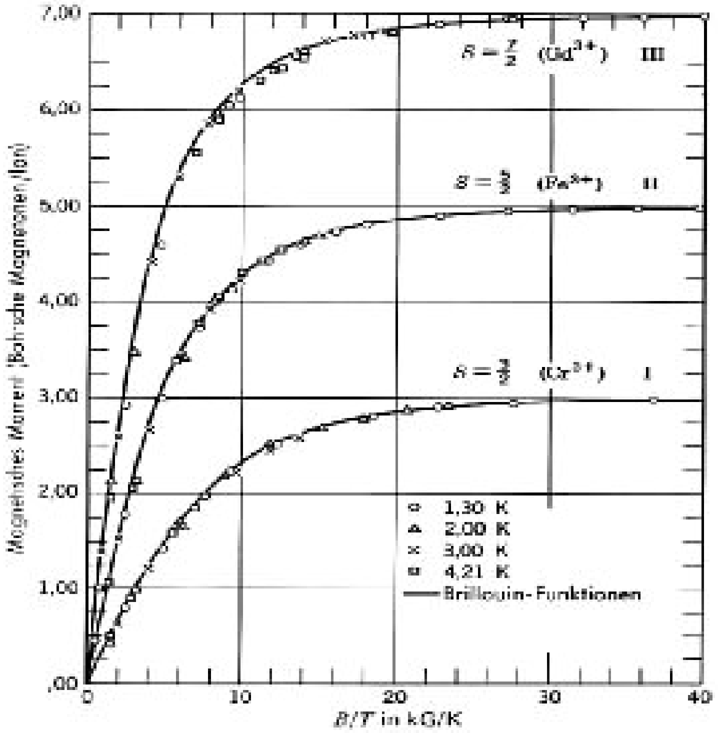
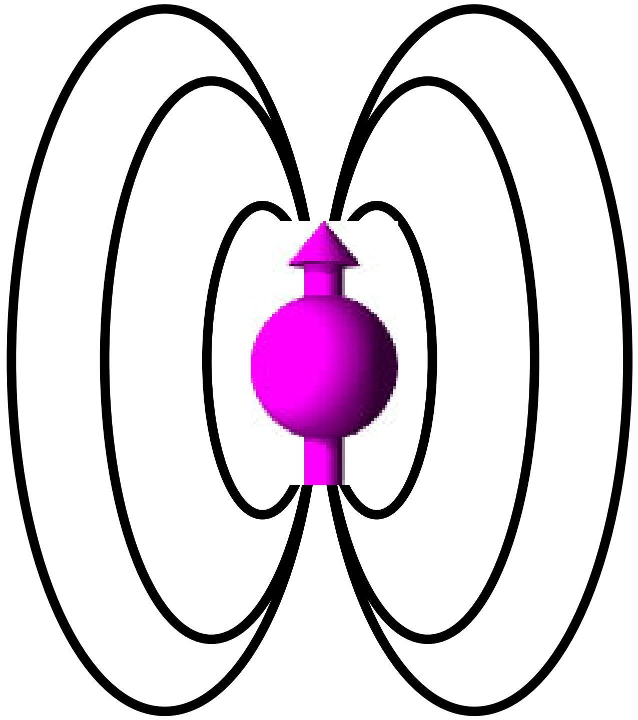
8) Magnetismus

Ferromagnetismus

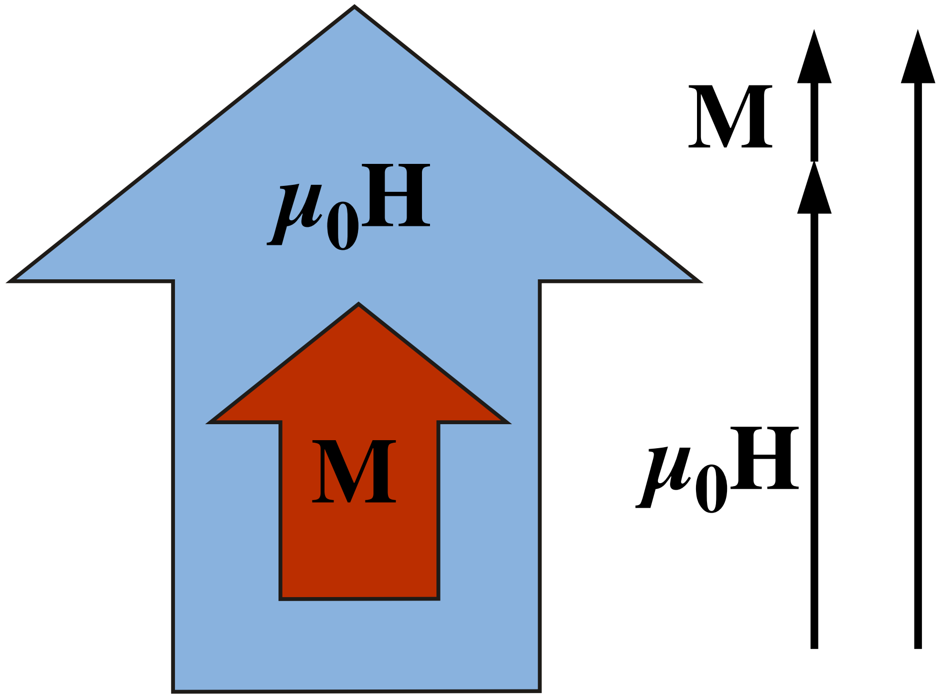
Paramagnetismus



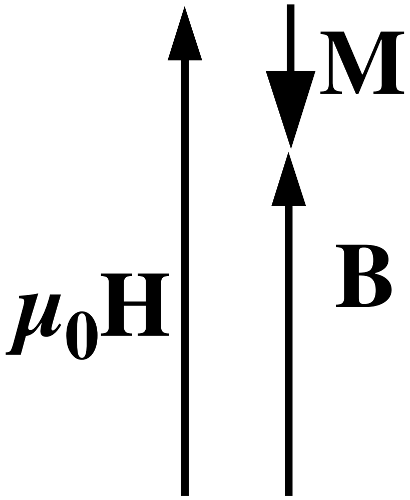


Diamagnetismus

Magnetisierung



$$\mathbf{B} = \mu_0\mathbf{H} + \mathbf{M}$$
$$= \mu_0(1+\chi_m)\mathbf{H}$$



$$\mathbf{M} = \mu_0\chi_m\mathbf{H}$$

$\chi_m > 0$

paramagnetisch

$\chi_m < 0$

diamagnetisch

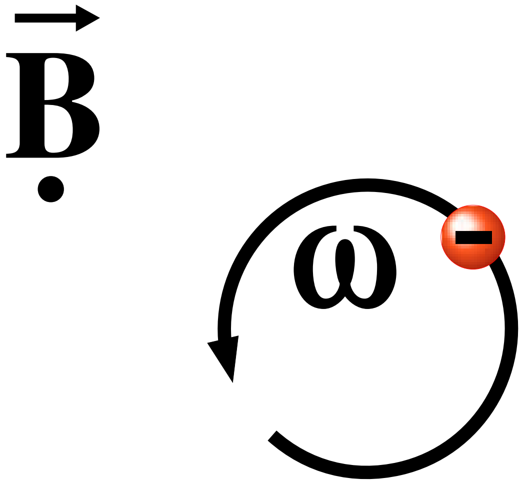
Magnetische Suszeptibilität

diamagnetisch	
Cu	$-9.6 \cdot 10^{-6}$
Ag	$-25.2 \cdot 10^{-6}$
Sb	$-70.9 \cdot 10^{-6}$
Bi	$-156.0 \cdot 10^{-6}$
NaCl	$-13.9 \cdot 10^{-6}$
SiO_2	$-29.6 \cdot 10^{-6}$
H_2O	$-7 \cdot 10^{-6}$
$N_2(g)$	$-6.75 \cdot 10^{-9}$

paramagnetisch	
Al	$+20.85 \cdot 10^{-6}$
Pt	$+257.4 \cdot 10^{-6}$
Mn	$+883.0 \cdot 10^{-6}$
V	$+340.0 \cdot 10^{-6}$
$O_2(g)$	$+1.9 \cdot 10^{-6}$
$O_2(fl)$	$+3.6 \cdot 10^{-3}$

Diamagnetische Suszeptibilität

klassisches Modell:



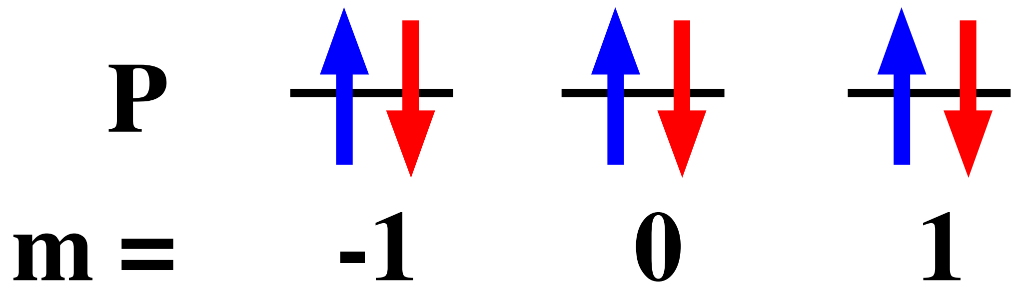
Larmor: $\omega = \frac{eB}{2m}$

Experimentelle Werte [Einheiten: 10^{-6} cm^3/Mol]

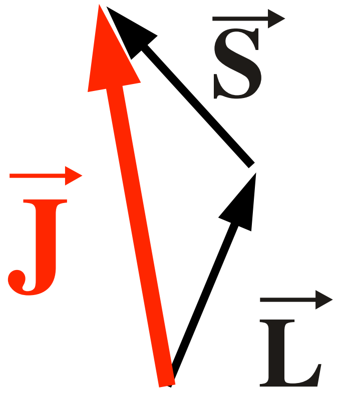
		He	-1.9	Li^+	-0.7
F^-	-9.4	Ne	-7.2	Na^+	-6.1
Cl^-	-24.2	Ar	-19.4	K^+	-14.6
Br^-	-34.5	Kr	-28	Rb^+	-22.0
I^-	-50.6	Xe	-43	Cs^+	-35.1

Addition magnetischer Momente

Atomarer Drehimpuls

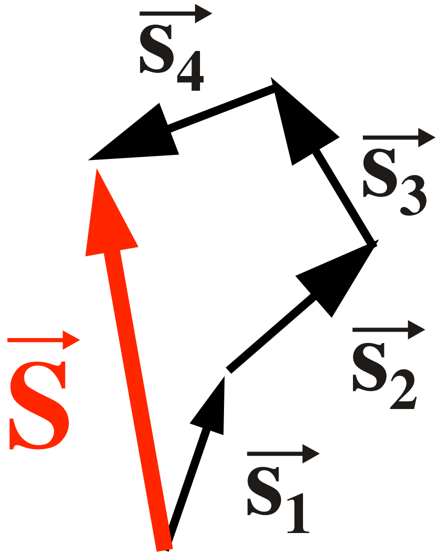


Bahndrehimpuls + Spin



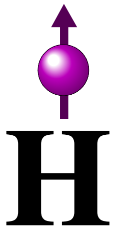
Gesamtdrehimpuls verschwindet für gefüllte Schalen !

Multi-Elektronen Systeme

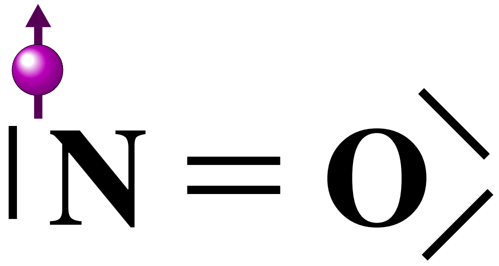


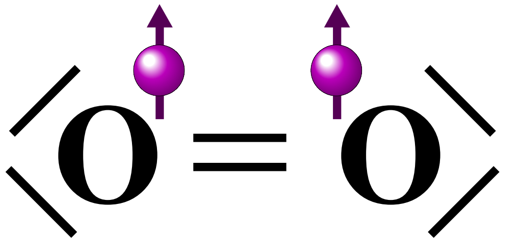
Teilweise gefüllte Schalen

Atome



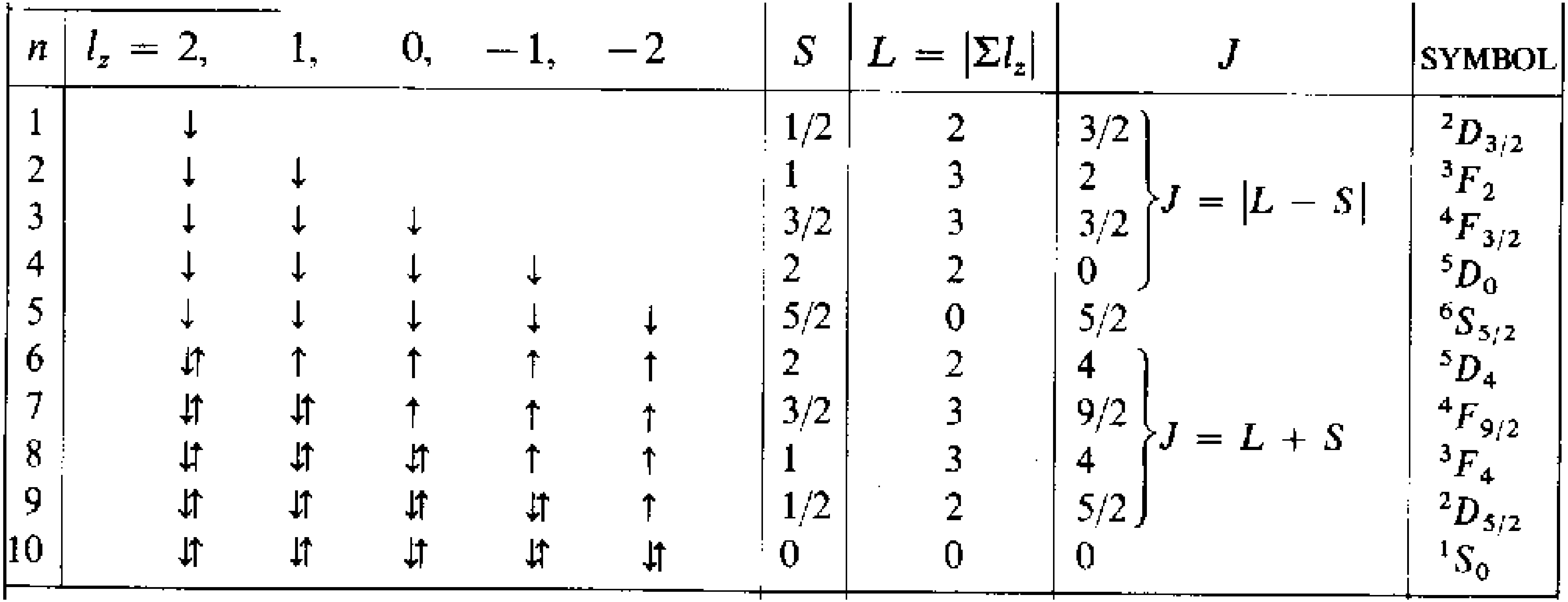
Moleküle





Hund’sche Regeln

Elektronische Grundzustände teilweise gefüllter d-Schalen (l=2)



n	$l_z = 2,$	$1,$	$0,$	$-1,$	-2	S	$L = \|\Sigma l_z\|$	J		SYMBOL
1	↓					1/2	2	3/2	$J = \|L - S\|$	$^2D_{3/2}$
2	↓	↓				1	3	2		$^3F_2$
3	↓	↓	↓			3/2	3	3/2		$^4F_{3/2}$
4	↓	↓	↓	↓		2	2	0		$^5D_0$
5	↓	↓	↓	↓	↓	5/2	0	5/2		$^6S_{5/2}$
6	↓↑	↑	↑	↑	↑	2	2	4	$J = L + S$	$^5D_4$
7	↓↑	↓↑	↑	↑	↑	3/2	3	9/2		$^4F_{9/2}$
8	↓↑	↓↑	↓↑	↑	↑	1	3	4		$^3F_4$
9	↓↑	↓↑	↓↑	↓↑	↑	1/2	2	5/2		$^2D_{5/2}$
10	↓↑	↓↑	↓↑	↓↑	↓↑	0	0	0		$^1S_0$

1) S maximal

2) L maximal

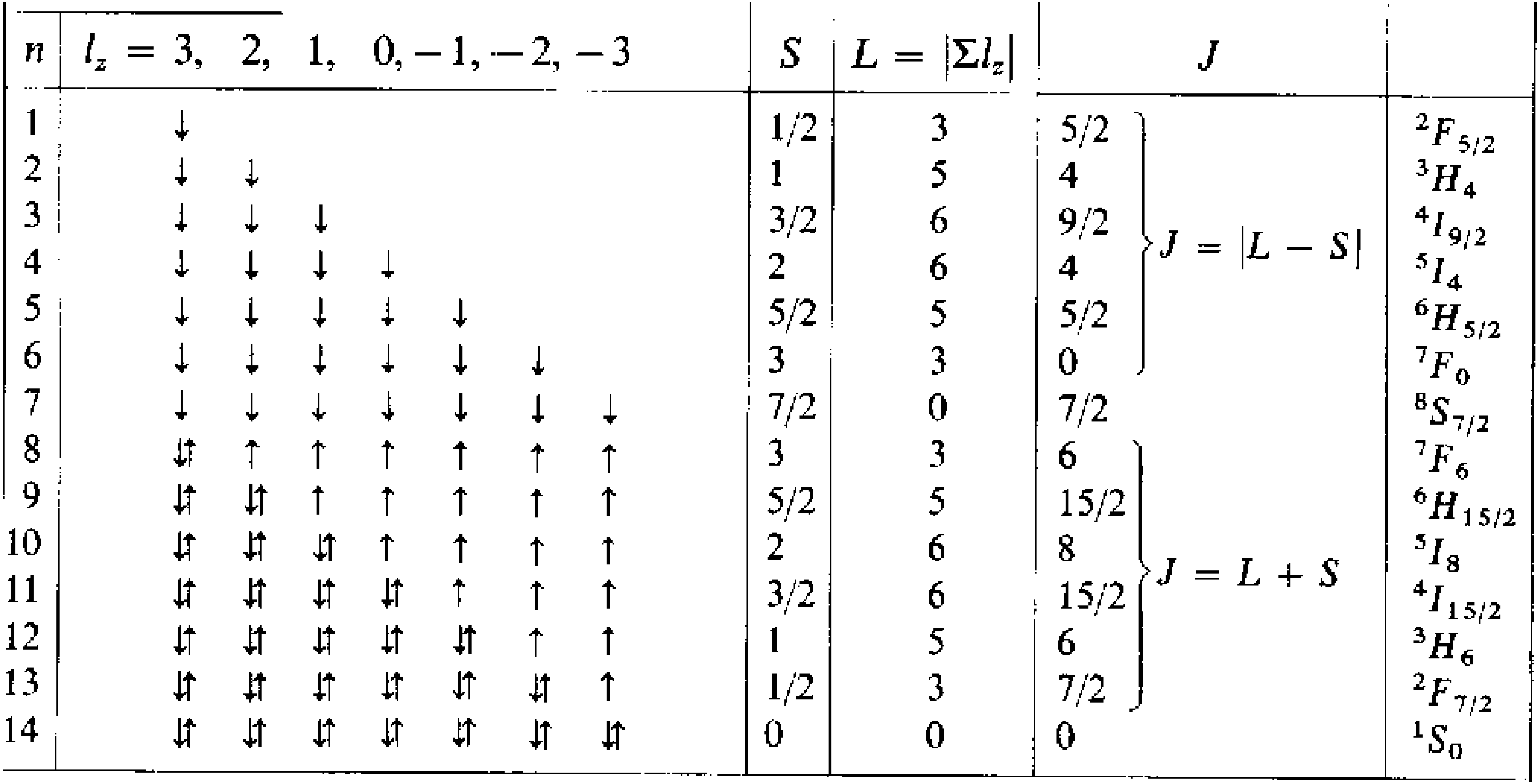
3) J = |L-S| für < halb volle Schalen

J = L+S für > halb volle Schalen

N.W. Ashcroft and N.D. Mermin, 'Solid state physics', Holt, Rinehart and Winston, New York (1976).

Hund'sche Regeln

Elektronische Grundzustände teilweise gefüllter f-Schalen (l=3)

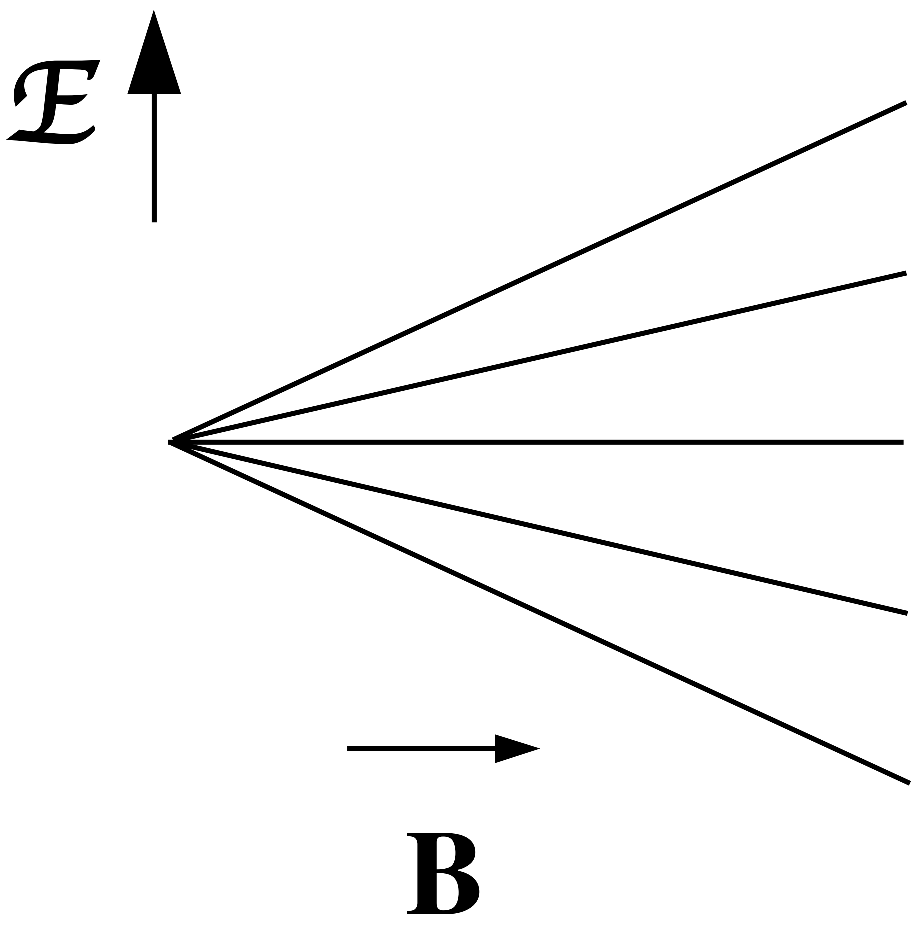


n	$l_z = 3,$	$2,$	$1,$	$0,$	$-1,$	$-2,$	-3	S	$L = \lvert\Sigma l_z\rvert$	J		
1	↓							1/2	3	5/2	$J = \lvert L - S\rvert$	$^2F_{5/2}$
2	↓	↓						1	5	4		$^3H_4$
3	↓	↓	↓					3/2	6	9/2		$^4I_{9/2}$
4	↓	↓	↓	↓				2	6	4		$^5I_4$
5	↓	↓	↓	↓	↓			5/2	5	5/2		$^6H_{5/2}$
6	↓	↓	↓	↓	↓	↓		3	3	0		$^7F_0$
7	↓	↓	↓	↓	↓	↓	↓	7/2	0	7/2		$^8S_{7/2}$
8	↓↑	↑	↑	↑	↑	↑	↑	3	3	6	$J = L + S$	$^7F_6$
9	↓↑	↓↑	↑	↑	↑	↑	↑	5/2	5	15/2		$^6H_{15/2}$
10	↓↑	↓↑	↓↑	↑	↑	↑	↑	2	6	8		$^5I_8$
11	↓↑	↓↑	↓↑	↓↑	↑	↑	↑	3/2	6	15/2		$^4I_{15/2}$
12	↓↑	↓↑	↓↑	↓↑	↓↑	↑	↑	1	5	6		$^3H_6$
13	↓↑	↓↑	↓↑	↓↑	↓↑	↓↑	↑	1/2	3	7/2		$^2F_{7/2}$
14	↓↑	↓↑	↓↑	↓↑	↓↑	↓↑	↓↑	0	0	0		$^1S_0$

N.W. Ashcroft and N.D. Mermin, 'Solid state physics', Holt, Rinehart and Winston, New York (1976).

Thermische Verteilung

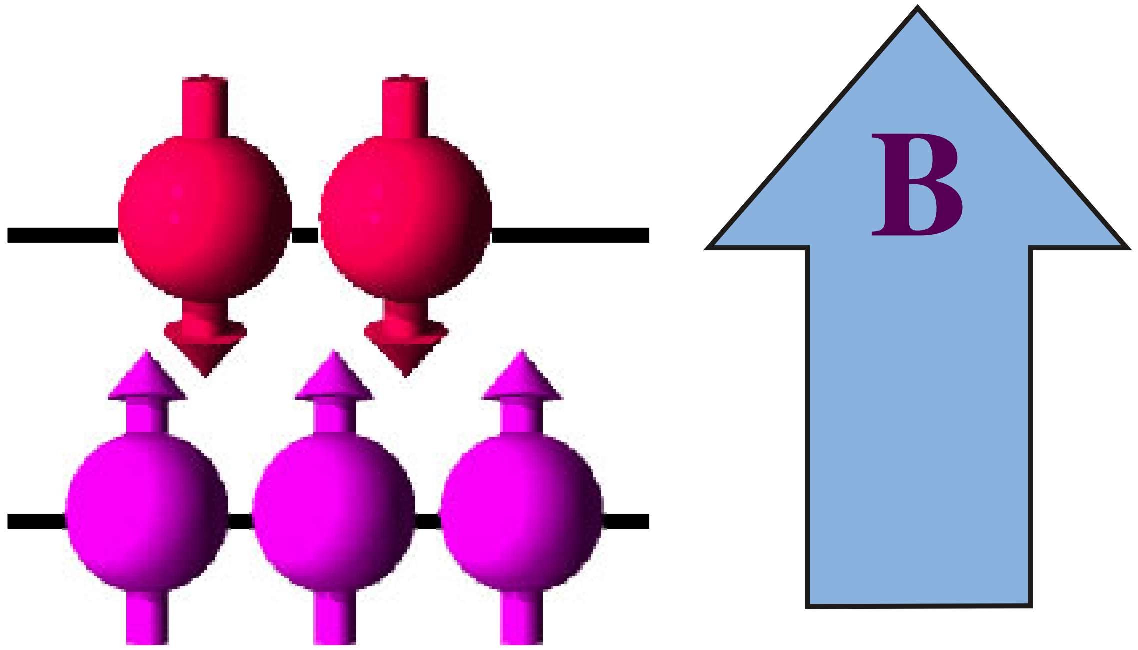
Energien im Magnetfeld



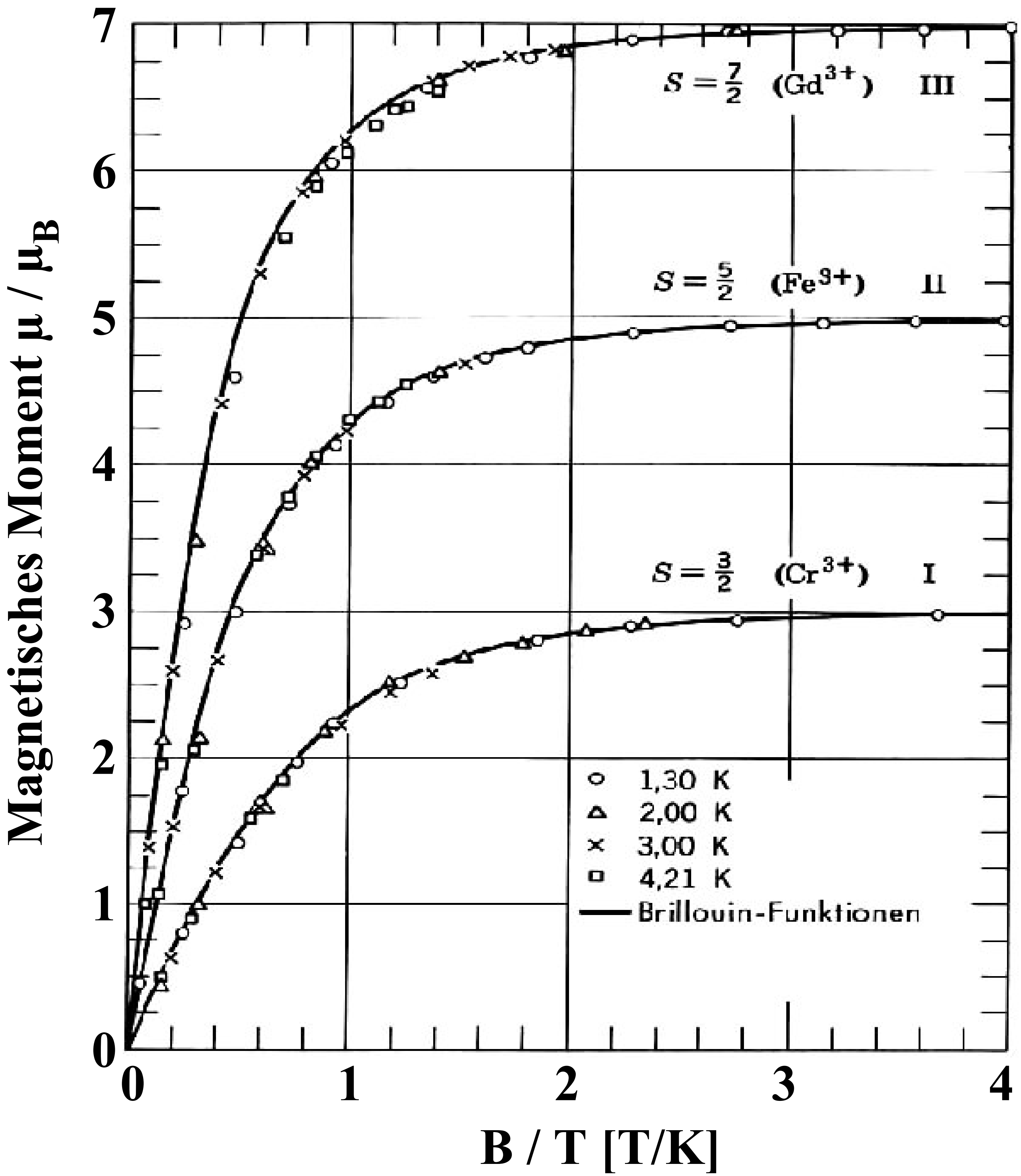
$$\mathcal{E} = -\,\vec{B}\cdot\vec{\mu}$$

$$= -\,m_J\, g\, \mu_B\, B$$

Besetzungszahlen



Temperaturabhängigkeit



$$M = N\, g\, \mu_B\, B_J(g\, \mu_B\, J\, B/k_BT)$$

Brillouin-Funktion:

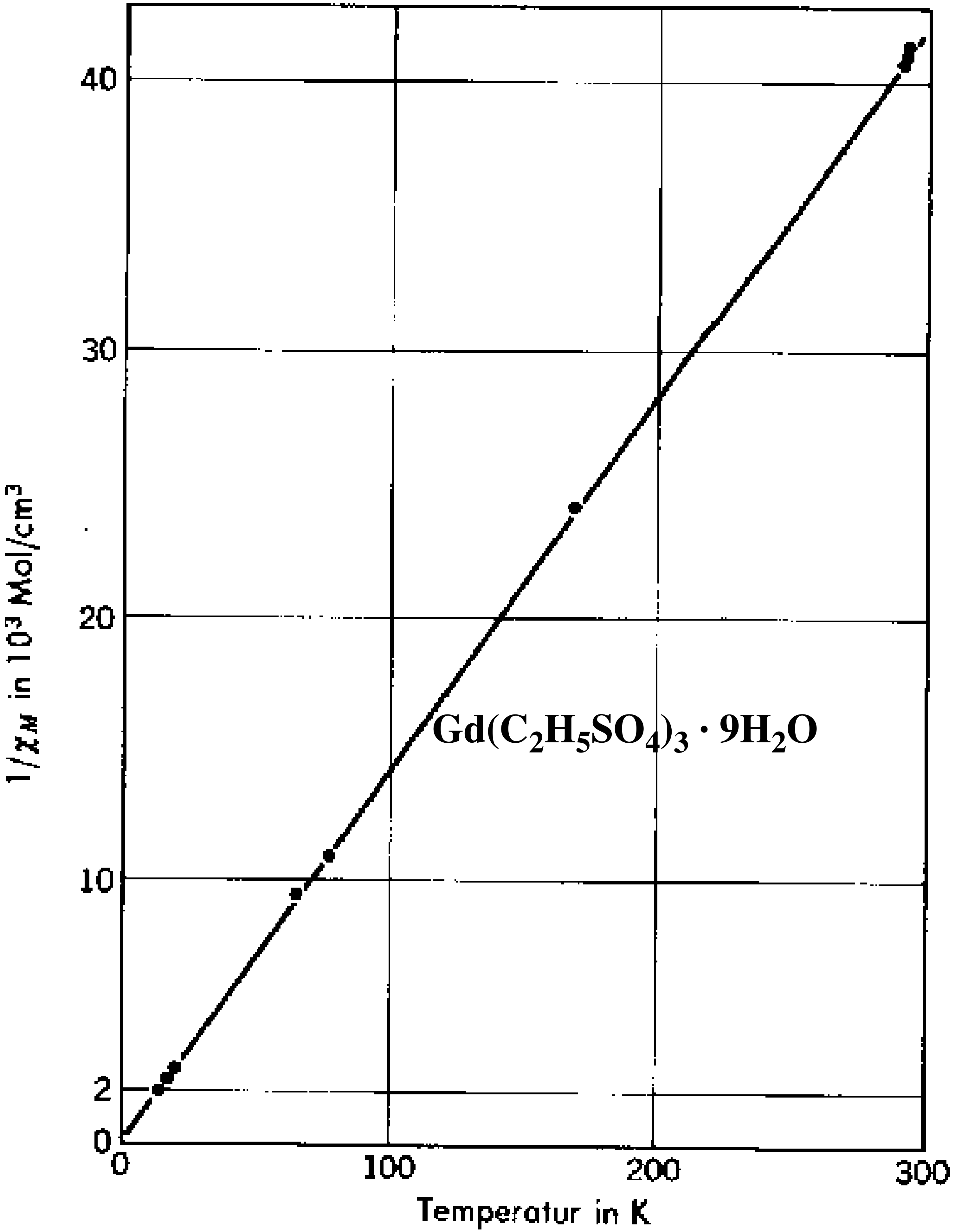
$$B_J(x) = \frac{2J+1}{2J} \coth\left(\frac{2J+1}{2J}x\right)$$

$$-\frac{1}{2J} \coth\left(\frac{1}{2J}x\right)$$

Abhängigkeit des magnetischen Moments von B/T für kugelförmige Proben aus (I) Kalium-Chrom-Alaun, (II) Eisen-III-Alaun und (III) Gadolinium-Sulfat-Oktahydrat. Bei 1,3 K und etwa 50 000 Gauß wird eine 99,5%ige magnetische Sättigung erreicht. [Nach W. E. Henry.]

C. Kittel, '*Einführung in die Festkörperphysik*', R. Oldenburg, München

Curie Gesetz

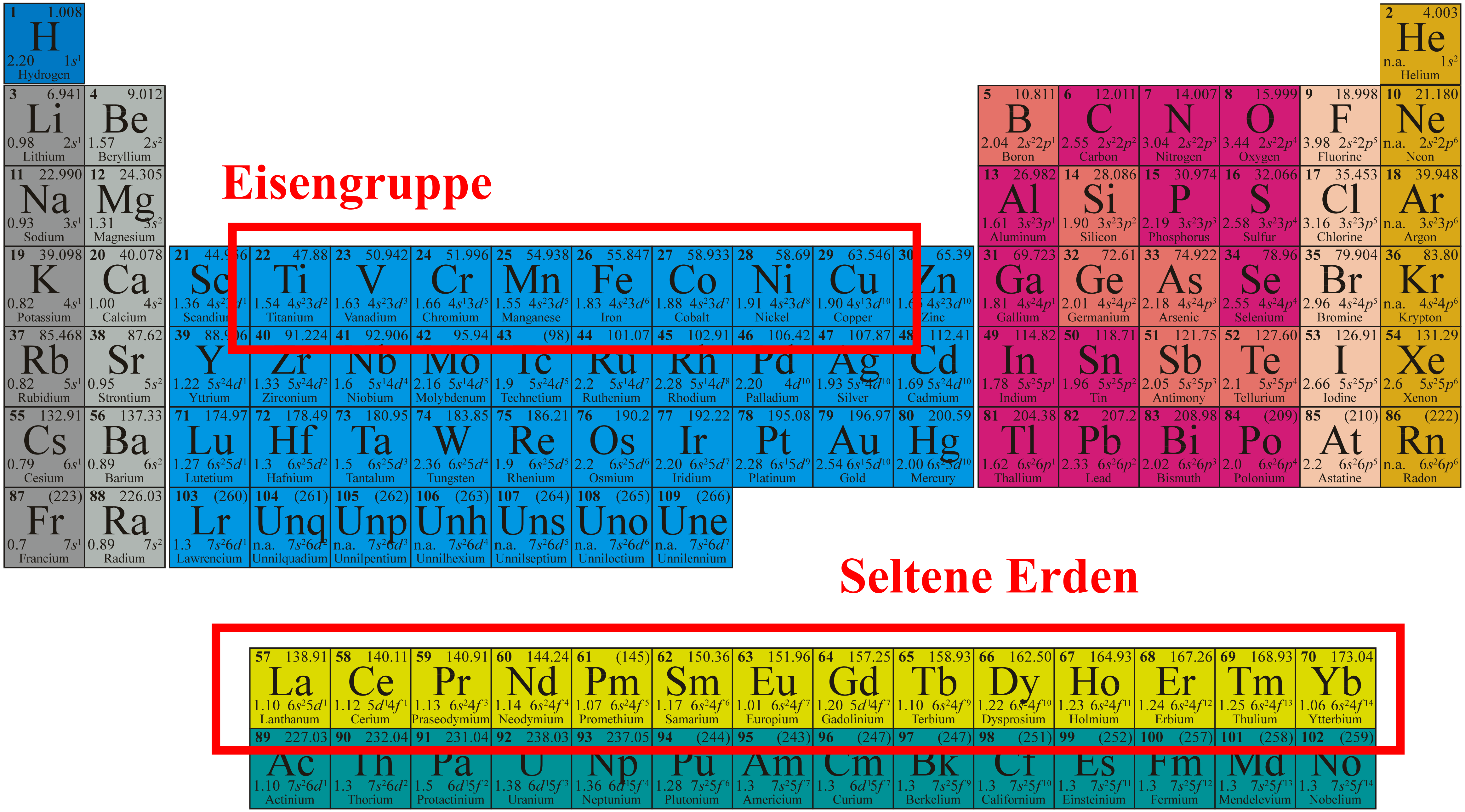


$$\chi_m = \frac{C}{T}$$

Temperaturabhängigkeit der reziproken Suszeptibilität $1/\chi$ eines Gadoliniumsalzes $Gd(C_2H_5SO_4)_3 \cdot 9H_2O$. Die gerade Linie entspricht dem Curiegesetz (nach L. C. Jackson und H. Kamerlingh Onnes)

C. Kittel, '*Einführung in die Festkörperphysik*',
R. Oldenburg, München

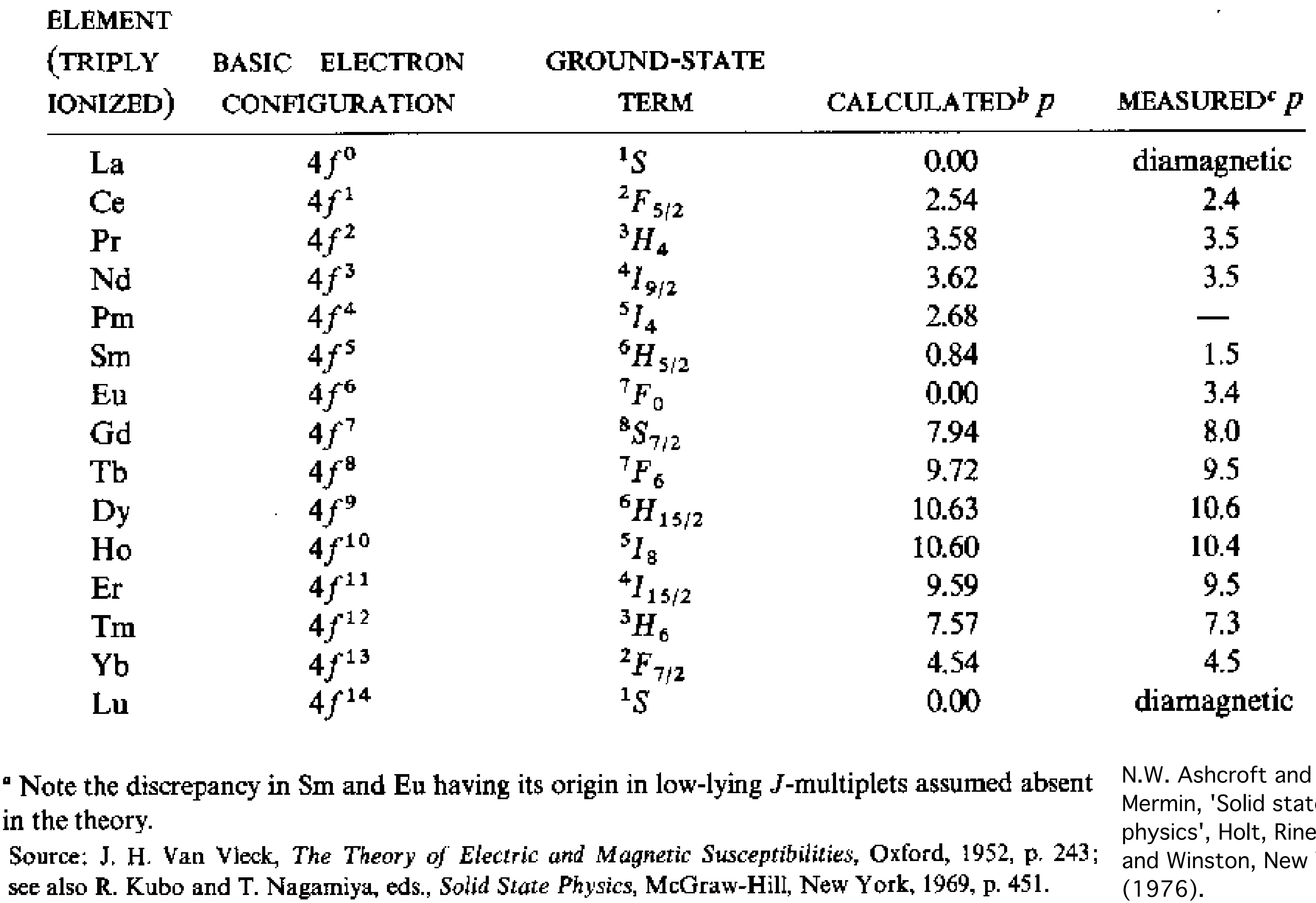
Magnetische Eigenschaften



1 1.008 H 2.20 $1s^1$ Hydrogen																	**2** 4.003 He n.a. $1s^2$ Helium
3 6.941 Li 0.98 $2s^1$ Lithium	**4** 9.012 Be 1.57 $2s^2$ Beryllium											**5** 10.811 B 2.04 $2s^2 2p^1$ Boron	**6** 12.011 C 2.55 $2s^2 2p^2$ Carbon	**7** 14.007 N 3.04 $2s^2 2p^3$ Nitrogen	**8** 15.999 O 3.44 $2s^2 2p^4$ Oxygen	**9** 18.998 F 3.98 $2s^2 2p^5$ Fluorine	**10** 21.180 Ne n.a. $2s^2 2p^6$ Neon
11 22.990 Na 0.93 $3s^1$ Sodium	**12** 24.305 Mg 1.31 $3s^2$ Magnesium											**13** 26.982 Al 1.61 $3s^2 3p^1$ Aluminum	**14** 28.086 Si 1.90 $3s^2 3p^2$ Silicon	**15** 30.974 P 2.19 $3s^2 3p^3$ Phosphorus	**16** 32.066 S 2.58 $3s^2 3p^4$ Sulfur	**17** 35.453 Cl 3.16 $3s^2 3p^5$ Chlorine	**18** 39.948 Ar n.a. $3s^2 3p^6$ Argon
19 39.098 K 0.82 $4s^1$ Potassium	**20** 40.078 Ca 1.00 $4s^2$ Calcium	**21** 44.9[illegible]6 Sc 1.36 $4s^2$[illegible]d^1 Scandiu[illegible]	**22** 47.88 Ti 1.54 $4s^2 3d^2$ Titanium	**23** 50.942 V 1.63 $4s^2 3d^3$ Vanadium	**24** 51.996 Cr 1.66 $4s^1 3d^5$ Chromium	**25** 54.938 Mn 1.55 $4s^2 3d^5$ Manganese	**26** 55.847 Fe 1.83 $4s^2 3d^6$ Iron	**27** 58.933 Co 1.88 $4s^2 3d^7$ Cobalt	**28** 58.69 Ni 1.91 $4s^2 3d^8$ Nickel	**29** 63.546 Cu 1.90 $4s^1 3d^{10}$ Copper	**30** 65.39 Zn 1.6[illegible] $4s^2 3d^{10}$ Zinc	**31** 69.723 Ga 1.81 $4s^2 4p^1$ Gallium	**32** 72.61 Ge 2.01 $4s^2 4p^2$ Germanium	**33** 74.922 As 2.18 $4s^2 4p^3$ Arsenic	**34** 78.96 Se 2.55 $4s^2 4p^4$ Selenium	**35** 79.904 Br 2.96 $4s^2 4p^5$ Bromine	**36** 83.80 Kr n.a. $4s^2 4p^6$ Krypton
37 85.468 Rb 0.82 $5s^1$ Rubidium	**38** 87.62 Sr 0.95 $5s^2$ Strontium	**39** 88.9[illegible]6 Y 1.22 $5s^2 4d^1$ Yttrium	**40** 91.224 Zr 1.33 $5s^2 4d^2$ Zirconium	**41** 92.906 Nb 1.6 $5s^1 4d^4$ Niobium	**42** 95.94 Mo 2.16 $5s^1 4d^5$ Molybdenum	**43** (98) Tc 1.9 $5s^2 4d^5$ Technetium	**44** 101.07 Ru 2.2 $5s^1 4d^7$ Ruthenium	**45** 102.91 Rh 2.28 $5s^1 4d^8$ Rhodium	**46** 106.42 Pd 2.20 $4d^{10}$ Palladium	**47** 107.87 Ag 1.93 $5s^1 4d^{10}$ Silver	**48** 112.41 Cd 1.69 $5s^2 4d^{10}$ Cadmium	**49** 114.82 In 1.78 $5s^2 5p^1$ Indium	**50** 118.71 Sn 1.96 $5s^2 5p^2$ Tin	**51** 121.75 Sb 2.05 $5s^2 5p^3$ Antimony	**52** 127.60 Te 2.1 $5s^2 5p^4$ Tellurium	**53** 126.91 I 2.66 $5s^2 5p^5$ Iodine	**54** 131.29 Xe 2.6 $5s^2 5p^6$ Xenon
55 132.91 Cs 0.79 $6s^1$ Cesium	**56** 137.33 Ba 0.89 $6s^2$ Barium	**71** 174.97 Lu 1.27 $6s^2 5d^1$ Lutetium	**72** 178.49 Hf 1.3 $6s^2 5d^2$ Hafnium	**73** 180.95 Ta 1.5 $6s^2 5d^3$ Tantalum	**74** 183.85 W 2.36 $6s^2 5d^4$ Tungsten	**75** 186.21 Re 1.9 $6s^2 5d^5$ Rhenium	**76** 190.2 Os 2.2 $6s^2 5d^6$ Osmium	**77** 192.22 Ir 2.20 $6s^2 5d^7$ Iridium	**78** 195.08 Pt 2.28 $6s^1 5d^9$ Platinum	**79** 196.97 Au 2.54 $6s^1 5d^{10}$ Gold	**80** 200.59 Hg 2.00 $6s^2 5d^{10}$ Mercury	**81** 204.38 Tl 1.62 $6s^2 6p^1$ Thallium	**82** 207.2 Pb 2.33 $6s^2 6p^2$ Lead	**83** 208.98 Bi 2.02 $6s^2 6p^3$ Bismuth	**84** (209) Po 2.0 $6s^2 6p^4$ Polonium	**85** (210) At 2.2 $6s^2 6p^5$ Astatine	**86** (222) Rn n.a. $6s^2 6p^6$ Radon
87 (223) Fr 0.7 $7s^1$ Francium	**88** 226.03 Ra 0.89 $7s^2$ Radium	**103** (260) Lr 1.3 $7s^2 6d^1$ Lawrencium	**104** (261) Unq n.a. $7s^2 6d^2$ Unnilquadium	**105** (262) Unp n.a. $7s^2 6d^3$ Unnilpentium	**106** (263) Unh n.a. $7s^2 6d^4$ Unnilhexium	**107** (264) Uns n.a. $7s^2 6d^5$ Unnilseptium	**108** (265) Uno n.a. $7s^2 6d^6$ Unniloctium	**109** (266) Une n.a. $7s^2 6d^7$ Unnilennium									
			57 138.91 La 1.10 $6s^2 5d^1$ Lanthanum	**58** 140.11 Ce 1.12 $5d^1 4f^1$ Cerium	**59** 140.91 Pr 1.13 $6s^2 4f^3$ Praseodymium	**60** 144.24 Nd 1.14 $6s^2 4f^4$ Neodymium	**61** (145) Pm 1.07 $6s^2 4f^5$ Promethium	**62** 150.36 Sm 1.17 $6s^2 4f^6$ Samarium	**63** 151.96 Eu 1.01 $6s^2 4f^7$ Europium	**64** 157.25 Gd 1.20 $5d^1 4f^7$ Gadolinium	**65** 158.93 Tb 1.10 $6s^2 4f^9$ Terbium	**66** 162.50 Dy 1.22 $6s^2 4f^{10}$ Dysprosium	**67** 164.93 Ho 1.23 $6s^2 4f^{11}$ Holmium	**68** 167.26 Er 1.24 $6s^2 4f^{12}$ Erbium	**69** 168.93 Tm 1.25 $6s^2 4f^{13}$ Thulium	**70** 173.04 Yb 1.06 $6s^2 4f^{14}$ Ytterbium	
			89 227.03 Ac 1.10 $7s^2 6d^1$ Actinium	**90** 232.04 Th 1.3 $7s^2 6d^2$ Thorium	**91** 231.04 Pa 1.5 $6d^1 5f^2$ Protactinium	**92** 238.03 U 1.38 $6d^1 5f^3$ Uranium	**93** 237.05 Np 1.36 $6d^1 5f^4$ Neptunium	**94** (244) Pu 1.28 $7s^2 5f^6$ Plutonium	**95** (243) Am 1.3 $7s^2 5f^7$ Americium	**96** (247) Cm 1.3 $6d^1 5f^7$ Curium	**97** (247) Bk 1.3 $7s^2 5f^9$ Berkelium	**98** (251) Cf 1.3 $7s^2 5f^{10}$ Californium	**99** (252) Es 1.3 $7s^2 5f^{11}$ Einsteinium	**100** (257) Fm 1.3 $7s^2 5f^{12}$ Fermium	**101** (258) Md 1.3 $7s^2 5f^{13}$ Mendelevium	**102** (259) No 1.3 $7s^2 5f^{14}$ Nobelium	

Effektive Magnetonenzahl

für seltene Erden



ELEMENT (TRIPLY IONIZED)	BASIC ELECTRON CONFIGURATION	GROUND-STATE TERM	CALCULATED[b] p	MEASURED[c] p
La	$4f^0$	^1S	0.00	diamagnetic
Ce	$4f^1$	$^2F_{5/2}$	2.54	2.4
Pr	$4f^2$	$^3H_4$	3.58	3.5
Nd	$4f^3$	$^4I_{9/2}$	3.62	3.5
Pm	$4f^4$	$^5I_4$	2.68	—
Sm	$4f^5$	$^6H_{5/2}$	0.84	1.5
Eu	$4f^6$	$^7F_0$	0.00	3.4
Gd	$4f^7$	$^8S_{7/2}$	7.94	8.0
Tb	$4f^8$	$^7F_6$	9.72	9.5
Dy	$4f^9$	$^6H_{15/2}$	10.63	10.6
Ho	$4f^{10}$	$^5I_8$	10.60	10.4
Er	$4f^{11}$	$^4I_{15/2}$	9.59	9.5
Tm	$4f^{12}$	$^3H_6$	7.57	7.3
Yb	$4f^{13}$	$^2F_{7/2}$	4.54	4.5
Lu	$4f^{14}$	^1S	0.00	diamagnetic

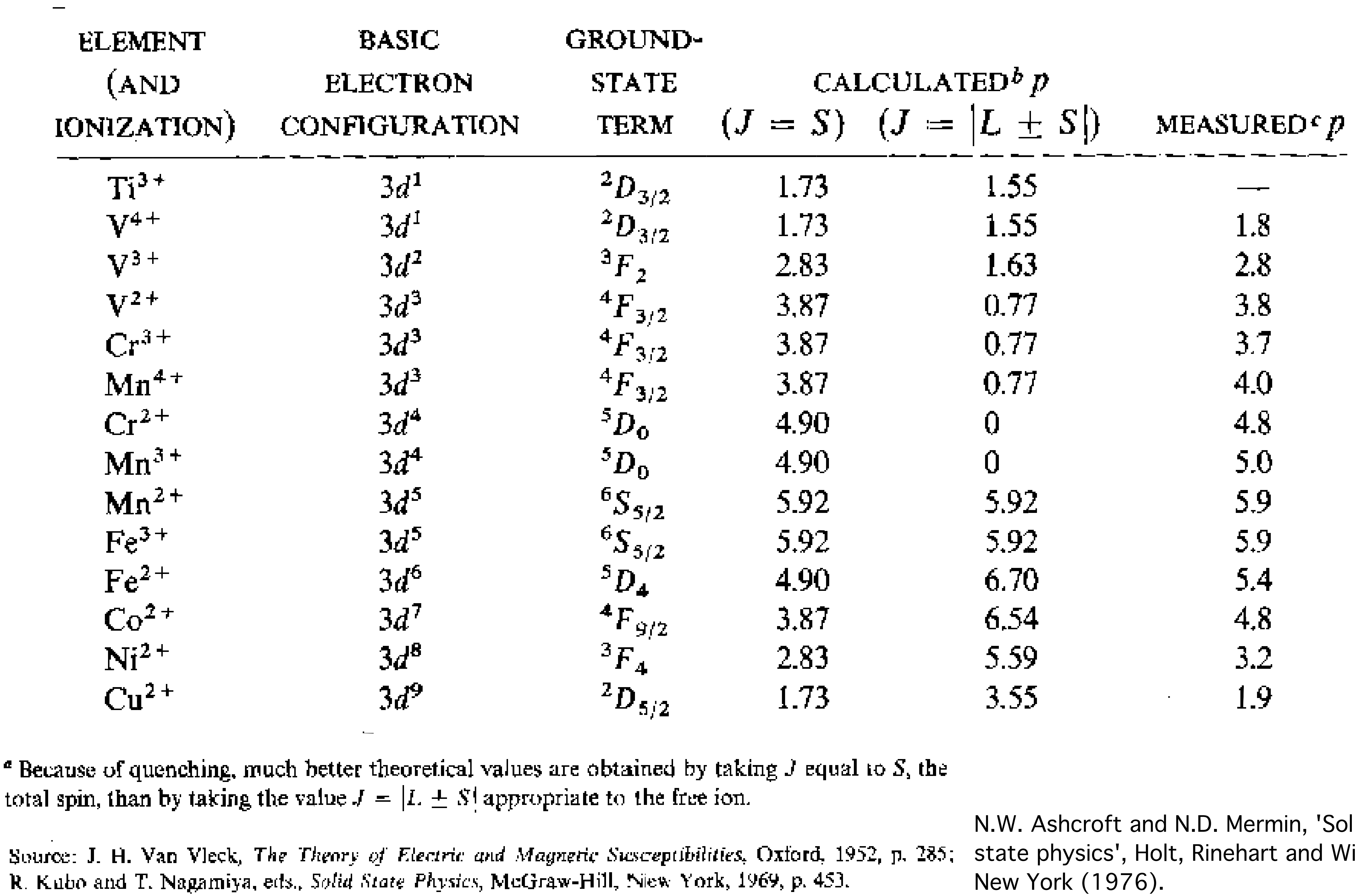
[a] Note the discrepancy in Sm and Eu having its origin in low-lying J-multiplets assumed absent in the theory.

Source: J. H. Van Vleck, *The Theory of Electric and Magnetic Susceptibilities*, Oxford, 1952, p. 243; see also R. Kubo and T. Nagamiya, eds., *Solid State Physics*, McGraw-Hill, New York, 1969, p. 451.

N.W. Ashcroft and N.D. Mermin, 'Solid state physics', Holt, Rinehart and Winston, New York (1976).

Effektive Magnetonenzahl

für Eisengruppe



ELEMENT (AND IONIZATION)	BASIC ELECTRON CONFIGURATION	GROUND-STATE TERM	CALCULATED[b] p $(J = S)$	$(J = \|L \pm S\|)$	MEASURED[c] p
Ti^{3+}	$3d^1$	$^2D_{3/2}$	1.73	1.55	—
V^{4+}	$3d^1$	$^2D_{3/2}$	1.73	1.55	1.8
V^{3+}	$3d^2$	$^3F_2$	2.83	1.63	2.8
V^{2+}	$3d^3$	$^4F_{3/2}$	3.87	0.77	3.8
Cr^{3+}	$3d^3$	$^4F_{3/2}$	3.87	0.77	3.7
Mn^{4+}	$3d^3$	$^4F_{3/2}$	3.87	0.77	4.0
Cr^{2+}	$3d^4$	$^5D_0$	4.90	0	4.8
Mn^{3+}	$3d^4$	$^5D_0$	4.90	0	5.0
Mn^{2+}	$3d^5$	$^6S_{5/2}$	5.92	5.92	5.9
Fe^{3+}	$3d^5$	$^6S_{5/2}$	5.92	5.92	5.9
Fe^{2+}	$3d^6$	$^5D_4$	4.90	6.70	5.4
Co^{2+}	$3d^7$	$^4F_{9/2}$	3.87	6.54	4.8
Ni^{2+}	$3d^8$	$^3F_4$	2.83	5.59	3.2
Cu^{2+}	$3d^9$	$^2D_{5/2}$	1.73	3.55	1.9

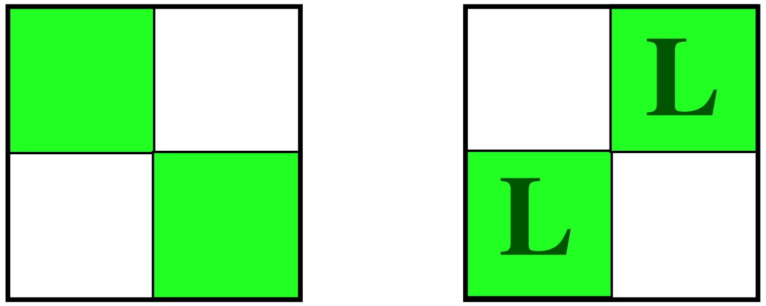
[a] Because of quenching, much better theoretical values are obtained by taking J equal to S, the total spin, than by taking the value $J = |L \pm S|$ appropriate to the free ion.

Source: J. H. Van Vleck, *The Theory of Electric and Magnetic Susceptibilities*, Oxford, 1952, p. 285; R. Kubo and T. Nagamiya, eds., *Solid State Physics*, McGraw-Hill, New York, 1969, p. 453.

N.W. Ashcroft and N.D. Mermin, 'Solid state physics', Holt, Rinehart and Winston, New York (1976).

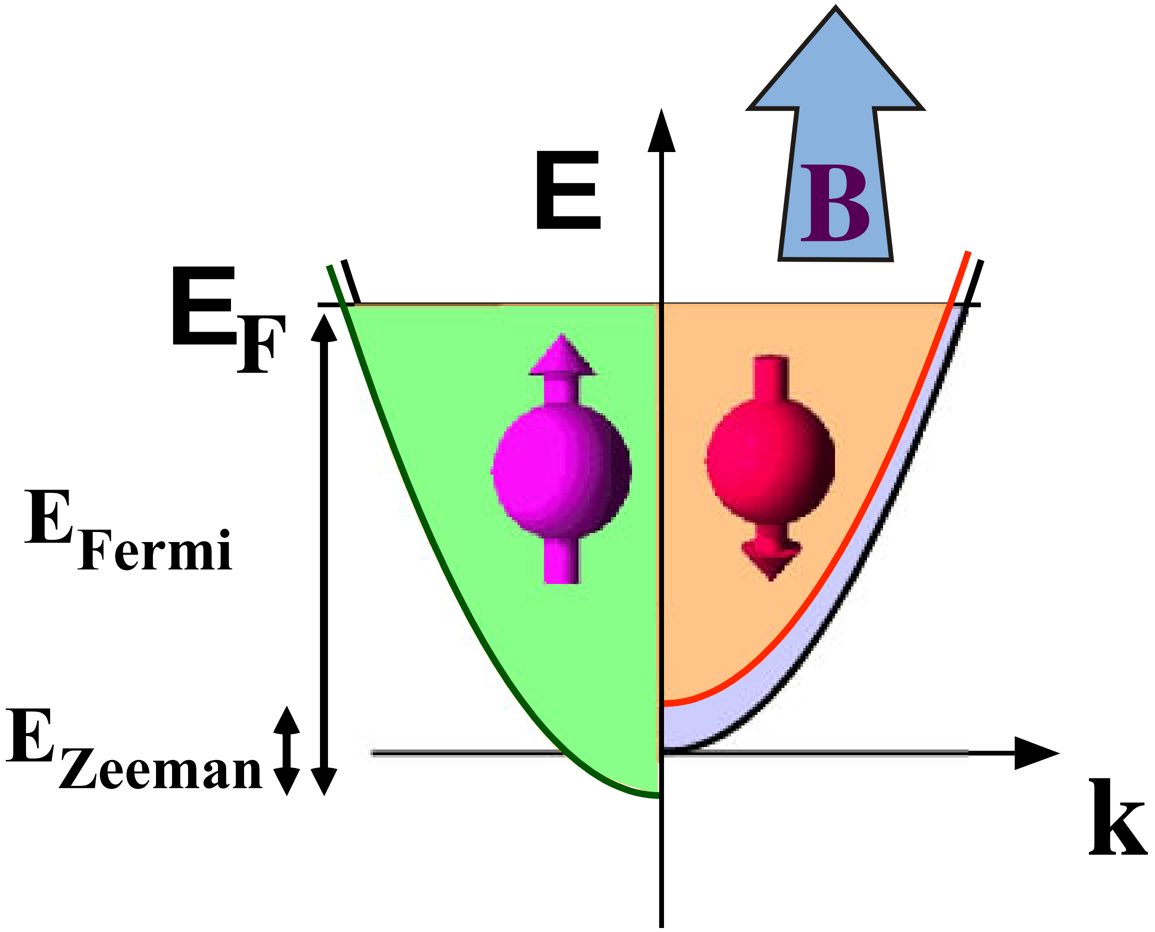
Magnetisierung als Störung

$$\mathbf{H} = V\, f(\vec{r}) + E_{kin}$$

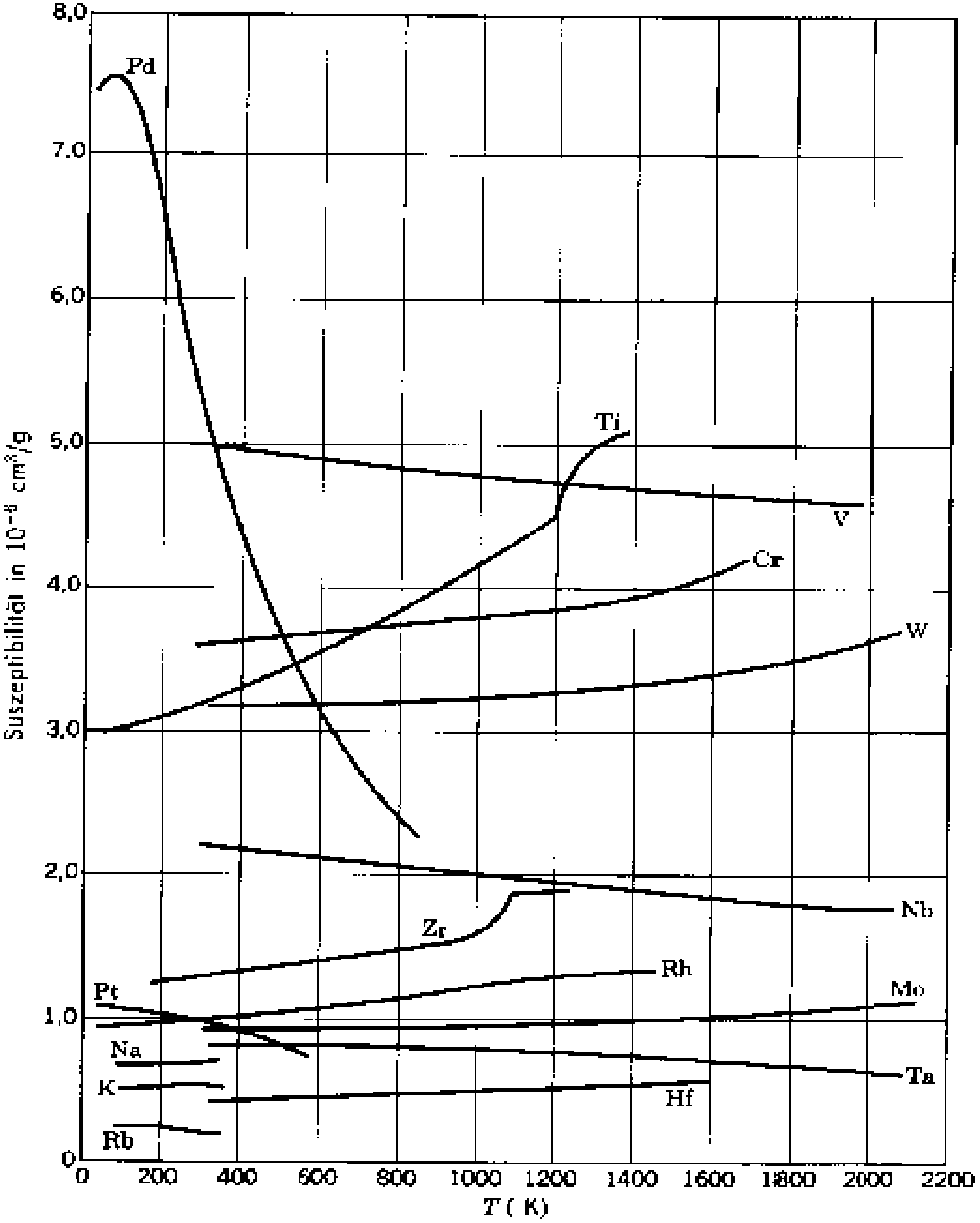


Paramagnetismus in Metallen

freie Elektronen



C. Kittel, '*Einführung in die Festkörperphysik*',
R. Oldenburg, München



Temperaturabhängigkeit der magnetischen Suszeptibilität von Metallen. (Mit freundlicher Genehmigung von C. J. Krisman.)

Temperaturabhängigkeit