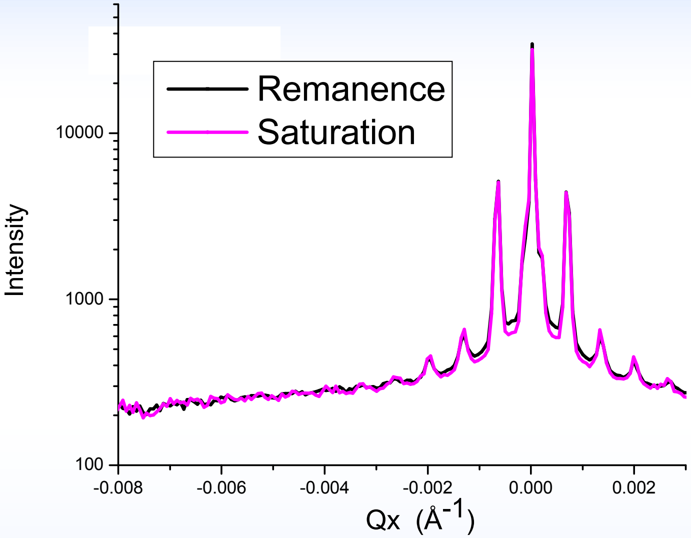


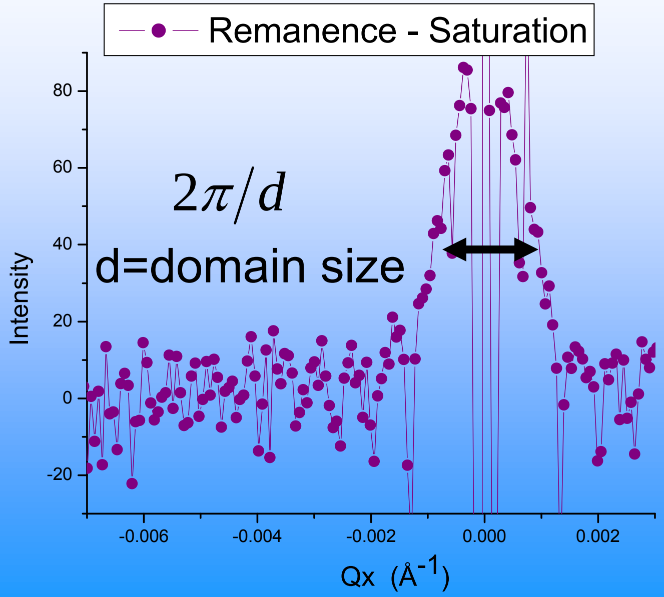


Extracting Magnetic Scattering By Varying Applied Field

Magnetic Hysteresis Loop



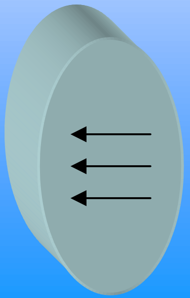




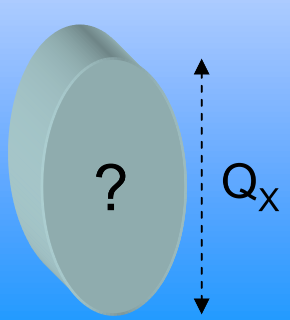
$2\pi/d$

d=domain size

A.
Saturate



B.
Remove Field
(Remanence)

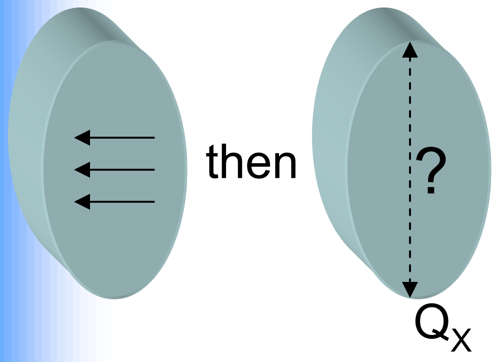


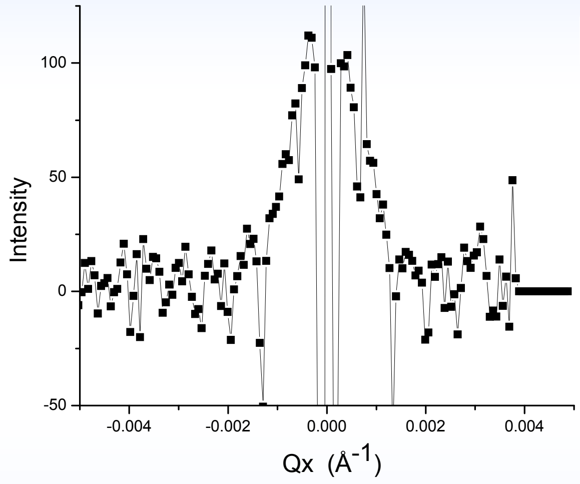
Magnetic Comparisons

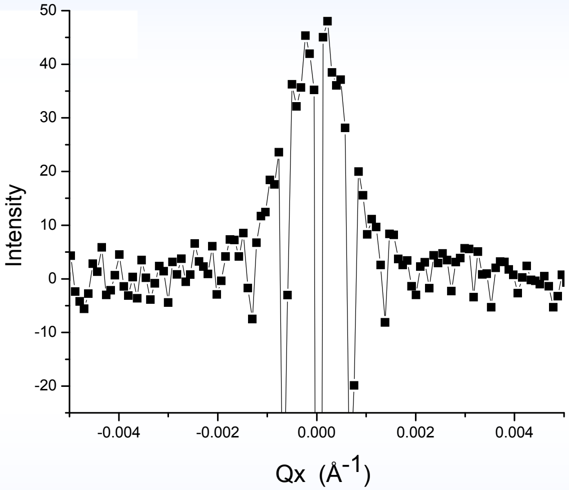
60 Å FeNi | Cu | 60 Å Co

60 Å FeNi | Cu | 40 Å Co

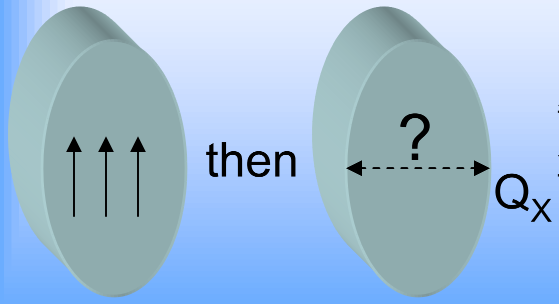
Top row sequence

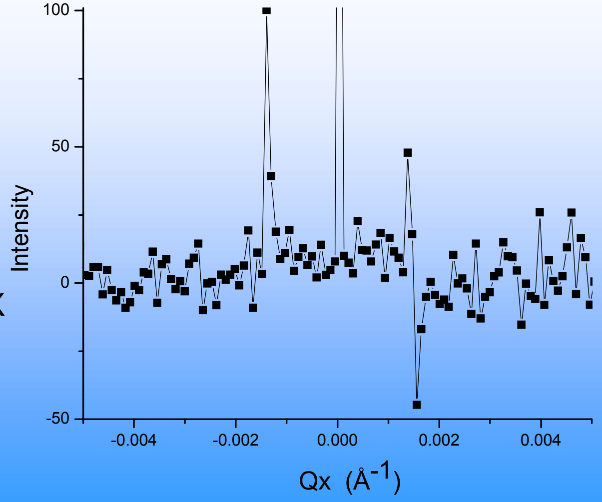


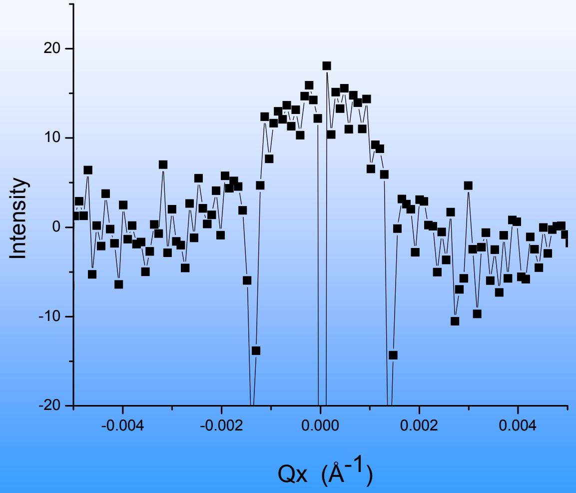




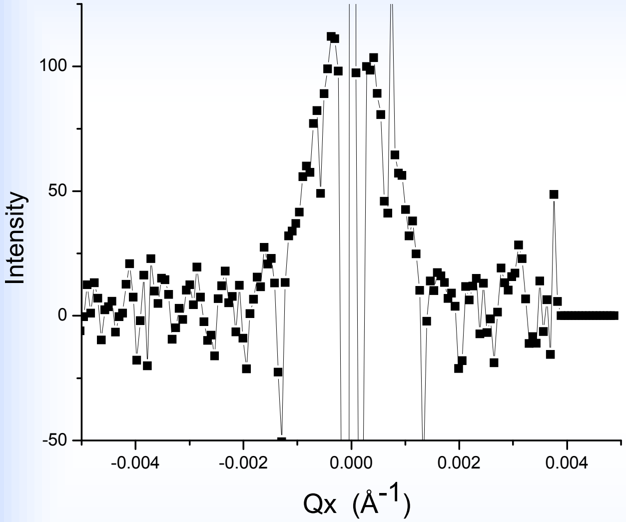
Bottom row sequence





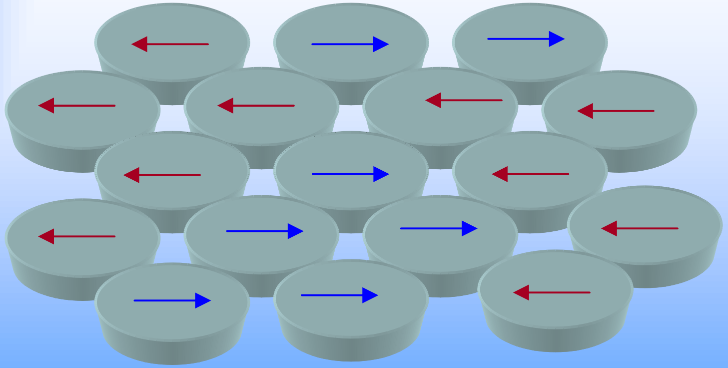


Limitations of Unpolarized Scattering



Unpolarized scattering provides information about magnetic structure, moment magnitude, and magnetic domains.

However, moment direction is unknown!!!



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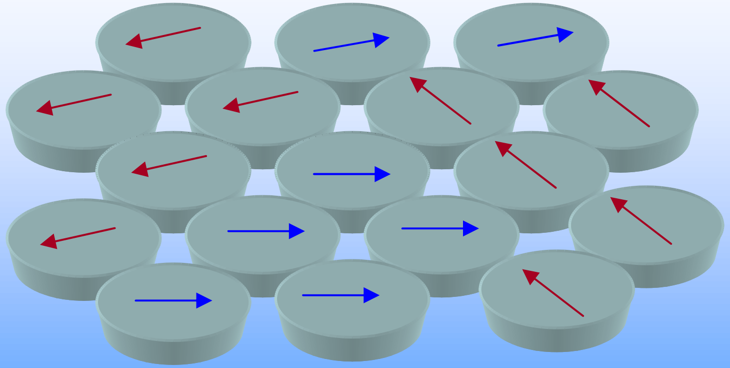


Strong magnetic anisotropy

Random magnetism

Neutron Polarization Rules

Scattering Rules*

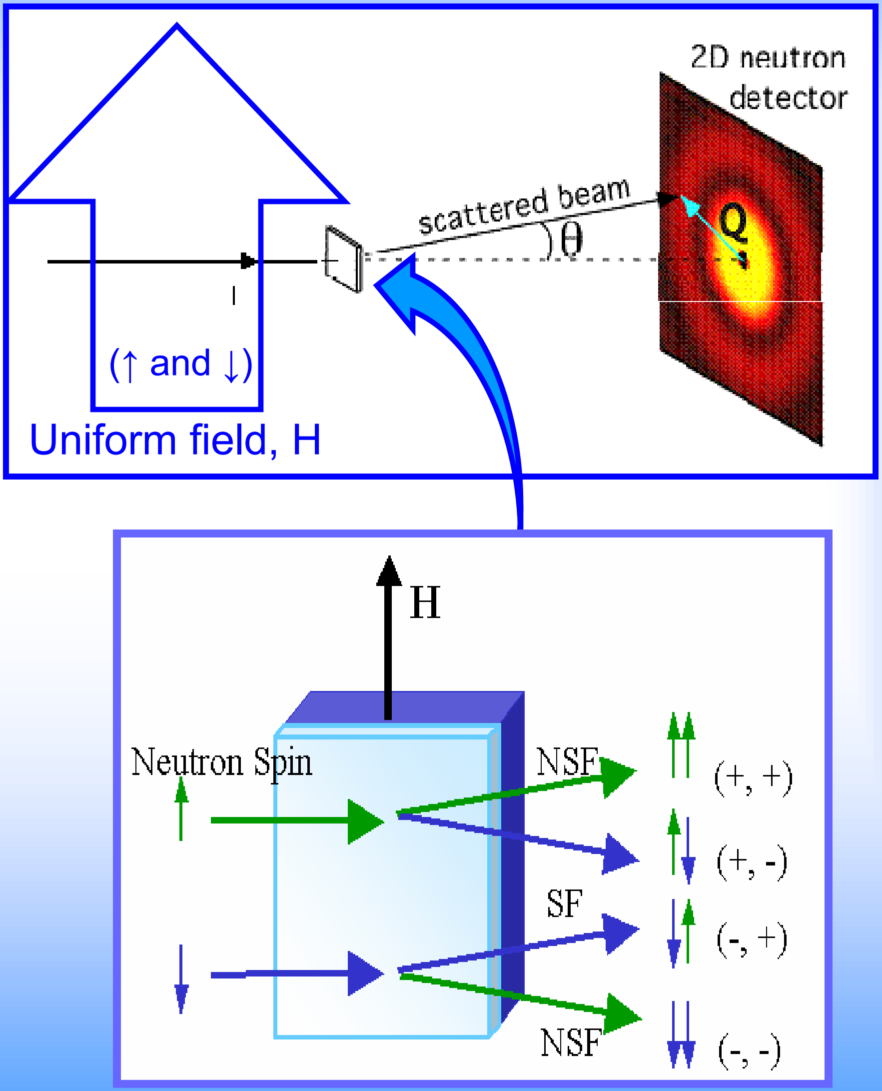
1) Neutrons magnetically scatter only from moments perpendicular to Q.

2) Magnetic field polarizes neutrons into up or down spin states (↑ and ↓)

3) Scattering from magnetic moments parallel to field do ***not*** flip neutrons (Non-Spin Flip)

4) Magnetic moments perpendicular to field flip the neutrons (Spin Flip)

5) Unpolarized nuclei show no net spin-flipping



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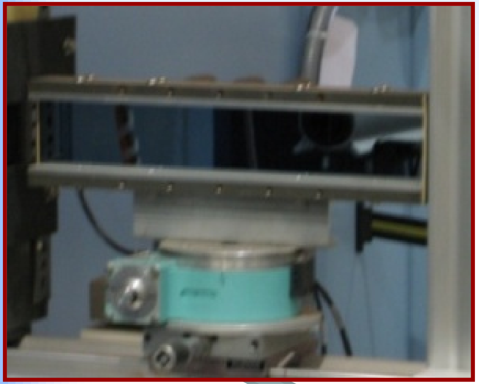
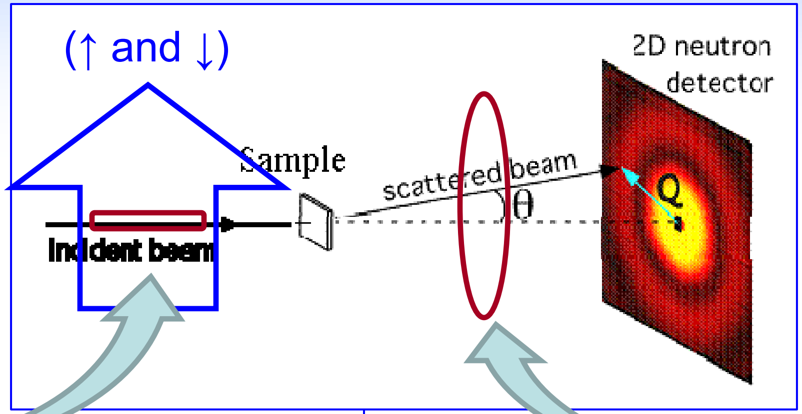
* Moon, Riste, and Koehler, Physical. Review 181, 920 (1969)

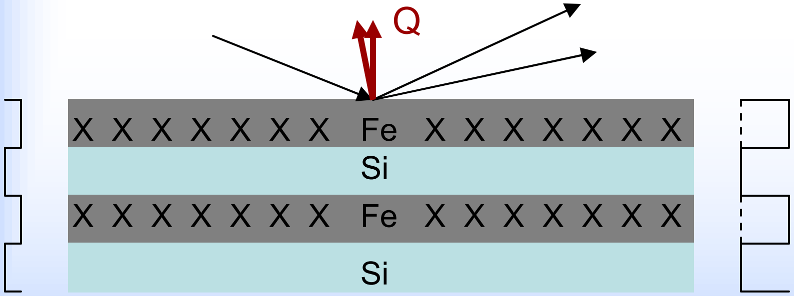
How To Achieve Polarization Analysis

FeSi Super Mirror





Polarized 3He Cell



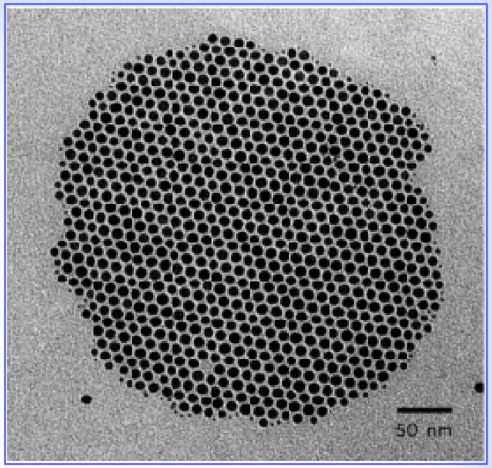
$$I \propto |b_c \pm M|^2 = b_c^2 + M^2 \boxed{\pm 2b_c M}$$

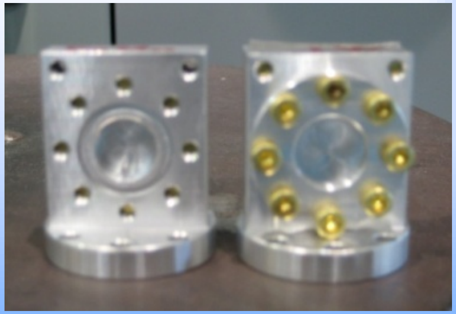
- ➢ FeSi super mirror is stable and can achieve polarization of ~95%.
- ➢ Coil flipper is used to reverse polarization

- ➢ Polarized 3He allows spin-up neutrons of one orientation to pass while absorbing the opposite orientation.
- ➢ 3He polarization can be reversed with NMR pulse.
- ➢ 3He cells cover divergent beam, but have lower transmission and polarization.

Example II: Magnetic nanospheres* (SANS)

- Magnetic nanoparticles for biomedical and data storage applications. Interparticle magnetic behavior is key.
- Ferromagnetic magnetite (Fe_3O_4) particles 7 nm in diameter
- 2.5 nm edge-to-edge separation induces strong magnetic interparticle interaction
- Range of magnetic behavior accessible since ferromagnetism kicks in below 65 K
- Ideally want a technique that can structurally and magnetically probe the entire ensemble. We are especially interested in magnetic domain formation and temperature.

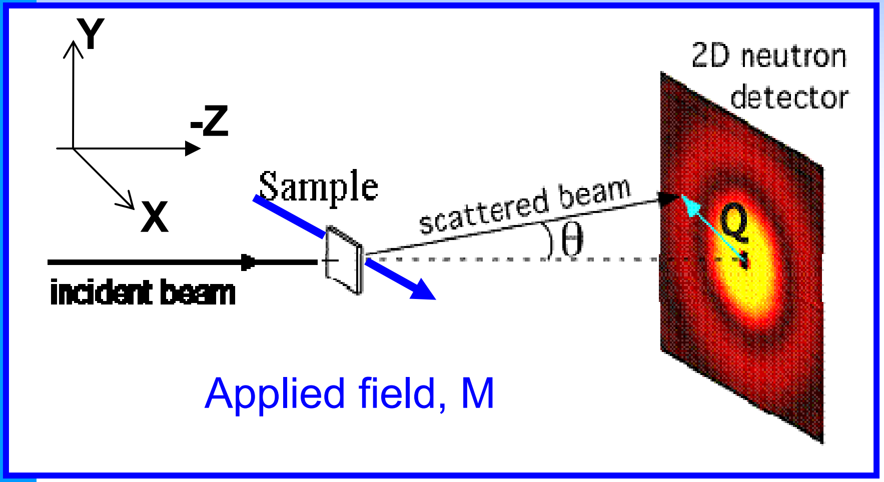


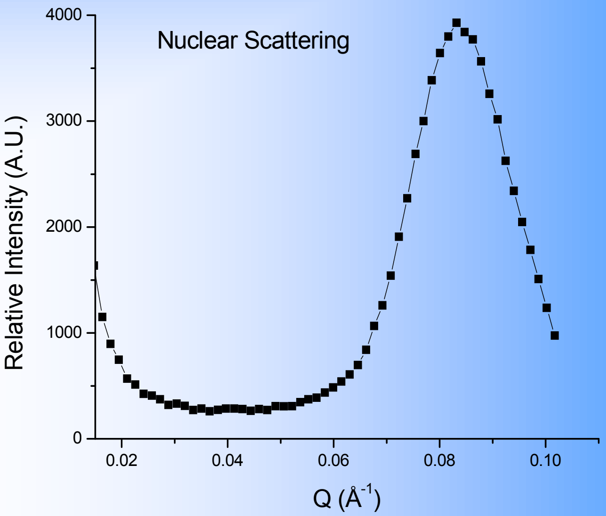


polycrystalline powder form

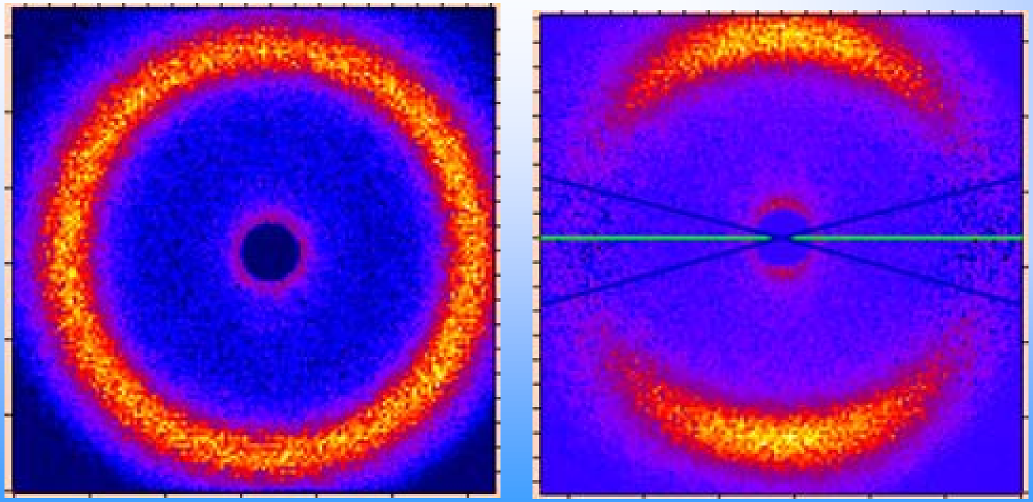
* Prepared by Carnegie Mellon group, synthesis described in J. Am. Chem. Soc. 124. 8204 (2002)

Small Angle Neutron Scattering (SANS)





If we only had magnetic scattering we might see something like this…



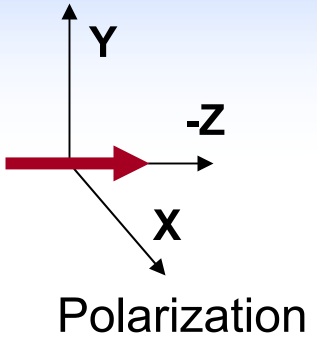
UNIFORM MAGNETIZATION

MAGNETIZATION ALONG X

<u>But</u> nuclear scattering dominates

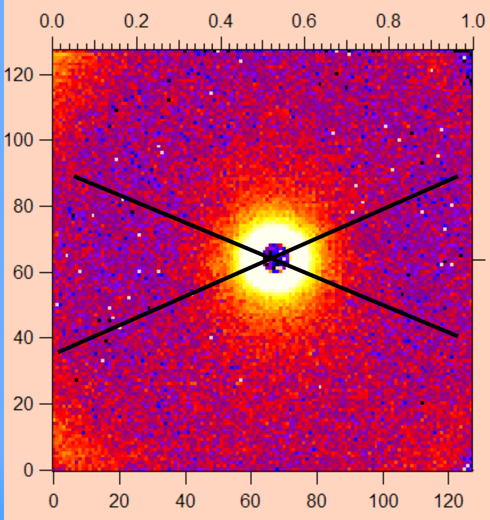
AND we want 3D capability.

3D Magnetometry Using Polarization Analysis

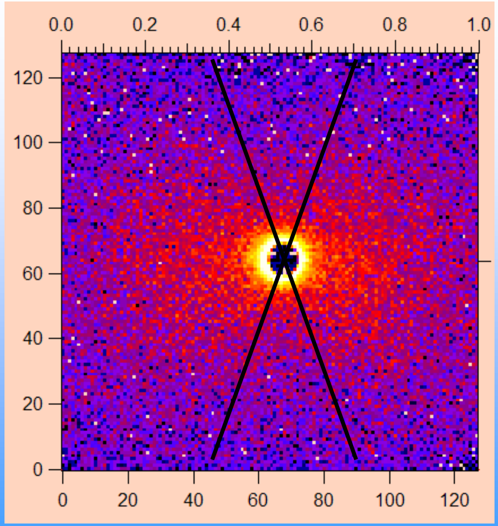


For X-axis polarization with beam along Z-axis:

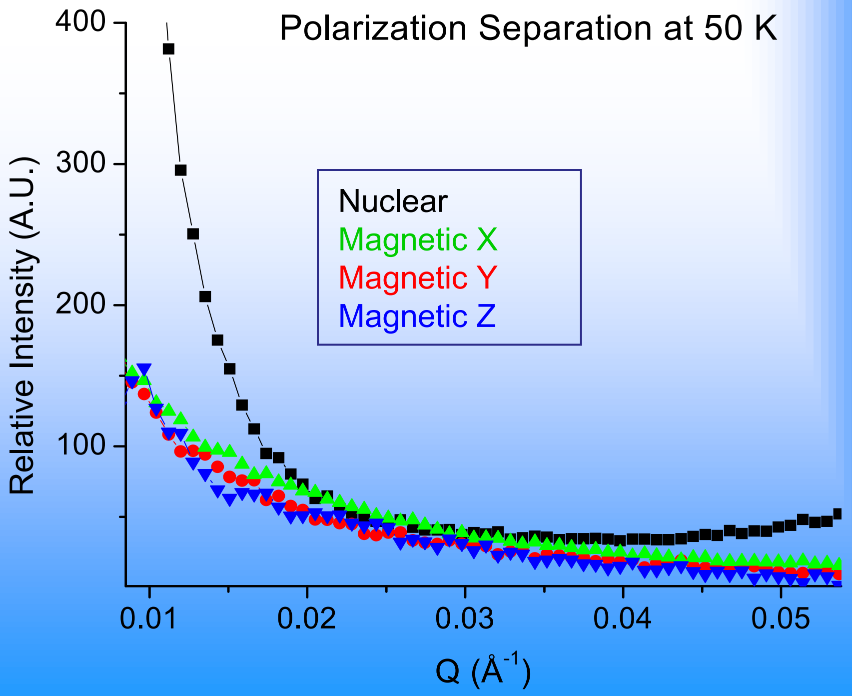
Nuclear = [↑ ↑ + ↓ ↓](X-axis)
M_Z = [↑↓ + ↓↑](Y-axis)
M_Y = [↑↓ + ↓↑](X-axis) - [↑↓ + ↓↑](Y-axis)
M_X = [↑ ↑ + ↓ ↓](Y-axis) – [↑ ↑ + ↓ ↓](X-axis)



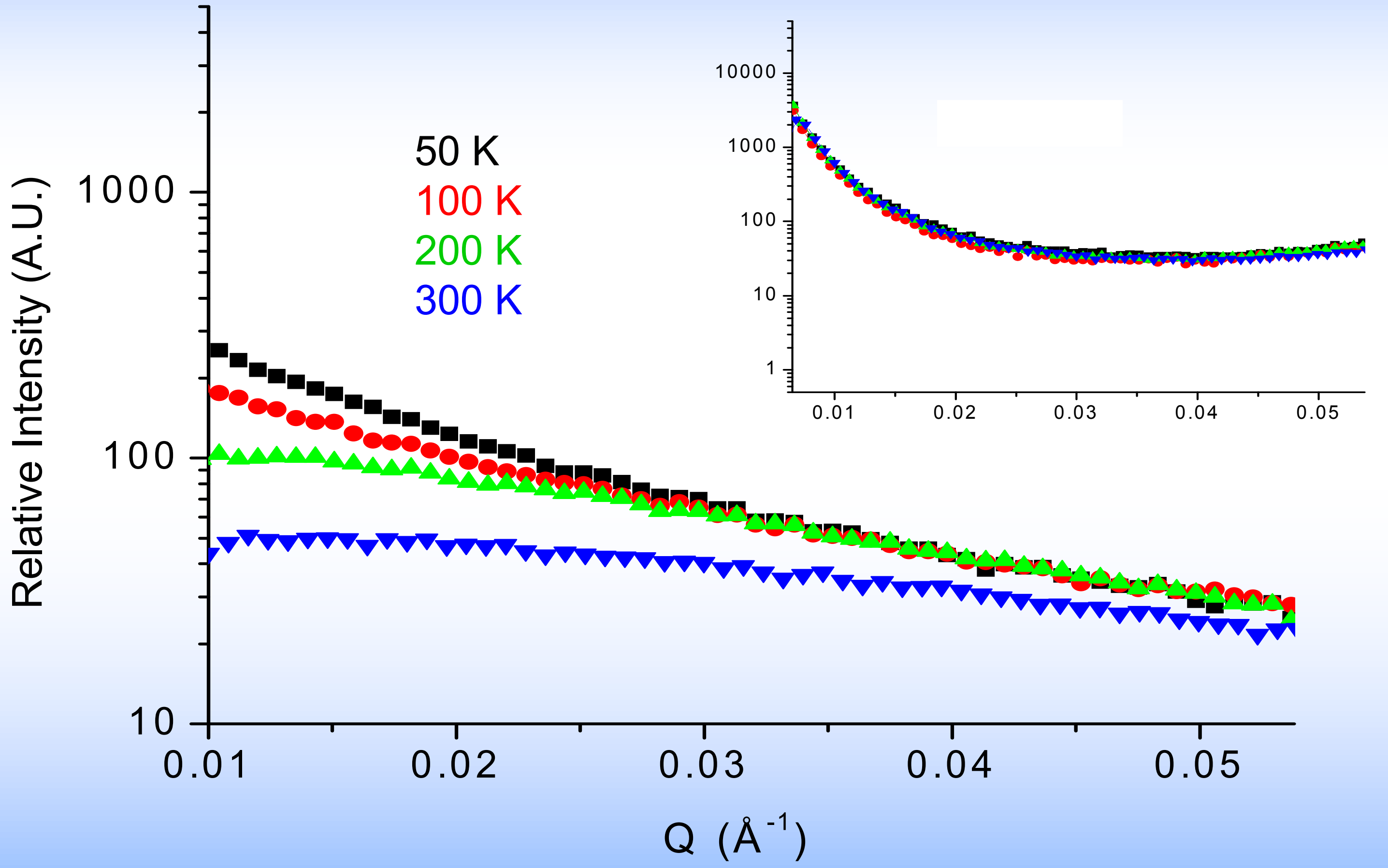
Non Spin-Flip



Spin-Flip



Result: Temperature Dependence of Magnetic Correlations


Pure Magnetic (main) and Nuclear (inset) Scattering

- ➢ Nuclear scattering remains constant (as expected)
- ➢ Long-range magnetic correlations decrease with increasing temperature
- ➢ Fitting shows the domains range from 1000 Å (~ 10 particles) to 100 Å (~ 1 particle)

Key points

- Neutron scattering is a valuable tool for magnetic analysis given

  (1) sensitivity of neutrons to magnetic moments

  (2) the ability of neutrons to penetrate below surfaces

  (3) large range of length scales they can probe.

- Unpolarized data produces the highest count rate.

- Polarization analysis delivers 3D magnetic profiling with no subtraction of different magnetic states.

- 3He cells allow for polarization analysis of divergent beams such as SANS, triple axis, and non-specular reflectivity.

- NCNR has broad range of polarization capabilities and is actively developing this mode of data collection.

- **If you have an interest in magnetic neutron scattering please feel free to contact one of the NCNR staff to discuss any questions and possible experiments.**

Acknowledgements

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NIST Center for Neutron Research, Gaithersburg, MD

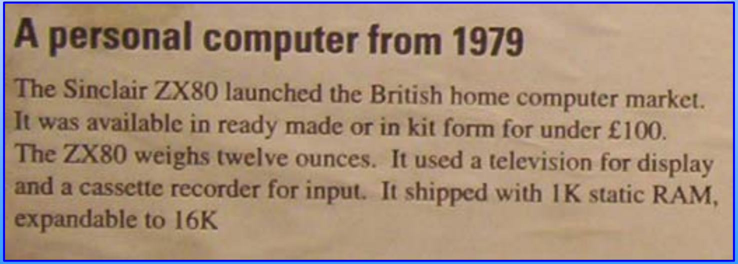
SANS Nanoparticle Experiment:

Charles Hogg, Ryan Booth, Sara Majetich
Carnegie Mellon University, Pittsburgh, PA

Yumi Ijiri, Benjamin Breslauer
Oberlin College, Oberlin, OH

Reflectometry Nanopillar Experiment:

Caroline Ross, Wonjoon Jung, Fernando Castano
Massachusetts Institute of Technology, MA



A personal computer from 1979

The Sinclair ZX80 launched the British home computer market. It was available in ready made or in kit form for under £100. The ZX80 weighs twelve ounces. It used a television for display and a cassette recorder for input. It shipped with 1K static RAM, expandable to 16K