

Anisotropy in Magnetic Materials

Kishan Sinha

Xu Group

Department of Physics and Astronomy

University of Nebraska-Lincoln

Magnetic Anisotropy

Magnetic anisotropy means that the magnetic properties depend on the direction in which they are measured.

It strongly affects the shape of the M-H curve.

Key phenomenon used in the design of most commercial magnetic materials.

Kinds of anisotropy:

- a) Crystal anisotropy (magnetocrystalline anisotropy)
- b) Shape anisotropy
- c) Stress anisotropy
- d) Exchange anisotropy
- e) Anisotropy induced by magnetic annealing, plastic deformation, and irradiation

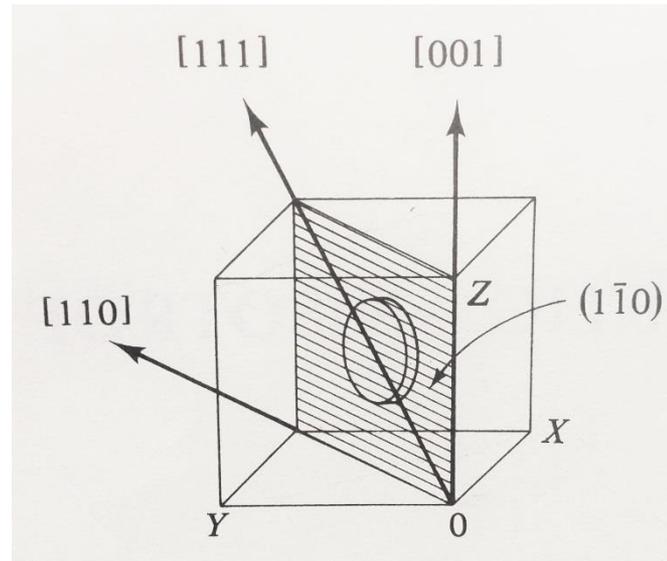
Of these, only crystal anisotropy is intrinsic to the material. Rest are extrinsic or induced.

In this talk, we will focus on Crystal anisotropy.

Anisotropy in Cubic Crystal

Suppose a single crystal is cut in the form of a disk parallel to plane $\{110\}$

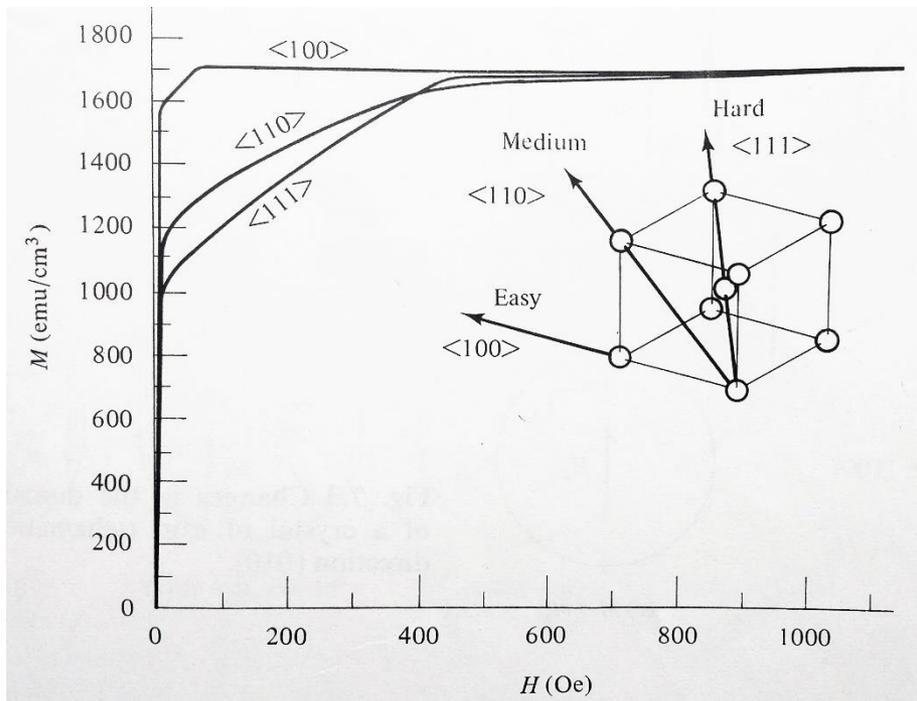
- ➔ The disk will have directions of the form $\langle 100 \rangle$, $\langle 110 \rangle$, and $\langle 111 \rangle$
The density of atoms along these three crystallographic directions differ.



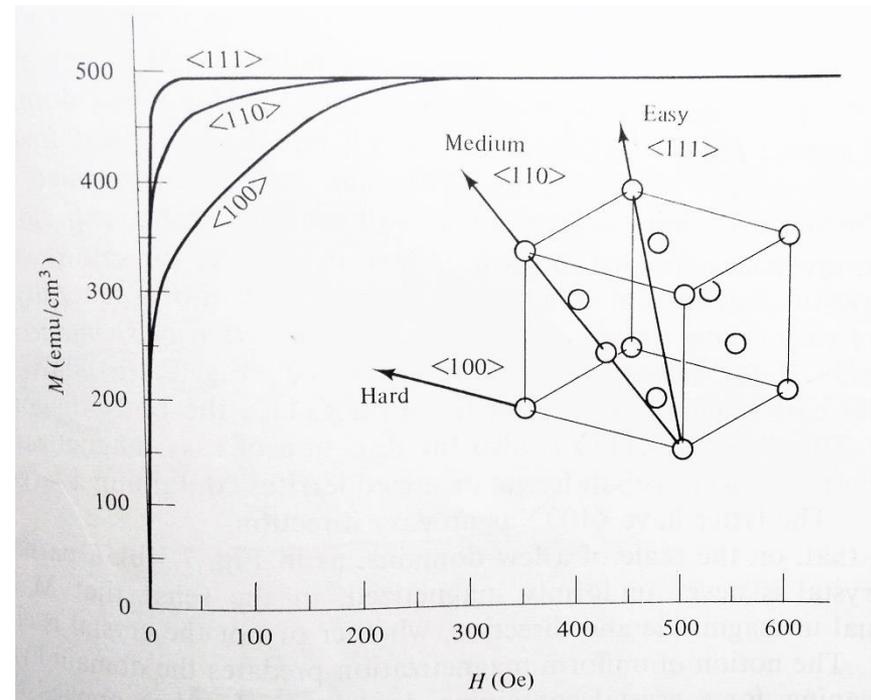
Should the differences atomic density affect the magnetic properties unevenly along these directions?

Experimental observation of magnetic anisotropy in Cubic Crystals

Fe: BCC crystal



Ni: FCC crystal

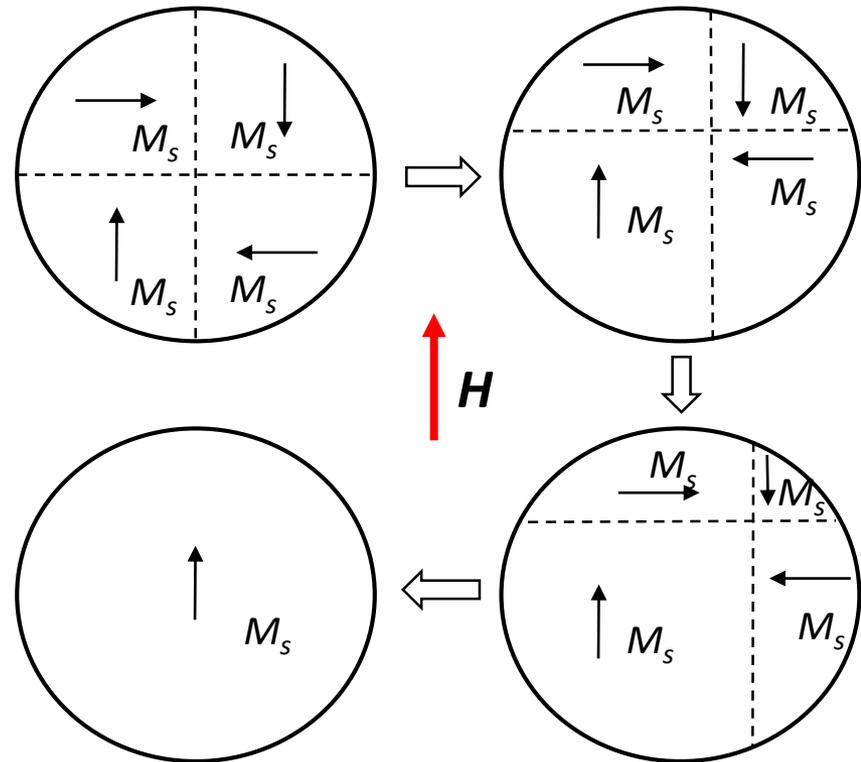
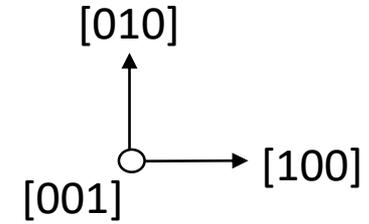
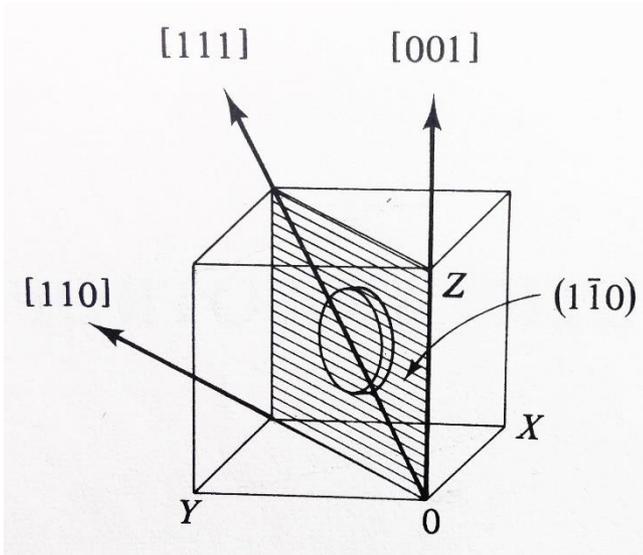


$\langle 100 \rangle$ are easy magnetization directions (axes)
 $\langle 111 \rangle$ axes are hard

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 $\langle 100 \rangle$ axes are hard

Field along Fe "easy axis"

Evolution of domains

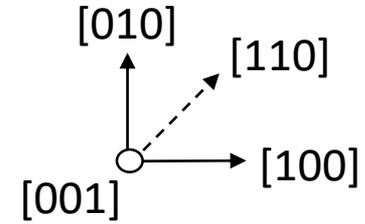
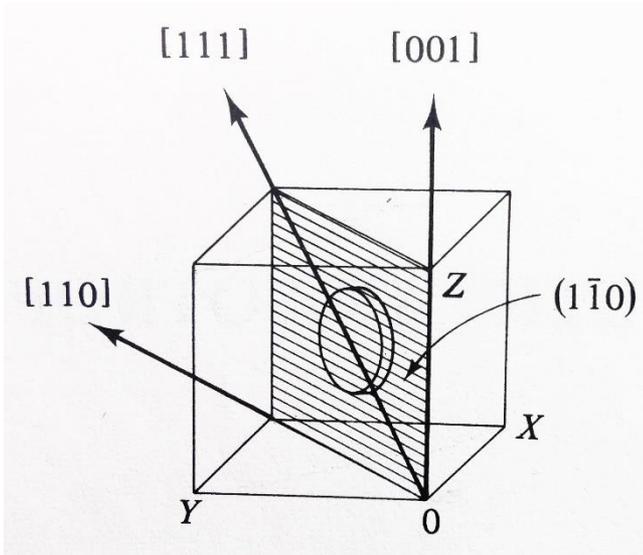


Magnetic potential energy

- Along [010]: $-M_s H$
- Along [0-10]: $+M_s H$
- Along [100]: 0

Field along Fe "hard axis"

Evolution of domains



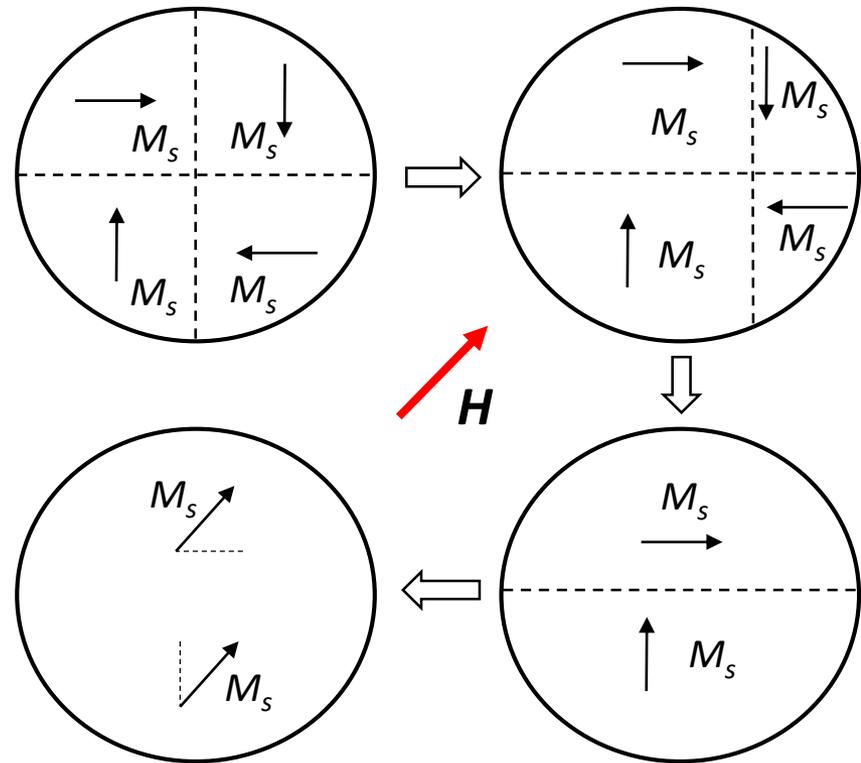
Magnetic potential energy

Along $[110]$: $-M_s H$

Along $[010]$: $-M_s H \cos 45^\circ$

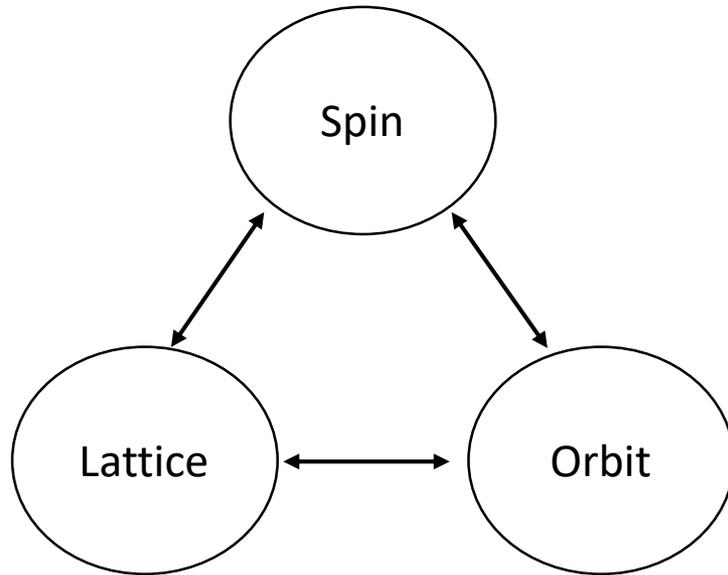
Along $[100]$: $-M_s H \cos 45^\circ$

Along $[-100]$: $+M_s H \sin 45^\circ$



Domain rotation
Requires high fields

Physical Origin of Crystal Anisotropy



Possible interactions (coupling):

- Spin-spin
- Spin-orbit
- Orbit-lattice
- Spin-lattice

Three degrees of freedom in a crystal

Origin of *crystal anisotropy* must be result from interactions (coupling) between these degrees of freedom

Physical Origin of Crystal Anisotropy

Spin-spin interaction

- Exchange interaction between two neighboring spins.
 - Strong, and keeps the neighboring spins parallel or anti-parallel.
 - It depends only on the relative orientation of adjacent spins
- ↓
- ***Exchange energy is isotropic;*** not dependent on direction of spin axis relative to crystal axis.

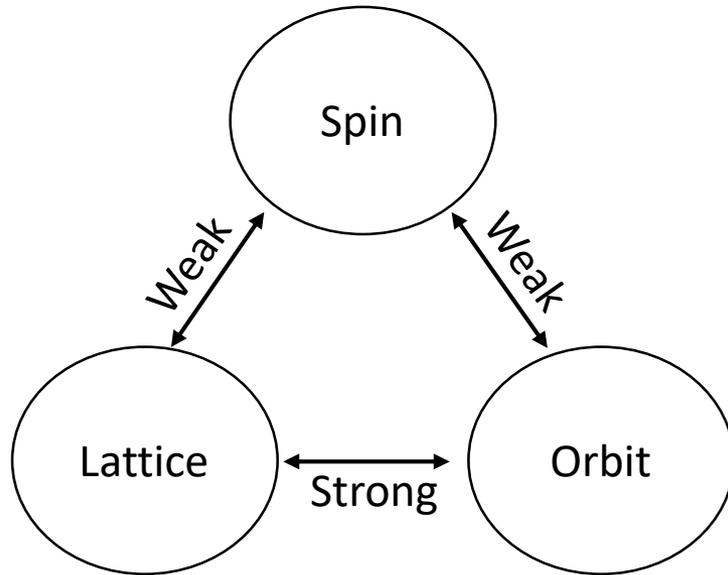
Spin-spin exchange can't contribute to crystal anisotropy.

Orbit-lattice interaction

- Orbital magnetic moments are almost entirely *quenched* in most crystals
 - Orientation of the orbit are fixed very strongly to the lattice.
- ↓
- Orientation can't be change even with large fields.
 - This arises due to action of the electric field of ligand atoms/ions on the atom/ion in question.

Orbit-lattice coupling is strong.

Physical Origin of Crystal Anisotropy



Spin-orbit interaction

- Spin and orbital motions of an electron also couple
- External magnetic field tries to re-orient spin → electron orbit also tends to re-orient.
- But the orbit is strongly coupled to the lattice → resists attempts to reorient the spin axis.
- The energy required to overcome this resistance stemming from SO coupling is called *anisotropy energy*.

**Anisotropy energy is the energy required to overcome the spin-orbit coupling.
Crystal anisotropy is due mainly to SO coupling.**

Important remarks

on *SO* coupling and crystal anisotropy

- In most materials, the crystal field effect is the dominant term
- Although there is no doubt that anisotropy stems from *SO* coupling, the details are not clear.
- It is yet not possible to calculate anisotropy constants from first principles.
- There is no simple relationship between the easy, or hard, axes and the way the atoms are arranged in a crystal.

Fe: BCC crystal

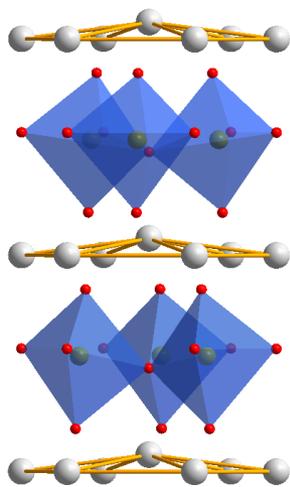
$\langle 111 \rangle$ is the direction of greatest atomic density
 $\langle 111 \rangle$ is the hard axis.

Ni: FCC crystal

$\langle 110 \rangle$ is the direction of greatest atomic density
 $\langle 110 \rangle$ is the medium hard magnetization.

When SO coupling dominates

4f- Rare-earths ions (R^{3+}): Lanthanides



Hexagonal $RFeO_3$

4f rare-earths in 3+ oxidation state.

Valence: $4f^1 - 4f^{14}$

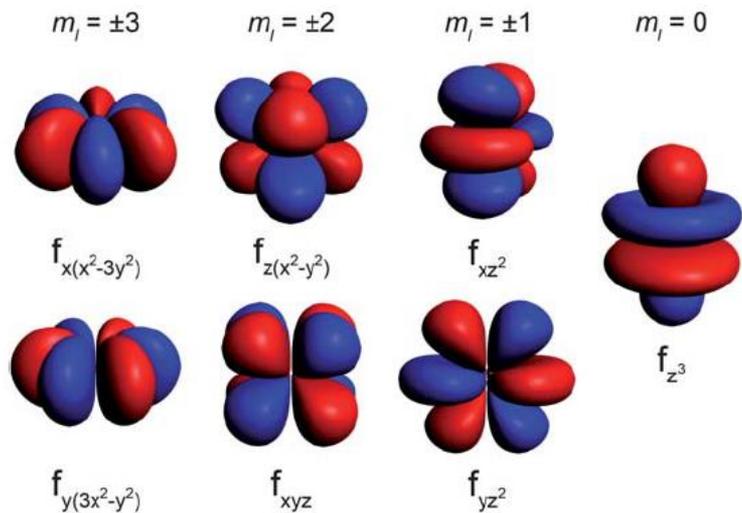
Highly anisotropic electron distribution

IUPAC Periodic Table of the Elements

1 H hydrogen [1.007, 1.009]																	2 He helium 4.003
3 Li lithium [6.938, 6.997]	4 Be beryllium 9.012											5 B boron [10.80, 10.83]	6 C carbon [12.00, 12.02]	7 N nitrogen [14.00, 14.01]	8 O oxygen [15.99, 16.00]	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium [24.30, 24.31]											13 Al aluminum 26.98	14 Si silicon [28.08, 28.09]	15 P phosphorus 30.97	16 S sulfur [32.05, 32.08]	17 Cl chlorine [35.44, 35.46]	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.87	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.38(2)	31 Ga gallium 69.72	32 Ge germanium 72.63	33 As arsenic 74.92	34 Se selenium 78.96(3)	35 Br bromine [79.90, 79.91]	36 Kr krypton 83.80
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.96(2)	43 Tc technetium	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 118.7	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs caesium 132.9	56 Ba barium 137.3	57-71 lanthanoids	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.8	75 Re rhenium 186.2	76 Os osmium 196.2	77 Ir iridium 192.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.6	81 Tl thallium [204.3, 204.4]	82 Pb lead 207.2	83 Bi bismuth 209.0	84 Po polonium	85 At astatine	86 Rn radon
87 Fr francium	88 Ra radium	89-103 actinoids	104 Rf rutherfordium	105 Db dubnium	106 Sg seaborgium	107 Bh bohrium	108 Hs hassium	109 Mt meitnerium	110 Ds darmstadtium	111 Rg roentgenium	112 Cn copernicium			114 Fl flerovium			116 Lv livermorium

57 La lanthanum 138.9	58 Ce cerium 140.1	59 Pr praseodymium 140.9	60 Nd neodymium 144.2	61 Pm promethium	62 Sm samarium 150.4	63 Eu europium 152.0	64 Gd gadolinium 157.3	65 Tb terbium 158.9	66 Dy dysprosium 162.5	67 Ho holmium 164.9	68 Er erbium 167.3	69 Tm thulium 168.9	70 Yb ytterbium 173.1	71 Lu lutetium 175.0
89 Ac actinium	90 Th thorium 232.0	91 Pa protactinium 231.0	92 U uranium 238.0	93 Np neptunium	94 Pu plutonium	95 Am americium	96 Cm curium	97 Bk berkelium	98 Cf californium	99 Es einsteinium	100 Fm fermium	101 Md mendelevium	102 No nobelium	103 Lr lawrencium

Electron distribution in 4f lanthanides



Representations of the 4f orbitals

Highest magnitude m_j - most oblate shape
Lowest magnitude m_j - most prolate shape

High $m_j \rightarrow$ high net magnetic moment along z-axis

Rare-earths metals exhibit strong spin-orbit (LS) coupling as opposed to their 3d transition metal counterparts.

Consequently, the “good” quantum number is j (total angular momentum) and not s .

This leads to weaker coupling between electronic distribution in rare-earth ions and the crystal field due to ligands.

\rightarrow Crystal field is treated as a perturbation on LS coupling term in the Hamiltonian.

This is in stark contrast with the way transition metal ions behave.

Thank you!