MRI
IN PRACTICE

Catherine Westbrook
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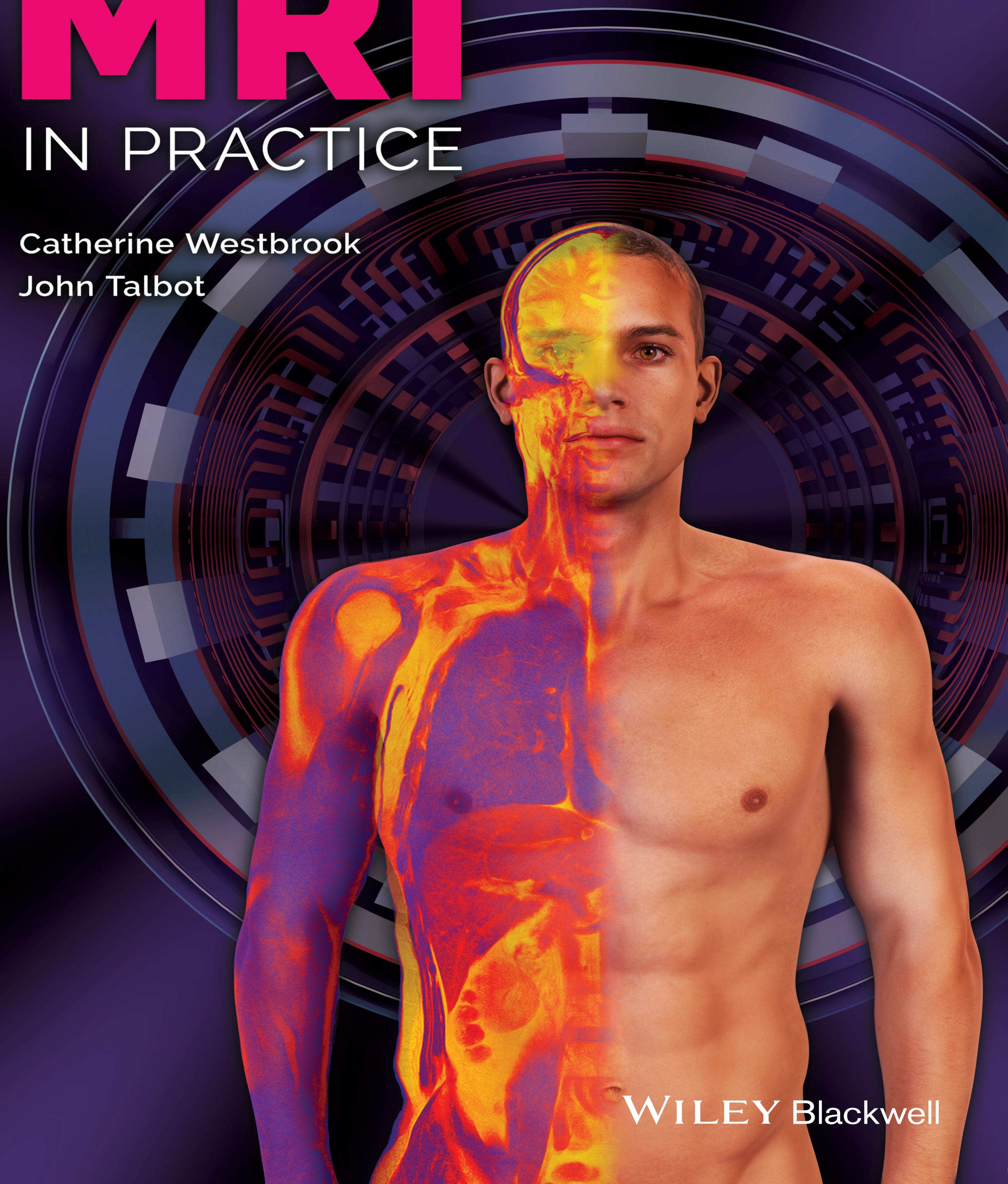

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Fifth Edition

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Preface to the fifth edition

The *MRI in Practice* brand continues to grow from strength to strength. The fourth edition of *MRI in Practice* is an international best-seller and is translated into several languages. At the time of writing, the accompanying *MRI in Practice* course is 26 years old. We have delivered the course to more than 10 000 people in over 20 countries and have a large and growing *MRI in Practice* online community. Our readers and course delegates include a variety of professionals such as radiographers, technologists, radiologists, radiotherapists, veterinary practitioners, nuclear medicine technologists, radiography students, postgraduate students, medical students, physicists, and engineers.

The unique selling point of *MRI in Practice* has always been its user-friendly approach to physics. Difficult concepts are explained as simply as possible and supported by clear diagrams, images, and animations. Clinical practitioners are not usually interested in pages of math and just want to know how it essentially "all works." We believe that *MRI in Practice* is so popular because it speaks your language without being oversimplistic.

This fifth edition has had a significant overhaul and specifically plays to the strengths of the *MRI in Practice* brand. We have created a synergy between the book and the course so that they are best able to support your learning. We purposefully focus on physics in this edition and on essential concepts. It is important to get the fundamentals right, as they underpin more specialist areas of practice. There are completely new chapters on MRI equipment and safety, and substantially revised and expanded chapters on gradient-echo pulse sequences, *k*-space, artifacts, and angiography. The very popular learning tips and analogies from previous editions are expanded and revised. There is also a new glossary, lots of new diagrams and images, and suggestions for further reading for those who wish to delve deeper into physics. The accompanying website includes new questions and additional animations. We also include some equations in this edition, but don't worry: they are there only for those who like equations, and we explain what they mean in a user-friendly style.

However, probably the most significant change in this edition is the inclusion of scan tips. Throughout the book, your attention is drawn to how theory applies to practice. Scan tips are specifically used to alert you to what is going on "behind the scenes" when you select a parameter in the scan protocol. We hope this helps you make the connection between theory and practice. Physics in isolation is of little value to the clinical practitioner. What is important is how this knowledge is applied. We stand by the *MRI in Practice* philosophy that physics does not have to be difficult, and we hope that our readers, old and new, find these changes helpful. Richard Feynman, who is considered one of the finest physics teachers of all time, was renowned for his ability to transfer his deep understanding of physics to the page with clarity and a minimum of fuss. He believed that it is unnecessary to make physics more complicated than it need be. Our aspiration is that the fifth edition of *MRI in Practice* emulates his way of thinking.

We hope that the many fans of *MRI in Practice* around the world continue to enjoy and learn from it. A big thank you for your continued support and happy reading!

Catherine Westbrook
John Talbot
November 2017
United Kingdom

Acknowledgments

Many thanks to all my loved ones for their continued support, especially Maggie Barbieri (my mother, whose brain scans feature many times in all the editions of this book and in the *MRI in Practice* course for the last 26 years. She must have the most viewed brain in the world!), Francesca Bellavista, Amabel Grant, Adam, Ben and Maddie Westbrook.

Catherine Westbrook

I'd like to thank my family Dannie, Joey, and Harry for bringing coffee, biscuits, and occasionally gin and tonic. I would also like to take the opportunity to acknowledge the work of a great MRI pioneer, Prof. Sir Peter Mansfield, who died this year. Prof. Mansfield's team created the first human NMR image in 1976, and he kindly shared all of his most important research papers with me when I first started writing about this amazing field.

John Talbot

Acronyms

Generic	**Siemens**	**GE**	**Philips**	**Hitachi**	**Toshiba**
Pulse sequences					
Conventional spin-echo (SE)	SE	SE	SE	SE	SE
Turbo spin-echo (TSE)	TSE	FSE	TSE	FSE	FSE
Single-shot TSE (SS-TSE)	HASTE	SS-FSE	SS-TSE	SS-FSE	FASE
TSE (with restoration pulse)	RESTORE	FRFSE	DRIVE	driven equilibrium FSE	T2 Puls FSE
Inversion recovery (IR)	IR	IR/MPIR	IR	IR	IR
Fast inversion recovery	TIR	Fast IR	IR-TSE	IR	IR
Short tau IR (STIR)	STIR	STIR	STIR	STIR	fast STIR
Fluid-attenuated IR (FLAIR)	turbo dark fluid	FLAIR	FLAIR	FLAIR	fast FLAIR
Gradient-echo (GRE)	GRE	GRE	FFE	GE	field echo
Coherent gradient-echo	FISP	GRASS	FFE	rephased SARGE	SSFP
Incoherent gradient-echo	FLASH	SPGR	T1 FFE	spoiled SARGE	fast FE
Reverse-echo gradient-echo	PSIF	SSFP	T2 FFE	time-reversed SARGE	—
Balanced gradient-echo	true FISP	FIESTA	BFFE	balanced SARGE	true SSFP
Echo-planar imaging (EPI)	EPI	EPI	EPI	EPI	EPI
Double-echo steady state	DESS	—	—	—	—
Balanced dual excitation	CISS	FIESTA-C	—	phase balanced SARGE	—
Multi-echo-data-image-combination	MEDIC	MERGE	MFFE	—	—
Fast gradient-echo	turbo FLASH	fast GRE, fast SPGR	TFE	RGE	Fast FE
Hybrid sequence	TGSE	—	GRASE	—	Hybrid EPI

Generic	**Siemens**	**GE**	**Philips**	**Hitachi**	**Toshiba**
Contrast parameters					
Repetition time (TR)	TR	TR	TR	TR	TR
Time to echo (TE)	TE	TE	TE	TE	TE
Time from inversion (TI)	TI	TI	TI	TI	TI
Flip angle	flip angle	flip angle	flip angle	flip angle	Flip angle
Number of echoes (in TSE)	turbo factor	ETL	turbo factor	shot factor	ETL
b factor/value	*b* factor	*b* factor	*b* factor	*b* factor	*b* factor
Geometry parameters					
Field of view (FOV)	FOV (mm)	FOV (cm)	FOV (mm)	FOV (mm)	FOV (mm)
Rectangular FOV	FOV phase	PFOV	rectangular FOV	rectangular FOV	rectangular FOV
Slice gap	distance factor	gap	gap	slice interval	gap
Data acquisition parameters					
Averages	average	NEX	NSA	NSA	NSA
Bandwidth	bandwidth (Hz/pixel)	receive bandwidth (KHz)	fat water shift (pixel)	bandwidth (KHz)	bandwidth (KHz)
Variable bandwidth	optimized bandwidth	variable bandwidth	optimized bandwidth	variable bandwidth	matched bandwidth
Partial averaging	half Fourier	fractional NEX	half scan	half scan	AFI
Partial echo	asymmetric echo	partial echo	partial echo	half echo	matched bandwidth
Parallel imaging (image based)	mSENSE	ASSET	SENSE	RAPID	SPEEDER
Parallel imaging (*k*-space based)	GRAPPA	ARC	—	—	—
Artifact reduction techniques					
Radial *k*-space filling	BLADE	PROPELLOR	multiVane	RADAR	JET
Gradient moment rephasing	GMR/flow comp	flow comp	flow comp/FLAG	GR	FC
Presaturation	pre SAT	Sat	REST	Pre SAT	Pre SAT
Moving sat pulse	travel SAT	walking SAT	travel REST	Sequential pre SAT	BFAST
Fat saturation	fat SAT	chem SAT	SPIR	Fat Sat	MSOFT
Out-of-phase imaging	DIXON	IDEAL	ProSET	Water excitation	PASTA
Respiratory compensation	respiratory gated	respiratory compensation	PEAR	MAR	respiratory gated
Antialiasing (frequency)	oversampling	antialiasing	frequency oversampling	frequency oversampling	frequency wrap suppression
Antialiasing (phase)	phase oversampling	no phase wrap	fold-over suppression	antiwrap	phase wrap suppression

Generic	**Siemens**	**GE**	**Philips**	**Hitachi**	**Toshiba**
Special techniques					
Volume TSE variable flip angle	SPACE	CUBE	VISTA	—	—
Volume gradient-echo	VIBE	LAVA-XV	THRIVE	TIGRE	—
Dynamic MRA	TWIST	TRICKS-SV	keyhole (4d Trak)	—	—
Noncontrast MRA gradient-echo	NATIVE – true FISP	inhance inflow IR	B-TRANCE	VASC ASL	TIME-SLIP
Noncontrast MRA spin- echo	NATIVE-SPACE	—	TRANCE	VASC FSE	FBI
Susceptibility weighting	SWI	SWAN	Venous BOLD	—	—
High-resolution breast imaging	VIEWS	VIBRANT-XV	BLISS	—	RADIANCE
Diffusion-weighted imaging	DWI	DWI	DWI	DWI	DWI
Diffusion tensor imaging	DTI	DTI	diffusion tensor imaging	—	DTI
Body diffusion imaging	REVEAL	—	DWIBS	—	body vision

Nomenclature

S	spin quantum number	
N^+	number of spins in the high-energy population (Boltzmann)	
N^-	number of spins in the low-energy population (Boltzmann)	
ΔE	energy difference between high- and low-energy populations (Boltzmann)	J
k	Boltzmann's constant	J/K
T	temperature of the tissue	K
ω_0	precessional or Larmor frequency	MHz
γ	gyromagnetic ratio	MHz/T
B_0	external magnetic field strength	T
E	energy of a photon	J
h	Planck's constant	J/s
θ	flip angle	°
ω_1	precessional frequency of B_1	μT
B_1	magnetic field associated with the RF excitation pulse	mT
τ	duration of the RF excitation pulse	ms
ϵ	emf	V
N	number of turns in a coil	
$\mathrm{d}\Phi$	changing magnetic flux in a single loop	V/s
$\mathrm{d}t$	changing time	s
Mz_t	amount of longitudinal magnetization at time t	
Mz	full longitudinal magnetization	
Mxy_t	amount of transverse magnetization at time t	
Mxy	full transverse magnetization	
SI	signal intensity in a tissue	
ΔB_0	variation in magnetic field	ppm
G	gradient amplitude	mT/m
δ	gradient duration	ms
Δ	time between two gradient pulses	ms

b	*b* value or *b* factor	s/mm^2
ST	scan time	s
E_S	echo spacing in turbo spin-echo (TSE)	ms
t	time from inversion (TI)	ms
Ernst	Ernst angle	°
TE_{eff}	effective TE	ms
TE_{act}	TE set at the console	ms
B_p	magnetic field strength at a point along the gradient	T
SI_t	slice thickness	mm
TBW	transmit bandwidth	KHz
$\omega_{sampling}$	digital sampling frequency	KHz
ΔT_s	sampling interval	ms
$\omega_{Nyquist}$	Nyquist frequency	KHz
RBW	receive bandwidth	KHz
W_s	sampling window	ms
M(f)	frequency matrix	
M(p)	phase matrix	
N_s	number of slice locations	
G(p)	max amplitude of the phase encoding gradient	mT/m
ϕ	incremental step between each *k*-space line	
$G(f)$	amplitude of the frequency encoding gradient	mT/m
FOV(f)	frequency FOV	cm
σ	standard deviation of background signal or noise	
S_p	separation between ghosts due to motion p	pixels
T_m	period of motion of something moving in the patient	ms
Re	Reynolds number	
d	density of blood	g/cm^3
v	velocity of flow	cm/s
m	diameter of a vessel	cm
vis	viscosity of blood	g/cm s
f_p	perceived frequency	KHz
f_t	actual frequency	KHz
ω_{csf}	chemical shift frequency difference between fat and water	Hz
C_s	chemical shift (3.5 ppm or 3.5×10^{-6})	ppm
CS_p	pixel shift	mm
H_0	magnetic intensity	A/m
q	charge of a particle	C
F	Lorentz force (total emf on a charged particle)	V
E	electric field vector	
B	magnetic field vector	

About the companion website

This book is accompanied by a companion website:

www.wiley.com/go/westbrook/mriinpractice

The website includes:

- Brand new 3D animations of more complex concepts from the book
- 100 short-answer questions to aid learning and understanding.

1

Basic principles

After reading this chapter, you will be able to:

- *Describe the structure of the atom.*
- *Explain the mechanisms of alignment and precession.*
- *Understand the concept of resonance and signal generation.*

INTRODUCTION

The basic principles of magnetic resonance imaging (MRI) form the foundation for further understanding of this complex subject. It is important to grasp these ideas before moving on to more complicated topics in this book.

There are essentially two ways of explaining the fundamentals of MRI: classically and via quantum mechanics. **Classical theory** (accredited to Sir Isaac Newton and often called Newtonian theory) provides a mechanical view of how the universe (and therefore how MRI) works. Using classical theory, MRI is explained using the concepts of mass, spin, and angular momentum on a large or bulk scale. **Quantum theory** (accredited to several individuals including Max Planck, Albert Einstein, and Paul Dirac) operates at a much smaller, subatomic scale and refers to the energy levels of protons, neutrons, and electrons. Although classical theory is often used to describe physical principles on a large scale and quantum theory on a subatomic level, there is evidence that all physical principles are explained using quantum concepts [1]. However, for our purposes, this chapter mainly relies on classical perspectives because they are generally easier to understand. Quantum theory is only used to provide more detail when required.

MRI in Practice, Fifth Edition. Catherine Westbrook and John Talbot.

Companion Website: www.wiley.com/go/westbrook/mriinpractice

In this chapter, we explore the properties of atoms and their interactions with magnetic fields as well as the mechanisms of excitation and relaxation.

ATOMIC STRUCTURE

All things are made of **atoms**. Atoms are organized into **molecules**, which are two or more atoms arranged together. The most abundant atom in the human body is **hydrogen**, but there are other elements such as oxygen, carbon, and nitrogen. Hydrogen is most commonly found in molecules of water (where two hydrogen atoms are arranged with one oxygen atom; H_2O) and fat (where hydrogen atoms are arranged with carbon and oxygen atoms; the number of each depends on the type of fat).

The atom consists of a central nucleus and orbiting **electrons** (Figure 1.1). The nucleus is very small, one millionth of a billionth of the total volume of an atom, but it contains all the atom's mass. This mass comes mainly from particles called **nucleons**, which are subdivided into **protons** and **neutrons**. Atoms are characterized in two ways.

- The **atomic number** is the sum of the protons in the nucleus. This number gives an atom its chemical identity.
- The **mass number** or **atomic weight** is the sum of the protons and neutrons in the nucleus.

The number of neutrons and protons in a nucleus is usually balanced so that the mass number is an even number. In some atoms, however, there are slightly more or fewer neutrons than protons. Atoms of elements with the same number of protons but a different number of neutrons are called **isotopes**.

Electrons are particles that spin around the nucleus. Traditionally, this is thought of as analogous to planets orbiting around the sun with electrons moving in distinct shells. However, according to quantum theory, the position of an electron is not predictable as it depends on the energy of an individual electron at any moment in time (this is called Heisenberg's Uncertainty Principle).

Some of the particles in the atom possess an electrical charge. Protons have a positive electrical charge, neutrons have no net charge, and electrons are negatively charged. Atoms are electrically stable if the number of negatively charged electrons equals the number of positively charged protons. This balance is sometimes altered by applying energy to knock out electrons from the atom. This produces a deficit in the number of electrons compared with protons and causes electrical instability. Atoms in which this occurs are called **ions** and the process of knocking out electrons is called **ionization**.

MOTION IN THE ATOM

Three types of motion are present within the atom (Figure 1.1):

- Electrons spinning on their own axis
- Electrons orbiting the nucleus
- The nucleus itself spinning about its own axis.

The principles of MRI rely on the spinning motion of specific nuclei present in biological tissues. There are a limited number of spin values depending on the atomic and mass numbers. A nucleus has no spin if it has an even atomic and mass number, e.g. six protons and six neutrons, mass number 12. In nuclei that have an even mass number caused by an even number of protons and neutrons, half of the nucleons spin in one direction and half in the other. The forces of rotation cancel out, and the nucleus itself has no net spin.

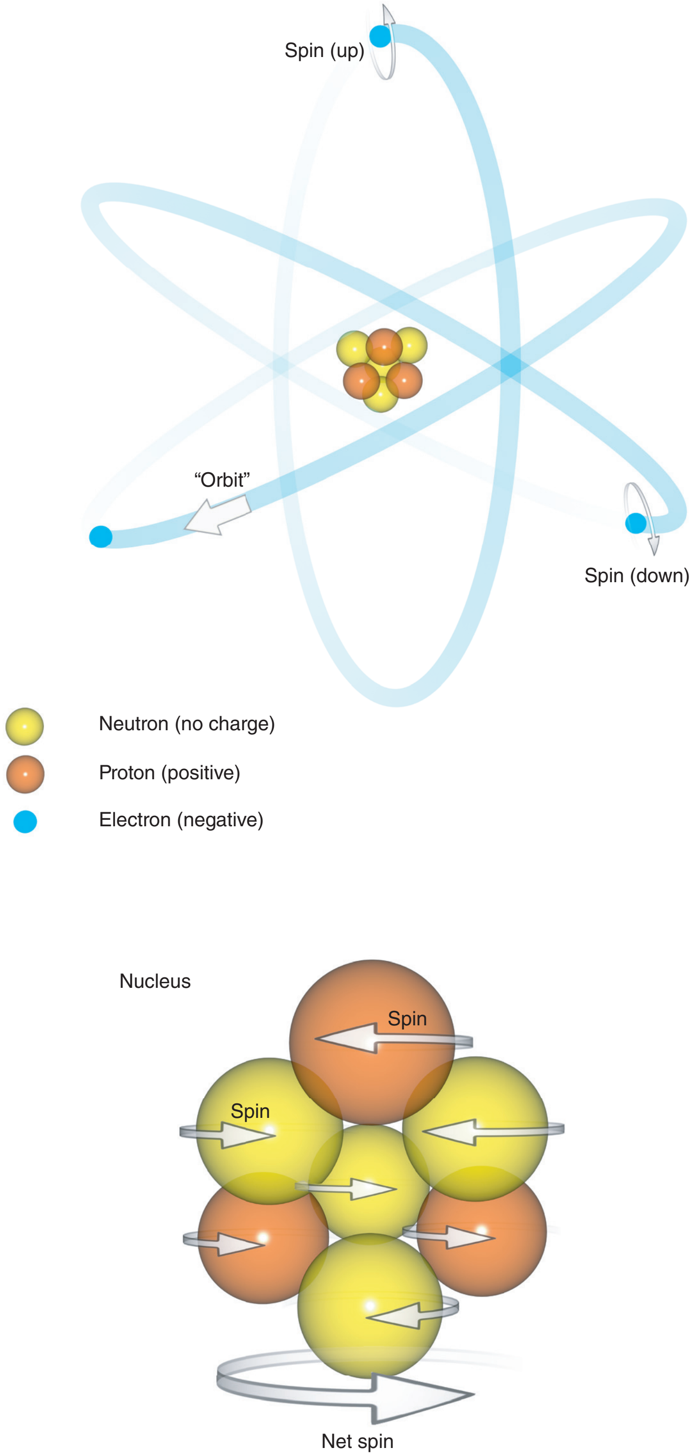

Figure 1.1 The atom.