Magnetic Anisotropy:

origin, intuitive models, examples

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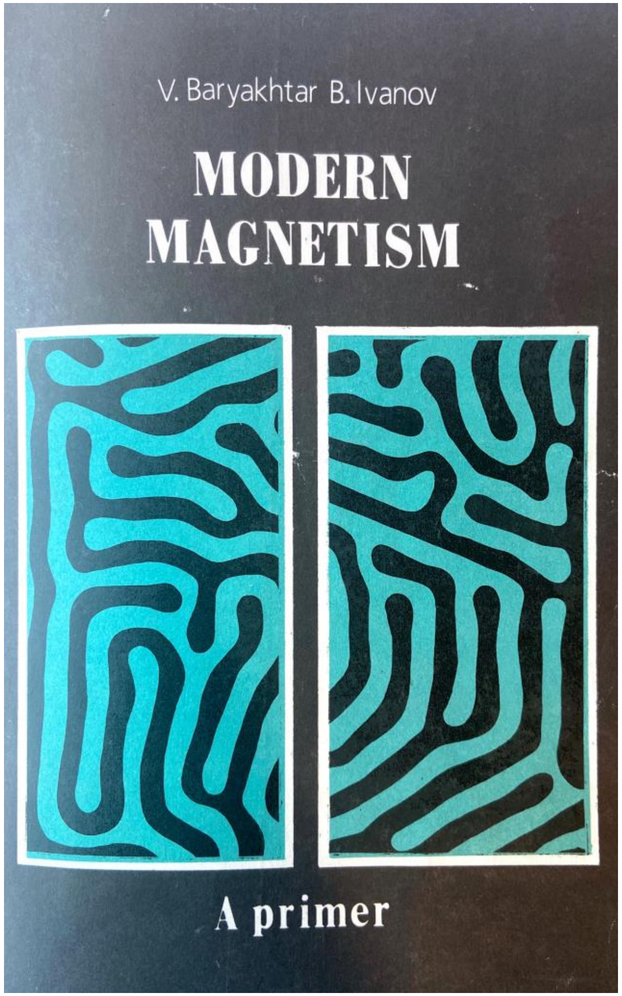
https://www.ru.nl/science/uscm/

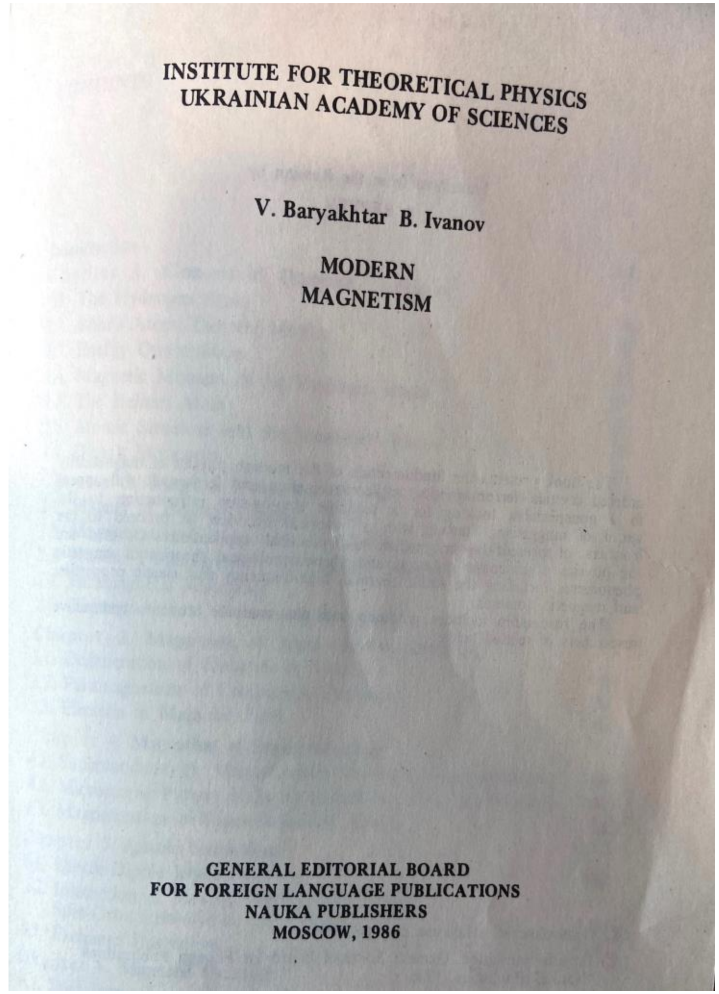
Questions to kick-off the lecture

- What are examples of anisotropy in physics?
- How does anisotropy show up in magnetism?
- Is anisotropy an important property of magnets?
- Where does magnetic anisotropy come from?
- How to control magnetic anisotropy?

Magnetic anisotropy

- How to describe it?
- Where does it come from?
- How to measure it?
- How to control it?





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MAGNETISM

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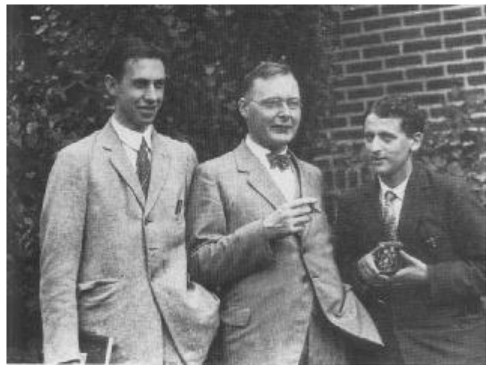
Magnetism –
quantum mechanical phenomenon

$S_z = \pm\hbar/2$

R. Kronig



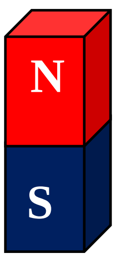
G. Uhlenbeck S. Goudsmit

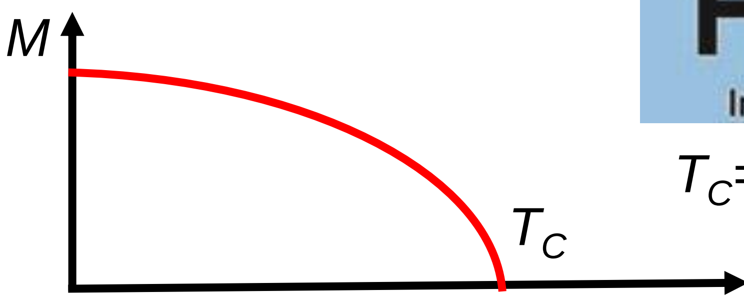
W. Pauli

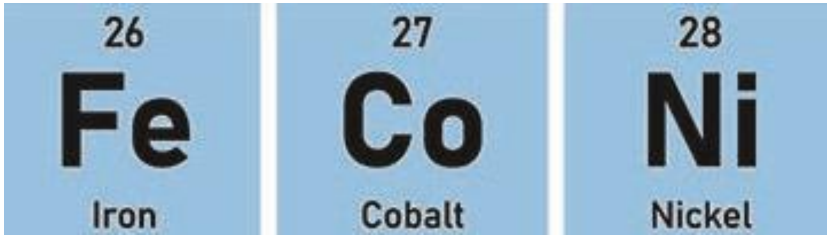
Spin
(1922-1925)

“clever, but nothing to do with reality”…
“two-valuedness not describable classically"

Ferromagnet





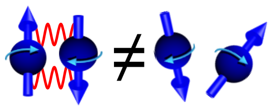


T_C= 1043 K 1390 K 629 K

Magnetism –
the strongest quantum mechanical phenomenon

$\mathbf{S_z = \pm\hbar/2}$

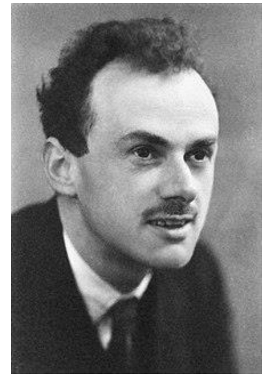
Spin
(1925)



$E_{ex}=-J\mathbf{S}_i\mathbf{S}_j$

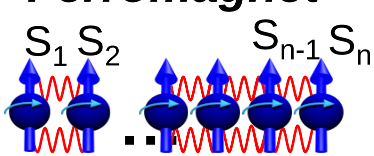
Exchange interaction
(1926)

W. Heisenberg



P. Dirac

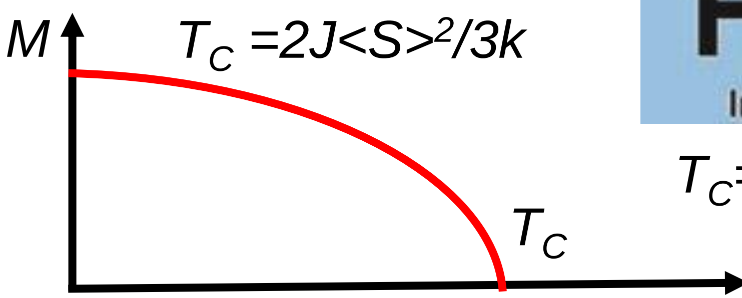
Ferromagnet



$$\mathbf{M} = -\gamma \frac{\sum s_i}{V}$$

Weiss-Heisenberg model

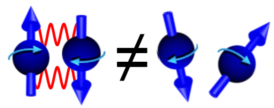
$T_C = 2J\langle S\rangle^2/3k$



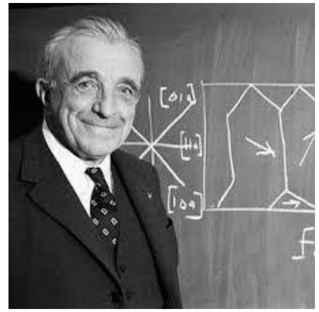
26 Fe Iron	27 Co Cobalt	28 Ni Nickel
T_C = 1043 K	1390 K	629 K

Magnetism –
the strongest quantum mechanical phenomenon

$S_z = \pm\hbar/2$



$E_{ex}=-J\mathbf{S}_i\mathbf{S}_j$



L. Néel

Spin (1925)

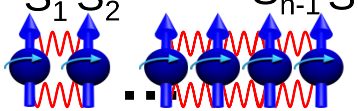
Exchange interaction (1926)

Antiferromagnetism (1930)

Ferrimagnetism (1948)

Ferromagnet (J>0)

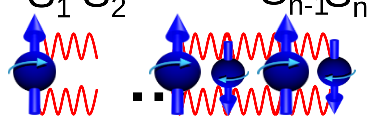
S_1 S_2 S_{n-1} S_n



$$\mathbf{M} = -\gamma\frac{\sum S_i}{V} \neq 0$$

Ferrimagnet (J<0)

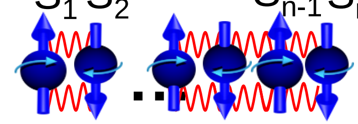
S_1 S_2 S_{n-1} S_n



$$\mathbf{M} \neq 0$$

Antiferromagnet (J<0)

S_1 S_2 S_{n-1} S_n



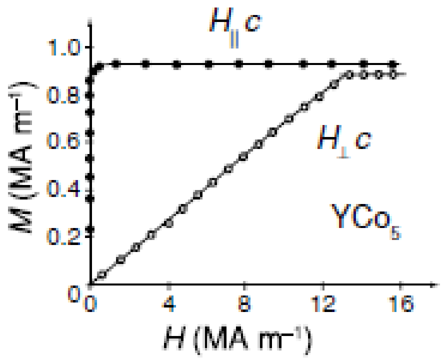
$$\mathbf{M} = 0$$

Theory

- Exchange interaction does not depend on direction of spins.
- There is no preferred direction for spins in magnets.

The simplest theoretical models describe isotropic magnets.

Experiment

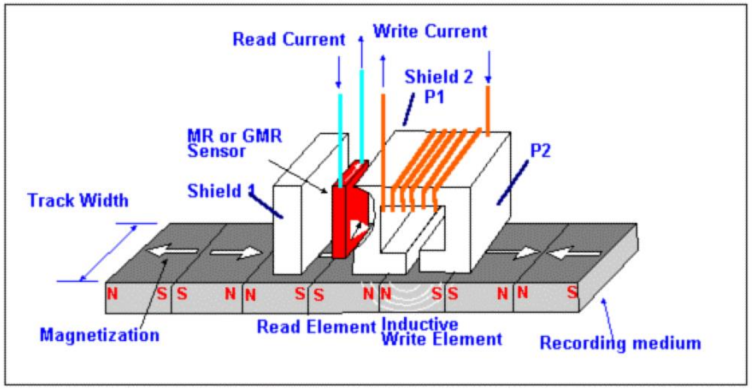


Taken from J. D. M. Coey, *Magnetism and magnetic Materials,* (Cambridge University Press 2009).

- Magnetic properties depend on the direction of external magnetic field (or stimulus of other kind).
- Spins in a magnet do have a preferred direction.

Strong magnetic anisotropy is often the main requirement for application of magnets.

Magnets in today's technology



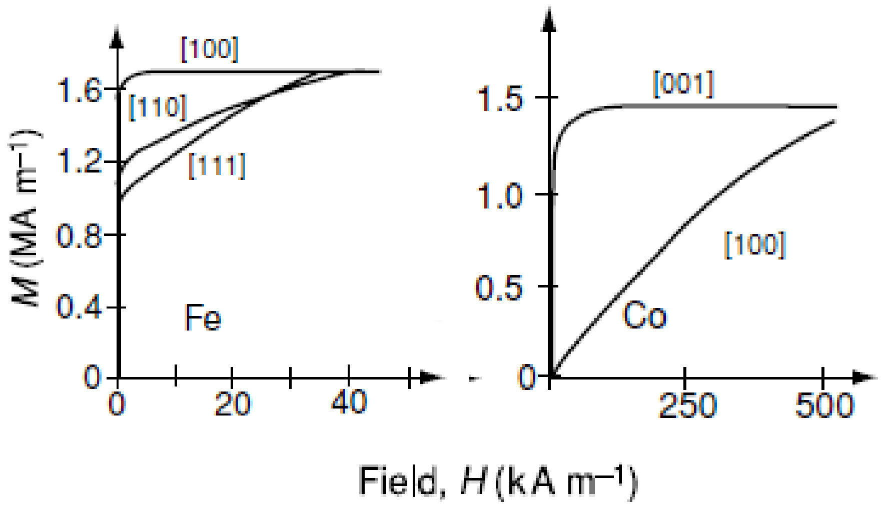
picture: IBM Research - Almaden

Composite head: inductive write, MR read

Magnetic anisotropy

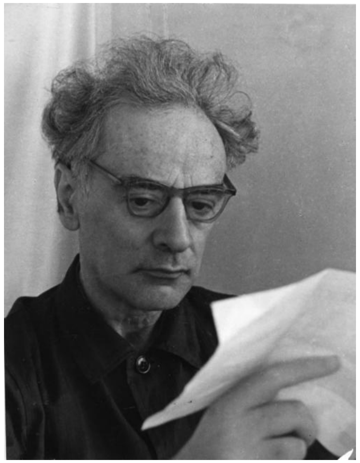
- **How to describe it?**
- **Where does it come from?**
- **How to measure it?**
- **How to control it?**

Description of magnetic anisotropy



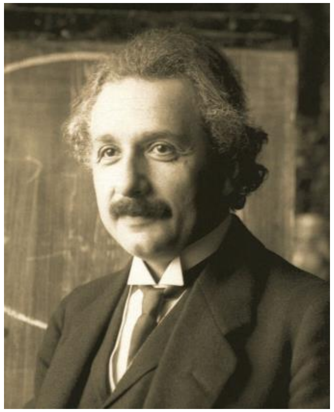
Easy magnetization axis or just “easy axis”
Fe - [001] direction (as well as [010] and [100])
Co – [001] direction

Taken from J. D. M. Coey, *Magnetism and magnetic Materials,* (Cambridge University Press 2009).



L. D. Landau
(*1908-1968*)

“ Physicist seeks to make complicated things simple, while a poet seeks to make simple things complicated.”



A. Einstein
(*1879-1955*)

Thermodynamics “is the only physical theory of universal content, which I am convinced, that within the framework of applicability of its basic concepts will never be overthrown.”

Macrospin approximation: *intuitive (classical) view of quantum (counter-intuitive) phenomenon*

$$\left.\begin{aligned} dU &= dW + dQ \\ dW &= \mu_0 \mathbf{H} d\mathbf{M} \\ dQ &\leq TdS \end{aligned}\right\}$$

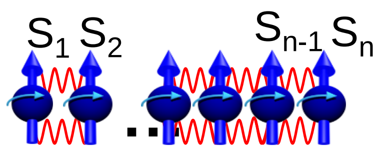
$$dU \leq \mu_0 \mathbf{H} d\mathbf{M} + TdS$$

$$\boxed{dU \leq 0}$$

U - internal energy
W - work
Q - heat
σ - entropy

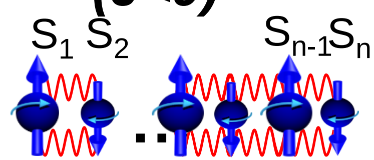
$$\mathbf{M} = -\gamma \frac{\sum S_i}{V} \neq 0$$

Ferromagnet (J>0)



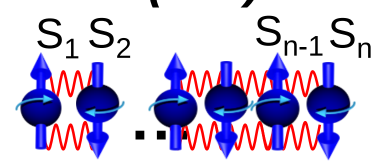
$$\mathbf{M} = -\gamma \frac{\sum S_i}{V} \neq 0$$

Ferrimagnet (J<0)



$$\mathbf{L} = -\gamma \frac{\sum(\mathbf{S}\uparrow - \mathbf{S}\downarrow)}{V}$$

Antiferromagnet (J<0)



Thermodynamic approach to magnetism

$$dU = dW + dQ$$

$$dW = \mu_0 \mathbf{H} d\mathbf{M}$$

$$dQ \leq TdS$$

$$dU \leq \mu_0 \mathbf{H} d\mathbf{M} + TdS$$

$$dU \leq 0$$

Two variables in our experiments are T and H.

We need to design a function Φ, which is being a function of T and H is also at minimum, if the magnet is at thermodynamic equilibrium.

$$\Phi = U - TS - \mu_0 \mathbf{H}\mathbf{M}$$

$$d\Phi = dU - TdS - SdT - \mu_0 \mathbf{H} d\mathbf{M} - \mu_0 \mathbf{M} dH \leq SdT - \mu_0 \mathbf{M} dH$$

For fixed T and H one finds $d\Phi \leq 0$.

If a system is on its own at fixed H and T, function Φ can only decrease or stay constant. Hence, at thermodynamic equilibrium Φ is at minimum.

$$\Phi = \Phi_0(M, 0) - \mu_0 \mathbf{H}\mathbf{M}$$

How to introduce magnetic anisotropy?

$$\Phi = \Phi_0(M,0) - \mu_0 \mathbf{HM} + U_{ani}$$

$$\mathbf{m} = \frac{\mathbf{M}}{|\mathbf{M}|}$$

$$m_x^2 + m_y^2 + m_z^2 = 1$$

Taylor series

$$U_{ani} = \sum_{ijk\ldots l} K_i m_i + K_{ij} m_i m_j + K_{ijk} m_i m_j m_k + \cdots + K_{ijk\ldots l} m_i m_j\, m_k \ldots m_l$$

How to introduce magnetic anisotropy?

$$\Phi = \Phi_0(M,0) - \mu_0 \mathbf{HM} + U_{ani}$$

$$\mathbf{m} = \frac{\mathbf{M}}{|\mathbf{M}|} \qquad m_x^2 + m_y^2 + m_z^2 = 1$$

Taylor series

$$U_{ani} = \sum_{ijk\ldots l} \cancel{K_i m_i} + K_{ij} m_i m_j + \cancel{K_{ijk} m_i m_j m_k} + \cdots + K_{ijk\ldots l} m_i m_j m_k \ldots m_l$$

All odd terns have no physical sense, as the energy of magnetic anisotropy must be invariant with respect to time reversal.

How to introduce magnetic anisotropy?

$$\Phi = \Phi_0(M, 0) - \mu_0 \mathbf{HM} + U_{ani}$$

$$\mathbf{m} = \frac{\mathbf{M}}{|\mathbf{M}|} \qquad m_x^2 + m_y^2 + m_z^2 = 1$$

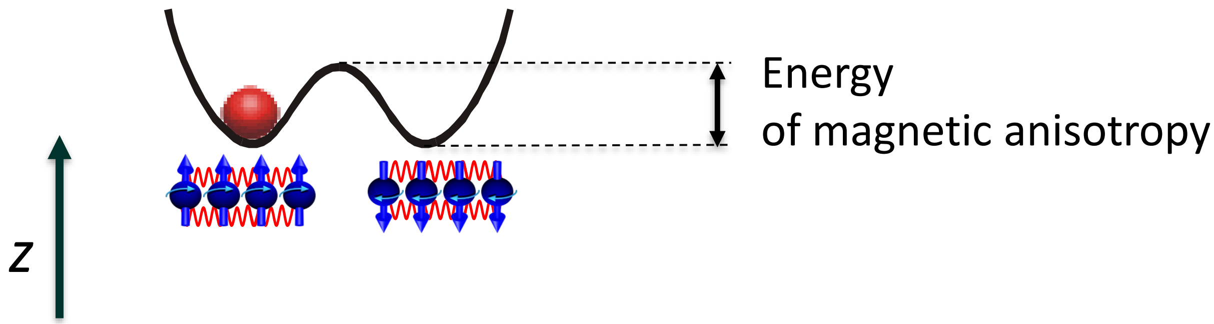
$$U_{ani} = \sum_{ijk\ldots l} K_i m_i + K_{ij} m_i m_j + K_{ijk} m_i m_j m_k + \cdots + K_{ijk\ldots l} m_i m_j\, m_k \ldots m_l$$

Uniaxial magnetic anisotropy, where the z-axis is a special one

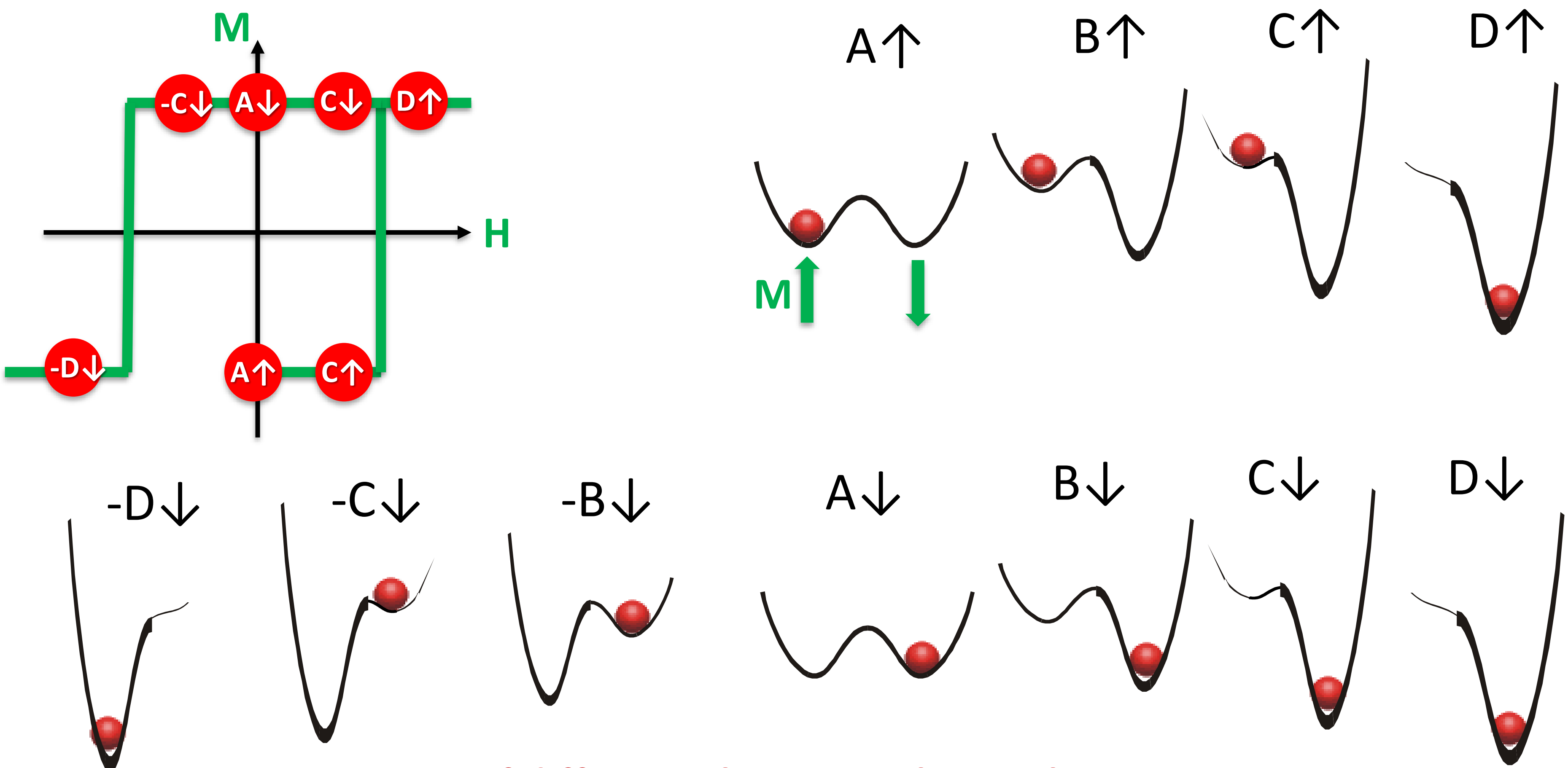
$$U_{ani} = K(m_x^2 + m_y^2)$$

$K > 0$ anisotropy of “easy-axis” type

$K < 0$ anisotropy of “easy-plane” type



Magnetic anisotropy and field hysteresis



Coexistence of different phases results in a hysteresis with the width defined by the barrier.

How to introduce magnetic anisotropy?

$$\Phi = \Phi_0(M, 0) - \mu_0 \mathbf{HM} + U_{ani}$$

$$\mathbf{m} = \frac{\mathbf{M}}{|\mathbf{M}|} \qquad m_x^2 + m_y^2 + m_z^2 = 1$$

Uniaxial magnetic anisotropy, where the z-axis is a special one

$$U_{ani} = K(m_x^2 + m_y^2)$$

$K > 0$ anisotropy of "easy-axis" type
$K < 0$ anisotropy of "easy-plane" type

If the second order terms are not sufficient to describe the magnetic anisotropy, one should take terms of the next i.e. fourth order. All the included terms must be invariant under all symmetry operation allowed by the crystal.

Cubic magnetic anisotropy

$$U_{ani} = -K(m_x^4 + m_y^4 + m_z^4)$$

Magnetic anisotropy

- How to describe it?
- **Where does it come from?**
- How to measure it?
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Magnetic anisotropy

- How to describe it?
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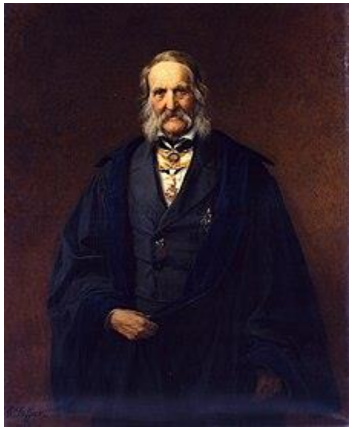
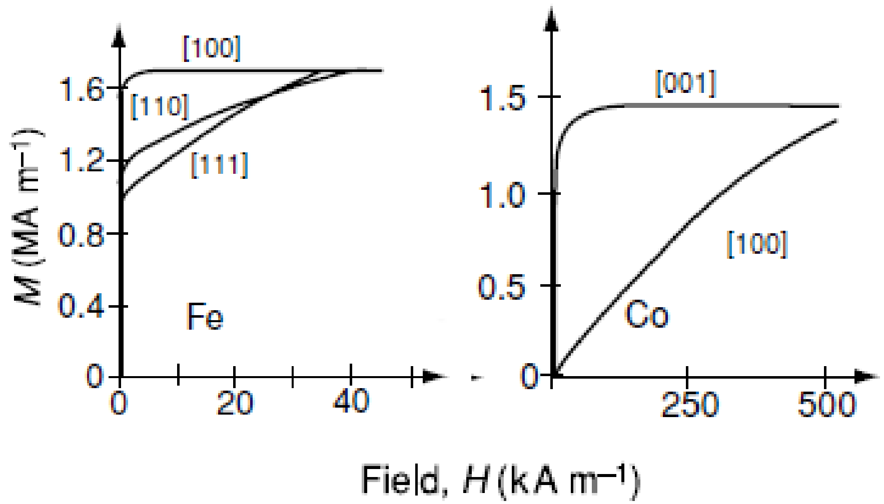
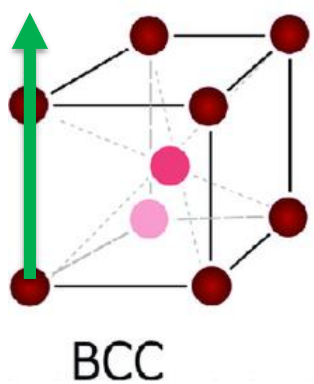


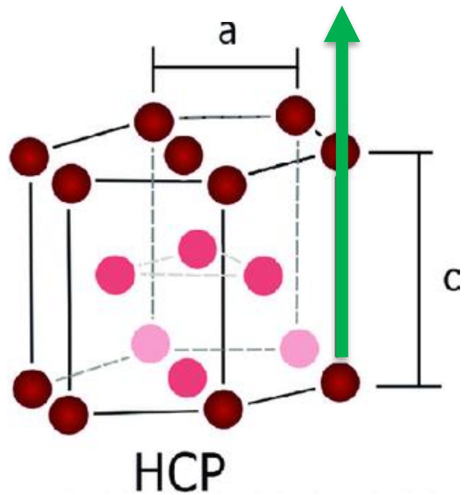
F. Neumann
(*1798-1895*)

"the symmetry elements of any physical property of a crystal must include the symmetry elements of the point group of the crystal'."

Magnetic anisotropy and crystal structure







Why does magnetization feel the crystal structure?

Anisotropy of dipole-dipole interaction

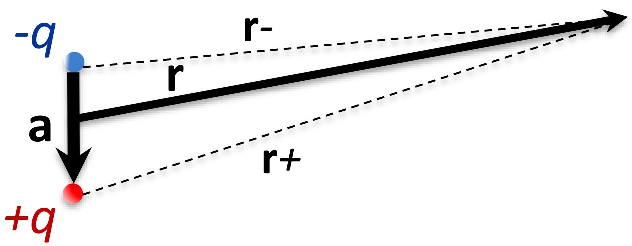
Consider dipole-dipole interaction of two magnetic dipoles (classical spins).

$\mathbf{m}_1$ $\mathbf{m}_2$

What is the energy of their interaction?

Intermezzo:

Interaction of electric dipoles



Dipole moment

$$\boxed{\mathbf{p} = q\mathbf{a}}$$

Electric field created by the dipole at $\mathbf{r}$

$$\mathbf{E} = \frac{1}{4\pi\varepsilon_0}\left[\frac{q\mathbf{r}_+}{(r_+)^3} - \frac{q\mathbf{r}_-}{(r_-)^3}\right]$$

$$\mathbf{r}_- = \mathbf{r} + \frac{1}{2}\mathbf{a} \qquad \mathbf{r}_+ = \mathbf{r} - \frac{1}{2}\mathbf{a}$$

Since $|\mathbf{r}| \gg |\mathbf{a}|$

$$r_-^2 = \left(\mathbf{r} + \frac{1}{2}\mathbf{a}\right)^2 \approx r^2 + \mathbf{ra} = r^2\left(1 + \frac{\mathbf{ra}}{r^2}\right)$$

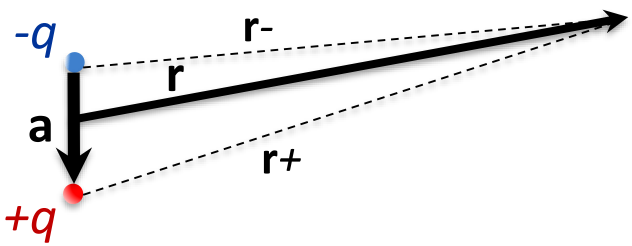
Since $(1+x)^n \approx 1 + nx$ for $x \ll 1$

$$(r_-)^{-3} = \left(r_-^2\right)^{-3/2} \approx r^{-3}\left(1 - \frac{3}{2}\frac{\mathbf{ra}}{r^2}\right)$$

Similarly

$$(r_+)^{-3} = \left(r_+^2\right)^{-3/2} \approx r^{-3}\left(1 + \frac{3}{2}\frac{\mathbf{ra}}{r^2}\right)$$

Intermezzo:
Interaction of electric dipoles



Dipole moment

$$\boxed{\mathbf{p} = q\mathbf{a}}$$

Electric field created by the dipole at $\mathbf{r}$

$$\mathbf{E} = \frac{1}{4\pi\varepsilon_0}\left[\frac{q\mathbf{r}_+}{(r_+)^3} - \frac{q\mathbf{r}_-}{(r_-)^3}\right] =$$

$$= \frac{1}{4\pi\varepsilon_0}\frac{q}{r^3}\left[\left(\mathbf{r} - \frac{1}{2}\mathbf{a}\right)\left(1 + \frac{3}{2}\frac{\mathbf{ra}}{r^2}\right) - \left(\mathbf{r} + \frac{1}{2}\mathbf{a}\right)\left(1 - \frac{3}{2}\frac{\mathbf{ra}}{r^2}\right)\right] = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^3}\left[-\mathbf{a} + \frac{3\mathbf{r}(\mathbf{ra})}{r^2}\right] =$$

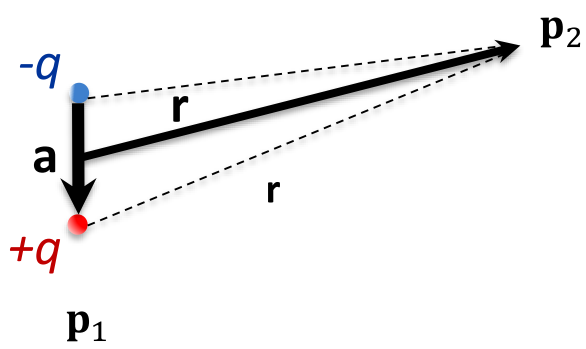
$$= \frac{1}{4\pi\varepsilon_0}\frac{1}{r^3}\left[-\mathbf{p} + \frac{3\mathbf{r}(\mathbf{rp})}{r^2}\right]$$

$$\mathbf{r}_- = \mathbf{r} + \frac{1}{2}\mathbf{a} \qquad \mathbf{r}_+ = \mathbf{r} - \frac{1}{2}\mathbf{a}$$

$$(r_-)^{-3} = \left(r_-^2\right)^{-3/2} \approx r^{-3}\left(1 - \frac{3}{2}\frac{\mathbf{ra}}{r^2}\right)$$

$$(r_+)^{-3} = \left(r_+^2\right)^{-3/2} \approx r^{-3}\left(1 + \frac{3}{2}\frac{\mathbf{ra}}{r^2}\right)$$

Intermezzo:
Interaction of electric dipoles



Dipole moment

$$\boxed{\mathbf{p} = q\mathbf{a}}$$

Electric field created by the dipole at $\mathbf{r}$

$$\boxed{\mathbf{E} = \frac{1}{4\pi\varepsilon_0}\frac{1}{r^3}(3(\mathbf{p}\cdot\hat{\mathbf{r}})\hat{\mathbf{r}} - \mathbf{p})} \qquad \hat{\mathbf{r}} = \frac{\mathbf{r}}{|\mathbf{r}|}$$

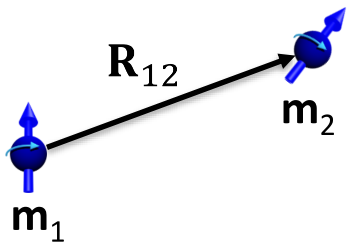
See also Chapter 3 and Problem 3.36 in D. J. Griffiths, *Introduction to electrodynamics* (Cambridge University Press, 2017).

Energy of interaction of dipoles $\mathbf{p}_1$ and $\mathbf{p}_2$

$$\boxed{U_{12} = \mathbf{E}(\mathbf{p}_1)\mathbf{p}_2}$$

Anisotropy of dipole-dipole interaction

Use the analogy between m and p, H and E.
Consider dipole-dipole interaction of two magnetic dipoles (classical spins)



Magnetic field created by dipole $\mathbf{m}_1$ at $\mathbf{r}$

$$\boxed{\mathbf{H} = \frac{1}{4\pi}\frac{1}{r^3}(3(\mathbf{m}_1 \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} - \mathbf{m}_1)}$$

Energy of interaction of dipoles $\mathbf{m}_1$ and $\mathbf{m}_2$

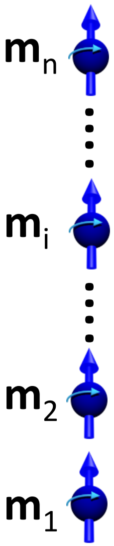
$$\boxed{U_{12} = -\mu_0 \mathbf{m}_2 \mathbf{H}}$$

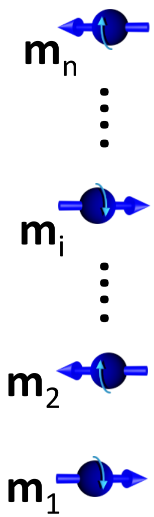
$$\boxed{U_{12} = \frac{1}{4\pi}\frac{\mu_0}{R_{12}^3}(\mathbf{m}_1\mathbf{m}_2 - 3\frac{(\mathbf{m}_1\mathbf{R}_{12})(\mathbf{m}_2\mathbf{R}_{12})}{R_{12}^2})}$$

Dipole-dipole interaction is anisotropic!

Anisotropy of dipole-dipole interaction

Consider a 1D-chain of magnetic dipoles (classical spins)





Total energy of dipole-dipole interactions

$$\boxed{U = \frac{1}{2}\frac{1}{4\pi}\sum_{i,k}\frac{\mu_0}{R_{ij}^3}\left(\mathbf{m}_i\mathbf{m}_k - 3\,\frac{(\mathbf{m}_i\mathbf{R}_{ik})(\mathbf{m}_k\mathbf{R}_{ik})}{R_{ik}^2}\right)}$$

If the spins are ordered ferromagnetically, dipole-dipole interaction results in “easy-axis” along the chain.

If the spins are ordered antiferromagnetically, dipole-dipole interaction results in “easy-plane” perpendicular to the chain.

Anisotropy of dipole-dipole interaction in real materials

PHYSICAL REVIEW B **68**, 144418 (2003)

Dipole interaction and magnetic anisotropy in gadolinium compounds

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(Received 2 June 2003; published 15 October 2003)

The influence of the dipole interaction on the magnetic anisotropy of Gd compounds is investigated. Available data on ferromagnets and antiferromagnets with different crystal structures are discussed and complemented by new neutron scattering experiments on $GdCu_2In$, $GdAu_2Si_2$, $GdAu_2$, and $GdAg_2$. If the propagation vector of the magnetic structure is known, the orientation of the magnetic moments as caused by the dipole interaction can be predicted by a straightforward numerical method for compounds with a single Gd atom in the primitive unit cell. The moment directions found by magnetic diffraction on $GdAu_2Si_2$, $GdAu_2$, $GdAg_2$, $GdCu_2Si_2$, $GdNi_2B_2C$, $GdNi_2Si_2$, $GdBa_2Cu_3O_7$, $GdNi_5$, GdCuSn, $GdCu_2In$, $GdCu_4In$, and GdX (X=Ag, Cu, S, Se, Sb, As, Bi, P) are compared to the predicted directions resulting in an almost complete accordance. Therefore, the dipole interaction is identified as the dominating source of anisotropy for most Gd compounds. The numerical method can be applied to a large number of other compounds with zero angular momentum.

What about other materials?

Spin-orbit interaction
as a mechanisms of magnetic anisotropy

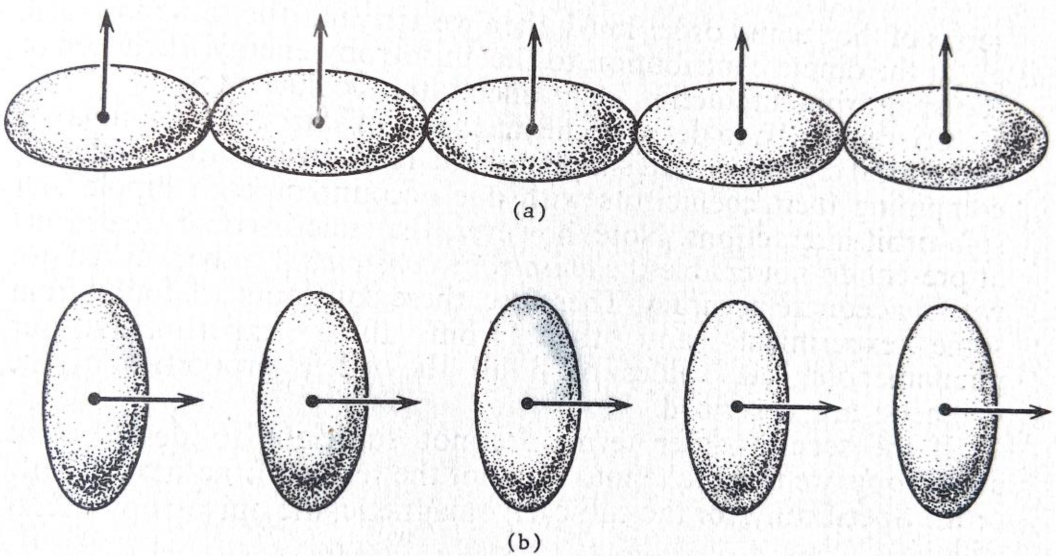


Fig. 38. Owing to spin-orbit interaction the electron cloud is no longer spherically symmetrical. In states (a) and (b) the electrostatic and exchange energies of the system are different, thus producing the magnetic anisotropy.

$$\mathcal{H}_{MD} = -\mu_0 \mathbf{m}\mathbf{H}$$

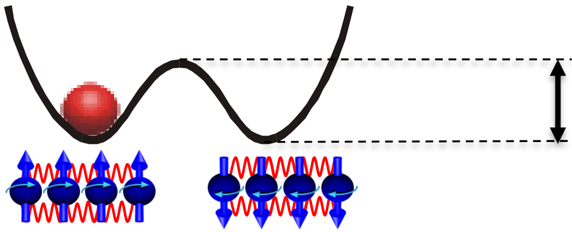
$$\mathbf{m} = -\mu_B(\mathbf{L} + 2\mathbf{S})$$

$$\mathcal{H}_i = -\sum_k \Big(\underbrace{J_{ik}\mathbf{S}_i\mathbf{S}_k}_{\substack{\textbf{Exchange}\\ \sim 1\text{ eV}}} + \underbrace{\mu_B\mu_0\mathbf{H}(\mathbf{L}_i + \mathbf{2S}_i)}_{\substack{\textbf{Magnetic}\\ \textbf{dipole}}} + \underbrace{\xi\mathbf{L}_i\mathbf{S}_i}_{\substack{\textbf{Spin-orbit}\\ \sim 10\text{ meV}}}\Big)$$

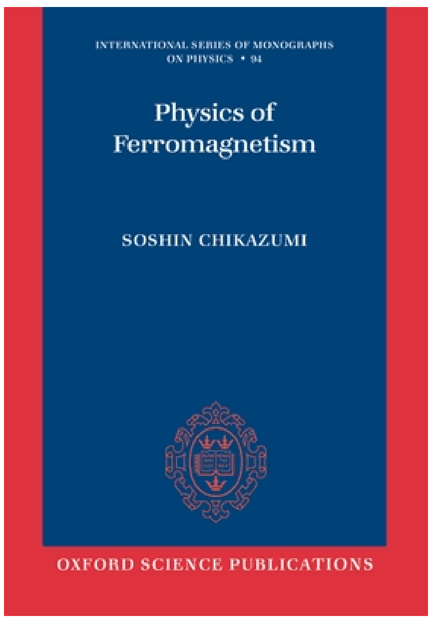
Magnetic anisotropy

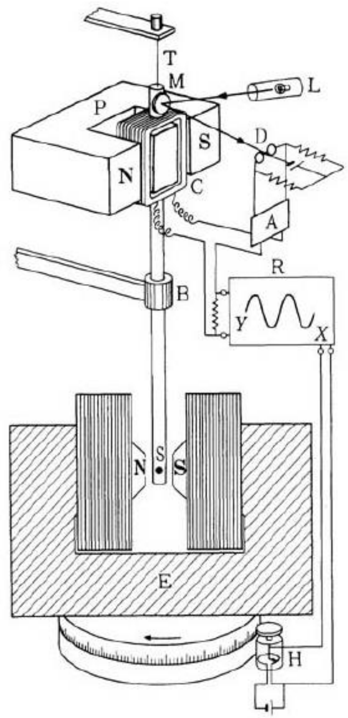
- Where does it come from?
- How to model it?
- **How to measure it?**
- How to control different types of magnetic anisotropy?

Measurements of magnetic anisotropy



Energy
of magnetic anisotropy





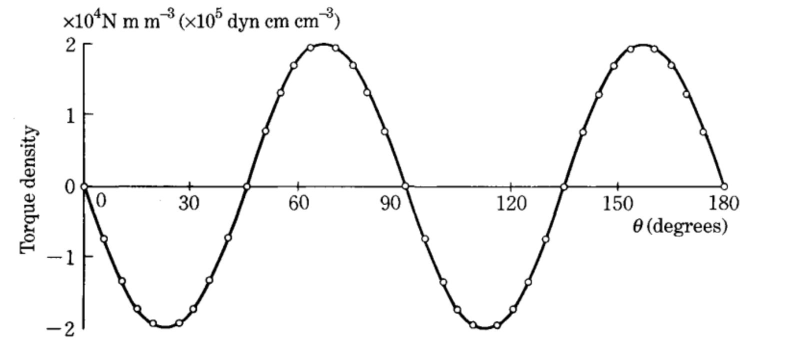


Fig. 12.10. Torque curve measured in (001) plane of 4% Si–Fe single crystal at room temperature (Chikazumi and Iwata).

Seemingly paradoxical temperature dependence of magnetic anisotropy

PHYSICAL REVIEW VOLUME 96, NUMBER 5 DECEMBER 1, 1954

Classical Theory of the Temperature Dependence of Magnetic Anisotropy Energy*

C. ZENER
Westinghouse Research Laboratories, East Pittsburgh, Pennsylvania

(Received May 7, 1954; revised manuscript received August 26, 1954)

The consequences are analyzed of the following two assumptions: (1) the effect of temperature upon magnetic anisotropy arises solely from the introduction of local deviations in the direction of magnetization; and (2) the local deviation in an elementary region is the resultant of a very large number of independent deviations. The influence of these local deviations upon the magnetic anisotropy is most conveniently expressed by representing the magnetic energy as a series of surface harmonics. The coefficient of the nth harmonic is found to vary with temperature as $\{J_s(T)/J_s(0)\}$ raised to the power $n(n+1)/2$. The first two exponents for cubic crystals have values of 10 and 21, respectively. The exponent 10 expresses almost precisely the observed temperature dependence of K_1 in iron. In nickel the anisotropy decreases much more rapidly than predicted. It is deduced that the above two assumptions are applicable to iron but not to nickel.

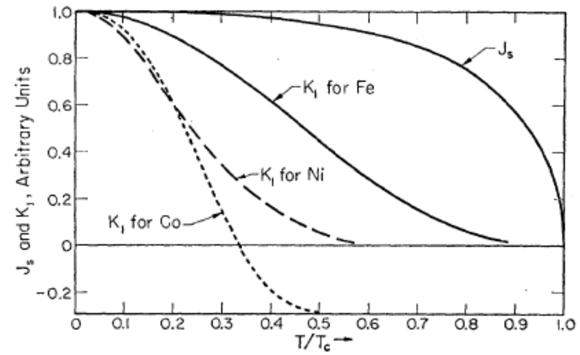


FIG. 1. Temperature dependence of anisotropy energy in Fe, Co, and Ni.

Seemingly paradoxical temperature dependence of magnetocrystalline anisotropy

PHYSICAL REVIEW VOLUME 96, NUMBER 5 DECEMBER 1, 1954

Classical Theory of the Temperature Dependence of Magnetic Anisotropy Energy*

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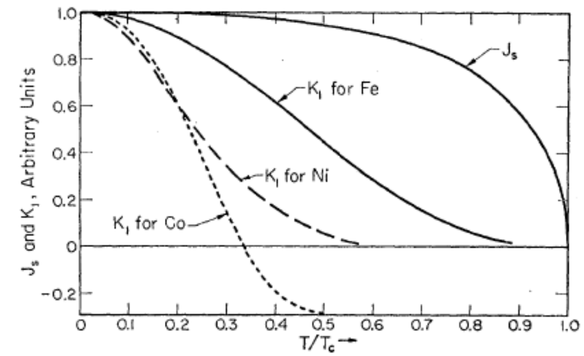


FIG. 1. Temperature dependence of anisotropy energy in Fe, Co, and Ni.

atures after Potter (see reference 4).

Thus, K_1, K_2, $\cdots$, are the first, second, $\cdots$, coefficients which symmetry requirements do not require to be precisely zero. As an example,

$$E_{\text{mag}}=E_0+K_1(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_3^2\alpha_1^2)+K_2\alpha_1^2\alpha_2^2\alpha_3^2+\cdots \quad (1)$$

for a crystal with cubic symmetry, and

$$E_{\text{mag}}=E_0+K_1\sin^2\theta+K_2\sin^4\theta+\cdots \quad (2)$$

for a crystal with hexagonal symmetry. Here α_1, α_2, α_3 are the cosines of the magnetization vector with respect to the cubic axes, and θ is the angle which the magnetization vector makes with the hexagonal axis.

The result of this analysis is that $E_{\text{mag}}(\alpha_1,\alpha_2,\alpha_3)$ averaged over the random walk function satisfies an equation identical to Eq. (3) except that now α_1, α_2, α_3 refer to the direction cosines of the macroscopic $\mathbf{J}$, and the coefficients $E_n(T)$ are related to the original coefficients $E_n(0)$ by the relation

$$E_n(T)/E_n(0)=\{J_s(T)/J_s(0)\}^{n(n+1)/2}, \quad (4)$$

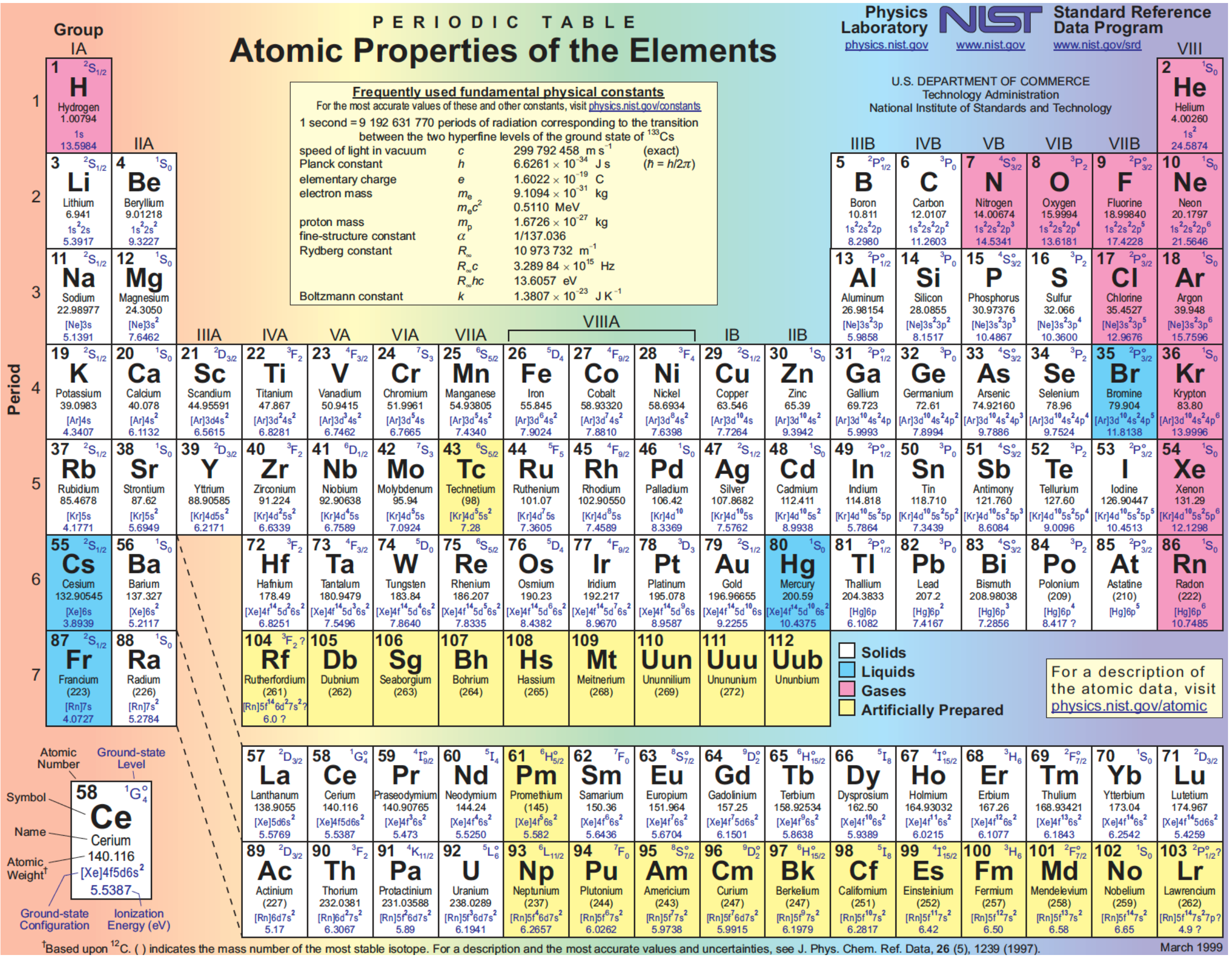
where J_s is the magnetic saturation. In particular,

$$E_4(T)/E_4(0)=\{J_s(T)/J_s(0)\}^{10}. \quad (5)$$

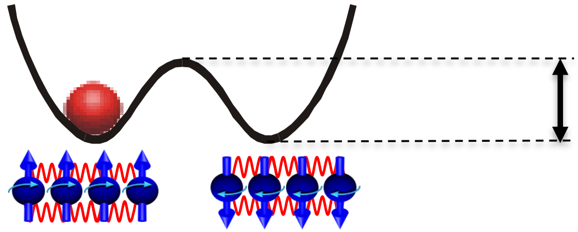
Magnetic anisotropy

- Where does it come from?
- How to model it?
- How to measure it?
- **How to control different types of magnetic anisotropy?**

Single-ion anisotropy and the periodic table



Intermezzo:
Magnetic anisotropy in magnetic data storage



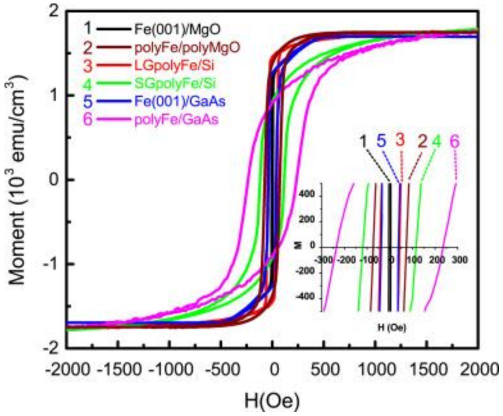
$$E_a = U_{ani}V$$

Data is stable >10 years, if $\frac{U_{ani}V}{kT} > 60$

Upon decreasing the size of magnetic bits, one needs magnetic materials with ever stronger magnetic anisotropy

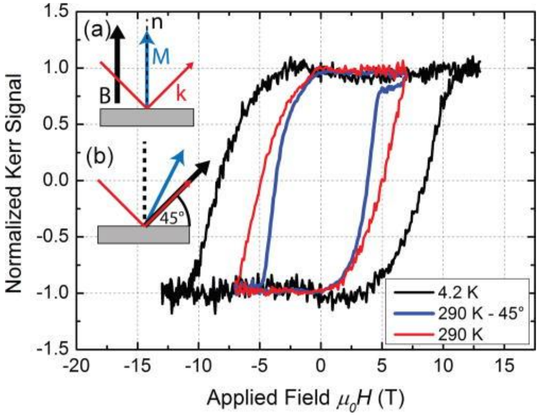
Fe

Y. Cao er al, JMMM **395**, 361 (2015).

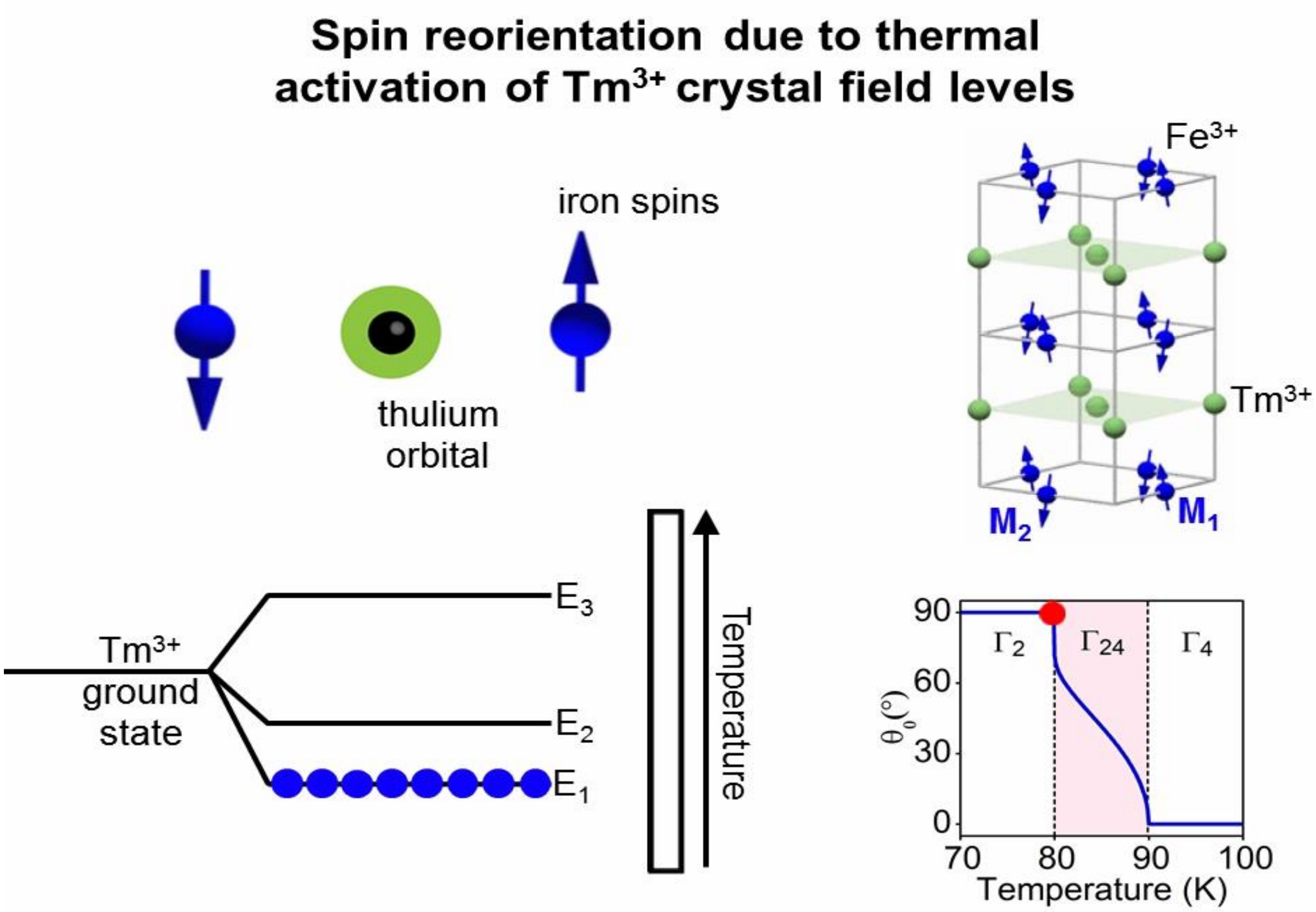


FePt

J. Becker et al, *APL* **104**, 15 (2014).



Spin-reorientation phase transitions in $TmFeO_3$



Model for spin reorientation phase transition

$$m_x = \sin\theta \qquad m_z = \sin\theta$$

$$U_{ani} = K_1 m_x^2 + K_2 m_x^4 = K_1 sin^2\theta + K_2 sin^4\theta$$

$$\Phi = \Phi_0(M, 0) - \mu_0 \cancel{\mathbf{HM}} + U_{ani}$$

$$\Phi = K_1 sin^2\theta + K_2 sin^4\theta + \text{const}$$

Assume that K_2 does not depend on temperature

The case of $K_2 > 0$

a) $K_1 \geq 0,\ \theta = 0, \pi$

b) $K_1 + 2K_2 \leq 0,\ \theta = \frac{\pi}{2}, \frac{3\pi}{2}$

c) $K_1 + 2K_2 \geq 0$ and $K_1 \leq 0,\ sin^2\theta = -\frac{K_1}{2K_2}$

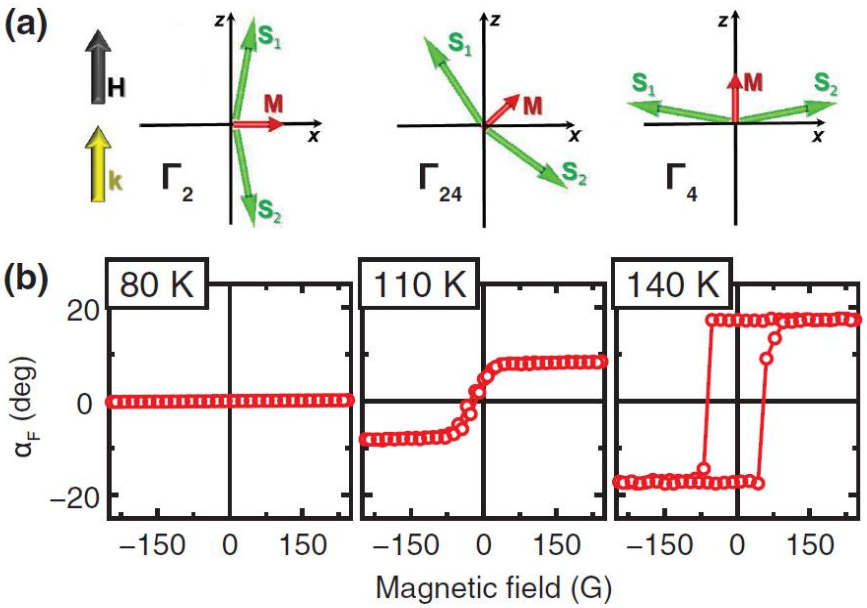


FIG. 1 (color online). (a) Magnetic structure of RE orthoferrites in the low-temperature (Γ_2), intermediate (Γ_{24}), and high-temperature (Γ_4) phases. (b) Hysteresis of the z component of the weak magnetization in $(SmPr)FeO_3$, probed by means of the Faraday rotation. The measurements show the presence of a phase transition region in which the net magnetic moment gradually rotates by 90° from the x axis to the z axis.

Model for spin reorientation phase transition

$m_x = \sin\theta \qquad m_z = \sin\theta$

$$U_{ani} = K_1 m_x^2 + K_2 m_x^4 = K_1 sin^2\theta + K_2 sin^4\theta$$

$$\Phi = \Phi_0(M, 0) - \mu_0 \cancel{\mathbf{HM}} + U_{ani}$$

$$\Phi = K_1 sin^2\theta + K_2 sin^4\theta + \text{const}$$

The case of $K_2 < 0$

a) $K_1 \geq 0,\ \theta = 0, \pi$

b) $K_1 + 2K_2 \leq 0,\ \theta = \frac{\pi}{2}, \frac{3\pi}{2}$

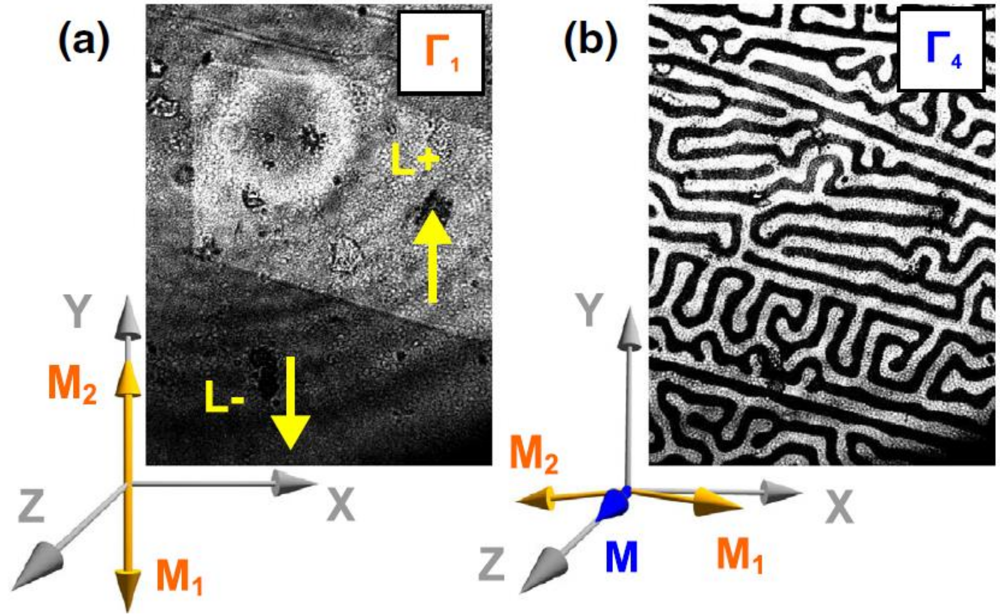


FIG. 1. (a) Magnetooptical images of the two types of antiferromagnetic domains in the low-temperature Γ_1 phase of the z-$DyFeO_3$ sample. The bias temperature of the sample is 20 K. (b) Magnetooptical image of the magnetic domain pattern in the high-temperature Γ_4 phase. The bias temperature of the sample is 50 K.

Surface anisotropy

Appl. Phys. A 49, 499–506 (1989)

Applied Physics A Solids and Surfaces

Magnetic Surface Anisotropy of Transition Metal Ultrathin Films

P. Bruno and J.-P. Renard

Institut d'Electronique Fondamentale, CNRS URA.D.0022, Bât. 220, Université Paris-Sud, F-91405 Orsay Cedex, France

Received 24 March 1989/Accepted 16 June 1989

J. Phys.: Condens. Matter 3 (1991) 4497–4522. Printed in the UK

REVIEW ARTICLE

Surface magnetism; magnetization and anisotropy at a surface

T Kaneyoshi

Department of Physics, Nagoya University, 464-01 Nagoya, Japan

Received 20 February 1991

PHYSICAL REVIEW B **98**, 054427 (2018)

Effective anisotropy due to the surface of magnetic nanoparticles

D. A. Garanin

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(Received 24 March 2018; published 27 August 2018)

Shape anisotropy

The demagnetizing field, also called the stray field (outside the magnet), is the magnetic field (H-field) generated by the magnetization M in a magnet.

The effective magnetic field in the magnet itself is thus not equal to the applied magnetic field, but corrected

$$H = H - NM$$

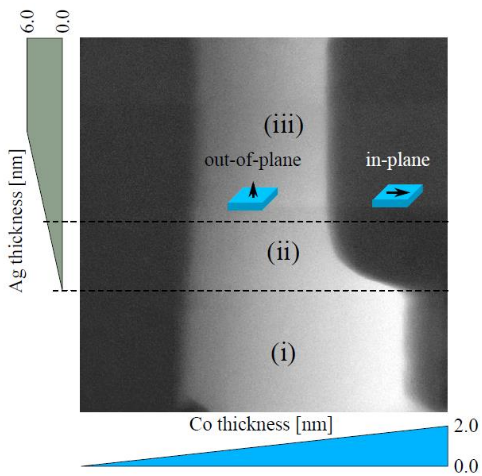

Figure 2.1: Preferred magnetization state, as a function of both Co and Ag thicknesses. Three regions: (i) Au/Co/Au; (ii) Au/Co/Ag/Au and (iii) Au/Co/Ag can be distinguished. The white color corresponds to the out-of-plane component of the magnetization. Figure was adapted from Ref. [14].

VOLUME 89, NUMBER 8 PHYSICAL REVIEW LETTERS 19 AUGUST 2002

New Possibilities for Tuning Ultrathin Cobalt Film Magnetic Properties by a Noble Metal Overlayer

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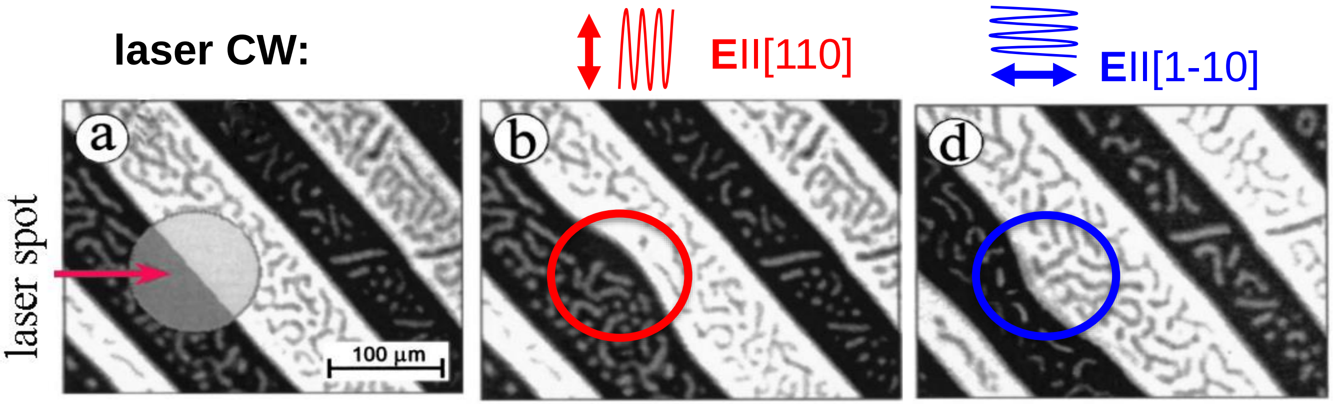
A. Wawro and L. T. Baczewski
Institute of Physics, Polish Academy of Sciences, Aleja Lotników 32/46, 02-668 Warsaw, Poland
(Received 19 April 2002; published 6 August 2002)

Complementary multiscale magneto-optical studies based on the polar Kerr effect are carried out on an ultrathin cobalt wedge covered with a silver wedge and subsequently with the Au thick layer. A few monolayers of Ag are found to have a substantial effect on magnetic anisotropy, the coercivity field, and Kerr rotation. The silver overlayer thickness-driven magnetic reorientation from easy axis to easy plane generates a new type of 90° magnetic wall for cobalt thicknesses between 1.3 and 1.8 nm. The tuning of the wall width in a wide range is possible. Tailoring of the overlayer structure can be used for ultrathin film magnetic patterning.

Photo-induced anisotropy

laser CW:

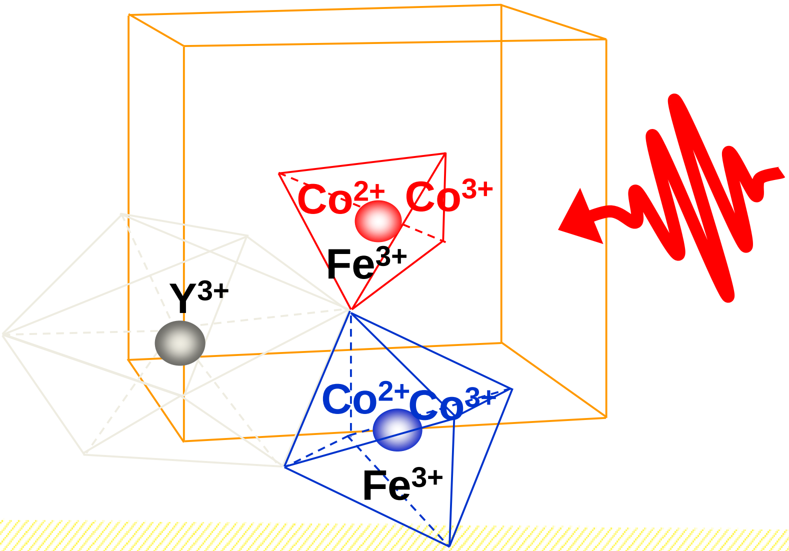


$Y_2CaFe_{3.9}Co_{0.1}GeO_{12}$ / GGG (001)

A.Chizhik et al. *PRB*, 57 (1998).

A.Stupakiewicz et al. *PRB*, 64 (2001).

Domain wall motion (~μm/sec)



Exchange bias

PHYSICAL REVIEW VOLUME 105, NUMBER 3 FEBRUARY 1, 1957

New Magnetic Anisotropy

W. H. Meiklejohn and C. P. Bean
General Electric Research Laboratory, Schenectady, New York

(Received October 15, 1956)

A new type of magnetic anisotropy has been discovered which is best described as an exchange anisotropy. This anisotropy is the result of an interaction between an antiferromagnetic material and a ferromagnetic material. The material that exhibits this exchange anisotropy is a compact of fine particles of cobalt with a cobaltous oxide shell. The effect occurs only below the Néel temperature of the antiferromagnetic material, which is essentially room temperature for the cobaltous oxide. An exchange torque is inferred to exist between the metal and oxide which has a maximum value at 77°K of ~2 dyne-cm/cm² of interface.

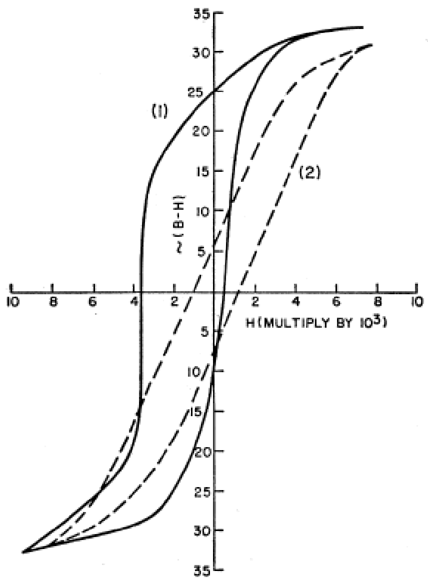
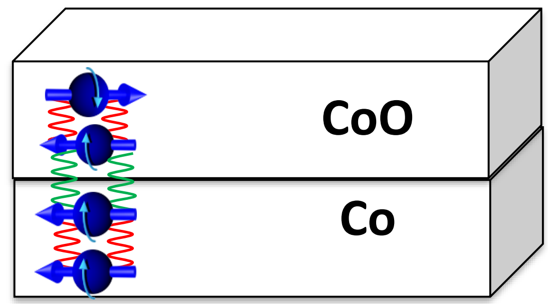


Fig. 1. Hysteresis loops at 77°K of oxide-coated cobalt particles. Solid line curve results from cooling the material in a 10 000 oersted field. The dashed line curve shows the loop when cooled in zero field.



Take-home message

- Magnetic anisotropy is an intrinsic property of magnets.

- Magneto-crystalline anisotropy as well as other types of magnetic anisotropy is convenient to model using the thermodynamic approach.

- There are many ways to control the strength and the type of magnetic anisotropy. The depends on chemical composition, shape, temperature of magnets. Magnetic anisotropy can also be controlled by light.

Gordon Research Conference
"*Spin Dynamics in Low Dimension and Low Symmetry Environment*"

June 29-July 4, 2025
Les Diablerets, Switzerland

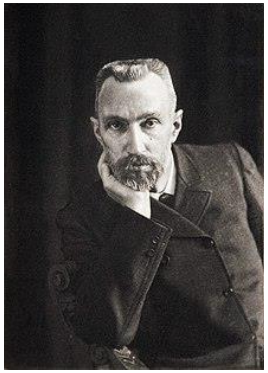




Macrospin approximation: *intuitive (classical) view of quantum (counter-intuitive) phenomenon*

$$\left.\begin{aligned} dU &= dW + dQ \\ dW &= \mu_0 \mathbf{H} d\mathbf{M} \end{aligned}\right\} \quad \mu_0 \mathbf{H}_{eff} = -\left(\frac{\partial U}{\partial \mathbf{M}}\right)_\sigma$$

U - internal energy
W - work
Q - heat
σ - entropy



P. Curie (1894):

"the symmetries of the causes are to be found in the effects".

$$\mathbf{F} = -\frac{\partial U}{\partial \mathbf{x}}$$

Cause	Effect	Work (W)
F	d**x**	**F**d**x**
E	d**P**	**E**d**P**
H	d**M**	**H**d**M**

Macrospin approximation: *intuitive (classical) view of quantum (counter-intuitive) phenomenon*

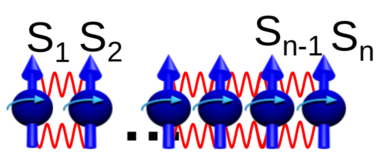
U - internal energy
W - work
Q - heat
σ - entropy
$\mathbf{T}$ - torque

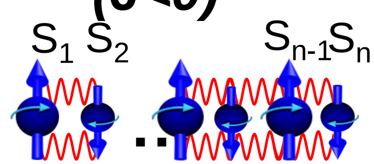
$$\left.\begin{aligned} dU &= dW + dQ \\ dW &= \mu_0 \mathbf{H} d\mathbf{M} \end{aligned}\right\} \quad \mu_0 \mathbf{H}_{eff} = \left(\frac{\partial U}{\partial \mathbf{M}}\right)_\sigma$$

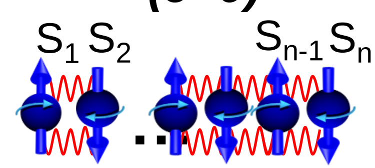
$$\frac{d\mathbf{S}}{dt} = \mathbf{T} \qquad \frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}_{eff}$$

Landau-Lifshitz equation (1935)

Ferromagnet	Ferrimagnet	Antiferromagnet
$\mathbf{M} = -\gamma \frac{\sum S_i}{V} \neq 0$	$\mathbf{M} = -\gamma \frac{\sum S_i}{V} \neq 0$	$\mathbf{L} = -\gamma \frac{\sum (\mathbf{S}_{2i-1} - \mathbf{S}_{2i})}{V}$
Ferromagnet (J>0)	***Ferrimagnet (J<0)***	***Antiferromagnet (J<0)***







Macrospin approximation: *intuitive (classical) view of quantum (counter-intuitive) phenomenon*

$$-\mu_0 H_{eff}^{(j)} = {}^{\partial E_{ex}}/_{\partial S_i} \sim 1 - 1000\ \mathrm{T}$$

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} \qquad \frac{\gamma}{2\pi} = 28\ \mathrm{GHz/T}$$

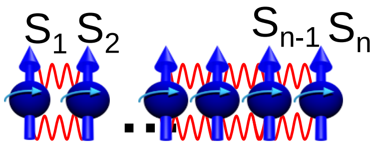
τ_{ex}=30 fs -30 ps

Nonequilibrium state **?** **Macrospin** *(classical)*

$t \sim \tau_{ex}$ $t >> \tau_{ex}$

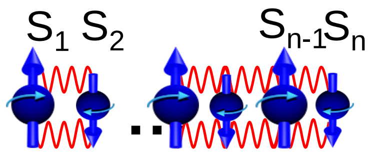
$$\mathbf{M} = -\gamma \frac{\sum S_i}{V} \neq 0$$

Ferromagnet (J>0)



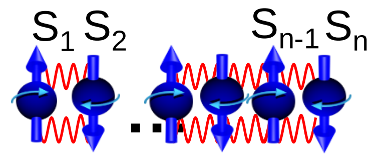
$$\mathbf{M} = -\gamma \frac{\sum S_i}{V} \neq 0$$

Ferrimagnet (J<0)



$$\mathbf{L} = -\gamma \frac{\sum(\mathbf{S}_{2i-1} - \mathbf{S}_{2i})}{V}$$

Antiferromagnet (J<0)



The case of antiferromagnet

$$\Phi = AL^2 + BL^4 - \mu_0 \mathbf{HM} + U_{ani}$$

$$\mathbf{l} = \frac{\mathbf{L}}{|\mathbf{L}|}$$

$$U_{ani} = K(l_x^2 + l_y^2)$$

$K > 0$ anisotropy of "easy-axis" type

$K < 0$ anisotropy of "easy-plane" type

Physics Reports 852 (2020) 1–46

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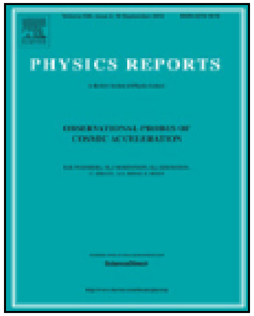

Fundamentals and perspectives of ultrafast photoferroic recording

A.V. Kimel [a,*], A.M. Kalashnikova [b,c], A. Pogrebna [a,1], A.K. Zvezdin [d,e]

Intermezzo. Elegant derivation of M(T)

$$\Phi = \Phi_0(M,0) - \mu_0 \mathbf{HM}$$

If H=0, $\Phi = \Phi_0(M,0)$. From our experience we know that states with magnetization "up" and "down" are absolutely equivalent. It means that $\Phi_0(M,0) = \Phi_0(-M,0)$i.e. Φ_0 must be even functions of m.

Lets express $\Phi_0(M,0)$ in a Taylor series

$$\Phi_0(M,0) = \Phi_0(0,0) + AM^2 + BM^4 + \cdots$$

Again, experimentally we observe that below the Curie temperature the stable state of a ferromagnet corresponds to a state with | M |>0. At the Curie temperature and above it | M |=0.

Since $\Phi_0(M,0)$ must be at minimum in thermal equilibrium, it is clear that A<0 below the Curie temperature and A>0 above the Curie temperature.

The simplest possible function A(T) that satisfies this requirement is A(T)=a(T-T_C), where T_C is the Curie temperature, a is a coefficient (a>0).

Intermezzo. Elegant derivation of M(T)

$F(m,0)=a(T-T_C)m^2+Bm^4$

F(m,0) is minimum, when dF(m,0)/dm=0

$dF(m,0)/dm=2a(T-T_C)m+4Bm^3$ $\qquad$ $2a(T-T_C)m+4Bm^3=0$

$$m=\sqrt{\frac{a}{2B}(T_C-T)}=\sqrt{\frac{aT_C}{2B}(1-\frac{T}{T_C})}$$

Experiment