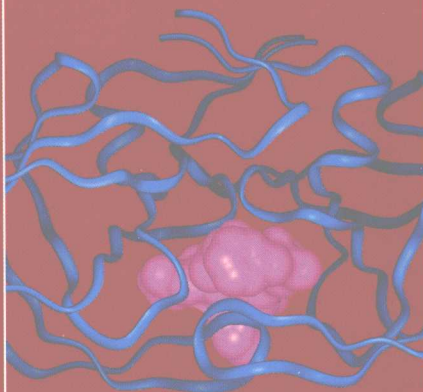


牛津大学 研究生教材系列

Magnetism in Condensed Matter

凝聚态物质中的磁性

S. Blundell



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Preface

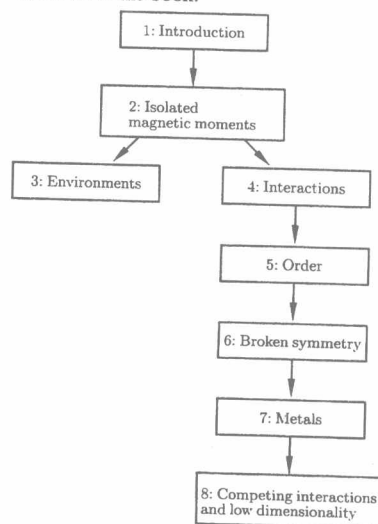
'... in Him all things hold together.'
(Colossians 1¹⁷)

Magnetism is a subject which has been studied for nearly three thousand years. Lodestone, an iron ore, first attracted the attention of Greek scholars and philosophers, and the navigational magnetic compass was the first technological product resulting from this study. Although the compass was certainly known in Western Europe by the twelfth century AD, it was not until around 1600 that anything resembling a modern account of the working of the compass was proposed. Progress in the last two centuries has been more rapid and two major results have emerged which connect magnetism with other physical phenomena. First, magnetism and electricity are inextricably linked and are the two components that make up light, which is called an electromagnetic wave. Second, this link originates from the theory of relativity, and therefore magnetism can be described as a purely relativistic effect, due to the relative motion of an observer and charges moving in a wire, or in the atoms of iron. However it is the magnetism in condensed matter systems including ferromagnets, spin glasses and low-dimensional systems, which is still of great interest today. Macroscopic systems exhibit magnetic properties which are fundamentally different from those of atoms and molecules, despite the fact that they are composed of the same basic constituents. This arises because magnetism is a collective phenomenon, involving the mutual cooperation of enormous numbers of particles, and is in this sense similar to superconductivity, superfluidity and even to the phenomenon of the solid state itself. The interest in answering fundamental questions runs in parallel with the technological drive to find new materials for use as permanent magnets, sensors, or in recording applications.

This book has grown out of a course of lectures given to third and fourth year undergraduates at Oxford University who have chosen a condensed matter physics option. There was an obvious need for a text which treated the fundamentals but also provided background material and additional topics which could not be covered in the lectures. The aim was to produce a book which presented the subject as a coherent whole, provided useful and interesting source material, and might be fun to read. The book also forms part of the Oxford Master Series in Condensed Matter Physics; the other volumes of the series cover electronic properties, optical properties, superconductivity, structure and soft condensed matter.

The prerequisites for this book are a knowledge of basic quantum mechanics and electromagnetism and a familiarity with some results from atomic physics. These are summarized in appendices for easy access for the reader and to present a standardized notation.

Structure of the book:



The interesting magnetic effects found in condensed matter systems have two crucial ingredients: first, that atoms should possess *magnetic moments* and second, that these moments should somehow *interact*. These two subjects are discussed in Chapters 2 and 4 respectively. Chapter 2 answers the question ‘why do atoms have magnetic moments?’ and shows how they behave and can be studied if they do not interact. Chapter 3 describes how these magnetic moments can be affected by their local environment inside a crystal and the techniques which can be used to study this. Chapter 4 then answers the question ‘how do the magnetic moments on different atoms interact with each other?’ With these ingredients in place, *magnetic order* can occur, and this is the subject of Chapters 5 and 6. Chapter 5 contains a description of the different types of magnetic order which can be found in the solid state. Chapter 6 considers order again, but starts from basic ideas of broken symmetry and describes phase transitions, excitations and domains. A strong emphasis is the link between magnetic order and other types of broken-symmetry ground states like superconductivity. Chapter 7 is devoted to the magnetic properties of metals, in which magnetism can often be associated with delocalized conduction electrons. Chapter 8 describes some of the subtle and complex effects which can occur when competing magnetic interactions are present and/or the system has a reduced dimensionality. These topics are the subject of intense research activity and there are many outstanding questions which remain to be resolved. Throughout the text, I discuss properties and applications to demonstrate the implications of all these ideas for real materials, including ferrites, permanent magnets and also the physics behind various magneto-optical and magnetoresistance effects which have become of enormous technological importance in recent years. This is a book for physicists and therefore the emphasis is on the clear physical principles of quantum mechanics, symmetry, and electromagnetism which underlie the whole field. However this is not just a ‘theory book’ but attempts to relate the subject to real measurements and experimental techniques which are currently used by experimental physicists and to bridge the gulf between the principles of elementary undergraduate physics and the topics of current research interest.

Chapters 1–7 conclude with some further reading and problems. The problems are of varying degrees of difficulty but serve to amplify issues addressed in the text. Chapter 8 contains no problems (the subjects described in this chapter are all topics of current research) but has extensive further reading.

It is a great pleasure to thank those who have helped during the course of writing this book. I am grateful for the support of Sönke Adlung and his team at Oxford University Press, and also to the other authors of this Masters series. Mansfield College, Oxford and the Oxford University Department of Physics have provided a stimulating environment in which to work. I wish to record my gratitude to my students who have sometimes made me think very hard about things I thought I understood. In preparing various aspects of this book, I have benefitted greatly from discussions with Hideo Aoki, Arzhang Ardavan, Deepto Chakrabarty, Amalia Coldea, Radu Coldea, Roger Cowley, Steve Cox, Gillian Gehring, Matthias Gester, John Gregg, Martin Greven, Mohamedally Kurmoo, Steve Lee, Wilson Poon, Francis Pratt, John Singleton and Candadi Sukumar. I owe a special debt of thanks to the friends and colleagues who have read the manuscript in various drafts and whose

Some possible course structures:

(1) Short course (assuming Chapter 1 is known):

- Chapter 2 (omit 2.6–2.8)
- Chapter 3 (omit 3.2)
- Chapter 4 (omit 4.2.5, 4.2.6)
- Chapter 5 (omit 5.4–5.7)
- Chapter 6 (omit 6.4–6.5)
- Chapter 7 (omit 7.1–7.2)

(2) Longer course:

- Chapters 1–4
- Chapter 5 (5.6 and 5.7 as background reading)
- Chapter 6
- Chapter 7 (7.5–7.9 as background reading)
- Chapter 8, selected topics

exacting criticisms and insightful questions have immensely improved the final result: Katherine Blundell, Richard Blundell, Andrew Boothroyd, Geoffrey Brooker, Bill Hayes, Brendon Lovett, Lesley Parry-Jones and Peter Riedi. Any errors in this book which I discover after going to press will be posted on the web-site for this book which may be found at:

<http://users.ox.ac.uk/~sjb/magnetism/>

Most of all, I want to thank Katherine, dear wife and soulmate, who more than anyone has provided inspiration, counsel, friendship and love. This work is dedicated to her.

Oxford

May 2001

S.J.B.

Note added at reprinting:

Thanks are due to the following who pointed out errors in the first printing of this book: Michael Brooks, Jonathan Coe, Ted Davis, Jonathan Fitt, Lucy Helme, Tom Lancaster, Gavin Morley, Oscar Moze, Shoichi Nagata, Toby Perring, Christopher Steer and David Thouless.

Oxford

January 2003

S.J.B.

Fundamental constants

Bohr radius for hydrogen	$4\pi\epsilon_0\hbar^2/m_0e^2 =$	a_H	$5.292 \times 10^{-11} \text{ m}$
Velocity of light in free space		c	$2.9979 \times 10^8 \text{ m s}^{-1}$
Electronic charge		e	$1.6022 \times 10^{-19} \text{ C}$
Gravitational constant		G	$6.673 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$
Planck's constant		h	$6.626 \times 10^{-34} \text{ J s}$
	$h/2\pi =$	$\hbar$	$1.0546 \times 10^{-34} \text{ J s}$
Boltzmann's constant		k_B	$1.3807 \times 10^{-23} \text{ J K}^{-1}$
Electron rest mass		m_0	$9.109 \times 10^{-31} \text{ kg}$
Proton rest mass		m_p	$1.6726 \times 10^{-27} \text{ kg}$
Avogadro's number		N_A	$6.022 \times 10^{23} \text{ mol}^{-1}$
Molar gas constant		R	$8.315 \text{ J mol}^{-1} \text{ K}^{-1}$
Rydberg's constant	$\alpha^2 m_0 c / 2h =$	R_∞	$1.0974 \times 10^7 \text{ m}^{-1}$
Rydberg's constant for hydrogen		R_H	13.606 eV
Standard molar volume		V_m	$22.414 \times 10^{-3} \text{ m}^3 \text{ mol}^{-1}$
Fine structure constant	$e^2/4\pi\epsilon_0\hbar c =$	α	$(137.036)^{-1}$
Electric permittivity of free space		ϵ_0	$8.854 \times 10^{-12} \text{ F m}^{-1}$
Bohr magneton		μ_B	$9.274 \times 10^{-24} \text{ A m}^2 \text{ or JT}^{-1}$
Nuclear magneton		μ_N	$5.051 \times 10^{-27} \text{ A m}^2 \text{ or JT}^{-1}$
Magnetic flux quantum	$h/2e =$	Φ_0	$2.0678 \times 10^{-15} \text{ T m}^2$
Stefan's constant		σ	$5.671 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
Magnetic permeability of free space		μ_0	$4\pi \times 10^{-7} \text{ H m}^{-1}$

Energy equivalents for photons $E = h\nu = k_B T = \frac{hc}{\lambda}$

E		ν	T	λ	λ^{-1}	
(J)	(eV)	(Hz)	(K)	(m)	(m ⁻¹)	(cm ⁻¹)
1	6.242×10^{18}	1.509×10^{33}	7.243×10^{22}	1.486×10^{-25}	5.034×10^{24}	5.034×10^{22}
1.602×10^{-19}	1	2.418×10^{14}	1.160×10^4	1.240×10^{-6}	8.066×10^5	8.066×10^3
6.626×10^{-34}	4.136×10^{-15}	1	4.799×10^{-11}	2.998×10^8	3.336×10^{-9}	3.336×10^{-11}
1.381×10^{-23}	8.617×10^{-5}	2.084×10^{10}	1	1.439×10^{-2}	69.50	0.6950
1.987×10^{-25}	1.240×10^{-6}	2.998×10^8	1.439×10^{-2}	1	1.0	0.01
1.987×10^{-25}	1.240×10^{-6}	2.998×10^8	1.439×10^{-2}	1.0	1	0.01
1.987×10^{-23}	1.240×10^{-4}	2.998×10^{10}	1.439	0.01	100	1

目 录

1 引论	1
1.1 磁矩	1
1.1.1 磁矩与角动量	2
1.1.2 旋进	3
1.1.3 Bohr 磁子	4
1.1.4 磁化强度与场	4
1.2 经典力学与磁矩	6
1.2.1 正则动量	7
1.2.2 Bohr-van Leeuwen 定理	8
1.3 自旋的量子力学	9
1.3.1 轨道与自旋角动量	9
1.3.2 Pauli 自旋矩阵与旋量	10
1.3.3 升降算子	12
1.3.4 二自旋的耦合	13
2 孤立磁矩	18
2.1 磁场中的原子	18
2.2 磁化率	19
2.3 抗磁性	20
2.4 顺磁性	23
2.4.1 顺磁性的半经典处理	23
2.4.2 $J=\frac{1}{2}$ 的顺磁性	25
2.4.3 Brillouin 函数	27
2.4.4 Van Vleck 顺磁性	30
2.5 离子的基态与 Hund 规则	30
2.5.1 精细结构	31
2.5.2 Hund 定则	32
2.5.3 L-S 与 j-j 耦合	35
2.6 绝热去磁	36
2.7 核自旋	38
2.8 超精细结构	40
3 环境	45
3.1 晶体场	45

3.1.1	晶体场的起源	45
3.1.2	轨道猝灭	48
3.1.3	Jahn-Teller 效应	50
3.2	磁共振技术	52
3.2.1	核磁共振	52
3.2.2	电子自旋共振	60
3.2.3	Mössbauer 谱	65
3.2.4	μ 子自旋旋转	68
4	相互作用	74
4.1	磁偶极相互作用	74
4.2	交换相互作用	74
4.2.1	交换的起源	74
4.2.2	直接交换	76
4.2.3	离子固体中的间接交换:超交换作用	77
4.2.4	金属中的间接交换	79
4.2.5	双交换作用	79
4.2.6	各向异性交换相互作用	81
4.2.7	连续统近似	82
5	序与磁性结构	85
5.1	铁磁性	85
5.1.1	铁磁体的 Weiss 模型	85
5.1.2	磁化率	89
5.1.3	磁场的作用	89
5.1.4	分子场的起源	90
5.2	反铁磁性	92
5.2.1	反铁磁体的 Weiss 模型	92
5.2.2	磁化率	93
5.2.3	强磁场的作用	94
5.2.4	反铁磁序的类型	96
5.3	亚铁磁性	97
5.4	螺旋序	99
5.5	自旋玻璃	100
5.6	核有序	101
5.7	磁序的测量	102
5.7.1	磁化强度与磁化率	102
5.7.2	中子散射	103
5.7.3	其他技术	107

6	序与破缺的对称性	111
6.1	破缺的对称性	111
6.2	模型	115
6.2.1	铁磁性的 Landau 理论	115
6.2.2	Heisenberg 与 Ising 模型	116
6.2.3	一维 Ising 模型($D=1, d=1$)	116
6.2.4	二维 Ising 模型($D=1, d=2$)	117
6.3	破缺对称性的后果	117
6.4	相变	119
6.5	刚性	121
6.6	激发	121
6.6.1	磁子	122
6.6.2	Bloch $T^{3/2}$ 定律	124
6.6.3	Mermin-Wagner-Berezinskii 定理	125
6.6.4	自旋波的测量	126
6.7	畴	127
6.7.1	畴壁	128
6.7.2	磁晶各向异性	128
6.7.3	畴壁宽度	129
6.7.4	畴形成	130
6.7.5	磁化过程	131
6.7.6	畴壁观测	132
6.7.7	小磁性粒子	133
6.7.8	Stoner-Wohlfarth 模型	134
6.7.9	软与硬材料	135
7	金属中的磁性	140
7.1	自由电子模型	140
7.2	Pauli 顺磁性	143
7.2.1	基本推导	143
7.2.2	与局域行为的交叠	144
7.2.3	实验技术	145
7.3	自发自旋分裂带	145
7.4	自旋密度泛函理论	147
7.5	Landau 能级	148
7.6	Landau 抗磁性	150
7.7	电子气体的磁性	153
7.7.1	电子气体的顺磁响应	153
7.7.2	电子气体的抗磁响应	156

7.7.3	RKKY 相互作用	156
7.8	电子气体中的激发	157
7.9	自旋密度波	159
7.10	Kondo 效应	161
7.11	Hubbard 模型	161
7.12	中子星	162
8	竞争相互作用与低维度	166
8.1	阻挫	166
8.2	自旋玻璃	167
8.3	超顺磁性	170
8.4	一维磁体	171
8.4.1	自旋链	172
8.4.2	自旋子	172
8.4.3	Haldane 链	173
8.4.4	自旋 Peierls 转变	173
8.4.5	自旋梯子	175
8.5	二维磁体	176
8.6	量子相变	178
8.7	薄膜与多层	180
8.8	磁-光学	182
8.9	磁电阻	183
8.9.1	铁磁体的磁电阻	184
8.9.2	各向异性磁电阻	185
8.9.3	巨磁电阻	185
8.9.4	交换各向异性	187
8.9.5	庞磁电阻	188
8.9.6	Hall 效应	190
8.10	有机与分子磁体	191
8.11	自旋电子学	192
A	电磁学中的单位	194
B	电磁学	197
B.1	磁矩	197
B.2	自由空间中的 Maxwell 方程	198
B.3	自由与边界电流	199
B.4	介质中的 Maxwell 方程	200
B.5	边界条件	200
C	量子与原子物理学	202
C.1	量子力学	202

C. 2	Dirac 左矢与右矢记号	203
C. 3	Bohr 模型	204
C. 4	轨道角动量	205
C. 5	氢原子	206
C. 6	g 因子	207
C. 7	d 轨道	209
C. 8	自旋-轨道相互作用	210
C. 9	Landé g 因子	210
C. 10	微扰理论	211
D	磁学中的能量与退磁化场	214
D. 1	能量	214
D. 2	退磁化因子	214
D. 3	任意形状的铁磁体	216
E	统计力学	219
E. 1	配分函数与热力学函数	219
E. 2	均分定理	220
F	精选问题的答案与提示	222
G	符号、常数与实用方程	230
	索引	234

Contents

1	Introduction	1
1.1	Magnetic moments	1
1.1.1	Magnetic moments and angular momentum	2
1.1.2	Precession	3
1.1.3	The Bohr magneton	4
1.1.4	Magnetization and field	4
1.2	Classical mechanics and magnetic moments	6
1.2.1	Canonical momentum	7
1.2.2	The Bohr–van Leeuwen theorem	8
1.3	Quantum mechanics of spin	9
1.3.1	Orbital and spin angular momentum	9
1.3.2	Pauli spin matrices and spinors	10
1.3.3	Raising and lowering operators	12
1.3.4	The coupling of two spins	13
2	Isolated magnetic moments	18
2.1	An atom in a magnetic field	18
2.2	Magnetic susceptibility	19
2.3	Diamagnetism	20
2.4	Paramagnetism	23
2.4.1	Semiclassical treatment of paramagnetism	23
2.4.2	Paramagnetism for $J = \frac{1}{2}$	25
2.4.3	The Brillouin function	27
2.4.4	Van Vleck paramagnetism	30
2.5	The ground state of an ion and Hund's rules	30
2.5.1	Fine structure	31
2.5.2	Hund's rules	32
2.5.3	L–S and j–j coupling	35
2.6	Adiabatic demagnetization	36
2.7	Nuclear spins	38
2.8	Hyperfine structure	40
3	Environments	45
3.1	Crystal fields	45
3.1.1	Origin of crystal fields	45
3.1.2	Orbital quenching	48
3.1.3	The Jahn–Teller effect	50
3.2	Magnetic resonance techniques	52
3.2.1	Nuclear magnetic resonance	52

3.2.2	Electron spin resonance	60
3.2.3	Mössbauer spectroscopy	65
3.2.4	Muon-spin rotation	68
4	Interactions	74
4.1	Magnetic dipolar interaction	74
4.2	Exchange interaction	74
4.2.1	Origin of exchange	74
4.2.2	Direct exchange	76
4.2.3	Indirect exchange in ionic solids: superexchange	77
4.2.4	Indirect exchange in metals	79
4.2.5	Double exchange	79
4.2.6	Anisotropic exchange interaction	81
4.2.7	Continuum approximation	82
5	Order and magnetic structures	85
5.1	Ferromagnetism	85
5.1.1	The Weiss model of a ferromagnet	85
5.1.2	Magnetic susceptibility	89
5.1.3	The effect of a magnetic field	89
5.1.4	Origin of the molecular field	90
5.2	Antiferromagnetism	92
5.2.1	Weiss model of an antiferromagnet	92
5.2.2	Magnetic susceptibility	93
5.2.3	The effect of a strong magnetic field	94
5.2.4	Types of antiferromagnetic order	96
5.3	Ferrimagnetism	97
5.4	Helical order	99
5.5	Spin glasses	100
5.6	Nuclear ordering	101
5.7	Measurement of magnetic order	102
5.7.1	Magnetization and magnetic susceptibility	102
5.7.2	Neutron scattering	103
5.7.3	Other techniques	107
6	Order and broken symmetry	111
6.1	Broken symmetry	111
6.2	Models	115
6.2.1	Landau theory of ferromagnetism	115
6.2.2	Heisenberg and Ising models	116
6.2.3	The one-dimensional Ising model ($D = 1, d = 1$)	116
6.2.4	The two-dimensional Ising model ($D = 1, d = 2$)	117
6.3	Consequences of broken symmetry	117
6.4	Phase transitions	119
6.5	Rigidity	121
6.6	Excitations	121
6.6.1	Magnons	122
6.6.2	The Bloch $T^{3/2}$ law	124
6.6.3	The Mermin–Wagner–Berezinskii theorem	125

6.6.4	Measurement of spin waves	126
6.7	Domains	127
6.7.1	Domain walls	128
6.7.2	Magnetocrystalline anisotropy	128
6.7.3	Domain wall width	129
6.7.4	Domain formation	130
6.7.5	Magnetization processes	131
6.7.6	Domain wall observation	132
6.7.7	Small magnetic particles	133
6.7.8	The Stoner–Wohlfarth model	134
6.7.9	Soft and hard materials	135
7	Magnetism in metals	140
7.1	The free electron model	140
7.2	Pauli paramagnetism	143
7.2.1	Elementary derivation	143
7.2.2	Crossover to localized behaviour	144
7.2.3	Experimental techniques	145
7.3	Spontaneously spin-split bands	145
7.4	Spin-density functional theory	147
7.5	Landau levels	148
7.6	Landau diamagnetism	150
7.7	Magnetism of the electron gas	153
7.7.1	Paramagnetic response of the electron gas	153
7.7.2	Diamagnetic response of the electron gas	156
7.7.3	The RKKY interaction	156
7.8	Excitations in the electron gas	157
7.9	Spin-density waves	159
7.10	The Kondo effect	161
7.11	The Hubbard model	161
7.12	Neutron stars	162
8	Competing interactions and low dimensionality	166
8.1	Frustration	166
8.2	Spin glasses	167
8.3	Superparamagnetism	170
8.4	One-dimensional magnets	171
8.4.1	Spin chains	172
8.4.2	Spinons	172
8.4.3	Haldane chains	173
8.4.4	Spin-Peierls transition	173
8.4.5	Spin ladders	175
8.5	Two-dimensional magnets	176
8.6	Quantum phase transitions	178
8.7	Thin films and multilayers	180
8.8	Magneto-optics	182
8.9	Magnetoresistance	183
8.9.1	Magnetoresistance of ferromagnets	184
8.9.2	Anisotropic magnetoresistance	185

8.9.3	Giant magnetoresistance	185
8.9.4	Exchange anisotropy	187
8.9.5	Colossal magnetoresistance	188
8.9.6	Hall effect	190
8.10	Organic and molecular magnets	191
8.11	Spin electronics	192
A	Units in electromagnetism	194
B	Electromagnetism	197
B.1	Magnetic moments	197
B.2	Maxwell's equations in free space	198
B.3	Free and bound currents	199
B.4	Maxwell's equations in matter	200
B.5	Boundary conditions	200
C	Quantum and atomic physics	202
C.1	Quantum mechanics	202
C.2	Dirac bra and ket notation	203
C.3	The Bohr model	204
C.4	Orbital angular momentum	205
C.5	The hydrogen atom	206
C.6	The g-factor	207
C.7	d orbitals	209
C.8	The spin-orbit interaction	210
C.9	Landé g-factor	210
C.10	Perturbation theory	211
D	Energy in magnetism and demagnetizing fields	214
D.1	Energy	214
D.2	Demagnetizing factors	214
D.3	A ferromagnet of arbitrary shape	216
E	Statistical mechanics	219
E.1	The partition function and thermodynamic functions	219
E.2	The equipartition theorem	220
F	Answers and hints to selected problems	222
G	Symbols, constants and useful equations	230
	Index	234

Introduction

1

This book is about the manifestation of magnetism in condensed matter. Solids contain magnetic moments which can act together in a cooperative way and lead to behaviour that is quite different from what would be observed if all the magnetic moments were isolated from one another. This, coupled with the diversity of types of magnetic interactions that can be found, leads to a surprisingly rich variety of magnetic properties in real systems. The plan of this book is to build up this picture rather slowly, piece by piece. In this introductory chapter we shall recall some facts about magnetic moments from elementary classical and quantum physics. Then, in the following chapter, we will discuss how magnetic moments behave when large numbers of them are placed in a solid but are isolated from each other and from their surroundings. Chapter 3 considers the effect of their immediate environment, and following this in Chapter 4, the set of possible magnetic interactions *between* magnetic moments is discussed. In Chapter 5 we will be in a position to discuss the occurrence of long range order, and in Chapter 6 how that is connected with the concept of broken symmetry. The final chapters follow through the implications of this concept in a variety of different situations. SI units are used throughout the book (a description of cgs units and a conversion table may be found in Appendix A).

1.1	Magnetic moments	1
1.2	Classical mechanics and magnetic moments	6
1.3	Quantum mechanics of spin	9

1.1 Magnetic moments

The fundamental object in magnetism is the **magnetic moment**. In classical electromagnetism we can equate this with a current loop. If there is a current I around an elementary (i.e. vanishingly small) oriented loop of area $|\mathbf{dS}|$ (see Fig. 1.1(a)) then the magnetic moment $\mathbf{d\mu}$ is given by

$$\mathbf{d\mu} = I\mathbf{dS}, \quad (1.1)$$

and the magnetic moment has the units of A m^2 . The length of the vector $\mathbf{dS}$ is equal to the area of the loop. The direction of the vector is normal to the loop and in a sense determined by the direction of the current around the elementary loop.

This object is also equivalent to a **magnetic dipole**, so called because it behaves analogously to an electric dipole (two electric charges, one positive and one negative, separated by a small distance). It is therefore possible to imagine a magnetic dipole as an object which consists of two magnetic monopoles of opposite magnetic charge separated by a small distance in the same direction as the vector $\mathbf{dS}$ (see Appendix B for background information concerning electromagnetism).