Unit-4

Magnetic Properties of Materials
Magnetic and Non-Magnetic Substances

The examination of the configuration of the first 103 elements of Mendeleev's periodic table shows that 79 atoms possess a magnetic moment in a fundamental state.
The following are not magnetic:

− the elements of the 2nd column (Be, Mg, Ca, Sr, Ba, Ra), of the 12th column (Zn, Cd, Hg), of the 14th (C-in $^3P_0$, Si, Ge, Sn, Pb);
− elements W ($^5D_0$) and Pd and those of the rare earths: Sm ($^7F_0$) and Yb ($^1S_0$) etc.

H																	He
Li	**Be**											B	C	N	O	F	Ne
Na	**Mg**											Al	Si	P	S	Cl	Ar
K	**Ca**	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	**Zn**	Ga	Ge	As	Se	Br	Kr
Rb	**Sr**	Y	Zr	Nb	Mo	*Tc*	Ru	Rh	**Pd**	Ag	**Cd**	In	Sn	Sb	Te	I	Xe
Cs	**Ba**	La	Hf	Ta	**W**	Re	Os	Ir	Pt	Au	**Hg**	Tl	Pb	Bi	Po	At	Rn
Fr	*Ra*	*Ac*															

			Ce	Pr	Nd	*Pm*	**Sm**	Eu	Gd	Tb	Dy	Ho	Er	Tm	**Yb**	Lu
			Th	*Pa*	U	*Np*	*Pu*	*Am*	*Cm*	*Bk*	*Cf*	*Es*	*Fm*	*Md*	*No*	*Lw*

Fig: Non magnetic elements (bold framed). The radioactive atoms are shown in italics.

On the contrary, as soon as the atoms are integrated into a solid substance, due to (molecular, metallic….) links obtained by putting together electrons coming from different components on the same orbit, only a small number of atoms are carriers of a permanent magnetic moment in the absence of the magnetic field.
Thus, let us consider the simplest case, the one-electron atom: the atomic hydrogen is magnetic. But the molecule of hydrogen H_2 does not possess magnetic properties in   a fundamental state. The two electrons are found on the same orbit, with a null kinetic moment, with the spin oriented in contrary directions. In the same way, in the case of methane CH_4, the settlement together two electrons on each of the 4 orbits of the links C-H makes hydrogen lack magnetic properties.

H

He
dia

Li para | Be dia — B dia | C dia | N dia | O AF | F dia | Ne dia

Na para | Mg para — Al para | Si dia | P dia | S dia | Cl dia | Ar dia

K para | Ca para | Sc para | Ti para | V para | Cr AF | Mn AF | Fe Ferro | Co Ferro | Ni Ferro | Cu dia | Zn dia | Ga dia | Ge dia | As dia | Se dia | Br dia | Kr dia

Rb para | Sr para | Y para | Zr para | Nb para | Mo para | Tc | Ru para | Rh para | Pd para | Ag dia | Cd dia | In dia | Sn * | Sb dia | Te dia | I dia | Xe dia

Cs para | Ba | La | Hf | Ta para | W para | Re para | Os para | Ir para | Pt para | Au dia | Hg dia | Tl dia | Pb dia | Bi dia | Po | At | Rn dia

Fr | Ra | Ac

Ce * | Pr para | Nd AF | Pm | Sm AF | Eu Ferri | Gd Ferro | Tb Ferro | Dy Ferro | Ho Ferri | Er Ferri | Tm Ferri | Yb para | Lu para

Th para | Pa | U para | Np | Pu | Am | Cm | Bk | Cf | Es | Fm | Md | No | Lw

Fig: The magnetic properties of pure elements in a solid state at low temperature. Bold framed elements are magnetically ordered substances: Ferro-Ferromagnetic; Ferri-Ferrimagnetic ; AF-Antiferromagnetic.
The substances painted grey are superconductors at very low temperature and those in italics are radioactive.

Similarly, while the free electrons of Na and Cl are magnetic, they no have the same characteristics in an ionic state Na^+ and Cl^-. Kitchen salt NaCl does not have magnetic properties.

Among the elements that posses a magnetic moment, very few are ferromagnetic and ferrimagnetic.

The ferromagnetic elements are: Fe, Co, Ni (series 3d) as well as some metals of series 4f of rare earths (Gd, Tb, Dy). In addition, the magnetic character can depend on the crystallographic structure: in phase c.c, iron ($\alpha - Fe$) is ferromagnetic up to 300K, while in the phase cfc ($y - Fe$) its magnetic moment is very sensitive to intra-atomic distances and to the atoms around it, namely to the substance to which it belongs.

The table in Fig shows the values of magnetic moments of atoms of Fe, at 0K and for H=0 in various materials.

Compound	$\gamma - Fe_2O_3$	$\alpha - Fe$ c.c.	YFe_2 c.f.c.	$\gamma - Fe$	YFe_2Si_2
Type	Ferri	Ferro	Ferro	AF	-
$N_{Fe}(\mu_B)$	5,0	2,2	1,45	instable	0

Fig: The magnetic moment

$N_{Fe}(\mu_B)$ of Fe atoms, at 0K and H=0 in various materials. μ_B is the Bohr magneton:

$$1\mu_B = 0.9274 \times 10^{-23} A \cdot N^2$$

In Romania the Bohr magneton μ_B is noted μ_{BP} because the romanian physicist Stefan Procopiu had major contributions in determining this value. The academician Stefan Procopiu was professor and head of the department at "Alex.I Cuza" University Jassy, Romania.

There are even ferromagnetic materials in which each of the components does not present ferromagnetism in a pure state.

In particular, the alloy Heusler Cu_2MnAl is ferromagnetic to 710K, while Cu is diamagnetic, Mn is antiferromagnetic and Al is paramagnetic. Only the quantic theory allows one to interpret such a surprising behavior.

To conclude, there are 15 elements whose atoms are magnetic moments in the absence of the field. These are elements 3d: Cr, Mn, Fe, Co and Ni, as well as most of elements 4f, rare earths, called lanthanides (Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm). O and Nd are AF.

Mention must be made of another series, that of actinides, characterized by the occupation of group 5f, even if it is less studied since most of these elements are radioactive.

CLASSIFICATION OF MAGNETIC SUBSTANCES

By appropriate methods we can measure the bulk magnetic properties of any substance and classify that substance as diamagnetic, paramagnetic, or ferromagnetic, etc.

All substances magnetize more or less in the external magnetic field. In order to characterize the magnetization of a substance the magnetization vector $\vec{M}$ is introduced:

$$\vec{M} = \frac{\Delta \vec{N}}{\Delta V} \ , \ (1)$$

defined as magnetic moment $\Delta \vec{N}$ of the volume unit. ΔV is the volume element.

At the same time, magnetization is equal to the vectorial sum of the magnetic moments $\vec{\mu}_i$ of atoms or molecules, per volume unit:

$$\vec{M} = \sum_i \vec{\mu}_i \quad (2)$$

Experimentally, it is shown that magnetization $\vec{M}$:

$$\vec{M} = \vec{M}_p + \vec{M}_t \quad (3)$$

is the sum between permanent magnetization $\vec{M}_p$ and temporary magnetization of substances $\vec{M}_t$. Permanent magnetization is a characteristic of permanent magnets, for all the other substances $\vec{M}_p = 0$.

The law of temporary magnetization, experimentally established , shows that in magnetic fields which are not very intense and if the materials have linear response, are homogeneous and isotropic :

$$\vec{M}_t = \chi^m \vec{H} \quad (4)$$

in which χ^m represents the magnetic susceptibility of the substance. χ^m represent a dimensionless scalar in SI units.

According to magnetic properties and the values of magnetic susceptibility, substances are divided into three important groups: diamagnetic, paramagnetic, and ferromagnetic. In addition, there are ferri and antiferromagnetic substances.

The microscopic interpretation of magnetic properties of bodies is based on the magnetic properties of atoms, of molecules, and of their constitutive parts: orbital magnetic moments and of spin of electrons, nuclear magnetic moments etc.

The magnetic properties in which we are interested are due entirely to the electrons of the atom which have a magnetic moment associated with the corresponding kinetic moment of their motion. The nucleus also has a small magnetic moment, but it is insignificant compared to that of the electrons, and it does not affect the dia, para and ferromagnetic properties.

DIAMAGNETIC SUBSTANCES

GENERAL CHARACTERISTICS

Diamagnetic substances have magnetic susceptibility $\chi^m < 0$.

They are characterized by very weak magnetic properties ($|\chi^m \ll 1|$)

Material	χ^m
Si	$-1,2 \cdot 10^{-6}$
Cu	$-1,08 \cdot 10^{-6}$
Zn	$-1,9 \cdot 10^{-6}$
Ge	$-1,5 \cdot 10^{-6}$
Se	$-4,0 \cdot 10^{-6}$
Ag	$-2,4 \cdot 10^{-6}$
Pb	$-1,4 \cdot 10^{-6}$
Al$_2$O$_3$	$-3,5 \cdot 10^{-6}$

Fig: The magnetic susceptibility values of some diamagnetic substances)

The atoms of diamagnetic substances have a null atomic magnetic moment: $\vec{\mu}_i = 0.$. Diamagnetic substances are divided into classical, anomalous, and superconductive substances. Some classical diamagnetic substances are: inert gases, some metals (Cu, Ag, Au, Zn, Ga, In, Sb, As, etc.), elements such as silicon and phosphorous, many organic compounds. For these substances 3^N has an absolute reduced value of order $(0.1 - 10) \cdot 10^{-6}$ and it does not depend on the temperature. In the second subgroup of diamagnetic anomalous substances there are bismuth, antimony, graphite etc. For these substances, 3^N depends on the temperature and it allows absolute values of the order $(1 - 100) \cdot 10^{-6}$.

Diamagnetism is due to the orbital movement of electrons, movement caused by the applied magnetic field. This movement can be considered as a microscopic current whose behavior would be comparative with that of the current in a solenoid. According to Lenz's law, the induced current opposes to the current which produces it: $3^N < 0$.
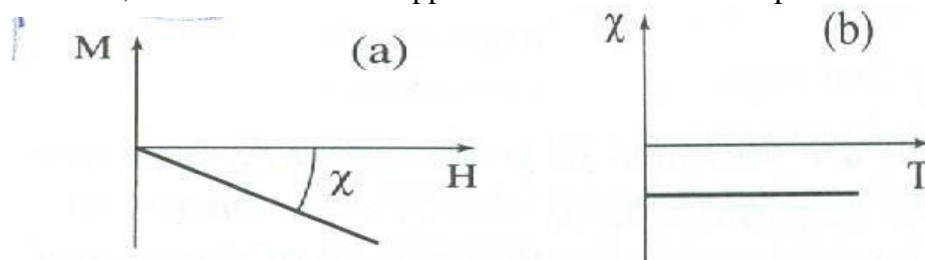
Fig: Dependence of the magnetization $\vec{\overline{M}}$ on the magnetic field intensity H, $\vec{M}$(H) and the dependence of magnetic susceptibility 3 on temperature T for most of diamagnetic substances 3(T). Attention, in this graph diamagnetic susceptibility is noted by 3

To sum up, rare gases, most metalloids, a large number of organic compound are diamagnetic substances.

As shown in table magnetic susceptibility of diamagnetic substances $3^N \cong 10^{-5}-10^{-6}$, therefore the interest for applications **was limited.**

But, strong diamagnetism is present in superconducting substances with a susceptibility equal to -1, which properties are associated with increasing number of technological applications.

Technological applications of superconducting diamagnetic substances .

Technological applications of superconductivity exceeds at this moment the initial predictions including an impressive number of realizations: motors and generators; low power cables; devices for the rapid limitation of electrical current defects; superconducting materials coils can generate magnetic fields with 6-14T (He liquid temperature). In high-performance cryostats, using low-temperature superconductors, values above 20 T can be achieved; sensitive magnetometers whose production is based on fast SQUIDs digital circuits; the strong superconducting electromagnets used in Maglev trains with levitation; magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR); machines for magnetic confinement fusion reactors; targeting beams and focus magnets used in particle accelerators; RF and microwave filters (for mobile stations and ultra-sensitive / selective military receivers); sensitive particle detectors including the transition edge sensor (TES), tunnel- effect detectors; superconducting bolometer, electromagnetic energy and thermal radiation detection devices of brilliance of the stars; Biomagnetism: for an infinite magnetic field of very high intensity, the hydrogen molecules are excited and release the received energy, which is subsequently processed in an image (magnetic resonance imaging machine); Computer science: it is speculated the appearance of microprocessors with a frequency of 4000 times larger than current processors, etc.

CLASSICAL THEORY OF DIAMAGNETISM

Diamagnetism consists in inducing of a magnetic moment in the electronic shells of atoms, under the action of an exterior magnetic field. That is why it is a general property of all substances: all bodies are diamagnetic, but it is noticed only when it is not masked by para and ferromagnetic effects, which are much stronger.

The classical interpretation of diamagnetism, given by Langevin, is based on Larmor theory which states that, in the presence of magnetic field of intensity $\vec{H}$ and induction $\vec{B}$, the movement of an electron in the atom results from two simultaneous movements: the movement on the orbit in the absence of magnetic field $\vec{H}$, to which a precession movement of the orbital kinetic moment (and of its orbit) is added, around the direction of the field, with a pulsation called Larmor pulsation m_L:

$$m_L = \frac{m_e}{B} = \mu_0 \cdot \frac{eK}{2N} \quad (5)$$

$\vec{B} = \mu_0\vec{H}$, μ_0 is vacuum permeability or permeability of free space and is: $\mu_0 = 4n \cdot 10^{-7}$ H/N
in the system SI of units.

If the atom contains Z electrons, the latter's precession around the magnetic field $\vec{H}$ is equivalent to a circular electric current whose axis is the direction of $\vec{H}$. The magnetic moment induced by this electric current is:

$$\mu_d = I \cdot S = \frac{e}{T} \cdot S \quad (6)$$

in which S is the area of the projection of the orbit of the electron on a plan perpendicular on induction $\vec{B}$, I is the intensity of the supplementary electric current due to pulsation Larmor, and

$T = \frac{2n}{m_L}$ is the period corresponding to this pulsation. Since $S = n\bar{R}^2$, where $\bar{R}$ is the projection of

the radius of the electronic orbit on a plan perpendicular on $\vec{B}$, for an electron it results:

$$\mu_d = \mu_0 \cdot \frac{e^2 K}{4N} \cdot \bar{R}^2 \ ; \ \mu_{di} = \mu_0 \cdot \frac{e^2 K}{4N} \cdot \bar{R}_i^2 \quad (7)$$

In the volume unit there are N atoms, and every atom has Z electrons, the magnetization of the diamagnetic substances being:

$$\vec{M}_d = N \cdot \sum_1^Z \vec{\mu}_{di} = \mu_0 \cdot N \cdot \frac{e^2 \vec{K}}{4N} \cdot \sum_1^Z \bar{R}_i^2 \quad (8)$$

Diamagnetic susceptibility: 0

$$\chi_d^N = \frac{M_d}{K} = \mu_0 \cdot \frac{Ne^2}{4N} \sum_1^Z \bar{R}_i^2 \quad (9)$$

If one considers that the distribution of the electronic charge in the atom has a spherical

symmetry, $\overline{R}_i^2 = \frac{2}{3} \cdot \overline{r}_i^2$, where $\overline{r}_i^2$ is the medium value of the square of the distance between the

electron and the nucleus, relation (7.9) is written:

$$\chi_d^N = \mu_0 \cdot \frac{N_e^2}{6N} \cdot \sum_1^Z \overline{r}_i^2$$

The formula is valid, on condition that quantity $\sum_1^Z \overline{r}_i^2$ does not vary due to the thermal

agitation of the atoms. In this case χ_d^N does not depend on the temperature. The experience verifies this result for diamagnetic classical substances, but for the anomalous ones χ_d^N depends
on the temperature. The dependence on temperature is explained by the fact that in general $\sum_1^Z \overline{r}_i^2$

is not stationary, but it depends on the thermal agitation of atoms.

The quanta theory of diamagnetism was elaborated by Van Vleck (1932), who found a similar result for the atoms or the molecules whose electronic shell has a spherical symmetry. In addition, quantic theory allows one the calculation of magnetic susceptibility for more general cases, when the symmetry of the electronic shell is not spherical.

PARAMAGNETIC SUBSTANCES

GENERAL CHARACTERISTICS

Paramagnetic substances are characterized by $\chi^N > 0$, but the values χ^N are small, in the range ($10^{-6} - 10^{-3}$).

Paramagnetism is specific to the substances whose atoms possess a permanent magnetic moment, if these moments are not coupled one to another ($\mu_i \neq 0$).

Material	χ_m
Na	$8,6 \cdot 10^{-6}$
Al	$7,7 \cdot 10^{-6}$
Mn	$1,2 \cdot 10^{-6}$
Ta	$1,1 \cdot 10^{-6}$
W	$3,5 \cdot 10^{-6}$
Pt	$1,2 \cdot 10^{-5}$
U	$3,3 \cdot 10^{-5}$
CoO	$0,75 \cdot 10^{-3}$
Fe$_3$C*	$3,7 \cdot 10^{-5}$
Fe*$_y$	$2,5 \cdot 10^{-5}$

Fig: The magnetic susceptibility values of some paramagnetic substances

Under the action of a magnetic field these moments tend to orient in the direction of the exterior magnetic field. However, the magnetization which results has low values, since the effect of the thermal agitation tends to orient them randomly, this effect remaining dominant.

With some exceptions, among which uranium and titanium, magnetic susceptibility verifies Curie's law, namely it varies with the absolute temperature in an inversely proportional way. The permanent moments of free atoms have negligible interactions with each other, and can orient themselves freely in any directions (paramagnetism of free atoms.

(a)
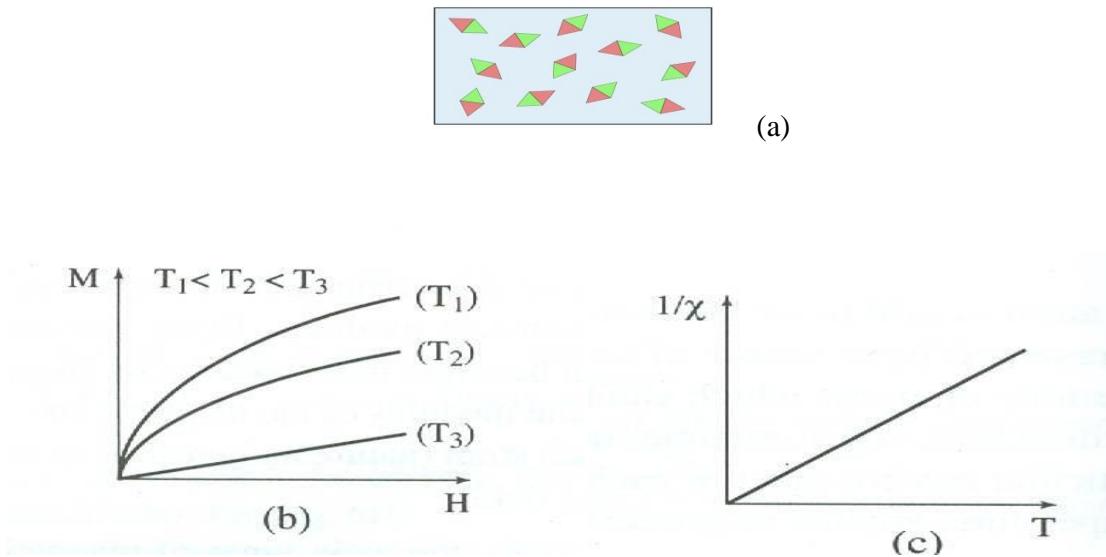
Fig: Paramagnetism of free atoms.

a) Permanent magnetic atoms of paramagnetic substances;
b) Dependence of induced magnetization M on intensity of magnetic field H : M(H)
c) variation of reciprocal susceptibility 3 with temperature T: 3(T). Attention, in this graph paramagnetic susceptibility is noted by 3 .

On applying a magnetic field magnetic moments are oriented parallel to the magnetic field , and an induced magnetization M parallel to the field appears. This magnetization is lower the higher the temperature, namely with thermal agitation. When increasing temperature
($T_1 < T_2 < T_3$) the variations of magnetization as function of the field become more and more linear. The low field susceptibility is positive, becomes infinite at 0K, and decreases when the temperature is increased. In the ideal case, the reciprocal susceptibility varies linearly with temperature (Curie law).

Paramagnetic substances are divided into normal paramagnetic substances, metallic substances with magnetic susceptibility non depending on temperature, and antiferromagnetic substances.

Normal paramagnetic substances are gases such as: O_2, NO, etc. platinum, palladium, iron, cobalt, and nickel salts, as well as these metals at temperatures $T > T_C$ (T_C being Curie temperature).

We previously mentioned that the temperature dependence of magnetic susceptibility 3^N of ideal paramagnetic substances depends on the temperature according to Curie's law in which C is Curie constant :

$$3^N = \frac{c}{T} \quad (10)$$

The Langevin theory of paramagnetism, which leads to the Curie law, is based on the assumption that the individual carriers of magnetic moment (atoms or molecules) do not interact with one another, but are acted on only by the applied field and thermal agitation. In real materials, deviations from Curie's law are often observed, in particular at low temperatures.

Many paramagnetics, do not obey Curie law; they obey instead the more general Curie–Weiss law. In 1907 Weiss pointed out that this behavior could be understood by postulating that the elementary moments do interact with one another. He suggested that this interaction could be expressed in terms of a fictitious internal or according to Curie-Weiss law:

$$3^N = \frac{c^F}{T+\Delta} \quad (11)$$

C^u is Curie constant. The constant Δ can be positive, negative, or null.

Typical paramagnetic metals for which 3^N does not depend on temperature are alkaline metals: lithium, sodium, potassium, rubidium, and cesium. They are very weak magnetic substances: $3^N \cong 10^{-6}$.

To conclude, paramagnetics are majority of gases, several metals, alkaline metals in particular, some salts, ferri and ferromagnetic materials when they are heated over Curie temperature.

CLASSICAL THEORY OF PARAMAGNETISM

Although the atoms of a paramagnetic substances have an atomic magnetic moment different from zero, in the absence of the exterior magnetic field $\vec{H}$, the magnetization $\vec{M}$ is null due to

the thermal agitation, which leads to a disorganized orientation of the magnetic moments. The magnetic moments of atoms are independent of the external magnetic field and their value is $\cong 10^{-23}\frac{J}{Mb/N}$. Upon the introduction of a paramagnetic body in an external magnetic field, one

can notice the precession of magnetic moments of electronic orbits and of vectors of magnetic moments of atoms around the direction of the external field. The action of the magnetic field and that of the thermal agitation are simultaneous and they produce the preferential orientation of the magnetic moments of atoms in the direction of the magnetic field.

Classical theory of paramagnetism was elaborated by Langevin (1905). Within this theory it is considered the totality of the magnetic moments of atoms resembling with "a classical gas of magnetic needles", which verifies the classical statistics of Boltzmann type. If N is the number of particles in the volume unit, the latter's' contribution to the paramagnetic magnetization equals with the mathematical product between N and the medium value of the projection of magnetic moments of atoms $\vec{\mu}$ on the direction of the external magnetic field:

$$M_p = N \cdot \mu \cdot \langle \cos\theta \rangle \qquad (12)$$

in which θ is the angle between $\vec{\mu}$ and $\vec{H}$, $\langle \cos\theta \rangle$ is a medium value.

The potential energy of a magnetic moment in the exterior magnetic field, of induction $\vec{B}=\mu_0\vec{H}$ is:

$$s = \vec{\mu} \cdot \vec{B} = -\mu_0 \cdot \mu \cdot H\cos\theta \quad (13)$$

θ being the angle between $\vec{\mu}$ and $\vec{B}$. The minus sign "−" has only physical significance. The probability for a particle to have the coordinates in intervals $(x, x + dx)$, $(y, y + dy)$ and $(z, z + dz)$ is determined with the help of Boltzmann distribution function, K being Boltzmann constant:

$$dP(x, y, z)=\text{const}.e^{-\frac{s}{KT}}dx \cdot dy \cdot dz \ (14)$$

Expressing (7.14) in spherical coordinates r, θ, φ, the volume element:

$$dV = dx.\ dy.\ dz = r^2\sin\theta \cdot dr \cdot d\theta \cdot d\varphi:$$

$$dP(r, \theta, \varphi) = \text{const.}\ e^{\frac{\mu_0\mu\cdot H\cos\theta}{KT}} \qquad (15)$$

Integrating (7.15) for the possible values of r and φ, it results that:

$$dP(\theta) = \text{const.}\ e^{\frac{\mu_0\mu\cdot H\cos\theta}{KT}} \cdot \sin\theta \cdot d\theta \ (16)$$

where the constant is determined from the normalization condition:
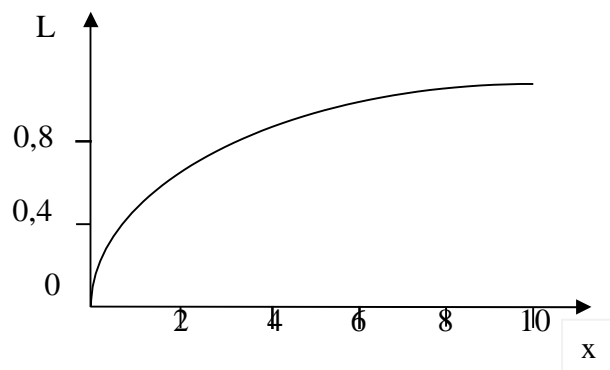
$$\int_0^n dP(8) = 1 .$$

We define:

$$\langle \cos 8 \rangle = \int_0^n \cos 8 \cdot dP(8) \quad (17)$$

By integrating (7.16) and by using prior relations one obtains paramagnetic magnetization:

$$M_p = N \cdot \mu \langle \cos 8 \rangle = N \cdot \mu \cdot L(x) \ (18)$$

in which $x = \dfrac{\mu 0 \mu K}{KT}$ and $L(x) = cthx - \dfrac{1}{s}$ is the Langevin function graphically represented in figure 7.8.

Fig: The Langevin function

At temperatures which are close to the environmental temperature, when H has small values, $x \ll 1$, and:

$$L(x) \approx \frac{s}{3} \text{ and } M_p = \frac{1}{3} N \cdot \mu \cdot x = \frac{\overline{\mu 0 \cdot N \cdot \mu^2}}{3KT} \cdot H \quad (19)$$

One obtains magnetic susceptibility of paramagnetic substances:

$$3N = \frac{M_p}{K} = \frac{\mu 0 \cdot N \cdot \mu^2}{\overline{3KT}} \quad (7.20)$$

Relation (7.20) represents Curie's law, in which Curie constant:

$$C = \frac{\mu 0 \cdot N \cdot \mu^2}{3K},$$

law experimentally verified for a large category of paramagnetic substances.

At low temperatures, or in intense magnetic fields, x has big values, $L(x) \approx 1$, and the saturation paramagnetic magnetization: $M_p = N\mu$, being independent of H.

QUANTIC THEORY OF PARAMAGNETISM

       Classical theory of magnetization, elaborated by Langevin, can be improved if one takes into account the spatial quantification of the movement of electrons, which makes that the angle θ take only discrete values, or by considering the quantic formula of the interaction of magnetic moments with the external magnetic field.

       In order to take the quantic formula into account we consider a simple system made of atoms with one electron, found in the fundamental state. The electron is characterized by the following values of quantic numbers: the principal number n=1, the orbital number l=0, the spin
number s=$\frac{1}{2}$, and the orbital magnetic moment $\mu_s = 0$ (see 3.2). .

    The total quantic number of the electron is $j = \frac{1}{2}$, and the magnetic total number of the

electron is $N_j = \pm\frac{1}{2}$. The energy level of the electron undergoes a Zeeman multiplication upon

the introduction in a magnetic field, according to the quantic relationship. The energy of the interaction between magnetic moments with the magnetic field of induction B, is:
$$E = g_J \cdot \mu_B \cdot N_J \cdot B \ . \ (21)$$

       Upon their introduction in a magnetic field, a part of the electrons of the atoms are situated on the lower energy level, of energy $(-\mu_B \cdot B)$, and the another part on the upper energy level $(+\mu_B \cdot B)$
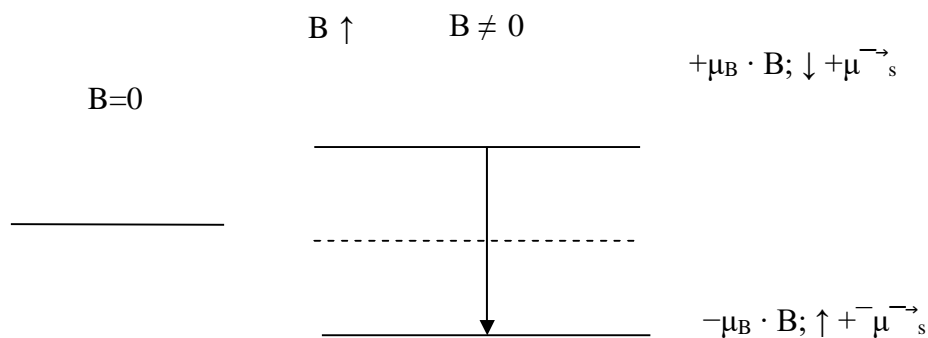
Fig: Zeeman multiplying of the energy levels of an electron in the fundamental state in an external magnetic field B.

On the upper energy level the magnetic moment of spin of the electron , μ_S , is oriented in the opposite direction of the magnetic field of induction $\vec{B}$, while on the lower energy level is oriented towards the same direction .

If N_1 and N_2 are the populations of the two levels: $\mu_S \cdot B$

$$N_1 = A \cdot e^{-\frac{\mu C \cdot B}{KT}} \; ; \; N_2 = A \cdot e^{\frac{\mu C \cdot B}{KT}} \quad (22)$$

in which A is a constant, and: $N = N_1 + N_2$ represents the total population.

Noting: $x = \dfrac{\mu C \cdot B}{KT}$, the magnetization of paramagnetic substances is written:

$$M_p = (N_1 - N_2) \cdot \mu_c = N \cdot \mu_c \cdot \frac{e^x - e^{-x}}{e^x + e^{-x}} = N \cdot \mu_c \cdot thx \quad (23)$$

For $x \ll 1$, $thx \approx x$ and it results:

$$M_p \approx N \cdot \mu_c \cdot x = \frac{N \cdot \mu_c^2}{KT} \cdot H . \quad (24)$$

Formula (7.24) represents Curie's law: paramagnetic susceptibility 3^N varies with the temperature. In the same way, it is shown that for a system made of atoms with total kinetic moment $\vec{J}$, for paramagnetic susceptibility, Curie's law is obtained, as well.

The paramagnetic properties of metals in fundamental state are due to the magnetic moments of spin μ_c of the electrons. The exterior magnetic field orients these magnetic moments as shown in figure, and it produces a paramagnetic magnetization.

ANTIFERROMAGNETISM

Antiferromagnetism is macroscopically similar to paramagnetism and represents a weak form of magnetism, namely with a weak and positive magnetic susceptibility.

Antiferromagnetism is characterized by a variation of magnetic susceptibility 3^N, according to
the temperature of a very particular form. The thermal variation was obtained by measurements on a polycrystalline sample.

The atoms of these materials have a permanent magnetic moment: the elementary magnetic moments are linked due to an antiferromagnetic coupling characterized by an antiparallel arrangement. This antiparallel arrangement of the atomic moments results from interactions between neighbouring atoms, called negative exchange interactions. The magnetic moments are distributed, in the most simple cases, into two sublattices, with their magnetization

equal and opposite, in such a way that, in the absence of magnetic field , the resulting magnetization is zero.

If the temperature rises, the arrangement of the moments is perturbed. The mitigation of the effects due to the alignment of magnetic moments makes the action of the external magnetic field stronger. This accounts the increase of the magnetic susceptibility until Néel temperature θ_N. Thus, Néel temperature θ_N is defined as being that temperature at which the antiferromagnetic coupling disappears.

For $T > \theta_N$, the observed behavior becomes comparable with the behavior of

paramagnetic substances, as extrapolated curve $\frac{1}{\chi_N}$ (T) does not cross the origin.

3

A large number of oxides, of chlorides, and of other compounds of transition metals (FeO,CoO,V_2O_4, MnO…) are antiferromagnetic substances.
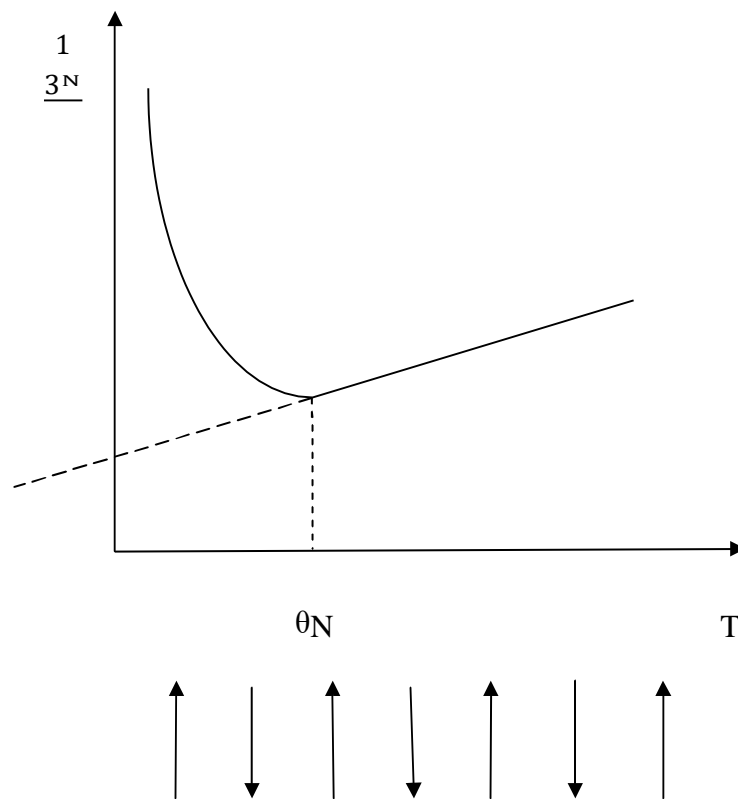
Fig: The dependence of the reciprocal paramagnetic susceptibility($\frac{1}{\chi_N}$) of the antiferromagnetic substances on the temperature. The importance of the Néel temperature θ_N
for these substances is observed. Are observed two antiparallel sublattices.

This is the simplest case of an antiferromagnetic material, made of two antiparallel sublattices. In fact many antiferromagnetic substances feature more complex magnetic structures, especially non collinear structures.

FERROMAGNETISM

The ferromagnetism is treated in detail in chapter 8.
What makes most solids be very weak from a magnetic point of view is not the fact that the individual atoms possess a reduced magnetic moment, but the fact that these magnetic moments are oriented in a disorganized way, since they are little influenced by the exterior magnetic field.

In these circumstances, a field of 10^5 Æ $(8 \cdot 10^6$ Oe$)$ would be necessary, at the temperature of

$$N$$

the surrounding environment, in order to obtain the magnetic saturation of Fe.

Experience has shown for ferromagnetic substances, a magnetic field which smaller than 1 A/m is enough to organize magnetic moments. Everything happens as inside the ferromagnetic samples would exist a magnetic field which orients the intrinsic magnetic moments of atoms.

In conclusion, the condition of a strong magnetization is that the magnetic moments of atoms should be globally oriented. Normally, this is not possible since the action of organization of the field is much surpassed by the disorder due to the movement of thermal agitation. The ferromagnetic substances are strongly magnetized in the direction of the field when placed in a magnetic field. The resultant magnetic field inside the ferromagnetic material is very large: thousand times greater than the magnetizing field. Then the magnetic susceptibility 3^N is positive and very large: for example about 8000 for soft iron . The relative permeability μ_r for such substances is very high too, of the order of several thousands.

Ferromagnetism is characterized by an alignment of permanent magnetic moments oriented in parallel by means of an interaction called positive exchange interaction. They have Curie temperature 8, over which they become paramagnetic, their susceptibility varying according to Curie-Weiss law:

$$3^N = \frac{C}{T - 8}$$

in which C is Curie constant. On account of the magnetic interactions, susceptibility becomes infinite at the Curie temperature. Below this temperature, interactions overcome thermal agitation, and a **remanent magnetization or spontaneous magnetization** (M_c) appears in the absence of an applied magnetic field. This spontaneus magnetization reaches its maximum value at 0K corresponding to parallelism of all the individual moment.
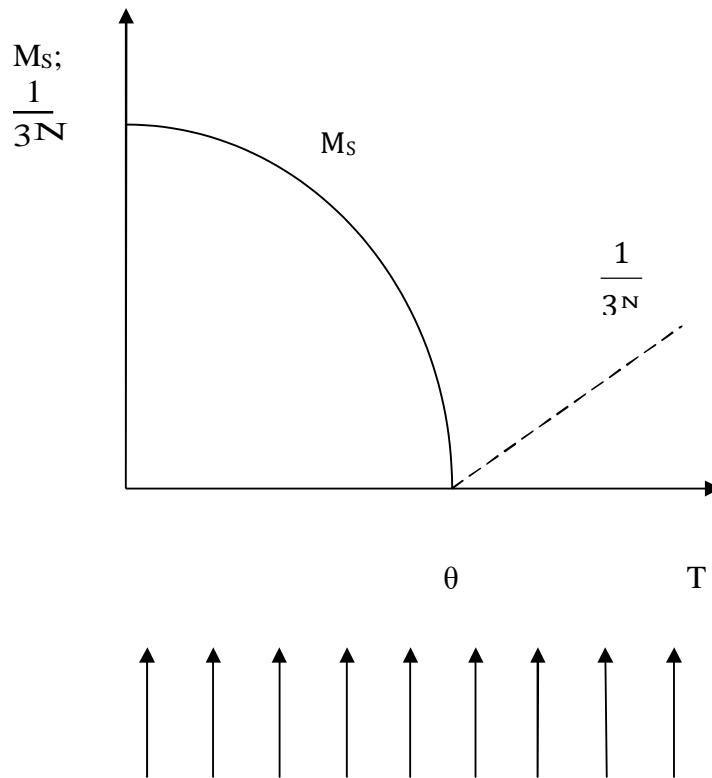

Fig: Dependence of spontaneous magnetization (M_c) and of reciprocal ferromagnetic susceptibility($\frac{1}{\_}$) on temperature T . 8 is Curie temperature. Is represented the spin lattice with

$$3^N$$

magnetic moments oriented parallel.

In spite of the existence of a spontaneous magnetization below, a piece of ferromagnetic material is not certainly spontaneously magnetised, the total moment magnetic being zero. In this case is said than the material is demagnetized. This results from the fact that the material is formed from magnetic domains, called Weiss domain. Each Weiss domain includes a large number of atoms and is spontaneously magnetised. From one domain to the other the orientation of the moments varies so that the resulting magnetic moment of the whole sample is zero.

Many experimental techniques have been proposed for displaying these magnetic domains and the domain walls that separate them: the Bitter method, magneto-optical effects, X-ray and neutron observation, Magnetic Force Microscopy, etc. Figure shows ferromagnetic domains revealed by neutron topography.
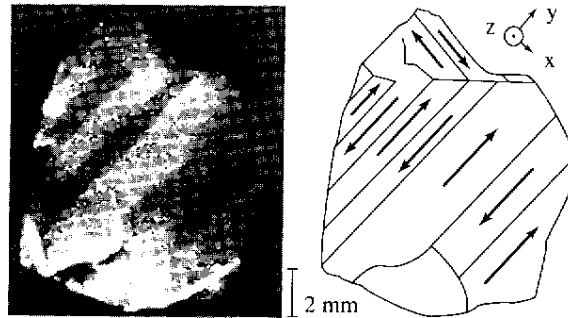
Fig: Ferromagnetic domains observed by polarized neutron topography. The sample is Fe-3% Si, surface (001), thickness 0.12mm, h=0.135nm.

Under the application of a magnetic field the distribution of domains is modified, giving rise the magnetization curve represented by the full line (initial magnetization curve) in Figure 7.13. In large magnetic fields magnetization tends to saturate. The existence of the Weiss domains explains the strong magnetization induced by a field. If the applied field is continuously changed between two extreme value of the intensity of field H, the magnetization process is not reversible and is described by **a hysteresis loop.**
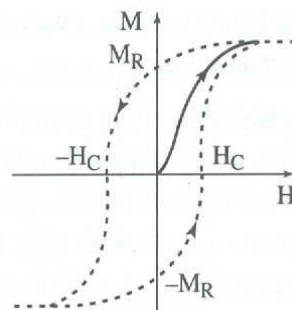

Fig: Magnetization curve M(H): magnetization M depending on the intensity of the magnetic field H of a demagnetised material. Initial magnetization curve (full line) and hysteresis loop (dashed line). M_R is remanent magnetization or spontaneous magnetization.

A small number of metals are ferromagnetic (Fe, Co, Ni), of rare earths (Gd, Dy), oxides (CrO_2, MnO,Fe_2O_3,FeO,$Y_3Fe_3O_{12\ldots}$).. To conclude, in addition to a strong magnetization , the initial magnetization curve as well as hysteresis loop are characteristics of ferromagnetic substances. Ferromagnetism is very important in technological applications. Most technological applications are based on the existence of the hysteresis loop.

FERRIMAGNETISM

Ferrimagnetism is the magnetism of a class of oxides called **ferrites,** and characterizes materials which microscopically are antiferromagnetics. In the crystalline structure of these materials there are two categories of positions A and B, occupied by ions which have magnetic moments $\vec{\mu}_Æ$ and

$\vec{\mu}_B$, respectively. The number of positions for A differs from B; in most cases: $\vec{\mu}_Æ \neq \vec{\mu}_B$.
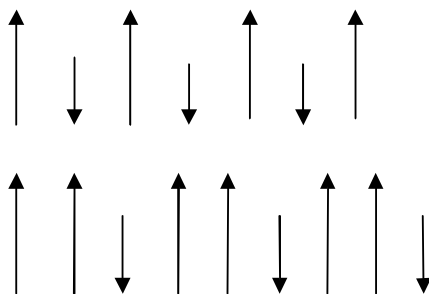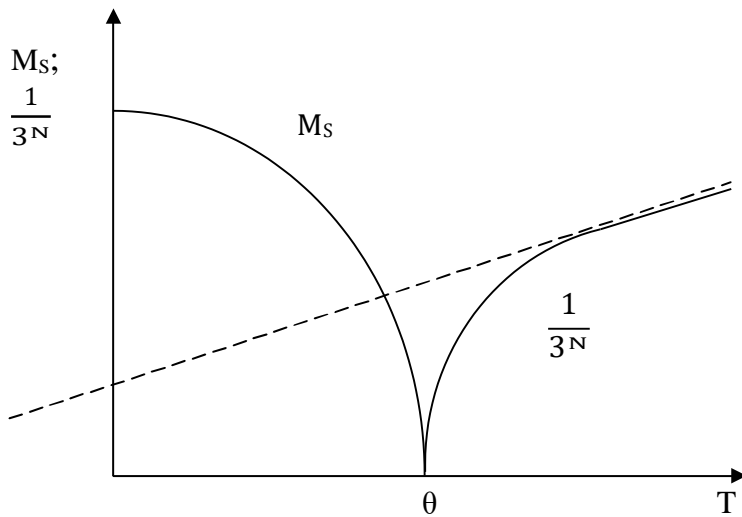
Fig: Thermal variation of reciprocal susceptibility $\frac{1}{3^N}$ and of spontaneous magnetization M_c for ferrimagnetic substances. Are represented spin lattices of ferrimagnetic substance