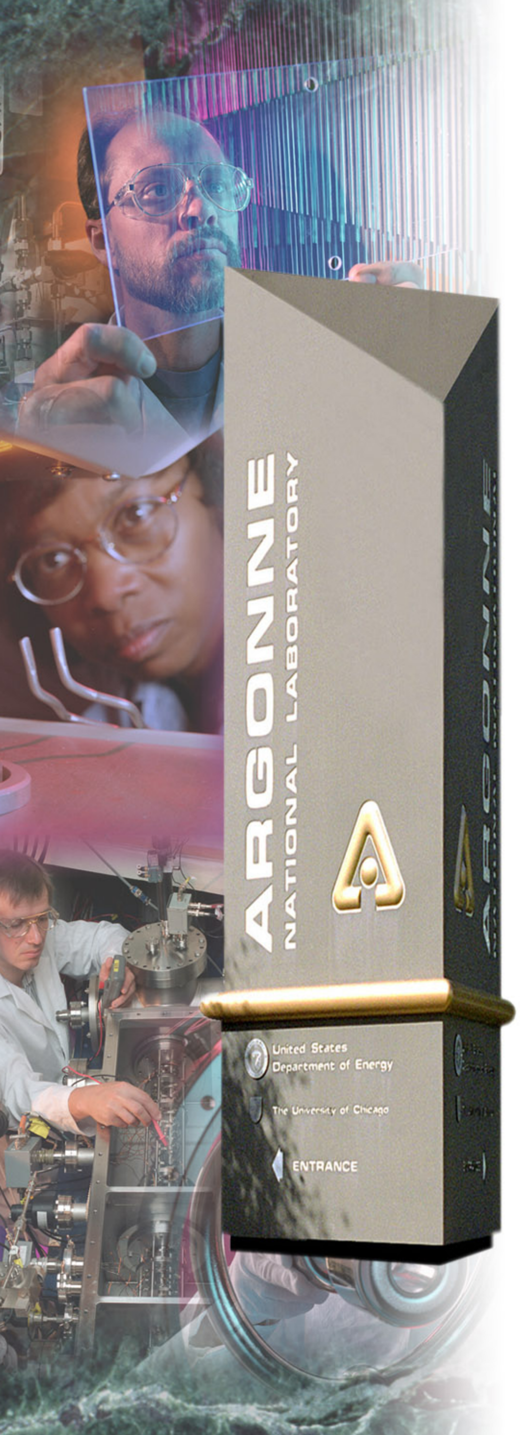
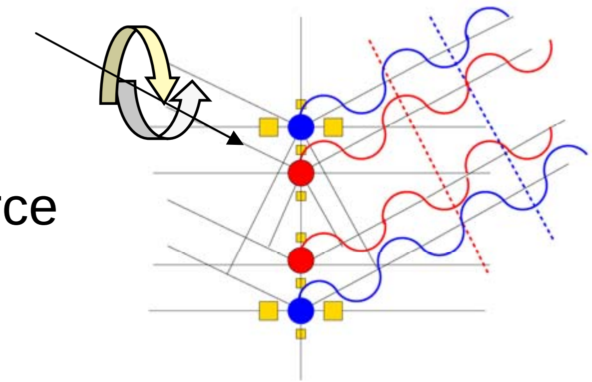


Insights into Permanent Magnets



Daniel Haskel
Advanced Photon Source

D. Haskel, J.C. Lang, Z. Islam, A. Cady, G. Srajer, M. van Veenendaal, P. C. Canfield, *Phys. Rev. Lett.* **95**, 217207 (2005).

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Argonne National Laboratory

Office of Science
U.S. Department of Energy

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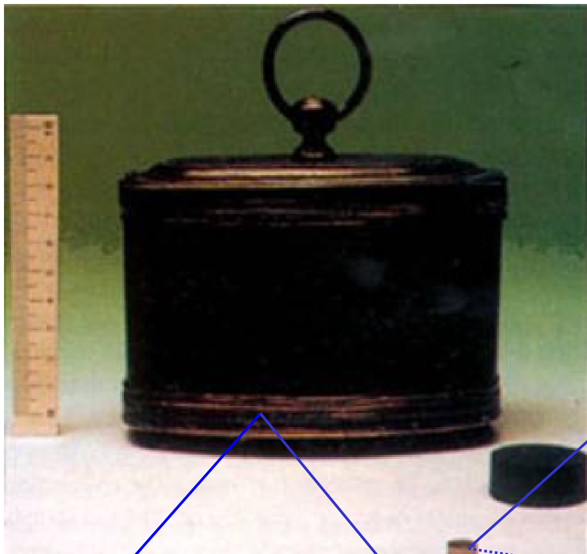
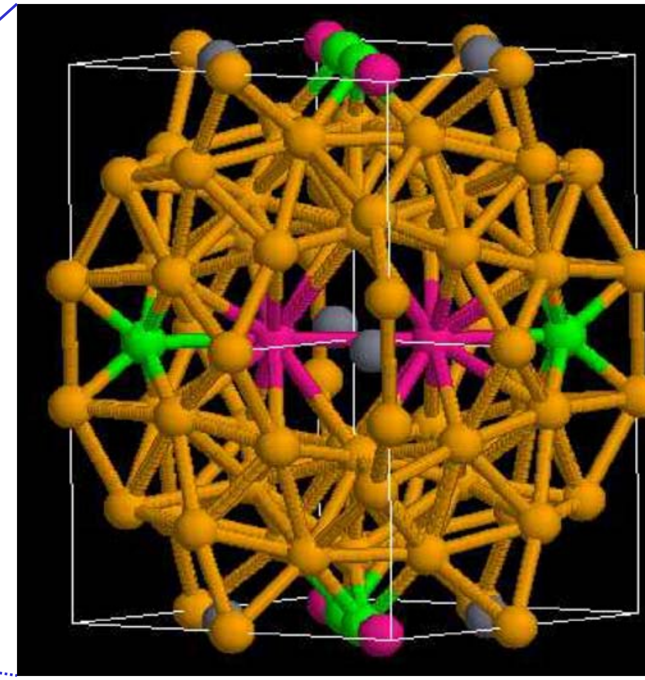
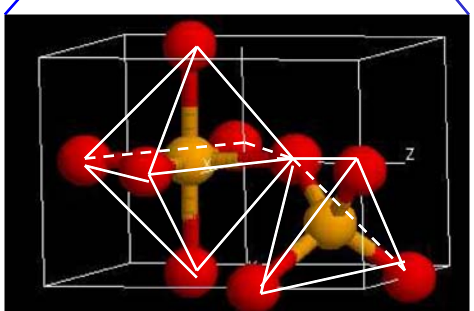
Operated by The University of Chicago

Permanent Magnets: Evolution brings complexity





$Nd_2Fe_{14}B$
(artificial)



Magnetite

O

Fe

24 Fe atoms

Fe Nd1 B
Nd2

64 magnetic atoms

2 magnetic elements (Fe, Nd)

6 Fe, 2 Nd crystal sites

Improved magnetic materials enable new technologies

ADVANCED PHOTON SOURCE
BEAM ACCELERATION & STORAGE SYSTEM

A. ELECTRON GUN

B. ELECTRON LINEAR ACCELERATOR
200 MeV-650 MeV

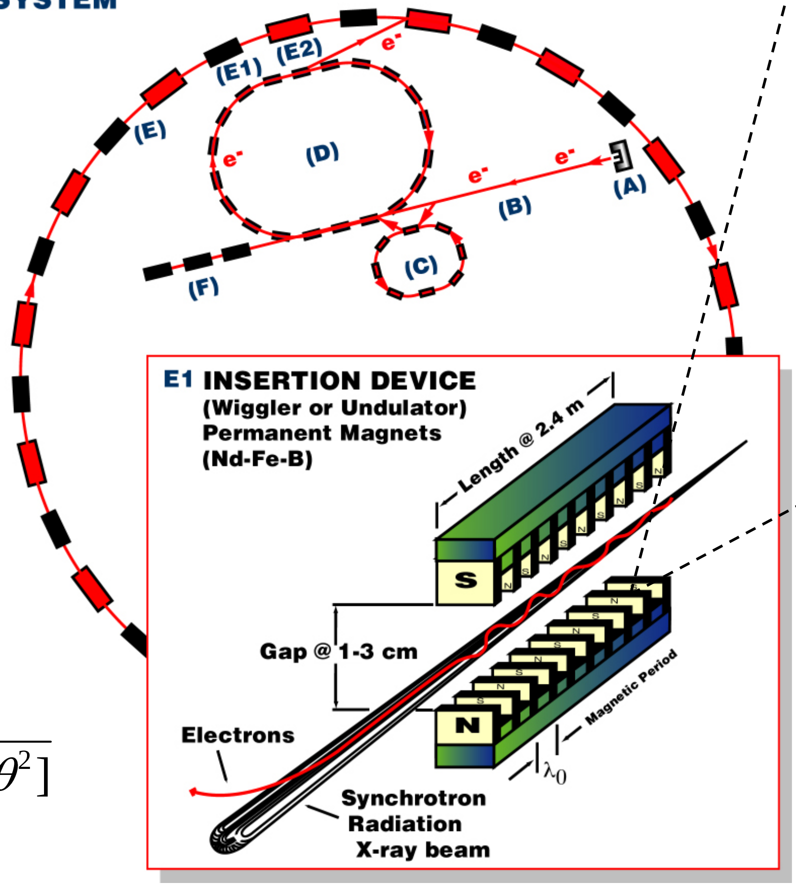
C. ACCUMULATOR RING

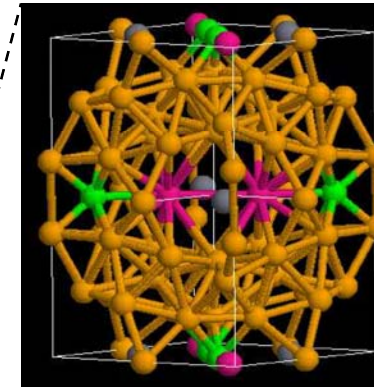
D. BOOSTER SYNCHROTRON
7 GeV

E. STORAGE RING
7 GeV nominal energy
E1 INSERTION DEVICE
E2 BENDING MAGNET

F. LOW-ENERGY UNDULATOR TEST LINE
400-650 MeV

NOTE: Diagrams not to scale





$$E_n[keV] = \frac{0.95E^2[GeV]n}{\lambda_u[cm][1+K^2/2+\gamma^2\theta^2]}$$

$$K = 0.934\lambda_u[cm]B_{eff}[T]$$

Period =3.3 cm
N=72
2.4 m long
Minimum gap: 8mm
Bmax=0.9 T
2.9-100 keV

Also: *Starter motors, brake systems, generators, seat adjusters, latches, etc.*

Modern magnets and the Rare-Earth role

Recipe for a good magnet:

- Large magnetization (pack high density of magnetic ions).
- Large coercivity (“magnetic hardness”, add rare-earth ions).

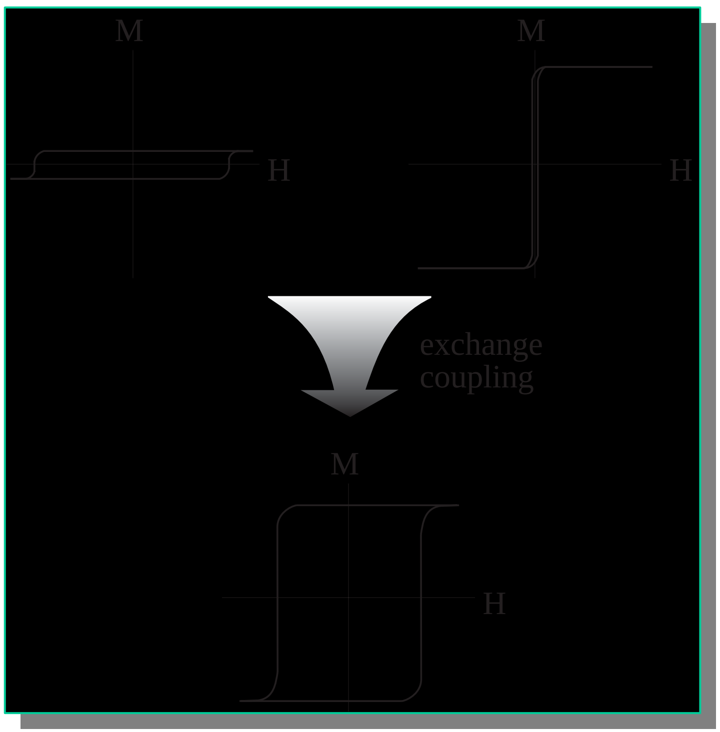
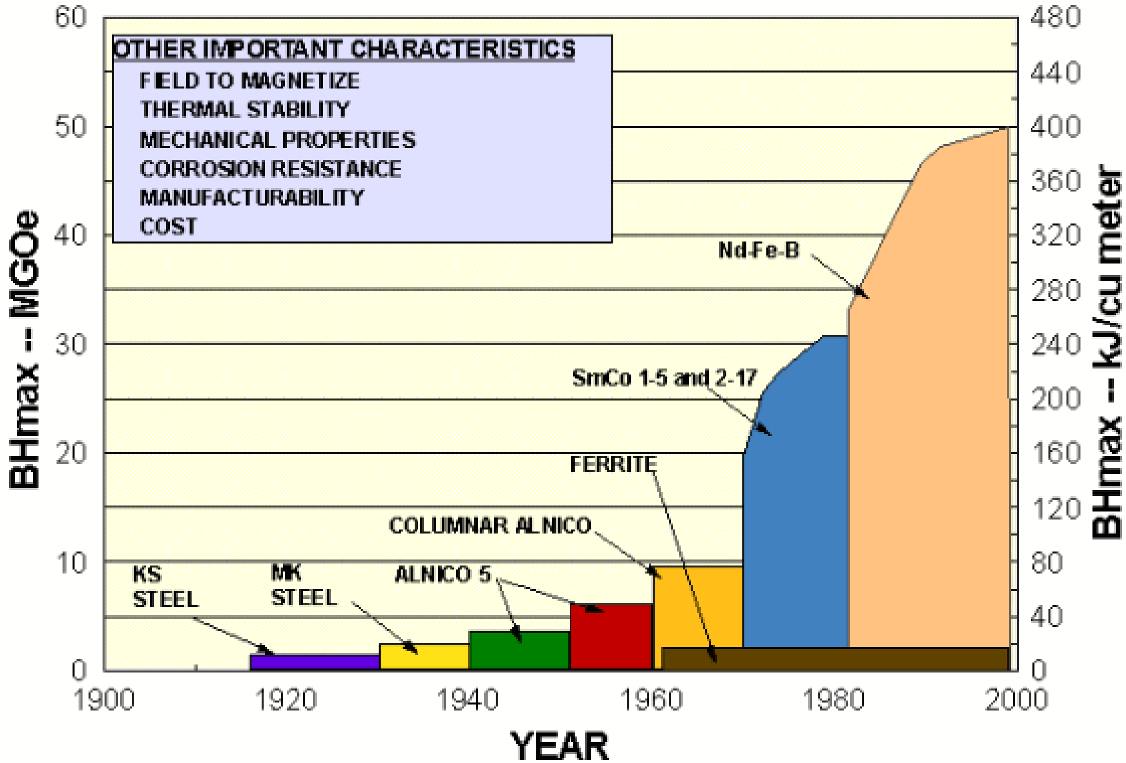
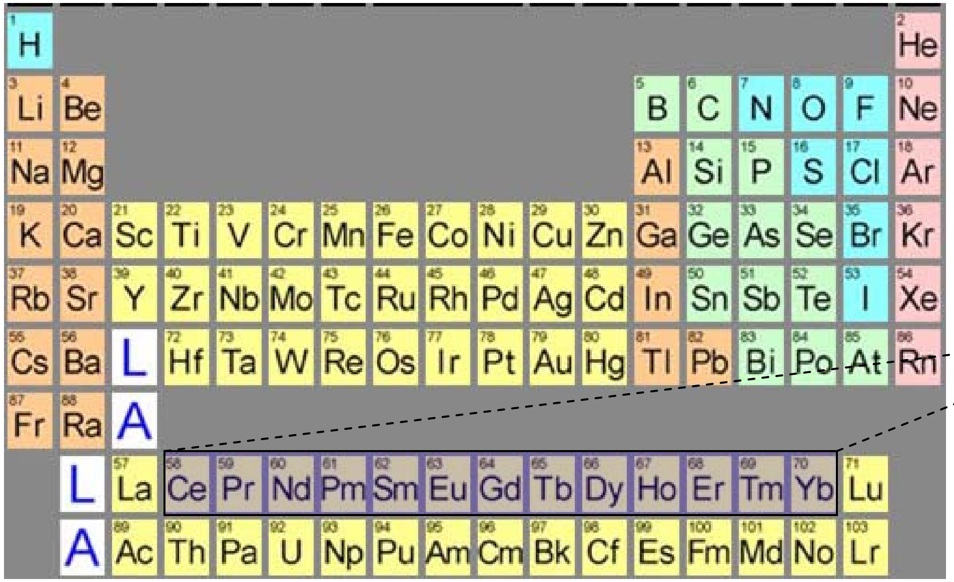


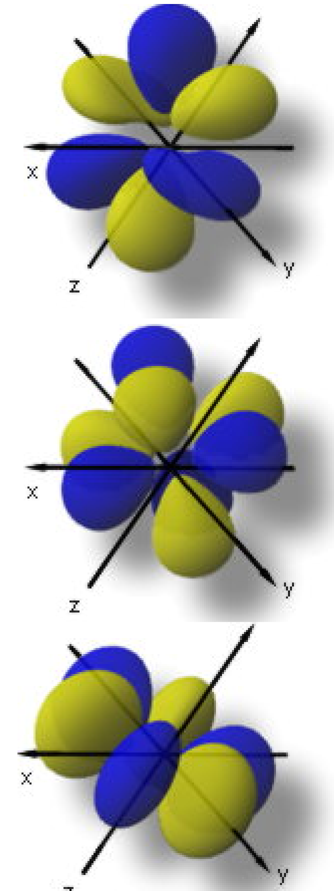
Figure I
Development of Permanent Magnets in the 1900’s

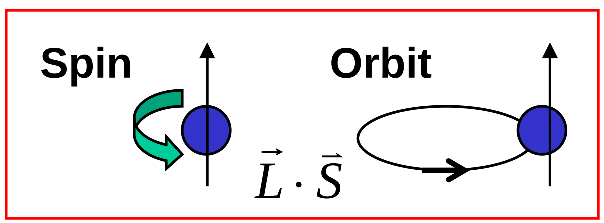


Modern magnets and the Rare-Earth role



Rare-Earths:
4f electrons



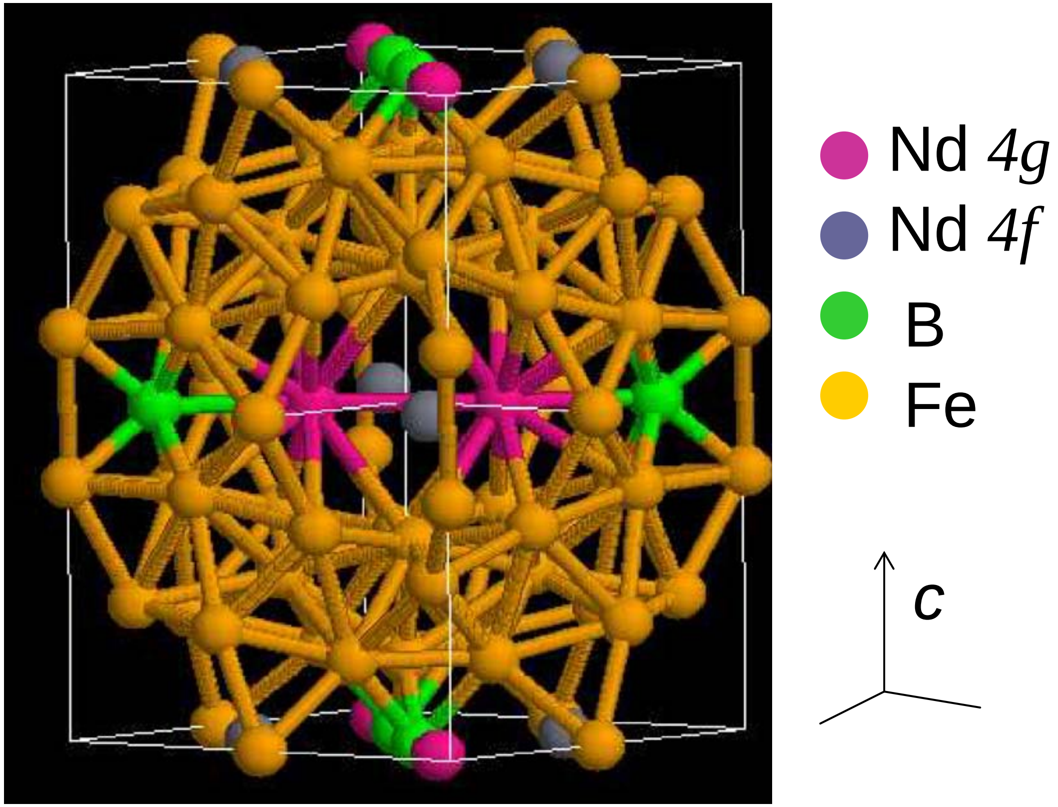


- *Aspherical* 4f orbitals interact with surrounding electrons (crystal field).
- *Spin-orbit coupling* + crystal field determine preferred spin orientation, “pinning” the magnetic moments.

$Nd_2Fe_{14}B$: Best in its class

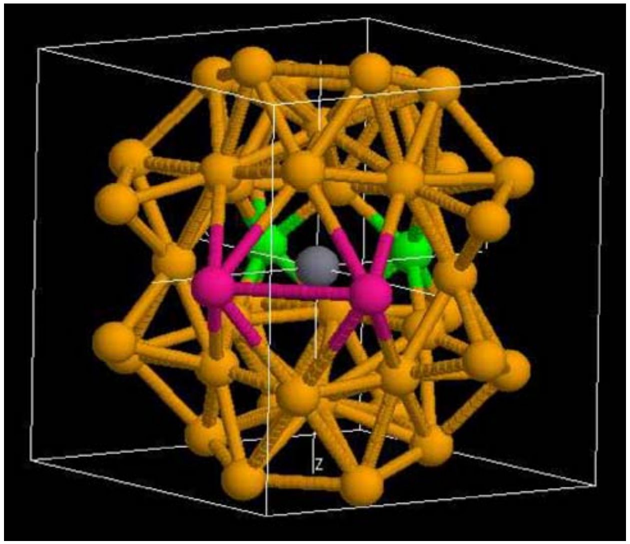
J.F.Herbst, *Reviews of Modern Physics* 63, 819 (1991)

- Tetragonal $P4_2/mnm$
  a=8.8Å, c=12.2Å
- 2 RE sites, 6 TM sites
  68 atoms/unit cell
- Fe: ~ 31 μ_B/f.u.
  Nd: ~ 6 μ_B/f.u.
- Ferromagnet: T_c ~ 585K

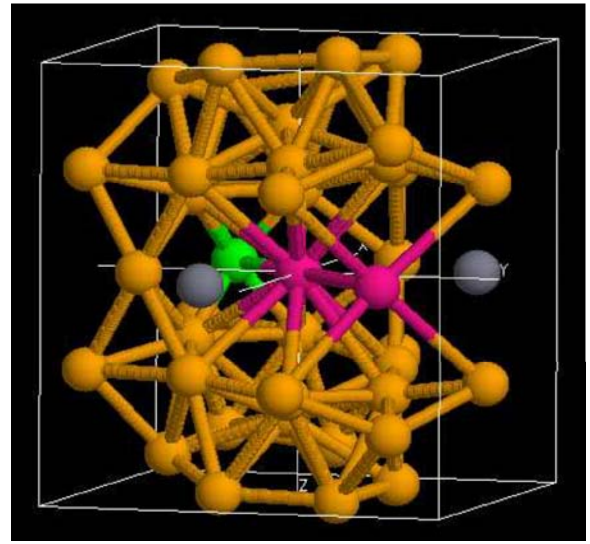


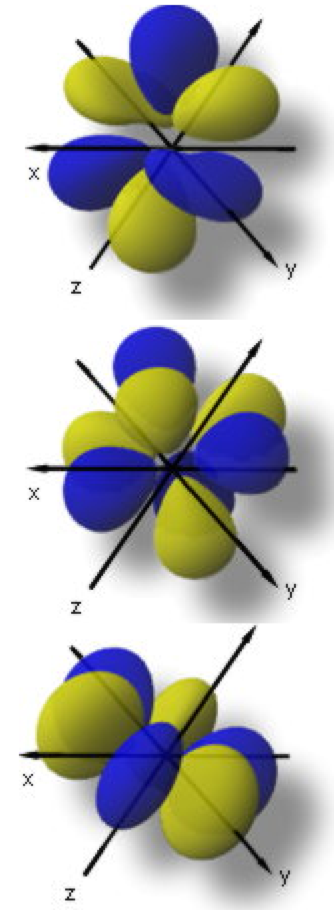
- Easy axis: [001] (c-axis) at room temperature.
- Magnetocrystalline anisotropy dominated by Nd RE ions.

The rare-earth role: $Nd_2Fe_{14}B$



Nd *g*
Nd *f*
B
Fe





Rare-earth Nd ions are simultaneously present in two different crystalline environments.
What are their roles?

Goal: To measure Nd site-specific magnetism.

Tool: Resonant diffraction and absorption of CP x-rays.

Diffraction: site selectivity.

Absorption: site-averaging.

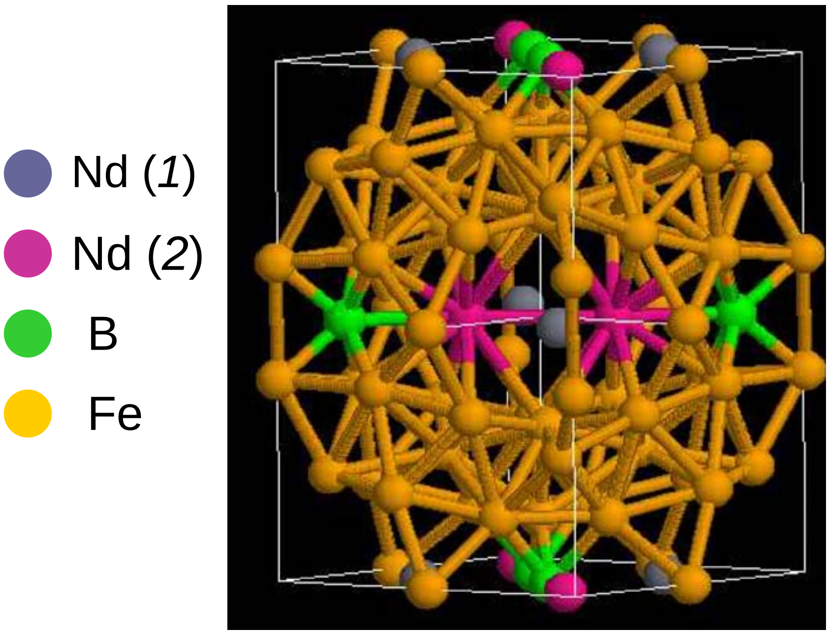
Atomic resonance: element specificity.

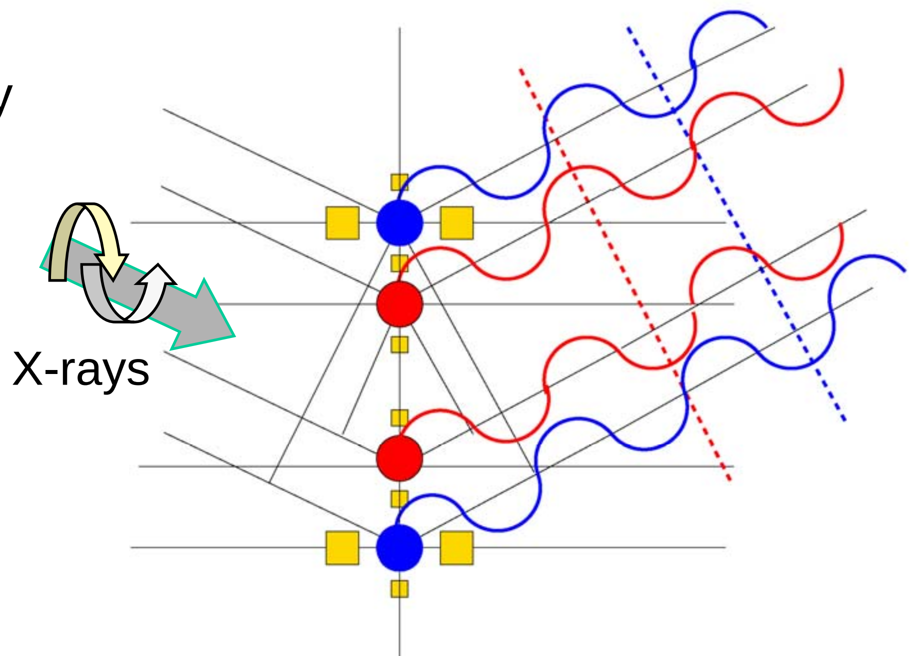
CP x-rays: coupling to magnetization.

Exploiting the crystal's symmetry for site separation

Diffraction = site selectivity
Atomic resonance = element specificity
CP x-rays = couple to magnetization

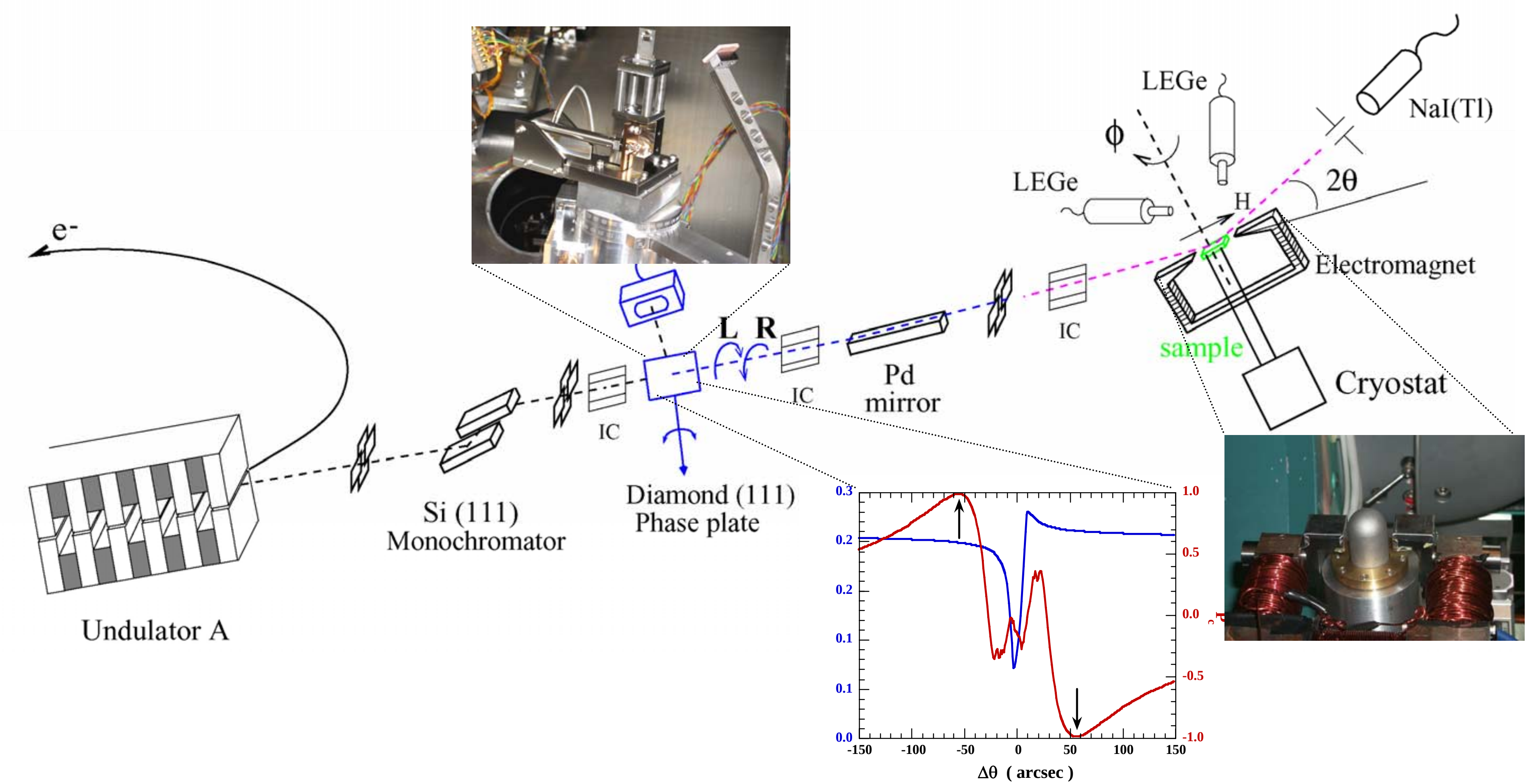
$Nd_2Fe_{14}B$





Site	(110)	(220)	(440)
Nd2 (*f*)	3%	96.4%	48.5%
Nd1 (*g*)	97%	3.6%	51.5%

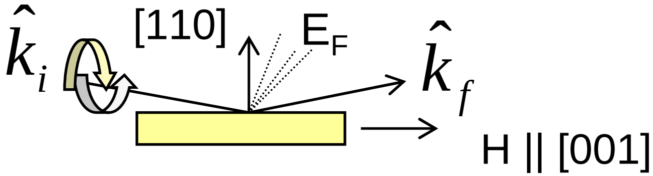
Experiment: Beamline 4-ID-D, Advanced Photon Source



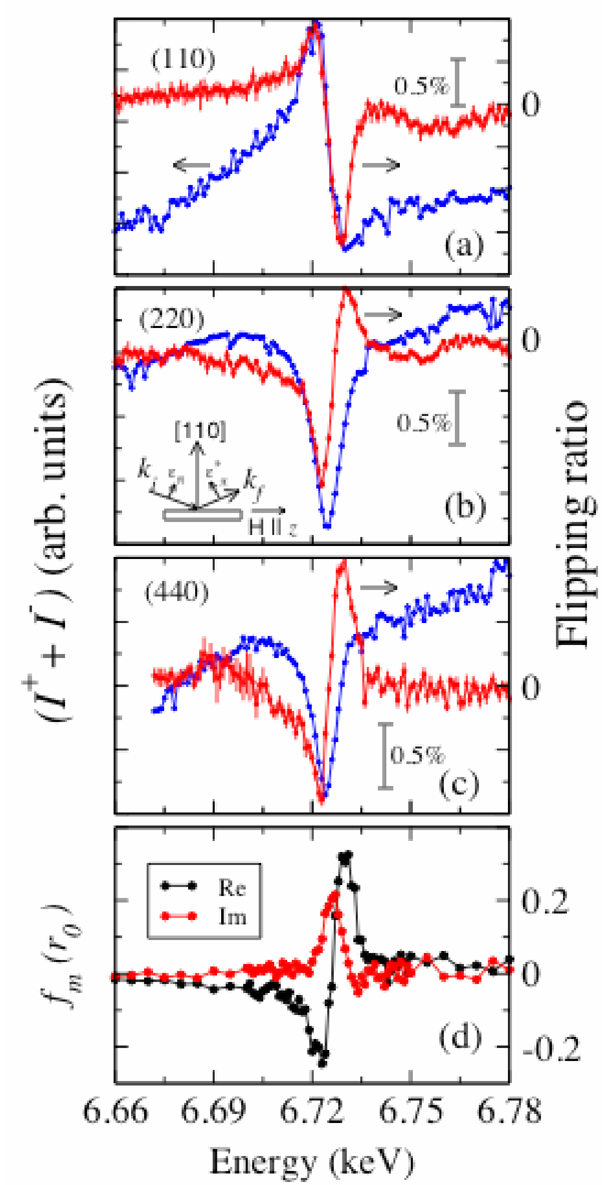
- Resonant diffraction (and absorption) at fix Q (scan ID gap; Monochromator, Phase plate, and sample angles with E. Flip helicity (many times) at each E point.

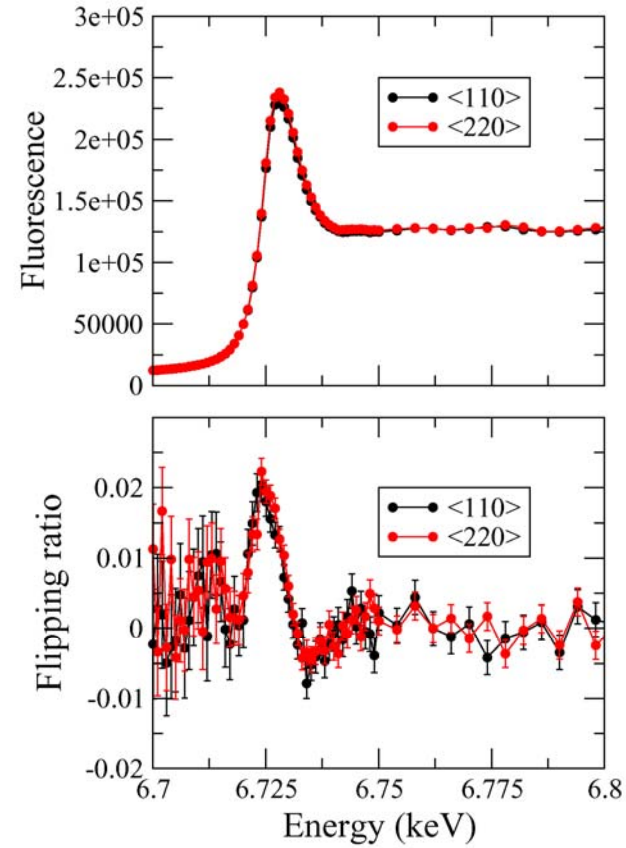
Diffraction: DANES and MDANES

Absorption: XANES and XMCD



Nd L_2 ($2p_{1/2}$)

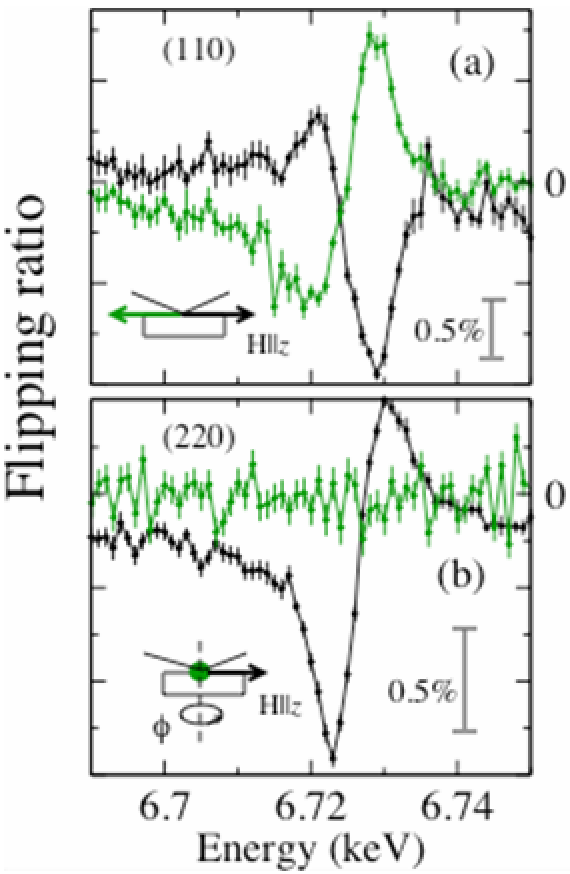




- (110) and (220) reflections probe element *and* site-specific magnetism.
- Absorption element specific but yields site-averaged magnetism.

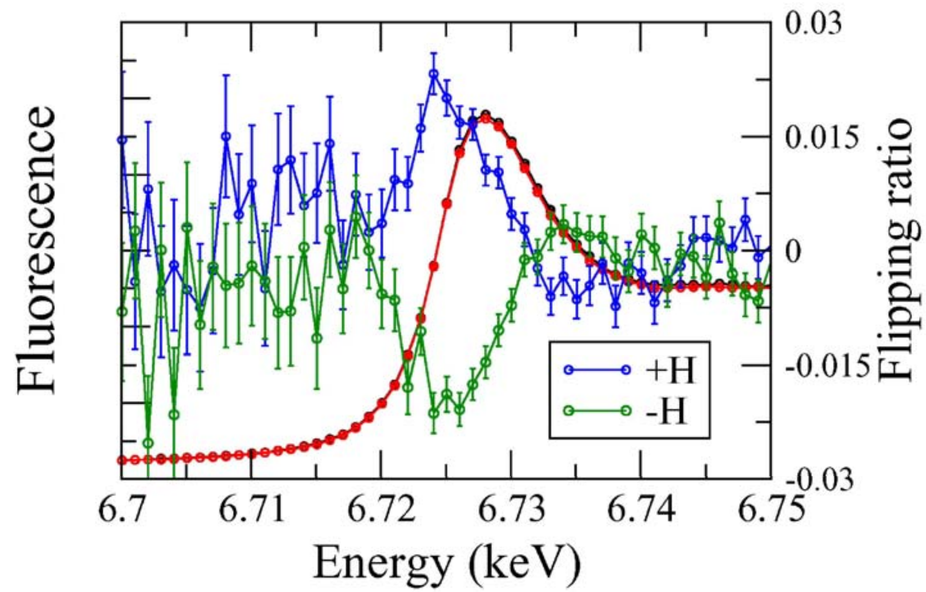
Orientation dependence of resonant magnetic scattering, absorption.

Diffraction



$$I_{cm} \propto [(\hat{k}_i \cdot \hat{m}) + (\hat{k}_f \cdot \hat{m})\cos 2\Theta]$$

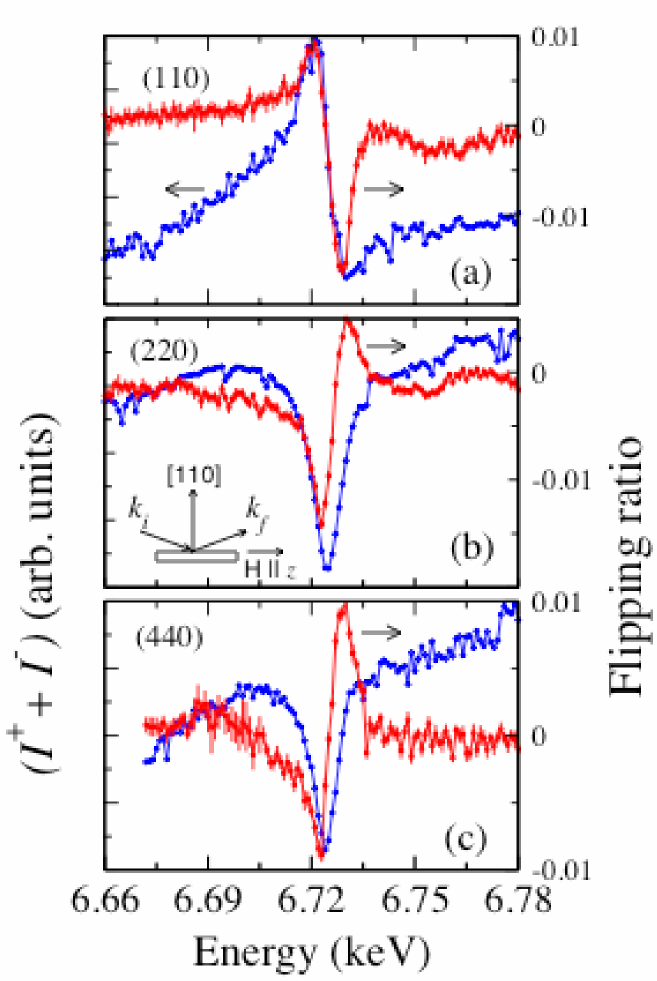
Absorption

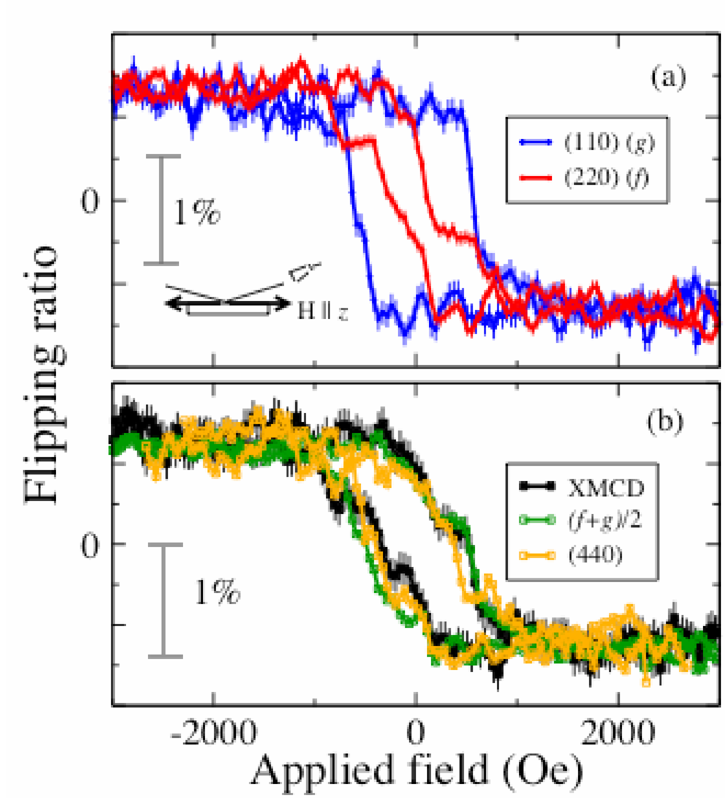


$$\mu_m \propto \hat{k} \cdot \vec{m}$$

- Exploit orientational dependence of diffraction and absorption to study magnetization reversal.

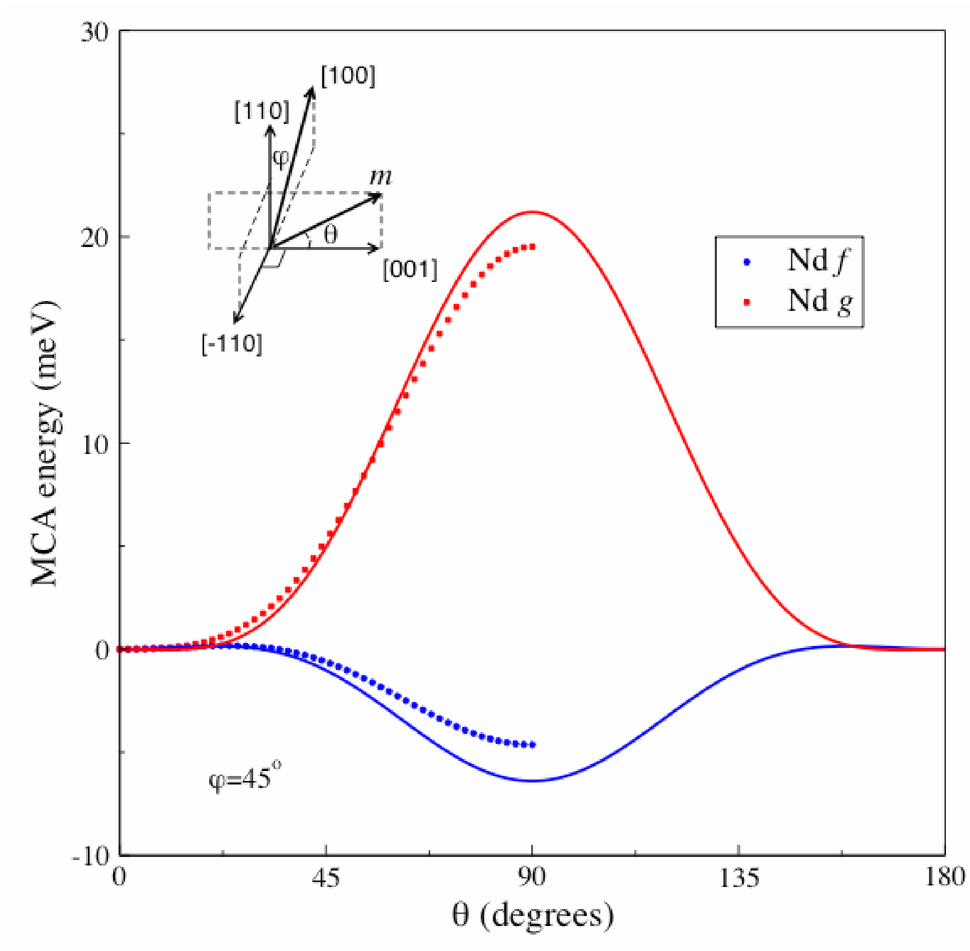
Nd magnetic moment reversal, site-by-site.

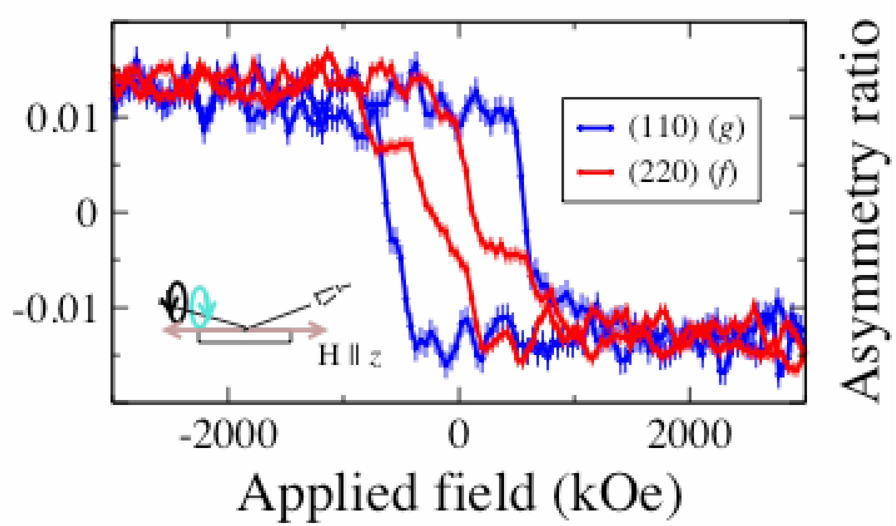




Site	(110)	(220)	(440)
Nd *f*	3%	96.4%	48.5%
Nd *g*	97%	3.6%	51.5%

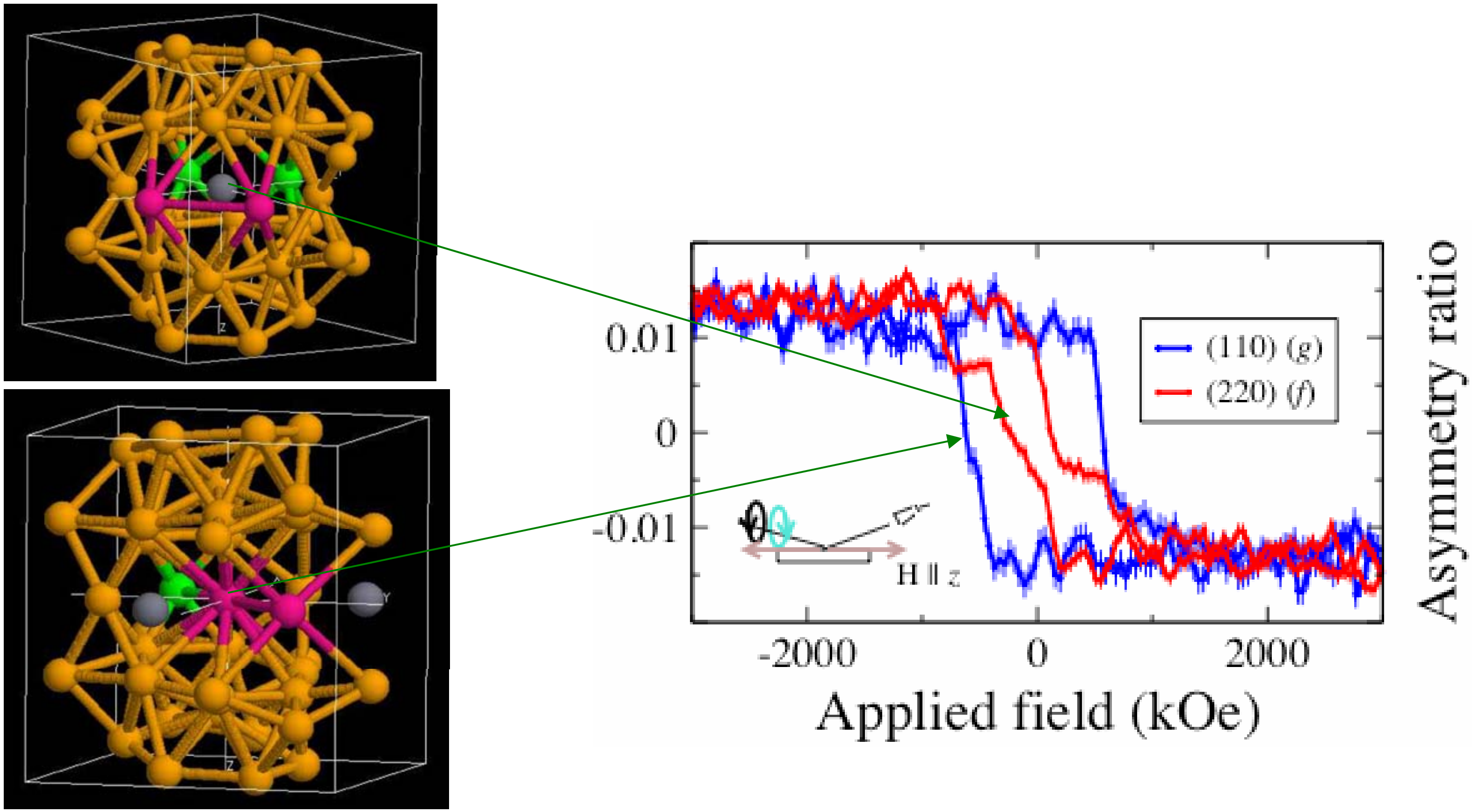
Theoretical calculations





M. Van Veenendaal (NIU, ANL), CEF parameters M. Yamada et al (1988).

Manipulate magnetic hardness by atomic engineering



- Only one Nd site responsible for magnetic hardness.
- Replace “faulty” ions with other RE ions, or even Gd (isotropic).

Acknowledgments

Samples

P. Canfield (Iowa State U./AMES)

Theory

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Polarization Studies Group (APS)

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Z. Islam

A. Cady

G. Srajer

Digital lock-in

Boris Deriy (ASD)

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