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Applications in Chemistry, Biomedicine, and Materials Science

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Preface

Stable nitroxide radicals have proved to be effective tools in solving many problems in chemistry, physics, biology, and biomedicine at the molecular level. The nitroxide labels are used as "molecular rulers" to measure the distances between chosen groups and to measure the size, form, and micro-relief of objects of interest. The labels provide information that helps the scientist to understand the structure and molecular dynamics of individual molecules, polymers, liquid crystals, enzymes, proteins, membranes, and nucleic acids and how they function. Recently, new important developments of nitroxides as redox-probes, spin-traps, imaging and pharmokinetic reagents, and magnetic materials have been reported. Nitroxide derivatives are successfully used for the investigation of chemical kinetics, photophysical, and photochemical processes. Therapeutic and clinical applications of nitroxides appear to be a new advance in medicine.

This volume covers all aspects of this field. It also critically discusses recent results obtained with the use of nitroxides and gives an analysis of developments in the field in the future.

This book is a view of the area by a group of scientists with long-term experience in the investigation of chemistry, physicochemistry, biochemistry, and biophysics of nitroxides. It is not intended to provide an exhaustive survey of each topic but rather a discussion of their theoretical and experimental background, and recent developments. The literature of nitroxides is vast and many scientists have made important contributions in the area so that it is impossible in the space allowed in this book to give a representative set of references. The authors apologize to those they have not been able to include. More than 1100 references are given, which should provide a key to essential relevant literature.

In Chapters 1 to 3 (J. Yamauchi) of the present monograph, the general theoretical, and experimental background is expounded for magnetic properties and ESR techniques. Chapter 4 (A. Smirnov) describes recent advances in modern ESR technique and related areas, which to a considerable extent were stimulated by the growing requirements of nitroxide application in biology and biomedicine. Fundamentals, recent results in preparation, and basic chemical properties of nitroxides are the main subject of Chapter 5 (S. Nakatsuji)

Chapters 6 and 7 (G.I. Likhtenshtein) offer a brief outline of principles and current results in nitroxide application as spin-labels and spin-probes in the investigation of the molecular dynamics and microstructure of biological and nonbiological objects, and as redox-probes and spin-traps. An important role of nitroxides as spin pH-meters, spin oximeters, and reactive radical–nitron adducts is elucidated. These chapters form the basis for subsequent profound studies of molecular properties of various objects such as polymers, inorganic materials, complexes of nitroxides with paramagnetic metals, photochemical systems, and so forth (Chapter 8 by G.I. Likhtenshtein). Advantages in a new area, the construction and investigation of magnetic materials on the basis of nitroxides are the subjects of Chapter 9 (R. Tamura). Chapter 10 (G.I. Likhtenshtein) discusses recent results from the utilization of the spin-labeling method for the investigation of molecular structure, dynamics, and functional activity of proteins, enzymes, biomembranes, nucleic acids, and polysaccharides. The concluding Chapter 11 (G.I. Likhtenshtein) considers biomedical, therapeutic, and clinical applications of nitroxides in areas which appear to be of great importance for human wellbeing.

Chemical, biochemical, biomedical, and material researchers may find in this book knowledge about fundamentals, instrumentation, data interpretation, capacity, and recent advances in nitroxide applications. It will help them to understand how nitroxides can help to solve their own problems. Physicists and experts in ESR instrumentation may learn about current problems and achievements in various areas of chemistry and molecular biology, and in the rapidly developing field of the application of nitroxides in biomedicine and medicine in particular. The book is also suited as a subsidiary text for instructors, graduate, and undergraduate students of university biochemical and chemical departments.

The authors are very grateful to Drs A. Rockenbauer, V. Khramtsov, F. Villamena, and A. Wasserman for their valuable advice and fruitful discussions. Finally, the authors are deeply indebted to Dr H. Tsue for his generous help in the preparation of the manuscript.

January 2008 *The authors*

Symbols and Abbreviations

Symbols

α	electron spin quantum number $m_S = 1/2$
	angle, alternating parameter
	anisotropic exchange parameter
α_n	nuclear spin quantum number $m_I = 1/2$
β	spin quantum number $m_s = -1/2$
	angle
β_n	nuclear spin quantum number $m_I = -1/2$
δ_{ij}	Kronecker δ
θ	angle
	Curie-Weiss constant
ΔH	line-width
$\Delta H_{1/2}$	half height line-width
ΔH_{pp}	peak-to-peak line-width
ΔH_{msl}	maximum-slope line-width
$\Delta H_{\omega 1/2}$, $H_{\omega pp}$	line-width in frequency
ε_0	dierectric constant
ε_F	Fermi energy
η	$\lvert J'/J \rvert$
Γ	molecular field coefficient
γ	gyromagnetic ratio
	exchange interaction parameter
	anisotropic exchange parameter
γ_n	nuclear gyromagnetic ratio
ϕ	molecular orbital
	relaxation function
Ψ	molecular orbital
ψ	atomic orbital
ν	frequency
μ	magnetic permeability
μ_0	magnetic permeability of free space

μ_{B}	Bohr magneton
μ_{n}	nuclear Bohr magneton
$\mathcal{H}$	Hamiltonian
ρ	spin density, life-time probability
Λ	$\Lambda_{\mu\nu}$-tensor
$\Lambda_{\mu\nu}$	second order perturbation of spin–orbit interaction
λ	spin–orbit coupling constant
τ, τ_{c}	correlation time, life time
τ_{C}	correlation time
ω	(angular) frequency
ω_{C}	cyclotron frequency
ω_{L}	Larmorfrequency
χ	magnetic susceptibility
$\chi_{//}$	parallel magnetic susceptibility
$\chi_{\perp}$	perpendicular magnetic susceptibility
χ_{dia}, χ_{para}, χ_{TIP}	diamagnetic, paramagnetic, and temperature-independent paramagnetic magnetic susceptibility
A	hyperfine coupling constant
$\mathrm{A}_{\mathrm{aniso}}$	anisoptpic hyperfine splitting
	A_x, A_y, A_z or A_{xx}, A_{yy}, A_{zz}
$\mathbf{A}_{\mathrm{dip}}$	dipolar hyperfine tensor
$\mathrm{A}_{\mathrm{iso}}$	average of **A**-tensor
A_{sol}	hyperfine coupling constant in solution
$\mathbf{A}_0$	hyperfine tensor of Fermi contact term
A_0	Fermi contact hyperfine coupling constant
$\boldsymbol{B}$	magnetic induction
B_{J}	Brillouin function
C	Curie constant
	Coulomb integral
c	light velocity
$\mathbf{D}$	**D**-tensor
D	zero-field splitting parameter
E	energy,
	zero-field splitting parameter
F	force
FT	Fourier transformation
G	Gaussian (function)
	complex magnetization
	autocorrelation function
g	g-value
g_{e}	free electron g-value
g_{n}	nuclear g-value
g_{iso}	average of g-tensor
g_{sol}	g-value in solution
h	Planck constant

\

$\boldsymbol{H}$, H	magnetic field (strength)
H_1	oscillating magnetic fiel
H_a	anisotropic field
H_e	exchange field
H_C	coercivity (coercive force)
H_cr	critical field
H_eff	effective field
H_dip	dipolar field
H_ex	exchange field
$\boldsymbol{H}_\mathrm{mol}$, H_mol	Wiss molecular field
$\mathbf{I}$	nuclear spin operator
$\boldsymbol{I}$	nuclear spin angular momentum
	light intensity
I	nuclear spin quantum number
	function of η
$\mathbf{J}$	total angular momentum operator
$\boldsymbol{J}$	total angular momentum
J	quantum number of total angular momentum
	exchange integral
	spectral density
	power spectrum
J	the resonance integral or coupling factor
K	anisotropy constant
k	Boltzmann constant
	rate constant
$\mathbf{L}$	orbital angular momentum operator
	nitary matrix
L	L-band
$\boldsymbol{L}$	orbital angular momentum
L	quantum number of orbital angular momentum
L	Lorentzian (function)
	Langevin function
l	azimutal quantum number
$\boldsymbol{M}$	magnetization
M	magnetization (M_x, M_y, M_z, M_0)
M_S	saturation magnetization
M_r	residual magnetization
$\boldsymbol{m}$	magnetic moment
$\boldsymbol{m}_\mathrm{eff}$, m_eff	effective magnetic momnt
m_e	mass of electron
m_p	mass of proton
m_i ($i = l$, S, I)	quantum number
n	principal quantum number
Q_{ij}^{i}	McConnell proprotionality

$\boldsymbol{R}$	relaxation term
$\mathbf{S}$	spin operator (electron)
$\boldsymbol{S}$	spin angular momentum (electron)
S	spin quantum number (electron)
s	spin quantum number $s = 1/2$ (electron) saturation factor
Tr	trace
T_i $(i = x,y,z)$	triplet basis functions
T_1	spin–lattice relaxation time
T_2	spin–spin relaxation time
T_C	Curie temperature
T_N	Neel temperature
t	time
u	magnetization
v	magnetization
X	X-ray, X-band
z	number of the nearest neighbor or the interchain paths

Abbreviations

CT	charge-transfer
CW-ESR	continuous wave-electron magnetic resonance
DANO	di-*p*-anisyl nitroxide
DDQ	2,3-dichloro-5,6-dicyano-*p*-benzoquinone
DEER	double electrone electron resonance
DMPO	5,5-dimethylpyrroline-*N*-oxide
DPPH	diphenyl picryl hydrazyl
DQC	double quantum coherence
DTBNO	di-*t*-butyl nitroxide
ED-ESR	echo detected ESR
ELDOR	electron double resonance
ESR	electron spin resonance
ENDOR	electron nuclear double resonance
ESEEM	electron spin echo envelope modulation
FT-ESR	Fourier transform-electron spin resonance
hfcc	hyperfine coupling constant
hfs	hyperfrine splitting
HOMO	highest occupied molecular orbital
HTS	high temperature-series (expansion)
IN	imine nitroxide
LCAO	linear combination of atomic orbital
LUMO	lowest unoccupied molecular orbital
MD	molecular dynamics
MM	molecular mechanics

MO	molecular orbital
NMR	nuclear magnetic resonance
NMLP	nitroxide mediated leavingpolymerization
NR, NRO·	nitroxide radical
NNR, NNRO·	nitronyl nitroxide radical
PBN	phenyl *t*-butyl nitrone
POBN	α–(4-pyridyl-1-oxide)-*N*-*t*-butylnitrone
SDSL	site-directed spin-labeling
SO	super oxide
SOD	super oxide dismutase
SOMO	singly occupied molecular orbital
SQUID	superconducting quantum interference device
PEDRI	proton electron double resonance imaging instrumentation
PELDOR	pulse electron-electron double resonance
ROS	reactive oxygen species
SIFTER	single-frequency technique for refocusing
TANOL	2,2,6,6-tetramethylpiperidin-4-ol-1-oxyl
TEMPOL	2,2,6,6-tetramethylpiperidinyl-1-oxyl
TEMPO	2,2,6,6-tetramethylpiperidinyl-1-oxy
TPV	1,3,5-triphenylverdazyl
PROXYL	2,2,5,5-tetramethylpyrrolidinyl-1-oxy
TCNE	tetracyanoethylene
TCNQ	7,7,8,8-tetracyanoquinodimethane
$TCNQF_4$	2,3,5,6-tetrafluoro-7,7,8,8-tetracyanoquinodimethane
TMM	trimethylenemethane
TTF	tetrathiafulvalene
	bis(ethylenedithio)tetrathiafulvalene
TMTSF	tetramethyltetrathiafulvalene
TRESR	time-resolved electron spin resonance

1

Fundamentals of Magnetism

Jun Yamauchi

1.1
Magnetism of Materials

1.1.1
Historical Background

Magnets play a crucial role in a modern life; as we know, a vast number of devices are employed in the electromagnetic industry. In ancient times human beings experienced magnetic phenomena by utilizing natural iron minerals, especially magnetite. It was not until modern times that magnetic phenomena were appreciated from the standpoint of electromagnetics, to which many physicists such as Oersted and Faraday made a great contribution. In particular, Ampère explained magnetic materials in 1822, based on a small circular electric current. This was the first explanation of a molecular magnet. Furthermore, Ampère's circuital law introduced the concept of a magnetic moment or magnetic dipoles, similar to electric dipoles. Macroscopic electromagnetic phenomena are depicted in Figure 1.1, in which a bar magnet and a circuital current in a wire are physically equivalent. Microscopic similarity is shown in Figure 1.2, in which a magnetic moment or dipole and a microscopic electron rotational motion are comparable but not

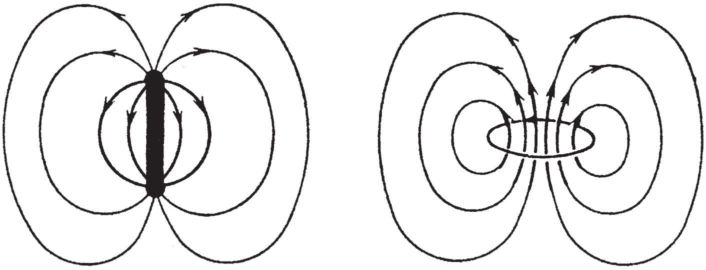

Figure 1.1 Magnetic fields due to a bar magnet and a circuital current.

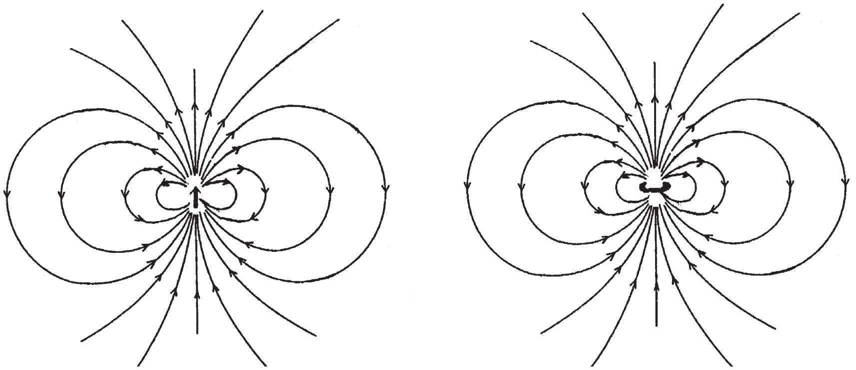

Figure 1.2 Magnetic fields due to a magnetic moment and a small circular current.

discriminated at all. The true understanding of the origin of magnetism, however, has come with quantum mechanics, newly born in the twentieth century.

Before the birth of quantum mechanics vast amounts of data concerning the magnetic properties of materials were accumulated, and a thoroughly logical classification was achieved by observing the response of every material to a magnetic field. These experiments were undertaken using magnetic balances invented by Gouy and Faraday. The principle of magnetic measurement is depicted in Figure 1.3, in which the balance measures the force exerted on the materials in a magnetic field. In general, all materials are classified into two categories, diamagnetic and paramagnetic substances, depending on the directions of the force. The former tend to exclude the magnetic field from their interior, thus being expelled effect in the experiments of Figure 1.3. On the other hand, some materials are attracted

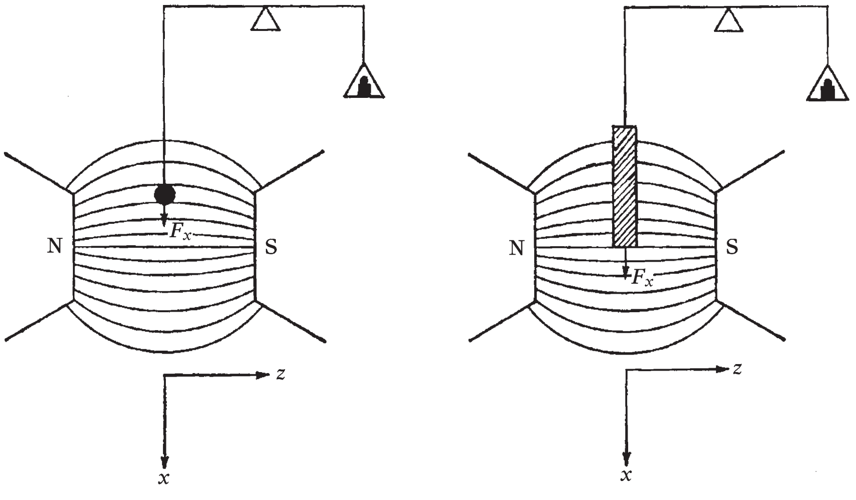

Figure 1.3 Faraday and Gouy balances for magnetic measurements. Force (F_x) is measured.

by the magnetic field. This difference between diamagnetic and paramagnetic substances is caused by the absence or presence of the magnetic moments that some materials possess in atoms, ions, or molecules. Curie made a notable contribution to experiments, and was honored with Curie's law (1895). Our understanding of magnetism was further extended by Weiss, leading to antiferromagnetism and ferromagnetism, which imply different magnetic interactions of magnetic moments with antiparallel and parallel configurations. These characteristics are involved in the Curie–Weiss law. The details will be described one after another in the following sections.

1.1.2

Magnetic Moment and its Energy in a Magnetic Field

The magnetic field generated by an electrical circuit is given as

$$\oint \boldsymbol{H} \cdot dl = I \tag{1.1}$$

That is, the total current, I, is equal to the line integral of the magnetic field, $\boldsymbol{H}$, around a closed path containing the current. This expression is called "Ampère's circuital law". The magnetic field generated by a current loop is equivalent to a magnetic moment placed in the center of the current. The magnetic moment is the moment of the couple exerted on either a bar magnet or a current loop when it is in an applied magnetic field [1]. If a current loop has an area of A and carries a current I, then its magnetic moment is defined as

$$|\boldsymbol{m}| = IA \tag{1.2}$$

The cgs unit of the magnetic moment is the "emu", and, in SI units, magnetic moment is measured in Am^2. The latter unit is equivalent to JT^{-1}. The magnetic field lines around the magnetic moment are shown above in Figure 1.2. In materials the origins of the magnetic moment and its magnetic field are the electrons in atoms and molecules comprising the materials. The response of materials to an external magnetic field is relevant to magnetic energy, as follows:

$$E = -\boldsymbol{m} \cdot \boldsymbol{H} \tag{1.3}$$

This expression for energy is in cgs units, and in SI units the magnetic permeability of free space, μ_0, is added.

$$E = -\mu_0 \boldsymbol{m} \cdot \boldsymbol{H} \tag{1.4}$$

This expression in SI units is also represented using the magnetic induction, $\boldsymbol{B}$, as defined in the next section. Therefore, the following expression is convenient in SI units:

$$E = -\boldsymbol{m} \cdot \boldsymbol{B} \tag{1.5}$$

The SI unit of magnetic induction is T (tesla).

1.1.3
Definitions of Magnetization and Magnetic Susceptibility

Each magnetic moment of a molecular magnet, including atoms or ions, is accounted for as a whole by vector summation. This physical parameter needs a counting base, such as unit volume, unit weight, or, more generally, unit quantity of substance. The last one is the mol (mole), which is widely used in chemistry. This is used in the definition of magnetization, $\boldsymbol{M}$, of materials. The units of magnetization, therefore, are emu cm^{-3}, emu g^{-1}, and emu mol^{-1}, or in SI units, A m^{-1}, A m^{2} kg^{-1}, and Am^{2} mol^{-1}, in which Am^{2} may be replaced by JT^{-1}.

$\boldsymbol{M}$ is a property of the material, depending on the individual magnetic moments of its constituent magnetic origins. Considering the vector sum of each magnetic moment, the magnetization reflects the magnetic interaction modes at a microscopic molecular level, resulting in remarkable experimental behaviors with respect to external parameters such as temperature and magnetic field. Magnetic induction, $\boldsymbol{B}$, is a response of the material when it is placed in a magnetic field, $\boldsymbol{H}$. The general relationship between $\boldsymbol{B}$ and $\boldsymbol{H}$ may be complicated, but it is regarded as a consequence of the magnetic field, $\boldsymbol{H}$, and the magnetization of the material, $\boldsymbol{M}$:

$$\boldsymbol{B} = \boldsymbol{H} + 4\pi\boldsymbol{M} \tag{1.6}$$

This is an expression in cgs units. In SI units the relationship between $\boldsymbol{B}$, $\boldsymbol{H}$, and $\boldsymbol{M}$ is given using the permeability of free space, μ_0, as

$$\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M}) \tag{1.7}$$

The unit of magnetic induction, in cgs and SI units, is G (gauss) and T (tesla), respectively, and the conversion between them is 1 G = 10^{-4} T.

Since the magnetic properties of the materials should be measured as a direct magnetization response to the applied magnetic field, the ratio of $\boldsymbol{M}$ to $\boldsymbol{H}$ is important:

$$\chi = \boldsymbol{M}/\boldsymbol{H} \tag{1.8}$$

This quantity, χ, is called "magnetic susceptibility". The magnetization of ordinary materials exhibits a linear function with $\boldsymbol{H}$. Strictly speaking, however, magnetization also involves higher terms of $\boldsymbol{H}$, and is manifested in the $\boldsymbol{M}$ vs. $\boldsymbol{H}$ plot (a magnetization curve). Ordinary weak magnetic substances follow $\boldsymbol{M} = \chi\boldsymbol{H}$. The unit of susceptibility is emu cm^{-3} Oe^{-1} in cgs units, and because of the equality of 1 G = 1 Oe, the unit emu cm^{-3} G^{-1} is also allowed. In some literature, especially in chemistry, χ is given in units of emu mol^{-1}. It should be noted that, in SI units, susceptibility is dimensionless.

The relation between $\boldsymbol{M}$ and $\boldsymbol{H}$ is the susceptibility: the ratio of $\boldsymbol{B}$ to $\boldsymbol{H}$ is called "magnetic permeability"

$$\mu = \boldsymbol{B}/\boldsymbol{H} \tag{1.9}$$

Two equations relating $\boldsymbol{B}$ with $\boldsymbol{H}$ and $\boldsymbol{M}$ (1.6 and 1.7) and the definitions of χ and μ lead to the following relations:

$$\mu = 1 + 4\pi\chi \quad \text{(in cgs units)} \tag{1.10}$$

$$\mu/\mu_0 = 1 + \chi \quad \text{(in SI units)} \tag{1.11}$$

Here, Equation 1.11 indicates the dimensionless relation, and the magnetic permeability of free space, μ_0, appears again. The permeability of a material measures how permeable the material is to the magnetic field. In the next section the physical explanation will be given after the introduction of magnetic flux.

1.1.4
Diamagnetism and Paramagnetism

Every material shows either positive or negative magnetic susceptibility, that is, $\chi > 0$ or $\chi < 0$. In magnetophysics or magnetochemistry this nature is referred to as "paramagnetism" (displayed by a "paramagnetic material") in the case of $\chi > 0$ and as "diamagnetism" (displayed by a "diamagnetic material") in the case of $\chi < 0$. In the $\boldsymbol{M}$–$\boldsymbol{H}$ curve this behavior is discriminated as a positive or negative slope, as shown in Figure 1.4. Usually, a diamagnetic response toward an external magnetic field is so minor that its slope is very small compared to the paramagnetic case. The difference between paramagnetism and diamagnetism is solely

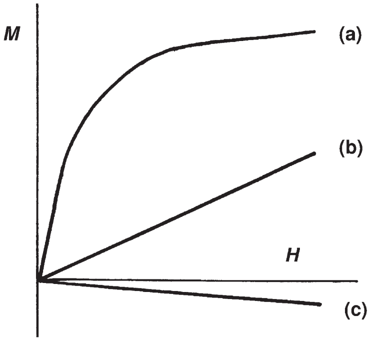

Figure 1.4 Schematic field dependencies of magnetization of (a) ferromagnetic, (b) paramagnetic, and (c) diamagnetic materials.

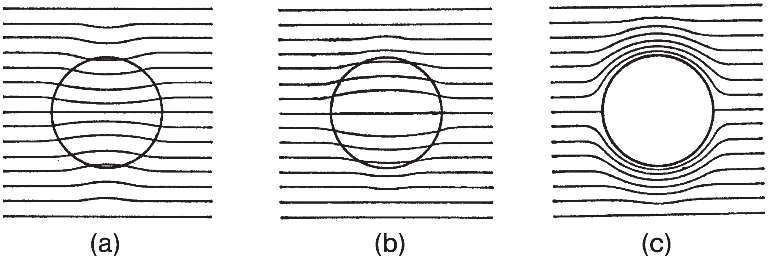

Figure 1.5 Magnetic flux in (a) paramagnetic, (b) diamagnetic, and (c) superconductive materials.

attributed to whether or not the material possesses magnetic moments in atomic, ionic, and molecular states.

Paramagnetic materials sometimes experience magnetic phase transitions at low temperatures. This means cooperative orderings of magnetic moments occur through exchange and dipolar interactions between them. There exist several ordering patterns which specify the vector arrangement of magnetic moments. Ferromagnetic and antiferromagnetic types are typical with parallel and antiparallel orientations, respectively. These magnetisms are called "ferromagnetism" and "antiferromagnetism". Phenomena concerning the cooperative ordering of magnetic moments are very attractive targets for investigation not only experimentally but also theoretically.

In view of the relationship between χ and μ, positive or the negative magnetic susceptibility corresponds to an increase or decrease in permeability, respectively, in comparison with the applied magnetic field. In order to gain more insight, the concept of "magnetic flux" or "flux density" is discussed here. Magnetic induction, $\boldsymbol{B}$, is the same idea as the density of flux, Φ/A, inside the medium, by analogy with $\boldsymbol{H} = \Phi/A$ in free space. Here, A is the cross-section. This indicates the difference between the external and internal flux, implying the degree of permeability of the magnetic field within a medium. This is illustrated in Figure 1.5, in which the lines indicate the magnetic flux. Perfect diamagnetism, see Figure 1.5c, is specified by $\boldsymbol{B} = 0$ and is manifested inside superconductors (the "Meissner effect"). From the standpoint of magnetic flux, materials are characterized as "diamagnetic" and either "paramagnetic" or "antiferromagnetic" when magnetic flux inside is less than outside, and the reverse, respectively. In the case of ferromagnetic materials magnetic flux inside is very much greater than that outside. Ferromagnetic materials tend to concentrate magnetic flux within the medium and are characterized by a net overall magnetic moment, which is referred to as "spontaneous magnetization".

1.1.5
Classification of Magnetic Materials

The basic concept of the magnetic materials is summarized diagrammatically with the help of magnetic moments represented by arrows. No magnetic moment exists

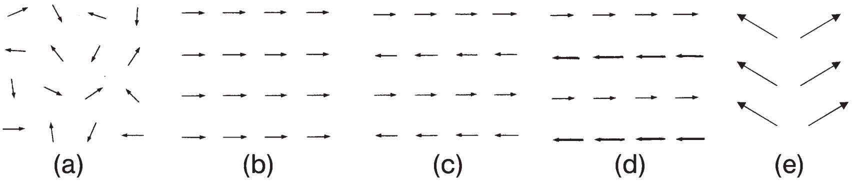

Figure 1.6 Disordered and ordered states of magnetic moments: (a) paramagnetic; (b) ferromagnetic; (c) antiferromagnetic; (d) ferrimagnetic; and (e) canting antiferromagnetic states.

in diamagnetic materials and the magnetic field applied induces a magnetic flux opposite to it. In substances possessing any magnetic moments, each magnetic moment is randomly orientated by thermal agitations, as shown in Figure 1.6a. A decrease of temperature, however, causes magnetic interactions between each magnetic moment to predominate over the thermal energy in the surroundings, thus some ordering of magnetic moments is brought about below the phase transition temperatures. Two typical ordering modes are depicted in Figure 1.6b (a ferromagnetic case) and in Figure 1.6c (an antiferromagnetic case). Materials possessing any magnetic moments respond positively to the magnetic field applied, resulting in both increases of χ and μ.

Here, a comment on the ordering in antiferromagnetism is appropriate. The antiparallel configuration of the magnetic moments has some orientational varieties. One variation concerns a different magnitude in the magnetic moments of each antiferromagnetically interacting pair. This case is termed "ferrimagnetism" (as applied to "ferrimagnetic materials") and is shown in Figure 1.6d. Such a ferrimagnetic material possesses a net magnetic moment even when the antiparallel array of each moment occurs. Because of this net magnetic moment, although the magnitude itself is far less compared with the ferromagnetic case, the magnetic susceptibility becomes far greater than for a paramagnetic material. The other typical antiparallel arrangement occurs in the case of deviation of co-linearity of magnetic moments (see, Figure 1.6e), which is called "canting antiferromagnetism". If the canting direction is not countervailed as a whole, then the net magnetic moment survives. Both ferrimagnetism and canting antiferromagnetism are sometimes termed "weak ferromagnetism" on the basis of their spontaneous magnetizations, though these are very small compared to genuine ferromagnetic materials.

1.1.6
Important Variables, Units, and Relations

In consideration of the difference of the unit systems, cgs and SI, the important variables and relations in magnetic study which we have introduced so far are summarized here [1].

	Variables	cgs	SI	Conversion
Energy	E	erg	J (joule)	$1\,\mathrm{erg} = 10^{-7}\,\mathrm{J}$
Magnetic field	$\boldsymbol{H}$	Oe (oersted)	$\mathrm{Am^{-1}}$	$1\,\mathrm{Oe} = 79.58\,\mathrm{Am^{-1}}$
Magnetic induction	$\boldsymbol{B}$	G (gauss)	T (tesla)	$1\,\mathrm{G} = 10^{-4}\,\mathrm{T}$
Magnetic flux	Φ	Mx (maxwell)	Wb (weber)	$1\,\mathrm{Mx} = 10^{-8}\,\mathrm{Wb}$
Magnetization	$\boldsymbol{M}$	$\mathrm{emu\,cm^{-3}}$	$\mathrm{Wb\,m^{2}}$	$1\,\mathrm{emu\,cm^{-3}} = 12.57\,\mathrm{Wb\,m^{-2}}$

	Relations	cgs units	Relations	SI units
Magnetic energy	$E = -\boldsymbol{m}\cdot\boldsymbol{H}$	erg	$E = -\mu_0\boldsymbol{m}\cdot\boldsymbol{H} = -\boldsymbol{m}\cdot\boldsymbol{B}$	J
Magnetic susceptibility	$\chi = \boldsymbol{M}/\boldsymbol{H}$	$\mathrm{emu\,cm^{-3}\,Oe^{-1}}$	$\chi = \boldsymbol{M}/\boldsymbol{H}$	dimensionless
Magnetic permeability	$\mu = \boldsymbol{B}/\boldsymbol{H}$ $= 1 + 4\chi$	$\mathrm{G\,Oe^{-1}}$	$\mu = \boldsymbol{B}/\boldsymbol{H} = \mu_0(1+\chi)$	$\mathrm{T\,A^{-1}\,m = H\,m^{-1}}$

SI units represented by SI fundamental constituents, kg, m, s, and A.

SI symbol	SI unit	Fundamental constituent
N	newton	$\mathrm{kg\,m\,s^{-2}}$
J	joule	$\mathrm{kg\,m^{2}\,s^{-2}}$
T	tesla	$\mathrm{kg\,s^{-2}\,A^{-1}}$
Wb	weber	$\mathrm{kg\,m^{2}\,s^{-2}\,A^{-1}}$
H	henry	$\mathrm{kg\,m^{2}\,s^{-2}\,A^{-2}}$

1.2
Origins of Magnetism

1.2.1
Origins of Diamagnetism

Diamagnetic materials innately possess no magnetic moments in the atoms, ions, or molecules which are their constituents, with the exception that magnetic moments interact with each other most strongly as an "antiparallel pair" so that at ambient temperatures they behave in a diamagnetic ways. Keeping this exception in mind, therefore, a rare origin of diamagnetism is strong twin coupling of magnetic moments in an antiferromagnetic manner. It may be pointed out that, in this case, paramagnetism turns up at an elevated temperature region. Apart