Magnetic ordering, magnetic anisotropy and the mean-field theory

THE EUROPEAN SCHOOL ON MAGNETISM

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Ferromagnets

Mean-field approximation

Curie temperature and critical exponents

Magnetic susceptibility

Temperature dependence of magnetization and Bloch law

Antiferromagnets

Neel temperature

Susceptibility

Magnetic anisotropy

Magnetic-dipole contribution

Magneto-crystalline anisotropy and its temperature dependence

Ferro- and antiferromagnets in an external field

Ferromagnets

Mean-field approximation

Curie temperature and critical exponents

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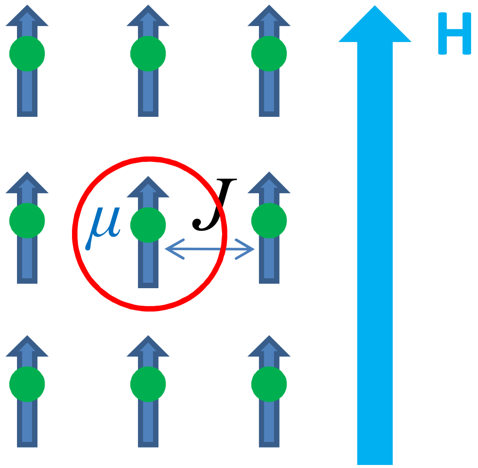
Temperature dependence of magnetization and Bloch law

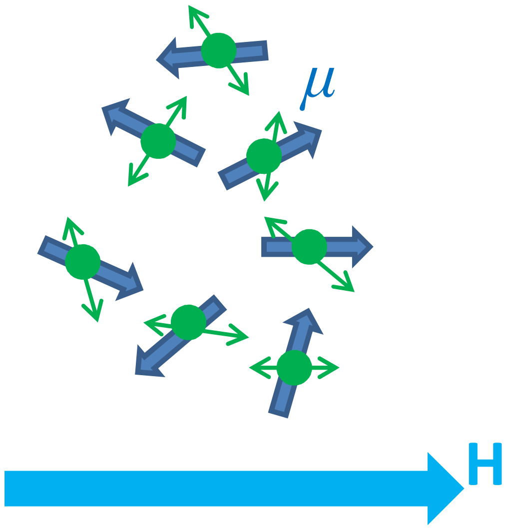
Mean-field approximation: Weiss molecular field



$$H_m = wM$$ **Weiss molecular field**
- field created by neighbor magnetic moments

Alignment of a magnetic moment μ
in the total field $H+wM$?

A brief reminder: independent magnetic moments in external field



➢ **Thermal energy:** $$U_T = kT$$

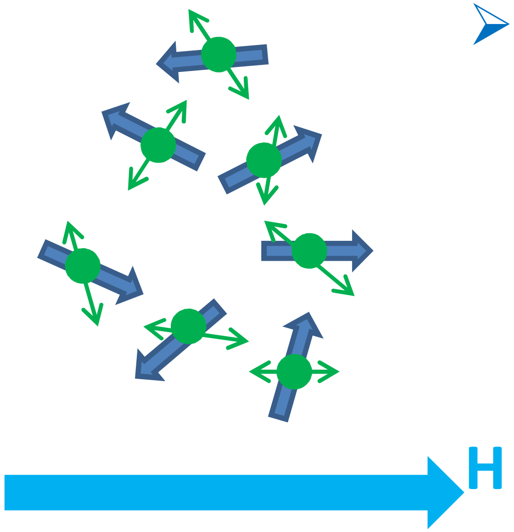
At room temperature: $4.1 \cdot 10^{-21} J$

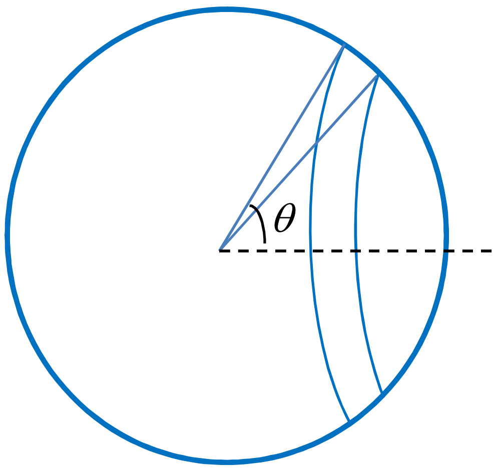
➢ **Potential energy of a magnetic moment in the field H:** $$U_H = -\mu H \cos\theta$$

In a field of 1MA/m: $1.2 \cdot 10^{-23} J$

$$U_H / U_T \sim 0.003$$

Paramagnetism: independent magnetic moments in external field





➢ Induced magnetization

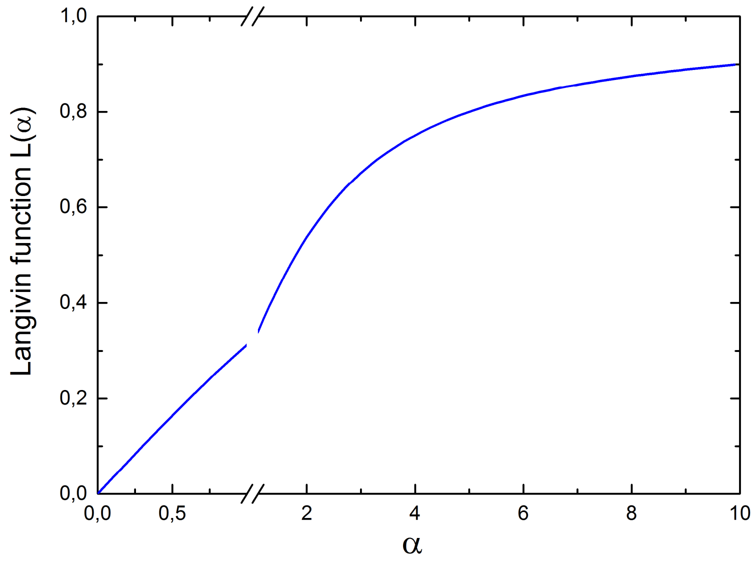
Probability for a magnetic moment to orient at the angle θ:

$$\exp\left(-\frac{U_H}{U_T}\right) = \exp\left(\frac{\mu H}{kT}\cos\theta\right)$$

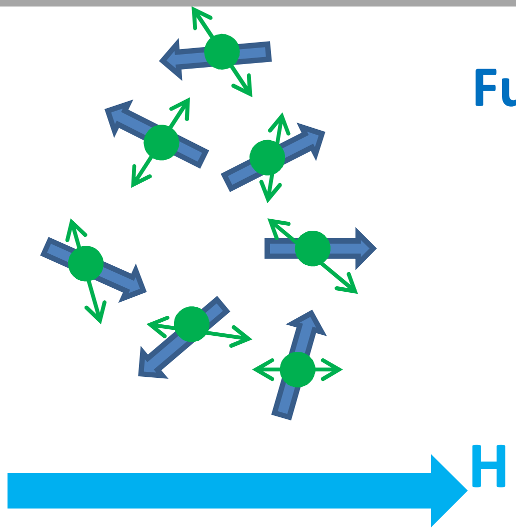
Full magnetization along the field:

$$M = N\mu\left(\coth\alpha - \frac{1}{\alpha}\right) \qquad \alpha = \frac{\mu H}{kT}$$

Langevine function $L(\alpha)$

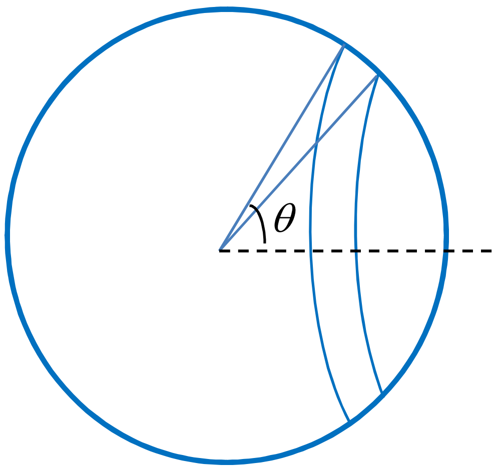


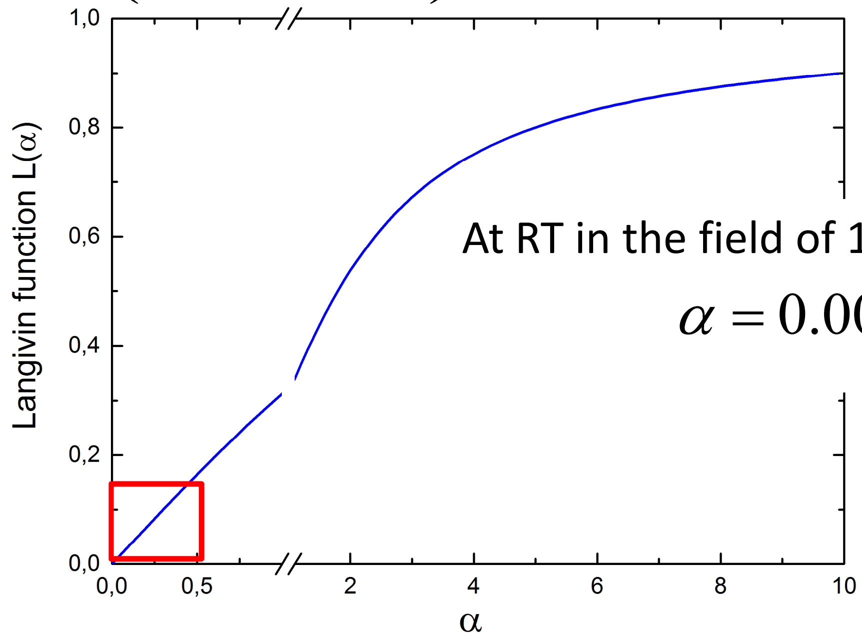
Paramagnetism: independent magnetic moments in external field



Full magnetization along the field:

$$M = N\mu\left(\coth\alpha - \frac{1}{\alpha}\right) \qquad \alpha = \frac{MH}{kT}$$





At RT in the field of 1MA/м:

$$\alpha = 0.003$$

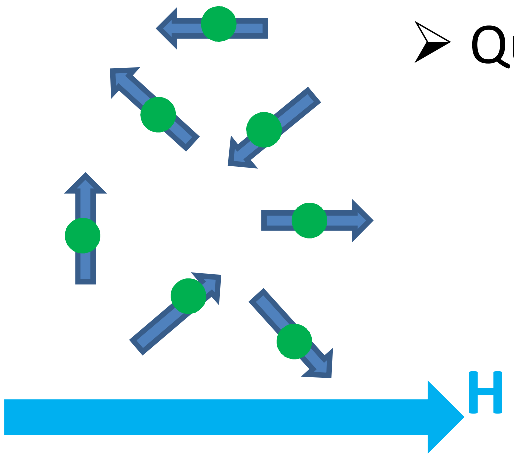
$$M = N\mu L(\alpha) = N\mu(\alpha/3 - ....) = \frac{N\mu^2}{3kT}H$$

Paramagnetic susceptibility:

$$\chi_{para} = \frac{\partial M}{\partial H} = \frac{N\mu^2}{3kT}$$

Curie law

Paramagnetism: independent magnetic moments in external field



- Quantization of the magnetic moment

$$\mu_z = g\mu_B J_z$$

$$J_z = J, J-1 \ldots -J$$

$$\alpha = \frac{gJ\mu_B H}{kT}$$

Resulting magnetization along the field:

$$M = NgJ\mu_B B_J(\alpha)$$

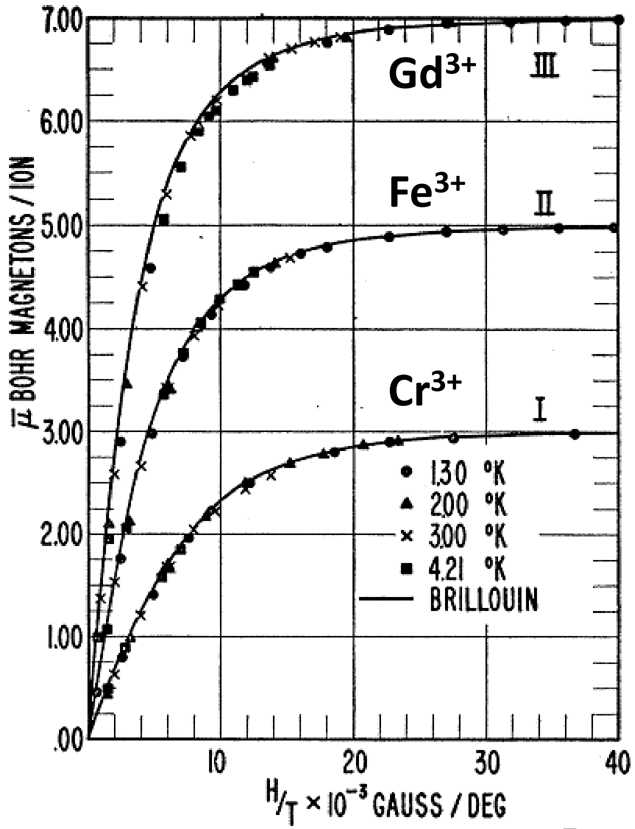
Brillouin function

At small α :

$$M = NgJ\mu_B\left(\frac{J+1}{3J}\alpha - \ldots\right)$$

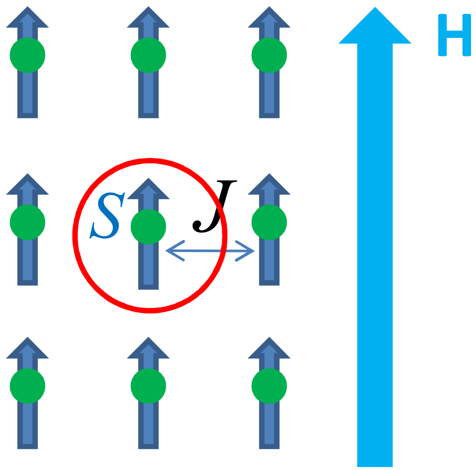
Curie law

$$\chi_{para} = \frac{Ng^2 J(J+1)\mu_B^2}{3kT}$$



[Henry, PR 88, 559 (1952)]

Ferromagnets: Weiss molecular field



Averaged projected magnetic moment:

$$\langle \mu_z \rangle = g\mu_B S B_S(\alpha)$$

$$\Downarrow$$

$$\langle S_z \rangle = S B_S(\alpha)$$

$$\alpha = \frac{g\mu_B S(H + H_m)}{kT}$$

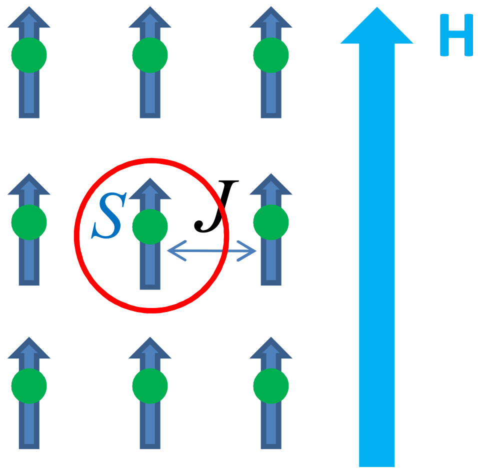
Weiss field due to exchange interactions *J* with N nearest neighbors:

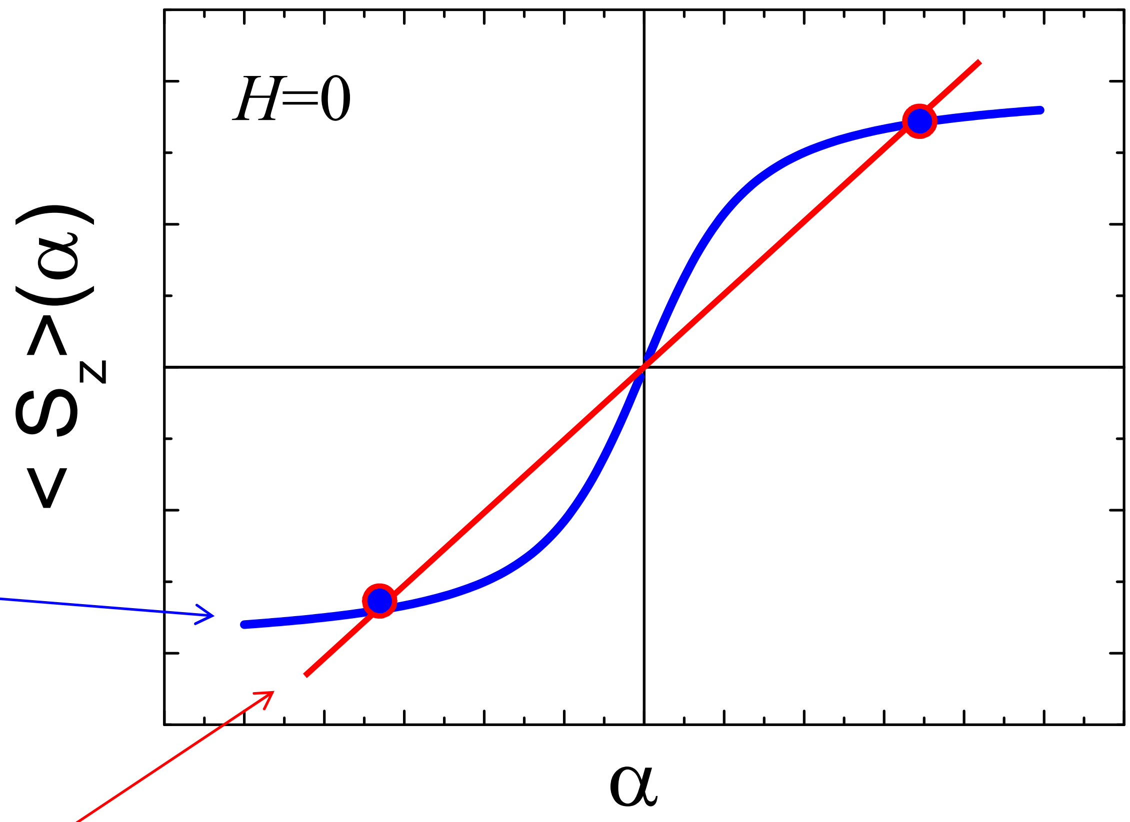
$$H_m = \frac{NJ\langle S_z \rangle}{g\mu_B}$$

$$\langle S_z \rangle = S B_S\left(\frac{g\mu_B S\left(H + \frac{NJ\langle S_z \rangle}{g\mu_B} \right)}{kT} \right)$$

$\Rightarrow$ Self-consistent solution

Back to ferromagnets: Weiss molecular field





$$\langle S_z \rangle = S B_S(\alpha)$$

$$\alpha = \frac{g\mu_B S(H + H_m)}{kT}$$

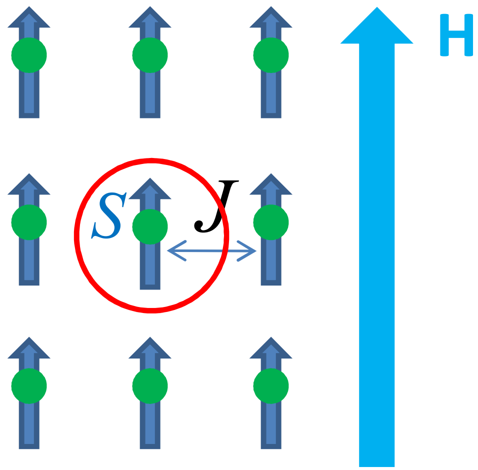
$$\langle S_z \rangle = \frac{kT}{NJS}\alpha - \frac{g\mu_B}{NJ}H$$

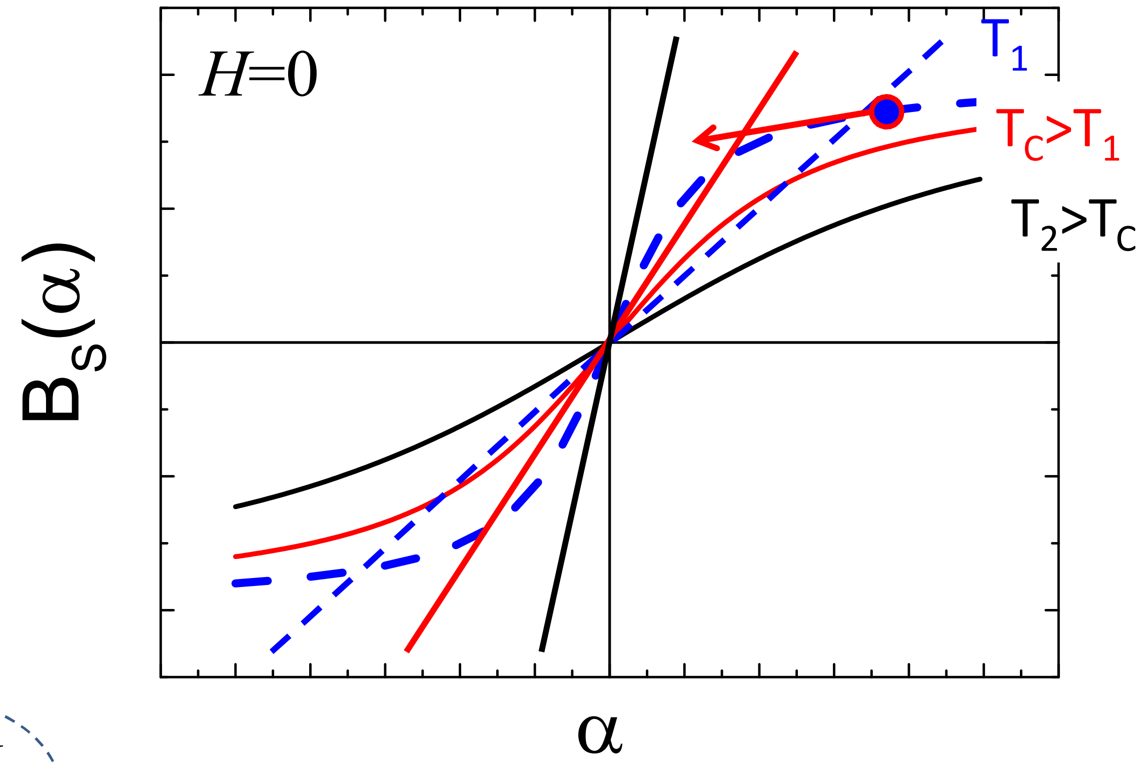
=0

2 non-zero solutions: $\pm\langle S_z \rangle$

2 opposite orientations of the order parameter

Ferromagnets (S=1/2): Curie temperature





Variations of these curves with T:

$$\langle S_z \rangle = S B_S(\alpha)$$

$$\langle S_z \rangle = \frac{kT}{NJS}\alpha - \frac{g\mu_B}{NJ}H$$

=0

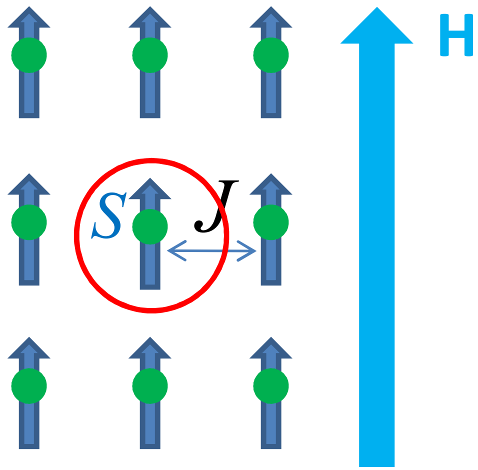
At $T \geq T_C$ $\langle S_z \rangle = 0$

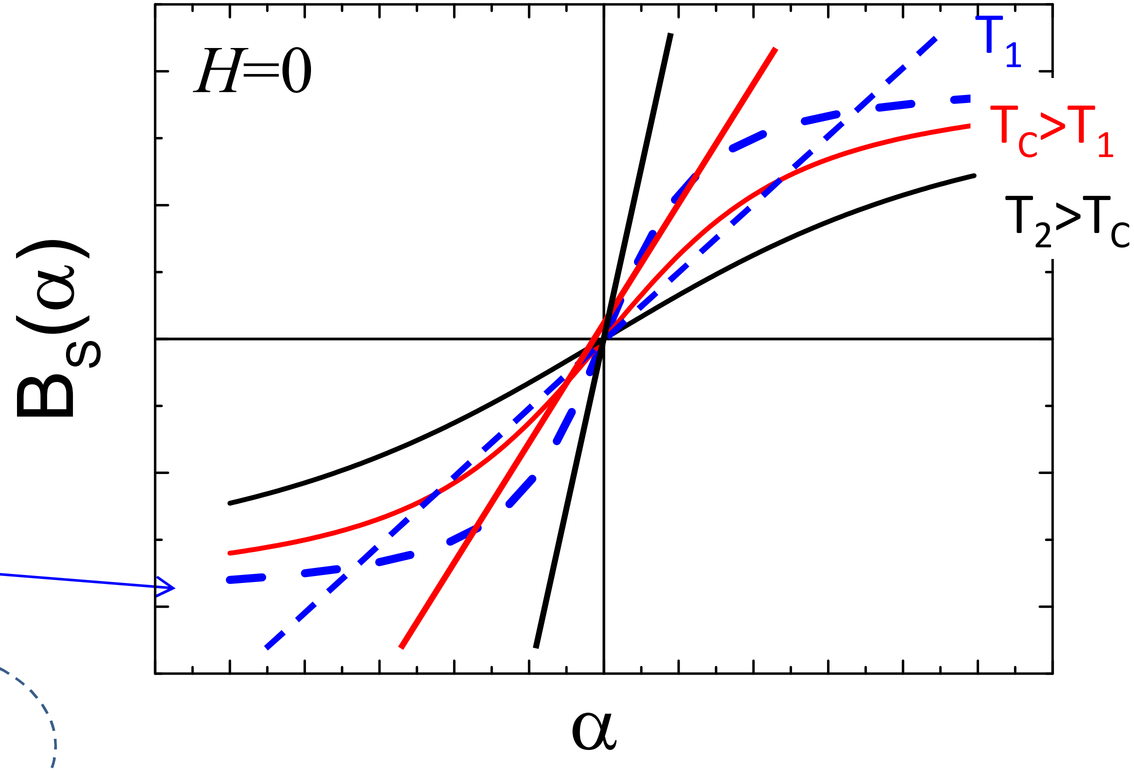
Ordering temperature: $T_C = \frac{JN}{k}$

$\langle S_z \rangle$ changes continuously with T

2nd order phase transition

Ferromagnets (S=1/2): Magnetization in a vicinity of T_C





$$\langle S_z \rangle = S B_S(\alpha)$$

$$\langle S_z \rangle = \frac{kT}{NJS}\alpha - \frac{g\mu_B}{NJ}H$$

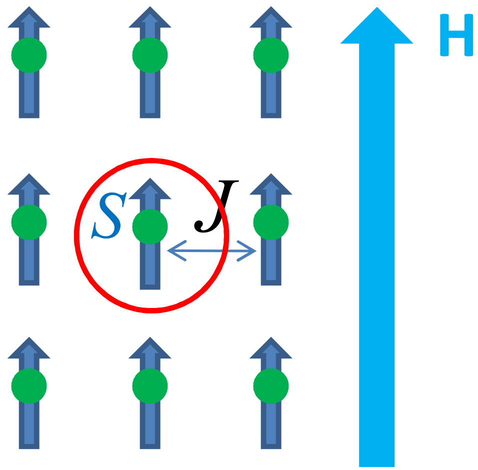
=0

At $T \to T_C$ $\quad \langle S_z \rangle \to 0$

$$\alpha \to 0$$

$$\langle S_z \rangle = \frac{3}{4}\left(1 - \frac{T_C}{T}\right)^{1/2}$$

Ferromagnets (S=1/2): Curie temperature



Ordering temperature: $T_C = \frac{JN}{k}$

2nd order phase transition

Mean-field approximation predicts:

1D case: $T_C = 2\frac{J}{k} > 0$

2D case: $T_C = 4\frac{J}{k}$

3D case: $T_C = 6\frac{J}{k}$

Reality:

No magnetic ordering

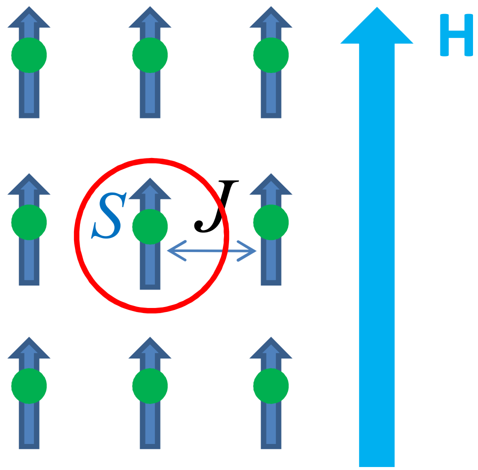
$T_C = 2.269\frac{J}{k}$

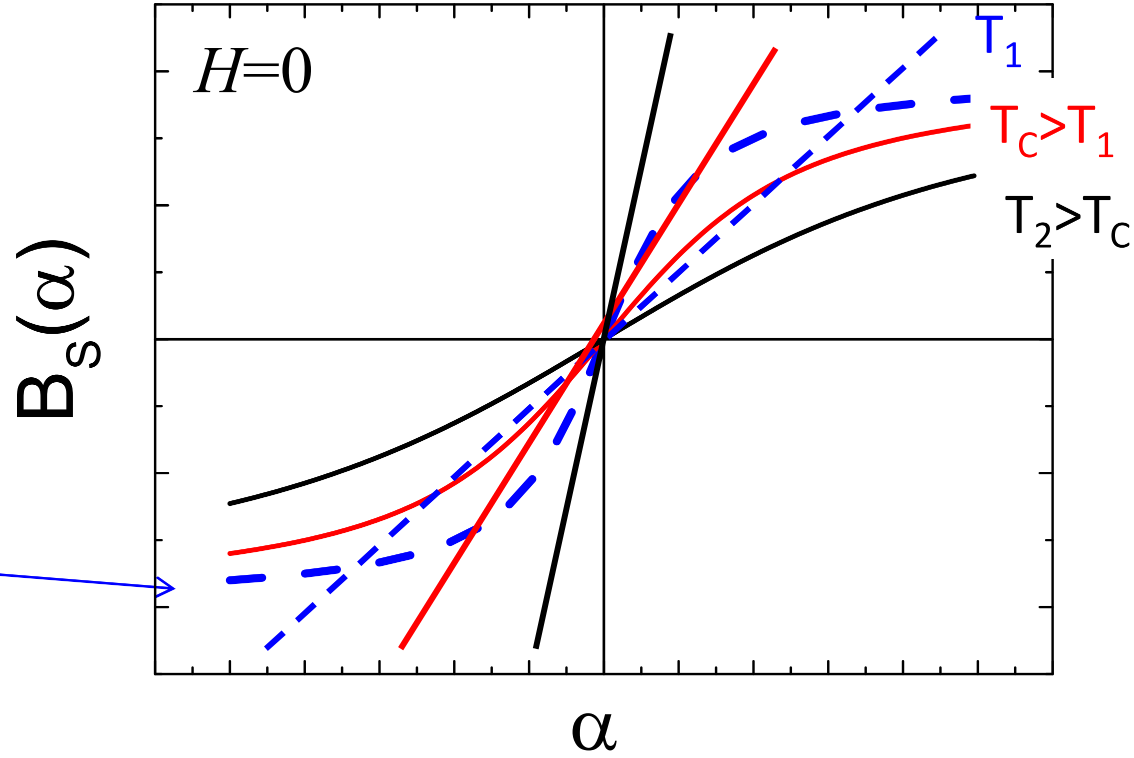
$T_C = 4.511\frac{J}{k}$

Agreement gets better for the 3D case

Reason: fluctuations were neglected

Ferromagnets (S=1/2): at low temperatures





$$\langle S_z \rangle = S B_S(\alpha)$$

$$\alpha = \frac{g\mu_B S(H + H_m)}{kT}$$

At T→0 $\quad \langle S_z \rangle \to S$

$$\alpha \to \infty$$

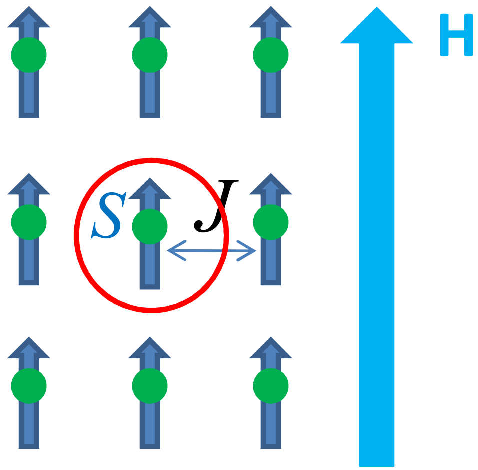
Prediction:

$$\langle S_z \rangle = \frac{1}{2}\left(1 - 2e^{-2T_C/T}\right)$$

Reality:

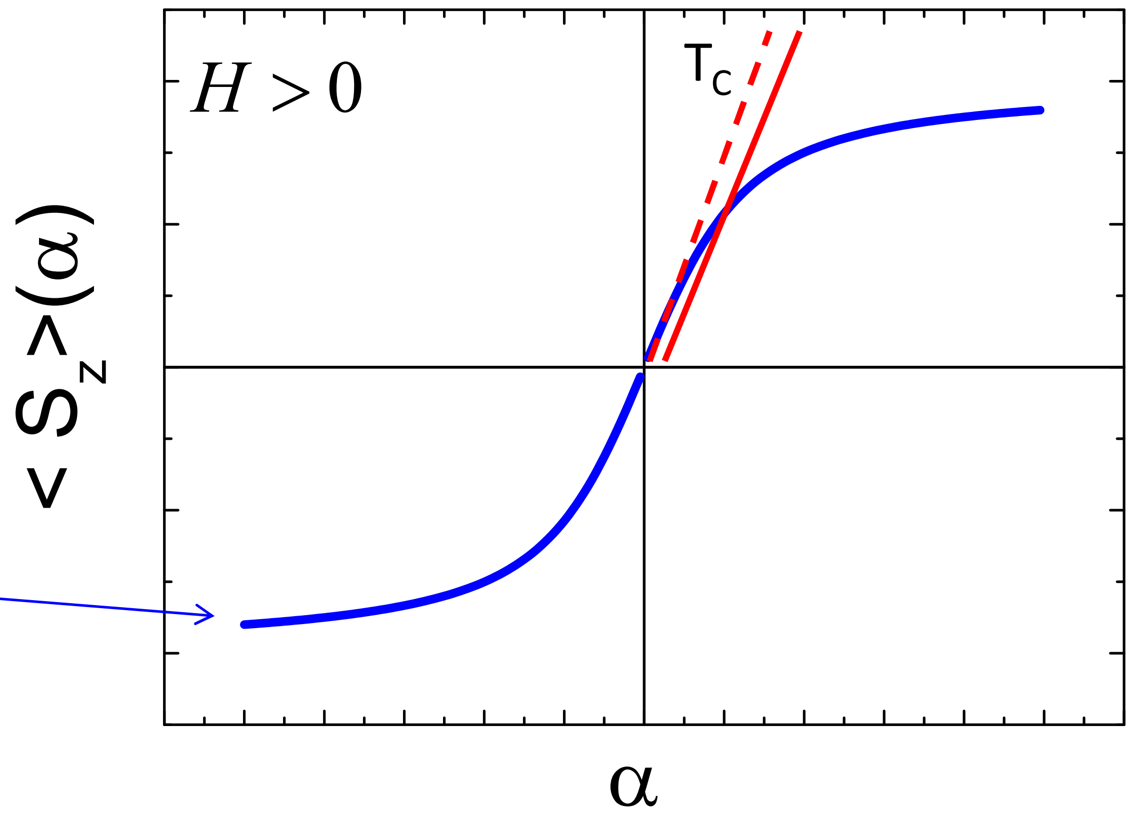
$$M(T) = M_0\left(1 - (T/T_C)^{3/2}\right)$$

Ferromagnets (S=1/2) in applied field



$$\langle S_z \rangle = S B_S(\alpha)$$

$$\alpha = \frac{g\mu_B S(H + H_m)}{kT}$$



Non-zero magnetization above T_C

Susceptibility

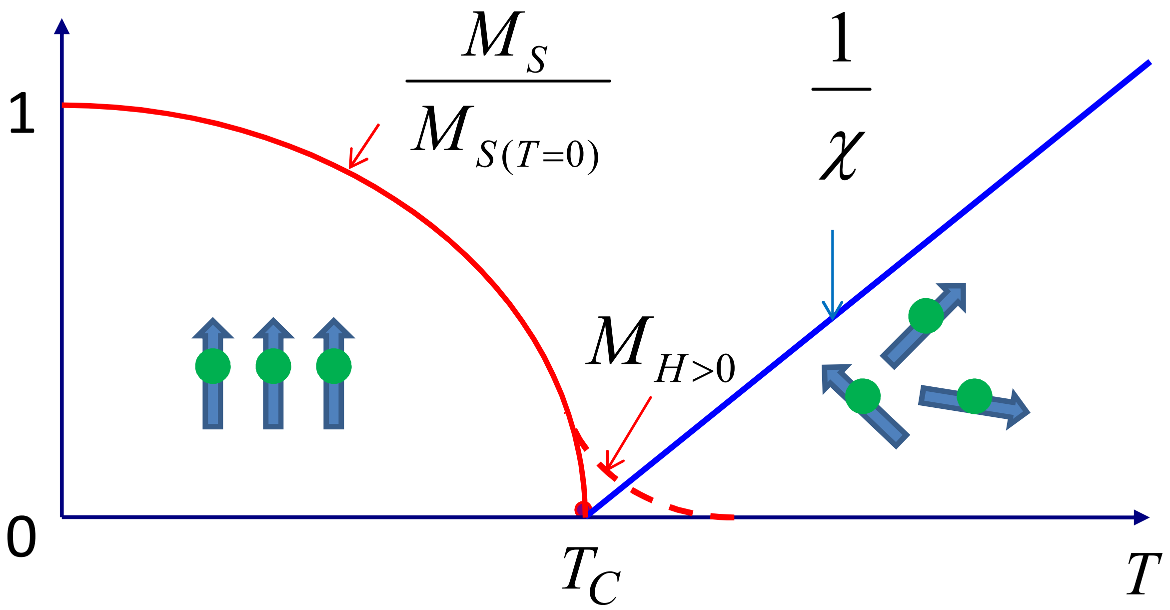
Above T_C
in small fields

$$\langle S_z \rangle \approx \frac{\mu_B H}{k(T - T_C)}$$

$$\chi_{T>T_C} \approx \frac{1}{k(T - T_C)}$$

Curie-Weiss law

Weiss molecular field theory:



Temperature Curie

$$T_C = \frac{JN}{k}$$

$$\langle S_z \rangle \propto \left(1 - \frac{T_C}{T}\right)^{1/2}$$

Critical exponent β=1/2

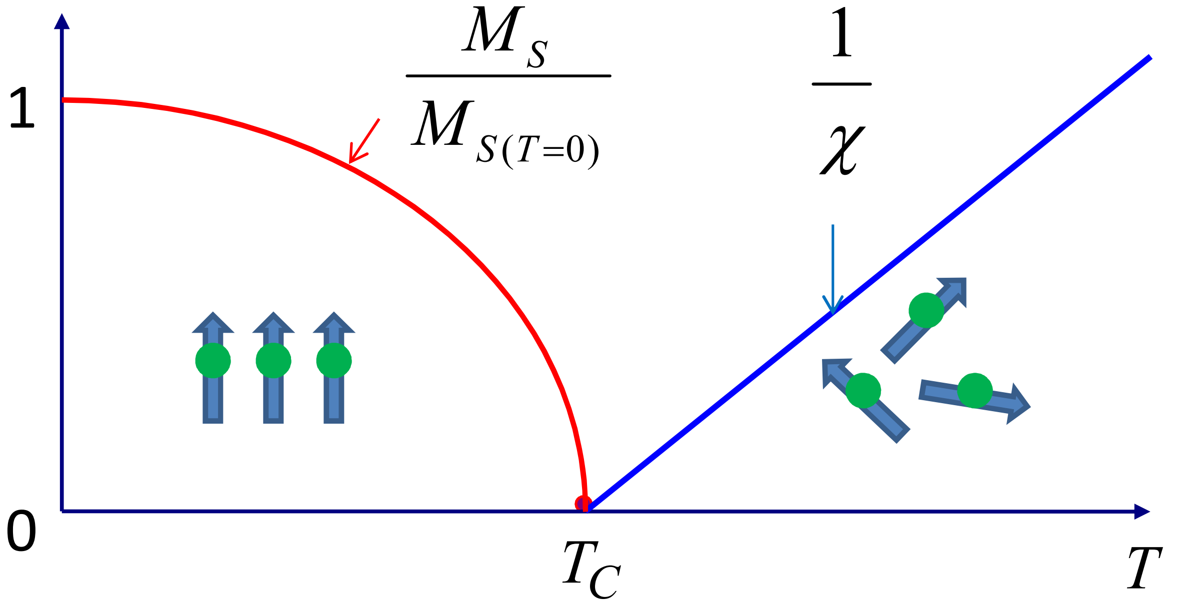
Curie-Weiss law

$$\chi_{T>T_C} \propto \frac{1}{k(T - T_C)}$$

Critical exponent γ=-1

Landau theory of phase transitions gives the same values of critical exponents

Weiss molecular field theory:



$$M_S \propto (T_C - T)^{\beta}$$

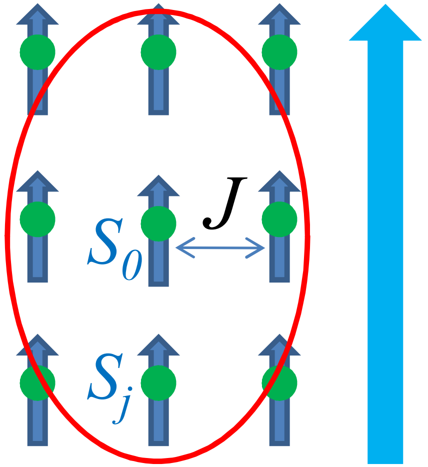
$$\chi \propto (T_C - T)^{-\gamma}$$

$$\xi \propto (T_C - T)^{-\nu}$$

Spin-spin correlations

System	β	γ	ν
2D Ising	0.125	1.75	1
2D XY system	0.231[a]	—	—
2D Heisenberg	—	—	—
3D Ising	0.325	1.241	0.630
3D XY system	0.345	1.316	0.669
3D Heisenberg	0.365	1.386	0.705
Landau theory and MF	0.5	1	0.5

Mean-field approximation: Bethe mean-field theory



From uncorrelated spins
to uncorrelated clusters of spins

- S_0 interaction with its 4 neighbors is treated exactly (cluster)
- S_j are subject to effective (Weiss) field

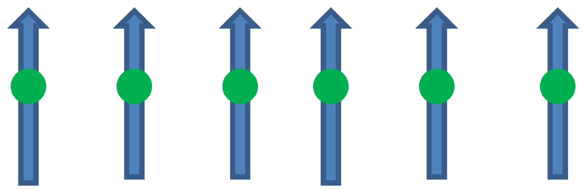
$$T_C = \frac{2J}{k\ln(N/(N-2))}$$

Approximation predicts:		**Reality:**	
1D case:	$T_C = 0$	No magnetic ordering	
2D case:	$T_C = 2.885\frac{J}{k}$	$T_C = 2.269\frac{J}{k}$	**Agreement is improved**
3D case:	$T_C = 4.993\frac{J}{k}$	$T_C = 4.511\frac{J}{k}$	

Temperature dependence of magnetization

At T=0

$$\langle S_z \rangle \to S$$

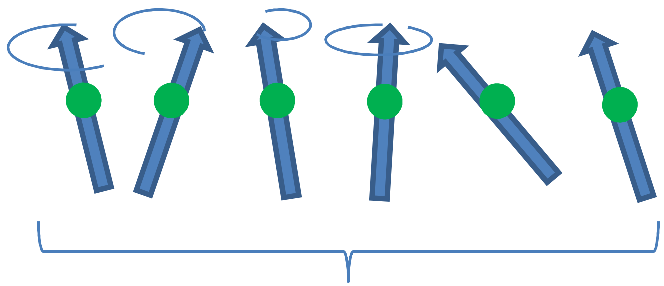


$\mathbf{M(r)=M_0}$

Minimum of the exchange energy

At T>0

Thermal fluctuations



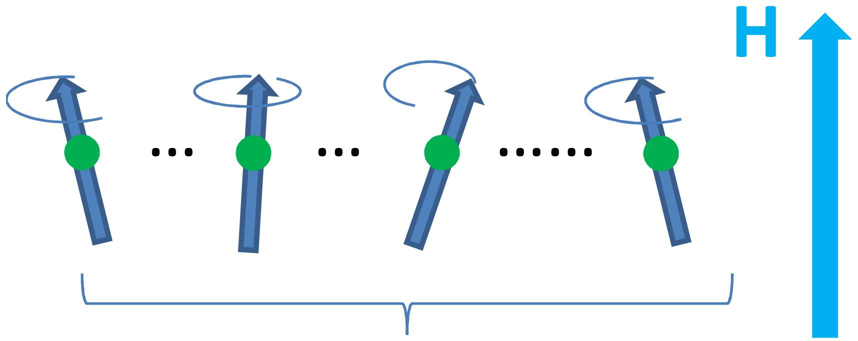
$\mathbf{M(r)}$

Superposition of harmonic waves – **thermal spin waves** (introduced by Bloch)

Nonparallel $\mathbf{S}_i$ ⇨ Increase of the exchange energy

The magnitude of the gradient of M is important!

Magnetization at T>0



Characteristic period
of magnetization variation λ

λ>> a (inter-atomic distance)

λ<< L (sample size)

$$\mathbf{M}(\mathbf{r})=\mathbf{M}_0+\Delta\mathbf{M}(\mathbf{r})$$

$$|\Delta\mathbf{M}(\mathbf{r})| \ll \mathbf{M}_0$$

Small deviation of **M** from $\mathbf{M}_0$

$$(\mathbf{M}(\mathbf{r}))^2 = M_0^2 = const$$

Length of **M** is conserved

⇒ **Plane waves in a continuous medium**
(some analogy with sound waves)

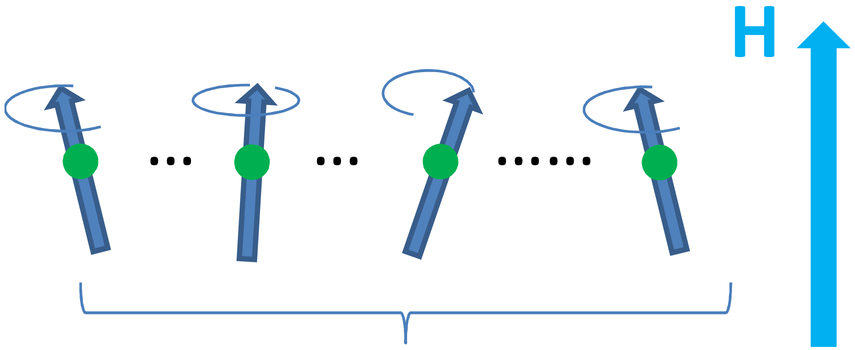
Energy of a ferromagnet as a function of the spatial distribution of magnetization?

Increase of the Zeeman energy: $-(\mathbf{M}(\mathbf{r})-\mathbf{M}_0)\mathbf{H}$

Increase of the exchange energy: $\left(\frac{A}{M_0^2}\right)\left[(\nabla M_x)^2+(\nabla M_y)^2+(\nabla M_z)^2\right]$

Exchange constant

Magnetization at T>0



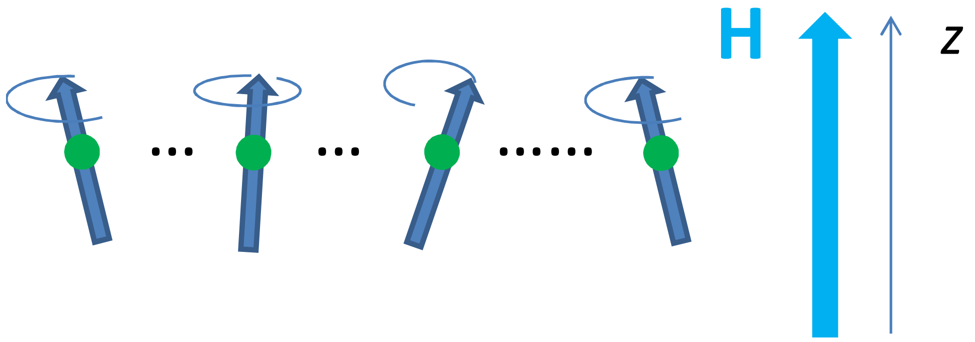
Energy of a ferromagnet as a function
of the spatial distribution of magnetization:

$$E = \int \left[\left(\frac{A}{M_0^2} \right) \left[(\nabla M_x)^2 + (\nabla M_y)^2 + (\nabla M_z)^2 \right] - (M - M_0) H_0 \right] dr$$

Increase of the Zeeman energy $\mathbf{-(M(r)-M_0)H}$

Increase of the exchange energy $\left(\frac{A}{M_0^2} \right) \left[(\nabla M_x)^2 + (\nabla M_y)^2 + (\nabla M_z)^2 \right]$

Magnetization at T>0



$$E = \int \left[\left(\frac{A}{M_0^2} \right) \left[(\nabla M_x)^2 + (\nabla M_y)^2 + (\nabla M_z)^2 \right] - (M - M_0) H_0 \right] dr$$

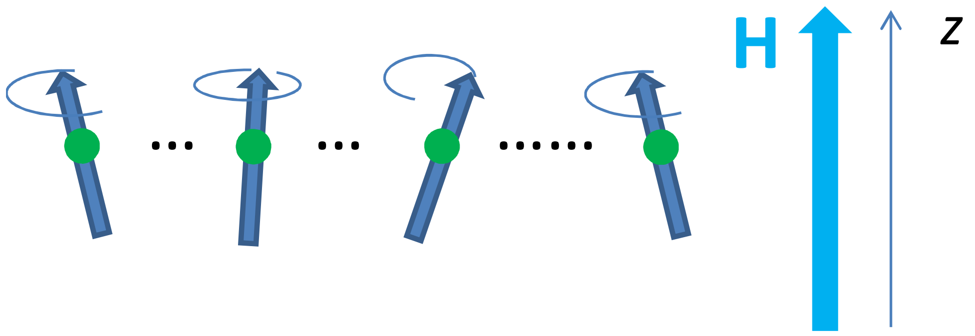
Small deviations of **M**:

$M_x, M_y << M_0$

$$M_z \approx \left(1 - \frac{M_x^2 + M_y^2}{2M_0^2} \right) M_0$$

$$E = \int \left[\left(\frac{A}{M_0^2} \right) \left[(\nabla M_x)^2 + (\nabla M_y)^2 \right] + \frac{H_0 \left(M_x^2 + M_y^2 \right)}{2M_0} \right] dr$$

Magnetization at T>0

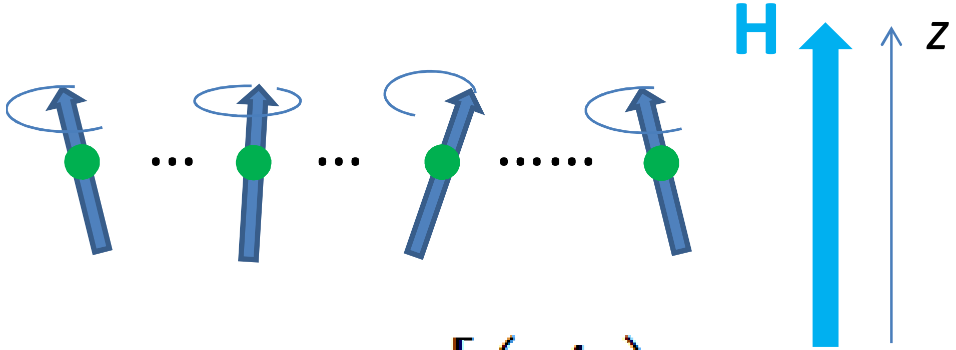


$$E = \int \left[\left(\frac{A}{M_0^2} \right) \left[(\nabla M_x)^2 + (\nabla M_y)^2 \right] + \frac{H_0 (M_x^2 + M_y^2)}{2M_0} \right] dr$$

Introduce complex combinations: $M^{\pm} = M_x \pm i M_y$

$$E = \int \left[\left(\frac{A}{M_0^2} \right) (\nabla M^+ \nabla M^-) + \left(\frac{H_0}{2M_0} \right) M^+ M^- \right] dr$$

Magnetization at T>0: Exchange waves



$$E = \int \left[\left(\frac{A}{M_0^2} \right) (\nabla M^+ \nabla M^-) + \left(\frac{H_0}{2M_0} \right) M^+ M^- \right] d\boldsymbol{r}$$

$$M^{\pm} = M_x \pm i M_y \quad \Rightarrow \quad M^-(\boldsymbol{r}) = \left(\frac{2\mu M_0}{V} \right) \sum_k b_k e^{i\boldsymbol{kr}}, \quad M^+(\boldsymbol{r}) = \left(\frac{2\mu M_0}{V} \right) \sum_k b_k^* e^{-i\boldsymbol{kr}}$$

$$E = \sum_k \left(\frac{2\mu A}{M_0} k^2 + \mu H_0 \right) b_k^* b_k$$

A sum of the energies of plane waves – **spin waves**

Magnetization at T>0: magnons

Energy of a ferromagnet:

$$E = \sum_k \left(\frac{2\mu A}{M_0} k^2 + \mu H_0\right) b_k^* b_k$$

$$n_k = b_k^* b_k$$

number of quasiparticles - **magnons** in the state with an energy:

$$\varepsilon_k = \frac{2\mu A}{M_0} k^2 + \mu H_0$$

Quasi-momentum of magnon $\boldsymbol{P} = \hbar \boldsymbol{k}$

Effective mass of a magnon $m^* = \frac{M_0 \hbar^2}{4\mu A} = \frac{M_0 \hbar}{4\gamma A}$

Bose-Einstein distribution of thermal magnons $n_k = \frac{1}{e^{\varepsilon_k / k_B T} - 1}$

Magnetization at T>0: magnons

$$\sum_k n_k = \frac{1}{\mu}\left(VM_0 - \int M_z dr\right)$$

Each magnon reduces the total magnetic moment of the sample by μ

⇓ Quadratic dispersion
Bose-Einstein distribution

$$M(T) = M_0 - \frac{5.157 \cdot 10^{-5}}{(\gamma A M_0)^{3/2}} T^{3/2}$$

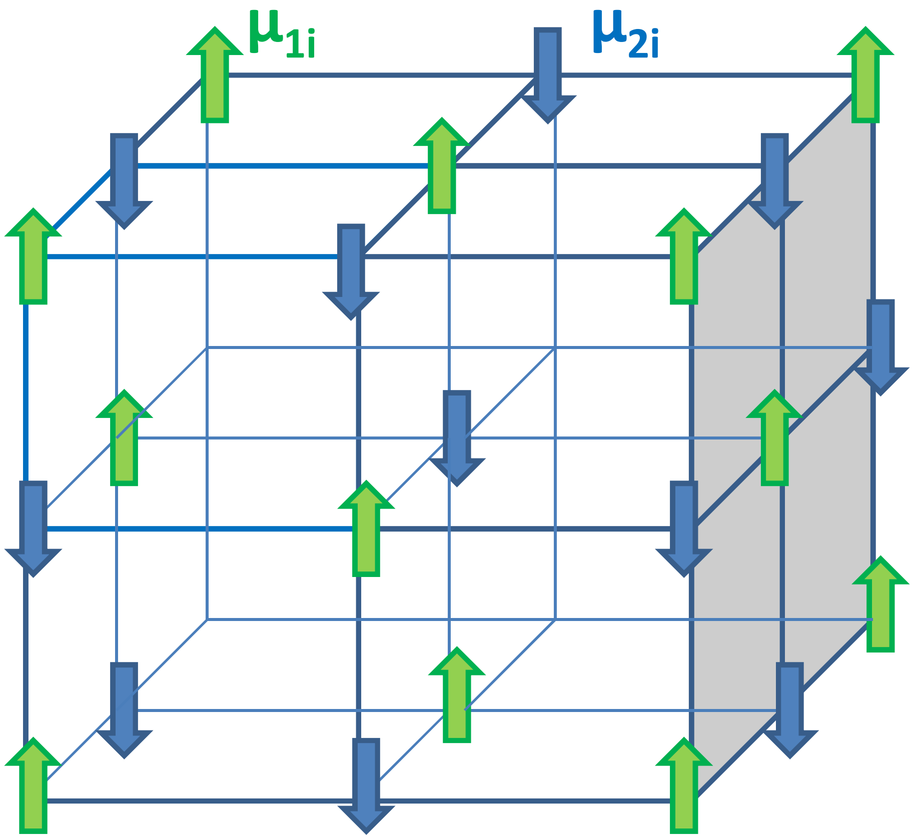
Bloch (3/2-) law: correct temperature dependence of magnetization at low T

Antiferromagnets

Neel temperature

Susceptibility

Antiferromagnets



Magnetic sublattices:

$M_1 = \Sigma \mu_{1i}/V$ $M_2 = \Sigma \mu_{2i}/V$

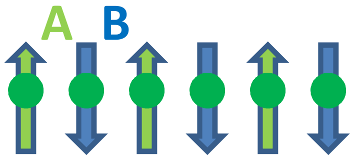
$M = M_1 + M_2$	Magnetization (ferromagnetic vector)
$L = M_1 - M_2$	Antiferromagnetic vector)

Equivalent magnetic sublattices

– same type of magnetic ions in the same crystallographic positions

Number of magnetic sublattices is equivalent to the number of magnetic ions in the magnetic unit cell

Antiferromagnets: Neél temperature



H=0

Molecular (Weiss) fields
for the case of two sublattices:

$$H_A = w_{AA} M_A + w_{AB} M_B$$

$$H_B = w_{BB} M_B + w_{BA} M_A$$

Equivalent sublattices:

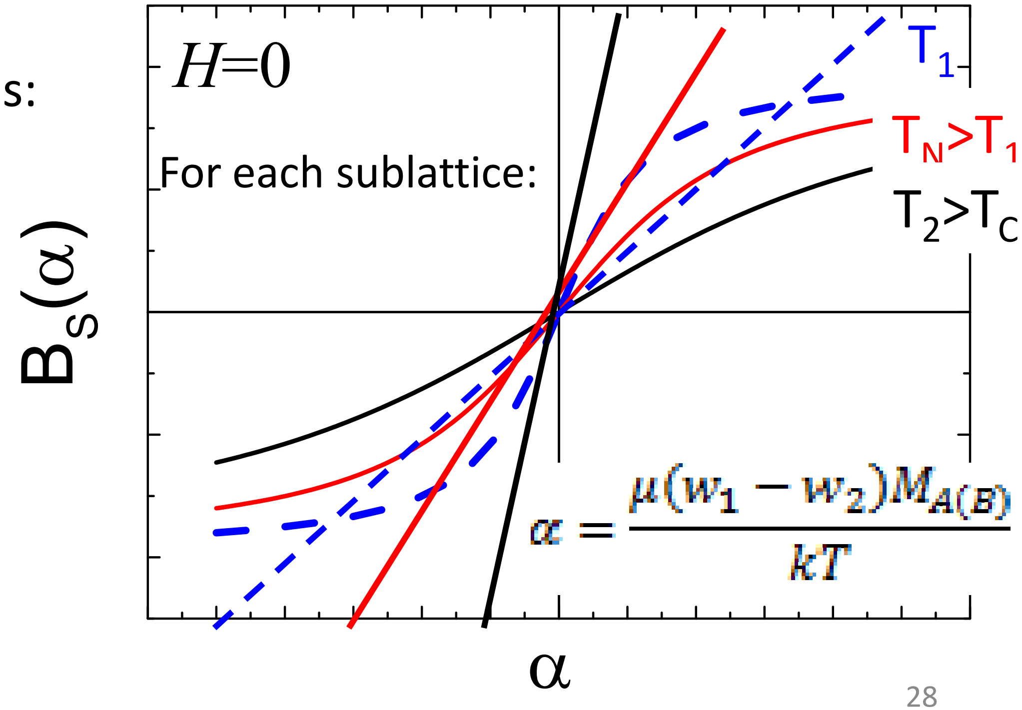
$$w_{AA} = w_{BB} = w_1$$

$$w_{AB} = w_{BA} = w_2$$

$$M_A = -M_B$$

Magnetization of a sublattice
in the presence of the molecular fields:

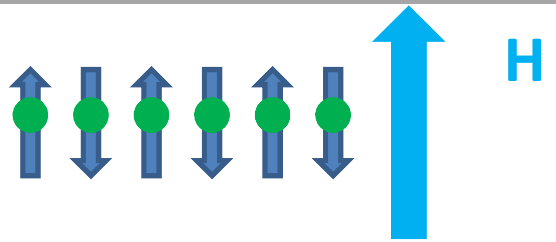
$$M_{A(B)} = \frac{N\mu}{2} L\left(\frac{\mu(w_1 - w_2) M_{A(B)}}{kT}\right)$$



Neél temperature:

$$T_N = \frac{N\mu^2}{6k}(w_1 - w_2)$$

Antiferromagnets: susceptibility



$$\chi_{afm} \leq \chi_{par}$$

$$H_A = w_{AA} M_A + w_{AB} M_B + H$$

$$H_B = w_{BB} M_B + w_{BA} M_A + H$$

Equivalent sublattices:

$$w_{AA} = w_{BB} = w_1 > 0$$

$$w_{AB} = w_{BA} = w_2 < 0$$

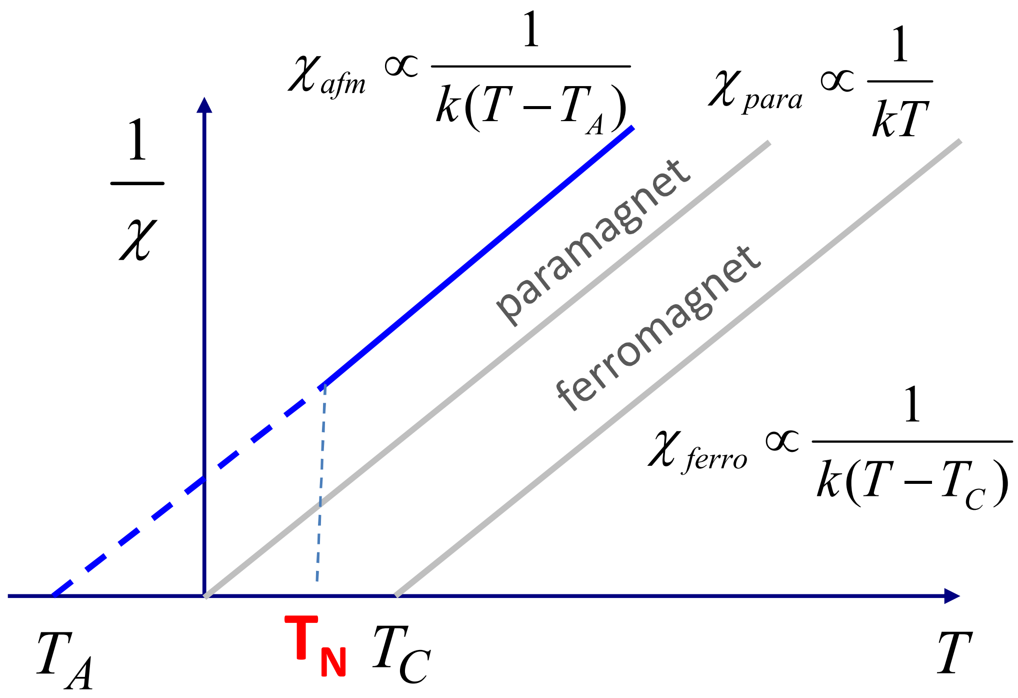
~~$M_A = -M_B$~~

Asymptotic Curie temperature:

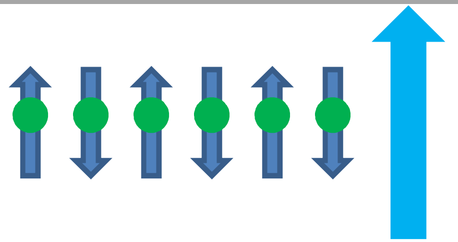
$$T_A = \frac{N\mu^2}{6k}(w_1 + w_2)$$

Susceptibility above T_N:

$$\chi = \frac{N\mu^2}{3k}\frac{1}{T - T_A}$$



Antiferromagnets: susceptibility



$$\chi_{afm} \le \chi_{par}$$

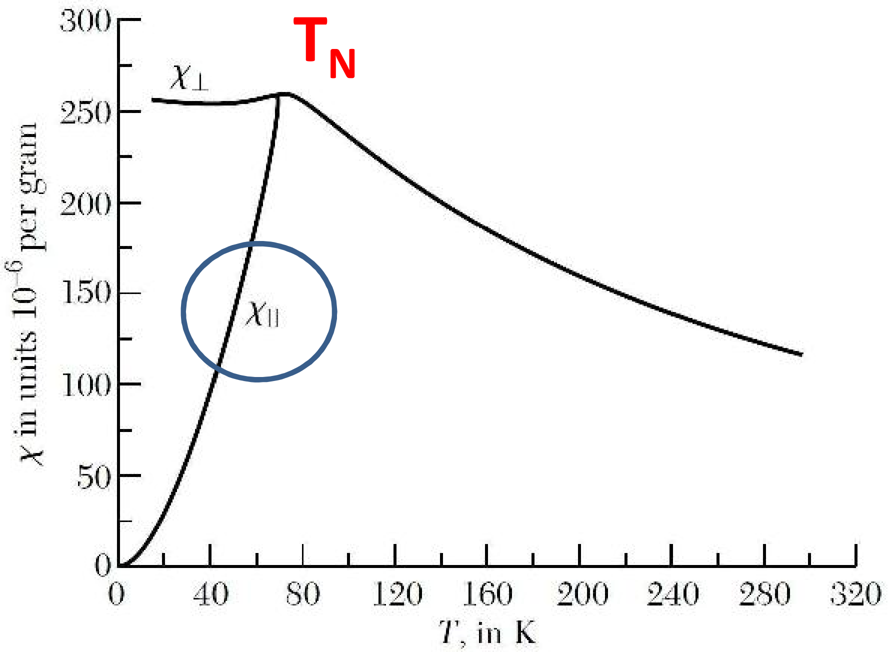
Equivalent sublattices:

$$w_{AA}=w_{BB}=w_1>0$$
$$w_{AB}=w_{BA}=w_2<0$$

~~$M_A=-M_B$~~

Susceptibility in the Neél point:

$$\chi_{max} = \frac{N\mu^2}{3k}\frac{1}{T_N - T_A} = -\frac{1}{w_2}$$



Susceptibility at T=0: $\chi=0$

Antiferromagnets: some examples

Compound	Crystal structure	Paramagnetic lattice structure	No. of sublattices	T_N
MnF_2	Rutile	Body-centered rectangular	2	72°
FeF_2	Rutile	Body-centered rectangular	2	79°
MnO	NaCl	f.c.c.	4	122°
FeO	NaCl	f.c.c.	4	198°
MnS	NaCl	f.c.c.	4	165°
MnSe[a]	NaCl	f.c.c.	4	~150°
$FeCl_2$	$CdCl_2$	Hexagonal layer structure	3	23.5°
$CoCl_2$	$CdCl_2$	Hexagonal layer structure	3	24.9°
$NiCl_2$	$CdCl_2$	Hexagonal layer structure	3	49.6°

[P. W. Anderson, Phys. Rev. 79, 705 (1950)]

Magnetic anisotropy

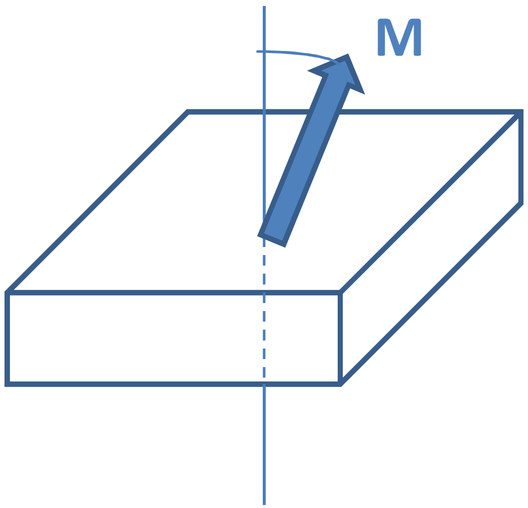
Magnetic-dipole contribution

Magneto-crystalline anisotropy and its temperature dependence

Magnetic anisotropy

Magnetic anisotropy energy – energy required to rotate magnetization from an “easy” to a “hard” direction

Without anisotropy net magnetization of 3D solids would be weak; in 2D systems it would be absent [Mermin and Wagner, PRL **17**, 1133 (1966)]



Magnetization – axial vector

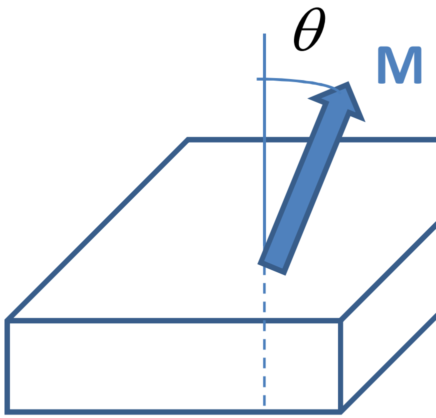
Sources of anisotropy:
- Deformation
- Intrinsic electrical fields
- Shape etc….

- polar impacts

Magnetic anisotropy sets an axis, not a direction

Magnetic anisotropy: phenomenological consideration

Uniaxial anisotropy



$$E_a = K_{u1}\sin^2\theta + K_{u2}\sin^4\theta + \ldots$$

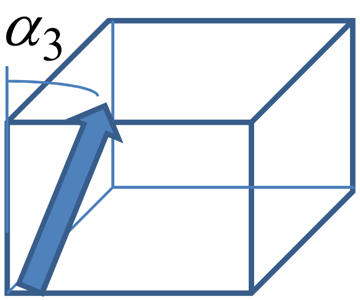
$K_{u1} > 0$ (001) – easy plane

$K_{u1} < 0$ [001] – easy axis

Effective anisotropy field

$$\mathbf{H}_a = -\frac{\partial E_a}{\partial \mathbf{M}} = -\frac{2K_{u1}}{M}\cos\theta\mathbf{n} + \ldots$$

Cubic anisotropy



$$w_a = K_1\left(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_1^2\alpha_3^2\right) + K_2\alpha_1^2\alpha_2^2\alpha_3^2 + \ldots$$

$K_1 > 0$ easy axes- {100}

$K_1 < 0$ easy axes- {111}

Magnetic anisotropy

Compound	k_1, erg cm^{-3}	k_2, erg cm^{-3}
Fe	$4{,}6 \cdot 10^5$	$1{,}5 \cdot 10^5$
Ni	$-5 \cdot 10^4$	$2{,}3 \cdot 10^4$
Co	$4{,}1 \cdot 10^6$	$1{,}0 \cdot 10^6$
$Y_3Fe_5O_{12}$	$6{,}5 \cdot 10^3$	
$NiFe_2O_4$	$-6{,}2 \cdot 10^4$	
$BaFe_{12}O_{19}$	$3{,}3 \cdot 10^6$	

Origins of magnetic anisotropy

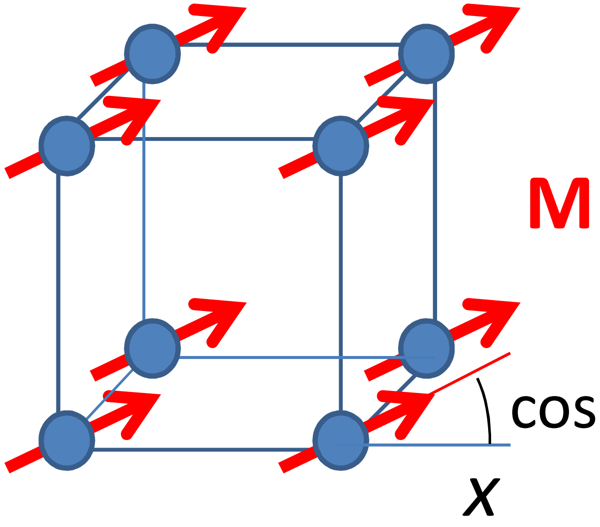
- **Single-ion anisotropy**
- **Anisotropic exchange**
- **Magnetic-dipolar interactions**

Spin-orbit interaction (Single-ion anisotropy, Anisotropic exchange)

Interactions between pairs of magnetic ions (Anisotropic exchange, Magnetic-dipolar interactions)

Magnetic-dipolar contribution to the anisotropy

Cubic crystal



For a pair of neighboring ions:

$$E(\phi) = w_{ex} - l\left(\alpha_1^2 - \frac{1}{3}\right) + q\left(\alpha_1^4 - \frac{6}{7}\alpha_1^2 + \frac{3}{35}\right) + \ldots$$

Dipolar interaction

Quadrupolar interaction

$$E_a = -2Nq\left(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_1^2\alpha_3^2\right) + \mathrm{const}$$

N – number of atoms per volume unit

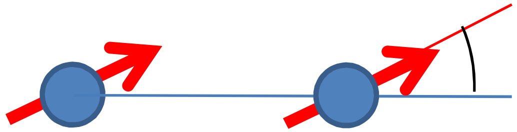
$$K_1 = -2Nq$$

– cubic anisotropy constant

fcc: $K_1 = 16/9Nq$

vcc: $K_1 = Nq$

Magnetic-dipolar contribution to the anisotropy



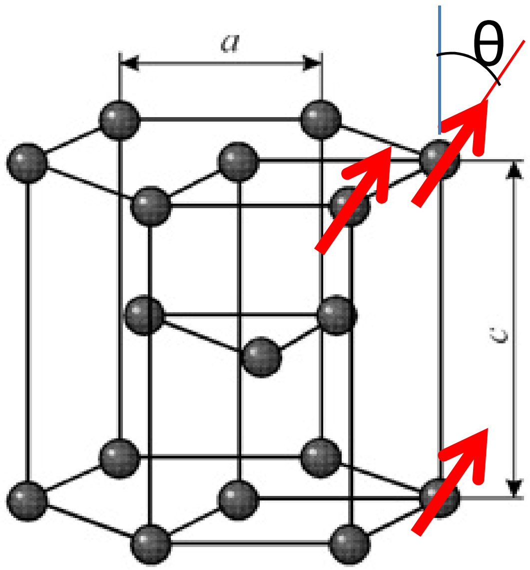
$\cos \phi = \alpha$

$$E(\phi) = l\left(\alpha_1^2 - \frac{1}{3}\right) + q\left(\alpha_1^4 - \frac{6}{7}\alpha_1^2 + \frac{3}{35}\right) + \ldots$$

Cubic crystal

$$E_a = K_1\left(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_1^2\alpha_3^2\right) + \ldots$$

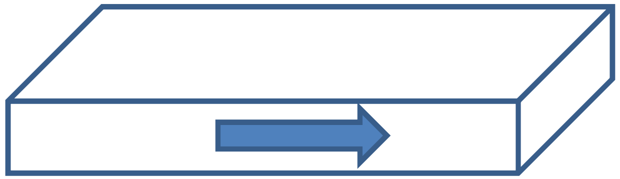
Hexagonal crystal



$$E_a = K_{u1}\sin^2\theta + K_{u2}\sin^4\theta + \ldots$$

$$K_{u1} \sim l > q$$

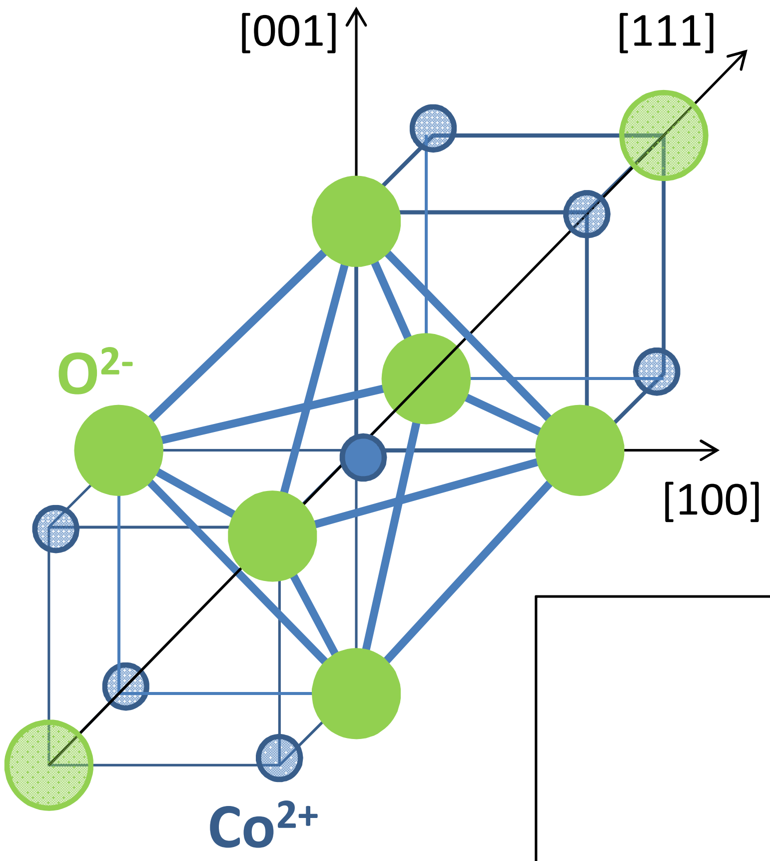
Contributes to the shape anisotropy



This films demonstrate in-plane anisotropy

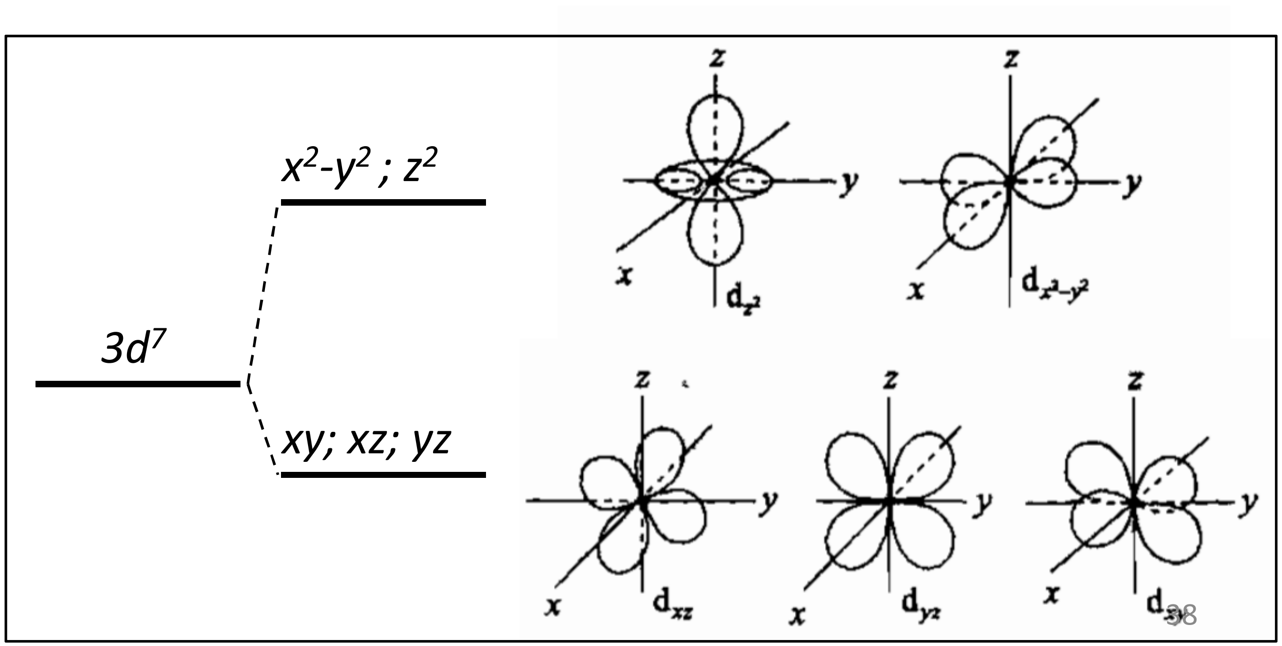
Single-ion anisotropy (crystal-field theory)

Spinel $CoFe_2O_4$

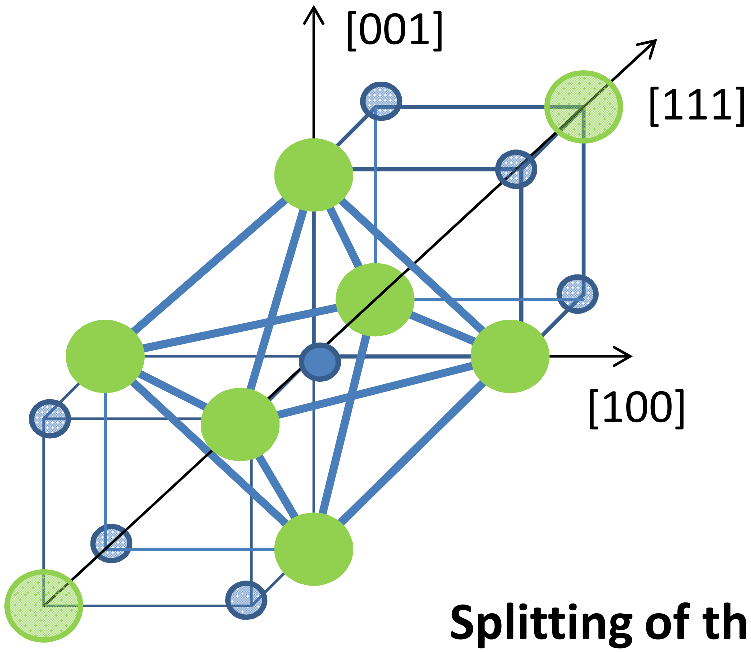


Co^{2+} in the octahedral coordination + trigonal distortion along [111]

Splitting of the 3d shell In the ligand field:

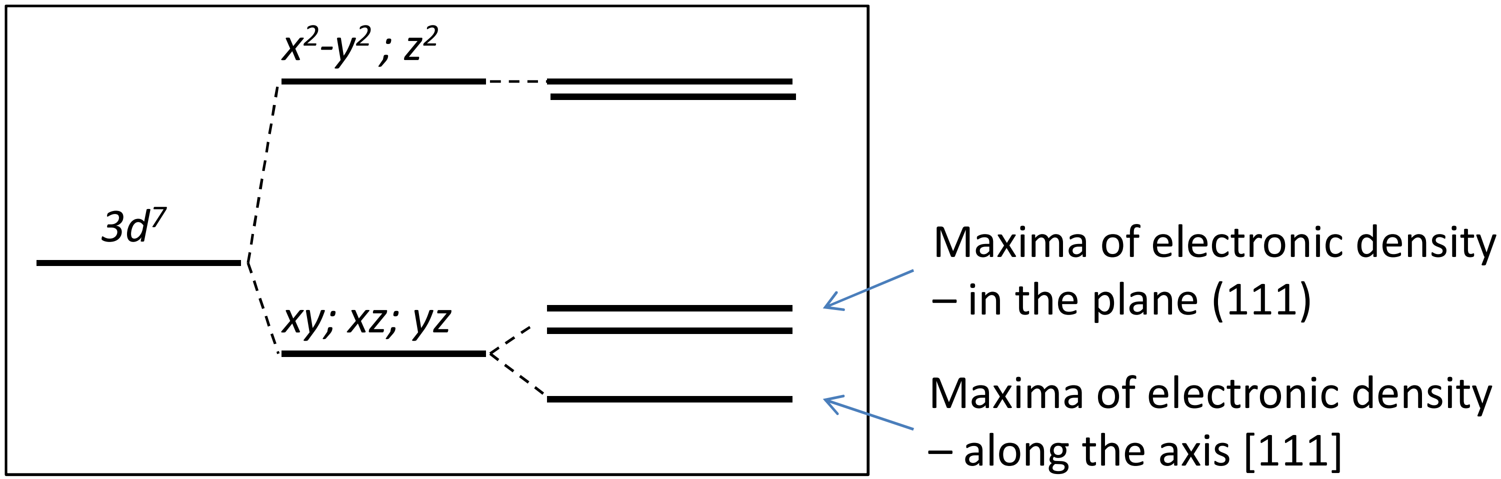


Single-ion anisotropy (crystal-field theory)

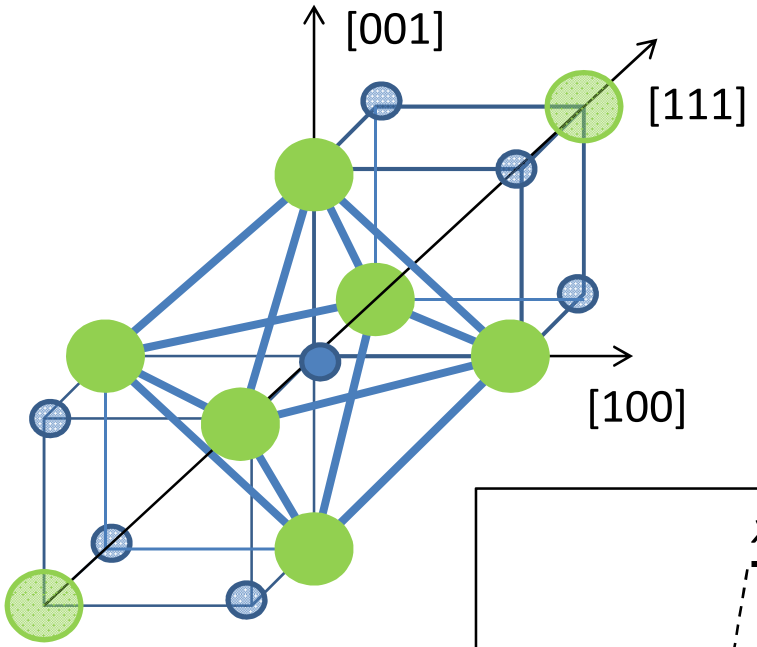


Co^{2+} in the octahedral coordination + trigonal distortion along [111]

Splitting of the 3d shell
In the ligand field + trigonal distortion

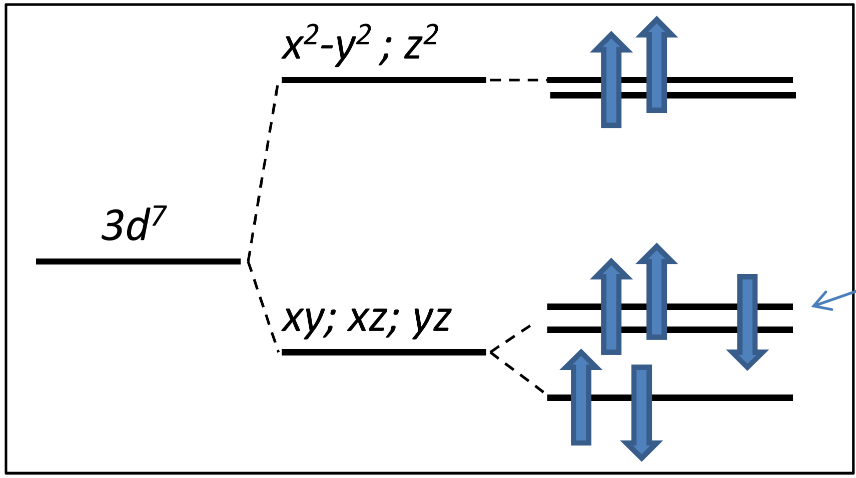


Single-ion anisotropy (crystal-field theory)



Co^{2+} in the octahedral coordination
+ trigonal distortion along [111]

Splitting of the 3d shell
In the ligand field + trigonal distortion



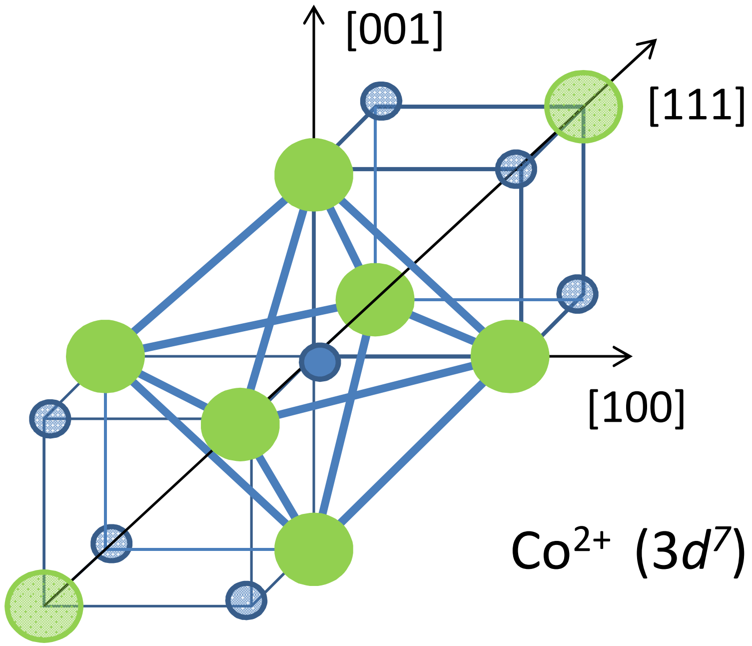
Orbital moment
L||[111]

Spin-orbit interaction $$w_{SO} = \lambda \mathbf{L} \cdot \mathbf{S} = \lambda L S |\cos\theta|$$

θ -angle between **S** и [111]

3rd Hunds rule: Co^{2+} ($3d^7$) $\longrightarrow$ $\lambda < 0$

Single-ion anisotropy (crystal-field theory)



Co^{2+} in the octahedral coordination
+ trigonal distortion along [111]

$$w_{SO} = \lambda \mathbf{L} \cdot \mathbf{S} = \lambda LS \left| \cos\theta \right|$$

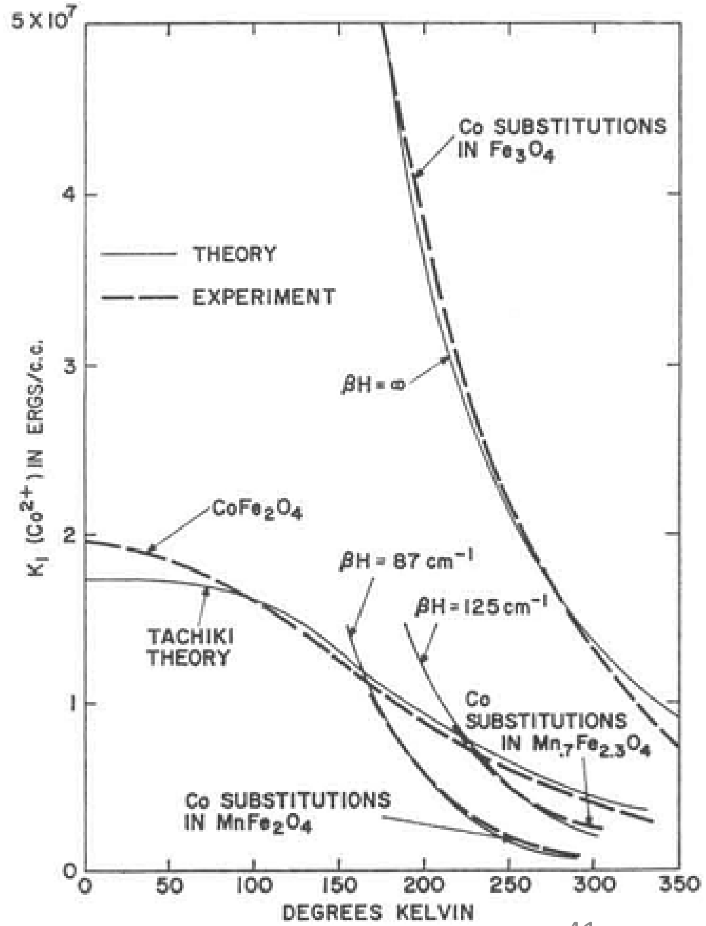
θ -angle between **S** и [111]

Co^{2+} $(3d^7)$ ⟶ $\lambda < 0$

Averaging over 4 types of Co^{2+} positions with distortions along different {111} axes:

$$w_a = -N\lambda LS(\alpha_x^2\alpha_y^2 + \alpha_y^2\alpha_z^2 + \alpha_z^2\alpha_x^2)$$

$$K_1 > 0$$



[Slonczewski, JAP **32**, S253 (1961)]

Temperature dependence of magneto-crystalline anisotropy

Classical theory gives:

$$E_a = K_n \alpha^n \quad \Rightarrow \quad \frac{K_n(T)}{K_n(0)} = \left(\frac{M_S(T)}{M_S(0)} \right)^{\frac{n(n+1)}{2}}$$

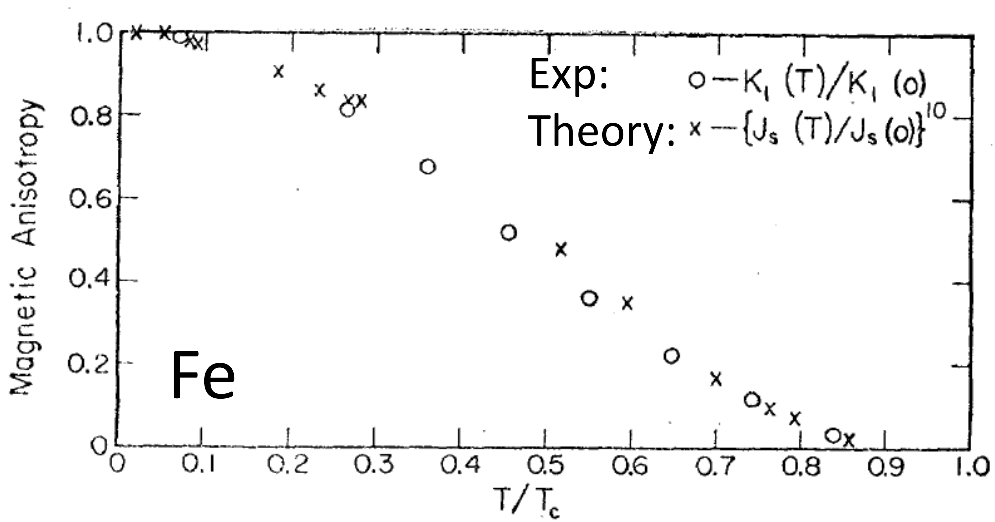
[Zener, Phys. Rev. 96, 1335 (1954)]

Cubic anisotropy

$$\frac{K_n(T)}{K_n(0)} = \left(\frac{M_S(T)}{M_S(0)} \right)^{10}$$

Uniaxial anisotropy

$$\frac{K_n(T)}{K_n(0)} = \left(\frac{M_S(T)}{M_S(0)} \right)^{3}$$

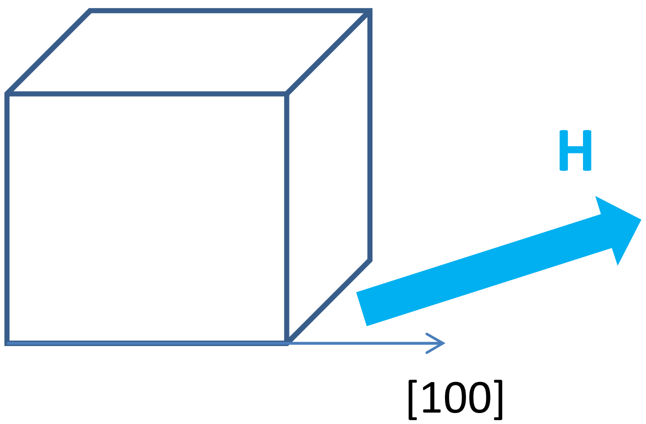


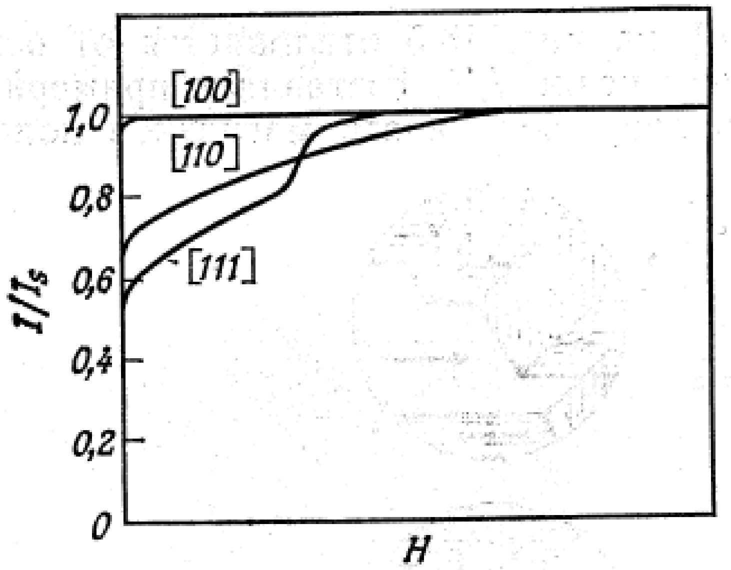
Competition between different anisotropies gives rise to spin-reorinetation transitions

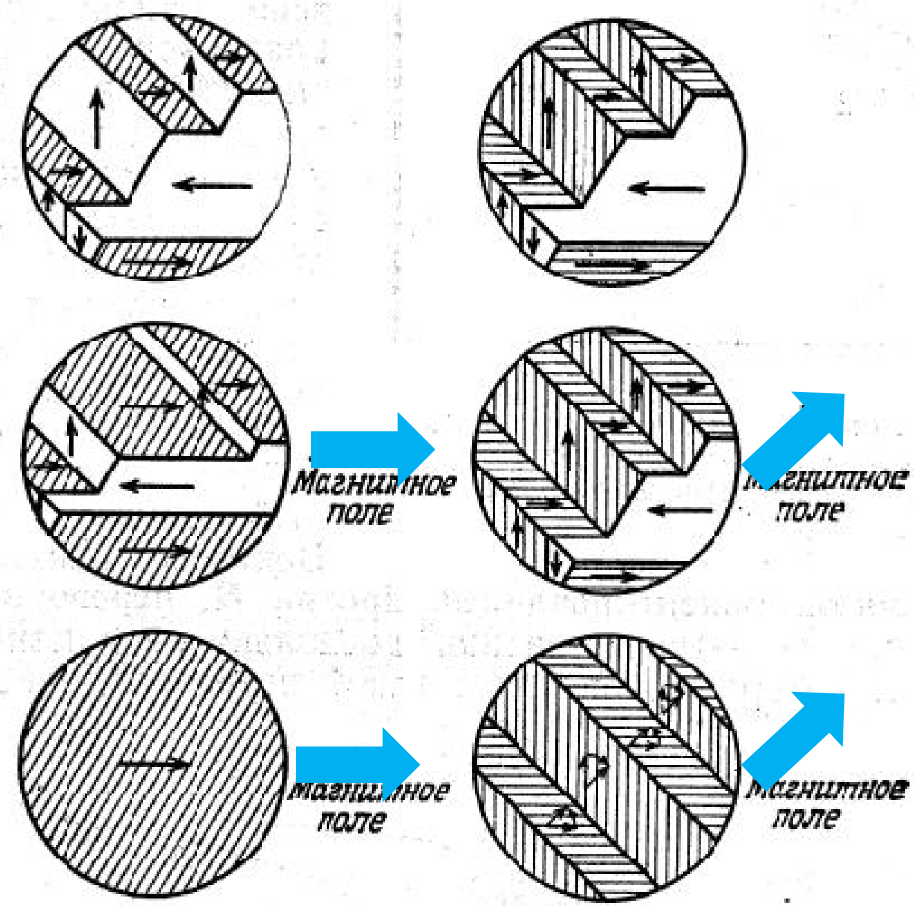
Ferro- and antiferromagnets in an external field

Ferromagnets in applied magnetic field:
domain walls displacement

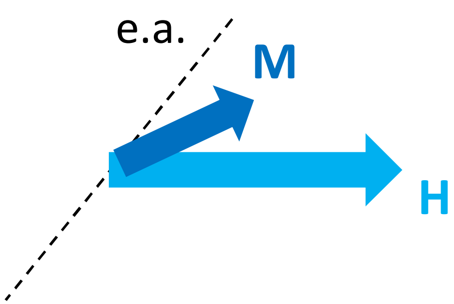
Cubic anisotropy (K_1>0)

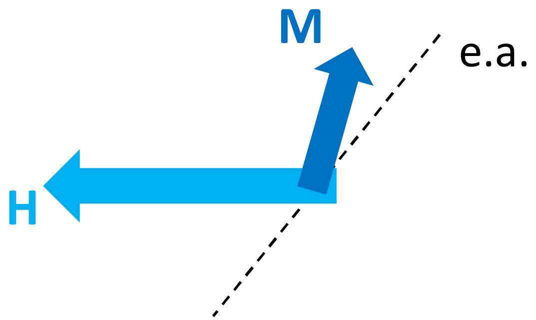






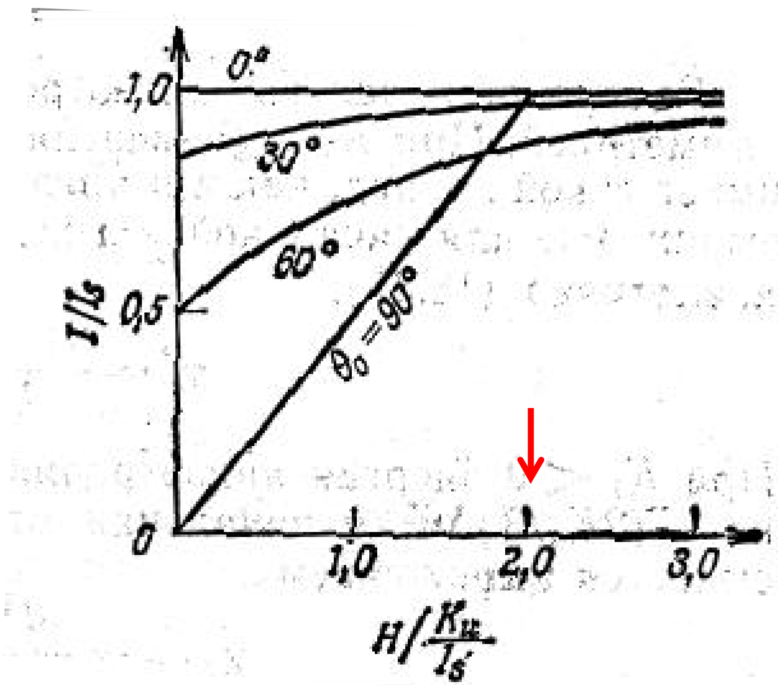
Ferromagnets in applied magnetic field:
rotation of magnetization

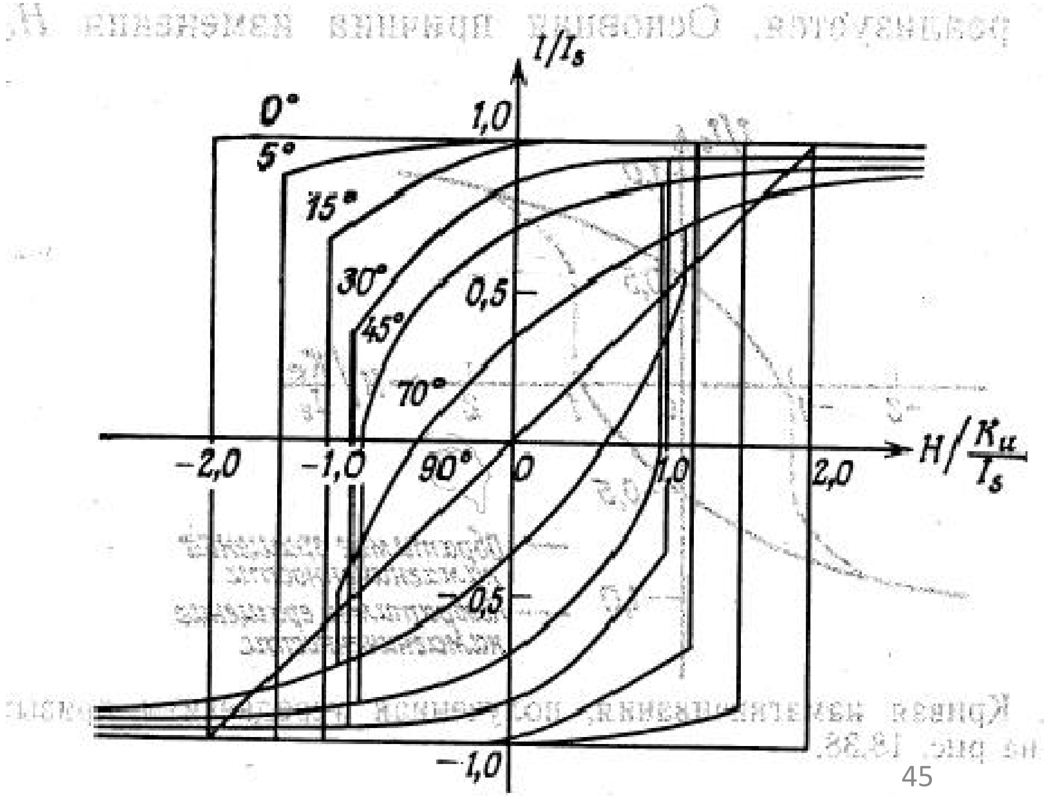




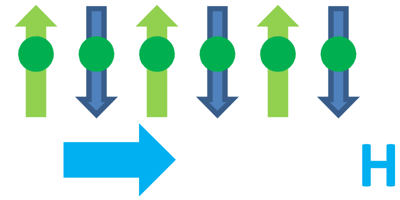
Reversible rotation towards the field

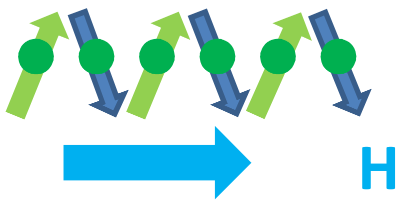
Irreversible rotation towards the field

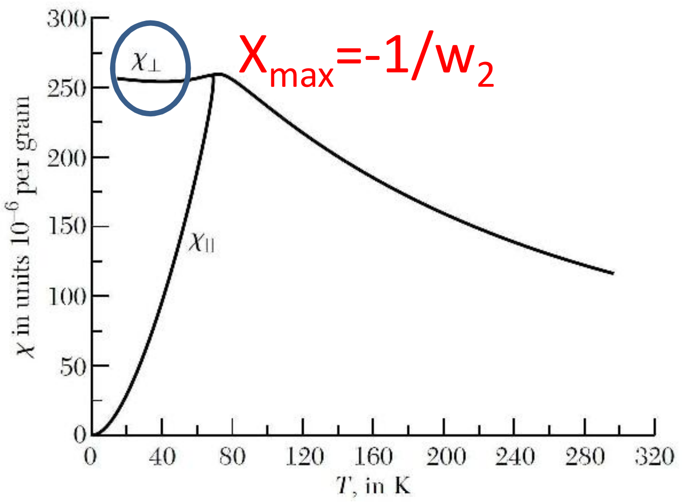


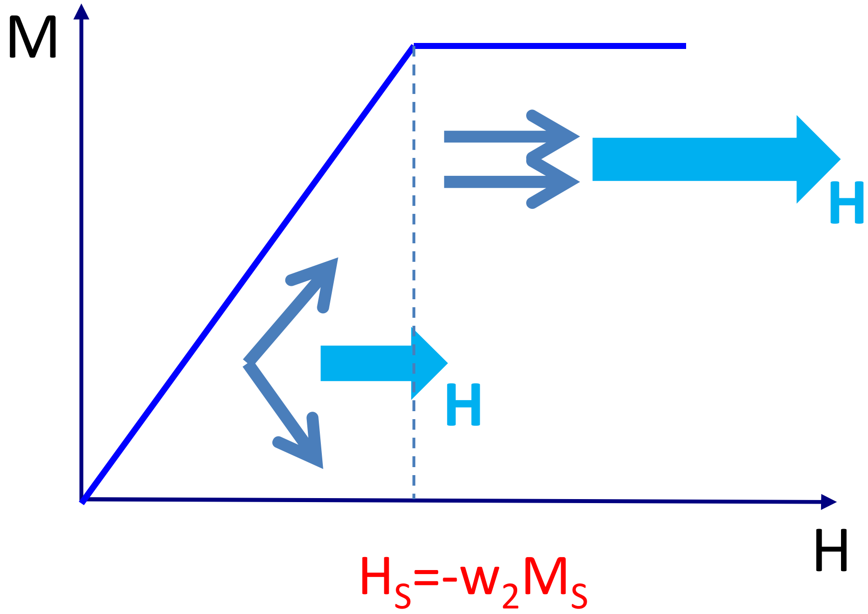


Magnetization process in a multisublattice medium:
spin-flop and spin-flip transitions in an antiferromagnet

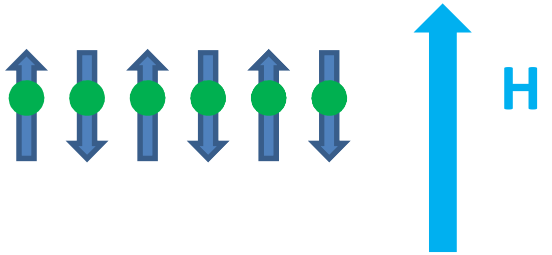


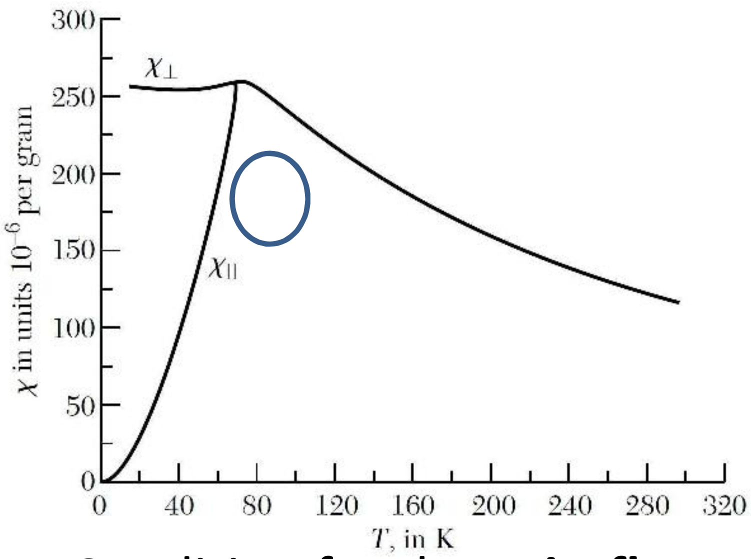




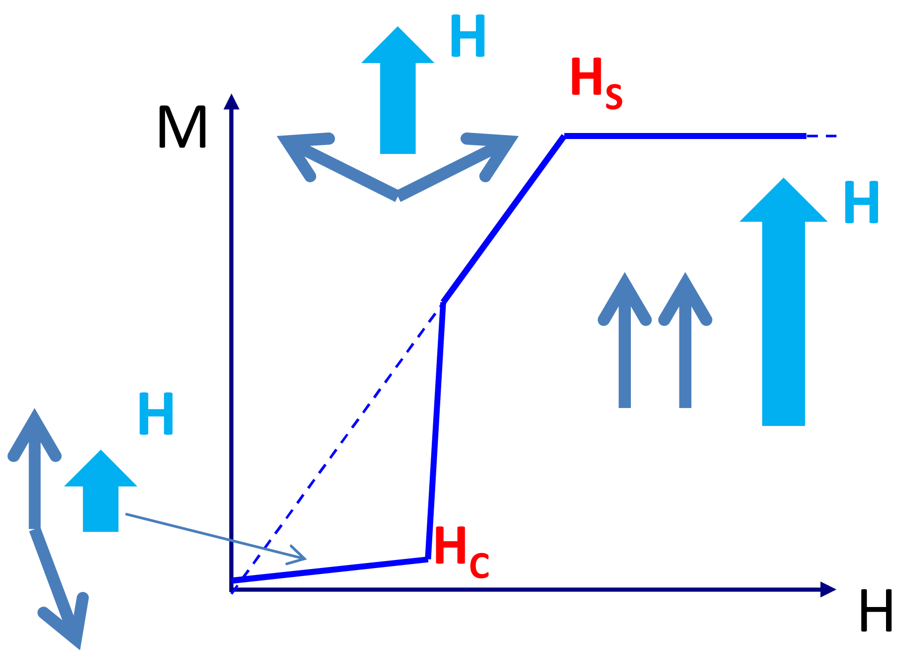


Magnetization process in a multisublattice medium:
spin-flop and spin-flip transitions in an antiferromagnet





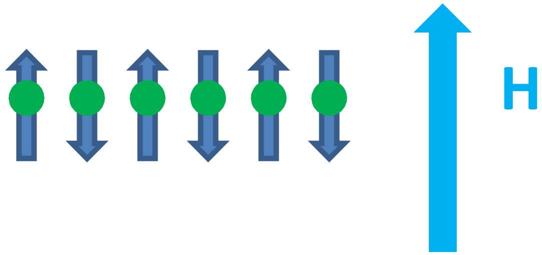
If the anisotropy is weak:

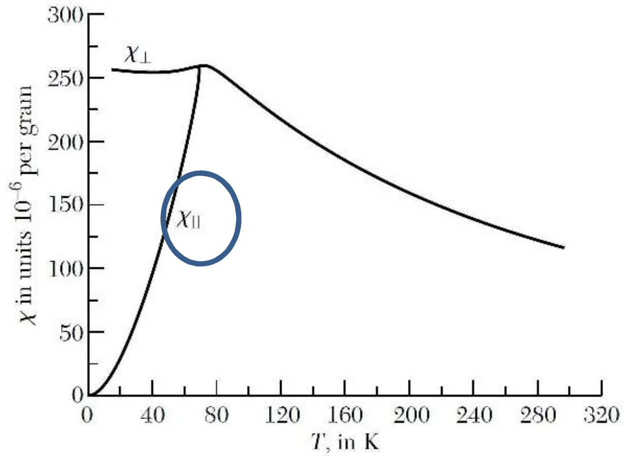


Condition for the **spin-flop** (spin-reorienetation transition)

$$H \geq \sqrt{\frac{2K_u}{\chi_\perp - \chi_\parallel}} = H_C$$

Magnetization process in a multisublattice medium:
spin-flop and spin-flip transitions in an antiferromagnet





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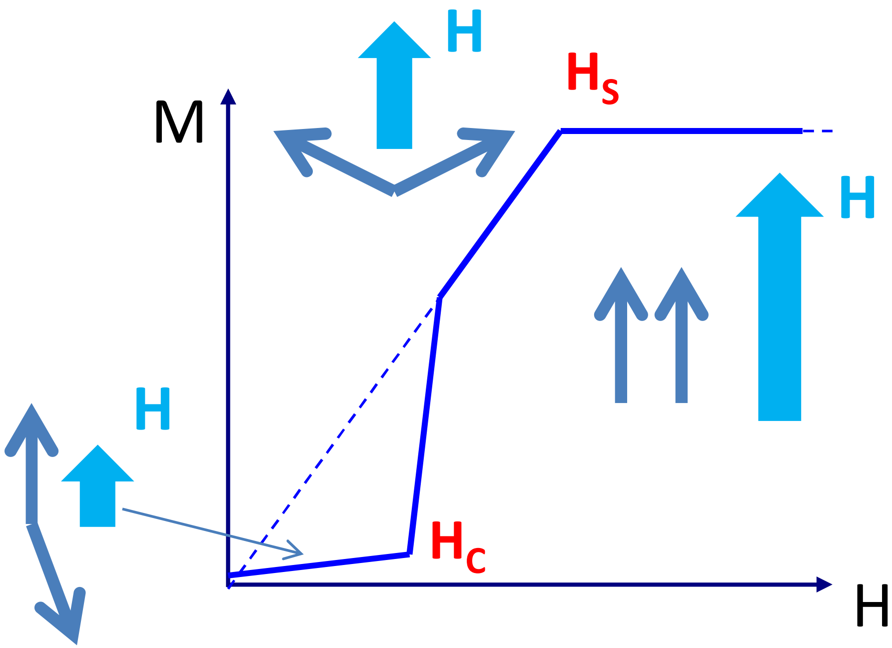

If the anisotropy is strong: