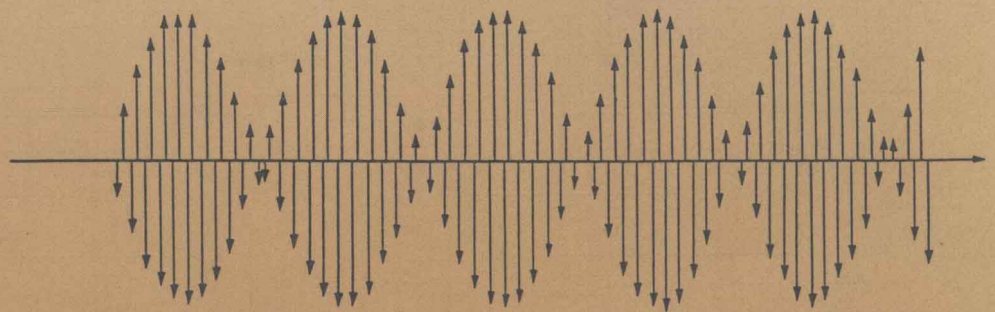


*Data in
Science and Technology*

Magnetic Properties of Metals

d-Elements, Alloys and Compounds



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Magnetic Properties of Metals

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Cover picture: Spin density wave in Cr (see Fig. 3 on page 3).

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Preface

During the last decades the knowledge of the magnetic properties of the d transition elements and of their metallic alloys and compounds has increased widely. The improvement of preparation techniques for well-defined substances, the development of sophisticated measuring methods and above all the drive to obtain more insight in the origin of magnetic interactions in solids have resulted in the publication of many specific magnetic properties for an abundance of all kinds of metallic materials.

The data assembled in this booklet are selected from the comprehensive compilation of magnetic and related properties of metals in the Landolt-Börnstein New Series Group III sub-volumes 19a, b and c. It has been attempted to include preferentially those properties which are of a basic character and which therefore are most often needed by scientists active in the field of solid state magnetism.

In the field of magnetism, there is a gradual transition from the use of cgs/emu units to SI units. It was, however, not intended to represent all data in the units of one system, regardless of how nice this would have been from a systematic point of view. Instead, mostly preference was given to the system of units that was originally used by the authors whose work is quoted. Thus cgs/emu units occur most frequently. Of course the user of the tables and figures is helped in several ways to convert the data to the units which he is most familiar with, see, e.g., the list of definitions, units and conversion factors for the magnetic quantities occurring most frequently.

Aachen, April 1991

The Editor

List of symbols

Symbol	Unit	Quantity
A	erg cm^{-3}	exchange stiffness constant
a, b, c	$\text{\AA}$	lattice parameters
B	bar	bulk modulus
C_g	$\text{cm}^3 \text{Kg}^{-1}$	Curie constant per unit mass
C_m	$\text{cm}^3 \text{K mol}^{-1}$	Curie constant per mole
C_p, C_v	cal K^{-1}	heat capacity at constant pressure/volume
D	$\text{eV \AA}^2$	spin wave stiffness constant
E_F	eV	Fermi energy
ΔE_Q	mm s^{-1}	quadrupole splitting
f	MG	dHvA frequency
g		spectroscopic splitting factor
g'		magnetomechanical ratio
H	Oe, Am^{-1}	magnetic field
H_{appl}	Oe, Am^{-1}	applied magnetic field
H_c	Oe	coercive field
H_{hyp}	Oe	magnetic hyperfine field
h_i		magnetostriction coefficient
h'_i	Oe^{-1}	forced magnetostriction coefficient
IS	mm s^{-1}	isomer shift
J	meV	exchange integral
K		Knight shift
K_i	erg cm^{-3}	magnetocrystalline anisotropy constant
k_F	$\text{\AA}^{-1}$	Fermi wavevector
k_B		Boltzmann constant
l	$\text{\AA}$	interatomic distance
M_s	G	spontaneous (saturation) magnetization
n		number of electrons per atom
p	kbar	pressure
p	μ_B	atomic magnetic moment in paramagnetic phase
p_{eff}	μ_B	atomic magnetic moment in paramagnetic phase, derived from Curie-Weiss law
$\bar{p}$	μ_B	average magnetic moment
$p_{\text{at}}(\bar{p}_{\text{at}})$	μ_B	(average) magnetic moment per atom
$p_{\text{ce}}(\bar{p}_{\text{ce}})$	μ_B	(average) conduction electron magnetic moment per atom
$\bar{p}_{\text{loc}}$	μ_B	average localized magnetic moment per atom
$p_M(\bar{p}_M)$	μ_B	(average) magnetic moment of atom M
p_{orb}	μ_B	orbital magnetic moment per atom
p_s	μ_B	spontaneous (saturation) magnetic moment per atom
Q	$\text{\AA}^{-1}$	spin density wavevector
Q	μVK^{-1}	thermoelectric power
R_H	$\Omega\text{cm G}^{-1}$	Hall coefficient
S		atomic long-range order parameter
S		Stoner enhancement factor
T	K, $^{\circ}\text{C}$	temperature
T_C	K	ferromagnetic Curie temperature
T_{ci}	K	commensurate-incommensurate transition temperature
T_M	K	martensitic transition temperature

Symbol	Unit	Quantity
T_m	K, °C	melting point temperature
T_N	K	Néel temperature
T_s	K	superconducting transition temperature; transition temperature between two types of magnetic order
T_{sf}	K	spin flip transition temperature
T_t	K	tetragonal phase transition temperature
t_a	s	annealing time
V	cm ³	volume
Z		atomic number
α	K ⁻¹	linear thermal expansion coefficient
α	rad, deg	Kerr effect
β	rad, deg	angle
γ	mJ mol ⁻¹ K ⁻²	electronic specific heat coefficient
γ	kHz G ⁻¹	gyromagnetic ratio
γ		fraction of 3d electrons in E_g state
δ		incommensurability parameter of spin density wave
δ		transverse (equatorial) Kerr effect
ϵ'_{ij}		real part of dielectric tensor element
ϵ''_{ij}		imaginary part of dielectric tensor element
Θ	K	paramagnetic Curie temperature
Θ_D	K	Debye temperature
θ	rad, deg	angle
λ	W cm ⁻¹ K ⁻¹	thermal conductivity
λ		electron-phonon interaction constant
λ	s ⁻¹	Landau-Lifshitz damping temperature
λ_s		linear saturation magnetostriction
λ_V		volume magnetostriction
μ_B		Bohr magneton
ν	Hz	frequency
ϱ	g cm ⁻³	density
ϱ	μΩ cm	electrical resistivity
ϱ_x	g cm ⁻²	X-ray density
σ	G cm ³ g ⁻¹	magnetic moment per unit mass
σ_m	G cm ³ mol ⁻¹	magnetic moment per mole
σ_s	G cm ³ g ⁻¹	spontaneous (saturation) magnetic moment per unit mass
ϕ	rad, deg	angle
χ_{ac}		magnetic ac susceptibility
χ_g	cm ³ g ⁻¹	magnetic mass susceptibility
χ_{HF}	cm ³ g ⁻¹	high-field magnetic susceptibility
χ_m	cm ³ mol ⁻¹	magnetic molar susceptibility
χ_o		temperature-independent contribution to paramagnetic susceptibility
χ_{orb}		orbital magnetic susceptibility
χ_{spin}		spin susceptibility
χ_{sp-orb}		spin-orbit interaction contribution to magnetic susceptibility
χ_V		magnetic volume susceptibility
ω		volume magnetostriction
$\partial\omega/\partial H$	Oe ⁻¹	forced volume magnetostriction

Definitions, units and conversion factors

In the SI, units are given for both defining relations of the magnetization, $B = \mu_0(H + M)$ and $B = \mu_0 H + M$, respectively. $\mu_0 = 4\pi \cdot 10^{-7} \text{ Vs A}^{-1} \text{ m}^{-1}$, A : molar mass, ρ : mass density.

Quantity	cgs/emu	SI	
B	$G = (\text{erg cm}^{-3})^{1/2}$ $1 \text{ G} \triangleq$	$T = \text{Vs m}^{-2}$ 10^{-4} T	
H	$\text{Oe} = (\text{erg cm}^{-3})^{1/2}$ $1 \text{ Oe} \triangleq$	Am^{-1} $10^3/4\pi \text{ Am}^{-1}$	
M	$B = H + 4\pi M$ G $1 \text{ G} \triangleq$	$B = \mu_0(H + M)$ Am^{-1} 10^3 Am^{-1}	$B = \mu_0 H + M$ T $4\pi \cdot 10^{-4} \text{ T}$
P	$P = MV$ G cm^3 $1 \text{ G cm}^3 \triangleq$	$P = MV$ Am^2 10^{-3} Am^2	$P = MV$ Vs m $4\pi \cdot 10^{-10} \text{ Vs m}$
σ	$\sigma = M/\rho$ $\text{G cm}^3 \text{ g}^{-1}$ $1 \text{ G cm}^3 \text{ g}^{-1} \triangleq$	$\sigma = M/\rho$ $\text{Am}^2 \text{ kg}^{-1}$ $1 \text{ Am}^2 \text{ kg}^{-1}$	$\sigma = M/\rho$ Vs m kg^{-1} $4\pi \cdot 10^{-7} \text{ Vs m kg}^{-1}$
σ_m	$\sigma_m = \sigma A$ $\text{G cm}^3 \text{ mol}^{-1}$ $1 \text{ G cm}^3 \text{ mol}^{-1} \triangleq$	$\sigma_m = \sigma A$ $\text{Am}^2 \text{ mol}^{-1}$ $10^{-3} \text{ Am}^2 \text{ mol}^{-1}$	$\sigma_m = \sigma A$ Vs m mol^{-1} $4\pi \cdot 10^{-10} \text{ Vs m mol}^{-1}$
χ	$P = \chi H$ cm^3 $1 \text{ cm}^3 \triangleq$	$P = \chi H$ m^3 $4\pi \cdot 10^{-6} \text{ m}^3$	$P = \chi \mu_0 H$ m^3 $4\pi \cdot 10^{-6} \text{ m}^3$
χ_v	$\chi_v = \chi/V$ $\text{cm}^3 \text{ cm}^{-3}$ $1 \text{ cm}^3 \text{ cm}^{-3} \triangleq$	$\chi_v = \chi/V$ $\text{m}^3 \text{ m}^{-3}$ $4\pi \text{ m}^3 \text{ m}^{-3}$	$\chi_v = \chi/V$ $\text{m}^3 \text{ m}^{-3}$ $4\pi \text{ m}^3 \text{ m}^{-3}$
χ_g	$\chi_g = \chi_v/\rho$ $\text{cm}^3 \text{ g}^{-1}$ $1 \text{ cm}^3 \text{ g}^{-1} \triangleq$	$\chi_g = \chi_v/\rho$ $\text{m}^3 \text{ kg}^{-1}$ $4\pi \cdot 10^{-3} \text{ m}^3 \text{ kg}^{-1}$	$\chi_g = \chi_v/\rho$ $\text{m}^3 \text{ kg}^{-1}$ $4\pi \cdot 10^{-3} \text{ m}^3 \text{ kg}^{-1}$
χ_m	$\chi_m = \chi_g A$ $\text{cm}^3 \text{ mol}^{-1}$ $1 \text{ cm}^3 \text{ mol}^{-1}$	$\chi_m = \chi_g A$ $\text{m}^3 \text{ mol}^{-1}$ $4\pi \cdot 10^{-6} \text{ m}^3 \text{ mol}^{-1}$	$\chi_m = \chi_g A$ $\text{m}^3 \text{ mol}^{-1}$ $4\pi \cdot 10^{-6} \text{ m}^3 \text{ mol}^{-1}$

List of abbreviations

AF	antiferromagnetic
AF ₀	commensurate spin density wave state
AF ₁	transverse incommensurate spin density wave state
AF ₂	longitudinal incommensurate spin density wave state
bcc	body-centered cubic
CAF	commensurate spin density wave state
dhcp	double hexagonal close-packed
dHvA	de Haas-van Alphen
F	ferromagnetic
fcc	face-centered cubic
GM	giant magnetic moment
hcp	hexagonal close-packed
IRM	isothermal remanent magnetization
I-SDW	incommensurate spin density wave
KS	Kohn-Sham potential
L	Lifshitz point
L-SDW	longitudinal spin density wave
MAG	magnetization
NMR	nuclear magnetic resonance
P	paramagnetic
RKKY	Rudermann-Kittel-Kasuya-Yosida
RT	room temperature
SDW	spin density wave
SG	spin glass
TQ	magnetic torque measurement method
T-SDW	transverse spin density wave
vBH	von Barth-Hedin exchange correlation potential

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1 3d elements

1.1 Ti, V, Cr, Mn

Survey

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		$\chi_g(T)$	9	

1.1.1 Ti

Titanium metal is a Pauli paramagnet; no localized magnetic moments have been observed. Since Ti becomes superconducting below 0.4 K, probably no magnetic ordering occurs.

The crystallographic structure of α -Ti, the most stable phase at room temperature, is hexagonal; in single crystals the magnetic susceptibility is therefore a function of the angle between the direction of the magnetic field and the c axis.

Next to α -Ti, there are two other phases of Ti known: β -Ti, with a body-centered cubic crystallographic structure, which is stable above 1155 K [56 M 1], and ω -Ti, with a hexagonal crystallographic structure, stable only under high pressure, but metastable at pressure zero [74 D 1].

1.1.2 V

Vanadium metal is a Pauli paramagnet. Neutron diffraction measurements revealed no localized magnetic moments; if they exist they are smaller than $0.01 \mu_B$ [77 A 1]. Since vanadium becomes a superconductor at 5.265 K, probably no magnetic ordering occurs.

Vanadium has a body-centered cubic crystallographic structure; the magnetic susceptibility is isotropic, and a smooth function of temperature above the superconducting transition, see Fig. 2; it is possible that χ shows a very shallow maximum between 100 K and 200 K [65 K 1]. A good room temperature value is: $\chi_g = 7.3 \cdot 10^{-8} \text{ m}^3/\text{kg}$.

Sometimes discontinuities have been observed in the susceptibility and other physical properties of V at temperatures between 120...240 K. Rostoker and Yamamoto [55 R 1] observed a crystallographic transition at -30°C ; this has not been confirmed by later investigations. Kostina [71 K 1] found a peak in the susceptibility at 240 K, and corresponding anomalies in the resistivity and the Hall effect. Kondorskii [73 K 1] found two peaks, respectively at 120 K and 190 K, and corresponding anomalies in the magnetostriction and thermal expansion.

The nature of these not very reproducible anomalies, which were sometimes interpreted as a hypothetical antiferromagnetic Néel point, is at the moment not understood.

The magnetomechanical ratio of vanadium is $g' = 1.18(10)$ [71 H 1].

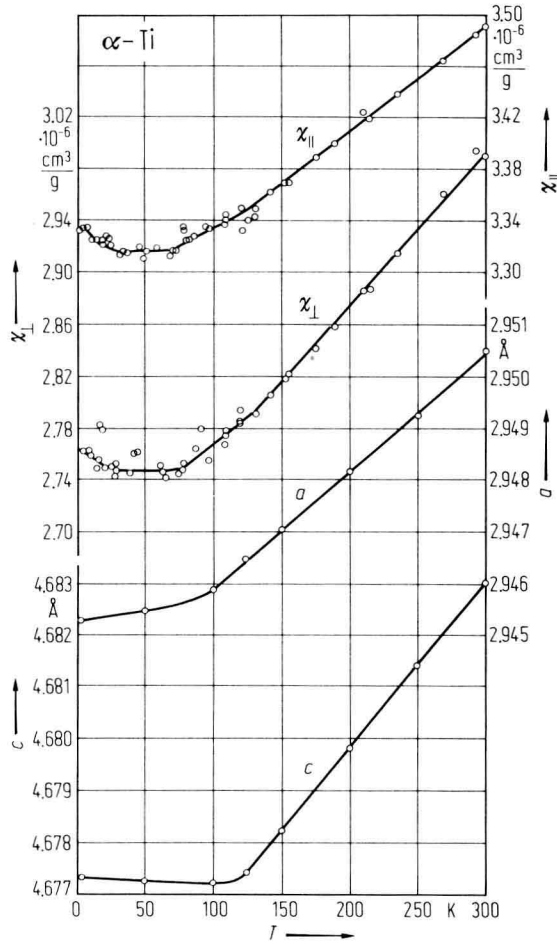


Fig. 1. Temperature dependence of the magnetic mass susceptibility χ_g of a single crystal of pure α -Ti compared with the temperature dependences of the lattice parameters a and c [67 E 1]. The susceptibility of Ti is seen to be practically temperature-independent up to about 70 K. The low-temperature upturn is accountable to a trace of dissolved Mn [71 C 1].

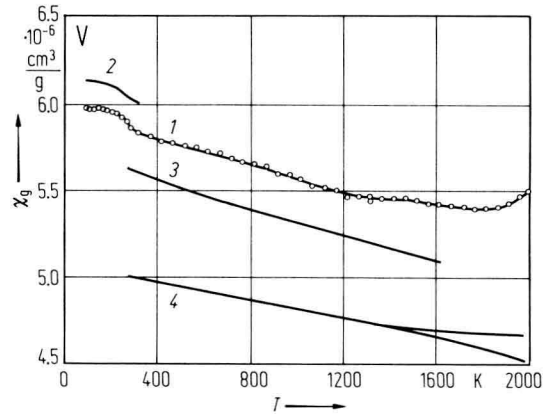


Fig. 2. Temperature dependence of the magnetic mass susceptibility χ_g for polycrystalline V. Curve 1: [65 K 1], sample impurities, in [wt%]: 0.032 C; 0.07 O₂; 0.031 N₂; 0.001 H₂; others < 0.095. 2: [61 B 1]. 3: [62 T 1]. 4: [53 K 1].

1.1.3 Cr

The crystallographic structure of chromium metal is body-centered cubic, and its magnetic structure is very peculiar. Chromium is antiferromagnetic at temperatures below the Néel point (T_N) of about 312 K. This antiferromagnetism is, however, not caused by local magnetic moments aligning themselves antiparallel; Overhauser [62 O 1] showed that the antiferromagnetic ordering in chromium may be described by a *spin density wave* in the itinerant 3d-electrons, having a wavelength incommensurate with the lattice constant. Whereas in some other substances spin density waves only exist as excitations, in Cr metal at low temperatures the ground state is a spin density wave with a finite amplitude, see Fig. 3.

Analytically, the magnetic moment per atom in antiferromagnetic Cr, as a function of the position in space, $\mathbf{R}$, is given by:

$$\mathbf{S}(\mathbf{R}) = \mathbf{S}_1 \cos(\mathbf{Q} \cdot \mathbf{R}) + \mathbf{S}_3 \cos(3\mathbf{Q} \cdot \mathbf{R}) + \dots,$$

where the main amplitude of the magnetic moment, $\mathbf{S}_1$, has a value of about $0.6 \mu_B$ at low temperatures, and a value of about $0.2 \mu_B$ just below T_N [65 A 1]. $\mathbf{S}_1$ is always directed along one of the cube axes of the body-centered cubic crystal lattice; $\mathbf{S}_3$ is always directed opposite to $\mathbf{S}_1$, and has an absolute value of a few percent of $\mathbf{S}_1$, the “spin density wave” $\mathbf{S}(\mathbf{R})$ is therefore somewhat more “rectangular-like” than a pure sine function, see [81 I 1].

Accurate measurements show no detectable hysteresis of the Néel point T_N in well-annealed, pure Cr [80 W 2]; T_{sf} has a hysteresis of about 1 K [82 B 1].

Free energy expressions, dependent on the applied field and/or the strain, are given by [81 B 1] (near T_{sf}) and [80 W 1] (near T_N).

Surface magnetization of Cr has been mentioned by [82 S 1].

The magnetic anisotropy torque of Cr in the $3Q$ -state, and of Cr in the $1Q$ -state, was measured by [64 M 1].

It appears that both at T_N and T_{sf} chromium has a first-order phase transition [65 A 1]. The latent heat of transition at T_{sf} is $0.04(2)$ J/mol [82 B 1].

The relative change in the volume at T_{sf} is $-1.4(6) \cdot 10^{-6}$ [69 S 1]; at T_N the change in volume could not be measured due to a change in the thermal expansion, it can be calculated to be about $-2 \cdot 10^{-5}$.

In the $1Q$ -state, chromium shows a tetragonal or, depending on the previous treatment, an orthorhombic deformation (or magnetostriction) of the order of magnitude 10^{-5} [69 S 1].

The magnetomechanical ratio of chromium metal is $g' = 1.21(7)$ [71 H 1].

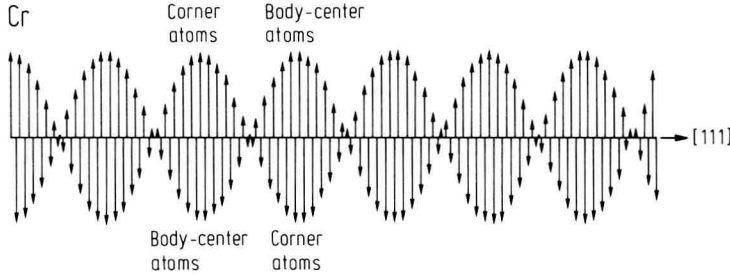


Fig. 3. Spin density wave in Cr [81 F 1]. The magnetic moments of two successive atoms on the body-diagonal of the cubic lattice are antiparallel. The magnitude of the atomic moments on each sublattice is given by a sinusoidal function of the position.

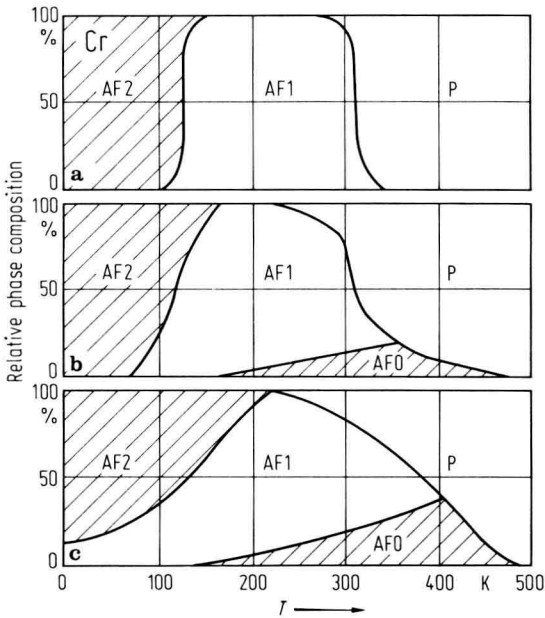


Fig. 4. Magnetic phase diagram in Cr for (a) annealed sample, (b) swaged sample, and (c) crushed powder sample [81 W 1]. P: paramagnetic, AF0: commensurate, $Q = 2\pi/a$, AF1: transverse incommensurate, AF2: longitudinal incommensurate.

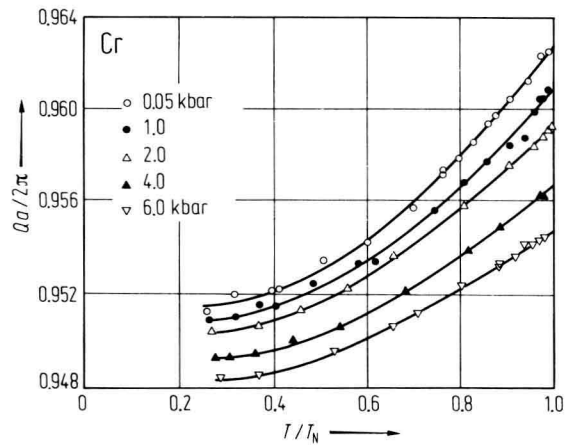


Fig. 5. Temperature dependence of the relative length $Qa/2\pi$ of the spin density wavevector for Cr as a function of the reduced temperature T/T_N , at various pressures [68 U 1].

Table 1. Data for the magnetic period of the spin density wave in Cr, based on the position of the (100) satellite lines in the neutron diffraction spectrum [64 K 1]. Q : spin density wavevector, $\delta^{-1} = (1 - Qa/2\pi)^{-1}$: length of antiferromagnetic modulation, see Fig. 3, divided by lattice constant a .

	T K	$Qa/2\pi$	δ^{-1}
Cr	197	0.9554	22.4(8)
	78	0.9519	20.8 *
Cr – 0.45 at% V	197	0.9480	19.2(8)
	78	0.9431	17.6(8)

*) [62 S 1].

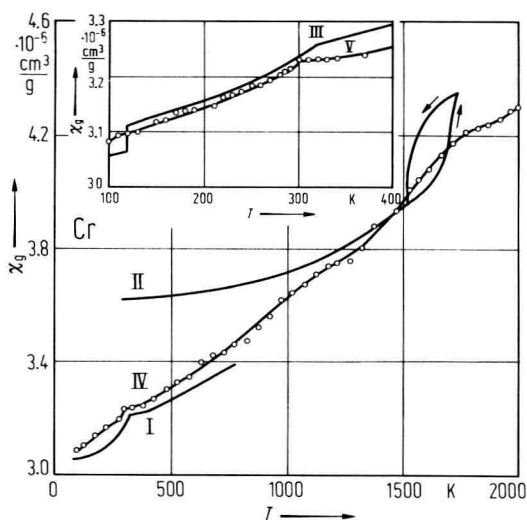


Fig. 6. Temperature dependence of the magnetic mass susceptibility χ_g for polycrystalline Cr. I: [58 L 1]; II: [52 M 1]; III: [64 M 2]; IV and V: [64 W 1].

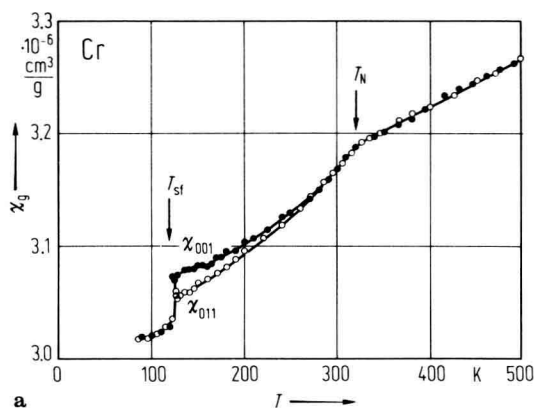
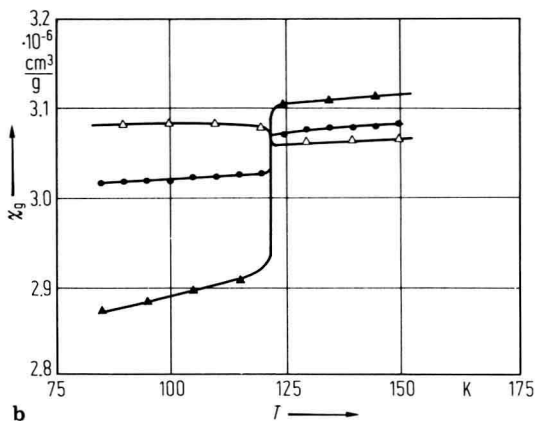


Fig. 7. Temperature dependence of the magnetic mass susceptibility χ_g of single-crystal Cr. (a) Cr cooled in zero applied field; χ_{001} and χ_{011} refer to measurements along cube edges and face diagonals, respectively.



(b) Cr cooled through T_N in an applied flux density of 5 T acting along [001]. Open triangles: measurements along [010]; solid triangles: measurements along [001]; solid circles: measurements along cube edge for Cr cooled in zero applied field, included for comparison [66 P 1].

1.1.4 Mn

The phase of manganese metal which is stable at room temperature, α -Mn, has probably the most complex crystallographic and magnetic structure of all elements. α -Mn has a cubic crystallographic symmetry, the cubic unit cell contains no less than 58 Mn atoms, distributed over 4 nonequivalent sites; the configuration of the surrounding of each site by the other Mn atoms is unique for each of the 4 different sites.

Below the Néel temperature $T_N = 95$ K, α -Mn is antiferromagnetic; since the magnitudes of the magnetic moments of the Mn atoms on different sites are highly different, an antiferromagnetic ordering can only be achieved if the atoms of each site order antiferromagnetically among themselves; the magnetization vectors of the 4 different sublattices are not collinear. This structure, which has been analyzed by Yamada in 1970 [70 Y 1–3], is depicted in Fig. 8.

From antiferromagnetic resonance measurements, Yamagata [72 Y 1] concluded that the site II atoms are divided into two subtypes (each 4 atoms/cubic cell) with a magnetic moment of $1.84 \mu_B$ and $1.75 \mu_B$, respectively; also for sites III and IV the situation is probably more complicated than depicted above.

The magnetic susceptibility of α -Mn is only slightly temperature-dependent; it shows a broad maximum above the Néel point, but no anomaly near T_N , see Fig. 9. A good room temperature value is $\chi_g = 11.7 \cdot 10^{-8} \text{ m}^3/\text{kg}$. A weak ferromagnetism, often observed below 45 K, is probably due to contamination of the sample with Mn_3O_4 [70 Y 3].

In antiferromagnetic- α -Mn the differential magnetic susceptibility increases by about 50% above its low-field value, if the applied field exceeds 11 T; this effect can possibly be interpreted as a change in the angle between the antiferromagnetic vectors of atoms on two different sites.

In paramagnetic α -Mn, the contributions of the different sites to the susceptibility has been analyzed by an interpretation of NMR measurements [81 M 1, 81 M 2]; the susceptibility of a site I atom is about twice that of a site II atom; the susceptibility of site III and site IV atoms is relatively small. Since there are four times as many site II as site I atoms, the major part of the total susceptibility is due to site II atoms.

In the temperature range $45 \text{ K} \leq T < T_N$ the principal axis of the magnetic symmetry is along a [100] direction [70 Y 3].

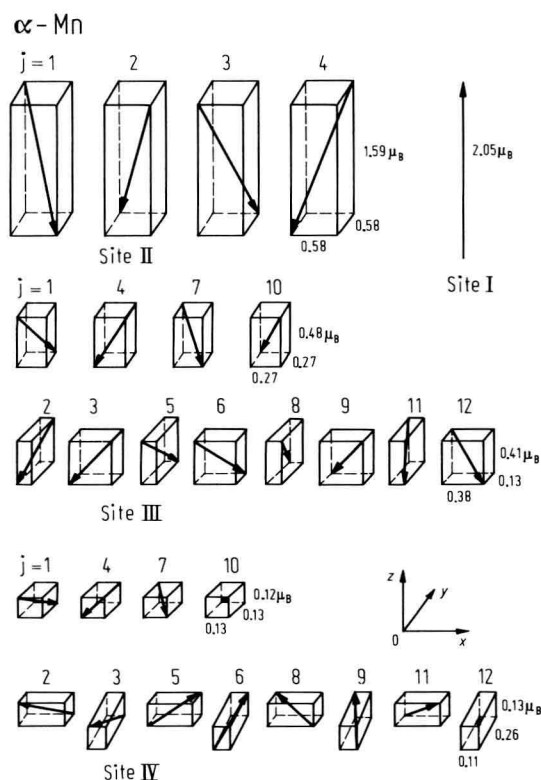


Fig. 8. Magnetic structure of α -Mn below 95 K as determined by Yamada. Vectors represent the magnetic moment for each of the 29 atoms in the primitive unit cell. The edges of the right prisms give, in units $[\mu_B]$, the components of the magnetic moment in, respectively, the x , y , z directions. Integers j number the atoms for each of the crystallographic sites I...IV [70 Y 1–3].

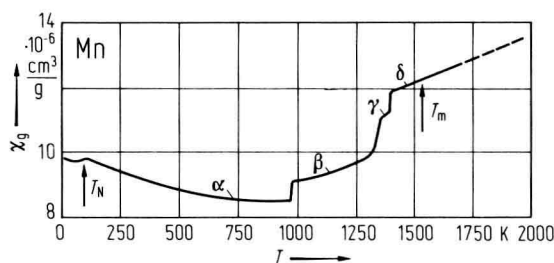


Fig. 9. Magnetic mass susceptibility χ_g vs. temperature for the various phases of Mn metal. T_N : Néel temperature; T_m : melting point [69 K 1].

Table 2. Low-temperature values of the magnetic moments p_{Mn} on the various atom sites in α -Mn [70 Y 2].

Site	Atoms/cubic cell	$p_{Mn} [\mu_B]$
I	2	1.9
II	8	1.7
III	24	0.6
IV	24	0.25

1.1.5 References for 1.1

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