

Spins Do -Experimenteller Magnetismus

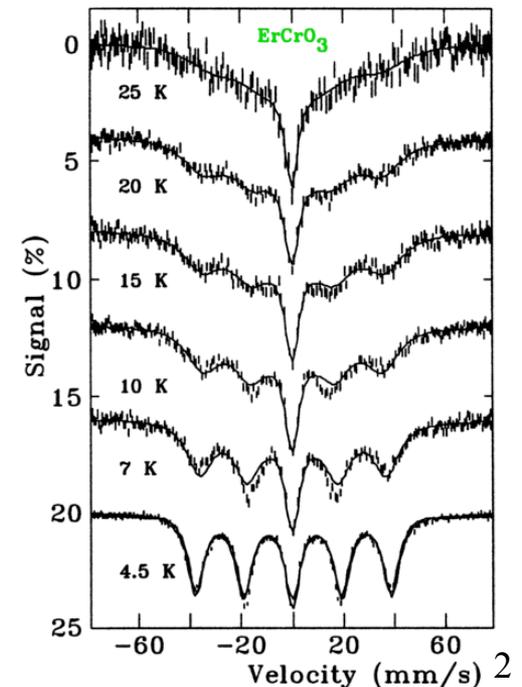
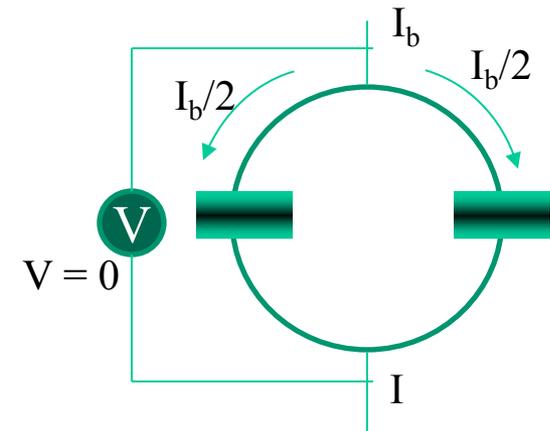
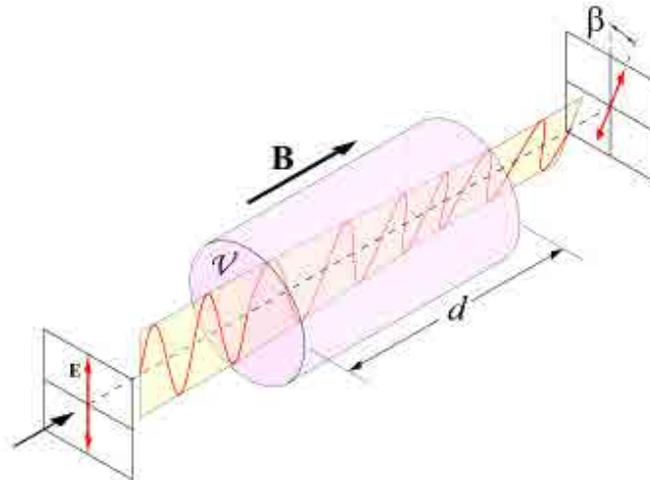


Martin Valldor

IBM-Ahmed

Rückblick auf Analyse

- Das makroskopische magnetische Moment wird mittels Waagen oder über Induktion gemessen. SQUID ist deutlich empfindlicher als alle andere Methoden.
- Dabei gibt es unzählige Quellen von Fehlern – Also aufpassen.
- Spektroskopisch kann man indirekt oder direkt auf magnetische Quantenzahlen rückschließen.
- Direkt mit ESR, XMCLD, Faraday-Drehung
- Indirekt mit Mössbauer, NMR, μ -SR



Magnetische Ordnung

Temperatur
($E = k_B * T$)

Spin zu Spin

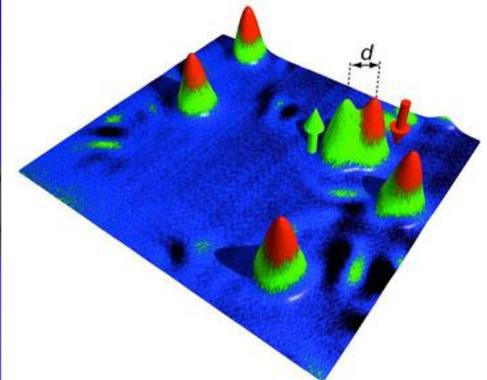
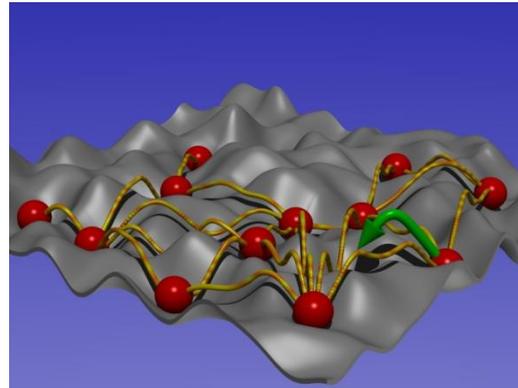
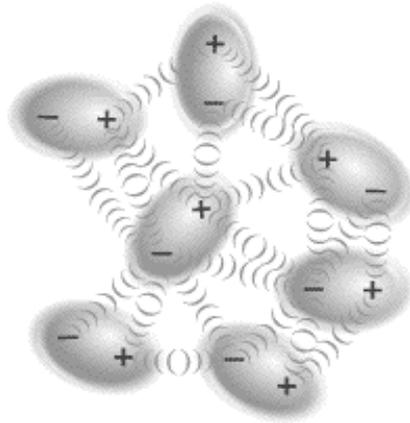
$$E \cong \sum_i^j J(S_i \cdot S_j)$$



Spin im Feld
 $E = S * g * \mu_B * B$

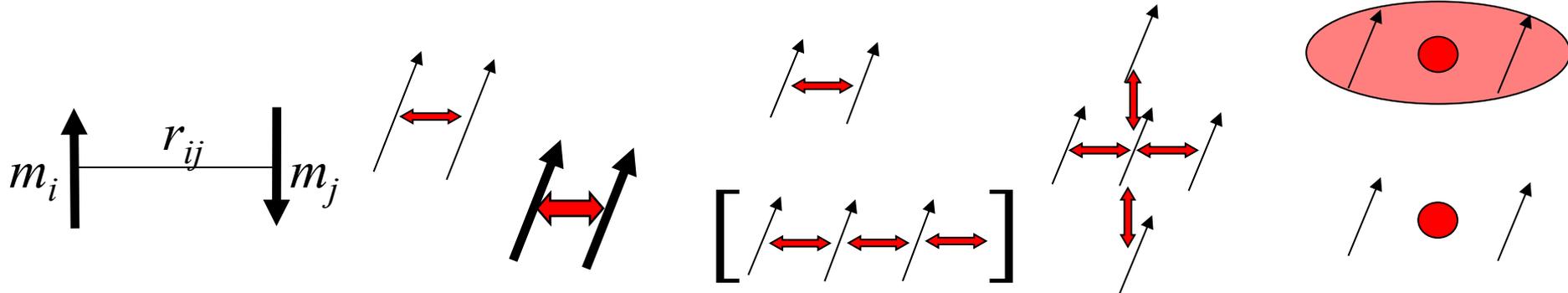


Spin-Spin Wechselwirkungen



Globale: Dipol-Dipol Super(Doppel)-Austausch RKKY

Die Stärke der Wechselwirkung hängt von folgenden ab:



Abstand

Spin-Grösse

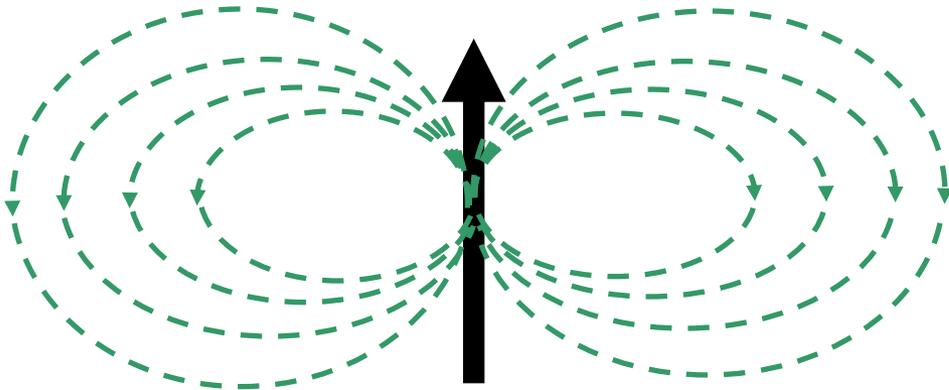
Anzahl der Spin Nachbarn

”Bote”

Isolatoren

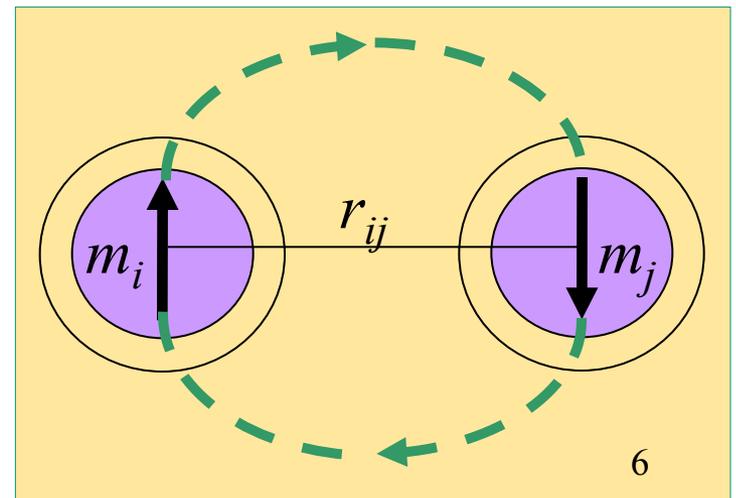
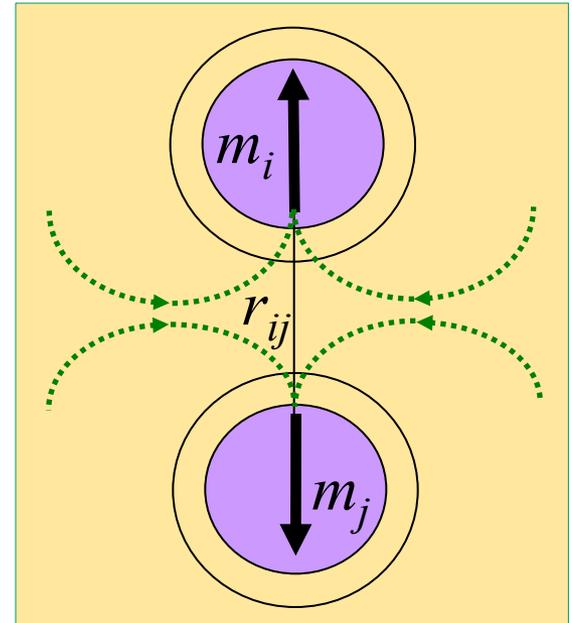
Wechselwirkungen in Isolatoren

Dipol-Dipol



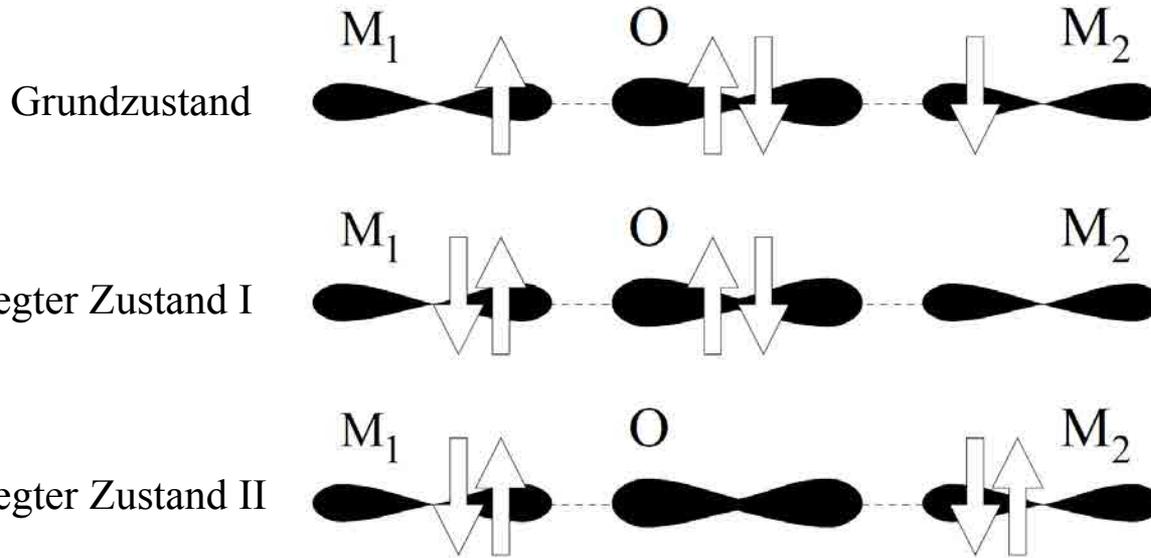
Ein Dipol erzeugt ein eigenes Feld,
aufdem die Nachbarn spielen

$$H = -\frac{\mu_0}{4\pi r_{ij}^3} (3(m_i \cdot e_{ij})(m_j \cdot e_{ij}) - m_i \cdot m_j)$$



Wechselwirkungen in Isolatoren

Superaustausch



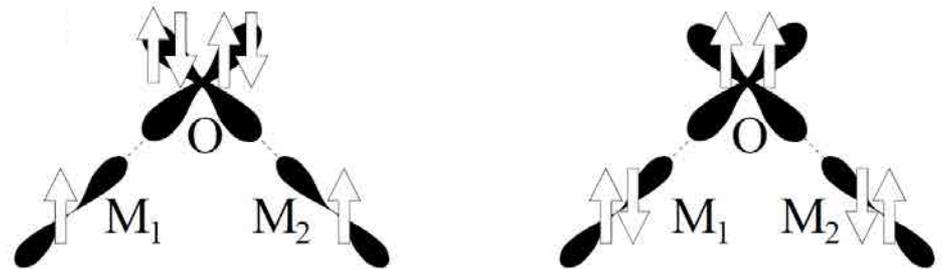
Me-O-Me

180°

Me-O-Me

90°

FM



AFM

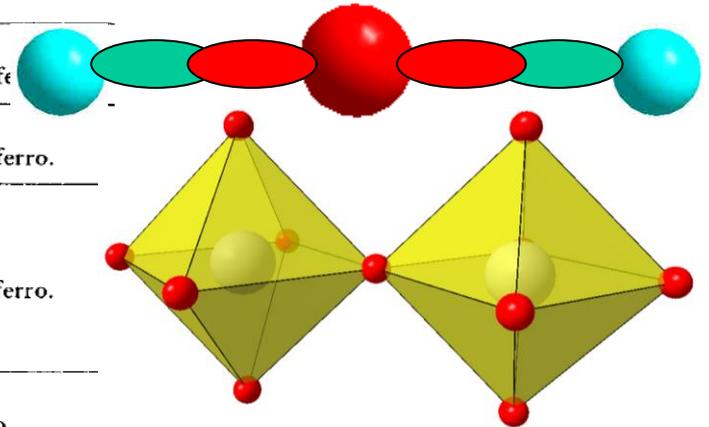


Relativ mehr Energie
nach dem Pauli-Prinzip

Super-Austausch

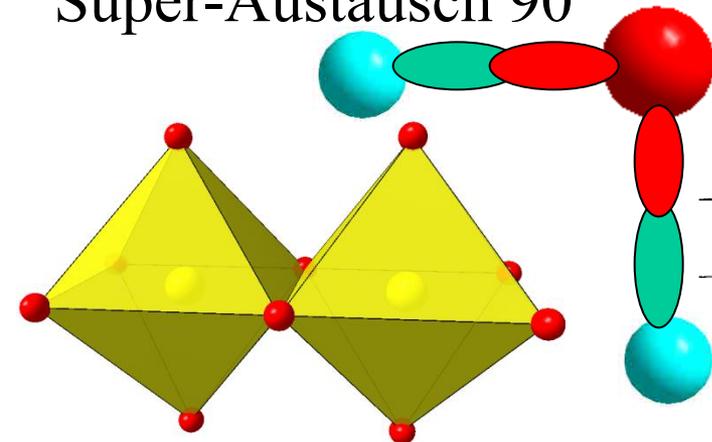
Number of 3d-electrons of interacting cations	Species of interacting cations	Relevant bond and mechanism	Resultant superexchange interaction	Total superexchange interaction
d^3-d^3	$Mn^{4+}-Mn^{4+}$ $Cr^{3+}-Cr^{3+}$	σ -bond and π -bond A, G, A-H, S	Antiferro.	Antiferro.
d^8-d^8	$Ni^{2+}-Ni^{2+}$	σ -bond A, G, A-H, S	Antiferro.	Antiferro.
d^5-d^5	$Mn^{2+}-Mn^{2+}$ $Fe^{3+}-Fe^{3+}$	σ -bond A, G, A-H, S π -bond G, A-H, S π -bond A	Antiferro. Antiferro. (weak) Uncertain (weak)	Antiferro.
d^8-d^3	$Ni^{2+}-V^{2+}$	σ -bond and π -bond A, G, A-H, S	Ferro.	Ferro.
d^5-d^3	$Fe^{3+}-Cr^{3+}$	σ -bond A, G, A-H, S	Ferro.	

Super-Austausch 180°



Ferro-, Antiferro-Magnetismus –
Welcher Typ bei welchem Winkel?

Super-Austausch 90°



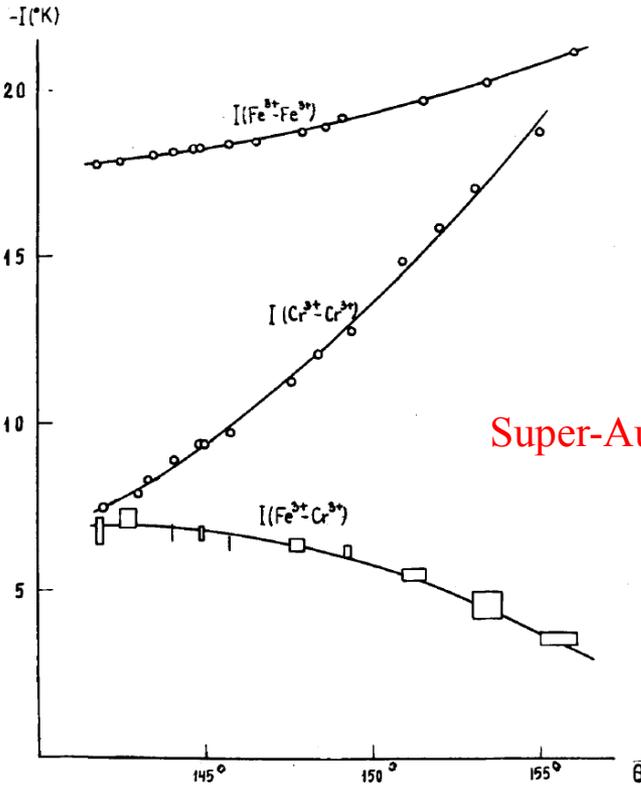
Number of 3d-electrons of interacting cations	Species of interacting cations	Relevant bond and mechanism	Resultant superexchange interaction	Total superexchange interaction
d^8-d^8	$Ni^{2+}-Ni^{2+}$	$p\sigma-d\gamma$ bond A, G S $s-d\gamma$ bond A, G, A-H, S	Ferro. Uncertain Antiferro.	Ferro.
d^5-d^5	$Mn^{2+}-Mn^{2+}$ $Fe^{3+}-Fe^{3+}$		Uncertain	*
d^3-d^3	$Cr^{3+}-Cr^{3+}$	$p\sigma-d\gamma$ and $p\sigma-d\epsilon'$ A, G, A-H, S $p\pi-d\epsilon$ and $s-d\gamma$ A, G, A-H, S	Ferro. Antiferro. (weak)	Ferro. 8
d^8-d^3	$Ni^{2+}-V^{2+}$	$p\sigma-d\gamma$ and $p\sigma-d\epsilon'$ A, G, A-H S	Antiferro. Uncertain (weak)	Antiferro.



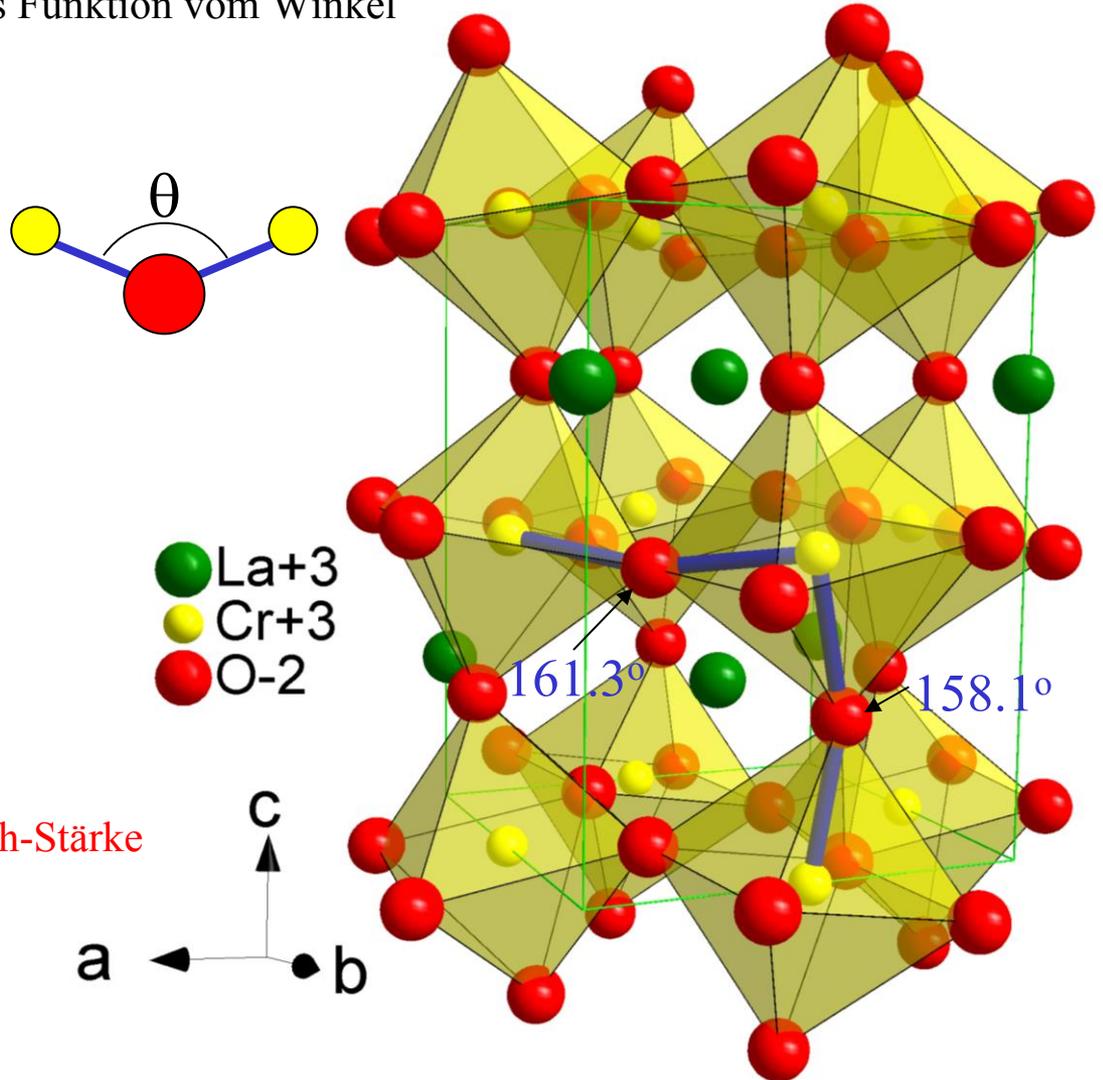
Super-Austausch

als Funktion vom Winkel

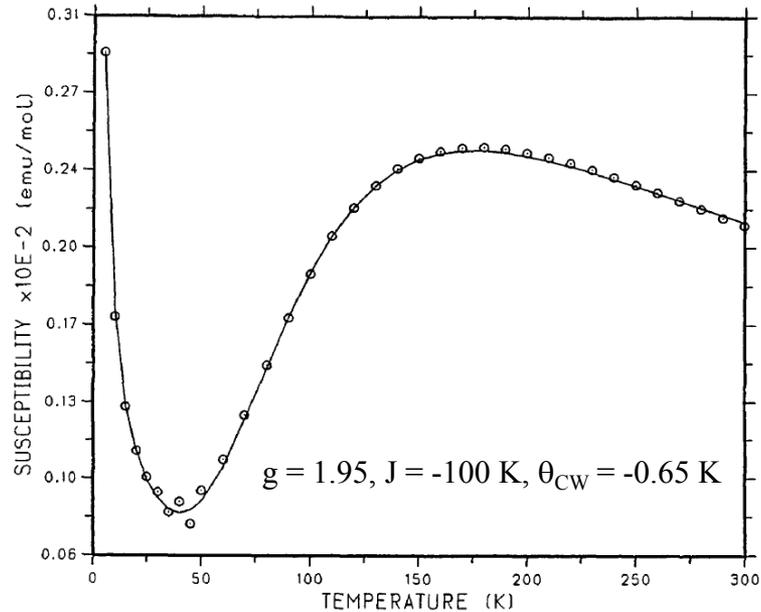
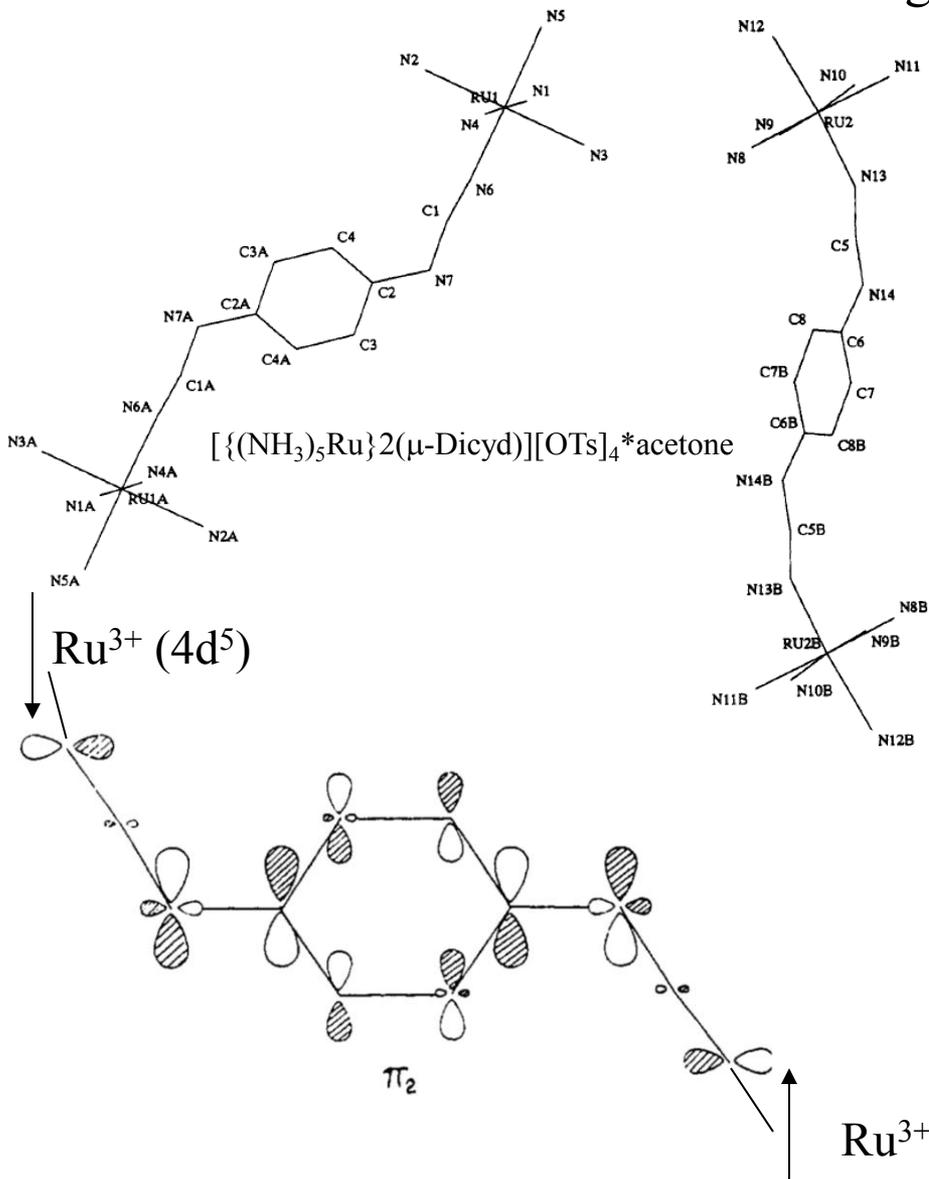
R	$I(\text{Fe}, \text{Cr})$ (°K)	T_N (°K)	θ
La	3.6 ± 0.2	282	155.4°
$\text{La}_{0.5}\text{Nd}_{0.5}$	4.6 ± 0.4	244	153.3°
Nd	5.5 ± 0.2	224	151.1°
Sm	6.2 ± 0.2	192	149.7°
Gd	6.4 ± 0.2	170	147.7°
Dy	6.4 ± 0.2	146	145.7°
Y	6.7 ± 0.2	141	144.9°
Er	6.7 ± 0.2	133	144.0°
Yb	7.2 ± 0.3	118	142.7°
Lu	6.8 ± 0.4	112	141.8°



Super-Austausch-Stärke



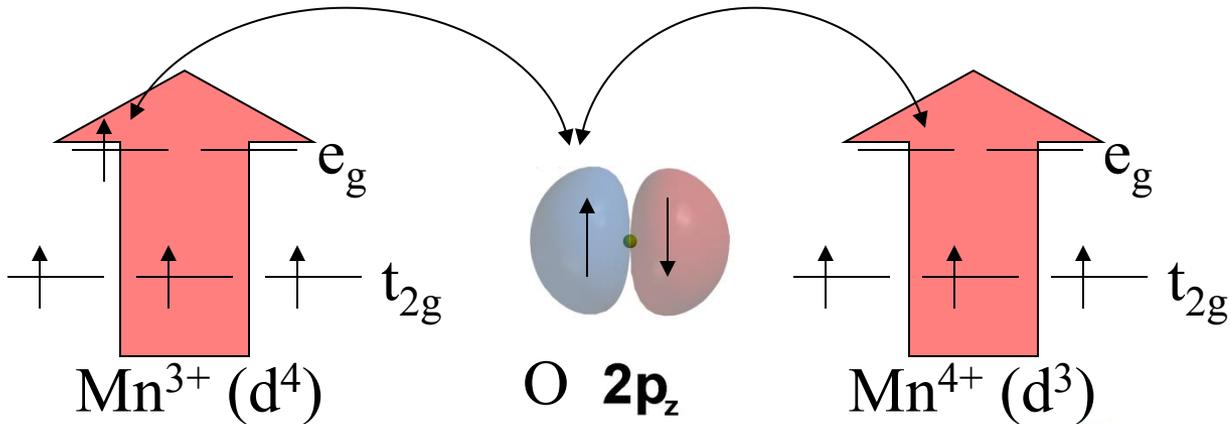
Super-Austausch in die Länge gezogen



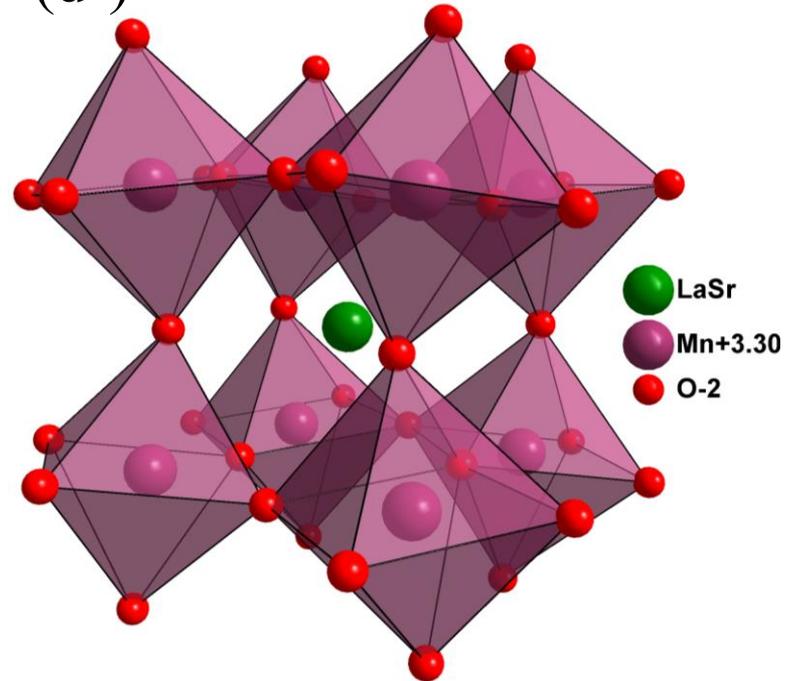
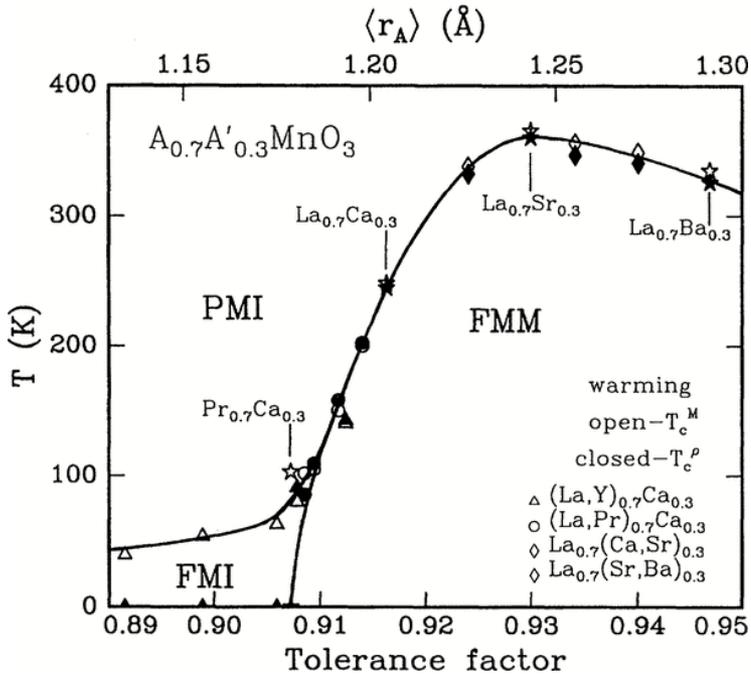
Antiferromagnetismus über etwa 15 Å

Metalle

Doppel-Austausch



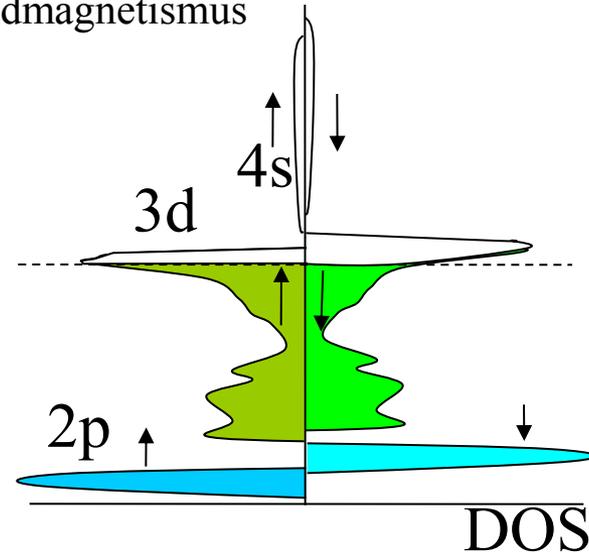
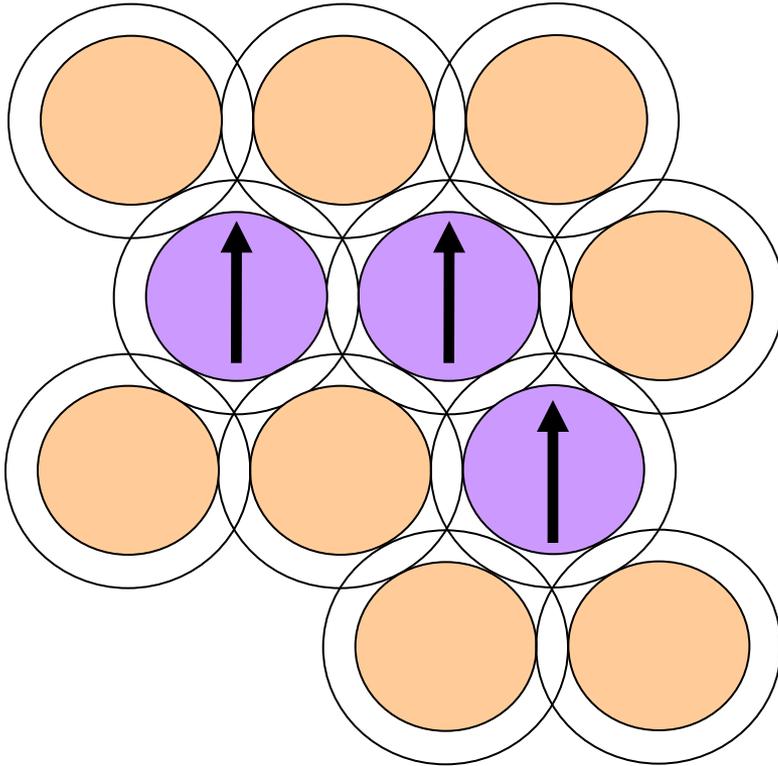
Ferromagnetismus
aber auch
Leitfähigkeit



Was passiert wenn nur Mn^{4+} oder Mn^{3+} da ist?

Wechselwirkungen in Metallen

Direkter Austausch - Bandmagnetismus



Warum ist ein Metall
Ferro-/Antiferro-magnetisch?

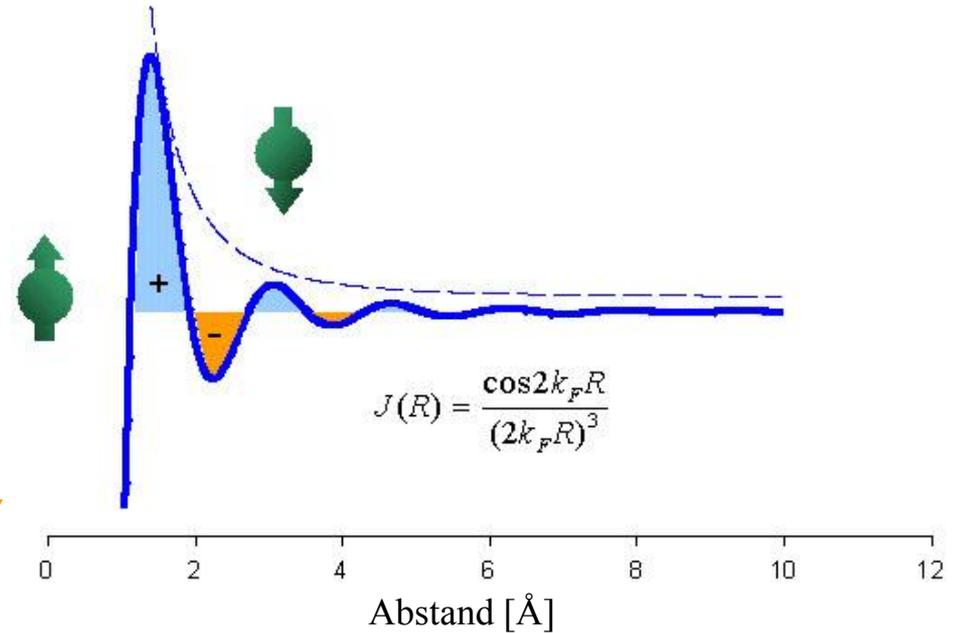
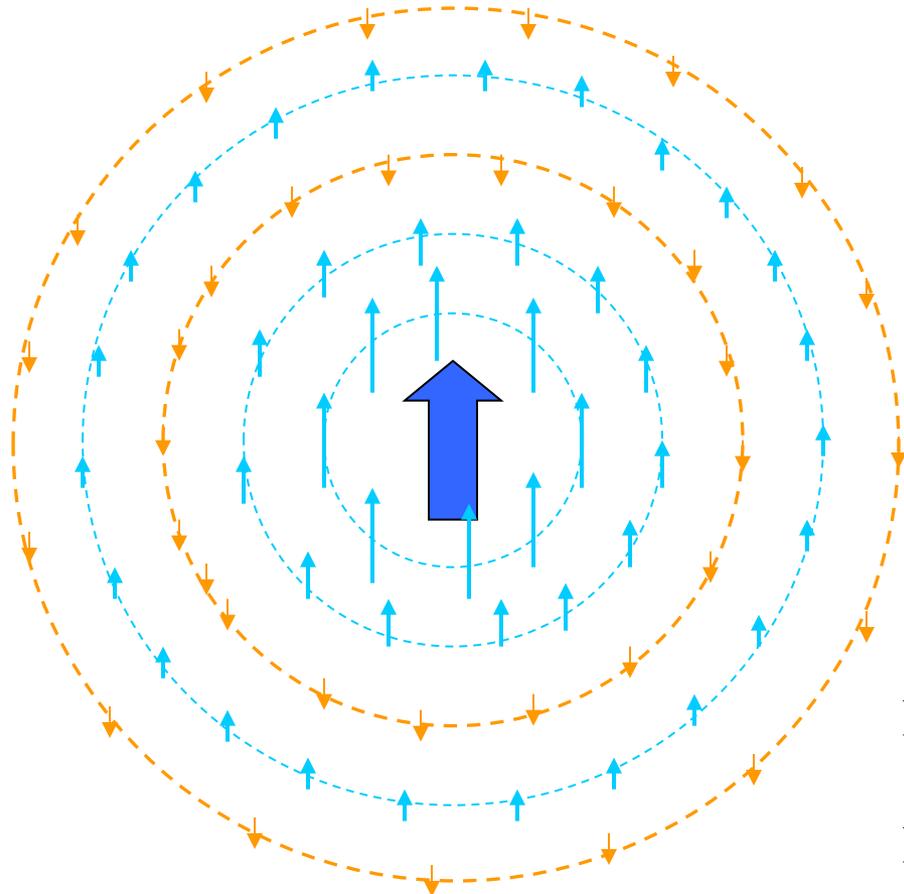
- Cr (bcc)
- Mn (komplex)
- Fe (bcc)
- Co (hcp)
- Ni (fcc)

Periodic Table of the Elements

1																	2	
1	H																	He
2	3	4											9	10				
	Li	Be											B	C	N	O	F	Ne
3	11	12	13	14	15	16	17	18										
	Na	Mg	Al	Si	P	S	Cl	Ar										
4	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
	Cs	Ba	*La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	87	88	89	104	105	106	107	108	109	110	111	112	113					
	Fr	Ra	+Ac	Rf	Ha	Sg	Ns	Hs	Mt	110	111	112	113					
			* Lanthanide Series															
			58	59	60	61	62	63	64	65	66	67	68	69	70	71		
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
			+ Actinide Series															
			90	91	92	93	94	95	96	97	98	99	100	101	102	103		
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

”RKKY”

Ruderman–Kittel–Kasuya–Yosida



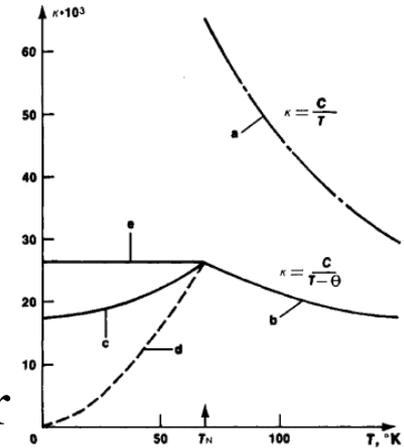
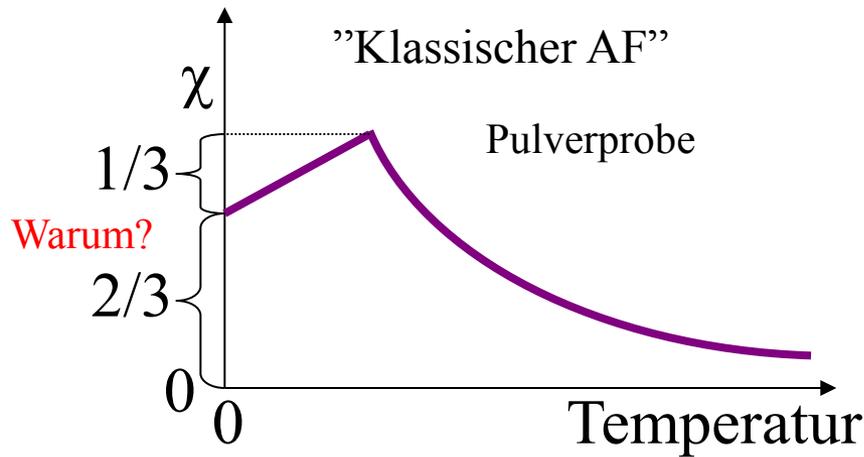
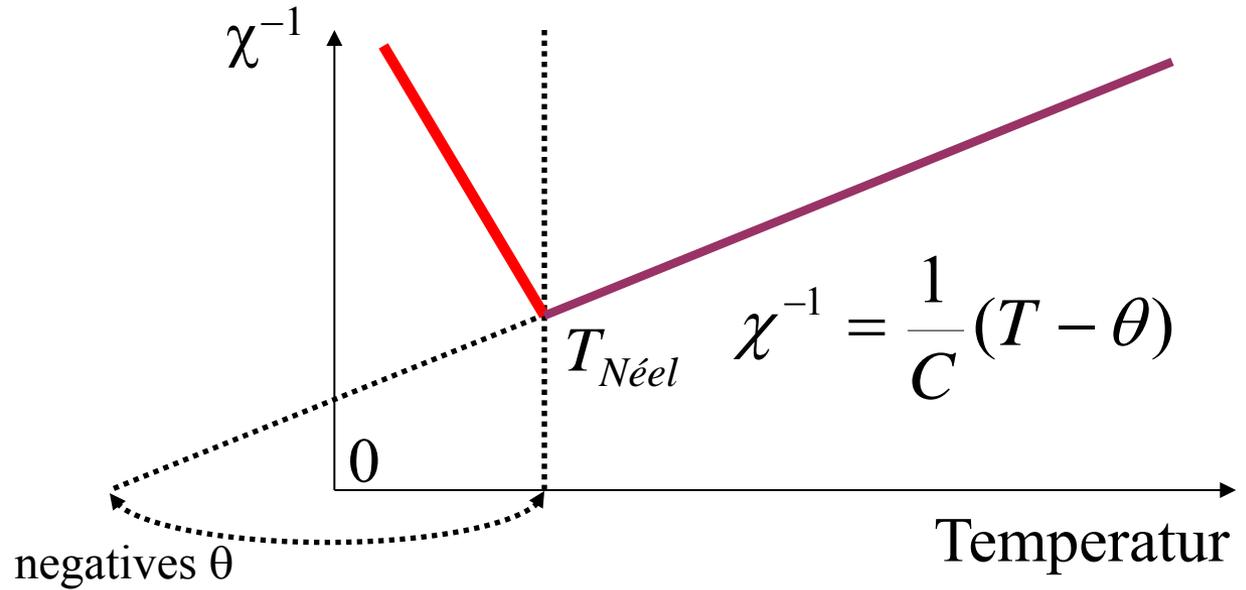
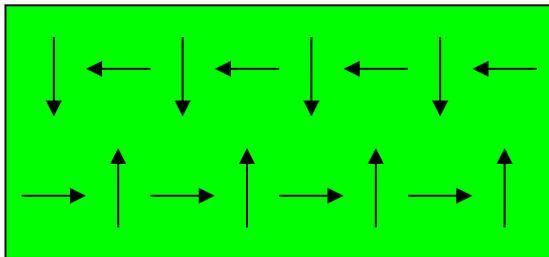
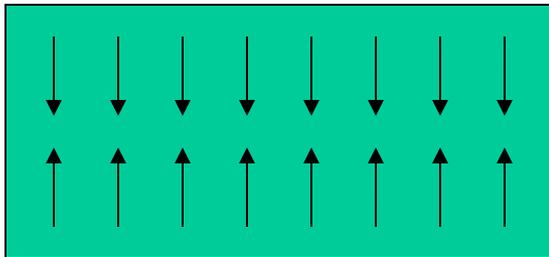
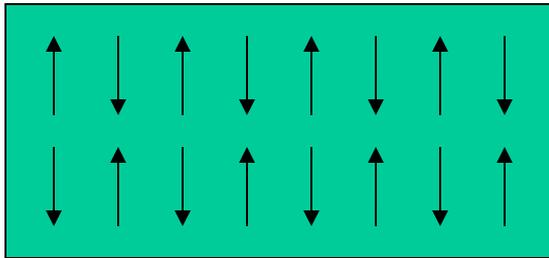
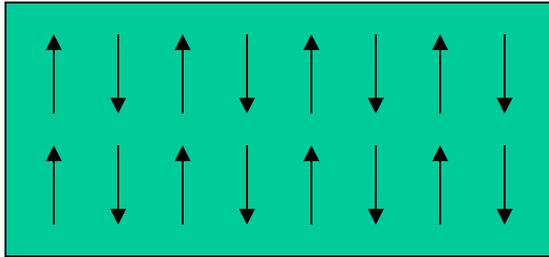
Magnetische WW über Leitungselektronen

Hier sind weitere Faktoren wichtig:

1. Leitfähigkeit des Wirtselements.
2. Gitterordnung (Kristall/Amorph)

Die magnetische Grundzustände

Antiferromagnetismus

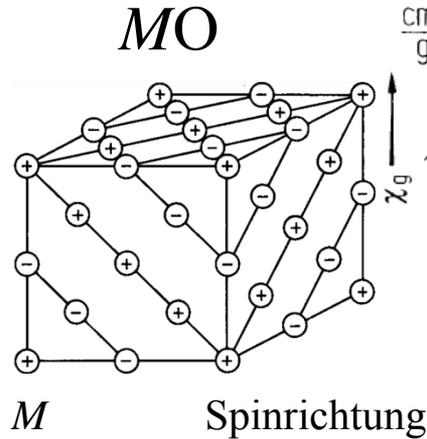
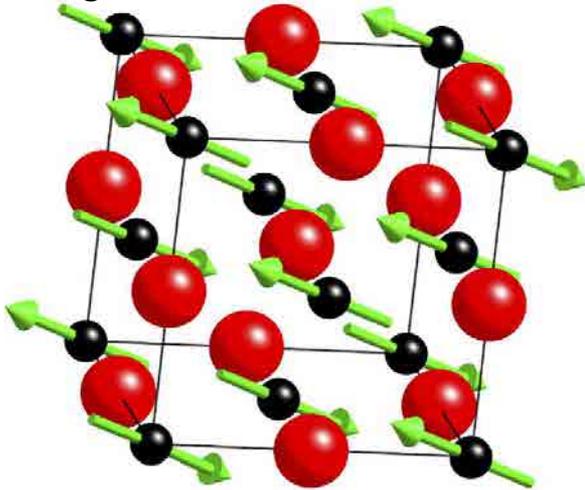


Addiert man alle Vektoren soll "Null" rauskommen

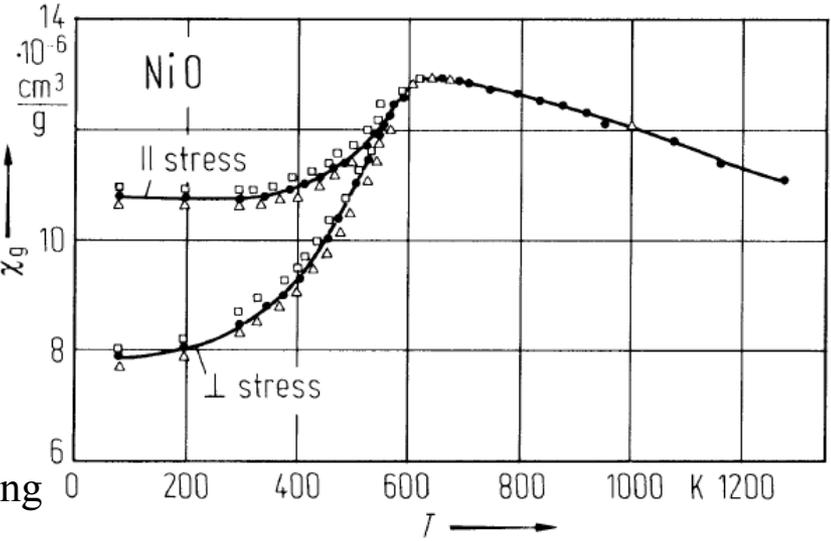
Wie wäre das gleiche für ein 2D AF?

Beispiel: Antiferromagnetismus

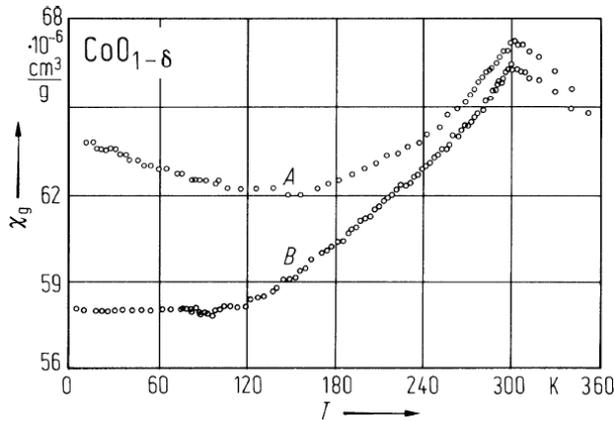
Magnetische Struktur von NiO



Ni, Mn [11-2]
 Fe [111]
 Co (110)-Fläche

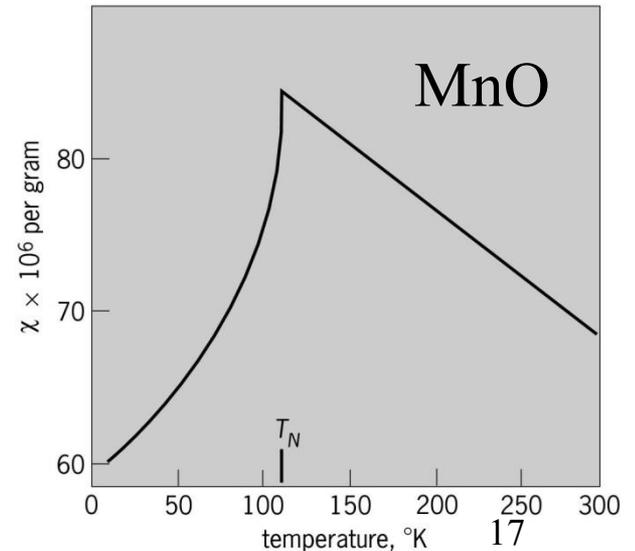


E. Ressouche, et al. Physica B 385-386 (2006) 394-397



Co_{1-δ}O (A: δ=0.01, B: δ=0.005)

MO	T _N (K)
MnO	118
Fe _{1-δ} O	198
CoO	289
NiO	523



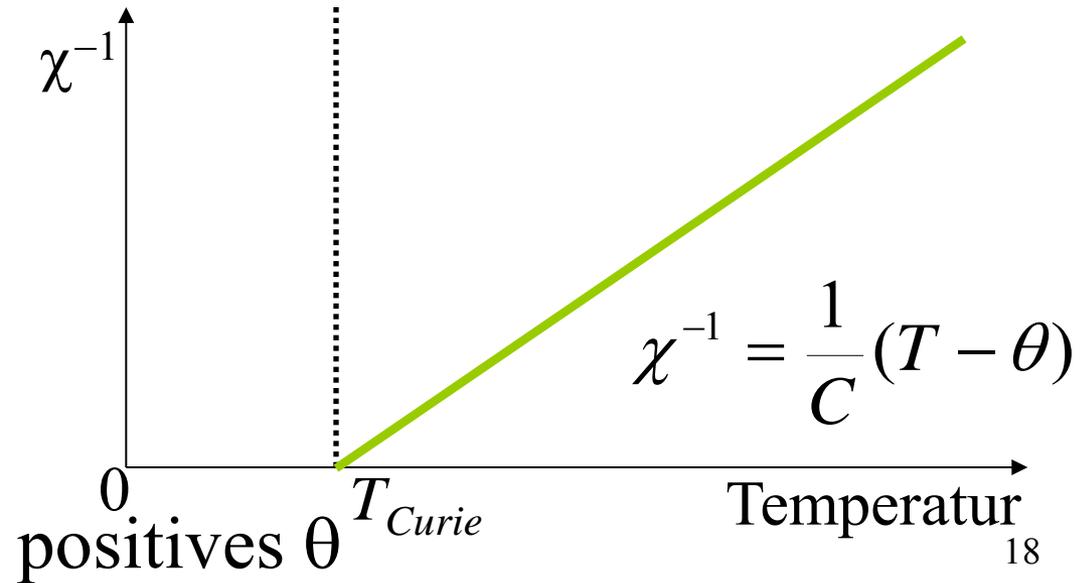
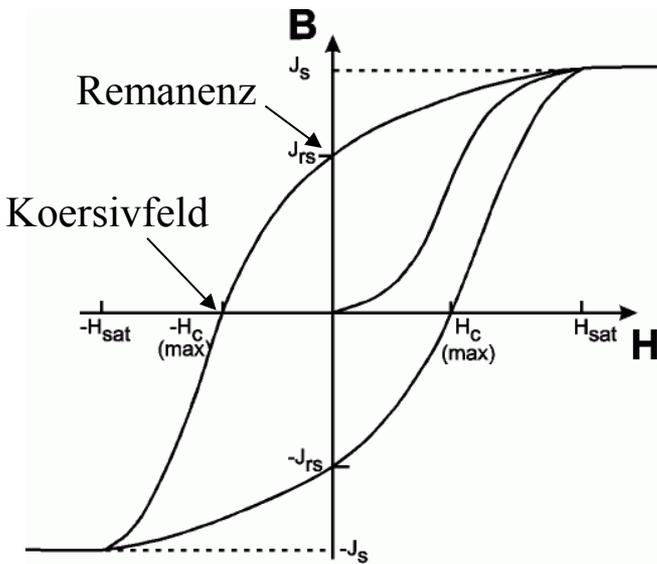
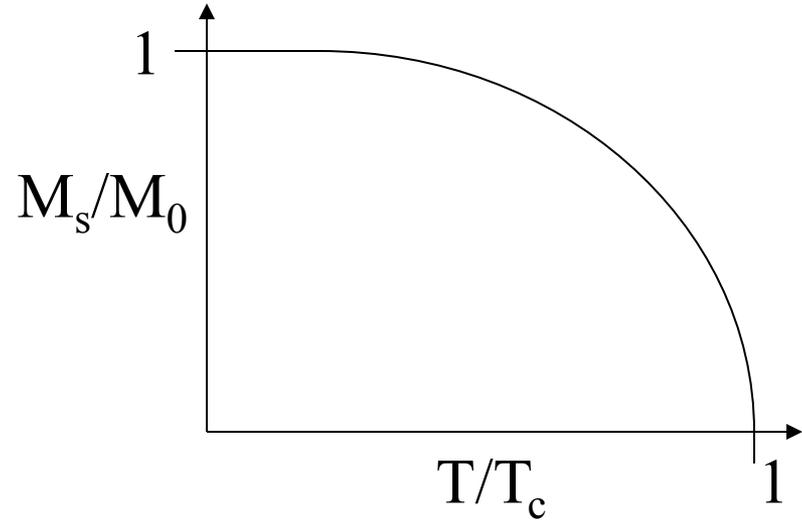
Ferromagnetismus



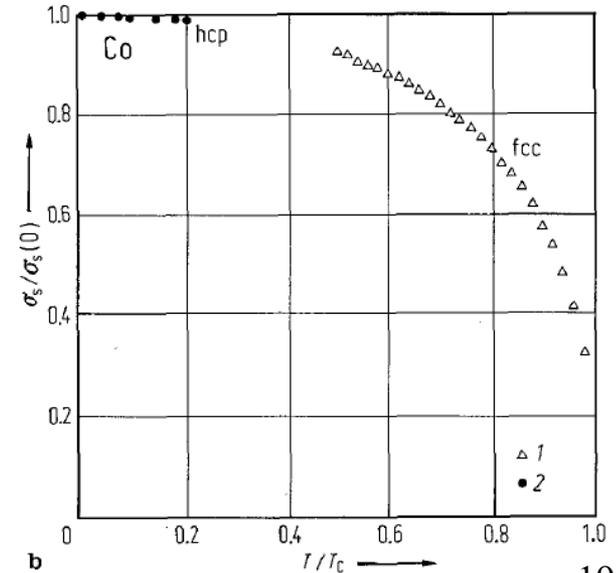
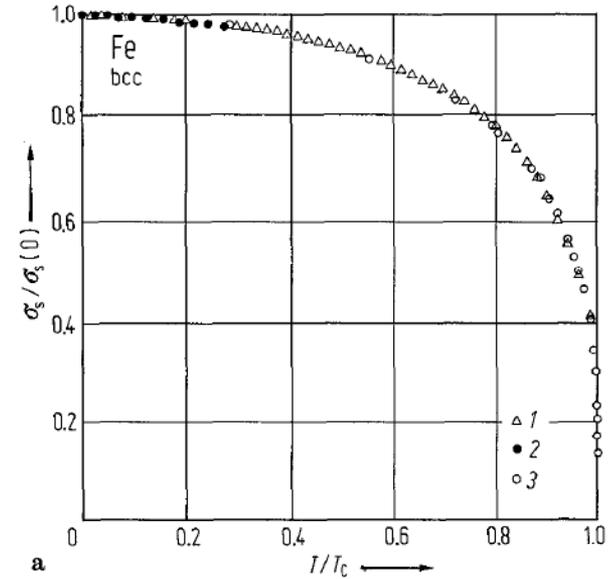
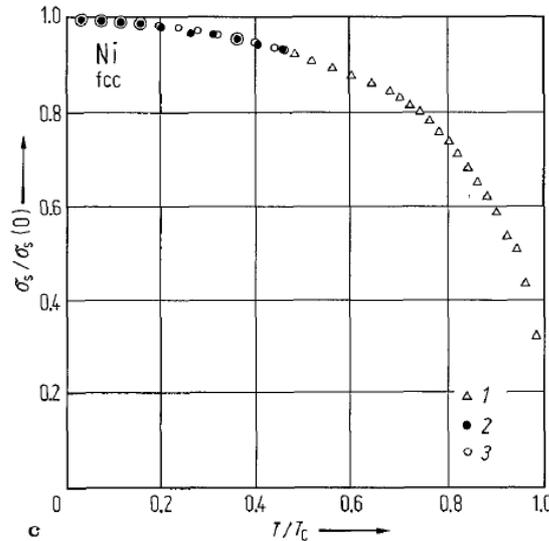
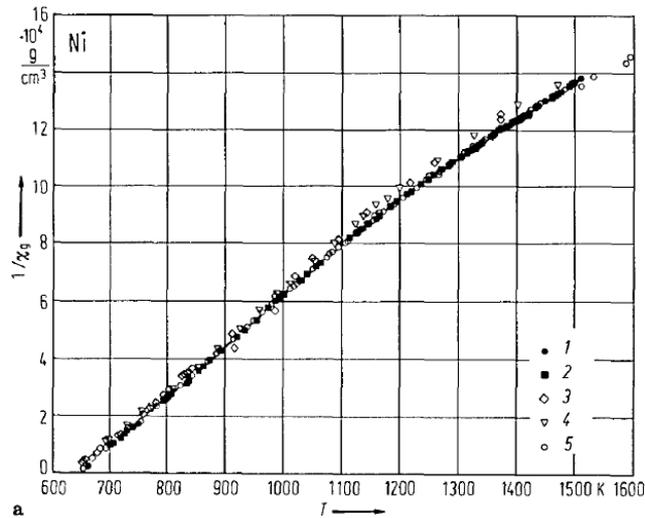
Vor Magnetisierung



Nach Magnetisierung



Beispiel: Ferromagnetismus



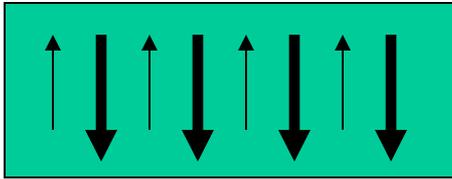
Metall	Atomvalenz
Fe	$d^{6}s^2$
Co	d^7s^2
Ni	d^8s^2
$Fe_{0.8}Co_{0.2}$	$d^{6.2}s^2$
$Ni_{0.4}Cu_{0.6}$	$d^{8.6}s^2$

Ferromagnetisch	
Ungepaarte Spin	Valenz
2.2	$d^{7.8}s^{0.2}$
1.7	$d^{8.3}s^{0.7}$
0.6	$d^{9.4}s^{0.6}$
2.4	$d^{7.6}s^{0.6}$
0	$d^{10}s^{0.6}$

Wie kommt man auf diese krumme Zahlen?

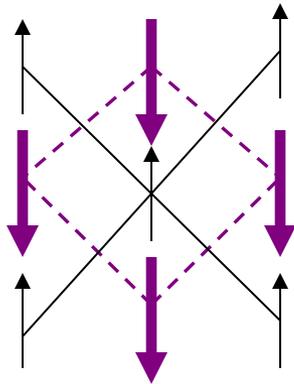
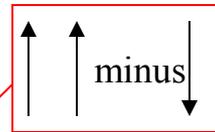
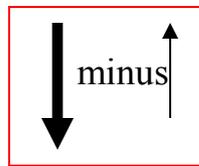
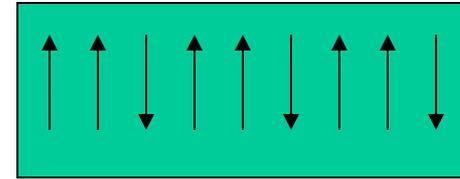
Ferrimagnetismus

Zwei unterschiedliche Spins



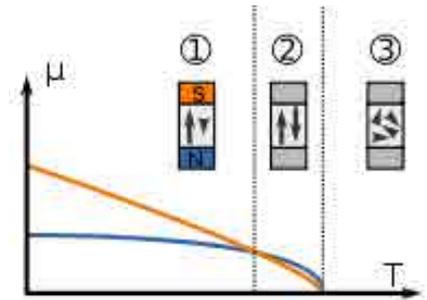
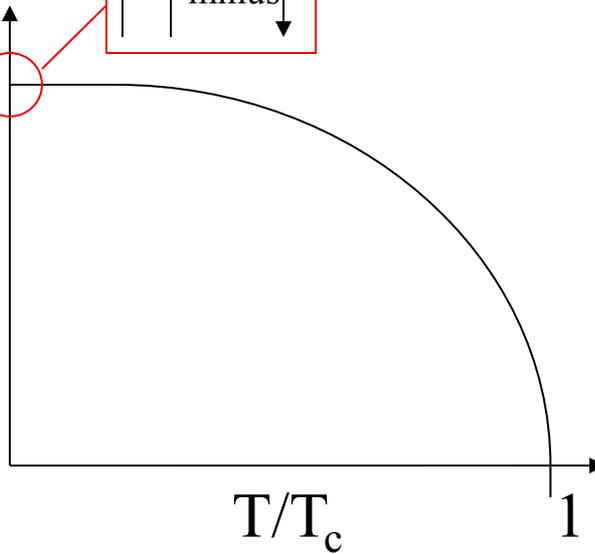
ODER

Die Anzahl der Spins im AF ist unterschiedlich

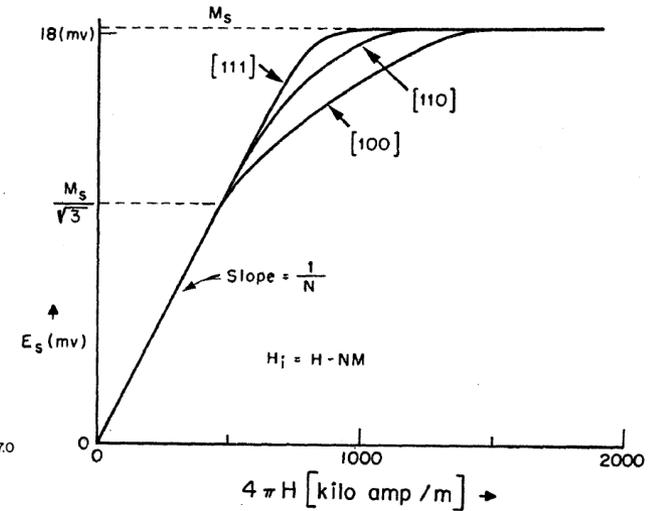
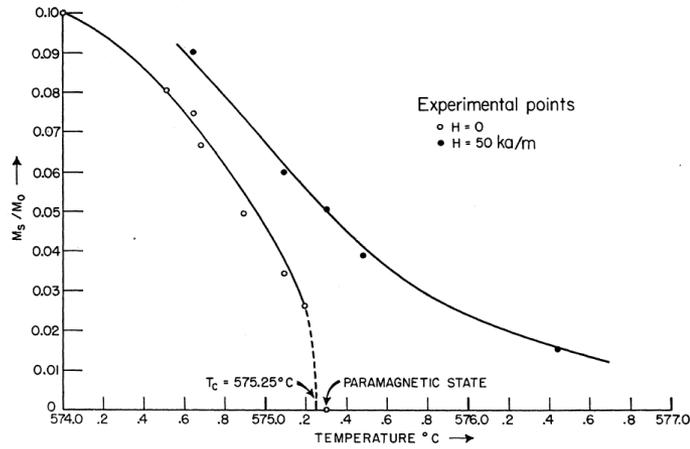
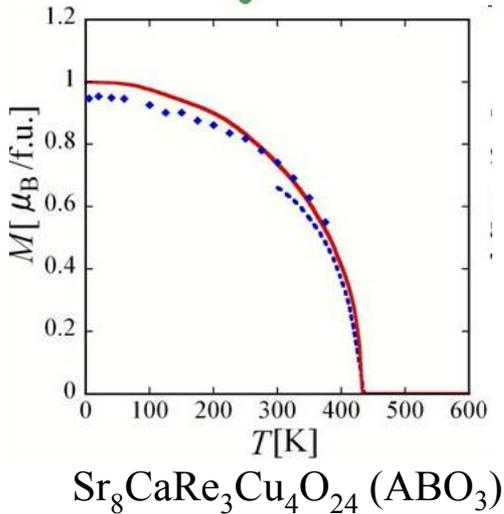
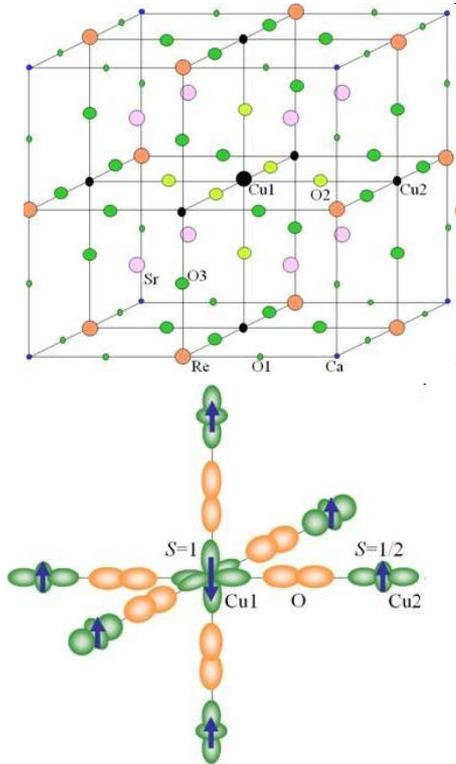


zwei "Untergitter"

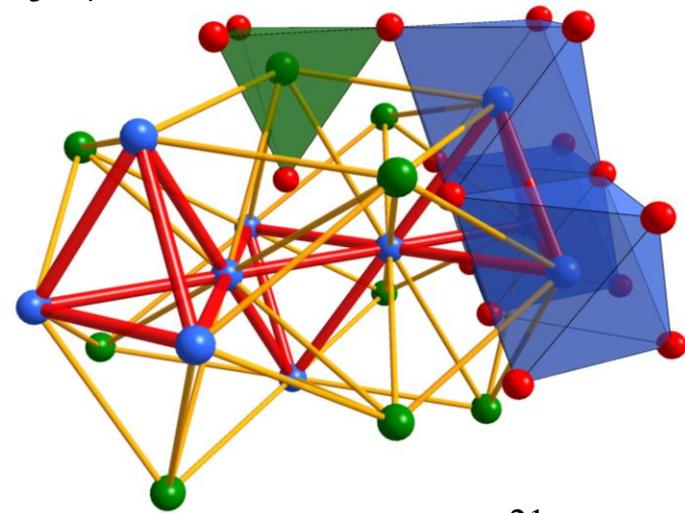
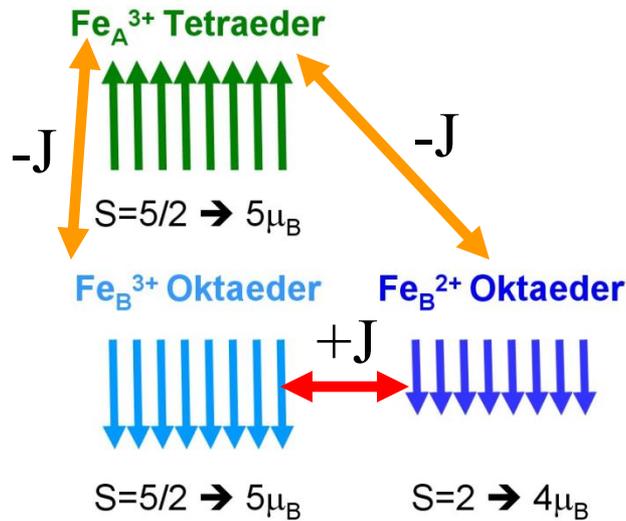
- können sogar unterschiedlich ordnen (T)



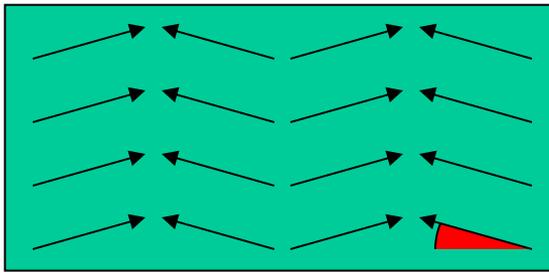
Beispiel: Ferrimagnetismus



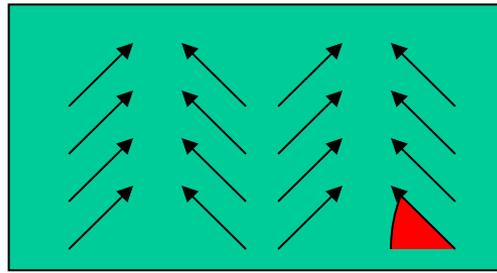
Magnetit: Fe_3O_4



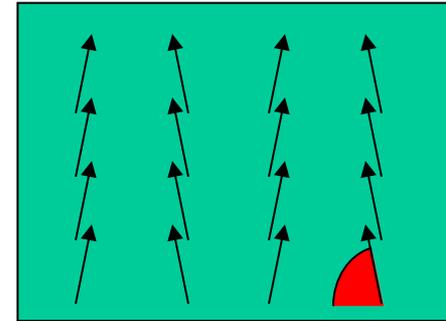
Canted Antiferromagnetismus



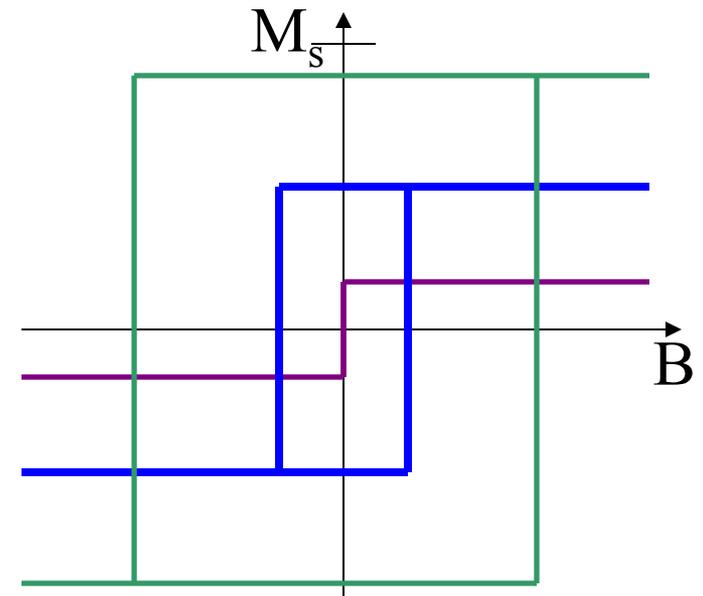
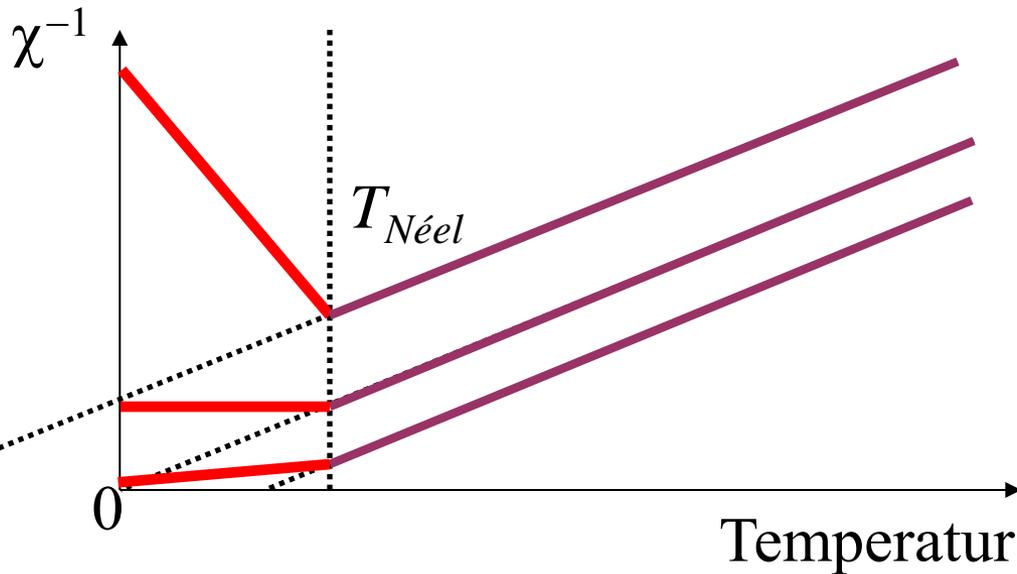
$AF > FM$



$AF \approx FM$



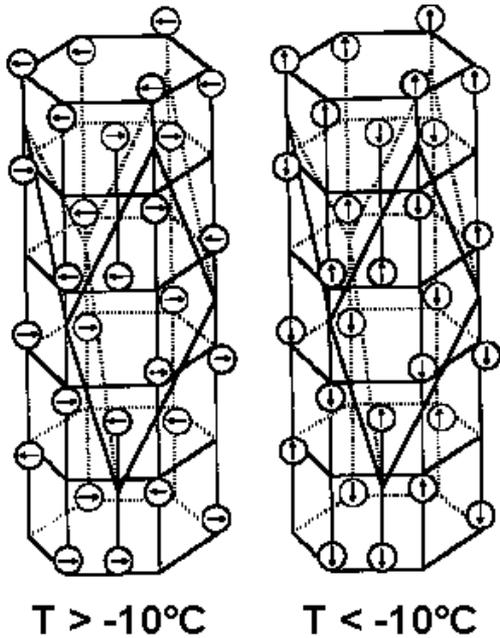
$AF < FM$



Welche Kurve zu welchem Zustand?

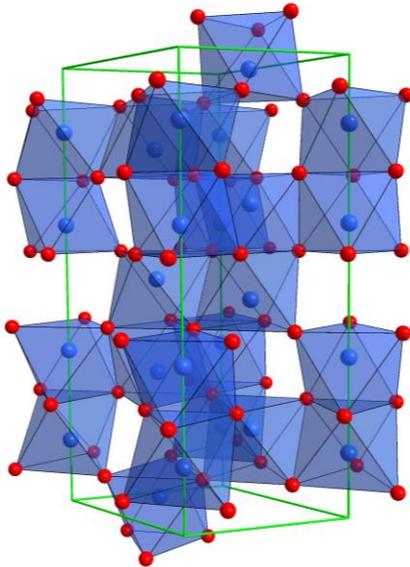
Sehr vereinfacht - Relative Skalen

Beispiel: *Canted* AF in $\alpha\text{-Fe}_2\text{O}_3$

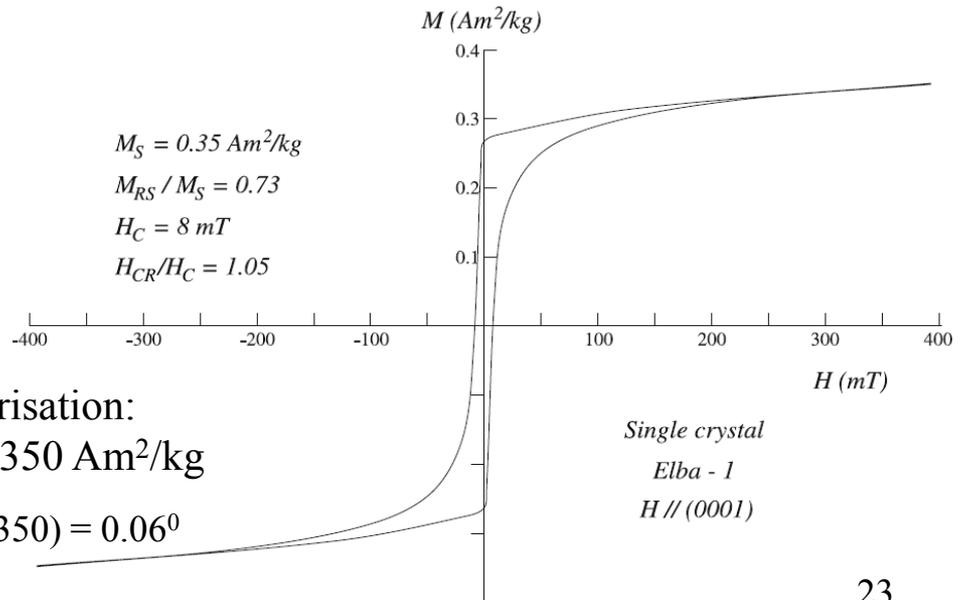
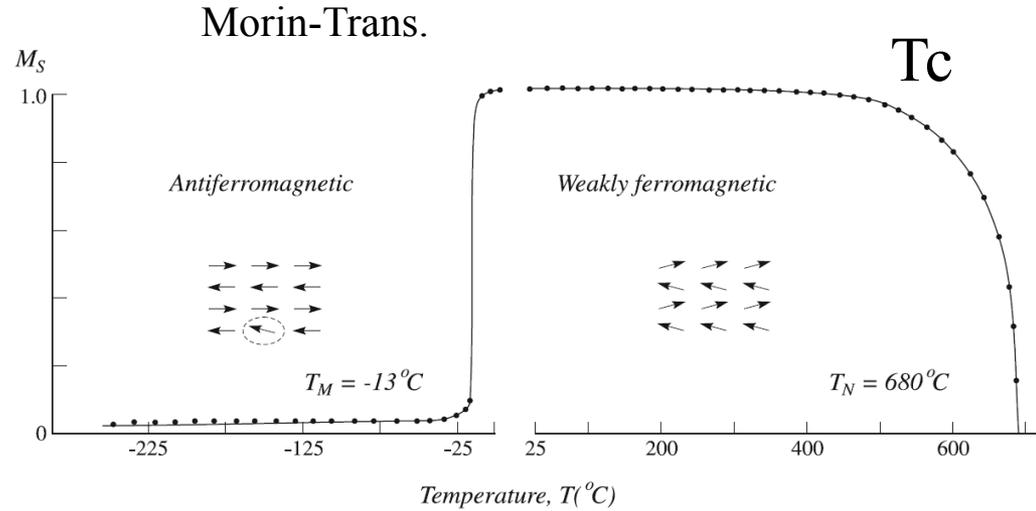


○ Fe^{3+} ion

Korund
Typstruktur

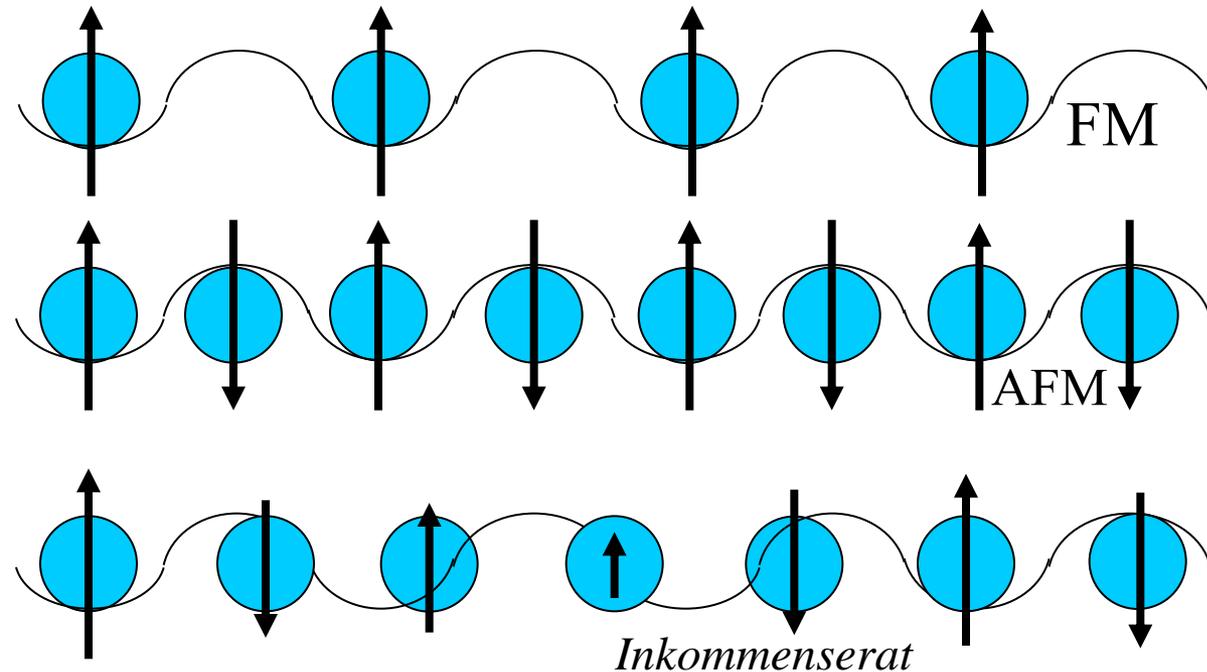


volle Polarisation:
 $M_s(\text{teo}) = 350 \text{ Am}^2/\text{kg}$
 $\sin^{-1}(0.35/350) = 0.06^\circ$



Die f-Elementen

Warum sind f-Elemente kompliziert?



hcp Gd-Gd 3.57 Å "FM"

hcp Tb-Tb 3.52 Å "AFM"

hcp Tm-Tm 3.45 Å "AFM"

I. D. Hughes et al., Nature 446 (2007) 650-653

Er

Konisches helix (FM)

$0 < T < 20$

Komplexe Oszillation (AF)

$20 < T < 53$

Sinusoidaler Antiferromagnet

$53 < T < 85$

Dy

Nichtkonisches helix (AF)

$85 < T < 179$

Ferromagnet

$0 < T < 85$

W.C. Koehler et al. Phys. Rev. 151 (1966) 414 - 424

Metall	T_N	T_C
Ce	12.5	
Pr	25	
Nd	19	
Sm	14.8	
Eu	90	
Gd		293
Tb	229	222
Dy	179	85
Ho	131	20
Er	85	20
Tm	56	25

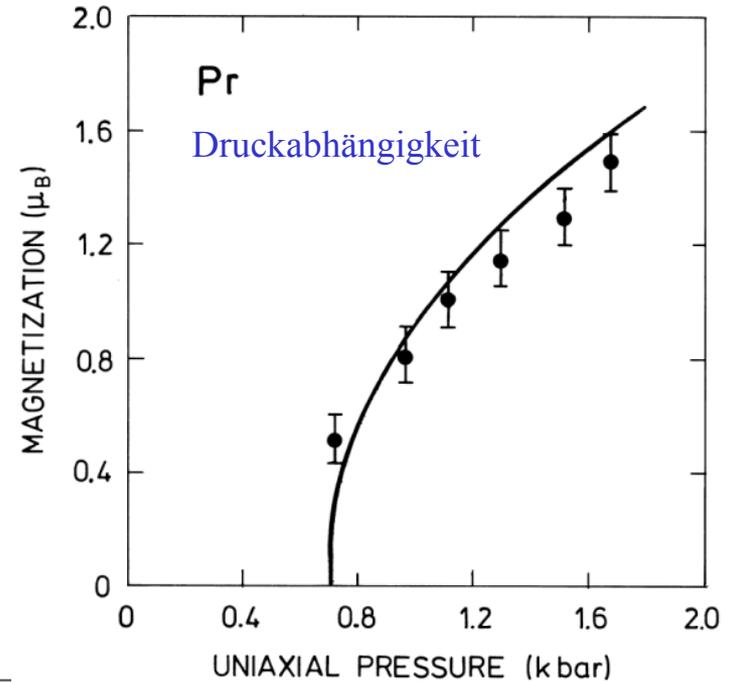
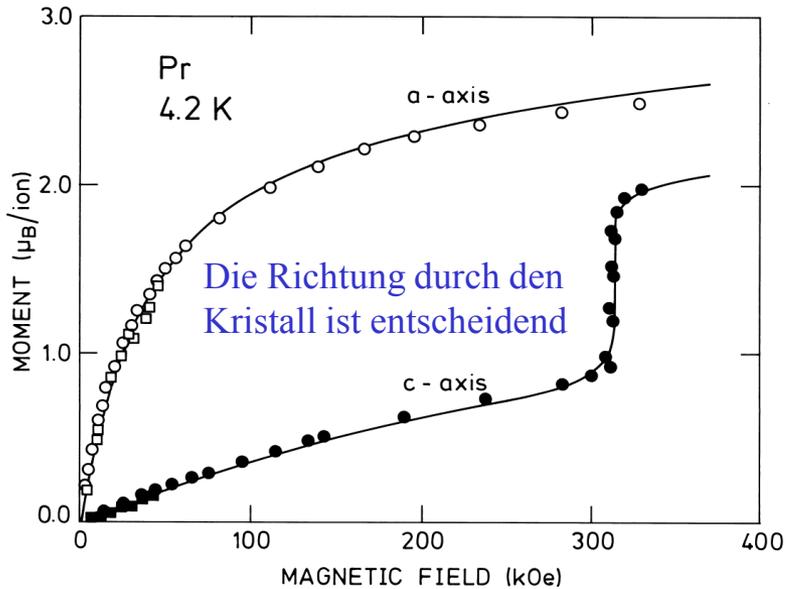
Was macht die Temperatur?

Was könnte Druck verursachen?

25

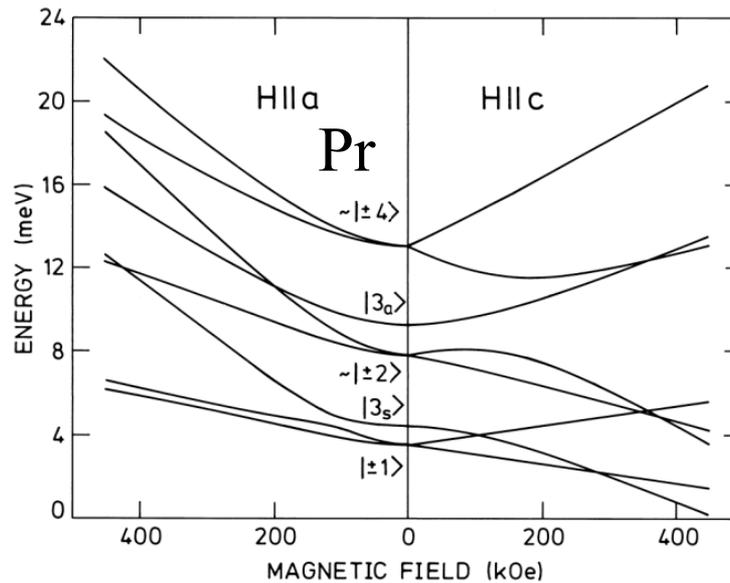
Martin Valldor

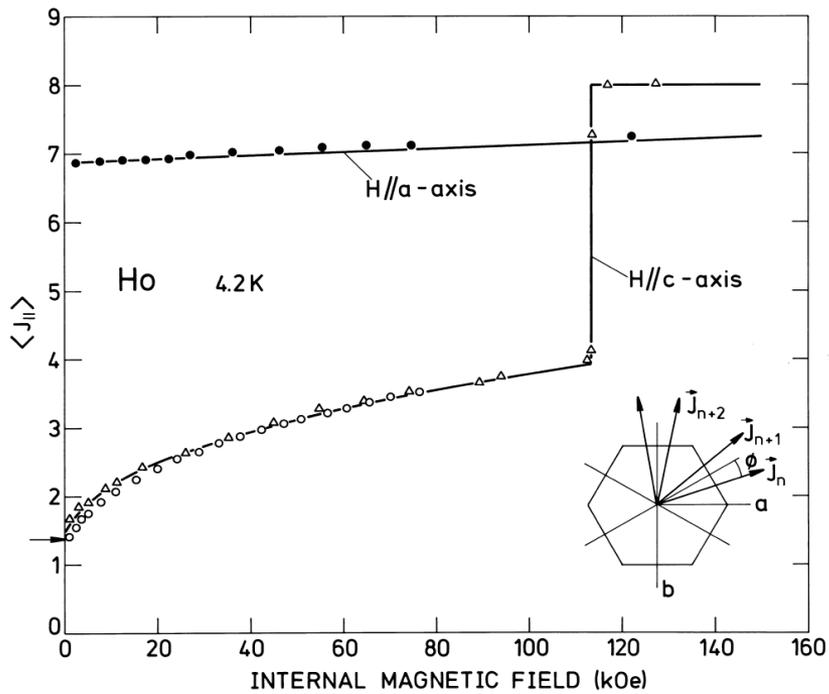
Beispiel: Pr



Was macht der Druck?

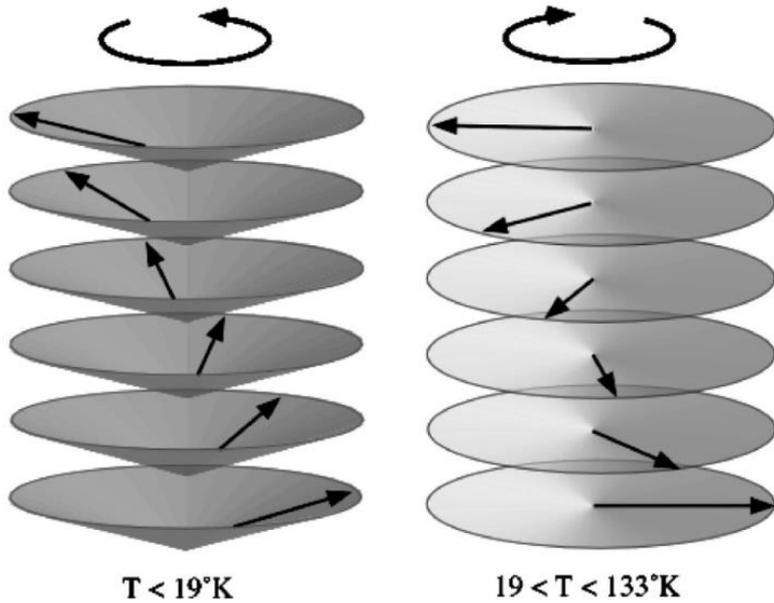
... und es hängt vom Feld ab!





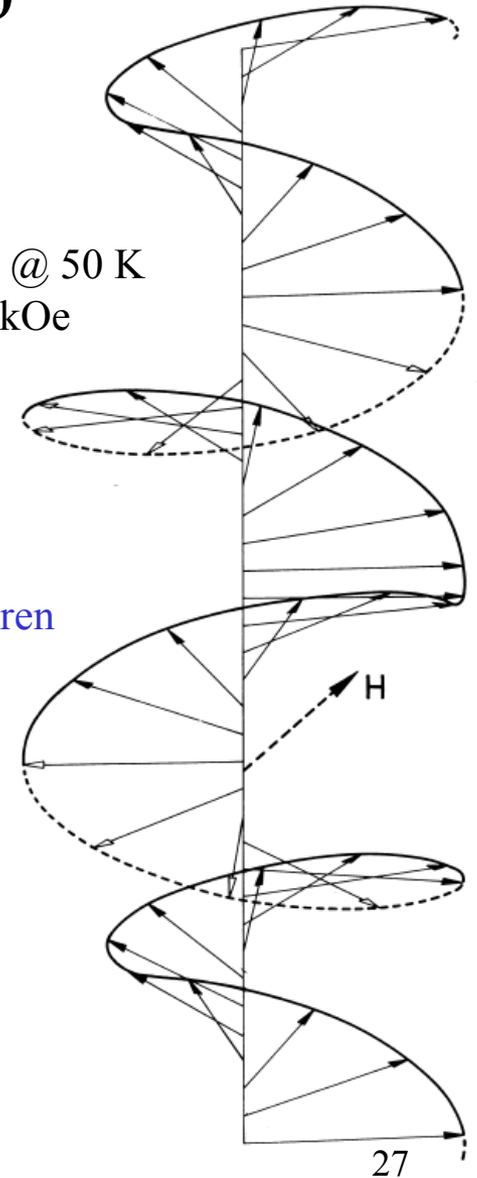
Beispiel: Ho

Komplexe
Magnetstrukturen



Ho @ 50 K
11 kOe

Helifan (3/2)



Zusammenfassung

- Spin-Spin-Wechselwirkung ist der Grund für magnetische Ordnung.
- Die Wechselwirkungen werden mit Dipol-Dipol, Superaustausch, Doppelaustausch, Direktaustausch und RKKY-Mechanismen beschrieben.
- Die Grundzustände sind Antiferromagnetismus und Ferromagnetismus.
- Durch weiteren Parametern entstehen Ferrimagnetismus und Canted Antiferromagnetismus.
- Die f-Elementen unterscheiden sich von den d-Elementen durch ihre Komplexität.