Magnetic anisotropies

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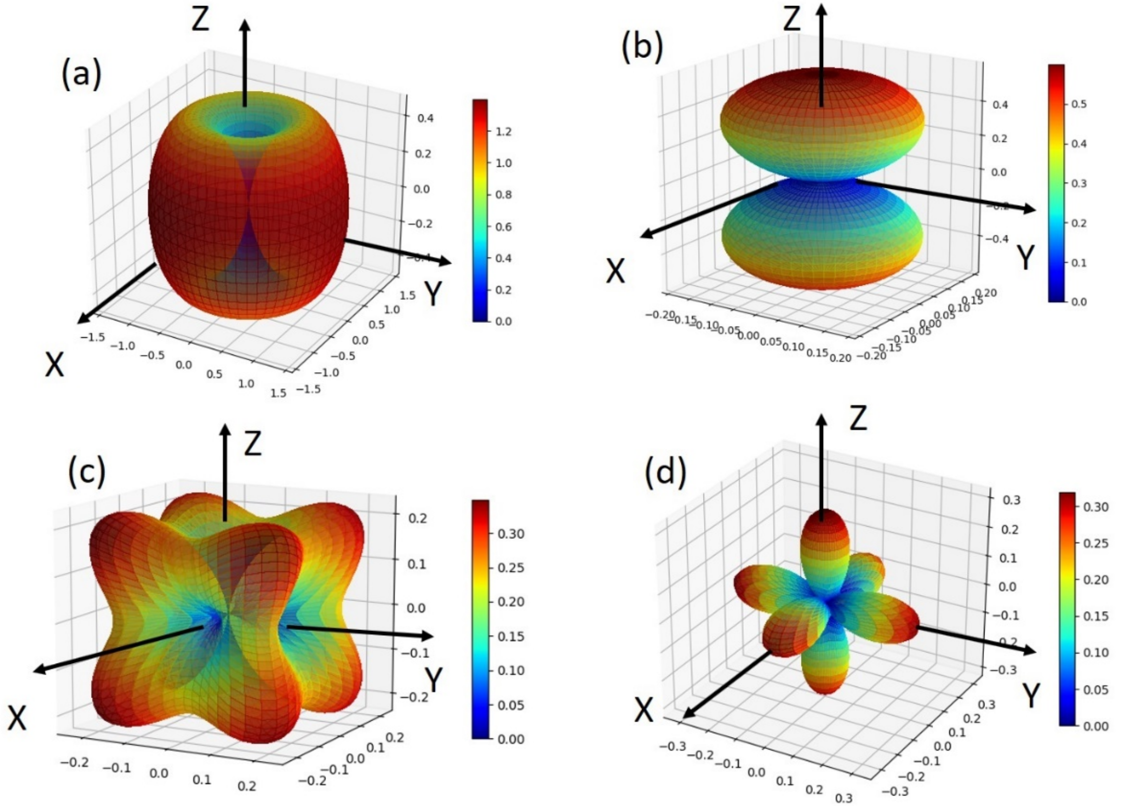


Magnetic anisotropies

Orientation of a single magnetic moment : isotropic, uniaxial, planar, intermediate…

Macroscopic magnetic state (long range order, spin liquid, paramagnets,….)

Magnetic domains (energy of the domain walls, shape of the domains, reversibility/irreversibility, …)

Dynamics: ferromagnetic gap (MHz-GHz), antiferromagnetic gap (THz) …..

Effect of a magnetic field : dependence on its orientation…

….

Anistotropic exchange interaction between neighboring spins

Macroscopic magnetic state (long range order, spin liquid,…)

Skyrmions and other topological objects …

Measuring the magnetic anisotropy

From fundamentals to applications…

bibliography

André HERPIN: Théorie du magnétisme 1986
Du Trémolet de Lacheisserie: Magnétisme I-Fondements / Magnetism I
Blundell: Magnetism
…
Quantum mechanical treatment

RH White: Quantum magnetism

Abragam and Bleaney: Electron paramagnetic resonance of transition ions
(single ion anisotropy for 3d elements)
Werth and Bolton : Electron spin resonance , elementary theory and practical applications
recent edition : Weil and Bolton
…

+ articles….

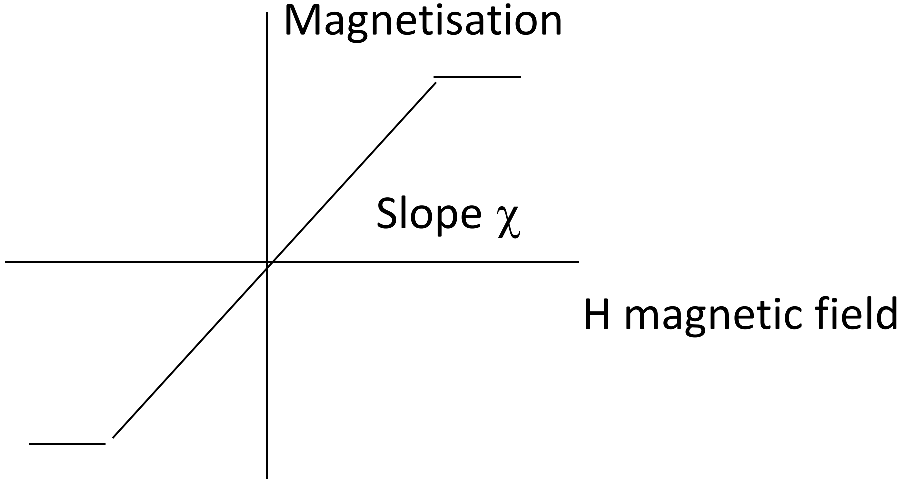
Magnetic anisotropies

1. **Importance of magnetic anisotropy**
2. Single ion Magnetic anisotropy: phenomenological description
3. Single ion Magnetic anisotropy: microscopic origin
4. Exchange anisotropy
5. Examples with magneto-electric effects

Example: domains in a ferromagnet magnetization curve M(H)

reversible magnetisation

$M = \chi H$



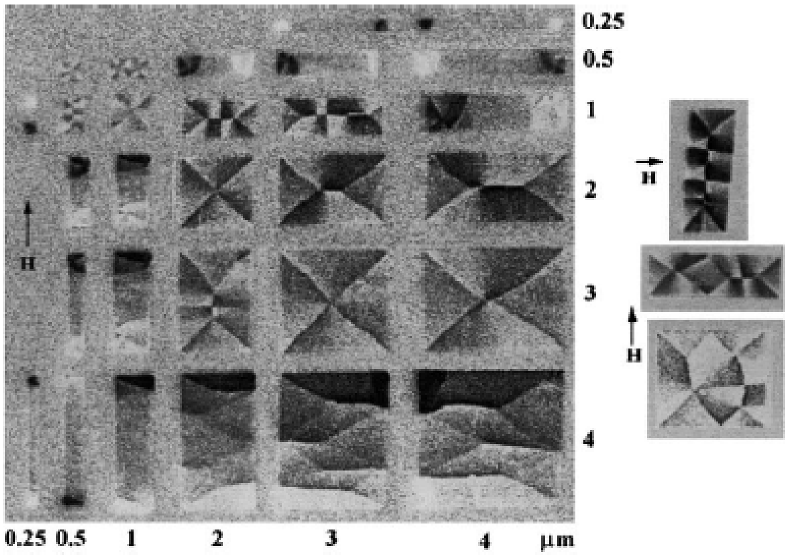
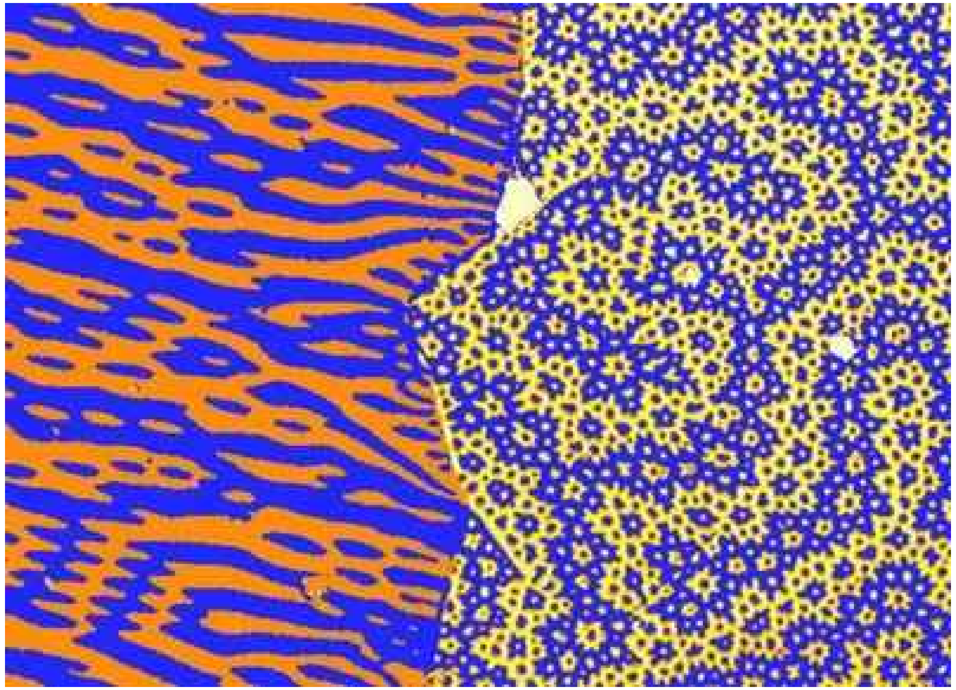


Fig. 3. MFM images of rectangular permalloy islands of various sizes and aspect ratios, in remanence [8].

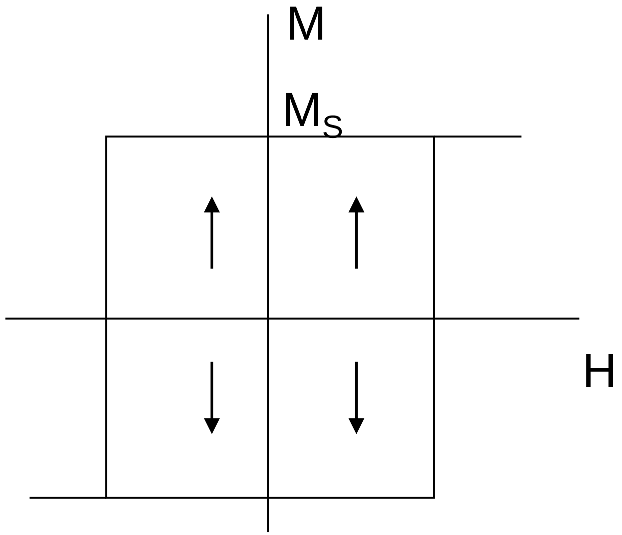
1. Importance of magnetic anisotropy: domains

Example: domains in a ferromagnet magnetization curve M(H)



NdFeB domains

Irreversible magnetisation:
Spontaneous magnetization
H = 0   M=Ms≠ 0



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reversible magnetisation

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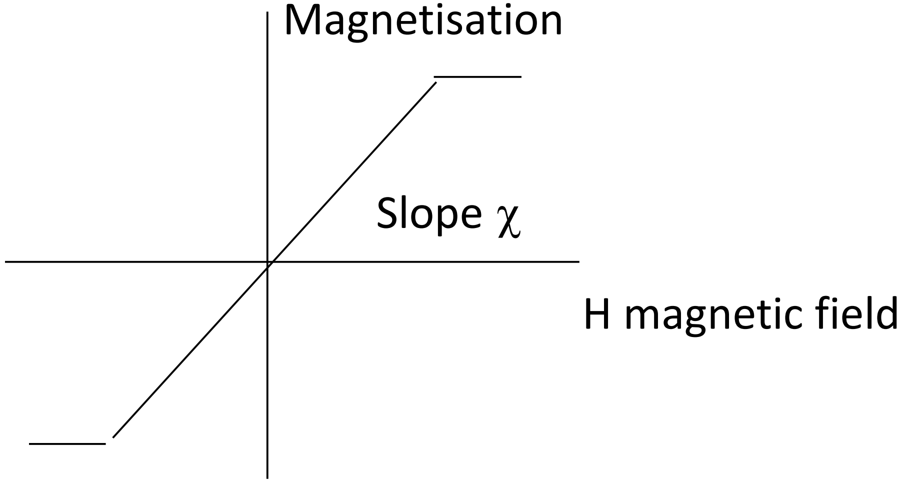
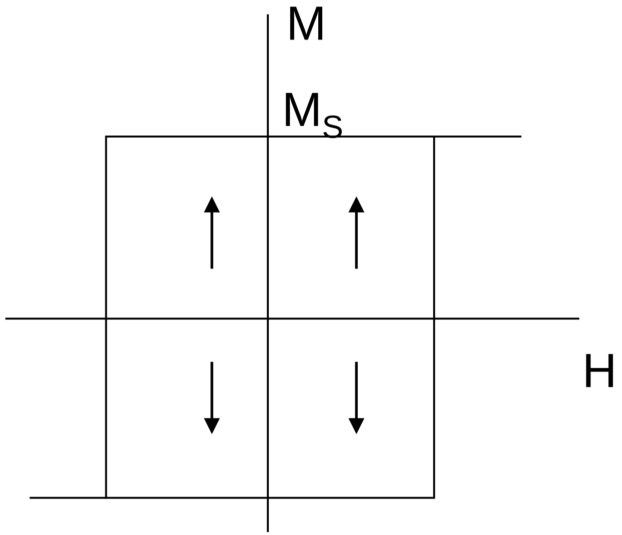


Irreversible magnetisation:

Spontaneous magnetization

$H = 0 \quad M=Ms \neq 0$



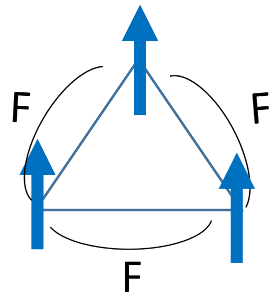
From fundamentals to applications:

Soft and hard magnetic magnetic materials (flux conductors and permanent magnets)

1. Importance of magnetic anisotropy: magnetic frustration

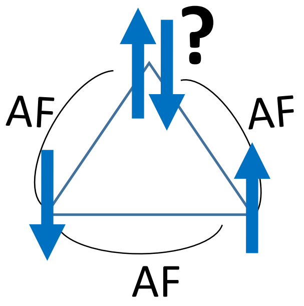
example of spins on a triangle

F first neighbor interaction



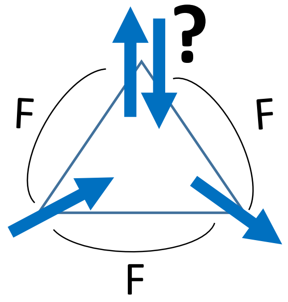
F long range magnetic order

AF first neighbor interaction



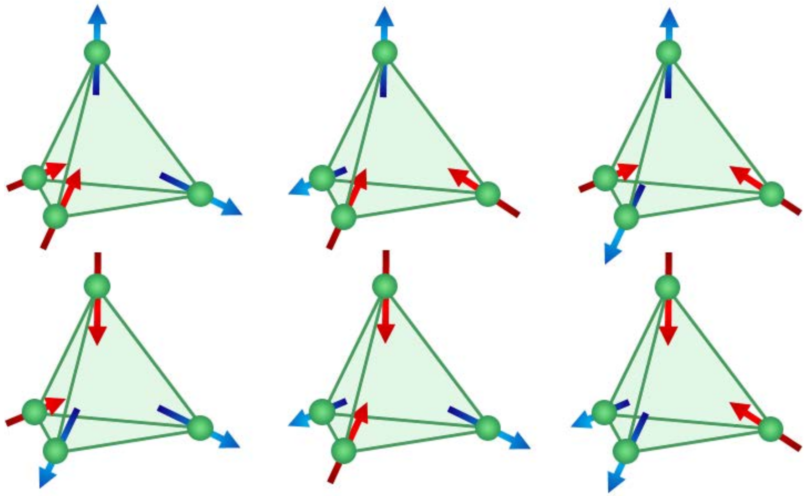
Magnetic frustration

F first neighbor interaction + **multiaxial anisotropy**



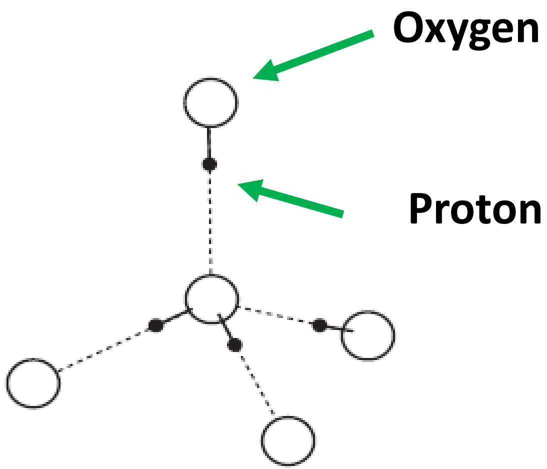
Magnetic frustration
SPIN ICES

1. Importance of magnetic anisotropy: spin ices

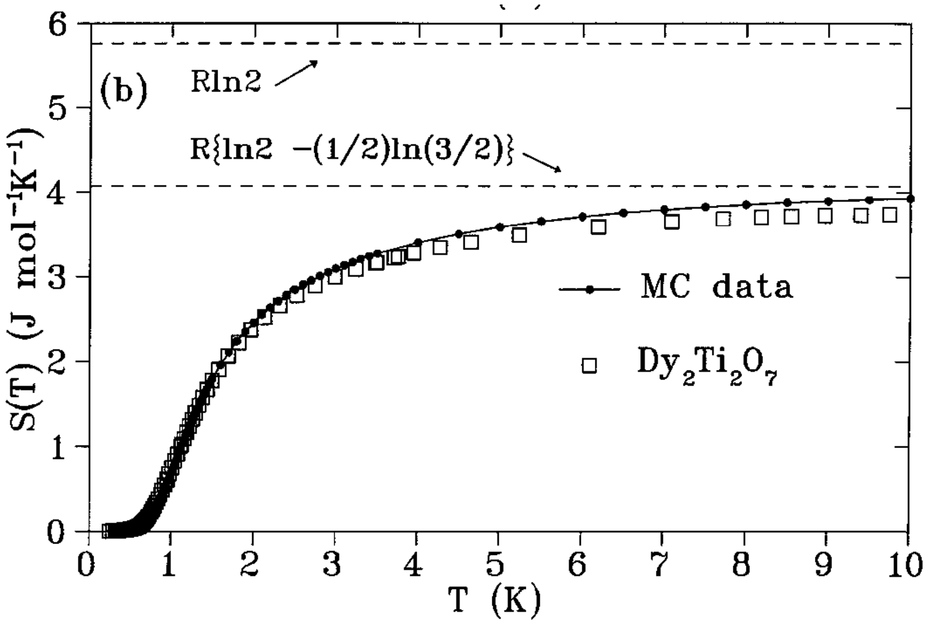


2 in – 2 out »
« ice rule »

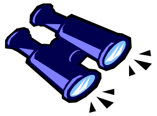
Local order of protons in water ice
« 2 close - 2 far » from Oxygen



Extensive degeneracy
Finite entropy



J.S.Gardner, M.J.P.Gingras, J.E.Greedan, Phys.Rev.Mod 82 (2010)

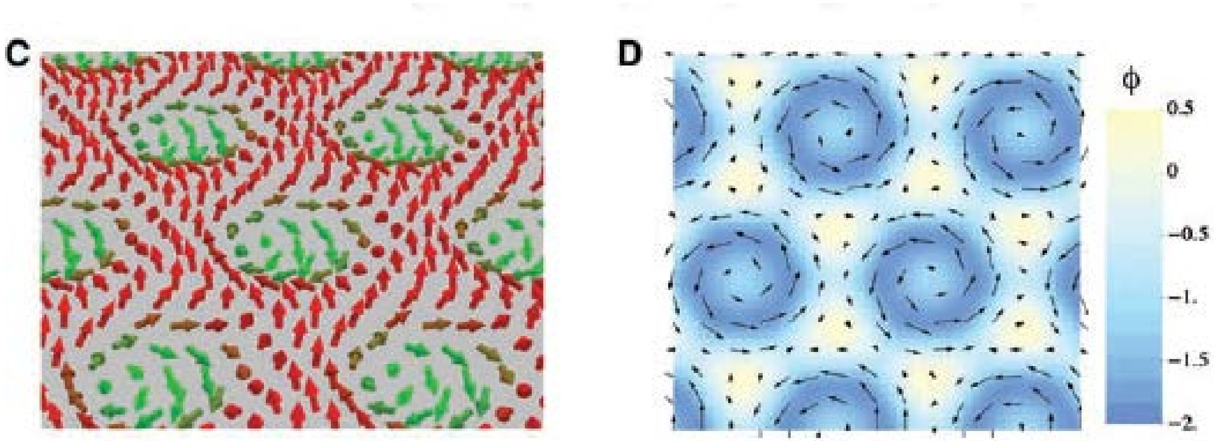


From fundamentals to applications: Magneto caloric effect…

1. Importance of magnetic anisotropy: non collinear phases

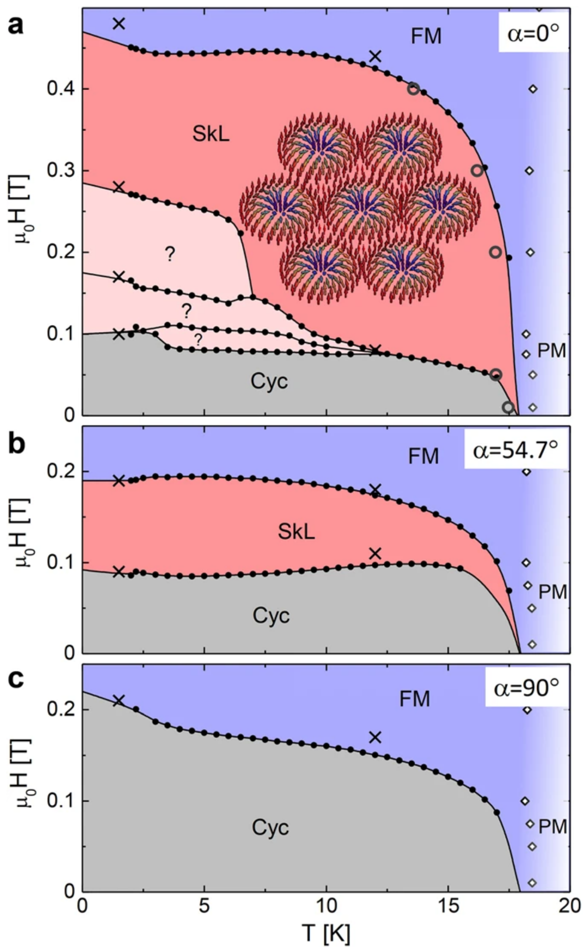
Example: skyrmions

MnSi
S. Mühlbauer *et al*
Skyrmion lattice in a chiral magnet
Science **323**, 915–919 (2009)
Neutron scatering



GaV_4Se_8

S. Bordács, *et al.* Equilibrium Skyrmion Lattice Ground State in a Polar Easy-plane Magnet. *Sci Rep* **7,** 7584 (2017). https://doi.org/10.1038/s41598-017-07996-x

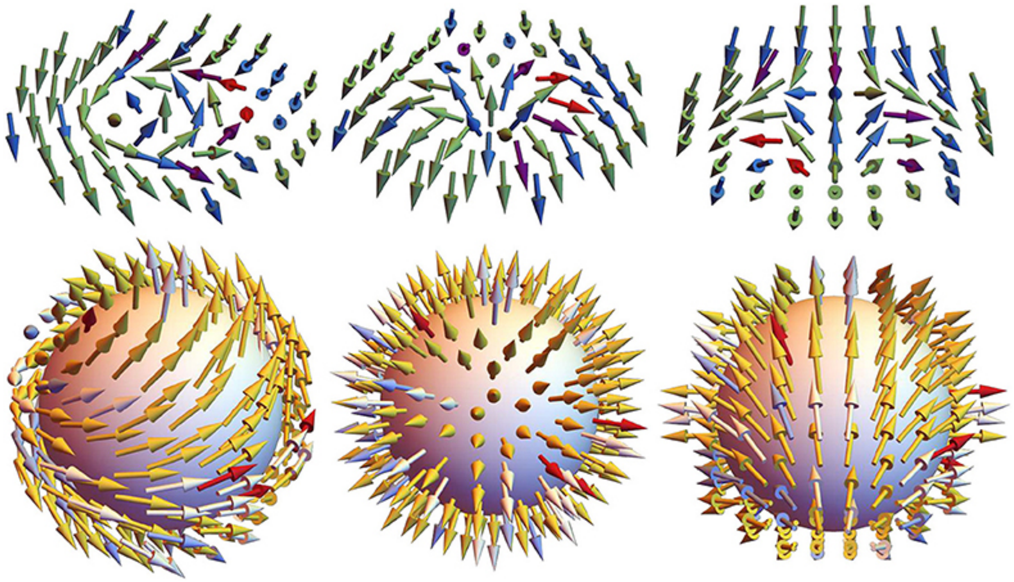


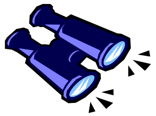
1. Importance of magnetic anisotropy: non collinear phases

Example: skyrmions

Skyrmions and Antiskyrmions in Quasi-Two-Dimensional Magnets

https://doi.org/10.3389/fphy.2018.00098



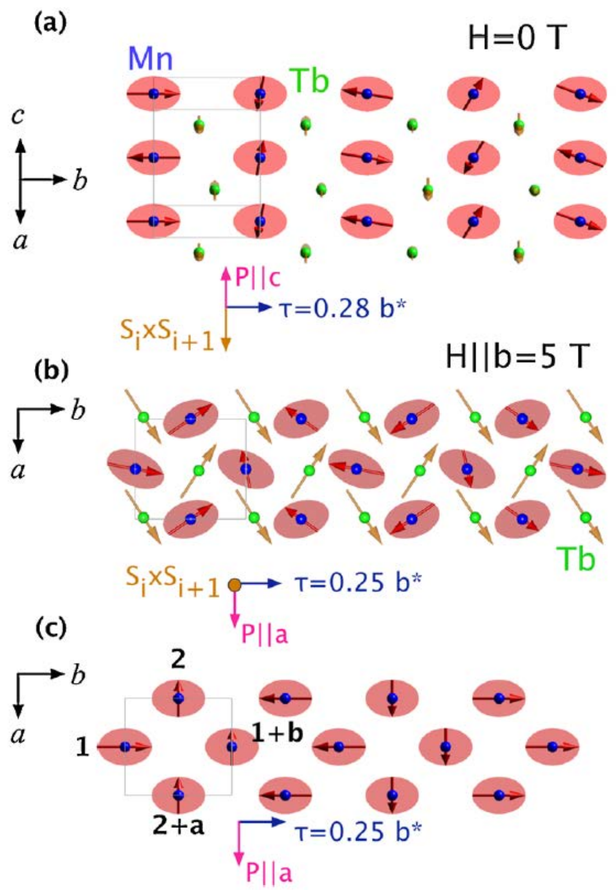


From fundamentals to applications: nano electronics….

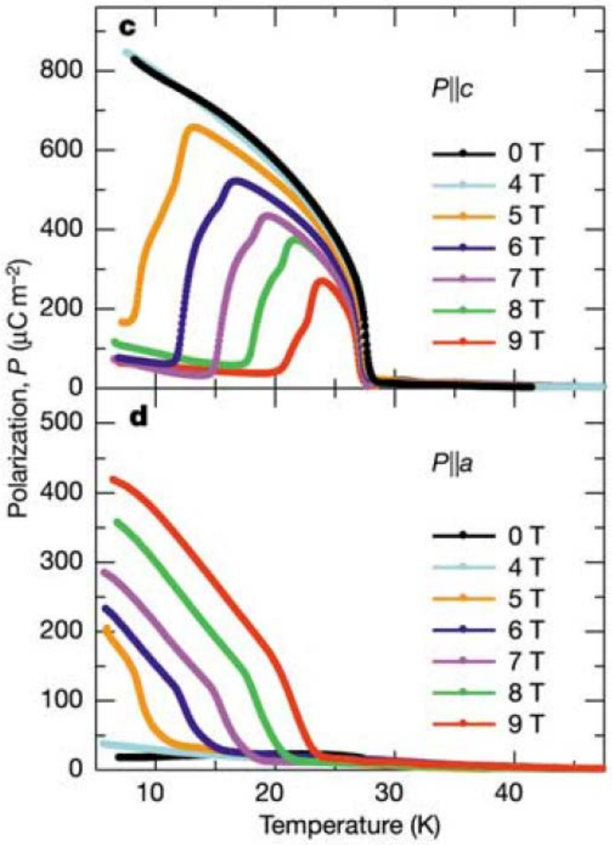
1. Importance of magnetic anisotropy: non collinear phases

Magnetically induced ferroelectricity

Cycloidal order and induced electric polaristion in TbMnO3

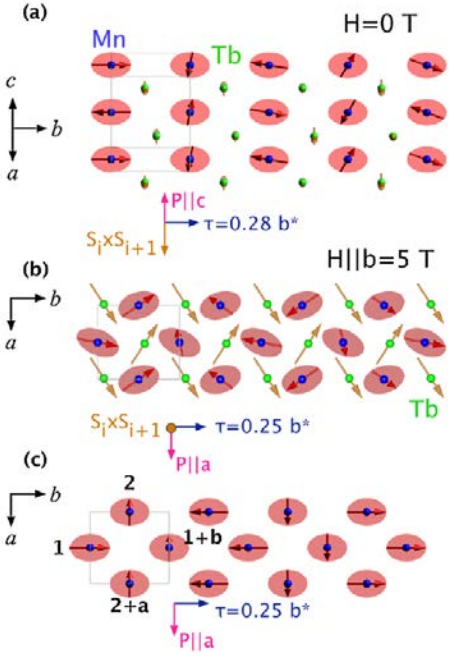


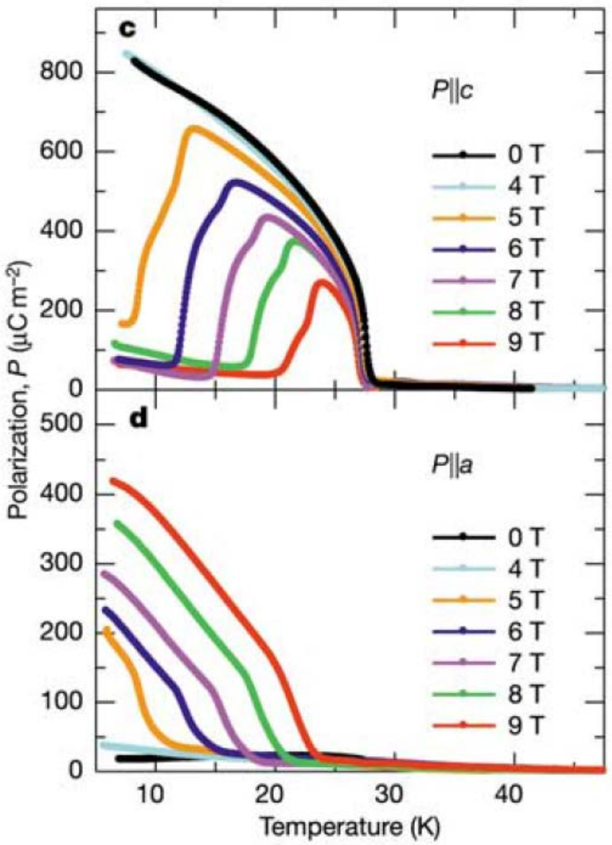
N. Aliouane et al, PRL 102, 207205 (2009)

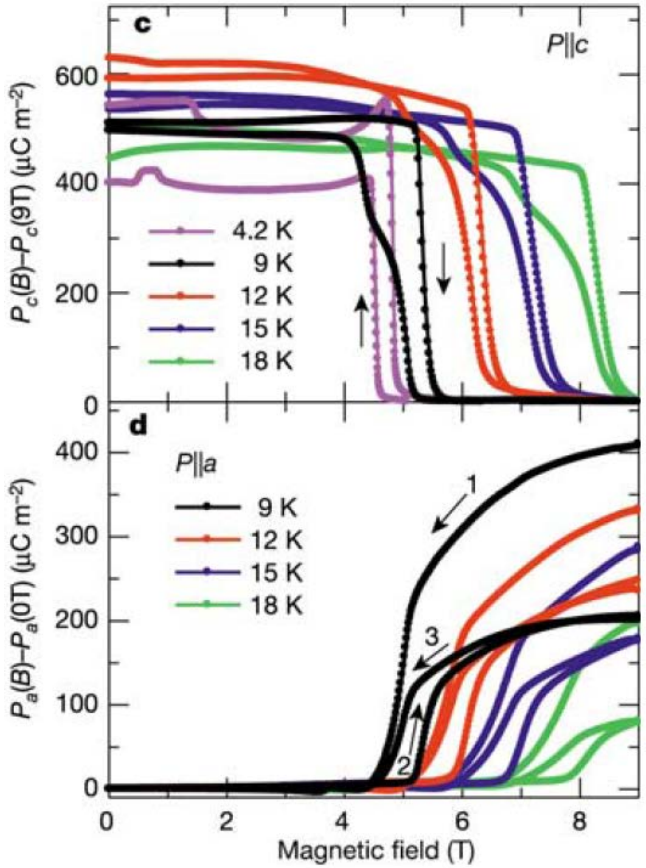


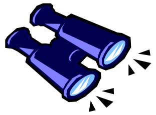
T. Kimura et al, NATURE |VOL 426 | 6 NOVEMBER 2003 p55

Magnetically induced ferroelectricity









From fundamentals
to applications:

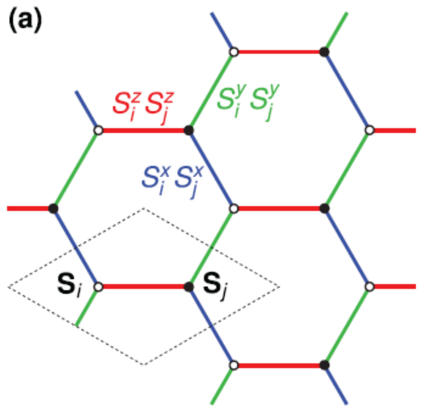
ME sensors / memory

1. Importance of magnetic anisotropy

Kitaev physics

Anisotropic Exchange interactions on a honeycombe lattice
Frustation leads to a spin liquid phase whose properties are exactly calculated
(search for experimental realisation…)

$$H_{Kitaev} = -\sum_{i,\alpha=1,2,3} (K_x S_i^x S_\alpha^x + K_y S_i^y S_\alpha^y + K_z S_i^z S_\alpha^z)$$



Lukas Janssen and Matthias Vojta 2019 *J. Phys.: Condens. Matter* **31** 423002

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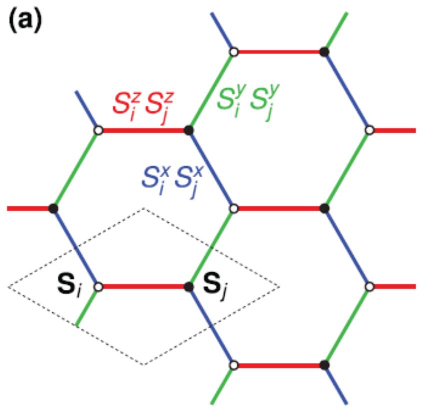
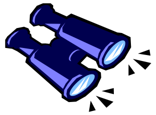
Lukas Janssen and Matthias Vojta 2019 *J. Phys.: Condens. Matter* **31** 423002





From fundamentals to applications:

Topologically protected excitations as building blocks for quantum computing

Magnetic anisotropies

1. Importance of magnetic anisotropy
2. **Single ion Magnetic anisotropy: phenomenological description**
3. Single ion Magnetic anisotropy: microscopic origin
4. Exchange anisotropy
5. Examples with magneto-electric effects

2. Single ion magnetic anisotropy : phenomelological description

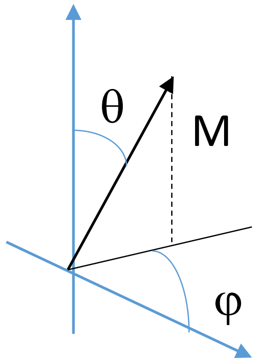
The magnetic moment is « pinned » to one/several directions in the periodic lattice thanks to its orbital momentum
It depends also on the local crystal symmetry

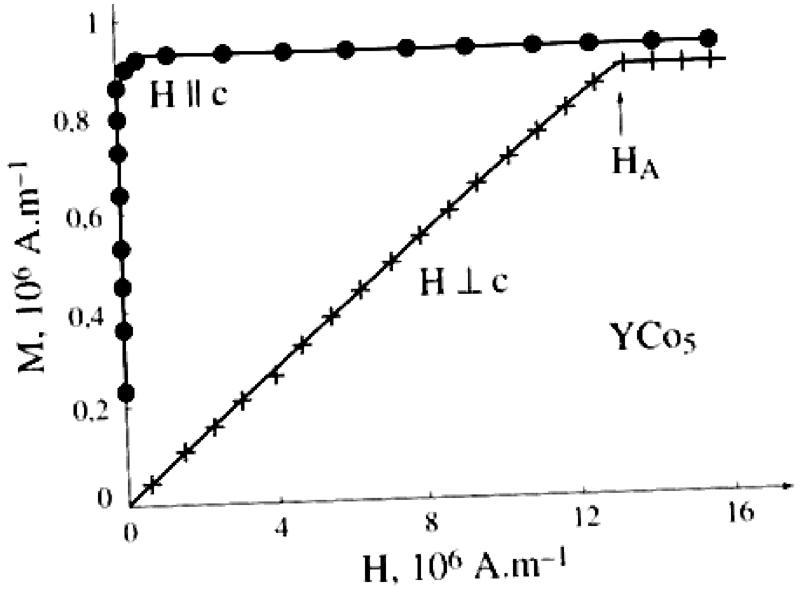
Phenomelological description: Magneto cristalline energy
Spherical coordinates θ, φ

Axial symmetry : $e_{an} = K_1 \sin^2 \theta$

$K_1 > 0$, e_{an} minimum for $\theta = 0$
uniaxial system

$K_1 < 0$, e_{an} minimum for $\theta = \pi/2$
planar system



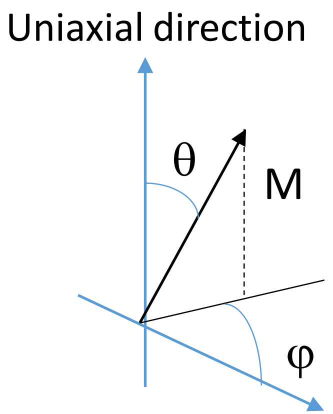


Example : magnetization curve of the uniaxial compound YCo5
$\mu_0 H_a = 2K_1 / M_s \approx 17\text{T}$

2. Single ion magnetic anisotropy : phenomelological description

Magneto cristalline energy in **hexagonal symmetry**

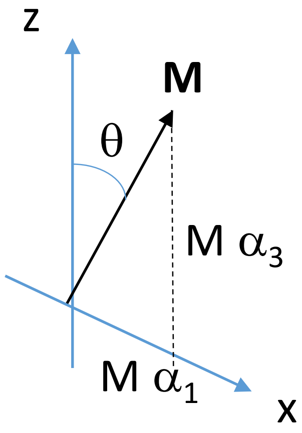
$$e_{an} = K_1 \sin^2\theta + K_2 \sin^4\theta + K_3 \sin^6\theta + K_6 \sin^6\theta \cos 6\varphi + K_{12} \sin^{12}\theta \cos 12\varphi + \ldots$$



Magneto cristalline energy in **cubic symmetry**

$$e_{an} = K_1 (\alpha_1^2 + \alpha_2^2 + \alpha_3^2) + K_2 \alpha_1^2 \alpha_2^2 \alpha_3^2 + \ldots$$

Where α_i is the direction cosine in **the i=x,y,z** direction



Note

K_i are temperature dependent…

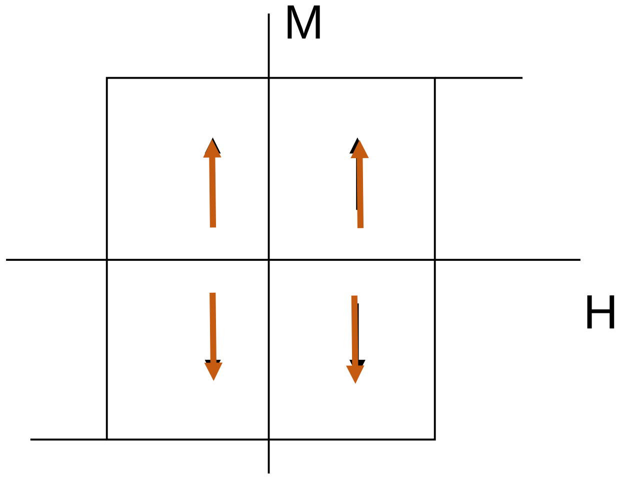
2. Magnetic anisotropy

Example: single domain grain with simple uniaxial anisotropy

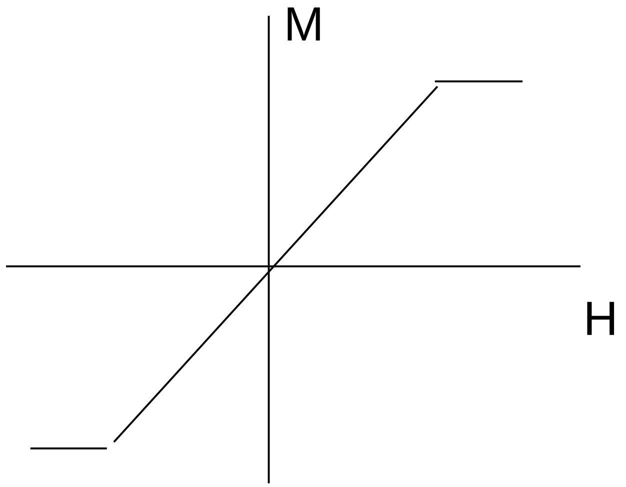
Large hysteresis for the magnetic field applied along the uniaxial direction, with a large magnetisation

$$H_c = H_a = \frac{2K}{\mu_0 M_S}$$

$$M = M_S$$



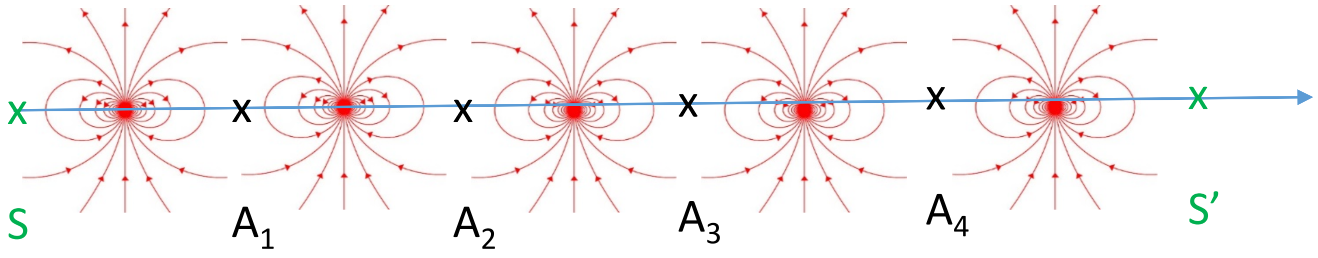
For a magnetic field perpendicular to the uniaxial direction, there is no hysteresis and a saturation occurs at H_a.



2. Shape anisotropy

At the surface of a macroscopic sample, there is a discontinuity in the magnetisation equivalent to magnetic ‘charges’. The associated magnetic field $\mathbf{H}_{\mathbf{dem}}$ is the demagnetising field that depends on the sample shape and its magnetisation

Example: A finite chain of magnetic dipoles



in A_i, the magnetic dipolar fields cancelled, not in S and S’…

$$\boldsymbol{H_{dem}} = -\, n\, \boldsymbol{M}$$

$$e_{ms} = -\frac{1}{2}\mu_0 \mathbf{M} \cdot H_{dem} = \frac{1}{2}\mu_{0_0} n\mathbf{M}^2$$

n is the demagnetising coefficent that depends on the sample shape

2. Shape anisotropy

At the surface of a macroscopic sample, there is a discontinuity in the magnetisation equivalent to magnetic ‘charges’. The associated magnetic field is the demagnetising field that depends on the sample shape.

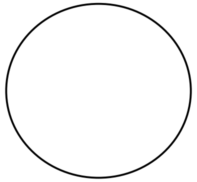
$$\boldsymbol{H}_{\boldsymbol{dem}} = -\,n\,\boldsymbol{M} \qquad e_{ms} = -\frac{1}{2}\mu_0 \mathbf{M}\cdot \boldsymbol{H}_{dem} = \frac{1}{2}\mu_0 n \mathbf{M}^2 \cdot$$

Examples :

Spheres

All directions are equivalent: no shape anisotropy

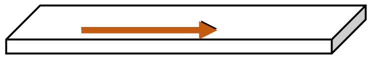
$$\boldsymbol{H}_{\boldsymbol{dem}} = -\,\frac{1}{3}\,\boldsymbol{M}$$



$$2\,e_{ms} = \mu_0 \frac{M^2}{3}$$

Thin film with in plane magnetisation:

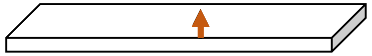
$$\boldsymbol{H}_{\boldsymbol{dem}} = 0$$



$$e_{ms} = 0$$

Thin film with out of plane magnetisation:

$$\boldsymbol{H}_{\boldsymbol{dem}} = -\,\boldsymbol{M}$$



$$2\,e_{ms} = \mu_0 M^2$$

This configuration is energetically defavorable: in a thin film the demagnetisation field acts as to maintain the magnetisation i n the plane: this is a planar **shape anisotropy**

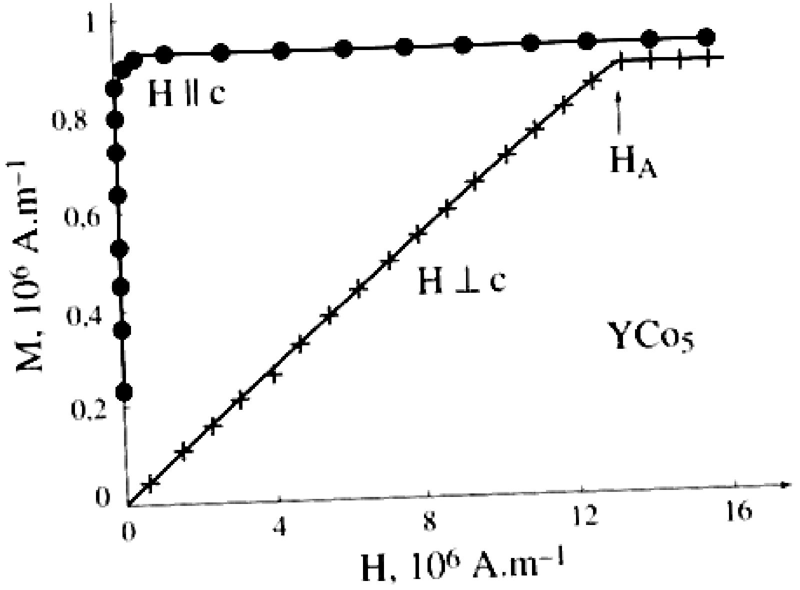
Note

n is a Tensor $\boldsymbol{H}_{dem} = -[n]\,\boldsymbol{M}$ $n = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ for a thin plate, $n = \begin{bmatrix} 1/3 & 0 & 0 \\ 0 & 1/3 & 0 \\ 0 & 0 & 1/3 \end{bmatrix}$ for a sphere …

2. Shape anisotropy

Example : YCo_5

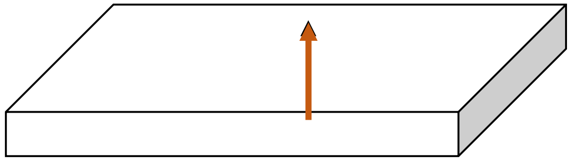
Intrinsic anistotropy



magnetization curve of the uniaxial compound YCo5

$\mu_0 H_a = 2K_1 / M_s \approx 17T$

Shape anistotropy

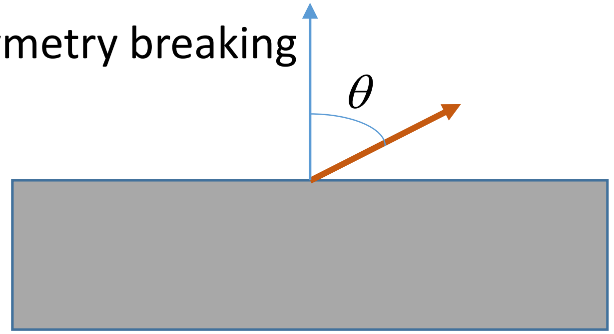


Thin film at saturated magnetization

$$\mu_0 H_{dem} = -\mu_0 M_S \approx -1.1\ T$$

2. Magnetic anisotropy

If the surface is large compared to the volume, you have to consider the surface symetry breaking



$$e_{an} = K_1 \cos^2 \theta$$

+ magnetoelastic anisotropy : Induced by the strain of the substrate

Shape anistropy + Magnetocrystaline anistotropy + magneto elastic anisotropy

$K_{eff} = K_{vol} + K_s / d$

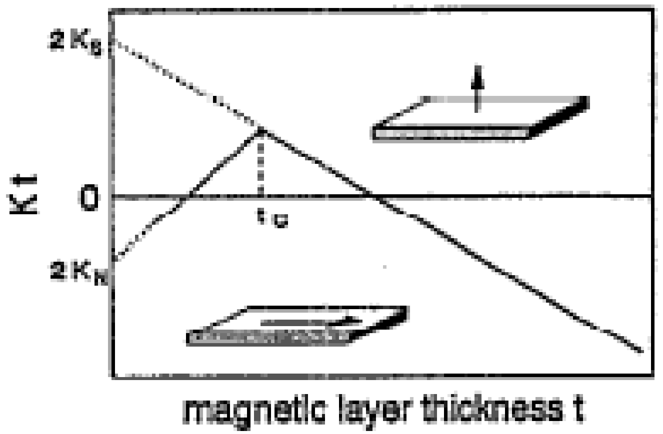


FIG. 1. Schematic dependence of Kt on layer thickness t, in the presence of negative Néel surface anisotropy K_N.

Magnetic anisotropies

3. Single ion Magnetic anisotropy : microscopic origin

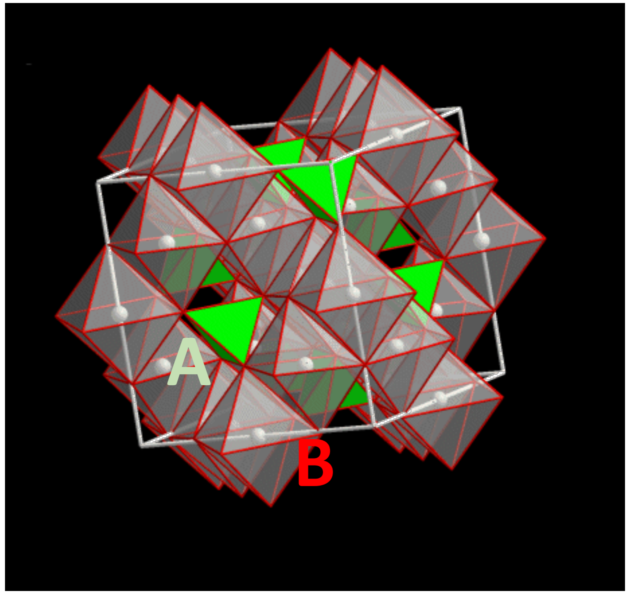
The **orbital part** of the magnetic moment is **sensitive to the electrostatic environment** (the spin part is not) created by the surroundings, **called crystal field.**

Example: spinel AB_2O_4

A and B sites with a magnetic ion surrounded by O^{2-}

A site: tetrahedral

B site: octahedral



How to describe this crystal field contribution?

Start with the quantum description of the single magnetic ion/element

Two main different cases: transition elements / rare earth elements

3. Magnetic anisotropy : microscopic origin

3d elements:

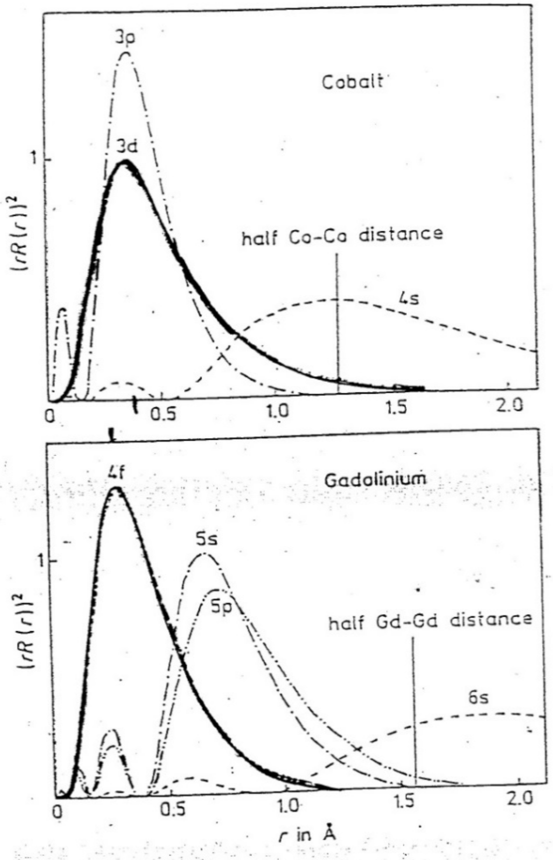
Extended electronic density

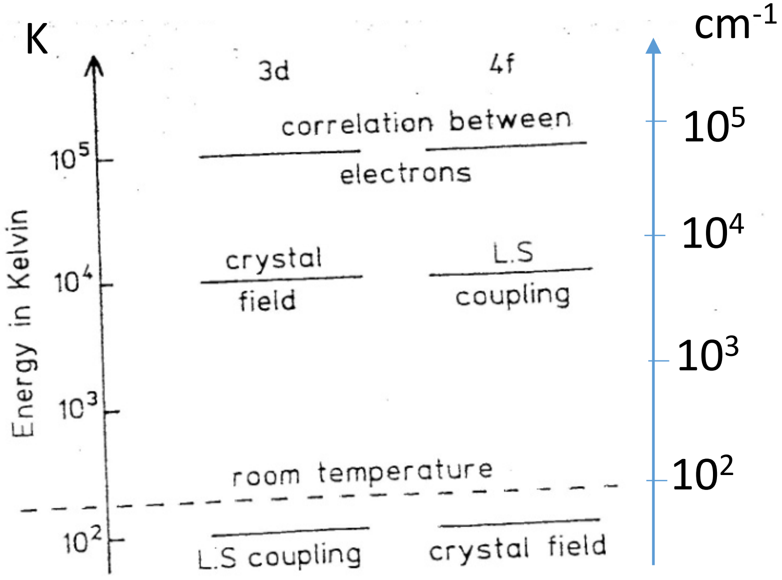
Sensitive to crystal field environnement

4f elements:

Localised electronic density

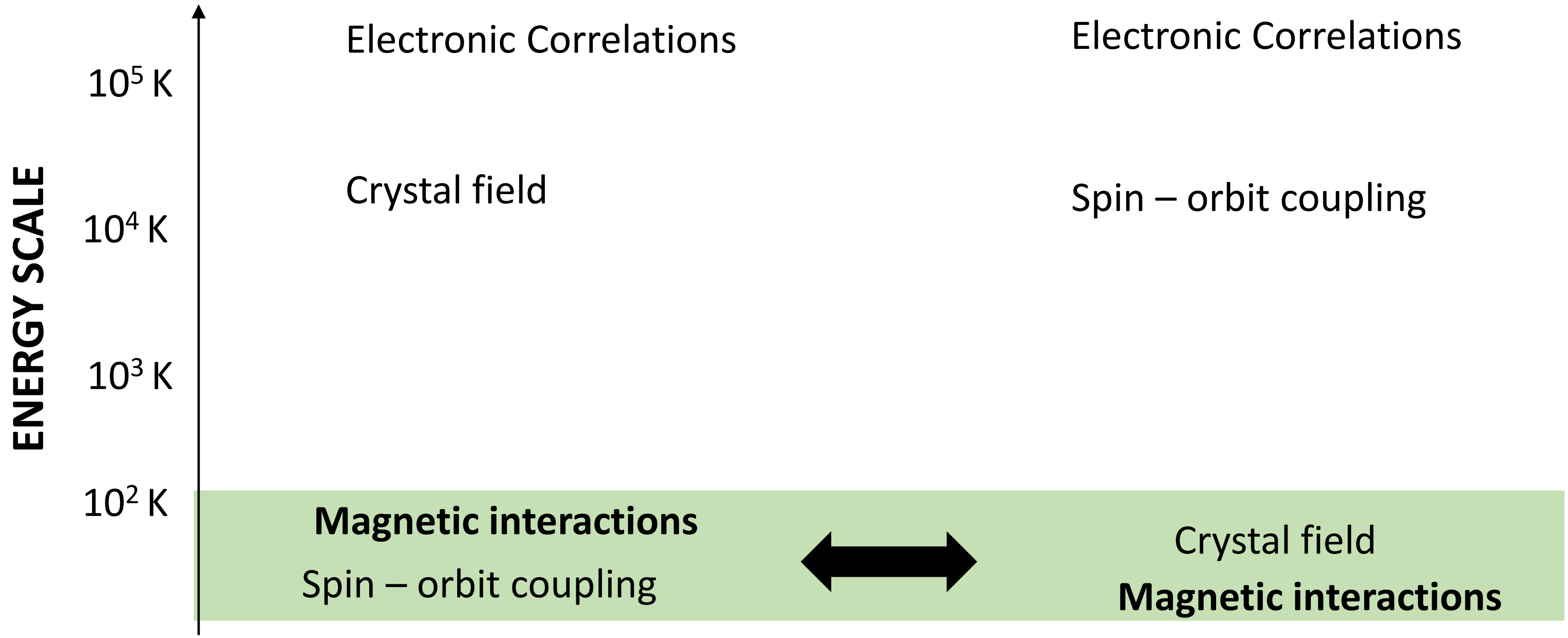
Weakly sensitive to crystal field environnement

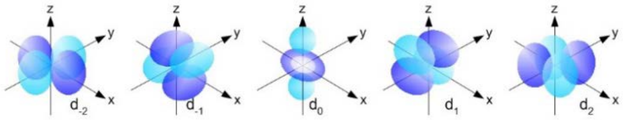




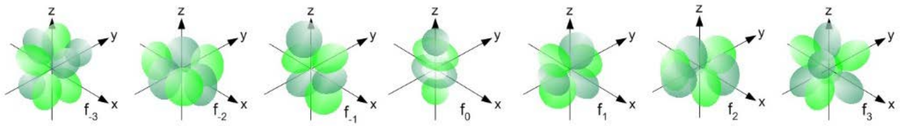
1 K = 0.0862 *meV* = 0.695 *cm*$^{-1}$

3. Magnetic anisotropy : microscopic origin





d orbitals



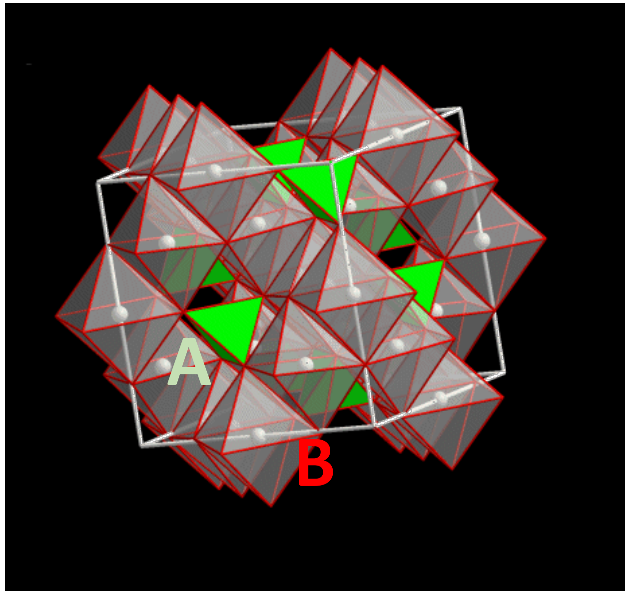
f orbitals

	Spin orbit (cm^{-1})	CF (cm^{-1})
Co^{2+}	-178	~ 1 000 -10 000
Tb^{3+}	- 1770	~ 10 -100

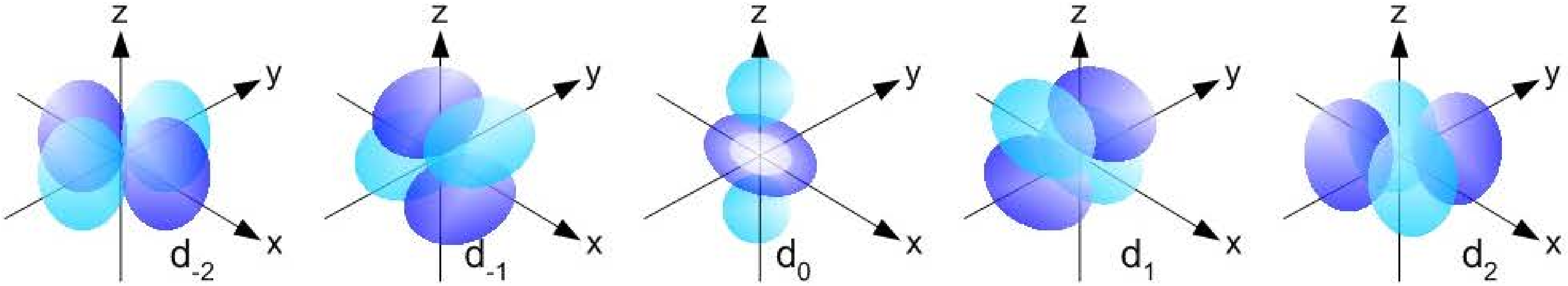
3. Magnetic anisotropy : microscopic origin

3d elements

Example : Co^{2+} , Ni^{2+} in octahedral environment
for instance B site in the spinel GeM_2O_4



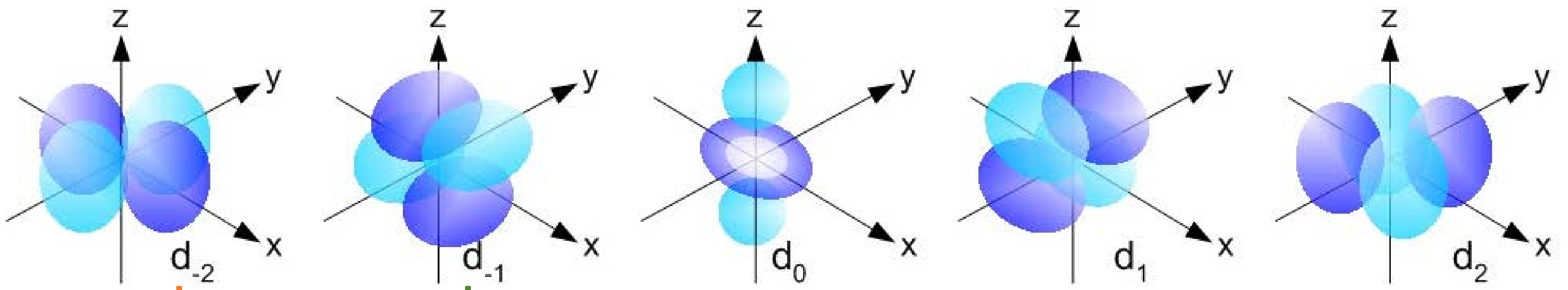
Shape of d orbitals: solutions of the Hamiltonian for electrons in the central electric potential of the positively charged nucleus



d_{x2-y2} d_{xz} d_{z2} d_{yz} d_{xy}

3. Magnetic anisotropy : microscopic origin

Shape of d orbitals



In cubic symmetry : d_{x2-y2} d_{xz} d_{z2-r2} d_{yz} d_{xy}

O_h(m-3m)	#	1	4	2	3	2'	-1	-4	m	-3	m'	functions
Mult.	-	1	6	3	8	6	1	6	3	8	6	·
A_{1g}	Γ_1^+	1	1	1	1	1	1	1	1	1	1	$x^2+y^2+z^2$
A_{1u}	Γ_1^-	1	1	1	1	1	-1	-1	-1	-1	-1	·
A_{2g}	Γ_2^+	1	-1	1	1	-1	1	-1	1	1	-1	·
A_{2u}	Γ_2^-	1	-1	1	1	-1	-1	1	-1	-1	1	·
E_g	**Γ_3^+**	**2**	**0**	**2**	**-1**	**0**	**2**	**0**	**2**	**-1**	**0**	**$(2z^2-x^2-y^2, x^2-y^2)$**
E_u	Γ_3^-	2	0	2	-1	0	-2	0	-2	1	0	·
T_{2u}	Γ_5^-	3	-1	-1	0	1	-3	1	1	0	-1	·
T_{2g}	**Γ_5^+**	**3**	**-1**	**-1**	**0**	**1**	**3**	**-1**	**-1**	**0**	**1**	**(xy,xz,yz)**
T_{1u}	Γ_4^-	3	1	-1	0	-1	-3	-1	1	0	1	(x,y,z)
T_{1g}	Γ_4^+	3	1	-1	0	-1	3	1	-1	0	-1	(J_x,J_y,J_z)

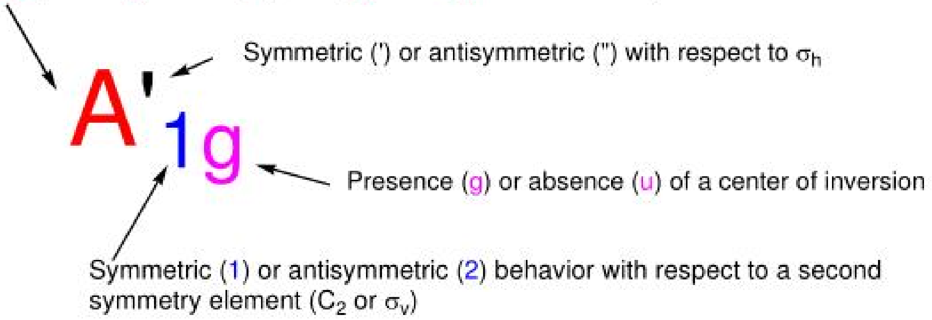
https://www.cryst.ehu.es/

REPRESENTATIONS OF SYMMETRY POINT GROUPS

1) Mulliken labels

A means *symmetric* with respect to the highest order axis C_n;
B - *antisymmetric*

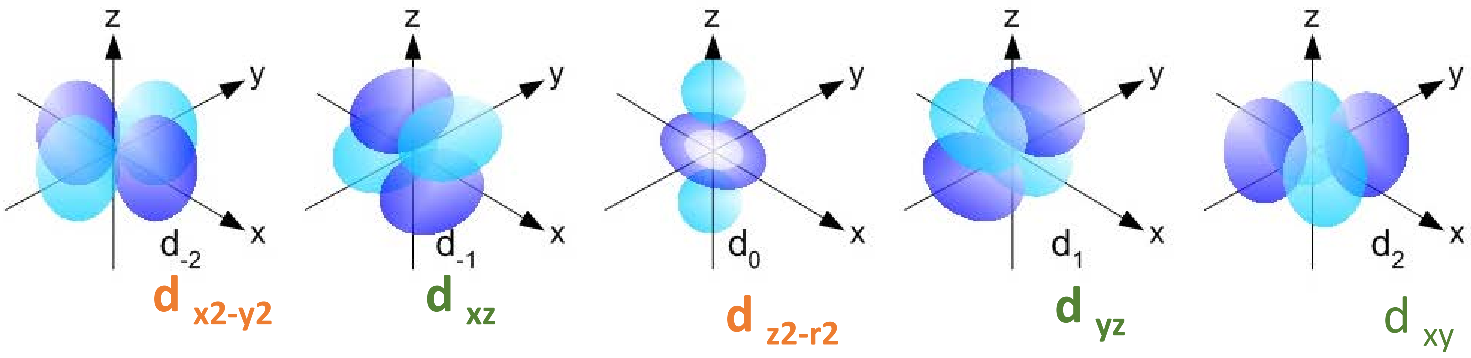
One- (A, B), two- (E), three- (T), four (G), five (H) dimensional representation



C_{2v}	E	C_2	σ_{xz}	σ_{yz}	
A_1	1	1	1	1	z
A_2	1	1	-1	-1	R_z
B_1	1	-1	1	-1	x, R_y
B_2	1	-1	-1	1	y, R_x

3. Magnetic anisotropy : microscopic origin

Shape of d orbitals

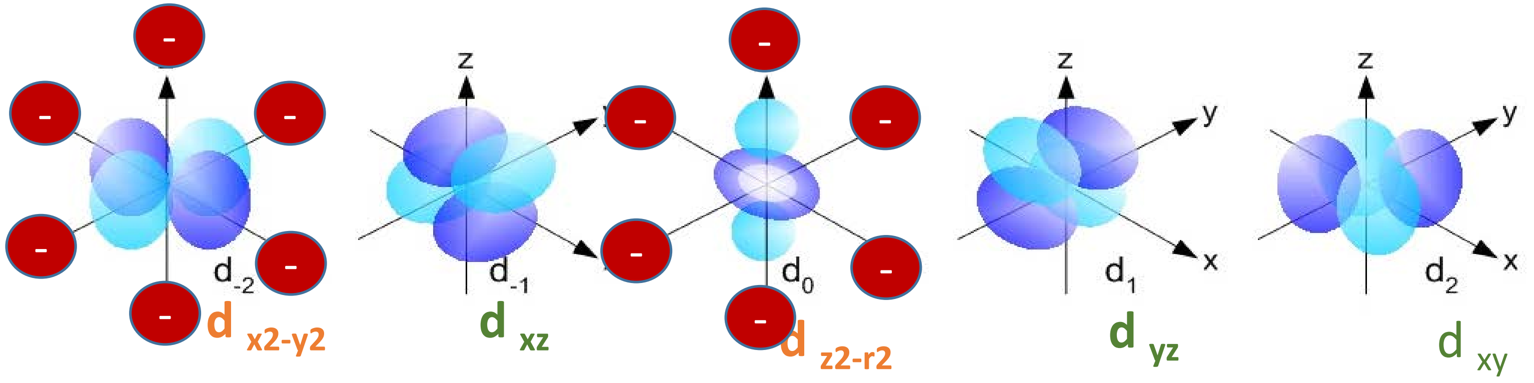


In cubic symmetry, e_g and t^2_g orbitals have the same energy

In an **octahedral crystal field symmetry**, it is no longer the case

3. Magnetic anisotropy : microscopic origin

In an octahedral crystal field:

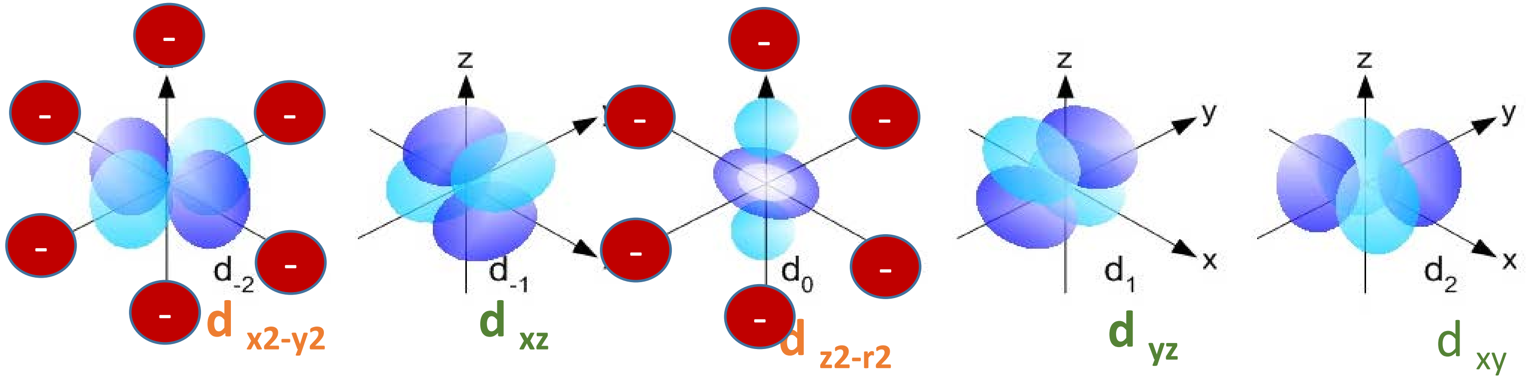


e_g Orbitals point towards the CF electric charges : strong repulsion

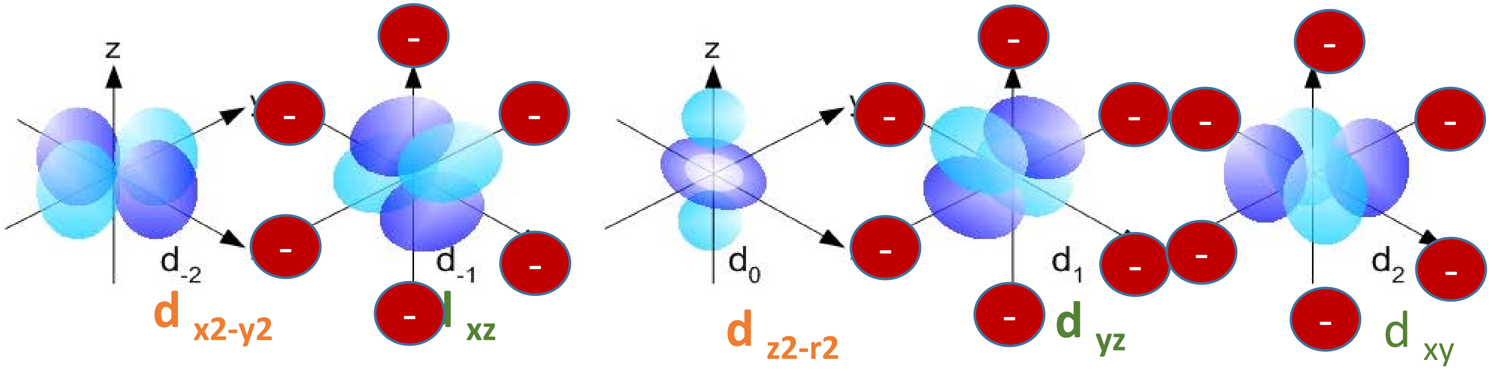
3. Magnetic anisotropy : microscopic origin

In an octahedral crystal field:

e $_g$ Orbitals point towards the CF electric charges : strong repulsion



t $_{2g}$ Orbitals point away from the CF electric charges : weak repulsion

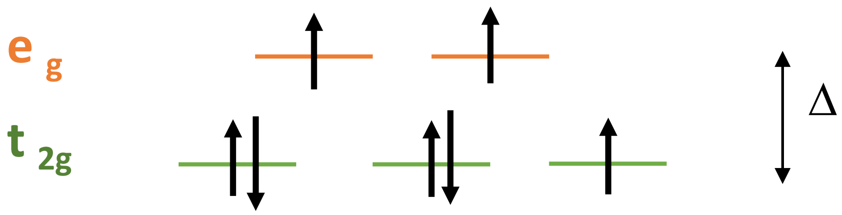


3. Magnetic anisotropy : microscopic origin

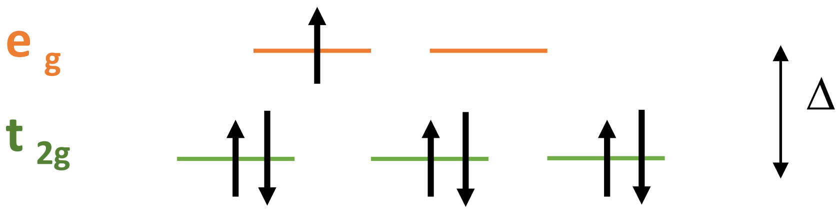
In an octahedral crystal field, there are two groups of orbitals:

Co^{2+}: $3d^7$

S = 3/2   high spin state
When Δ << U Hund coupling

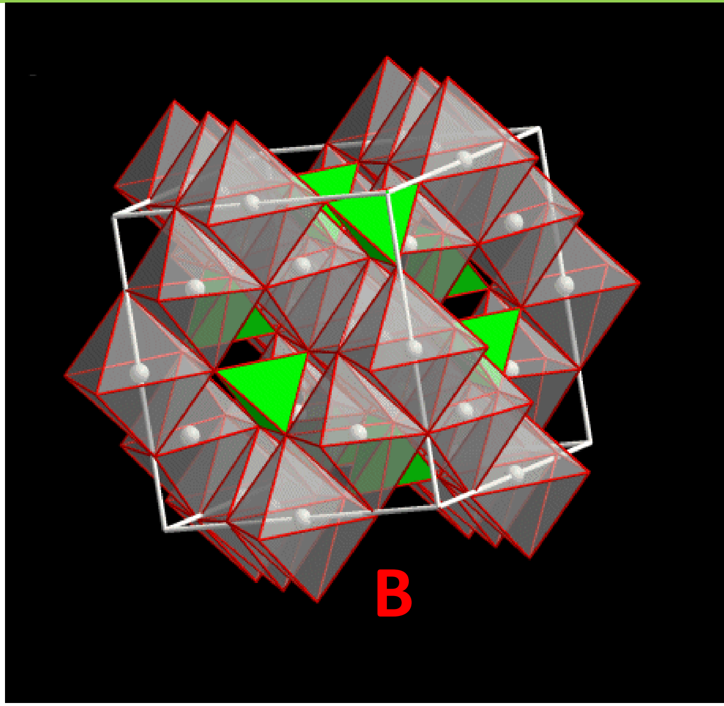


S = 1/2   low spin state
When Δ >> U Hund coupling



What is the magnetic anisotropy for these two states? INCLUDE ORBITAL CONTRIBUTION AND SPIN ORBIT COUPLING

Crystal field: quantum mechanical treatment



Crystal field:
For one electron i at position $\boldsymbol{r_i}$ experiencing the elecrostatic potential of charges q_j at position $\boldsymbol{R_j}$:

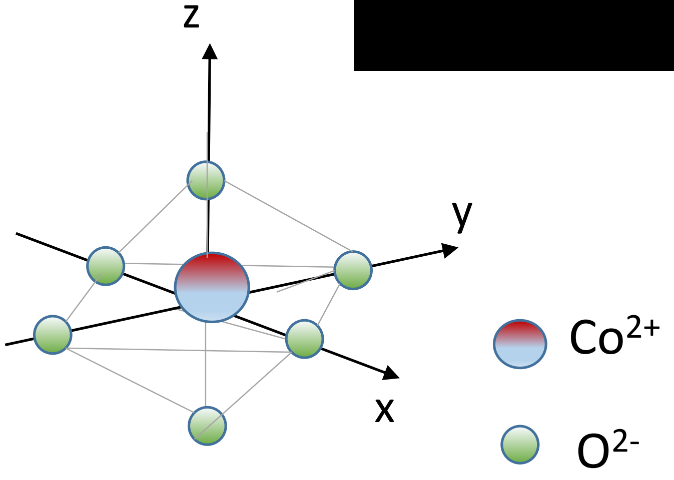
$$V_i = \frac{1}{4\pi\varepsilon_0}\sum_j \frac{q_j}{|\boldsymbol{R}_j - \boldsymbol{r}_i|}$$

In a cubic coordination :

$$V_c(x,y,z) = C_4\left[(x^4+y^4+z^4) - \frac{3}{5}r^4\right] + C_6\left[(x^6+y^6+z^6)\right. \qquad (2.51)$$

$$\left. + \frac{15}{4}(x^2y^4+x^2z^4+y^2x^4+y^2z^4+z^2x^4+z^2y^4) - \frac{15}{14}r^6\right],$$

where $C_4 = +\frac{35}{4}qq'/d^5$ for sixfold coordination.



R. White p 35 Werth and Bolton p 266

Crystal field: quantum mechanical treatment

Crystal field:
For one electron i at position $\boldsymbol{r_i}$ experiencing the elecrostatic potential of charges q_j at position $\boldsymbol{R_j}$:

$$V_i = \frac{1}{4\pi\varepsilon_0}\sum_j \frac{q_j}{|\boldsymbol{R}_j - \boldsymbol{r}_i|}$$

In a cubic coordination :

$$V_c(x,y,z) = C_4\left[(x^4+y^4+z^4) - \frac{3}{5}r^4\right] + C_6\left[(x^6+y^6+z^6) + \frac{15}{4}(x^2y^4+x^2z^4+y^2x^4+y^2z^4+z^2x^4+z^2y^4) - \frac{15}{14}r^6\right], \qquad (2.51)$$

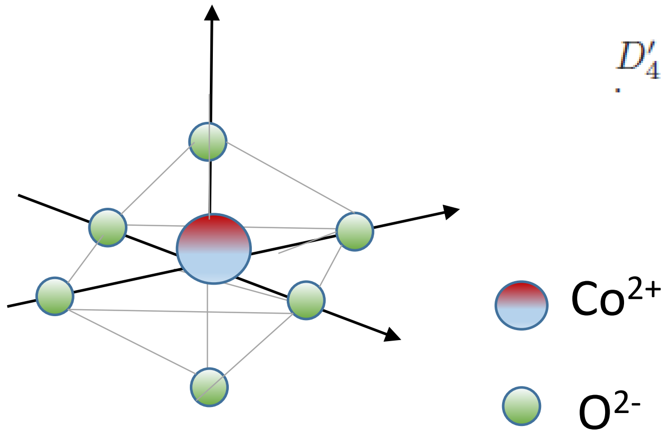
where $C_4 = +\frac{35}{4}qq'/d^5$ for sixfold coordination.

Spherical coordinates

$$V(r,\theta,\varphi) = \sum_{L'}\sum_{M'} A_{L'}^{M'} r^{L'} Y_{L'}^{M'}(\theta,\varphi)\,.$$

$$V_c(r,\theta,\varphi) = D_4'\left\{Y_4^0(\theta,\varphi) + \sqrt{\frac{5}{14}}\left[Y_4^4(\theta,\varphi)+Y_4^{-4}(\theta,\varphi)\right]\right\} + D_6'\left\{Y_6^0(\theta,\varphi) - \sqrt{\frac{7}{2}}\left[Y_6^4(\theta,\varphi)+Y_6^{-4}(\theta,\varphi)\right]\right\}$$

$D_4' = +\frac{7}{3}\sqrt{\pi}q'r^4/d^5$ for sixfold coordination.



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Crystal field: quantum mechanical treatment

The crystal field potential can be expressed in spherical harmonics $\boldsymbol{Y_L^M(\theta,\varphi)}$ or more conveniently using angular momentum operators

Operator equivalent method: matrix elements of operators involving *x,y,* and *z* within a given *L* or *J* manifold are proportional to those of *Lx, Ly* and *Lz* or *Jx, Jy* and *Jz*

$$\sum\left(x^4+y^4+z^4-\frac{3}{5}r^4\right)$$

$$\Rightarrow \frac{\beta\overline{r^4}}{8}\left[35L_z^4-30L(L+1)L_z^2+25L_z^2-6L(L+1)+3L^2(L+1)^2\right]$$

$$+\frac{\beta\overline{r^4}}{8}\left[(L^+)^4+(L^-)^4\right]\equiv\frac{\beta\overline{r^4}}{20}O_4^0+\frac{\beta\overline{r^4}}{4}O_4^4=B_4^0O_4^0+B_4^4O_4^4\,,\quad(2.52)$$

where $\overline{r^4}$ is the average value of the fourth power of the electron radius. The operators O_n^m appear frequently in the literature. The ground state β is a constant which depends on the term; for a ^2D or a ^5D term $\beta=\frac{2}{63}$.

Racah operators O_m^l are also used (or Wybourne….). They are linear combinations, with eventually a radial contribution and a renormalization coefficient, that are tabulated . See for instance **Point-Charge Calculations of Energy Levels of Magnetic Ions in Crystalline Electric Fields***M.T.Hutchings

3. Magnetic anisotropy : the case of Co^{2+}

•**Co^{2+}:** $3d^7$ $S=3/2$ $L=3$ $J= 9/2$ $\mathbf{{}^4F_{9/2}}$

orbital degeneracy: 7 (/ 3>, /2> /1> /0> /-1> /-2> /-3>)

lifted by the crystal field

In an octahedral crystal field:

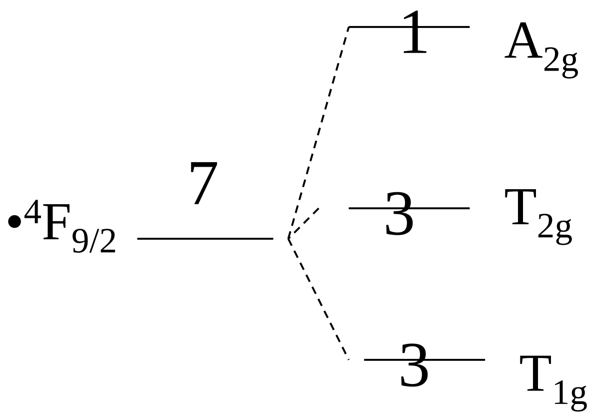
$W(T_{1g})=3/5\,\Delta$ triply degenerate

$W(T_{2g})=-1/5\,\Delta$ triply degenerate

$W(A_{2g})=-6/5\,\Delta$ non degenerate

$\Delta = 30\,\beta_c$ is the crystal field strength in the CF hamiltonian

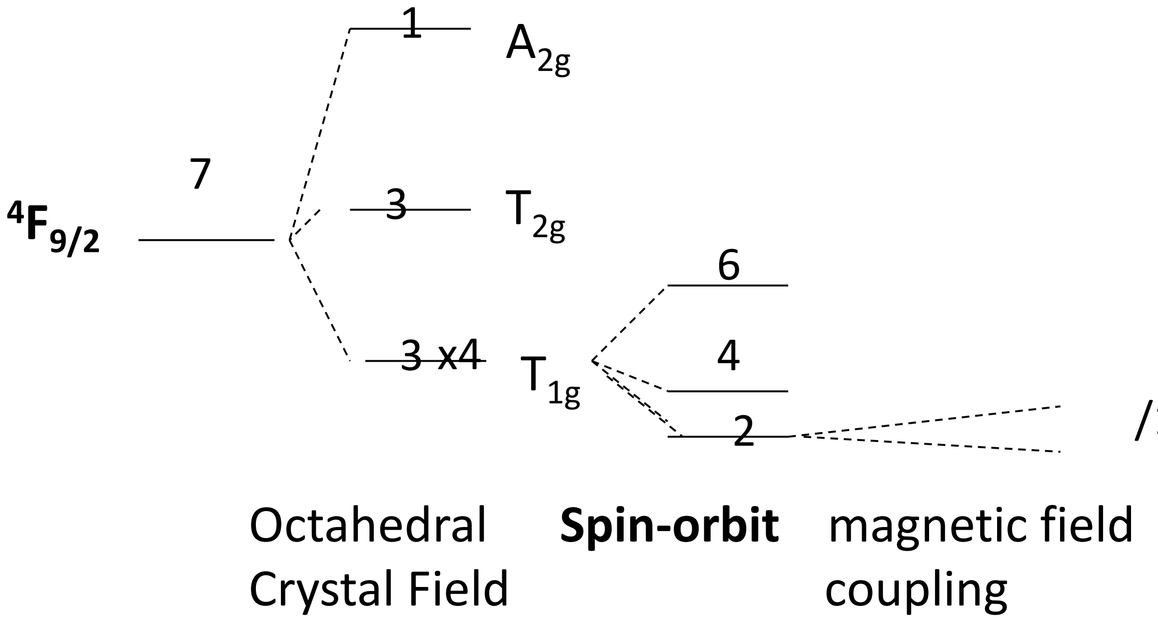
Where Δ is negative for $3\,d^7$: the ground state is T_{1g} and triply degenerate



Spin degeneracy: $2S+1=4$

from Wertz and Bolton

3. Magnetic anisotropy : the case of Co^{2+}



/1/2,±1/2>=0.71/±1, ±3/2> - 0.58 /0, ±1/2> +0.41 /±1, ±1/2>

high spin state Doublet: Seff = ½ g = 4.33

ex: Co^{2+} in MgO: g=4.28 **isotropic**

Note

In a distorted octahedra, strong g anisotropy

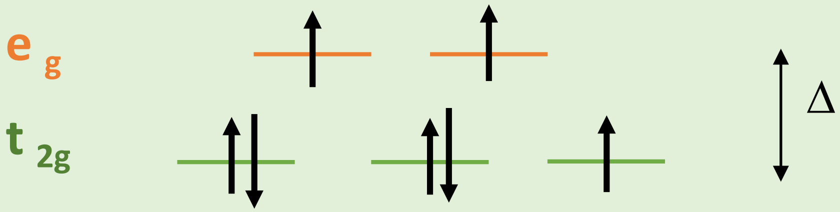
ex: Co^{2+} in TiO_2: g_{xx}=2.09, g_{YY}=3.72, g_{ZZ}=5.86

3. Magnetic anisotropy : the case of Co^{2+}

Co^{2+}: $3d^7$

Orbital degeneracy

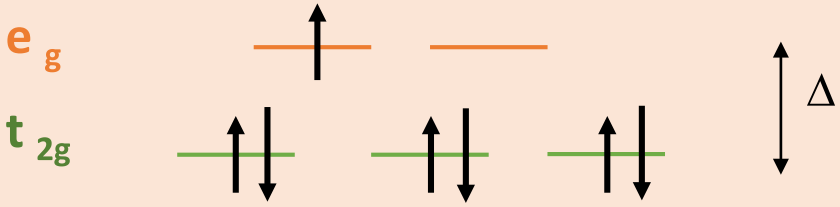
S = 3/2   high spin state
When Δ << U Hund coupling



$^4T_{1g}$

triplet: Jeff= 1

S = 1/2   low spin state
When Δ >> U Hund coupling



^2E_g

Doublet: Jeff= 1/2

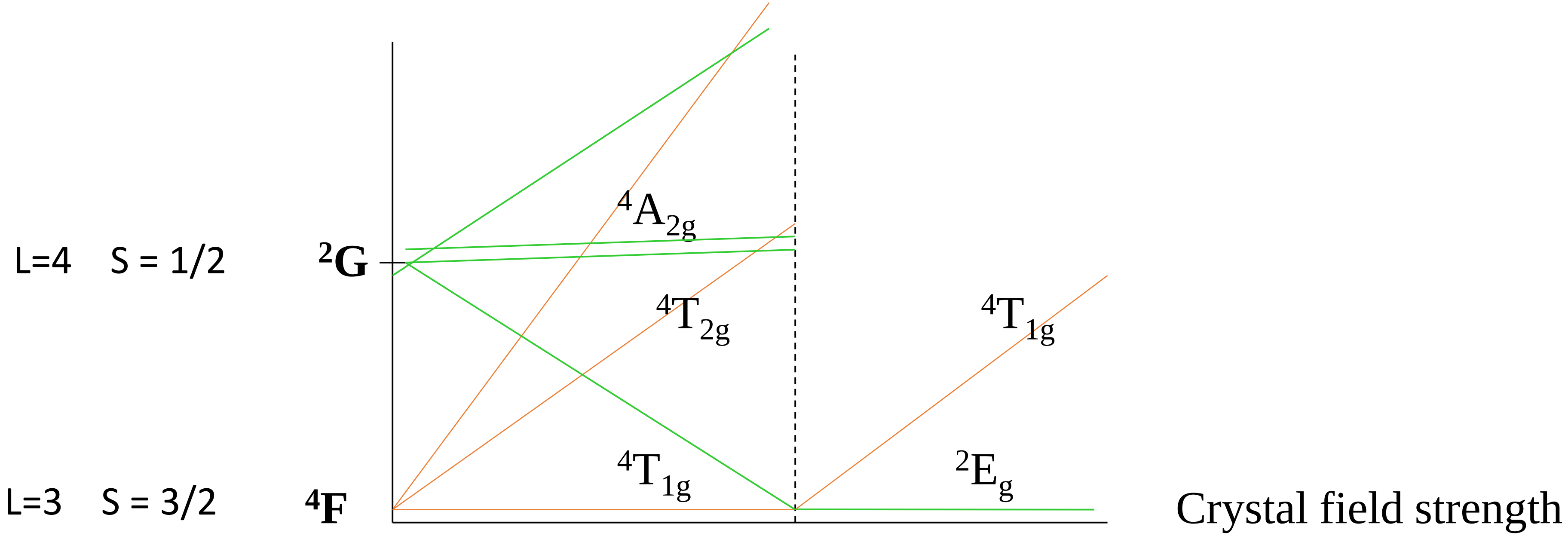
Isotropic but anisotropic under Jahn Teller distorsion

3. Magnetic anisotropy : the case of Co^{2+}

- **Co^{2+}: $^{4}F_{9/2}$**

  octahedral crystal field

  Dependence on the CF strength



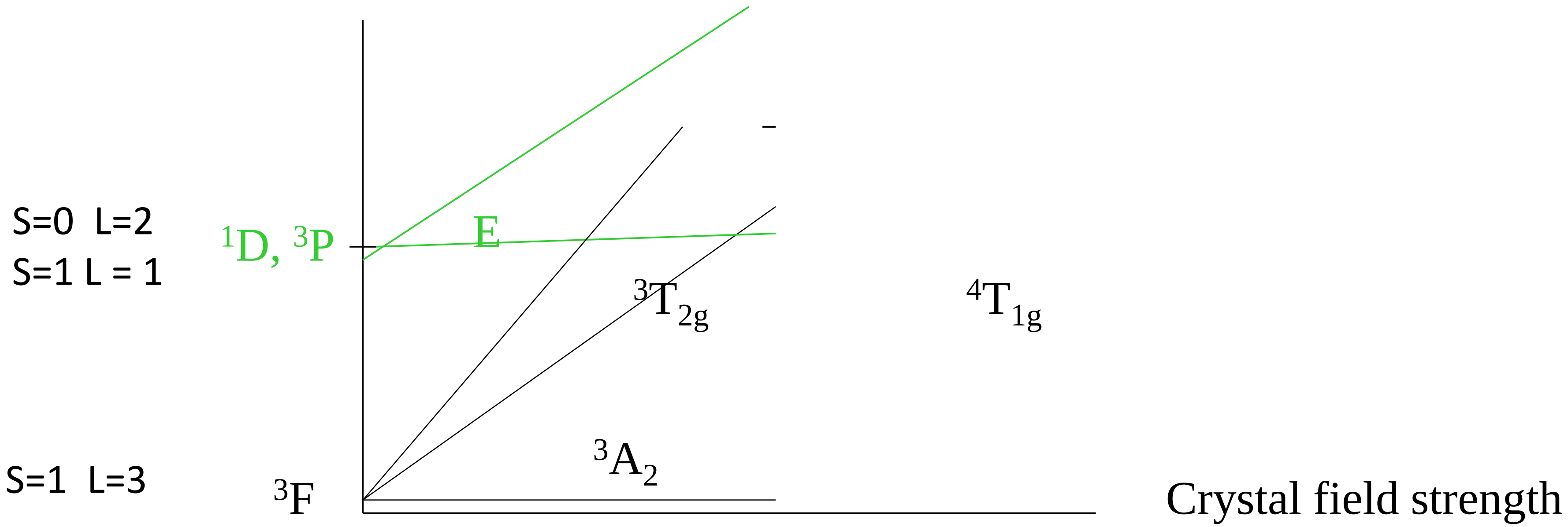
High spin state:
Ground state $^{4}T_{1g}$
Triply degenerate
(L'=1)

Low spin state:
ground state
Doubly degenerate $^{2}E_{g}$

3. Magnetic anisotropy : the case of Ni^{2+}

•**Ni^{2+}: $3d^8$** S=1, L=3, J=4 **$^3F_4$**

In octahedral crystal field:



Non degenerate ground state $^3A_{2g}$

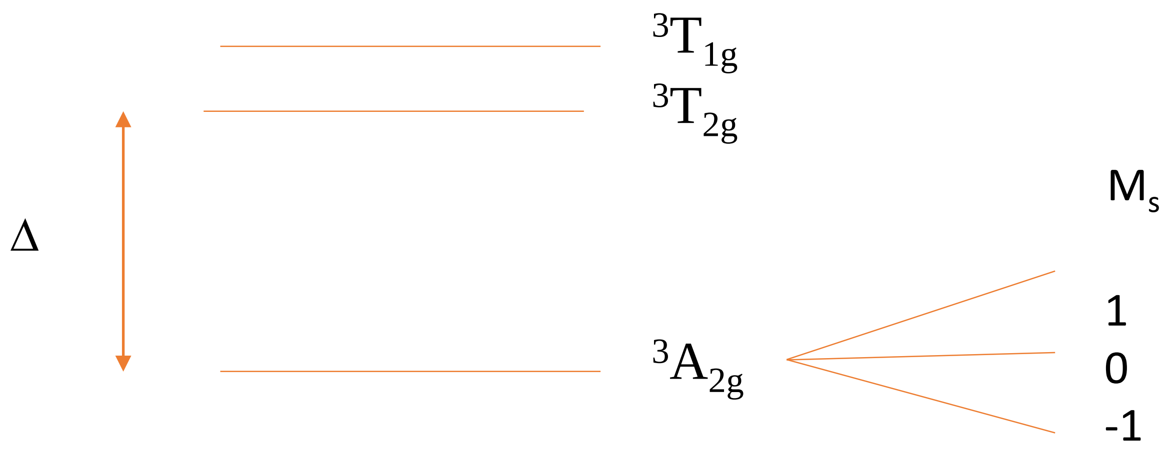
3. Magnetic anisotropy : the case of Ni^{2+}

Ni^{2+} $^{3}F_{4}$

- in octahedral crystal field: $^{3}A_{2g}$
- Spin orbit coupling with excited T2g state, S = 1

g isotropic $g=g_e-8\lambda/\Delta$

- litterature g=2.1-2.33 (λ = -325 cm^{-1} $\Delta \approx$ 12 000 cm^{-1})



3. Magnetic anisotropy : CF origin

Single ion orbitals in the CF environment created by the ion surroundings

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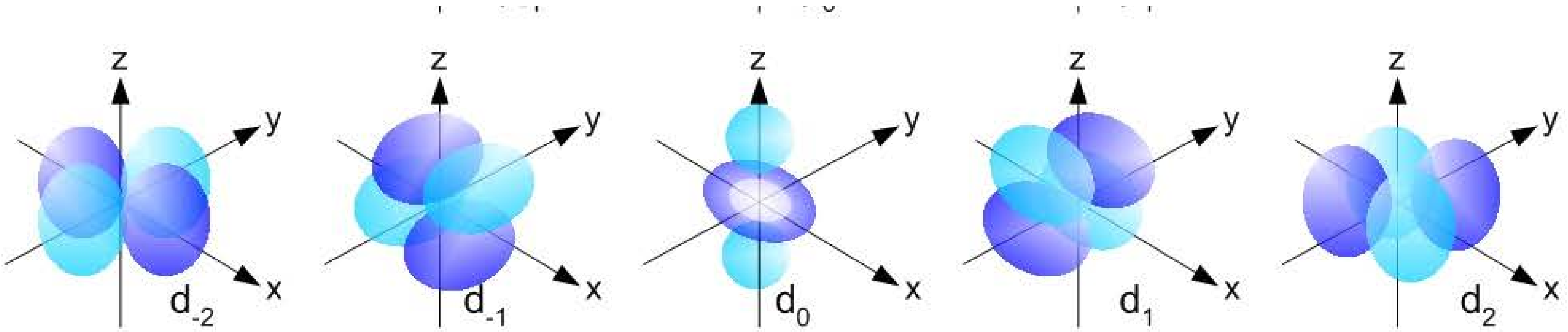
Quantum calculations in a point charge model

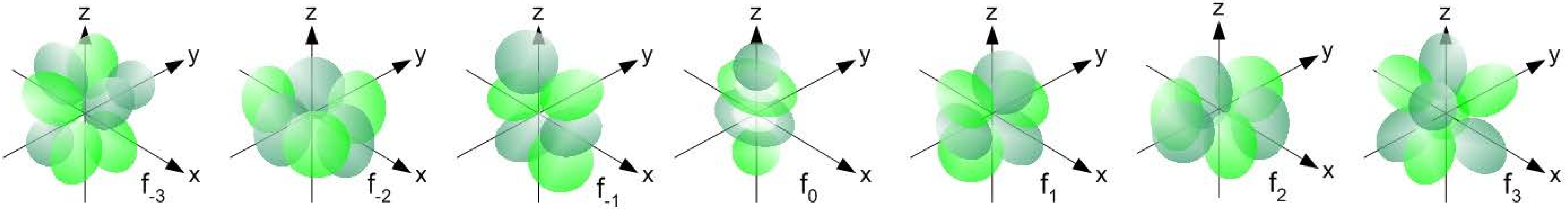
Note

Limitation: charge screening effects from delocalized electrons : conduction electrons or covalency effects

Description of the single ion/element magnetic moment

3d elements





4f elements

Crystal field: quantum mechanical treatment

Spectroscopic notation
According to the total
orbital momentum

L	0	1	2	3	4	5	6
symbol	S	P	D	F	G	H	I

$^{2S+1}L_J$

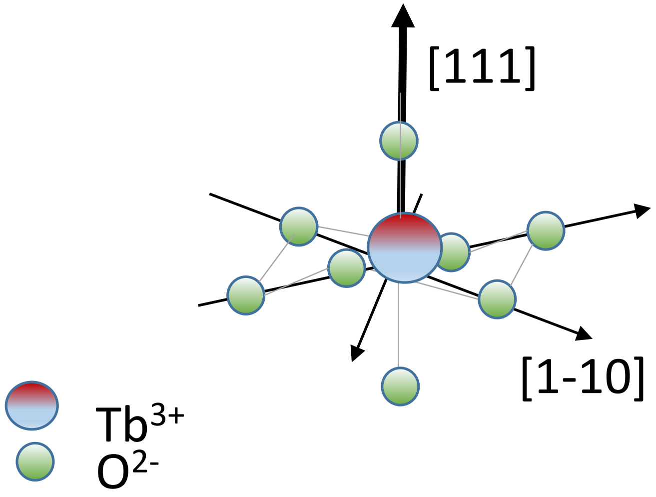
3d elements

No. of electrons	S	L	J	Orbital degeneracy	Spectroscopic symbol	examples
	Of the ground state					
1	1/2	2	3/2	5	$^2D_{3/2}$	Sc^{2+}, Ti^{3+}
2	1	3	2	7	$^3F_2$	Ti^{2+}, V^{3+}, Cr^{4+}
3	3/2	3	3/2	7	$^4F_{3/2}$	V^{2+}, Cr^{3+}, Mn^{4+}
4	2	2	0	5	$^5D_0$	Cr^{2+}, Mn^{3+}
5	5/2	0	5/2	1	$^6S_{5/2}$	Mn^{2+}, Fe^{3+}
6	2	2	4	5	$^5D_4$	Fe^{2+}
7	3/2	3	9/2	7	$^4F_{9/2}$	**Co^{2+},** Ni^{3+}
8	1	3	4	7	$^3F_4$	**Ni^{2+},** Cu^{3+}
9	1/2	2	5/2	5	$^2D_{5/2}$	Cu^{2+}

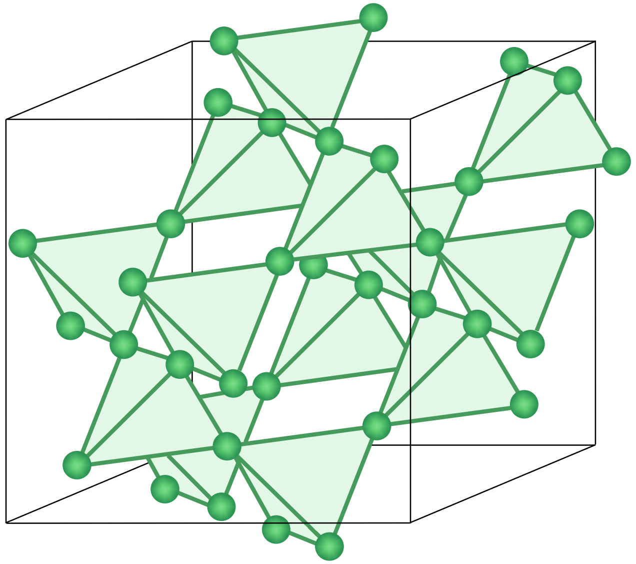
4f elements

No. of electrons	S	L	J	Orbital degeneracy	Spectroscopic symbol	examples
	Of the ground state					
1	1/2	3	5/2	7	$^2F_{5/2}$	Ce^{3+}
2	1	5	4	11	$^3H_4$	Pr^{3+}
3	3/2	6	9/2	13	$^4I_{9/2}$	Nd^{3+}
4	2	6	4	13	$^5I_4$	Pm^{3+}
5	5/2	5	5/2	11	$^6H_{5/2}$	Sm^{3+}
6	3	3	0	7	$^7F_0$	Eu^{2+}
7	7/2	0	7/2	0	$^8S_{7/2}$	Gd^{3+}
8	3	3	6	7	$^7F_6$	**Tb^{3+}**
9	5/2	5	15/2	11	$^6H_{15/2}$	Dy^{3+}
10	2	6	8	13	$^5I_8$	Ho^{3+}
11	3/2	6	15/2	13	$^4I_{15/2}$	Er^{3+}
12	1	5	6	11	$^3H_6$	Tm^{3+}
13	1/2	3	7/2	7	$^2F_{7/2}$	Yb^{3+}

3. Magnetic anisotropy : the case of Tb3+ in the pyrochlore Tb2Ti2O_7



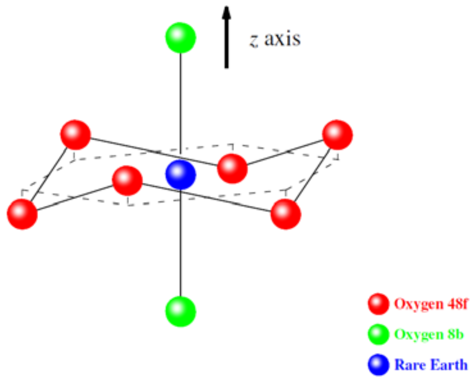
D3d symmetry

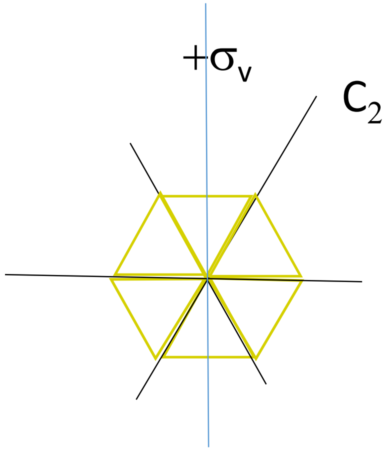


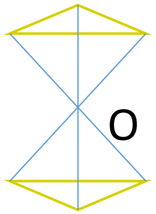
Quantum Spin ice

$$\widehat{\mathcal{H}}_{\mathrm{CF}} = B_2^0\widehat{\mathcal{O}}_2^0 + B_4^0\widehat{\mathcal{O}}_4^0 + B_4^3\widehat{\mathcal{O}}_4^3 + B_6^0\widehat{\mathcal{O}}_6^0 + B_6^3\widehat{\mathcal{O}}_6^3 + B_6^6\widehat{\mathcal{O}}_6^6.$$

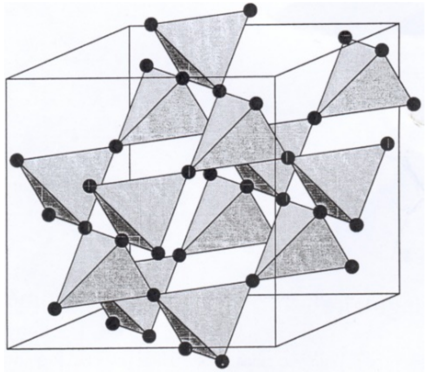
3. Tb^{3+} in the pyrochlore Tb2Ti2O7







D3d= C3 principal axes along [111]=z + $3C_2$ axis along [1-10]=x +120°+120°
+ 3 σ_v mirrors bisecting the angles formed by pairs of C2 axes centrosymmetric
Tb^{3+} (16d) surrounded by 6 O^{2-} (O1 at 48f) at 0.250 nm and 2 O^{2-} (O2 at 8b) at 0.225 nm along [111] centrosymmetric



3. Tb^{3+} in the pyrochlore Tb2Ti2O7

$$\widehat{\mathcal{H}}_{\mathrm{CF}} = B_2^0\widehat{\mathcal{O}}_2^0 + B_4^0\widehat{\mathcal{O}}_4^0 + B_4^3\widehat{\mathcal{O}}_4^3 + B_6^0\widehat{\mathcal{O}}_6^0 + B_6^3\widehat{\mathcal{O}}_6^3 + B_6^6\widehat{\mathcal{O}}_6^6,$$

Stevens operators

$$\widehat{X} = J(J+1)\widehat{I},$$

$$\widehat{\mathcal{O}}_2^0 = \widehat{\mathcal{O}}_{z^2} = 3\widehat{J}_z - \widehat{X}$$

$$\widehat{\mathcal{O}}_2^1 = \widehat{\mathcal{O}}_{xz} = \frac{1}{2}(\widehat{J}_z\widehat{J}_x + \widehat{J}_x\widehat{J}_z)$$

$$\widehat{\mathcal{O}}_2^{-1} = \widehat{\mathcal{O}}_{yz} = \frac{1}{2}(\widehat{J}_z\widehat{J}_y + \widehat{J}_y\widehat{J}_z)$$

$$\widehat{\mathcal{O}}_2^2 = 2\widehat{\mathcal{O}}_{x^2-y^2} = \frac{1}{2}(\widehat{J}_+^2 + \widehat{J}_-^2) = \widehat{J}_x^2 - \widehat{J}_y^2$$

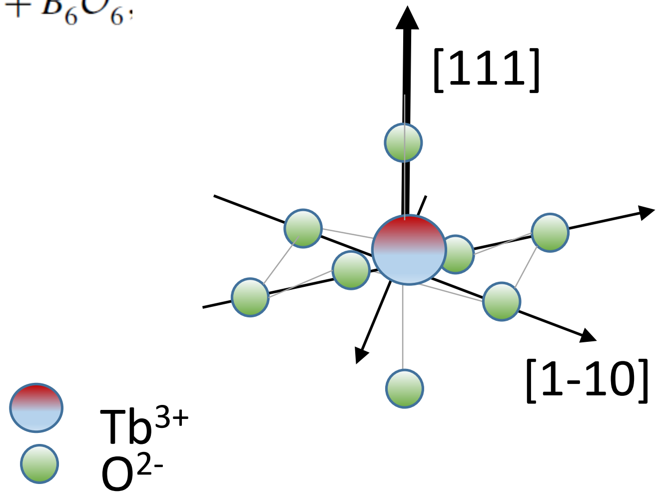
$$\widehat{\mathcal{O}}_2^{-2} = 2\widehat{\mathcal{O}}_{xy} = -\frac{i}{2}(\widehat{J}_+^2 - \widehat{J}_-^2) = \widehat{J}_x\widehat{J}_y + \widehat{J}_y\widehat{J}_x$$

$$\widehat{\mathcal{O}}_4^0 = 35\widehat{J}_z^4 - [30\widehat{X} - 25\widehat{I}]\widehat{J}_z^2 + [3\widehat{X}^2 - 6\widehat{X}]$$

$$\widehat{\mathcal{O}}_4^3 = \frac{1}{4}[\widehat{J}_z(\widehat{J}_+^3 + \widehat{J}_-^3) + (\widehat{J}_+^3 + \widehat{J}_-^3)\widehat{J}_z]$$

$$\widehat{\mathcal{O}}_4^4 = \frac{1}{2}(\widehat{J}_+^4 + \widehat{J}_-^4)$$

$$\widehat{\mathcal{O}}_6^0 = 231\widehat{J}_z^6 - [315\widehat{X} - 735\widehat{I}]\widehat{J}_z^4 + [105\widehat{X}^2 - 525\widehat{X} + 294\widehat{I}]\widehat{J}_z^2 - [5\widehat{X}^3 - 40\widehat{X}^2 + 60\widehat{X}]$$



Whybourne operators operators

$$\widetilde{\mathcal{O}}_n^m = (\lambda_n^m)^{-1}\left(\widehat{C}^n_{-m} + (-1)^m\widehat{C}^n_m\right)$$

TABLE II. Values of λ_n^m parameters involved in the CF Hamiltonian of the studied pyrochlore.

λ_2^0	λ_4^0	λ_4^3	λ_6^0	λ_6^3	λ_6^6
1/2	1/8	$-\sqrt{35}/2$	1/16	$-\sqrt{105}/8$	$\sqrt{231}/16$

$$\widehat{C}^n_m = \sqrt{\frac{4\pi}{2n+1}}\widehat{Y}^m_n.$$

Other Stevens operators…

$$\widetilde{\mathcal{O}}_n^m = \theta_n(J)\widehat{\mathcal{O}}_n^m.$$

TABLE III. Matrix element $\theta_n(J)$ for Tb^{3+} ($J = 6$).

θ_2	θ_4	θ_6
$-1/99$	2/16335	$-1/891891$

K. Amelin, **Y. Alexanian** et al PHYSICAL REVIEW B **102**, 134428 (2020)

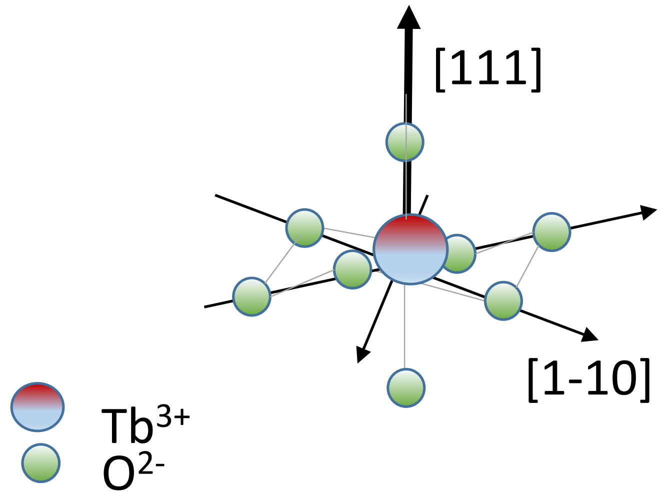
3. Tb^{3+} in the pyrochlore Tb2Ti2O7

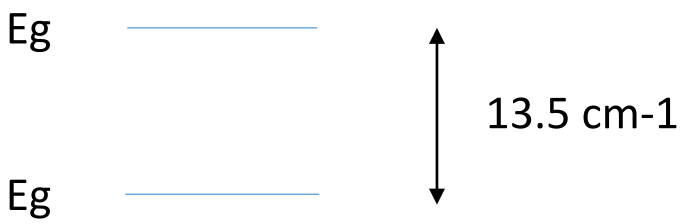
$$\widehat{\mathcal{H}}_{\mathrm{CF}} = B_2^0\widehat{\mathcal{O}}_2^0 + B_4^0\widehat{\mathcal{O}}_4^0 + B_4^3\widehat{\mathcal{O}}_4^3 + B_6^0\widehat{\mathcal{O}}_6^0 + B_6^3\widehat{\mathcal{O}}_6^3 + B_6^6\widehat{\mathcal{O}}_6^6.$$

TABLE I. CF parameters used in the CF Hamiltonian.

B_k^q	meV	K
B_2^0	-0.26	-3.0
B_4^0	4.5×10^{-3}	5.2×10^{-2}
B_4^3	-4.1×10^{-2}	-4.8×10^{-1}
B_6^0	-4.5×10^{-6}	-5.2×10^{-5}
B_6^3	-1.2×10^{-4}	-1.4×10^{-3}
B_6^6	-1.4×10^{-4}	-1.6×10^{-3}

	$\|\psi_+^0\rangle(0.0)$	$\|\psi_-^0\rangle(0.0)$	$\|\psi_+^1\rangle(13.5)$	$\|\psi_-^1\rangle(13.5)$
$\|6\rangle$				
$\|5\rangle$	0.35		−0.89	
$\|4\rangle$		−0.91		−0.37
$\|3\rangle$				
$\|2\rangle$	0.18		−0.25	
$\|1\rangle$		−0.13		−0.14
$\|0\rangle$				
$\|-1\rangle$	−0.13		−0.11	
$\|-2\rangle$		−0.18		0.25
$\|-3\rangle$				
$\|-4\rangle$	0.91		0.37	
$\|-5\rangle$		0.35		−0.89
$\|-6\rangle$				

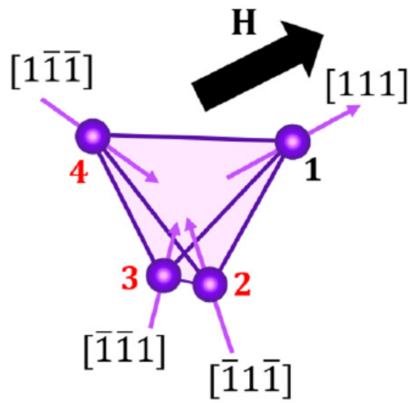




B_k^q parameters have been fitted using the experimental values of the excited states energies

3. Tb^{3+} in the pyrochlore Tb2Ti2O7

$$\widehat{\mathcal{H}}_{\mathrm{CF}} = B_2^0\widehat{\mathcal{O}}_2^0 + B_4^0\widehat{\mathcal{O}}_4^0 + B_4^3\widehat{\mathcal{O}}_4^3 + B_6^0\widehat{\mathcal{O}}_6^0 + B_6^3\widehat{\mathcal{O}}_6^3 + B_6^6\widehat{\mathcal{O}}_6^6,$$



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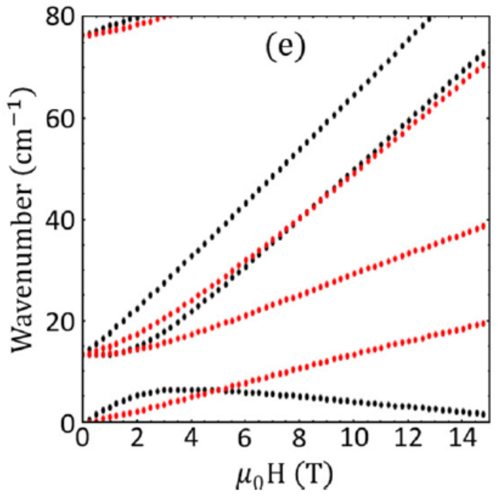
B_6^0	-4.5×10^{-6}	-5.2×10^{-5}
B_6^3	-1.2×10^{-4}	-1.4×10^{-3}
B_6^6	-1.4×10^{-4}	-1.6×10^{-3}



Uniaxial Ising spins or the ground and first excited state
OK spin ice BUT first excited state close in energy ➡ quantum spin ice

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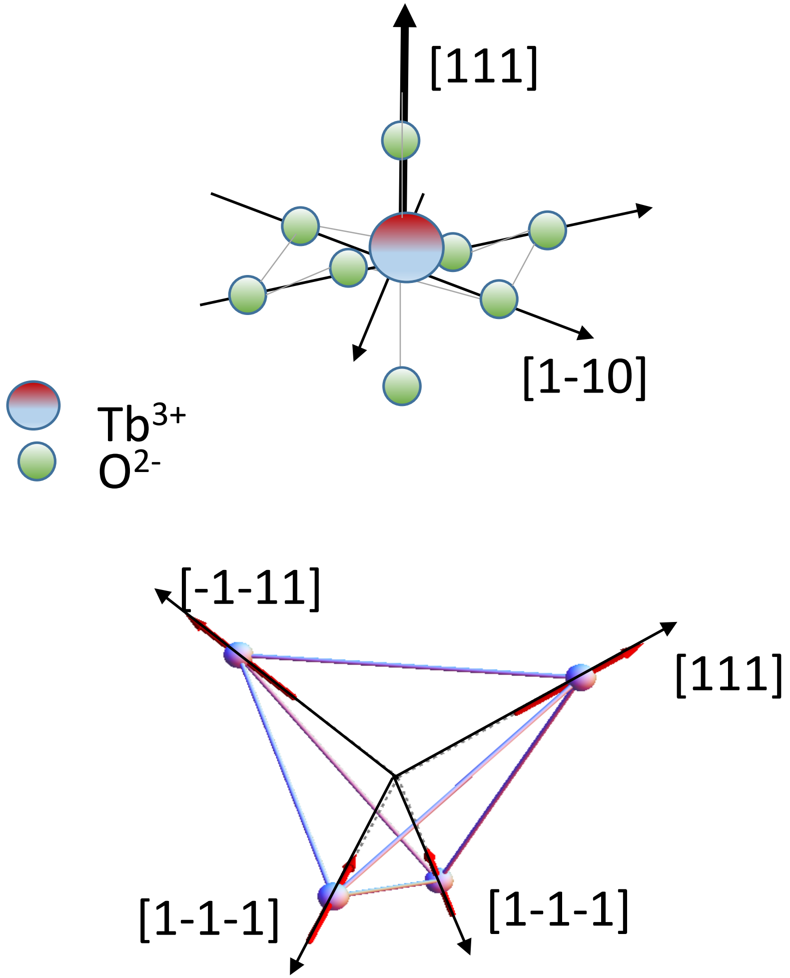
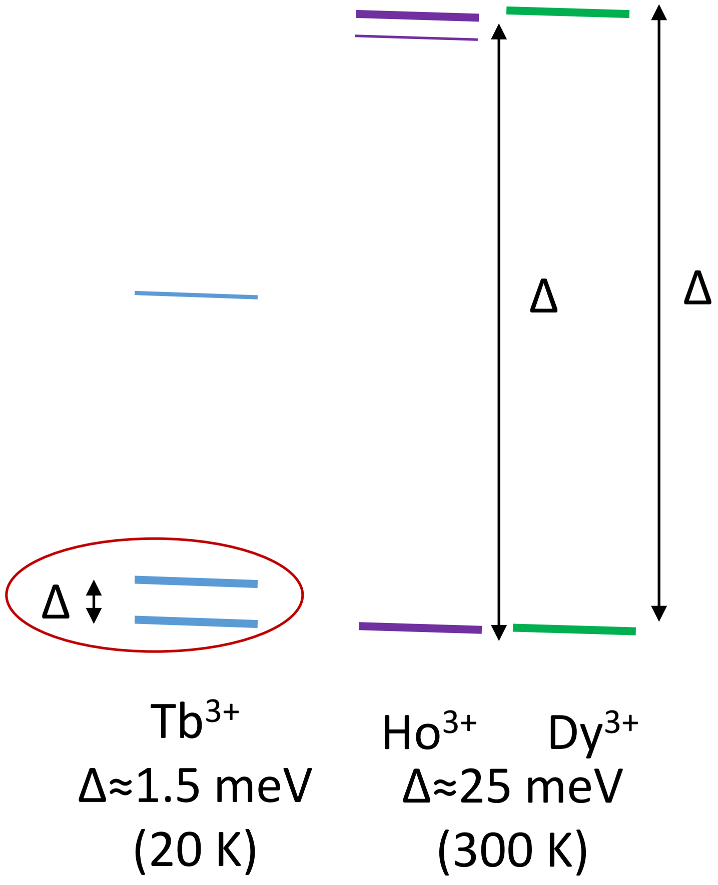
$Tb_2Ti_2O_7$ peculiarities: Crystal Electric Field (CEF)

Local symmetry: D3d



Crystal Electric Field levels :



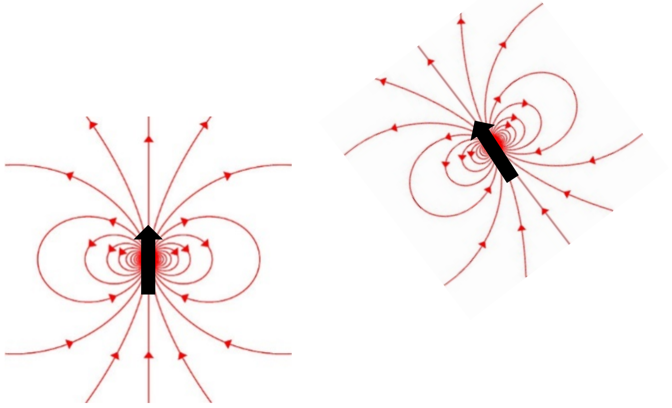
Weak Ising: Crystal Electric Field (CEF) level at 20 K (300 K for $Ho_2Ti_2O_7$)

Magnetic anisotropies

1. Importance of magnetic anisotropy
2. Single ion Magnetic anisotropy: phenomenological description
3. Single ion Magnetic anisotropy: microscopic origin
4. **Exchange anisotropy**
5. Examples with magneto-electric effects

4. Exchange anisotropy

The exchange energy between two ions depends on the direction of the magnetic moment of each ion



Dipolar anisotropy between two magnetic elements of magnetic moment μ_i and μ_j at a distance r_{ij} from each other :

$$\mathcal{H}_{\rm dip} = \sum_{\substack{i,j \neq j \\ i}} \frac{1}{r_{ij}^3} \left[\boldsymbol{\mu}_i \cdot \boldsymbol{\mu}_j - 3(\boldsymbol{\mu}_i \cdot \hat{\boldsymbol{r}}_{ij})(\boldsymbol{\mu}_j \cdot \hat{\boldsymbol{r}}_{ij}) \right] \times \frac{\mu_0}{4\pi}$$

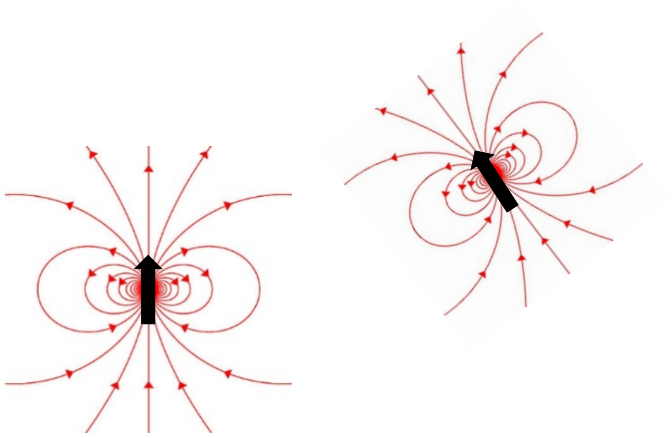
All the more large that the **TOTAL magnetic moments** are large :

Ho^{3+}, Dy^{3+} m=$10\mu_B$
ER^{3+}, Tb^{3+} m= 9 μ_B
In pyrochore $R_2Ti_2O_7$ 1-2 K

4. Exchange anisotropy

Dipolar anisotropy between two magnetic elements of magnetic moment μ_i and μ_j at a distance r_{ij} from each other :

$$\mathcal{H}_{\rm dip} = \sum_{\substack{i,j\neq j \\ i}} \frac{1}{r_{ij}^3} \left[\boldsymbol{\mu}_i \cdot \boldsymbol{\mu}_j - 3(\boldsymbol{\mu}_i \cdot \hat{\boldsymbol{r}}_{ij})(\boldsymbol{\mu}_j \cdot \hat{\boldsymbol{r}}_{ij}) \right] \times \frac{\mu_0}{4\pi}$$



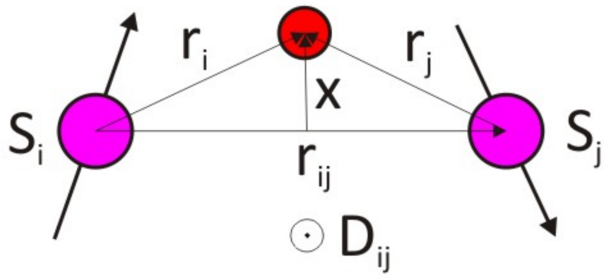
Depends on the symmetry of the magnetic elements lattice:

Cubic lattice (infinite) : $\mathcal{H}_{dip}$= 0 to first order . Example: cubic α Fe, even though μ = 2.2 μ_B

4. Exchange anisotropy

The exchange energy between two ions depends on the direction of the magnetic moment of each ion

Dzyaloshinskii-Moriya interaction (DMI) or antisymmetric interaction



Wikipedia

$$e_{DM}^{i,j} = D_{ij} . S_i \times S_j$$

Symmetry requirement for **the bond**: no inversion center
See original paper by Moriya

Anisotropic Superexchange Interaction and Weak Ferromagnetism
Tôru Moriya
Phys. Rev. 120, 91 – Published 1 October 1960

PHYSICAL REVIEW VOLUME 120, NUMBER 1 OCTOBER 1, 1960

Anisotropic Superexchange Interaction and Weak Ferromagnetism

TÔRU MORIYA*
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received May 25, 1960)

A theory of anisotropic superexchange interaction is developed by extending the Anderson theory of superexchange to include spin-orbit coupling. The antisymmetric spin coupling suggested by Dzialoshinski from purely symmetry grounds and the symmetric pseudodipolar interaction are derived. Their orders of magnitudes are estimated to be $(\Delta g/g)$ and $(\Delta g/g)^2$ times the isotropic superexchange energy, respectively. Higher order spin couplings are also discussed. As an example of antisymmetric spin coupling the case of $CuCl_2 \cdot 2H_2O$ is illustrated. In $CuCl_2 \cdot 2H_2O$, a spin arrangement which is different from one accepted so far is proposed. This antisymmetric interaction is shown to be responsible for weak ferromagnetism in α-Fe_2O_3, $MnCO_3$, and CrF_3. The paramagnetic susceptibility perpendicular to the trigonal axis is expected to increase very sharply near the Néel temperature as the temperature is lowered, as was actually observed in CrF_3.

CRYSTAL SYMMETRY AND THE ANTISYMMETRIC SPIN COUPLING

In the preceding section a general theory of calculating the anisotropic superexchange interaction was developed. In an actual crystal, some components of the symmetric and antisymmetric coupling tensors vanish because of the crystal symmetry. Here we discuss the antisymmetric coupling (1.1) from the crystal symmetry point of view.

The coupling between two ions in the crystal is considered first. The two ions 1 and 2 are located at the points A and B, respectively, and the point bisecting the straight line AB is denoted by C. The following rules are obtained easily.

1. When a center of inversion is located at C,

$$\mathbf{D}=0.$$

2. When a mirror plane perpendicular to AB passes through C,

$$\mathbf{D} \parallel \text{mirror plane or } \mathbf{D} \perp AB.$$

3. When there is a mirror plane including A and B,

$$\mathbf{D} \perp \text{mirror plane.}$$

4. When a two-fold rotation axis perpendicular to AB passes through C,

$$\mathbf{D} \perp \text{two-fold axis.}$$

5. When there is an n-fold axis ($n \geq 2$) along AB,

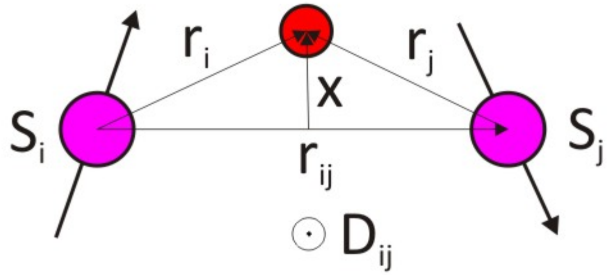
$$\mathbf{D} \parallel AB.$$

For example, for an $Fe^{3+}-Fe^{3+}$ pair in α-Fe_2O_3 oriented along the three-fold axis, $\mathbf{D}$ is parallel to the trigonal axis when the two ions are (1 or 4) and (2 or 3) in Fig. 1 and $\mathbf{D}$ is zero for the other pairs. For the rutile type iron group difluorides, $\mathbf{D}$ is not zero for the pairs of corner and body-center ions. $\mathbf{D}$ for the nearest neighbor interaction is given by the following table.

The Positions of the Ions	Direction	Magnitude
000 and $\frac{1}{2}, \frac{1}{2}, \pm\frac{1}{2}$	$[1\ \bar{1}\ 0]$	$\pm D$
000 and $-\frac{1}{2}, -\frac{1}{2}, \pm\frac{1}{2}$	$[1\ \bar{1}\ 0]$	$\pm D$
000 and $-\frac{1}{2}, \frac{1}{2}, \pm\frac{1}{2}$	$[1\ 1\ 0]$	$\pm D$
000 and $\frac{1}{2}, -\frac{1}{2}, \pm\frac{1}{2}$	$[1\ 1\ 0]$	$\pm D$

4. Exchange anisotropy

Dzyaloshinskii-Moriya interaction (DMI) or antisymmetric interaction



$$e_{DM}^{i,j} = D_{ij} \,.\, S_i \times S_j$$

Will induce a rotation of the magnetic moment

- weak ferromagnetism in antiferromagnet (α-Fe2O3)
- spiral or cycloidal phases
- skyrmions

4. Exchange anisotropy

Anisotropic exchange :

$$H_{\mathrm{AE}} = \mathbf{S}_i \cdot \Gamma_{i,j} \cdot \mathbf{S}_j \,,$$

example

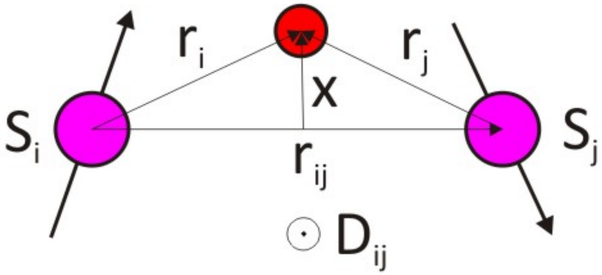
$$\Gamma_{1,2} = \begin{pmatrix} 0.00 & 0.00 & 0.00 \\ 0.00 & 0.05 & \underline{0.12} \\ 0.00 & \underline{0.12} & 0.05 \end{pmatrix}$$

That couples site 1 and 2 with their x,y,z components

T. Moriya PR 1960

4. Exchange anisotropy

Dzyaloshinskii-Moriya interaction (DMI) or antisymmetric interaction



$$e_{DM}^{i,j} = D_{ij} . S_i \times S_j$$

Strength of DM anisotropy (D) versus exchange anisotropy (Γ) :
a function of the anistotropy of the g factor $\Delta g/g$

$$D \sim (\Delta g/g) J, \quad \Gamma \sim (\Delta g/g)^2 J.$$

T. Moriya PR 1960

DM: first order spin orbit effect
exchange anisotropy: second order spin orbit effect

Note

D and Γ can be non zero even though there is no single ion anisotropy (no *g* anisotropy)
It arises then from the couplings to the first excited multiplet.

4. Exchange anisotropy

Superexchange and beyond
Direct exchange
Double exchange

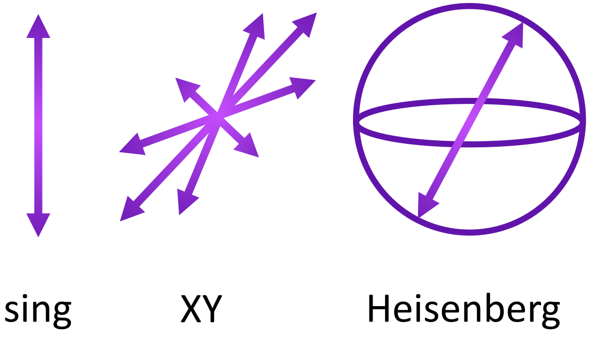
through different orbitals (Goodenough Kanamori rules)

RKKY interactions in metals

through different electronic bands

. . .

Build the appropriate , solvable Hamiltonian
Dimensionality of the spin
Form/ Strength /sign of the dominant interaction
Magnetic network



Magnetic ground state
Static and dynamical properties

5. Measuring the magnetic anisotropy

Static properties

Magnetization curve
Torque
Neutron scattering for the magnetic texture
Magnetic imaging for nano-microscale (AFM, …)
…

Dynamical properties

Magnetic resonance
Spin waves
Spectroscopy
…

Beware !

When several magnetic sites or multiaxial system, the macroscopic properties do not reflect the single site properties …

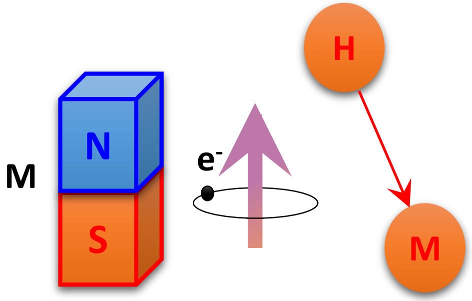
Magnetic anisotropies

1. Importance of magnetic anisotropy
2. Single ion Magnetic anisotropy: phenomenological description
3. Single ion Magnetic anisotropy: microscopic origin
4. Exchange anisotropy
5. Examples with magneto-electric effects

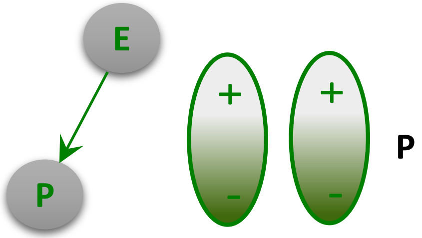
5. Example 1: electromagnons in multiferroics

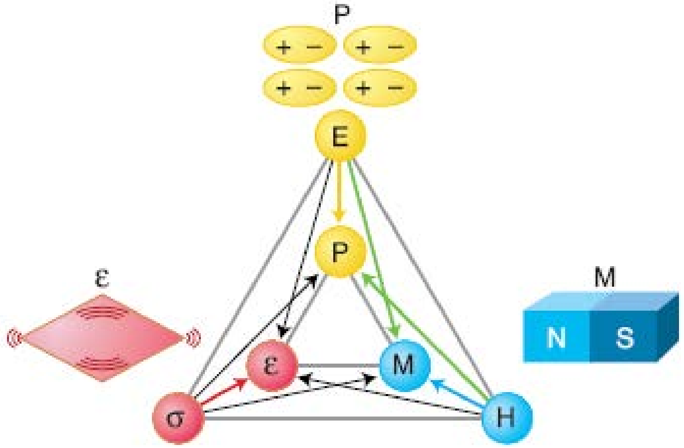
Static /dynamical properties

Magnetic moment / magnetic field

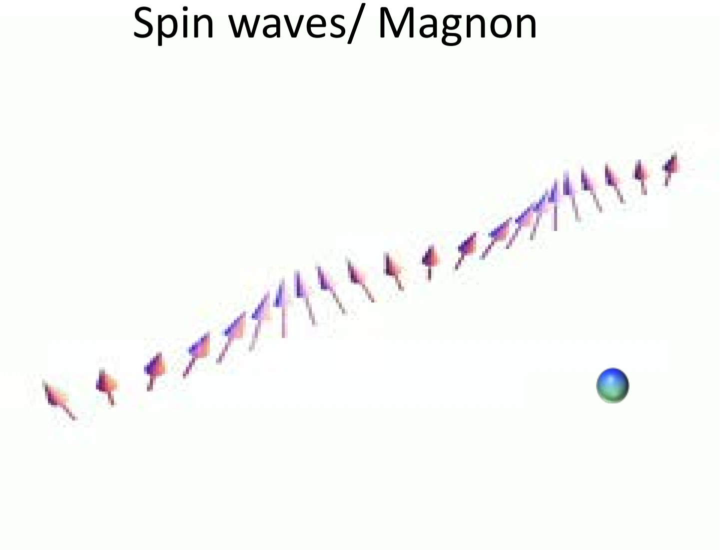


Dipolar electric moment / Electric field





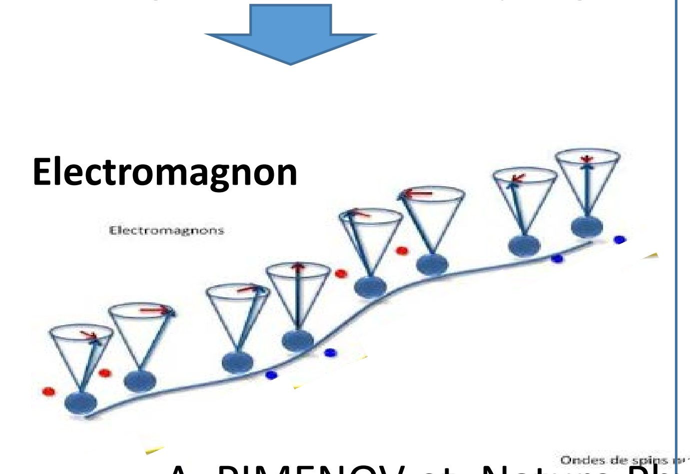
Spin waves/ Magnon



Lattice vibration / Phonon

Magneto-electric coupling

Electromagnon



A. PIMENOV et, Nature Physics 2006

5. Example 1: electromagnons in multiferroics

Possible evidence for **electromagnons** in multiferroic manganites

A. PIMENOV et al, Nature Physics 2006

THz dielecric constant
Real part

Imaginary part

Additionnal contribution in $GdMnO_3$ and $TbMnO_3$ for e//a

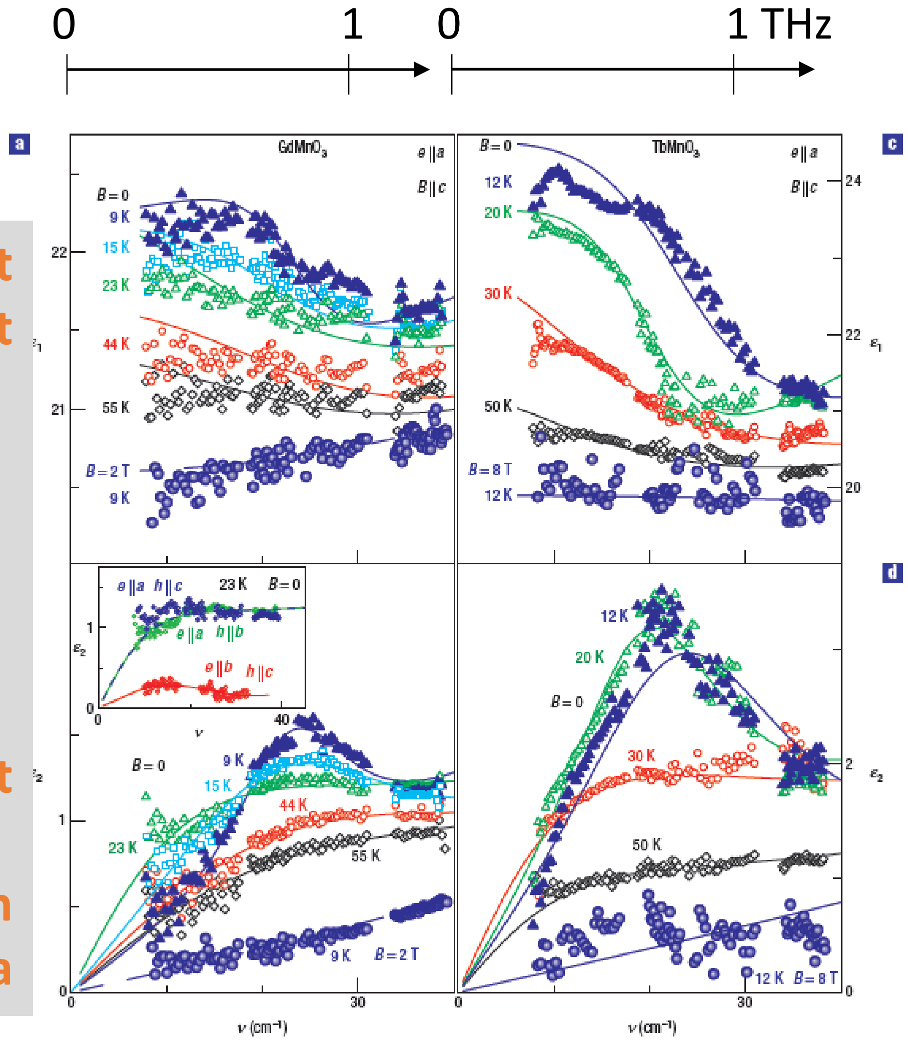
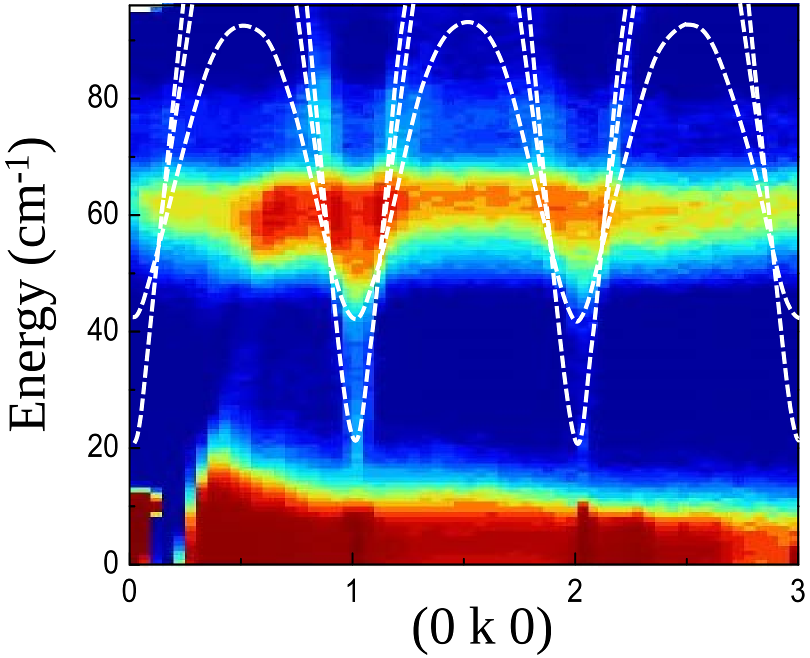


Figure 2 Spectra of electromagnons in $GdMnO_3$ and $TbMnO_3$. a–d, Frequency dependence of the real (a,c) and imaginary (b,d) parts of the terahertz-dielectric function in

5. Electromagnons in the multiferroic h-ErMnO3

h-ErMnO3 a type I multiferroic
T_C =800K T_N (Mn)= 80 K

Neutron inelastic scattering measurements



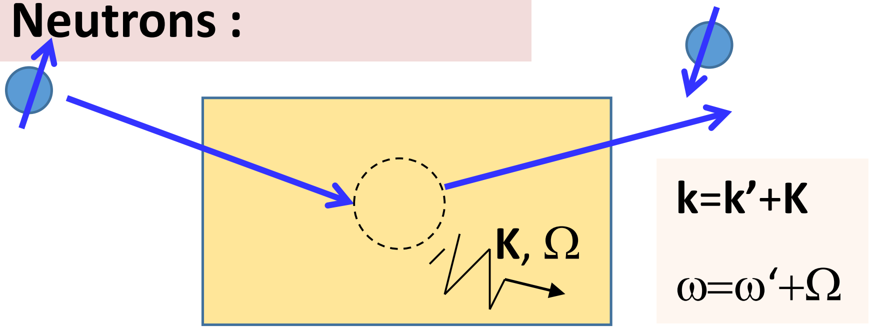
NEUTRONS FOR SOCIETY

T = 10 K

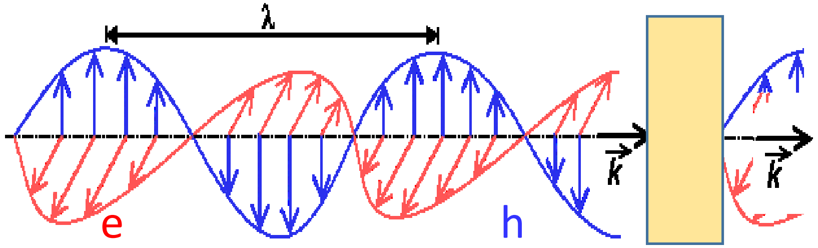
*L. CHAIX et al PRL **112**, 137201(2014)*

2. NEUTRON / THZ SPECTROSCOPY : COMPLEMENTARY TECHNIQUES

Neutrons :



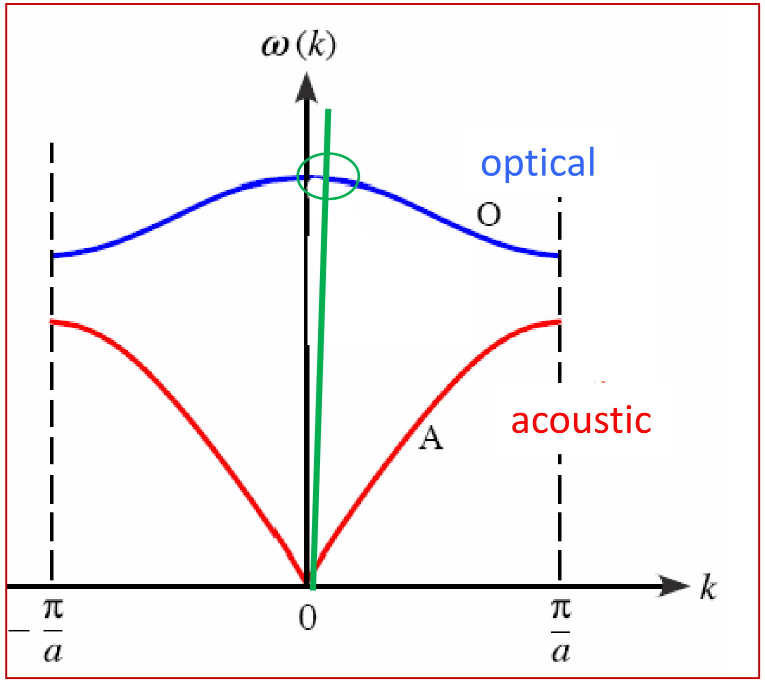
THz wave :



DISPERSION CURVES
Ω(K)
χ_2 (Ω, K) ⊥ K

<u>MAGNETIC</u> AND
ATOMIC PROBE

Whole reciprocal space



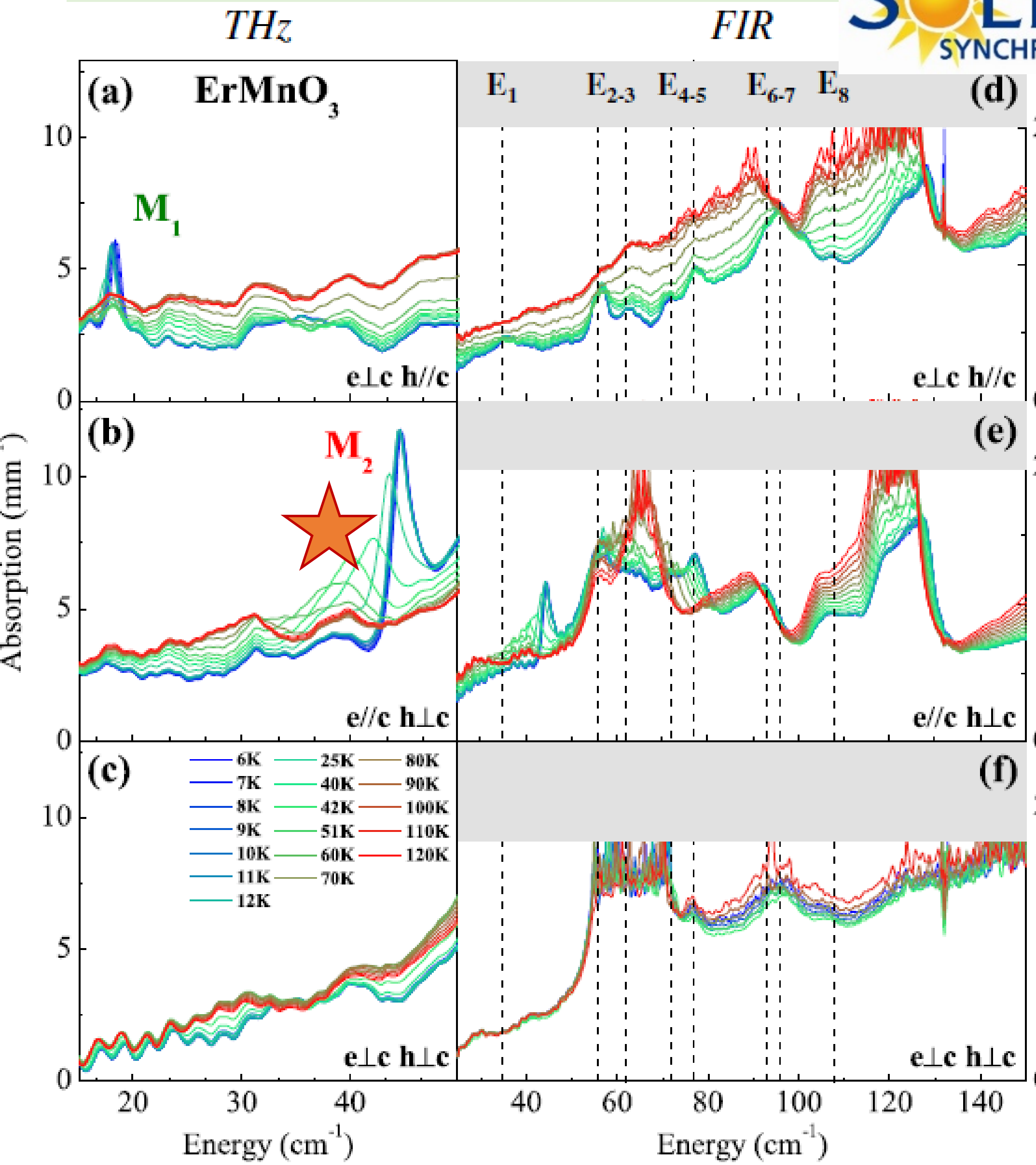
ABSORBTION CURVES
Ω (K ≈ 0)
χ_2 (Ω, 0)

<u>MAGNETIC</u> AND
ELECTRIC PROBE

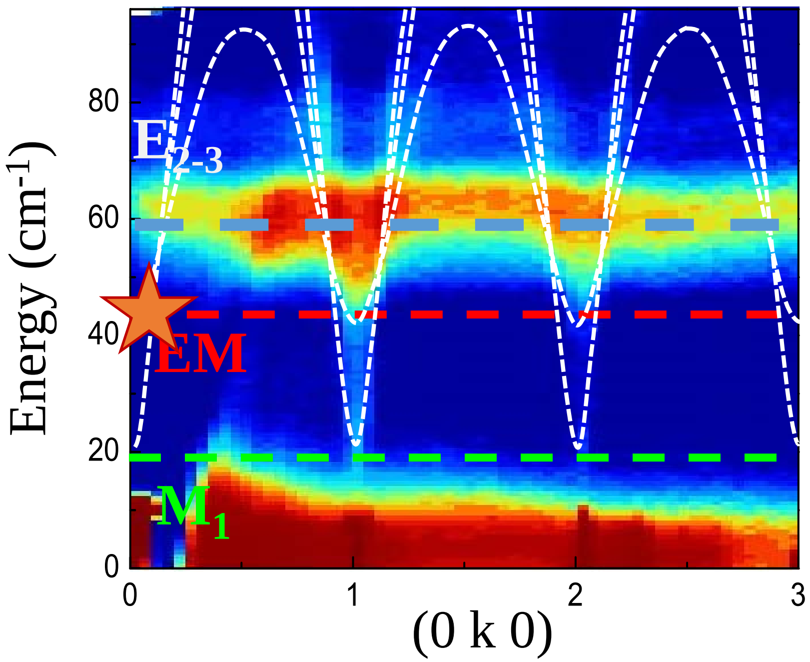
Smaller sample
Increased energy resolution

2. Hexagonal manganites : $ErMnO_3$

THz measurements



Neutron measurements



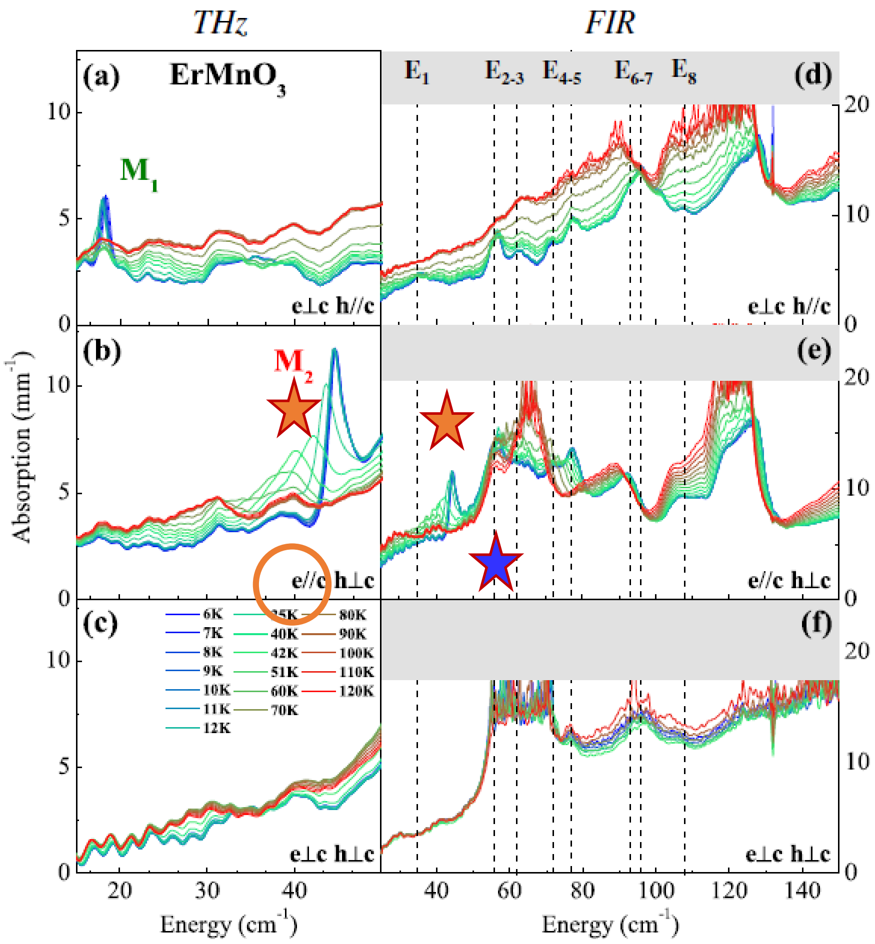
Mn MAGNON

+ Er^{3+} CRYSTAL FIELD EXCITATION at 60 cm-1

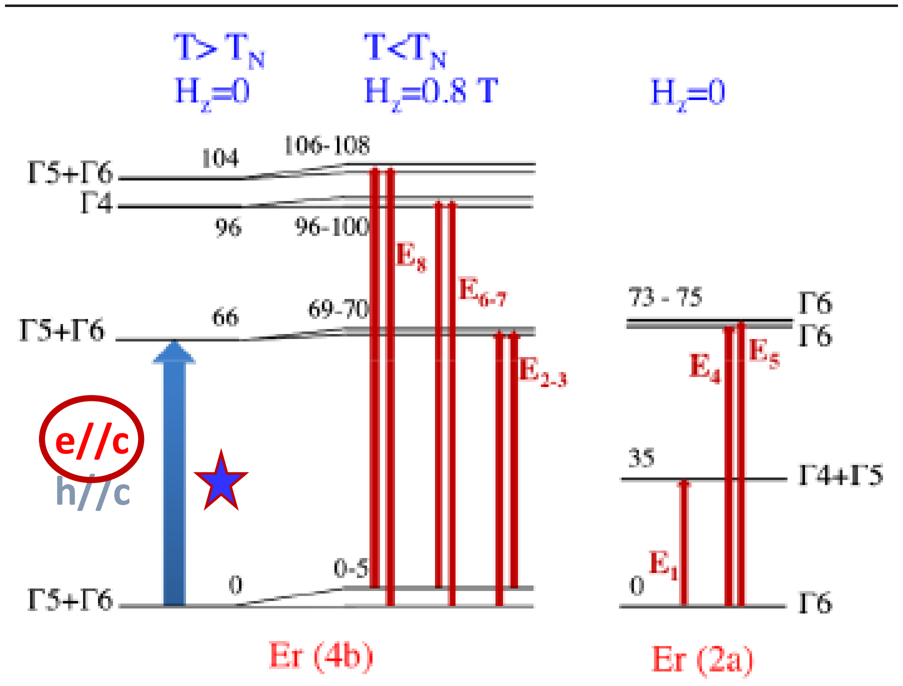
→ ELECTRO ACTIVE MAGNON at 45 cm-1

2. Hexagonal manganites : $ErMnO_3$

THz measurements



Er Crystal field excitations

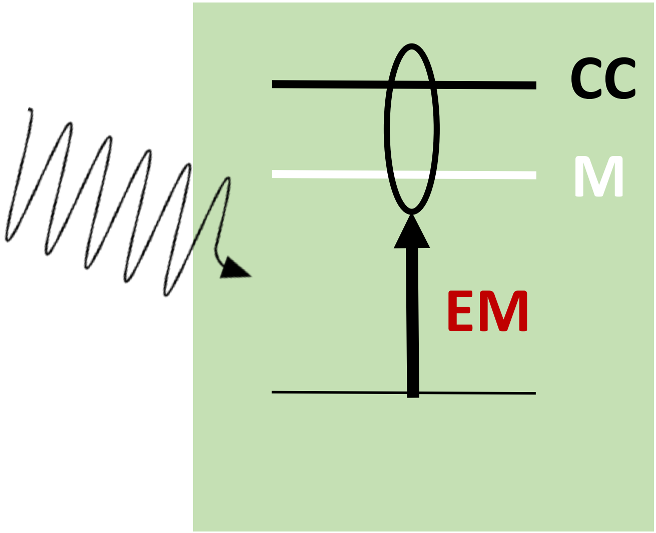


Er/Mn dynamical coupling : electroactive magnon
Mn MAGNON / Er CRYSTAL FIELD HYBRIDE EXCITATION

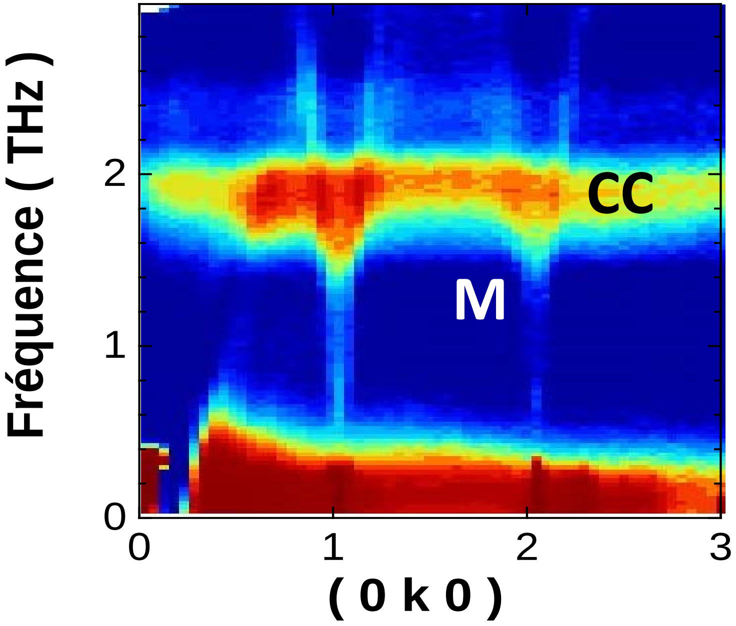
*L. CHAIX et al PRL **112**, 137201(2014)*

EXAMPLE 1 : TRANSMUTATION OF A MAGNON into an ELECTRIC EXCITATION in the THz range

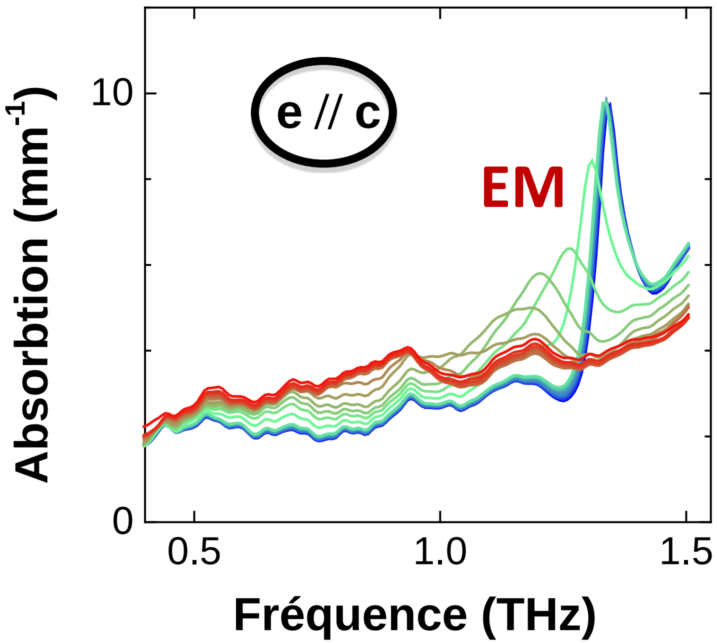
Multiferroic h-$ErMnO_3$



neutron



THz

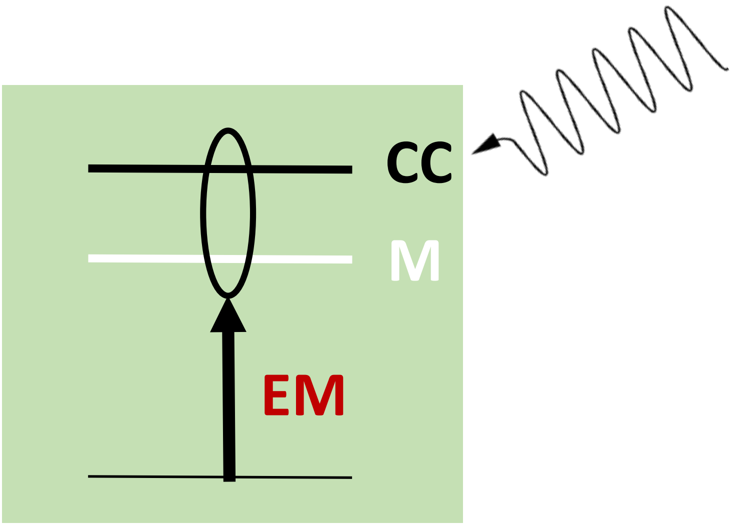


Towards manipulation of magnon through elecric field…
Check through pump probe experiment…

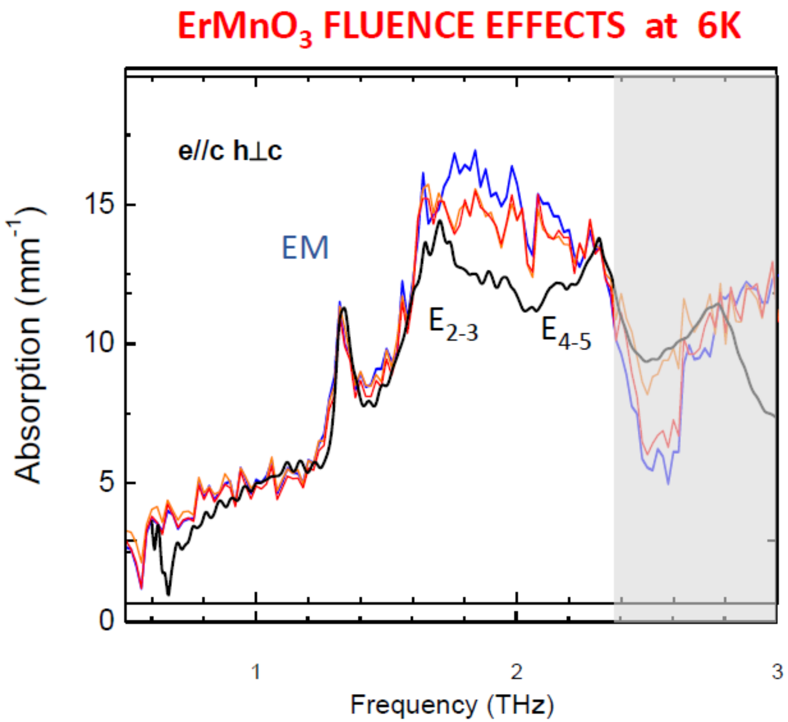
5. Example 2 : electro-magnetic monopoles in spin ices

THZ *FEL*

Pump probe experiment



TERAFERMI @ Trieste



ErMnO3 THz spectrum at 6K.

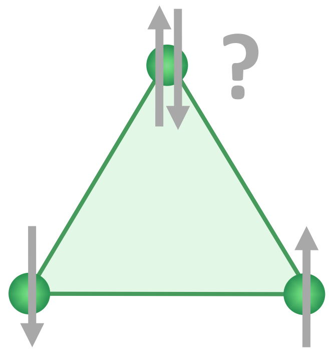
Black line: linear response from AILES@SOLEIL source. Red and blue

Red and blue lines:

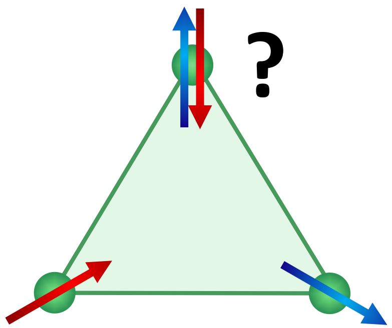
response from 0.54 μJ and 1.6 μJ pulses respectively provided by TERAFERMI.

Magnetic frustration and spin ices

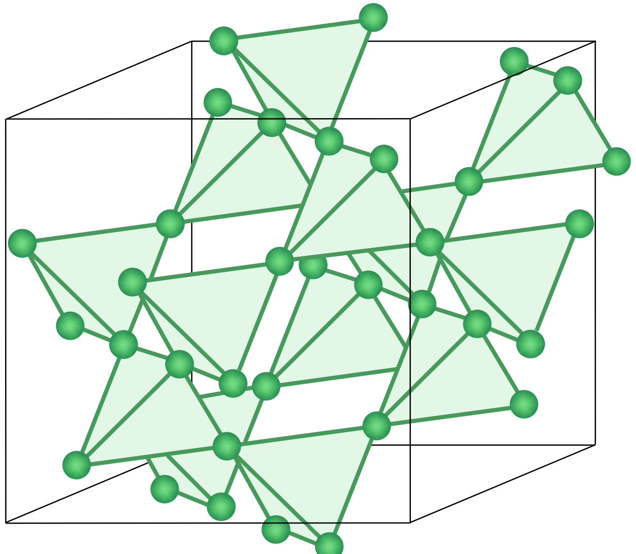
Magnetic frustration : *One or several competing interactions can not be satisfied simultaneously*



Antiferromagnetic interactions



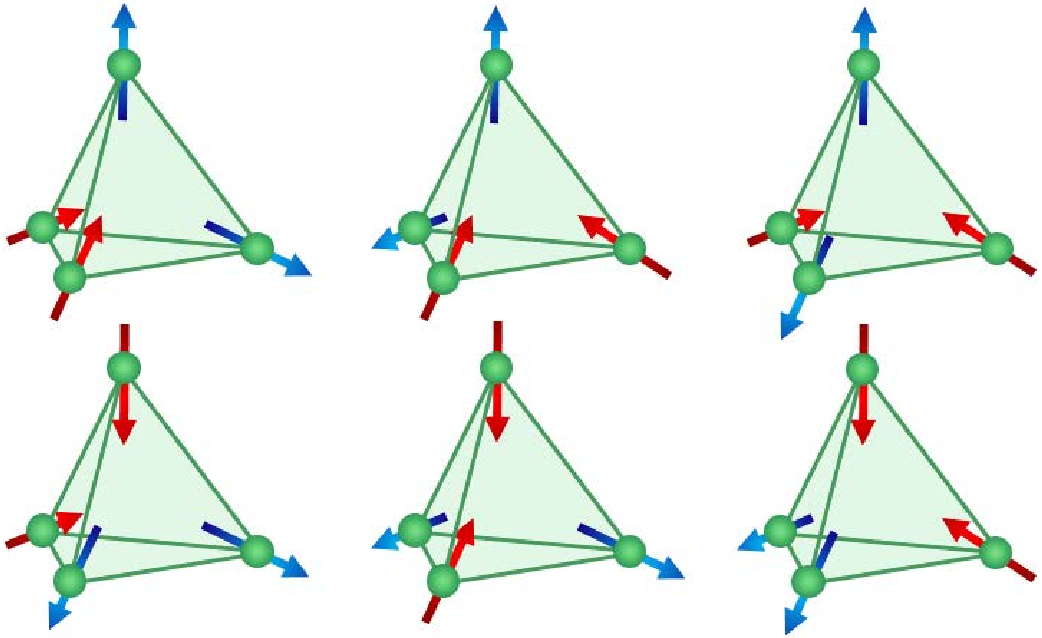
Ferromagnetic interactions + multiaxial anisotropy

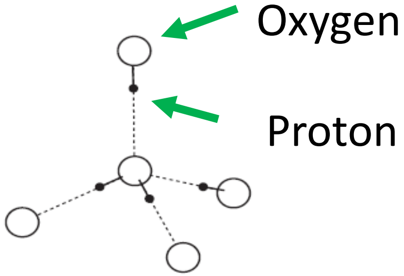


Pyrochlore

Spin ice : multiaxial anisotropy + ferromagnetic interactions

« 2 in – 2 out » degenerate state : ice rule



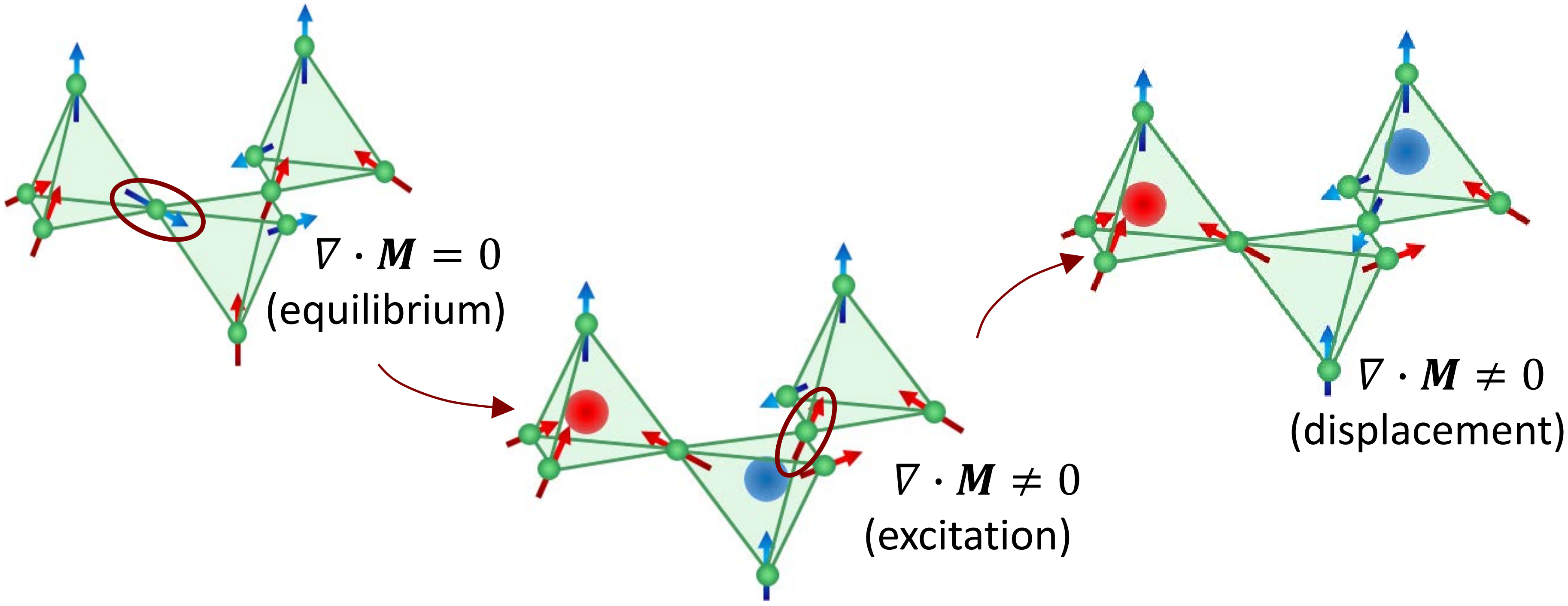


Local order of protons in **water ice**

« 2 close - 2 far » from oxygen

Spin ices and magneto-electric effects

« 2 in – 2 out » spin ice

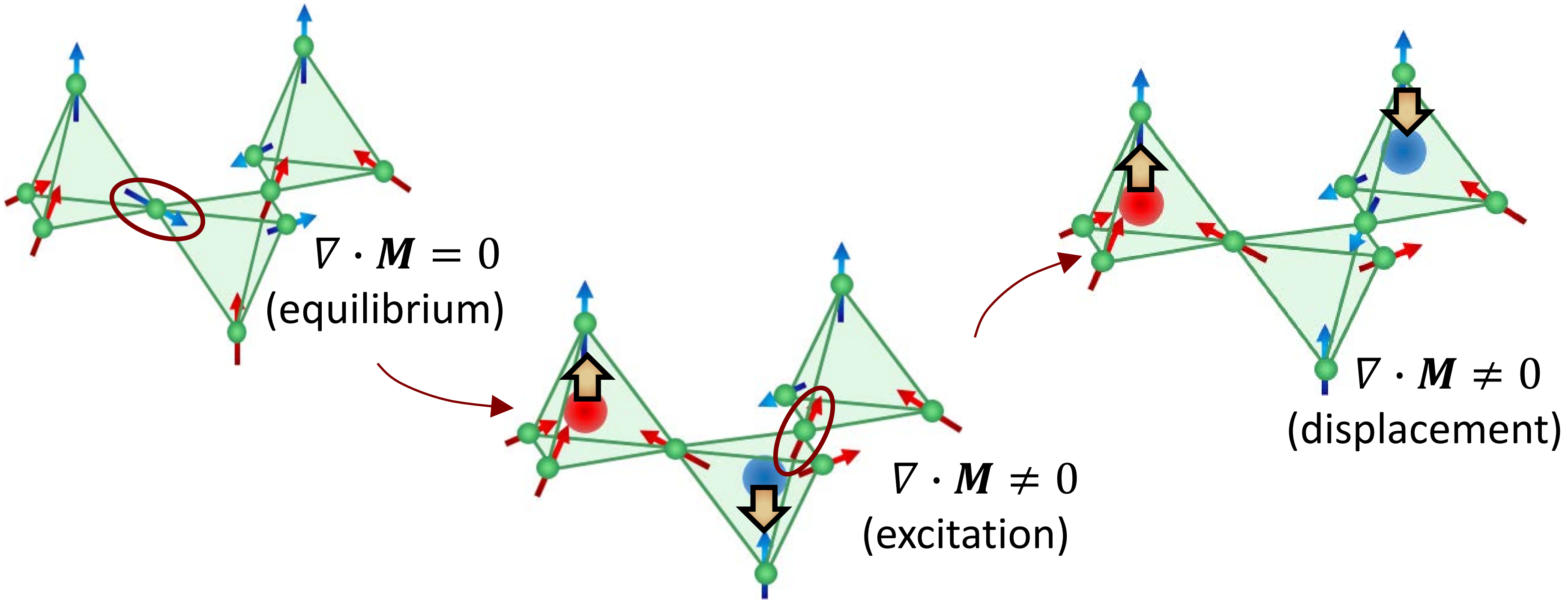


« magnetic monopoles »

C. Castelnovo et al., Nature 451: 42-45 (2008)

Spin ices and magneto-electric effects

« 2 in – 2 out » spin ice



« magnetic monopoles » + electric dipoles

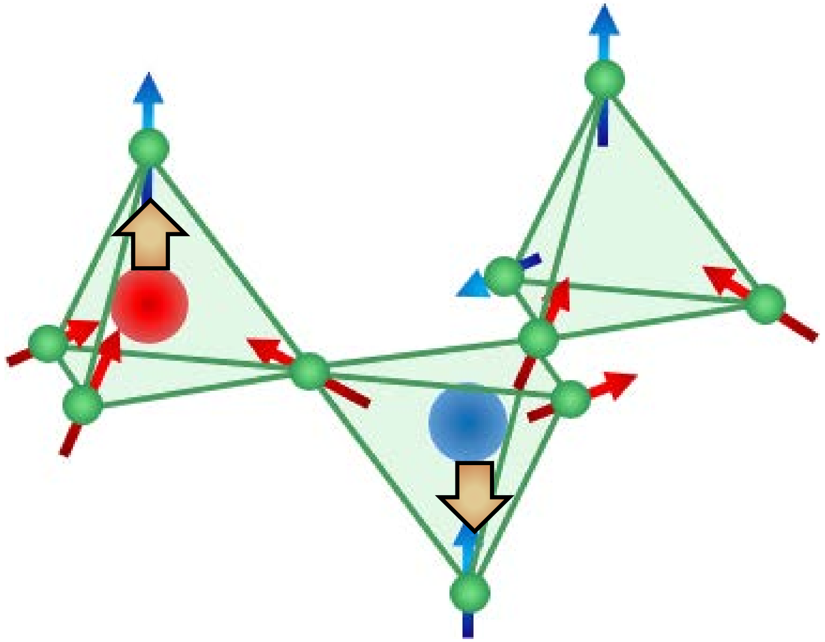
ARTICLE

Received 23 Feb 2012 | Accepted 14 May 2012 | Published 19 Jun 2012 DOI: 10.1038/ncomms1904

Electric dipoles on magnetic monopoles in spin ice

D.I. Khomskii

Spin ices and magneto-electric effects



Theorerical investigations

D. I. Khomskii, Nat. Commun. 3: 904 (2012)
L. Jaubert and R. Moessner, Phys. RevB 91: 214422(2015)

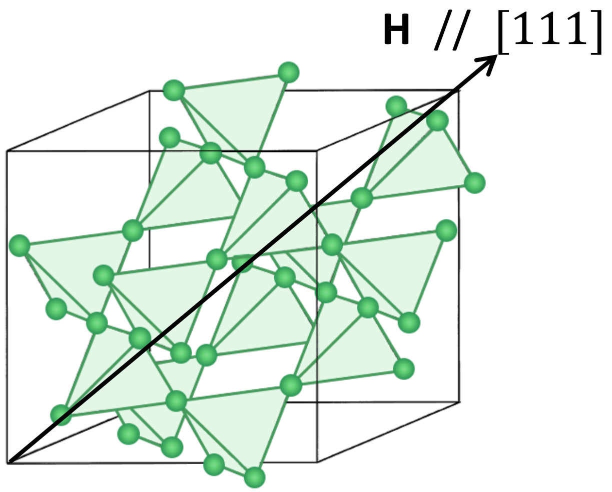
Experimental evidences

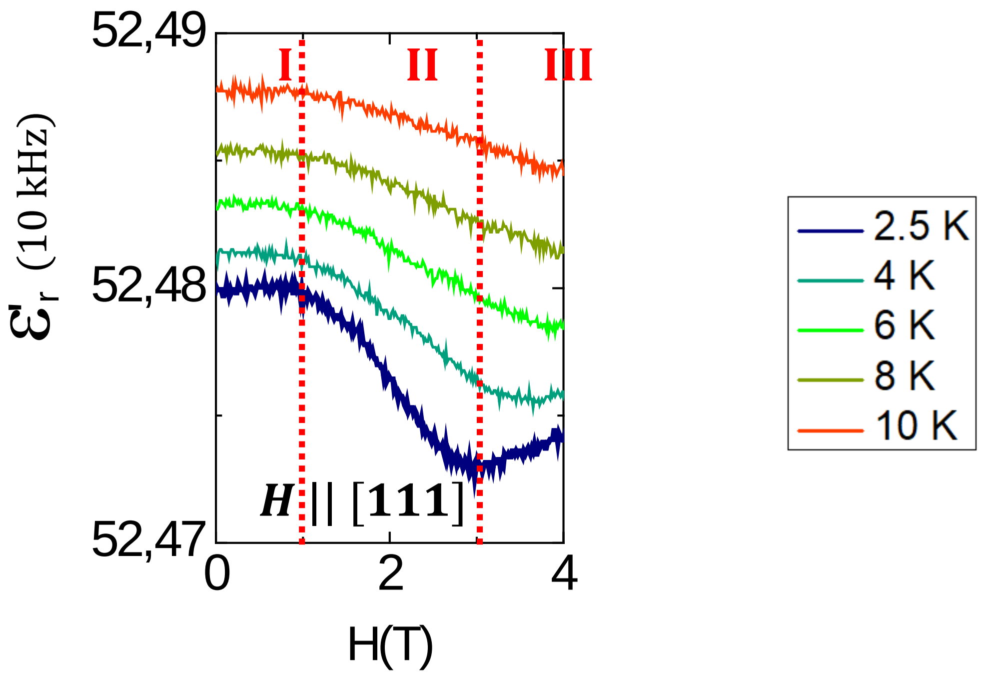
P. Grams et al, Nat. Commun. 5: 4853 (2013) in $Dy_2Ti_2O_7$
D. Liu et al , J. Appl. Phys. 113: 17D901 (2013) in $Ho_2Ti_2O_7$
F. Jin et al, Phys. Rev. Lett. 124: 087601 (2020) in $Tb_2Ti_2O_7$

Magneto-electric effects in the spin ice compound $Ho_2Ti_2O_7$

Y. Alexanian, V. Simonet, R. Ballou, J. Robert, C. Decorse, J. Debray, F. Gay, and S. de Brion

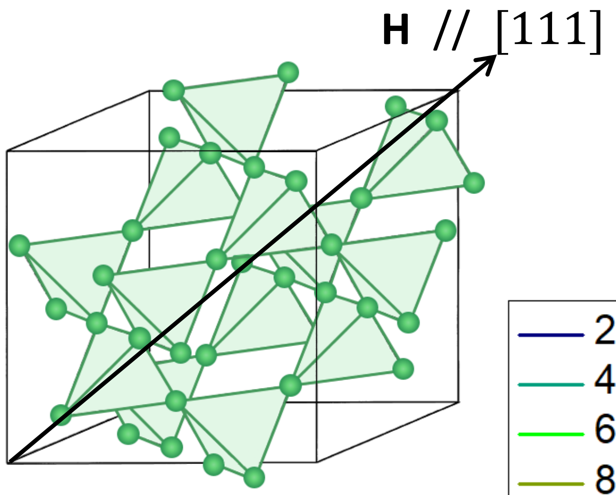
Magneto – electric effects in $Ho_2Ti_2O_7$

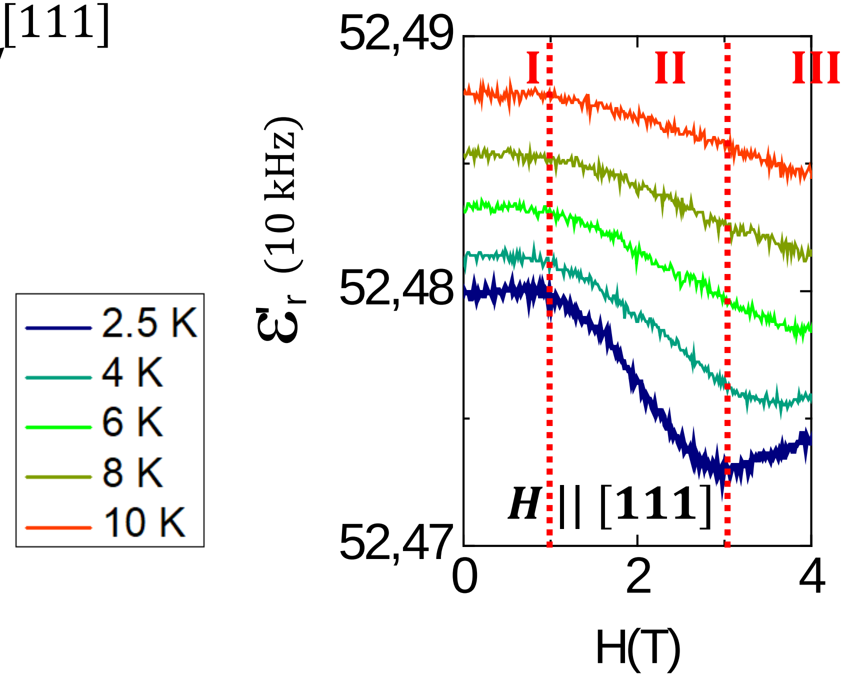




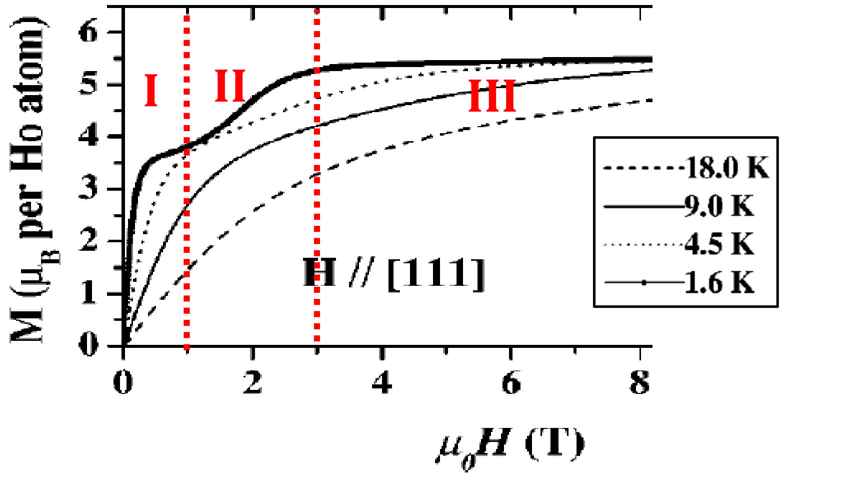
At low temperature below 4 K, 3 different regims are observed as a function of the applied magnetic field

Magneto – electric effects in $Ho_2Ti_2O_7$

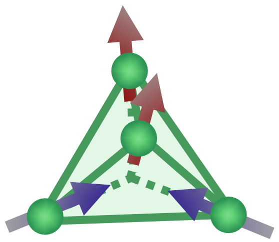




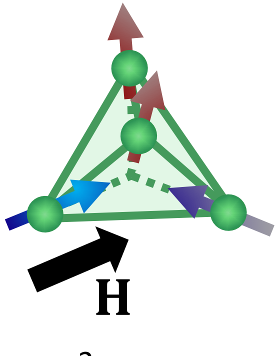
O. A. Petrenko et al., PRB 68, 012406 (2003)



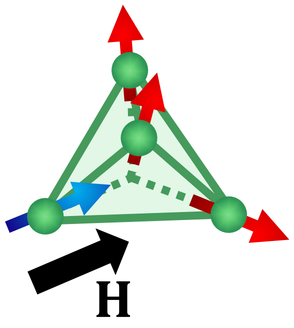
I : Spin ice
$Fd\bar{3}m1'$



II : Kagome ice
$R\bar{3}m'$



III : Monopoles ice
$R\bar{3}m'$

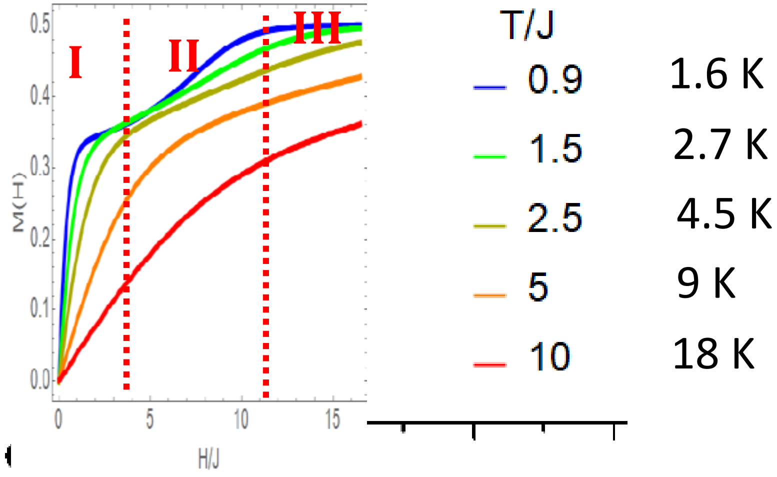


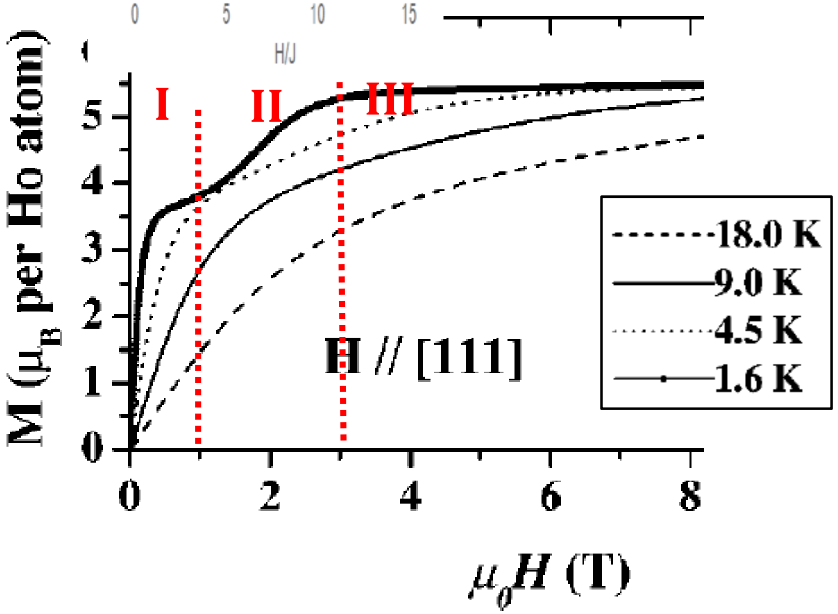
Allowed terms in ε (H): H^2 | $H^2 + H$ | $H^2 + H$

Monte Carlo simulation H // [111]

Magnetisation curves

2 × 2 × 2 units of 16 spins





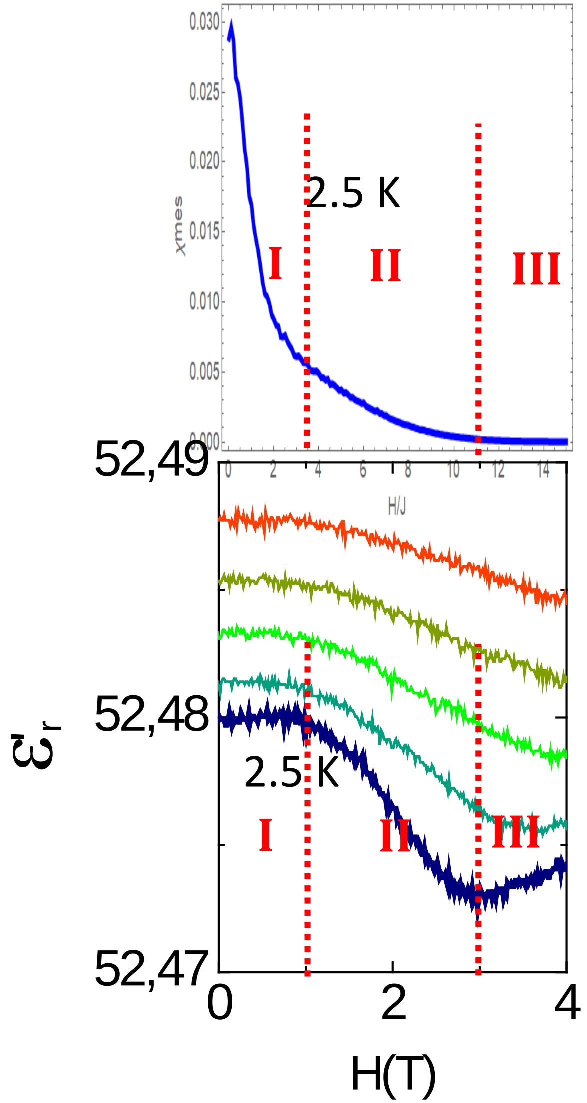
MC calculations

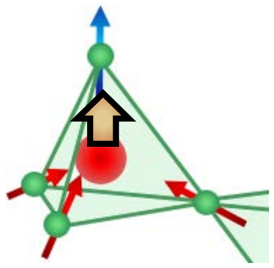
Experiments

Dielectric permittivity

4 × 4 × 4 units of 16 spins

Electric dipole oriented according to Komskii's model

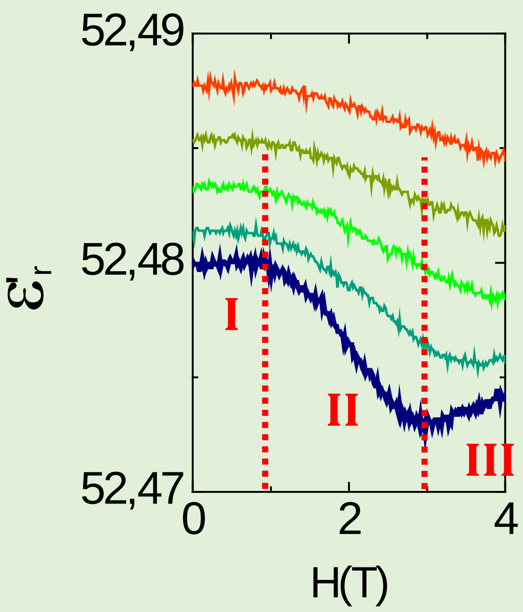




Conclusion : are spin ices multiferroics?

NO BUT

Magneto-elecric effects are present



Signature of the different phases are observed but not explained within the Komskii's model

Y. Alexanian

END