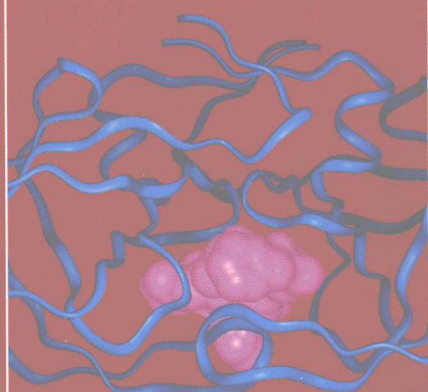
牛津大学研究生教材系列

Magnetism in Condensed Matter

凝聚态物质中的磁性

S. Blundell



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Preface

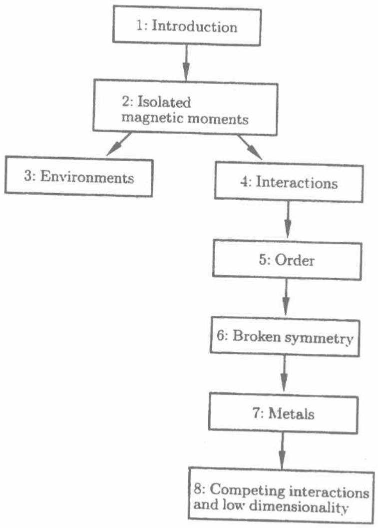
'... in Him all things hold together.'
(Colossians 1[17]*)*

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.

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

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

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

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

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

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Introduction

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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

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 $\mathbf{d}\boldsymbol{\mu}$ is given by

$$\mathbf{d}\boldsymbol{\mu} = I\mathbf{dS}, \tag{1.1}$$

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).

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