KATHOLIEKE UNIVERSITEIT
LEUVEN

Neutron scattering for the investigation of magnetic nanostructures

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XLVI School of Physics,
Zakopane, Poland, May 16th-21st, 2011

MOTIVATION and OUTLINE

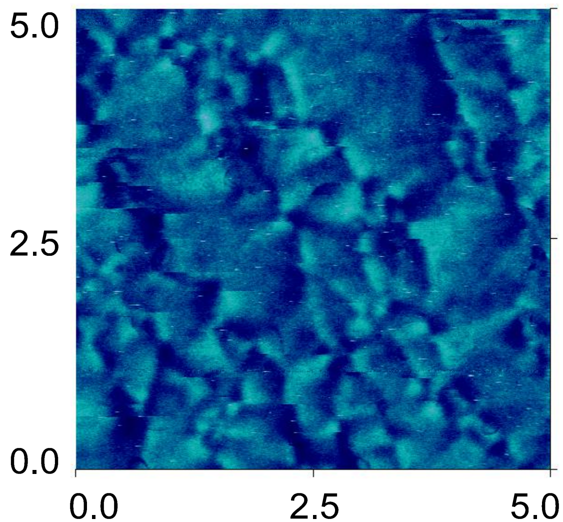
Aim: study magnetism in confined conditions

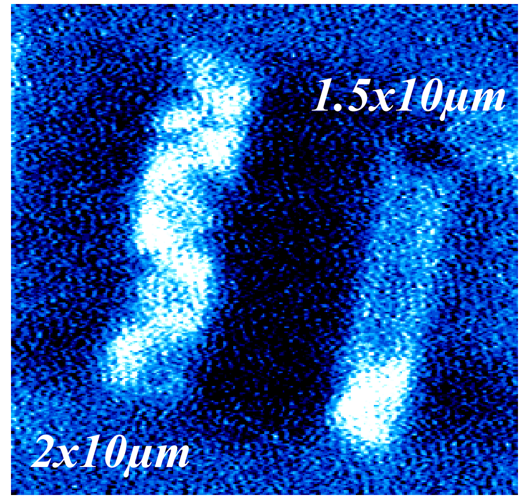
Link between structural and magnetic properties ?

- Introduction to neutron scattering
- Specular reflectivity: multilayers & exchange bias
- Off-specular reflectivity: patterned structures
- Conclusions

RELEVANCE: mesoscopic magnetism

In large samples: creation of ferromagnetic domains
(exchange vs. demagnetization)



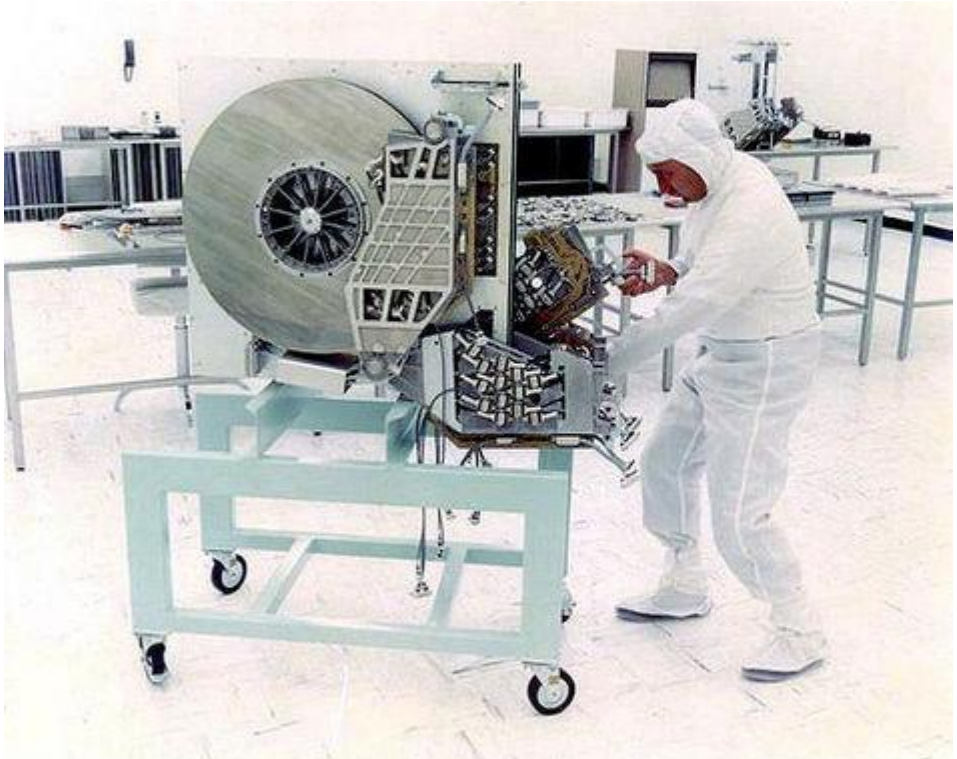


Brown’s Fundamental Theorem:

‘As a magnet is reduced in size, there should be a point where exchange dominates over demagnetisation and where the magnet must, hence, adopt the single-domain state.’

This regime is now accessible, thanks to lithography techniques !

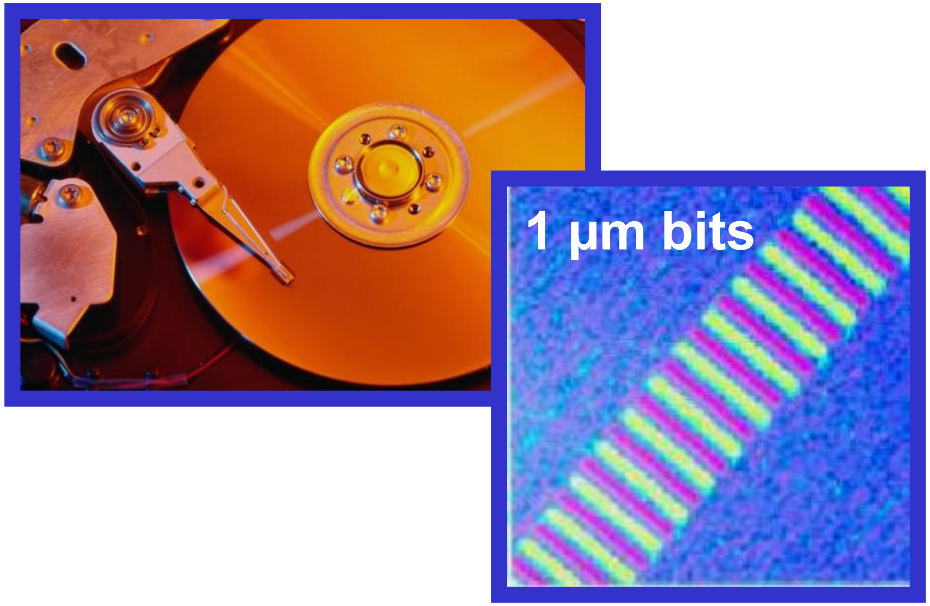
Size does matter! Example: hard disk

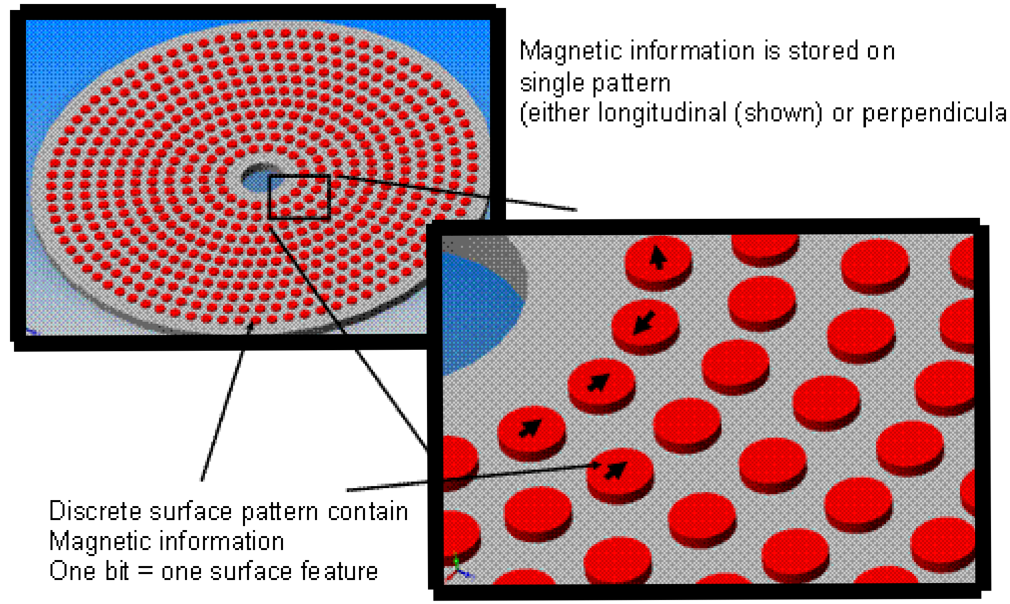


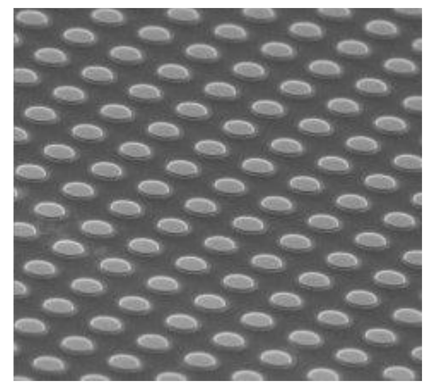
Anno 1975

Anno 2011

From continuous to patterned media



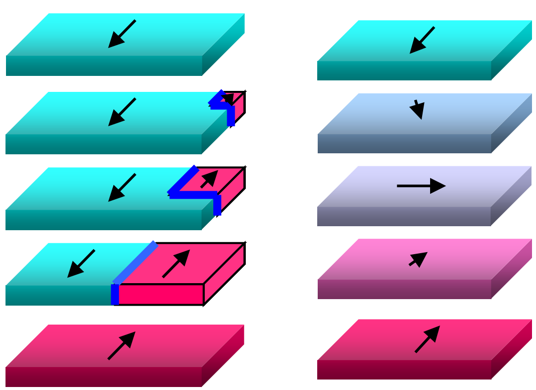




From continuous to patterned media

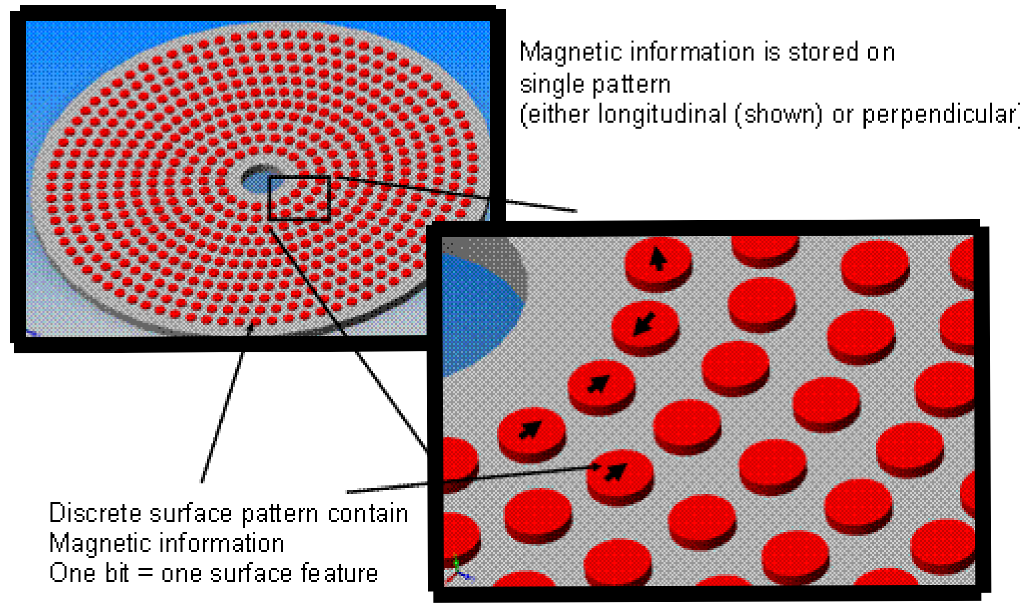
Fundamental questions:

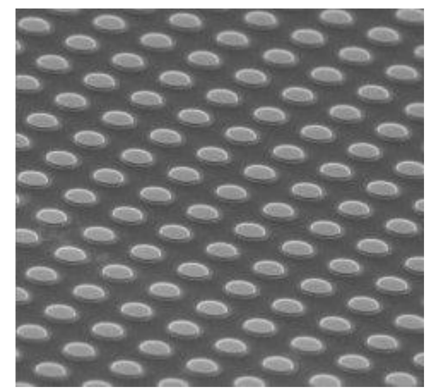
Reversal time ?



Reversal mechanism ?

Magnetic depth profile ?





Progress is strongly rooted in fundamental studies of (nano)magnetism

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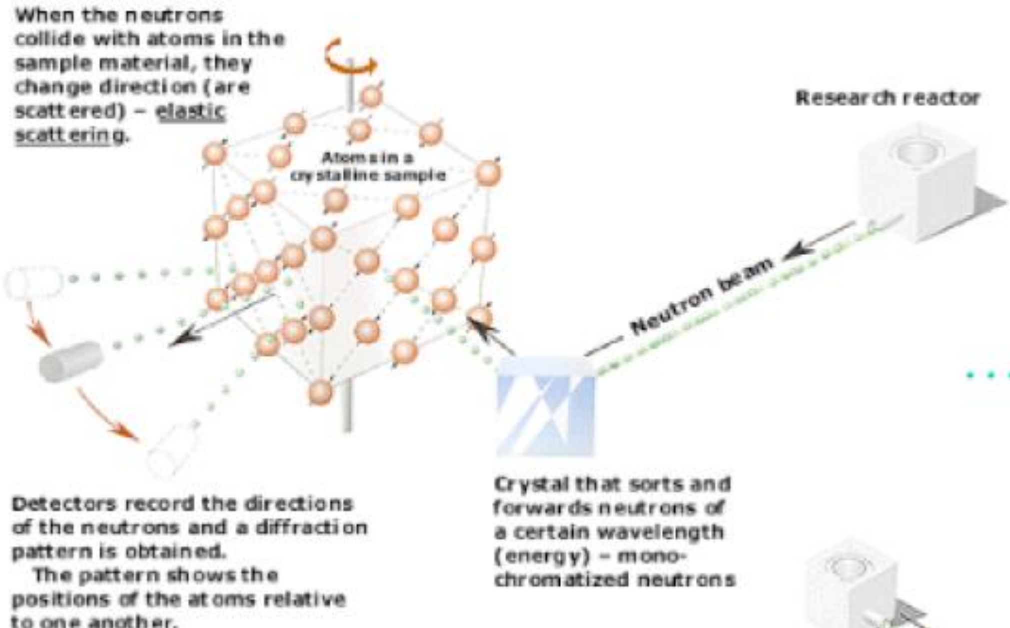
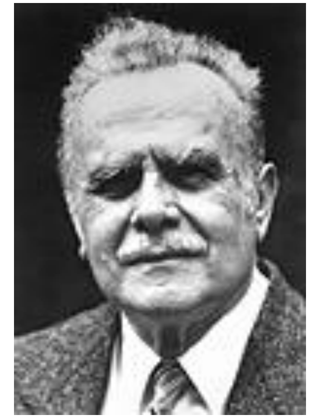
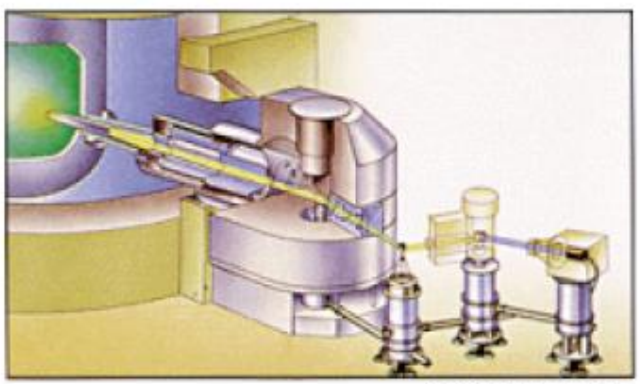
The 1994 Nobel Prize in Physics – Shull & Brockhouse

Neutrons show where the atoms are….

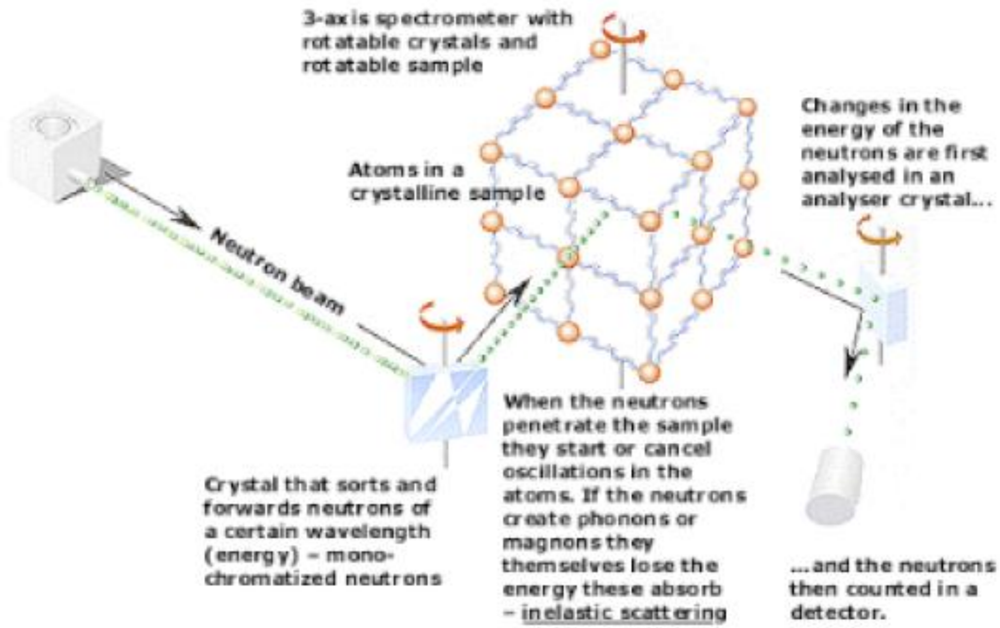




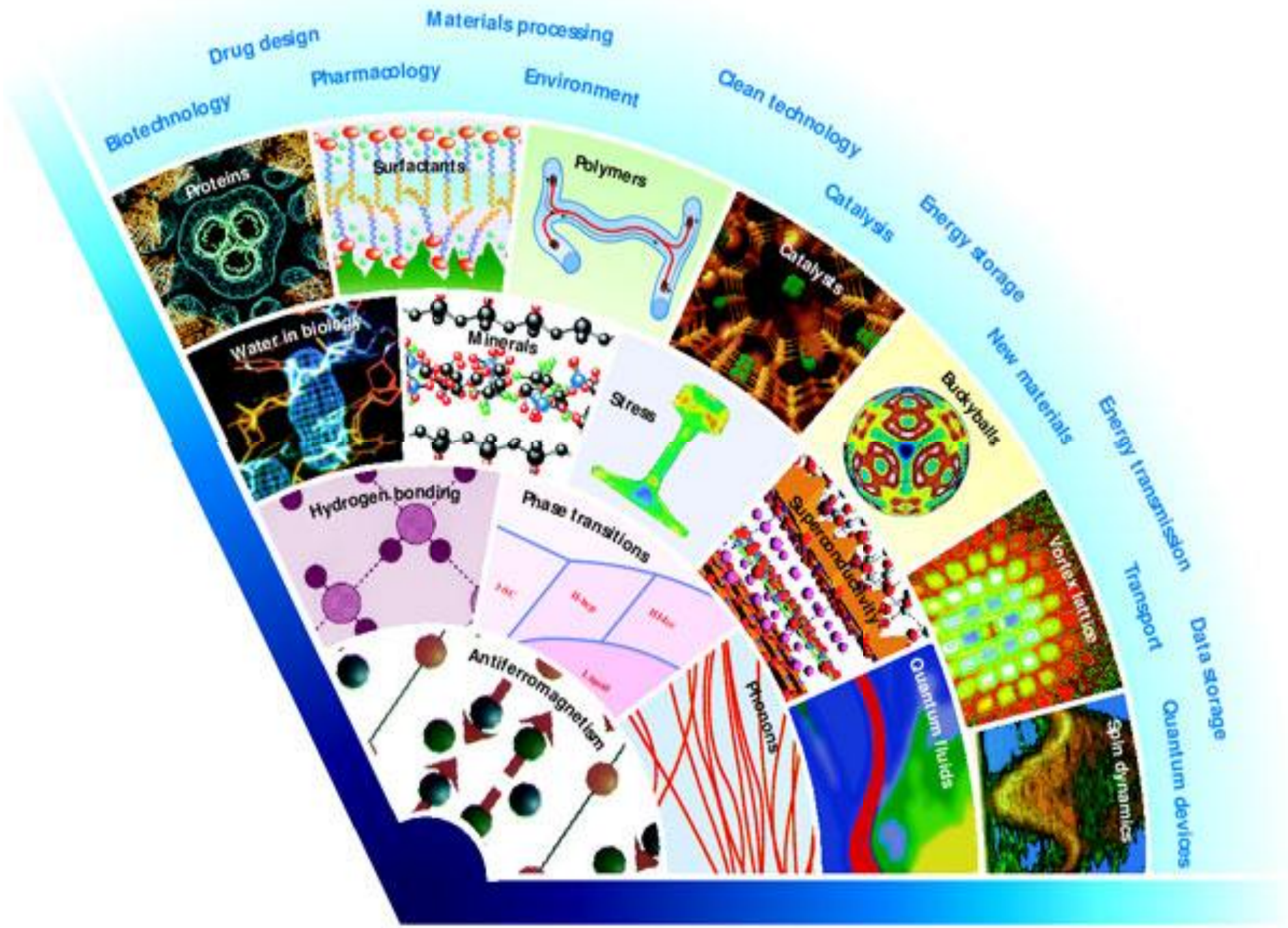
…and what the atoms do.



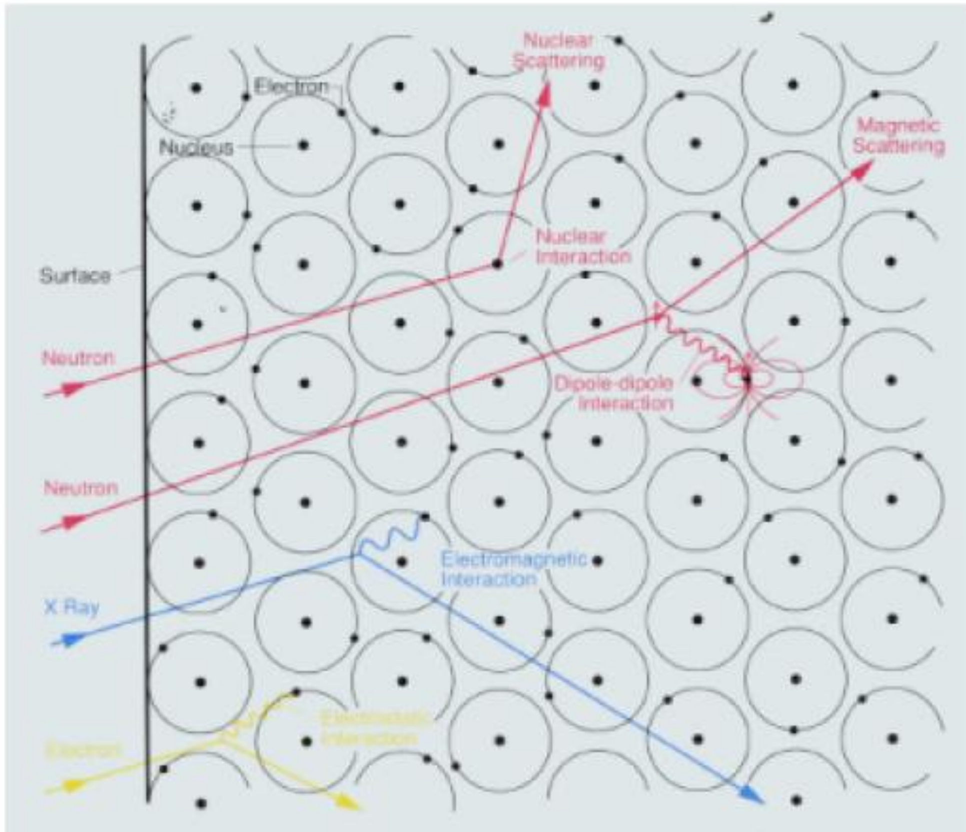
3-axis spectrometer



Very broad range of applications



Interaction mechanisms

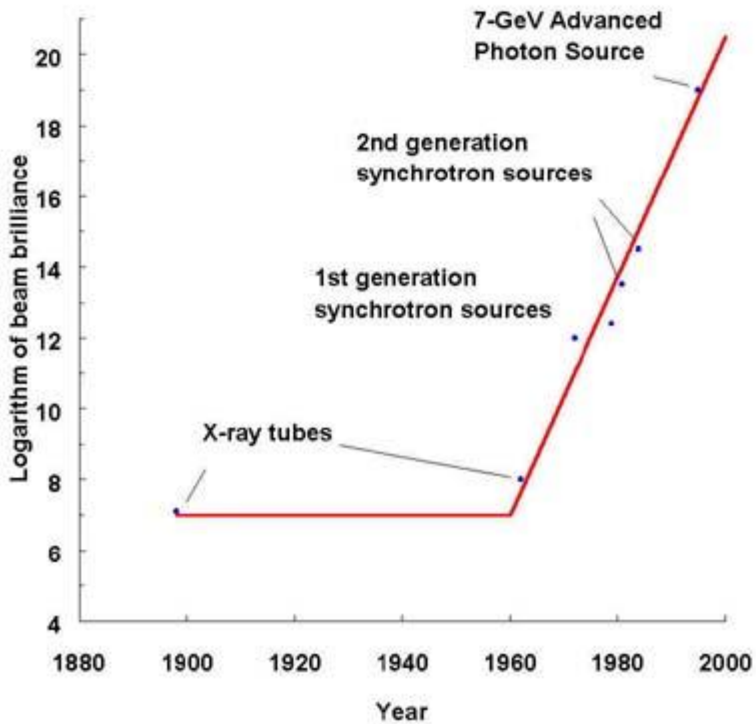


Neutrons interact with atomic nuclei via very short range (fm) forces

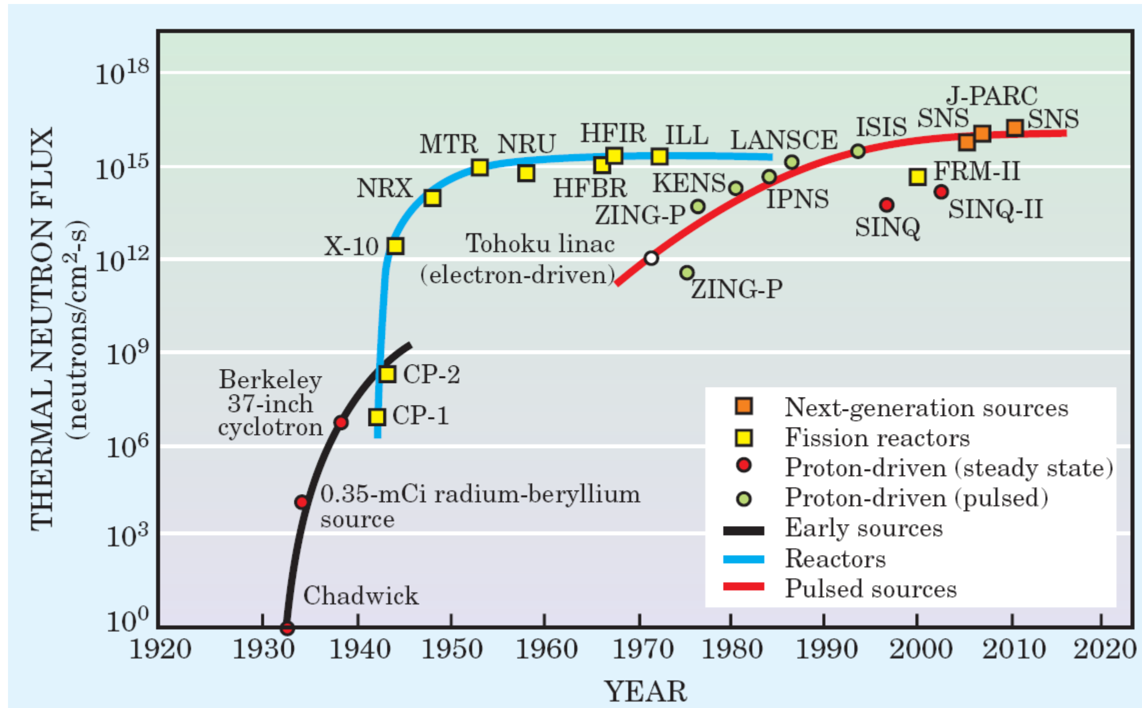
Neutrons interact with unpaired electrons via a magnetic dipole interaction

Neutrons vs. X-rays: evolution of brightness/flux

X-rays



Neutrons

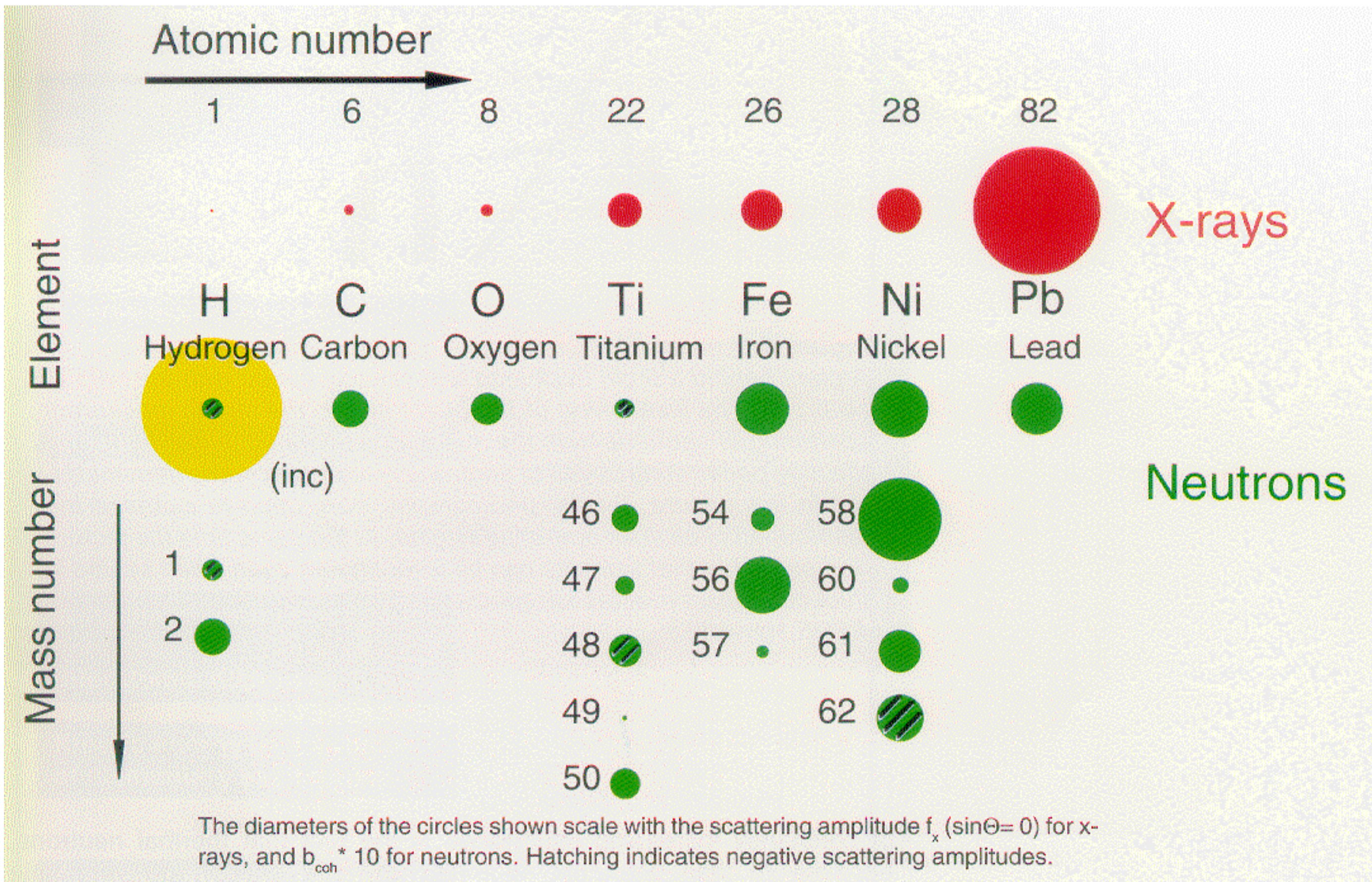


X-ray photon fluxes have increased tremendously !

Neutrons vs. X-rays: scattering power

-Intensity of neutron beams is much lower than at synchrotron

-Scattering power very different



Methods are complementary !

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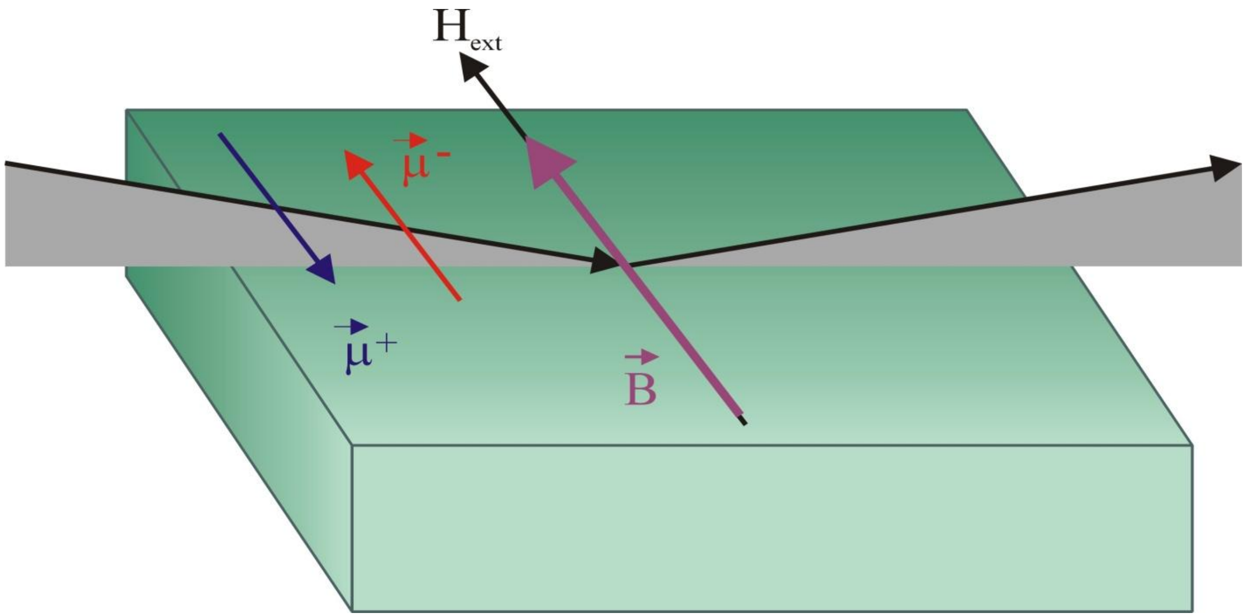
Neutron reflectivity: nuclear and magnetic interaction



$$V = V_{nuc} + V_{mag} = \frac{2\pi\hbar^2}{m}\rho b - \vec{\mu}\vec{B} = \frac{2\pi\hbar^2}{m}\rho\left(b_{nuc} \pm b_{mag}\right)$$

Allows to reconstruct chemical and magnetic depth profile !

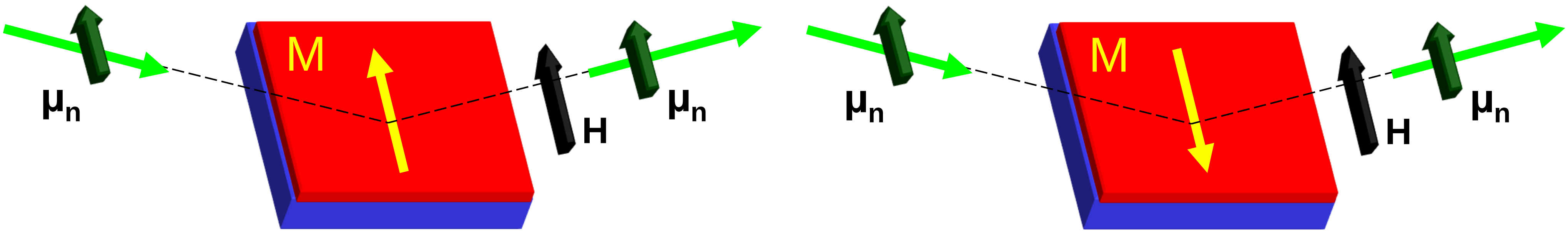
See also: X-ray and Neutron Reflectivity: Principles and Applications (J. Daillant & A. Gibaud)

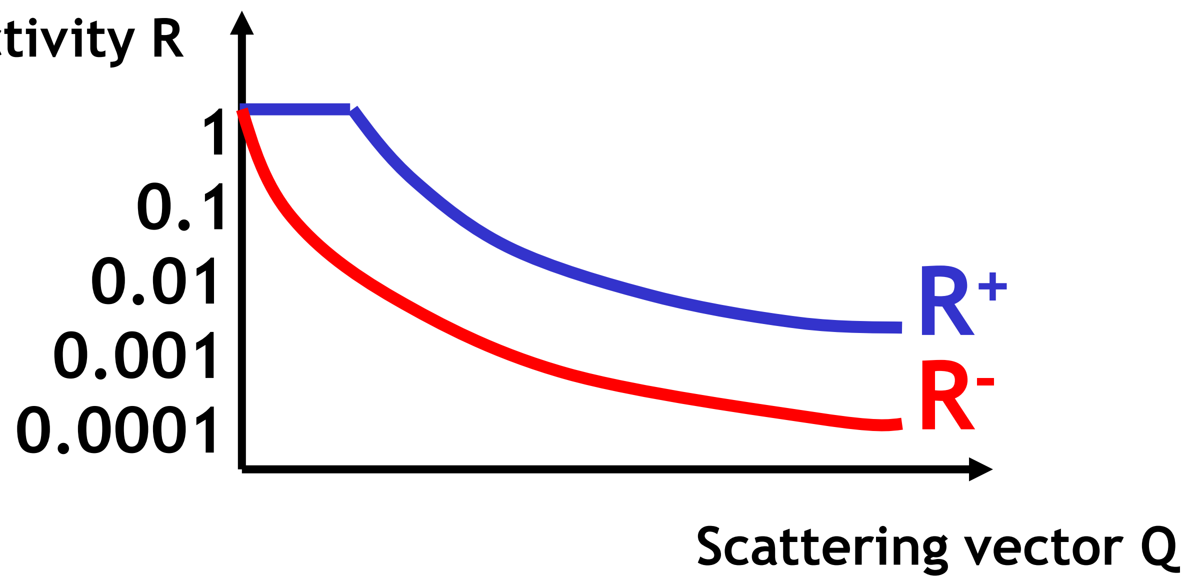
NEUTRON REFLECTIVITY

Neutron beam can be polarized, i.e. spin up or down

If neutron spin parallel to sample magnetization:

spin is conserved (NSF, non-spin-flip process)





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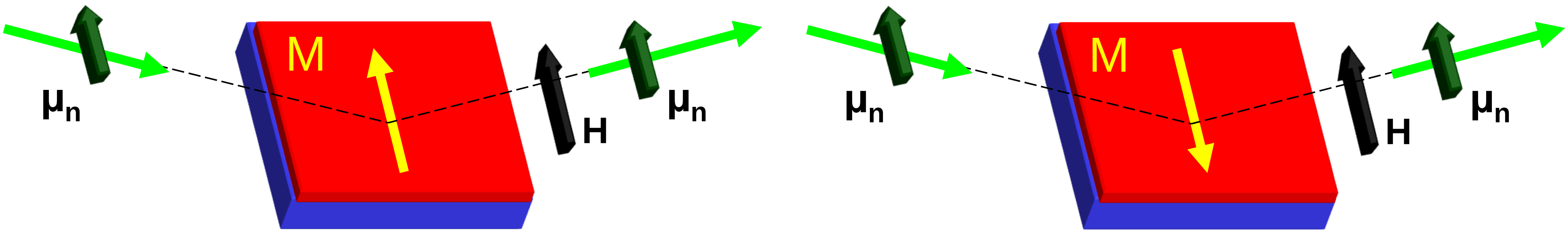
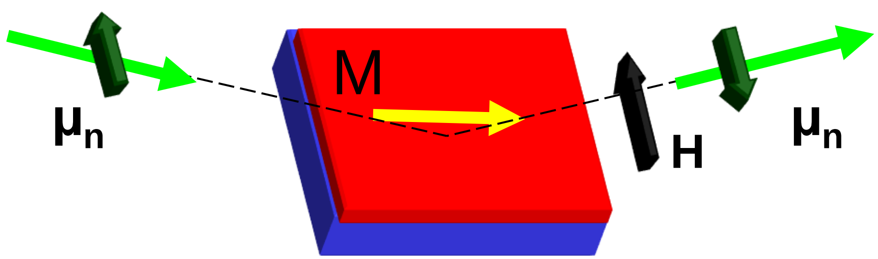


If neutron spin perpendicular to sample magnetization

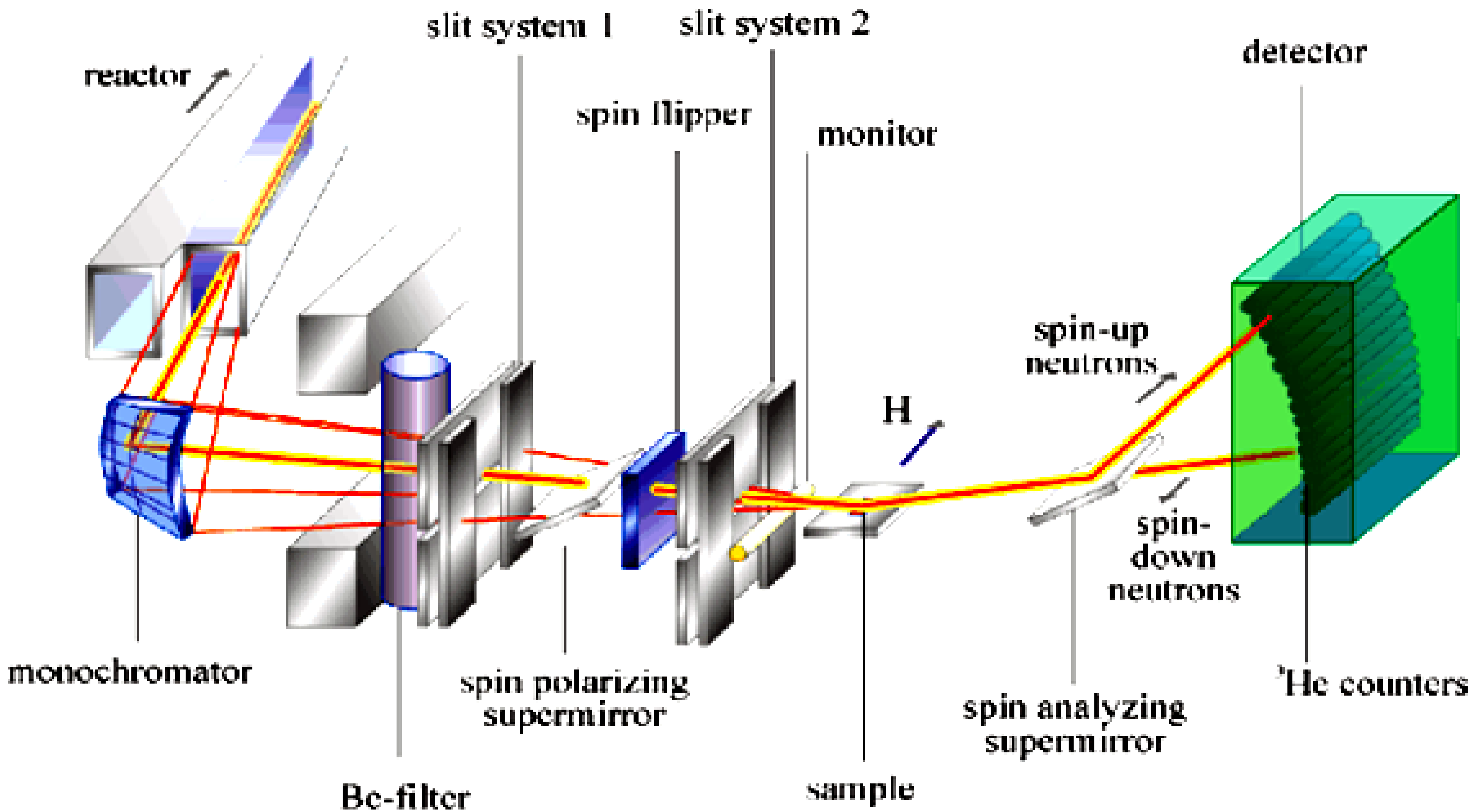
spin is reversed (SF, spin-flip process)



Spin analysis after reflection: magnetization directions.

Neutron Reflectometer

V6, HZB, cold neutrons



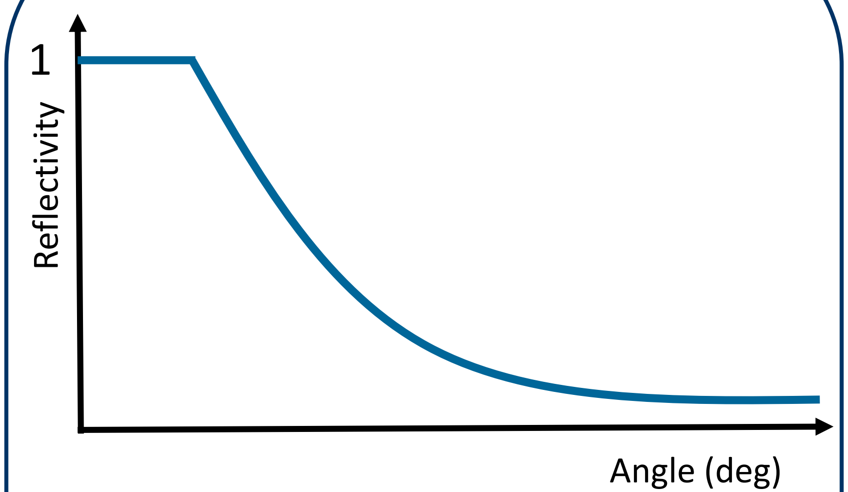
Polarization

Analysis

Interaction

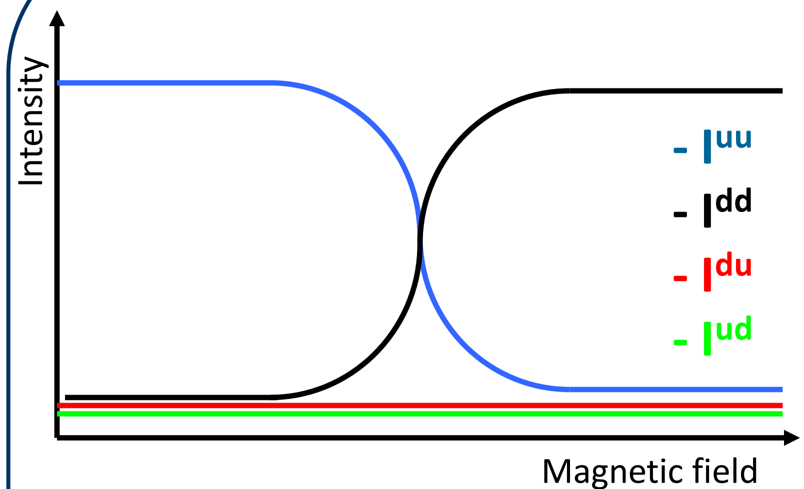
Neutron Reflectometry

Two modes:



Specular reflectivity scan at fixed field

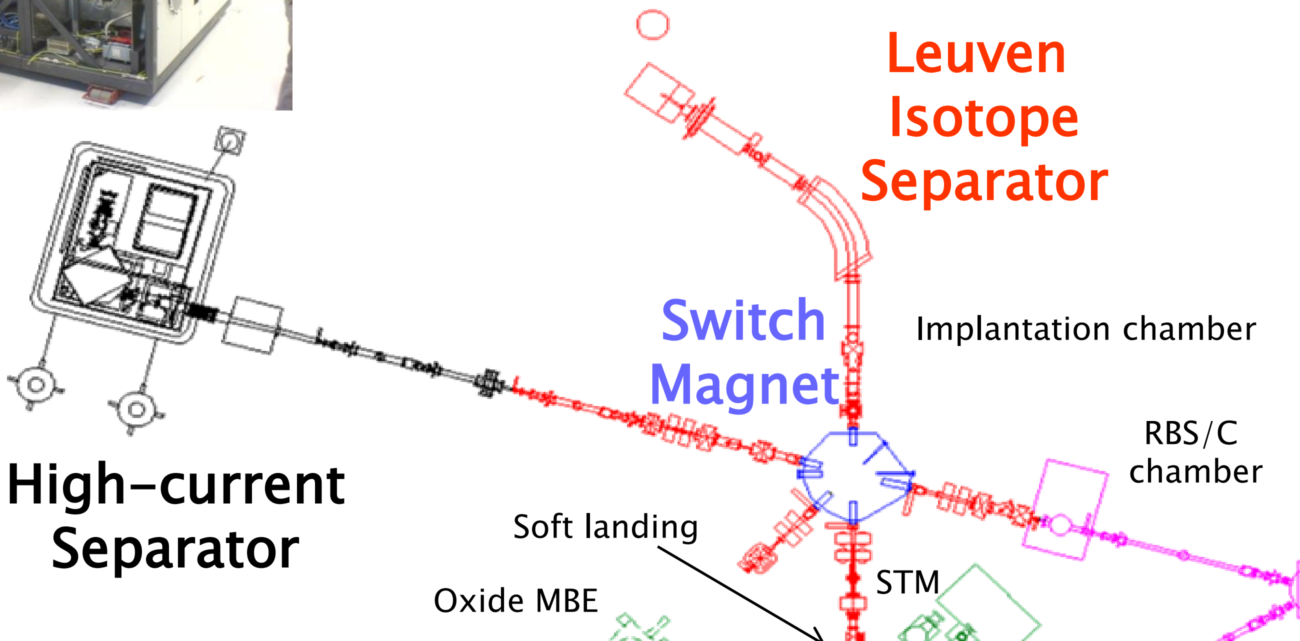
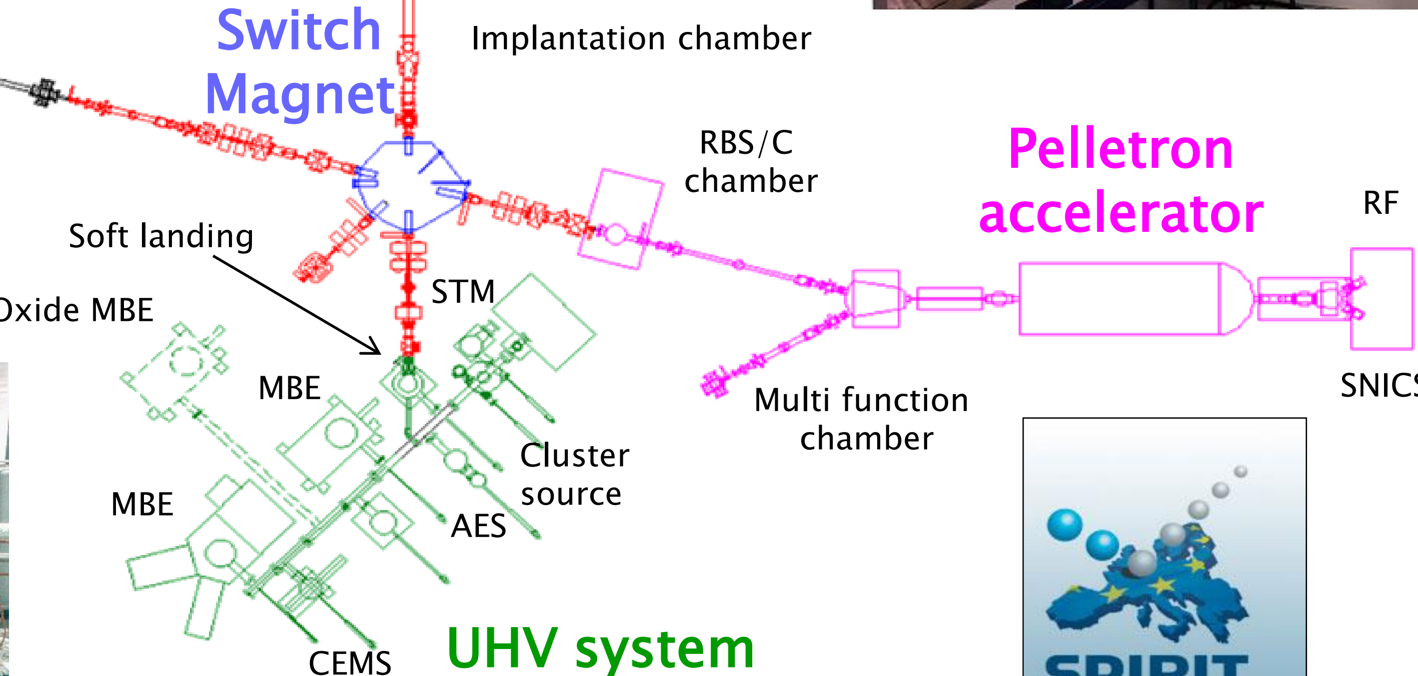
Depth profile



Magnetic field scan at fixed angle

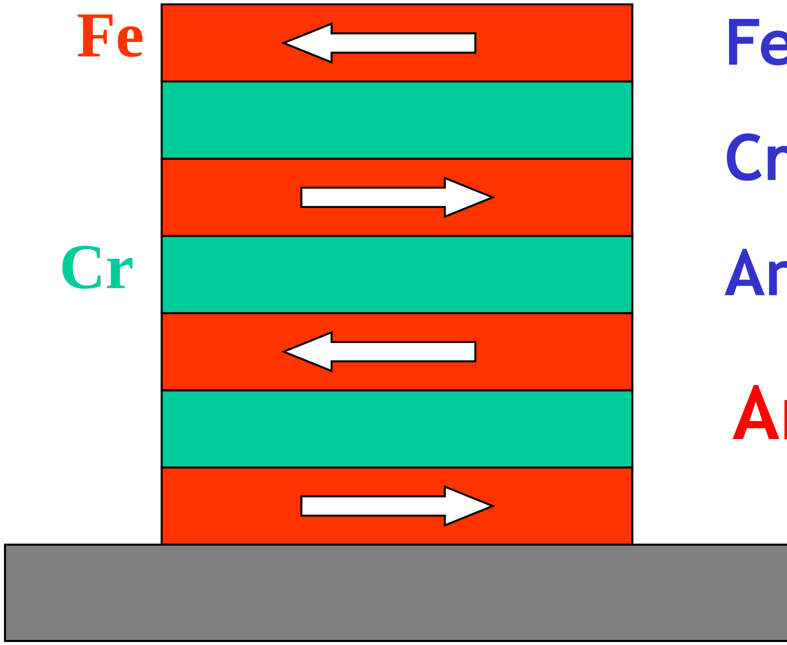
Magnetic reversal mechanism

Ion and Molecular Beam Laboratory, K.U.Leuven

SPIRIT

Neutron reflectometry on Fe/Cr multilayers



Fe layers: 2.5 nm thick

Cr layers: 1.3 nm thick

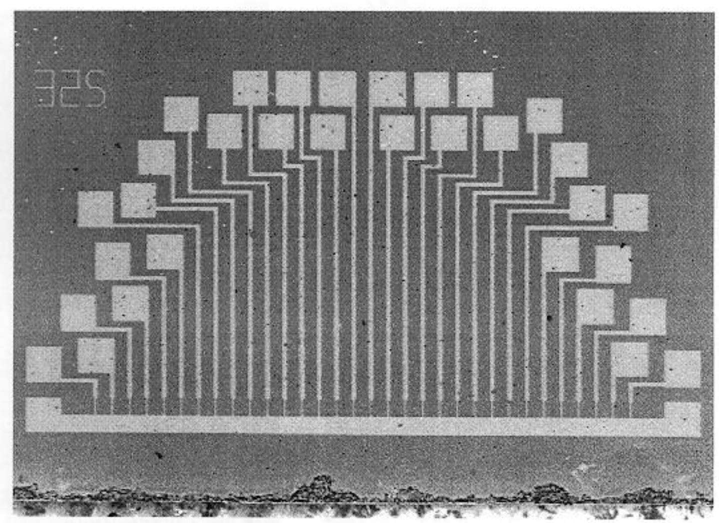
Antiparallel coupling between Fe

Artificial antiferromagnet !

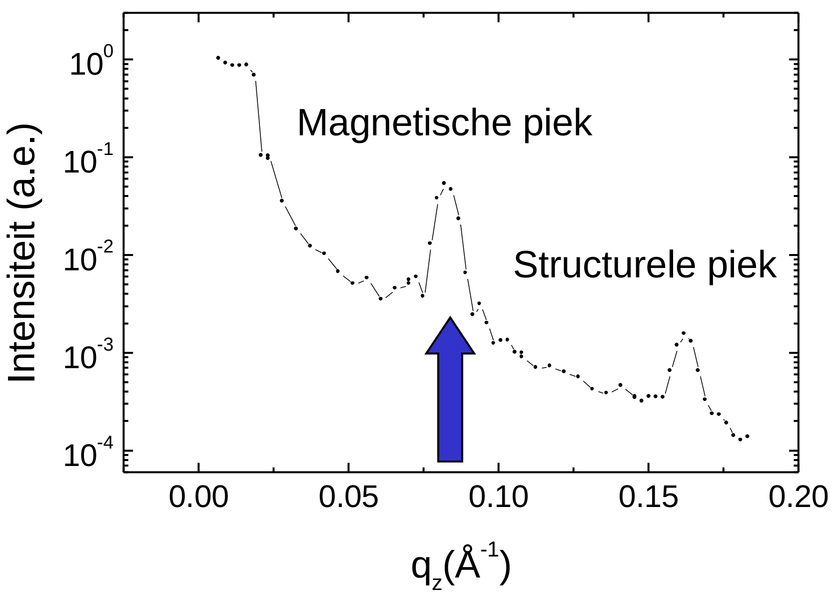
Importance: GMR

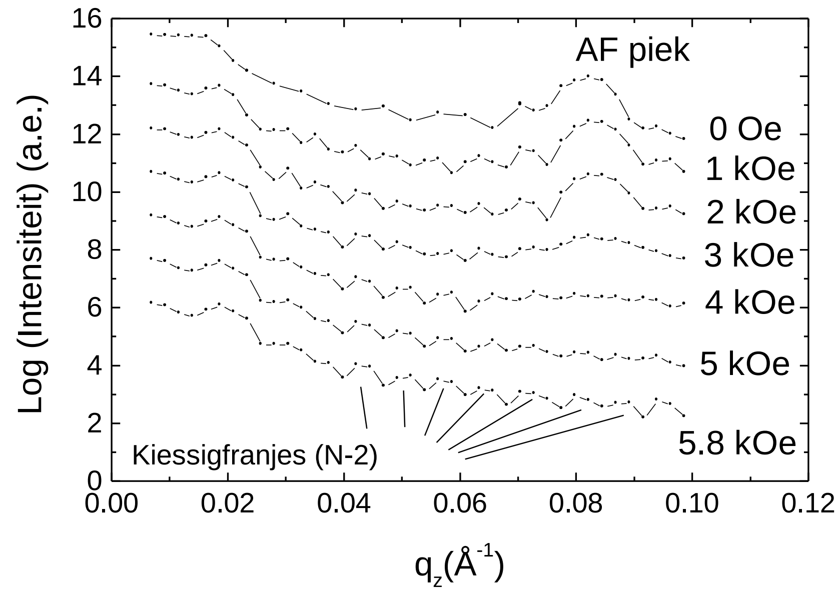
Applied in field sensors

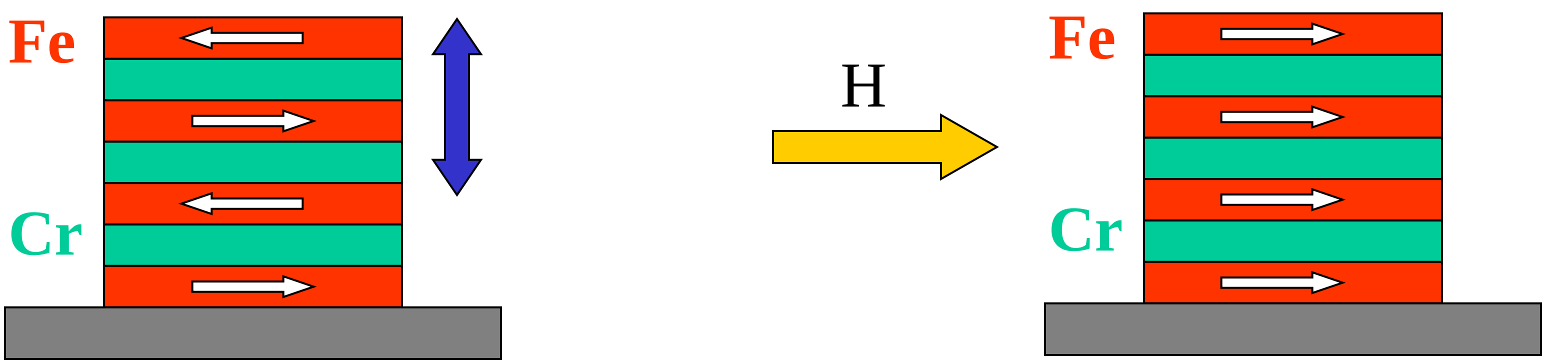
(hard disks, ABS, ...)



Neutron reflectometry on Fe/Cr multilayers



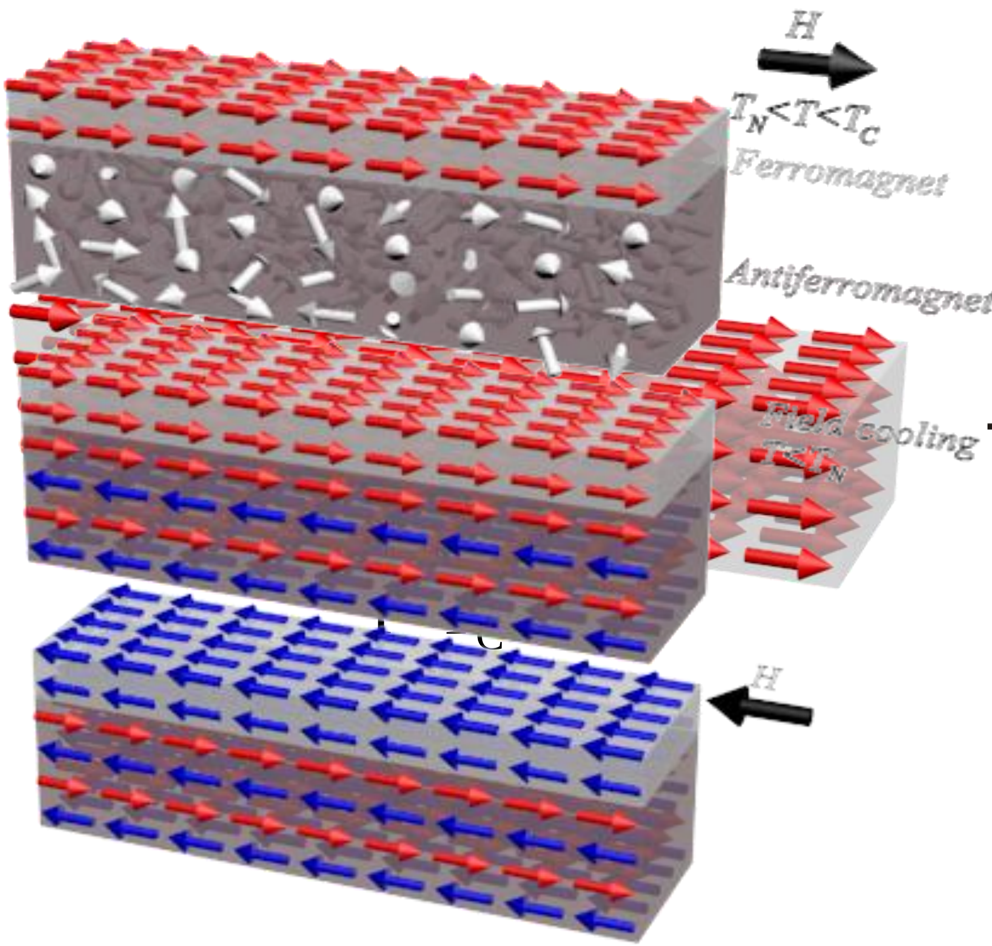


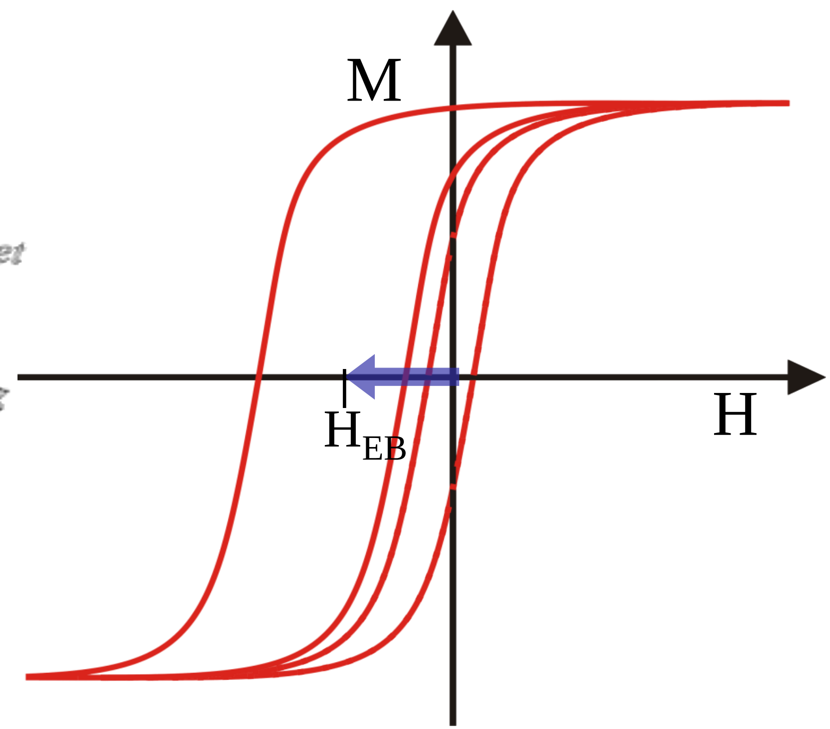


Antiferromagnetic coupling

In field: coupling is destroyed

Exchange bias effect

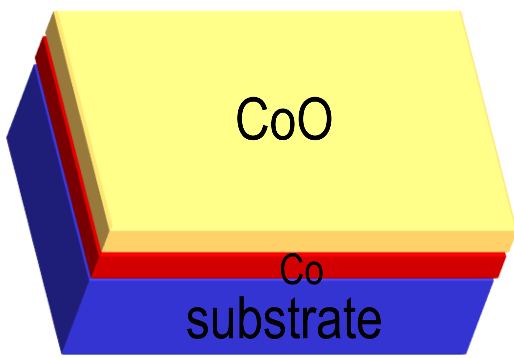


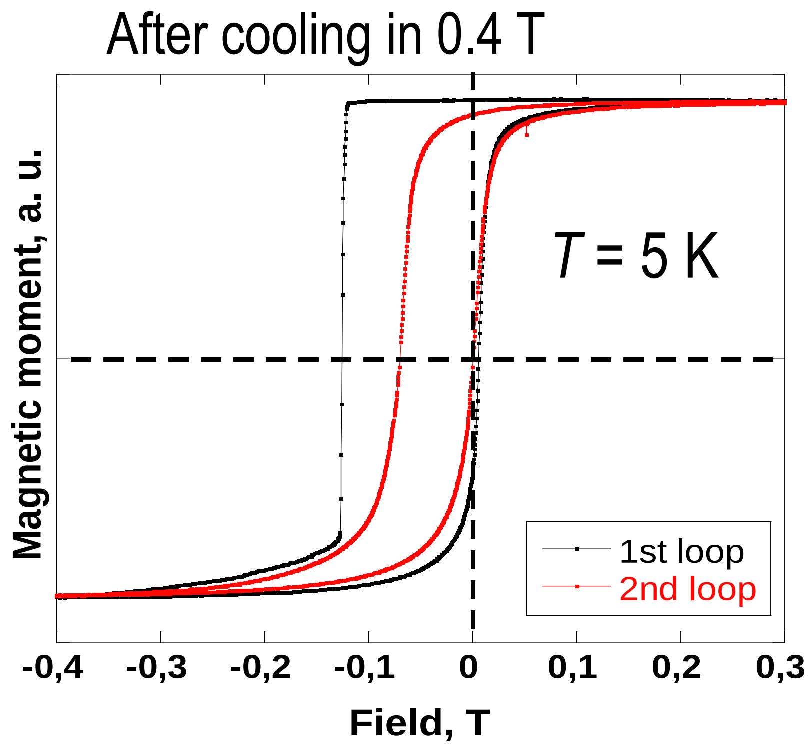


See J. Nogués and Ivan K. Schuller, JMMM 192 (1999)

Co/CoO thin film exchange bias system

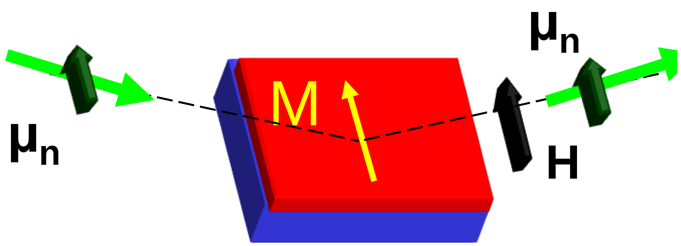
- Substrate : Si + 100 nm amorphous SiO_2
- MBE-grown Co thin film:
- Oxidation : in situ formed oxide : 10^{-4} Torr O_2

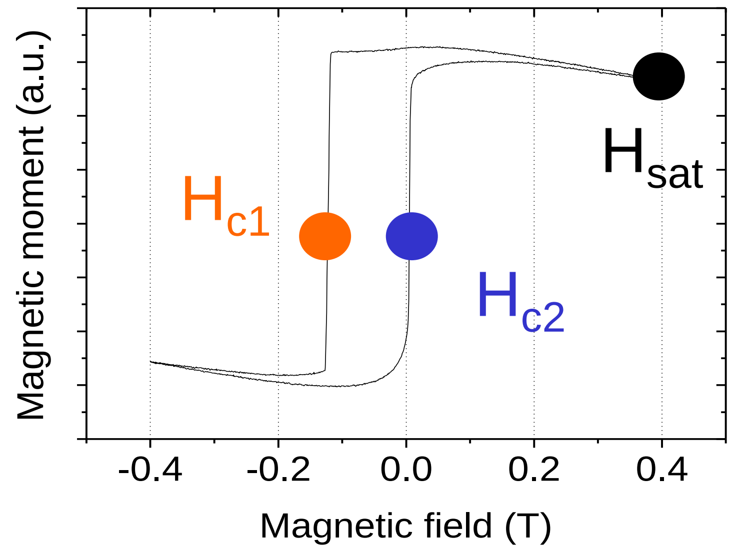




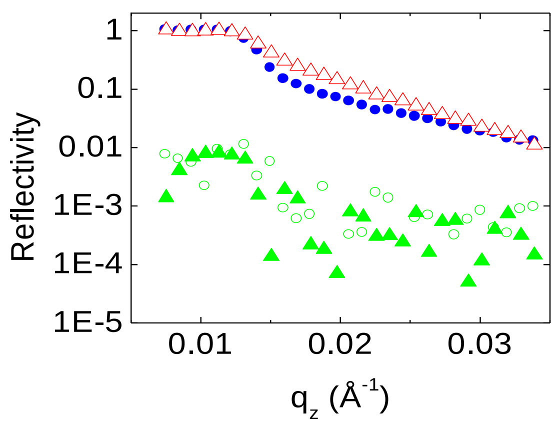
Typical exchange bias and training effect

Neutron reflectivity on Co/CoO film



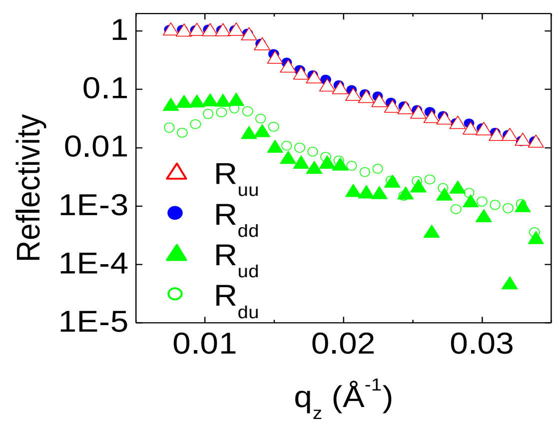


H_{sat} = 0.40 T



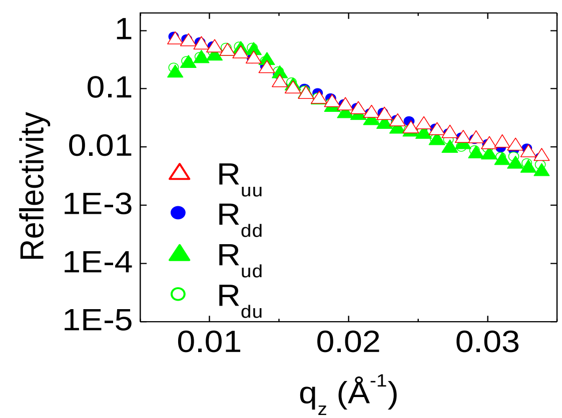
Splitting in NSF

H_{c1} = -0.12 T



Mainly NSF

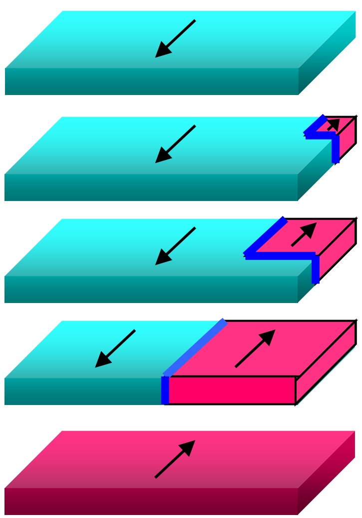
H_{c2} = 0.009 T



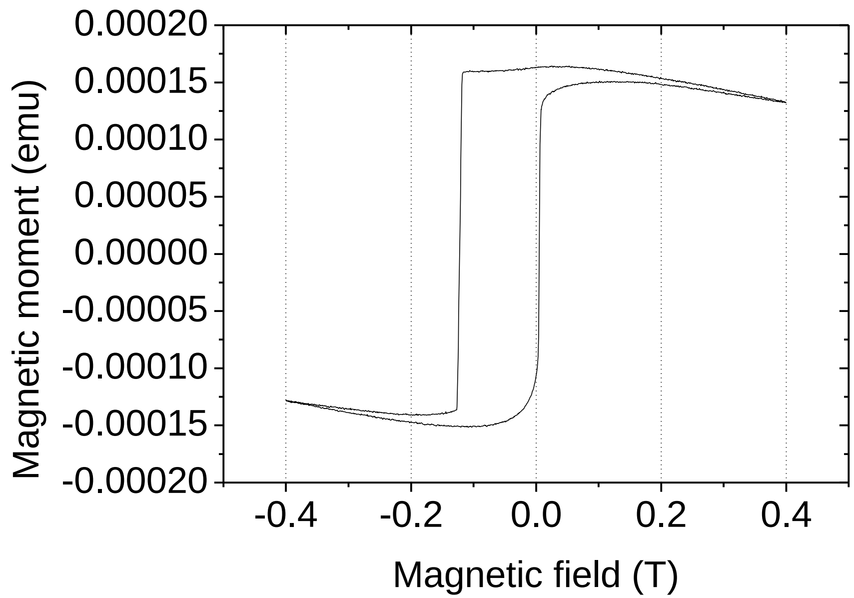
Strong SF

Neutron reflectivity experiments on Co/CoO films

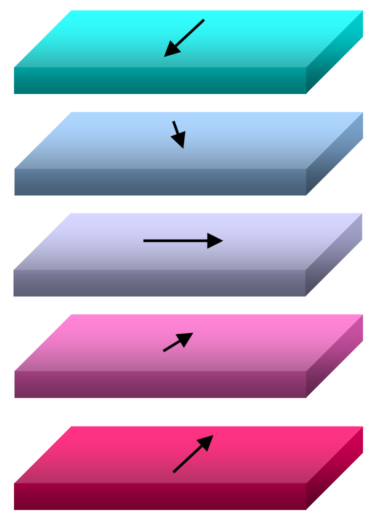
Small spin-flip



Domain wall motion



Strong spin-flip



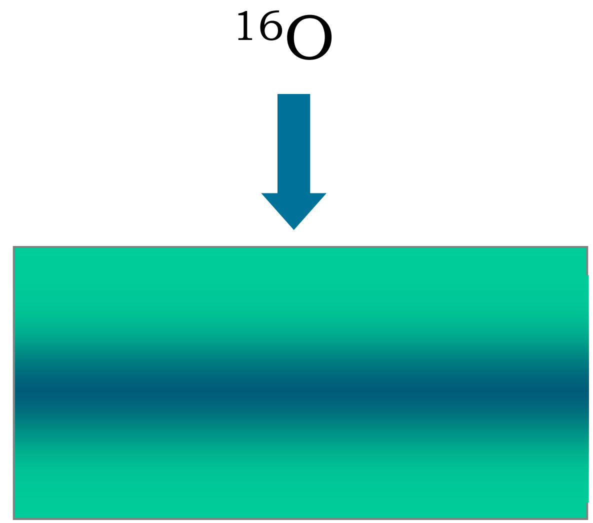
Rotation

Different reversal mechanisms!

See also F. Radu et al. (Bochum): Phys. Rev. B 67, 134409 (2003)

Exchange bias: new approach

Bilayer system



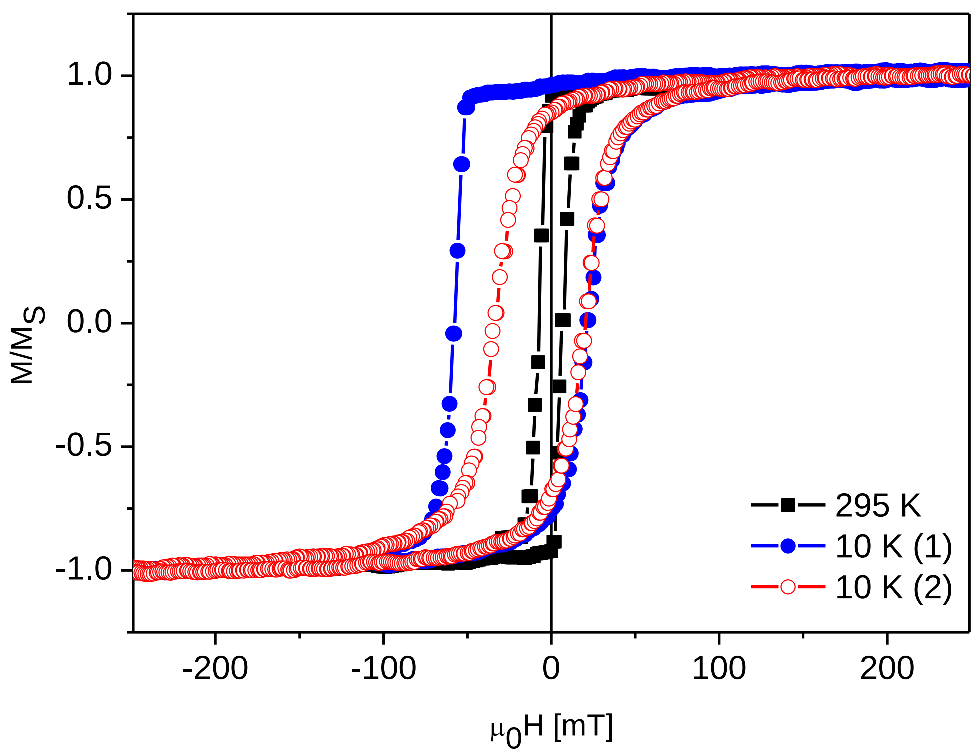
Implanted system

Motivation

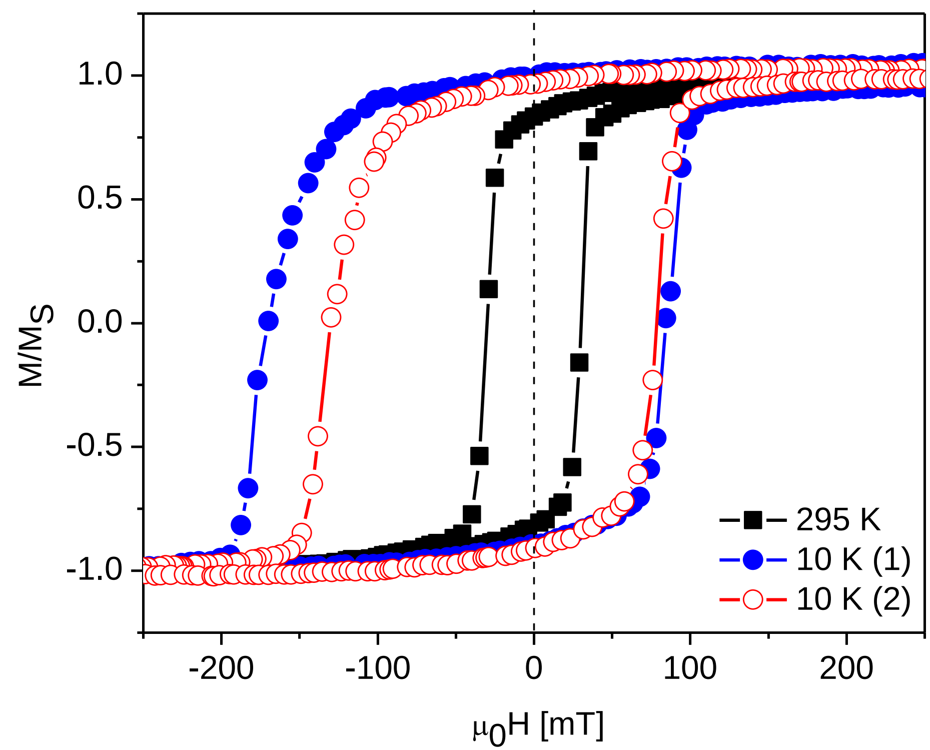
- Control oxide formation.
- Increase interface area.

? Same behaviour **?**

EB by ion implantation vs. bilayer



Bilayer system
30 nm Co film
surface oxidation



Implanted system
100 nm Co film
$1x10^{17}$ ^{16}O at 60 keV

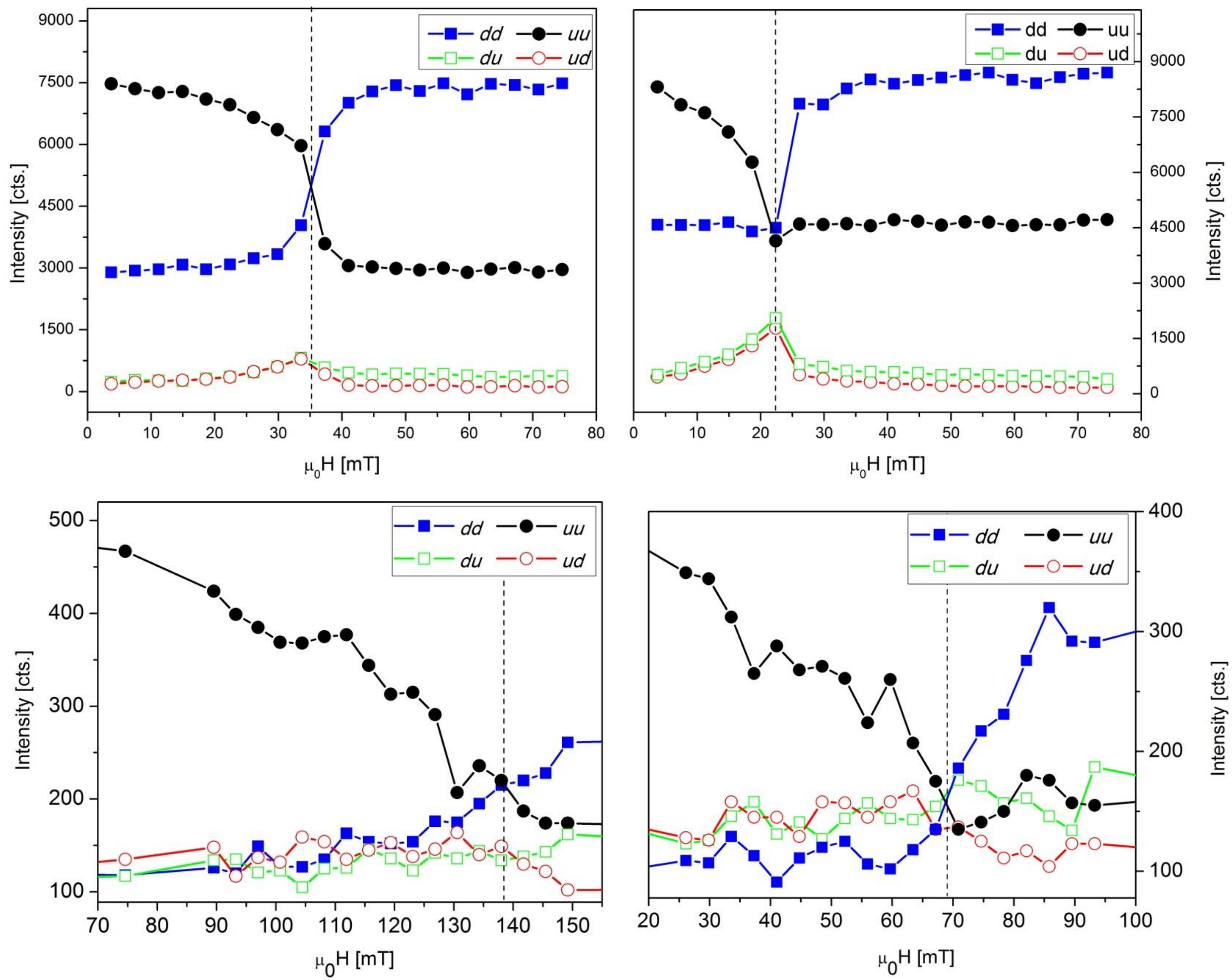
Magnetization reversal mechanism

bilayer
Co/CoO
EB system

change in reversal mechanism

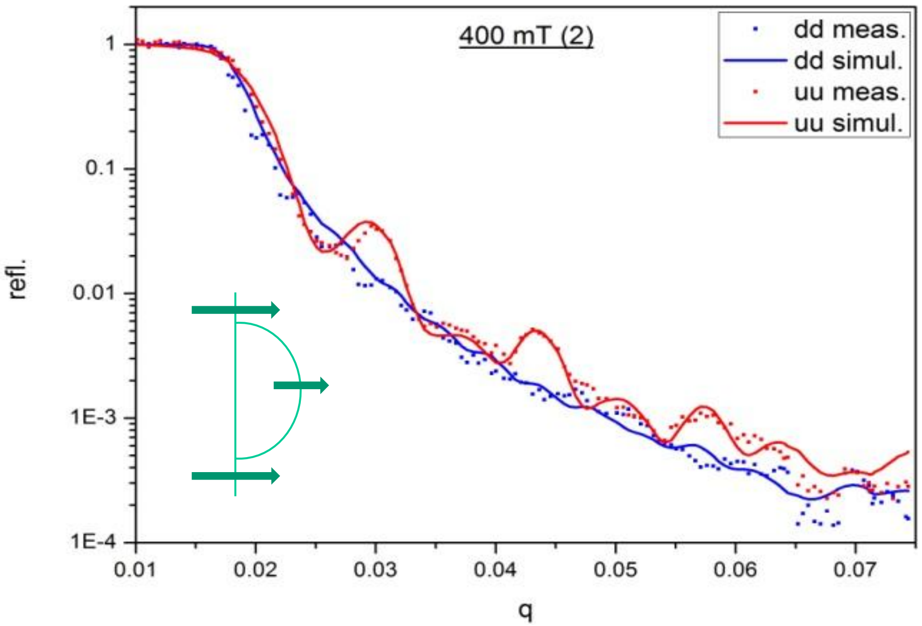
implanted
$Co\text{-}Co_xO_y$
System

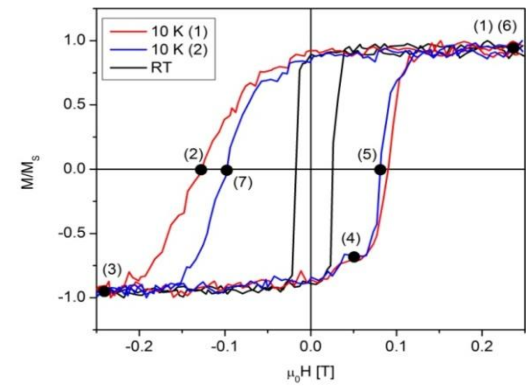
domain wall nucleation and motion



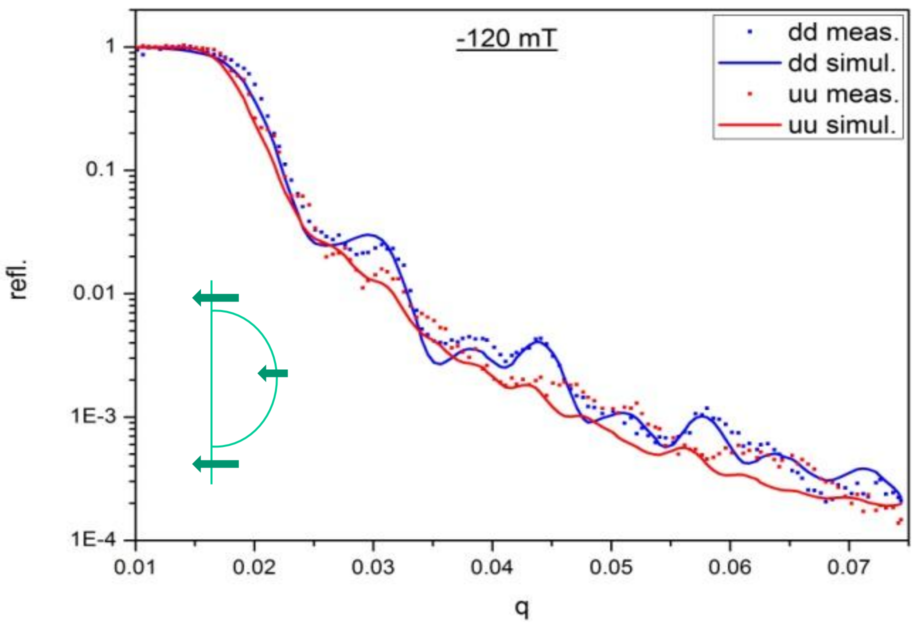
J. Demeter *et. al.*, Appl. Phys. Lett. **96**, 132503 (2010)

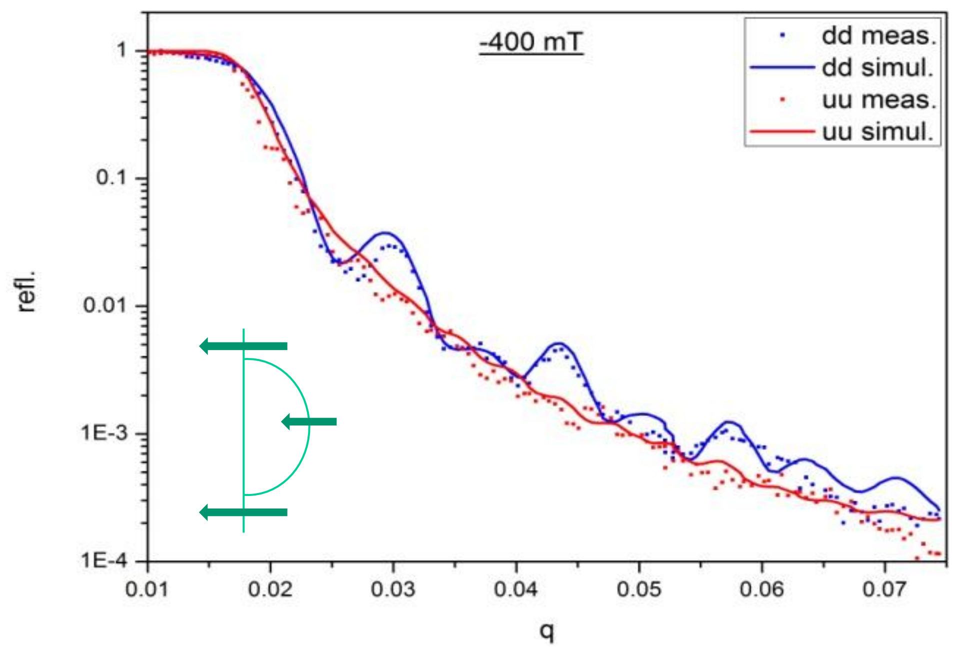
Magnetic depth profile of implanted Co film





Magnetic depth profile correlates with gaussian implantation profile





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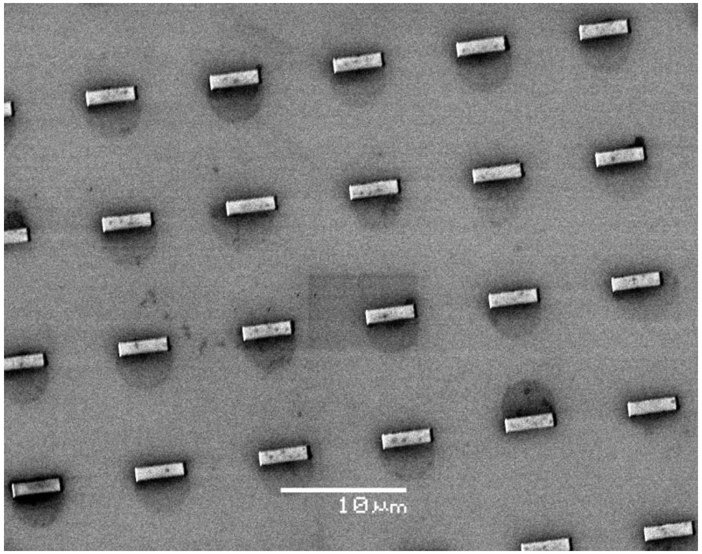
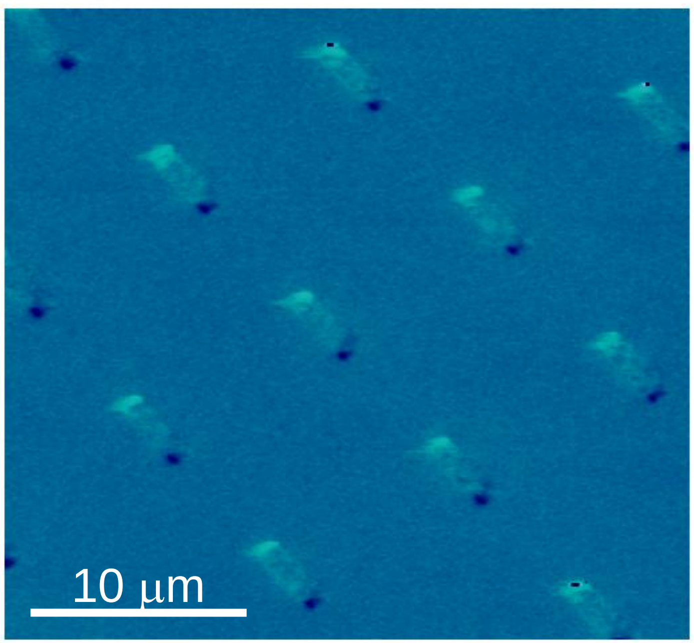
Magnetization reversal in micron-sized Co bar magnets ?



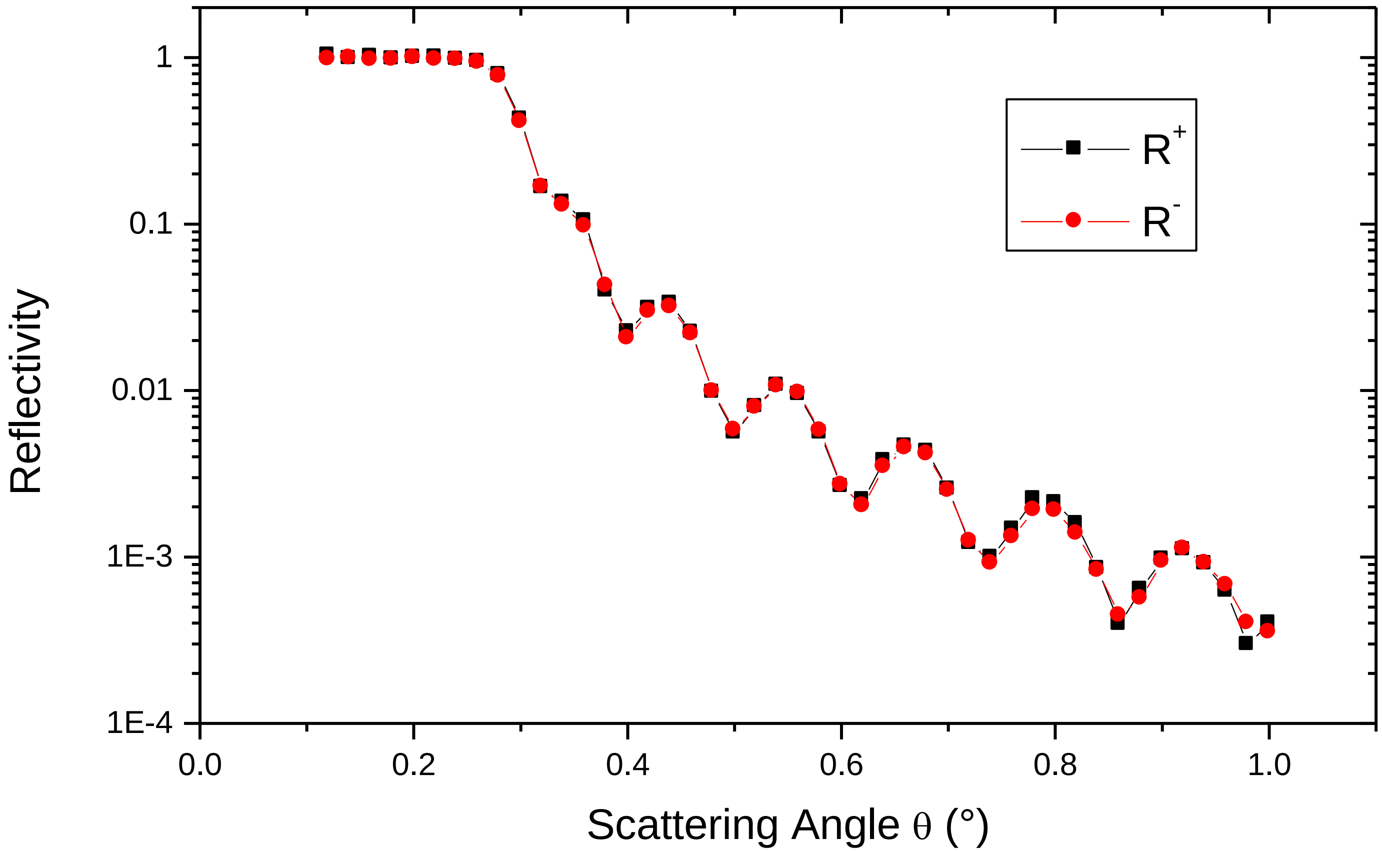
- electron beam lithography on SiO_2
- islands 1 µm x 4 µm
- periodicity 10 µm
- Au(7.5 nm)/Co(20 nm)/Au(7.5 nm) trilayer deposited in MBE
- patterned area 4 cm^2



- strong contrast in MFM image
- indicates a single-domain state after saturation
- same result over macroscopically large area

SPECULAR REFLECTIVITY

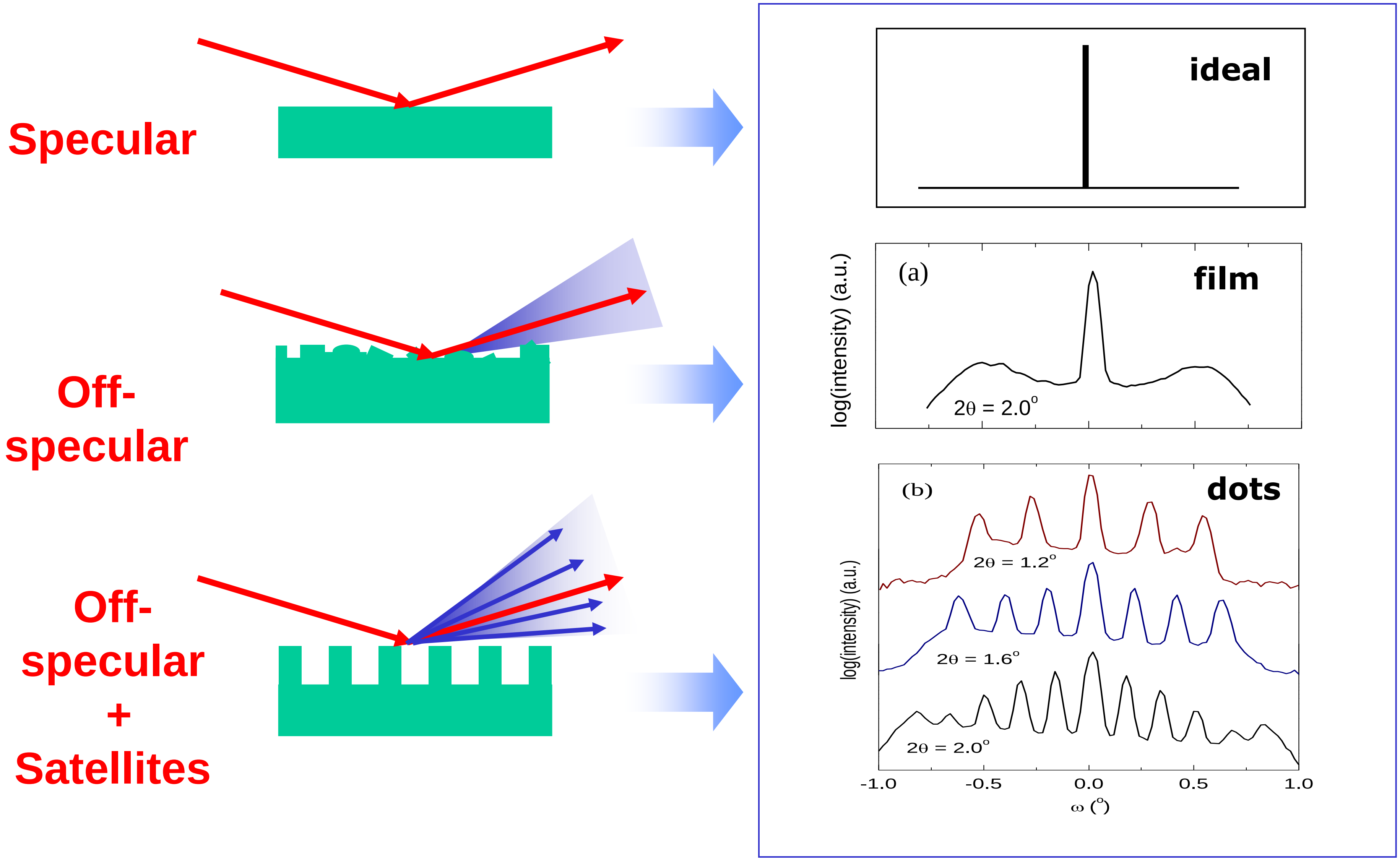
Sample in saturated state (H=2400 G)



No clear splitting between R⁺ and R⁻

Specular reflectivity dominated by non-magnetic substrate

X-ray reflectivity of a film surface

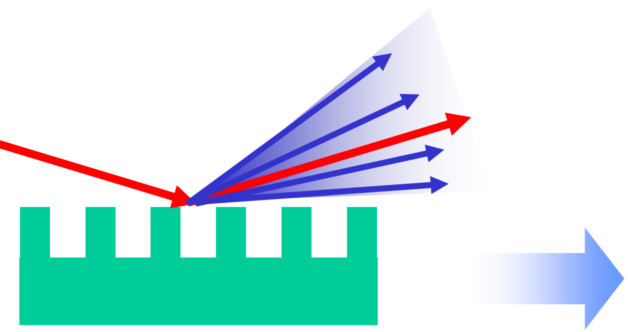


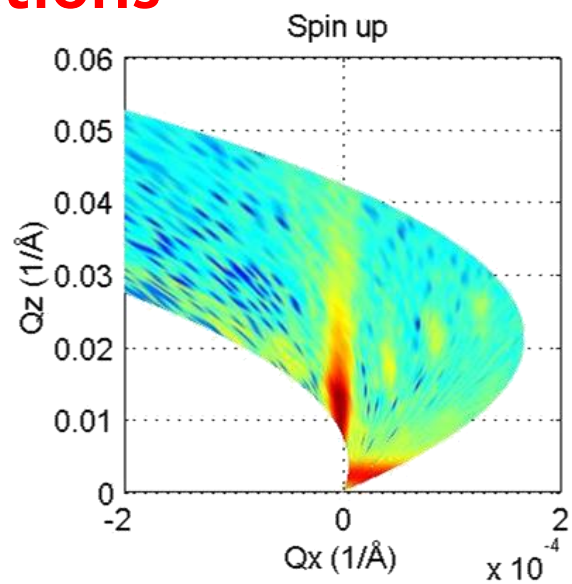
*S.K. Sinha et al., Phys. Rev. B **38**, 2297 (1988)*

Specular and off-specular reflections

Specular +

Satellites





Use polarized neutron beam (neutron spin parallel to field)

Measure four scattering cross-sections:

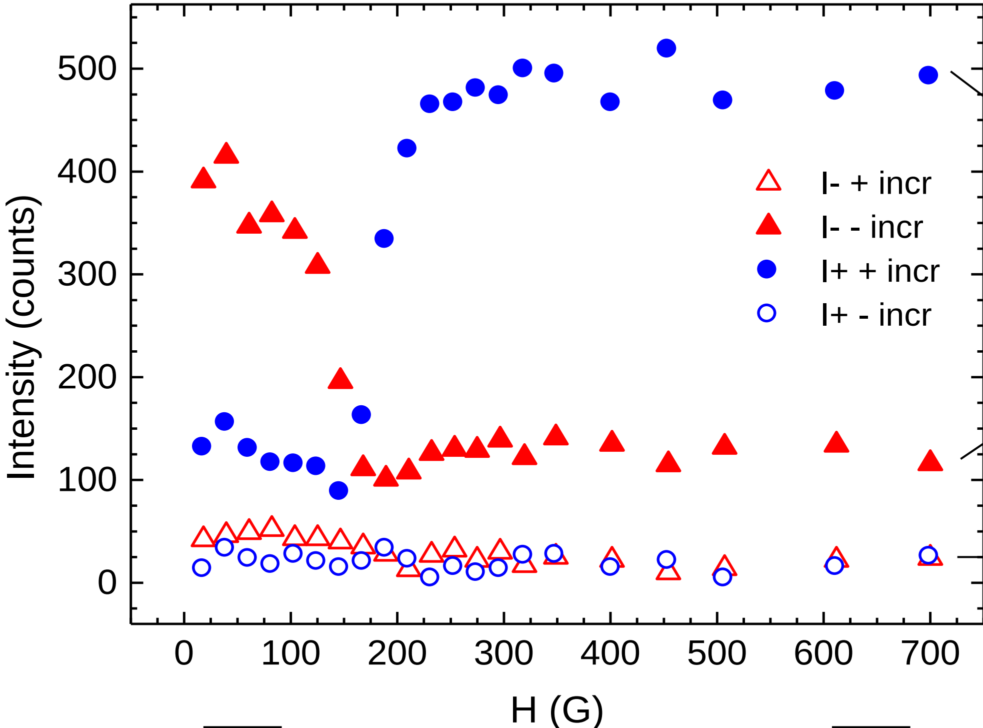
$I^{+\,+}$
$I^{-\,-}$ } **NSF: magnetization components parallel to field**

$I^{+\,-} = I^{-\,+}$ **SF: magnetization components perpendicular to field**

K. Temst et al., Appl. Phys. Lett. ***79****, 991 (2001)*

NON-SPECULAR REFLECTIVITY in field along easy direction

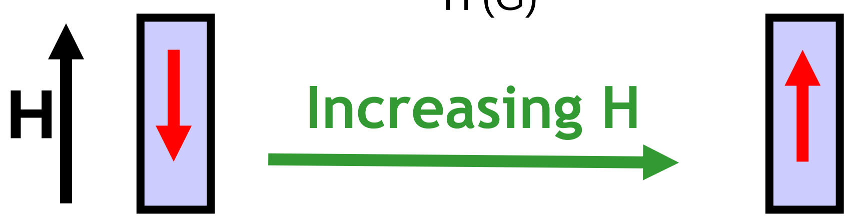
Sample first saturated in negative field

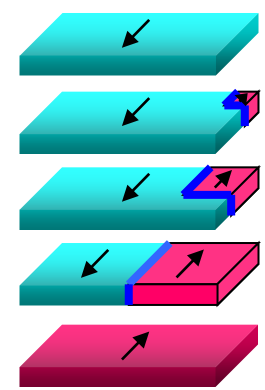


most sensitive to ↑ moments

most sensitive to ↓ moments

limited spin flip scattering: very few moments perpendicular to field

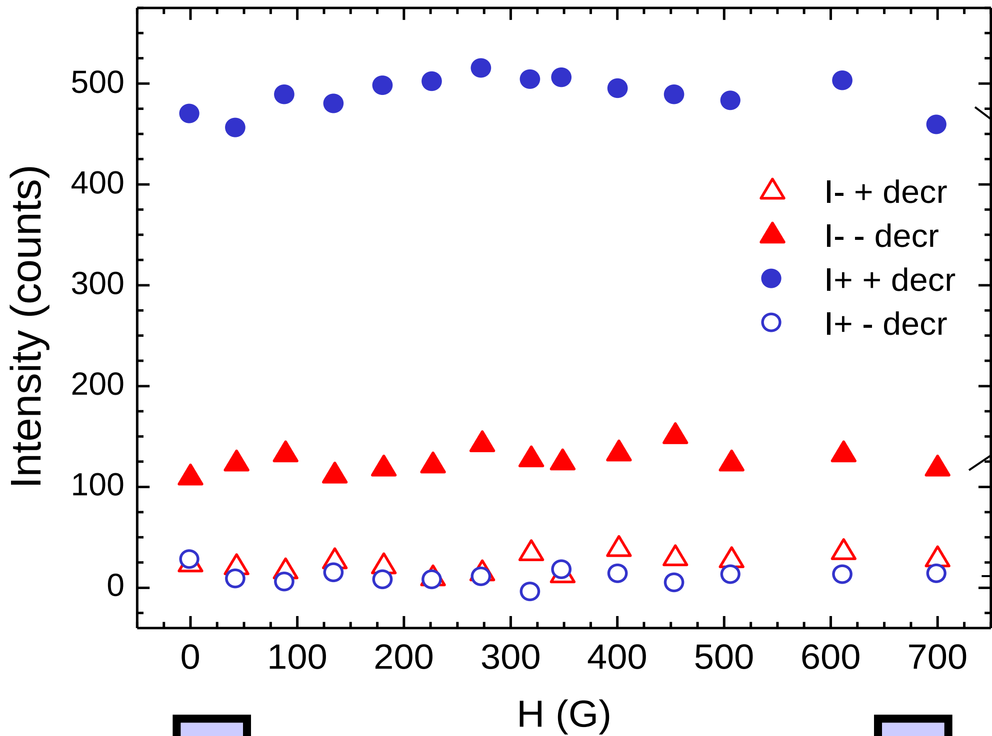




Characteristic for domain wall nucleation and motion

K. Temst et al., JVST B 21, 2043 (2003)

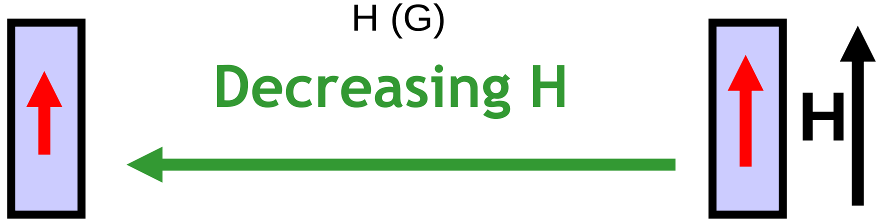
NON-SPECULAR REFLECTIVITY in field along easy direction



most sensitive to ↑ moments

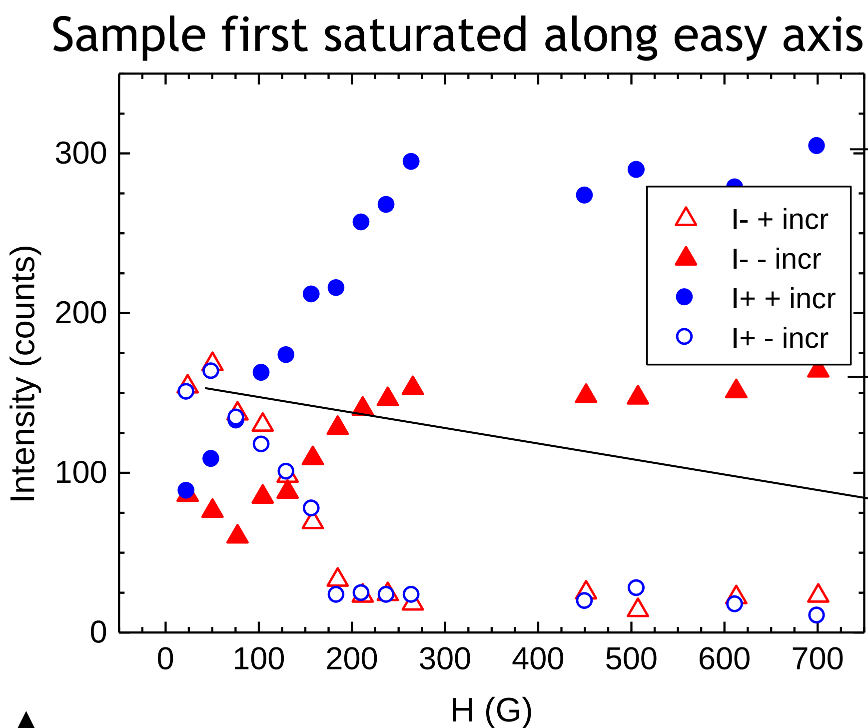
most sensitive to ↓ moments

no spin flip scattering:
no moments
perpendicular to field



High remanence due to shape anisotropy

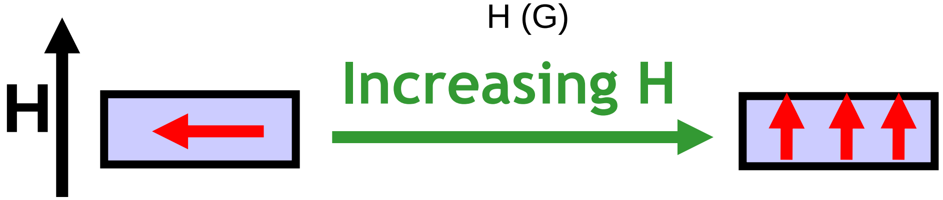
NON-SPECULAR REFLECTIVITY in field along hard direction



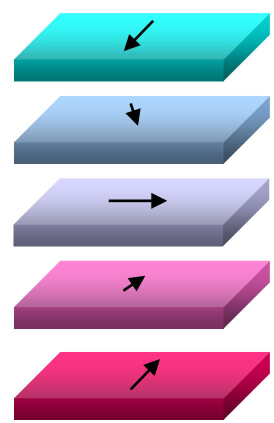
most sensitive to ↑ moments

most sensitive to ↓ moments

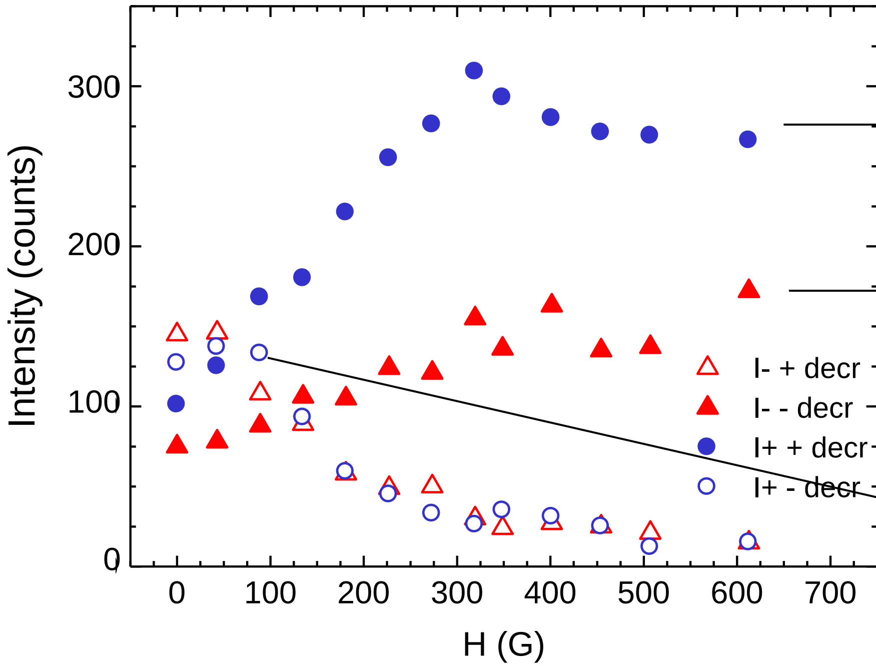
strong spin flip scattering: magnetization mainly perpendicular to field



Slow rotation of moments towards hard direction



NON-SPECULAR REFLECTIVITY in field along hard direction



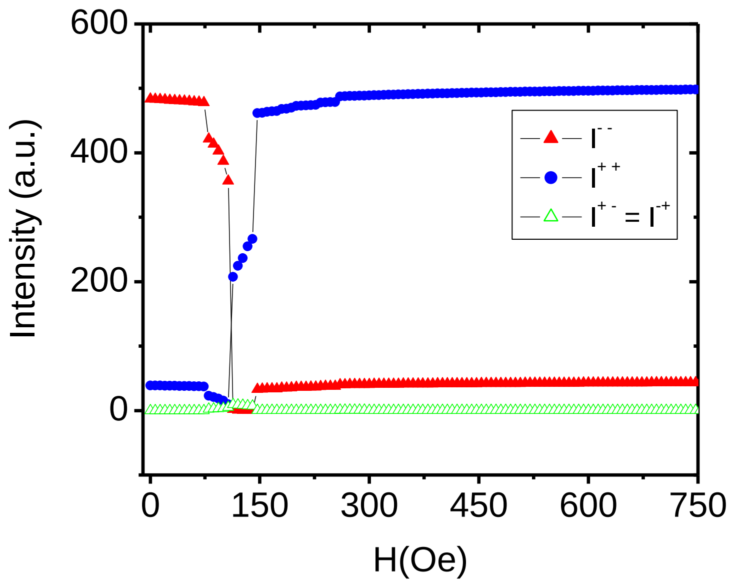
most sensitive to ↑ moments

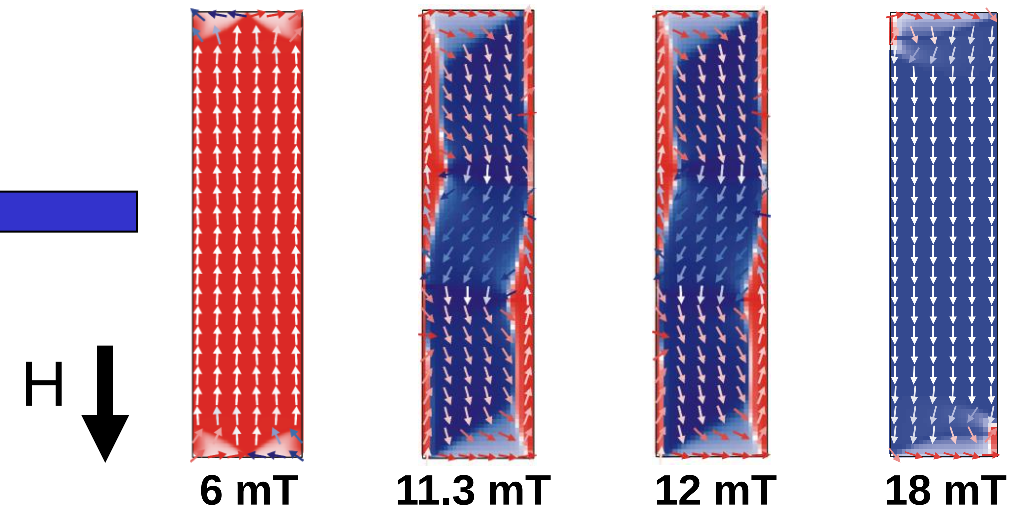
most sensitive to ↓ moments

strong spin flip scattering: magnetization mainly perpendicular to field

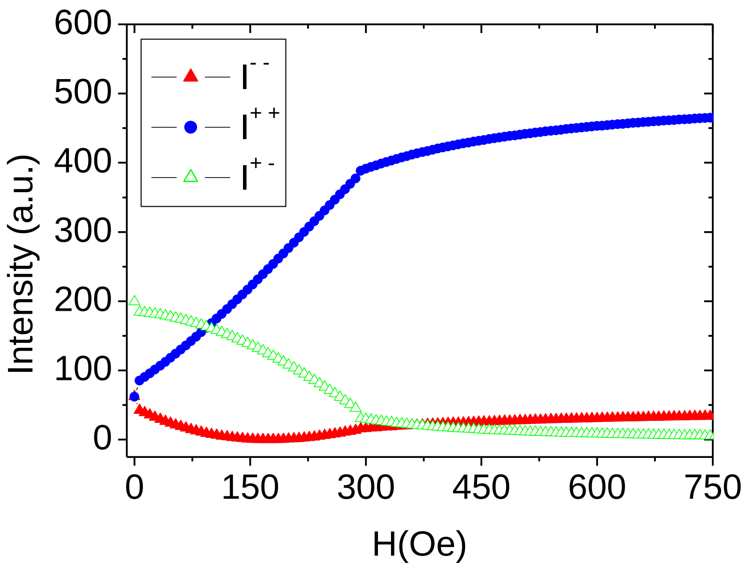
When field decreases, moments rotate back to easy direction

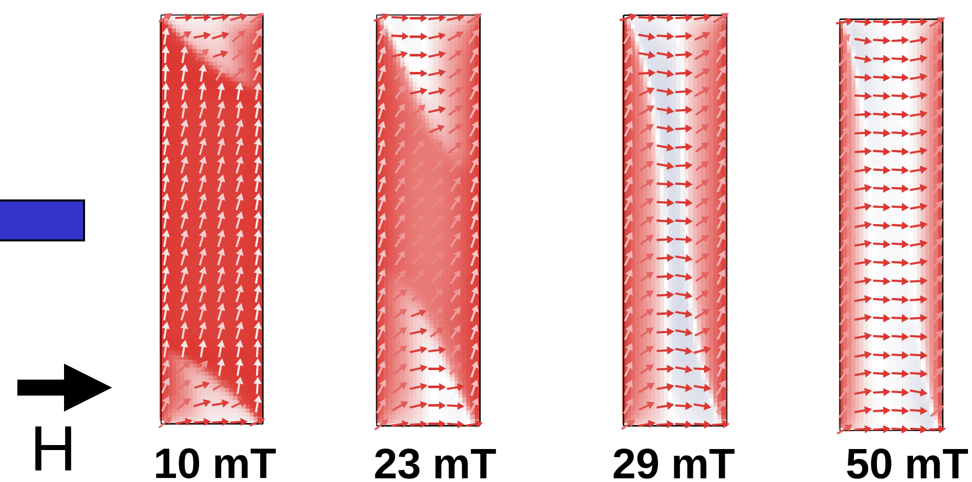
NON-SPECULAR REFLECTIVITY: simulation





OOMMF (NIST)

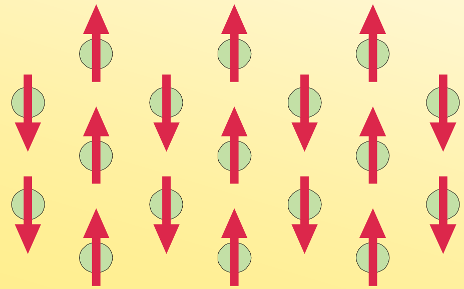




Good agreement with experiment

Conclusions

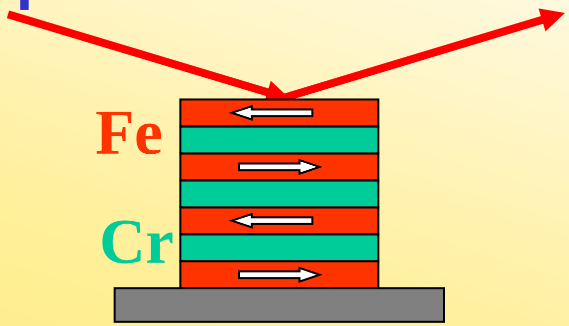
Neutron scattering



Introduction to neutrons

Neutrons vs. X-rays

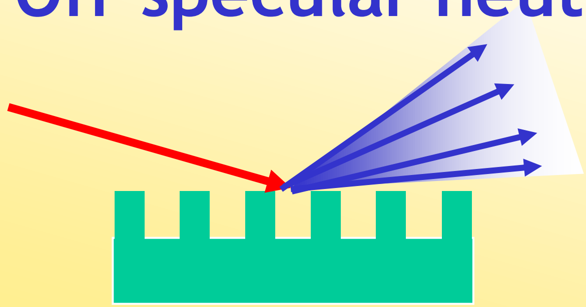
Specular reflectivity: Fe/Cr and Co/CoO



Antiferromagnetic ordering.

Asymmetric reversal

Off-specular neutron reflectivity



Selective information from dots.

Field dependence shows magnetization reversal.

Thank you !

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