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Ralph A. Llewellyn

MODERN PHYSICS

FOURTH
EDITION

Modern Physics

FOURTH EDITION

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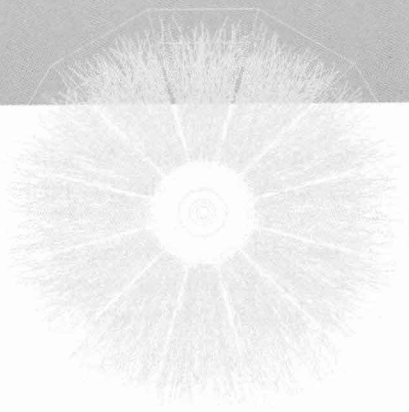
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About the cover: The head-on collision of two bare gold nuclei, each traveling at 99.99 percent of the speed of light, produces thousands of particles whose trajectories were recorded by the STAR detector at Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC). [*Courtesy of Brookhaven National Laboratory, STAR experiment.*]



Preface



This new edition of *Modern Physics* brings to the fore the discoveries and developments that have augmented modern physics during the opening years of the twenty-first century and continues to respond to the numerous helpful suggestions that were offered by the users of the previous editions. As the term *modern physics* has evolved to mean the physics of the modern era—relativity and quantum theory—we have preserved the historical and cultural flavor and carefully maintained the mathematical level of the third edition. We have continued, indeed enhanced, the flexibility for instructors to match the book to a wide variety of teaching modes, including both one- and two-semester courses and media-enhanced courses.

Features

The successful features of the third edition have been retained. Among them are the following:

- The logical structure—beginning with an introduction to relativity and quantization and following with applications—has been continued. Opening the book with relativity has been endorsed by the overwhelming majority of reviewers.
- As with the third edition, we have put great effort into the problem sets, resulting in the greatest quantity and variety you'll find. The end-of-chapter problems are separated into sets based on difficulty, with the Level I (easiest) ones grouped by chapter section.
- The first edition's *Instructor's Solutions Manual* with solutions, not just answers, to all end-of-chapter problems was the first such aid to accompany a physics (and not just a modern physics) textbook, and that leadership has been continued in this edition. The *Instructor's Solutions Manual (ISM)* is available in print or on CD for those adopting *Modern Physics*, Fourth Edition, for their classes. A paperback *Student's Solution Manual* containing one-quarter of the solutions is also available.
- We have continued the use of real data in figures, photos of real people and apparatus, and short quotations by many scientists who were key participants in the development of modern physics. These features, along with the Notes at the end of each chapter, bring to life many events in the history of science and help

counter the too-prevalent view among students that physics is a dull, impersonal collection of facts and formulas.

- We have continued to use many examples in every chapter. As before, we use combined quantities such as hc , $\hbar c$, and ke^2 in $\text{eV} \cdot \text{nm}$ to simplify many numerical calculations.
- The summaries and reference lists at the end of every chapter have been retained, including the two-column format of the former that improves its clarity.
- Questions for discussion and review at the ends of various sections continue to appear throughout the new edition.
- EXPLORING sections, identified by an atom icon  and dealing with related topics of high student interest, are distributed throughout the text.
- The book's Web site, containing Chapter 14, "Astrophysics and Cosmology," and the MORE sections, and enthusiastically endorsed by both students and instructors, has been significantly improved. MORE sections are indicated by an icon  and a brief description. Both the MORE sections and Chapter 14 are provided in Adobe Acrobat® for easy download and printing.

New Features

Several new features have been added for the fourth edition. Among them:

- We have added or modified numerous sections and paragraphs that reflect discoveries and advances that have been made in modern physics since the previous edition. Among these are neutrino oscillations, gravity wave experiments, and dark energy. Responding to users and reviewers, we have also added a new section on magnetism to Chapter 10.
- More than 15 percent of the over 700-plus end-of-chapter problems are new or modified from the previous edition.
- The *Instructor's Solutions Manual*, containing solutions to all end-of-chapter problems is now available on a CD to instructors adopting the text.
- The book's site on the World Wide Web has been expanded to become even more helpful to instructors and students. In addition to Chapter 14 and 30-plus MORE sections, it now has a "Physics in the Twenty-first Century" section, updated frequently by the authors, to keep users better informed about what is happening in modern physics *now*. Located at <http://www.whfreeman.com/modphysics4e>, it may be directly accessed by students or linked by instructors to their own course home pages.
- The instructor's side of the Web site and the Instructor's Resource CD include about 50 percent of the figures from the text in PowerPoint®. This enables the examination of figure details on individual computer screens and large-screen projection in multimedia classrooms. Given the accuracy of the actual data diagrams, measurements can be made directly from the projected images for in-class examples and calculations.
- A new MORE section, "How Transistors Work," has been added to those located on the Web site to amplify, extend, and provide examples of selected material in the book.
- Chapter 14, "Astrophysics and Cosmology," located on the book's Web site, has been thoroughly revised. Extensive use is made of the dramatic, high-resolution color imagery available from the many observatories throughout the world and the Hubble Space Telescope. Chapter 14 is designed according to specifications of the text and is provided in Adobe Acrobat® for color or black-and-white printing. The outline of this chapter is included in the printed book's table of contents.

Organization and Coverage

This edition, as the earlier ones, is divided into two parts: Part 1, “Relativity and Quantum Mechanics: The Foundations of Modern Physics,” and Part 2, “Applications.” We continue to open Part 1 with the two relativity chapters. This location for relativity is firmly endorsed by users and reviewers. The rationale is that this arrangement avoids separation of the foundations of quantum mechanics in Chapters 3 through 8 from its applications in Chapters 9 through 14. The two-chapter format for relativity provides instructors the flexibility to cover only the basic concepts or to go deeper into the subject. Chapter 1 covers the basics of special relativity and includes discussions of several paradoxes, such as the twin paradox and the pole-in-the-barn paradox, that never fail to excite student interest. Relativistic energy and momentum are covered in Chapter 2, which concludes with an expanded qualitative section on general relativity that emphasizes experimental tests. Because the relation $E^2 = p^2c^2 + (mc^2)^2$ is the main result needed for the later applications chapters, it is possible to omit this chapter without disturbing continuity. Chapters 3 through 7 have been updated with several improved explanations and new diagrams. Many quantitative topics are included as MORE sections on the Web site. Examples of these are the derivation of Compton’s equation (Chapter 3), the details of Rutherford’s alpha scattering theory (Chapter 4), the graphical solution of the finite square well (Chapter 6), the excited states and spectra of two-electron atoms (Chapter 7), and an analysis of how bipolar transistors work (Chapter 10). The section on “The Schrödinger Equation for Two (or More) Particles” has been moved from Chapter 6 to Chapter 7 at the suggestion of several reviewers. Chapter 8, “Statistical Physics,” which completes Part 1, uses the quantum statistics chapter of the first edition as its core. The kinetic theory material in the second chapter of that edition is a MORE section, serving as an introductory review for classical statistics. The comparisons of classical and quantum statistics are illustrated with several examples, and Chapter 8, unlike other chapters in Part 1, is arranged to be covered briefly and qualitatively, if desired. This chapter, like Chapter 2, is not essential to the understanding of those in Part 2 and may be used by instructors as an application chapter or omitted without loss of continuity.

Preserving the approach used in the previous edition, in Part 2 the ideas and methods discussed in Part 1 are applied to the study of molecules, solids, nuclei, particles, and the cosmos. Chapter 9 (“Molecular Structure and Spectra”) is a broad, detailed discussion of molecular bonding and the basic types of lasers. Chapter 10 (“Solid-State Physics”) includes sections on the quantum Hall effect and high-temperature superconductivity. A new Section 10–7 on magnetism has been added and material on the operation of transistors has been moved to a MORE section on the Web site. Chapter 11 (“Nuclear Physics”) focuses on nuclear properties and the structure of nuclei; it contains a new discussion of the neutrino mass experiments. Discussion of the semiempirical mass formula continues as a topic in a MORE section. Fission, fusion, and applications of nuclear reactions are the focus of Chapter 12, which includes a new discussion of accelerator mass spectrometry and particle-induced x-ray emission elemental analysis. The interactions of particles and radiation with matter and a discussion of radiation dosage continue as MORE sections. The material on particle physics, Chapter 13, has been revised to reflect the advancements of that field since the previous edition. The emphasis is on qualitatively discussing the fundamental particle interactions, conservation laws, and the standard model. Finally, an extensively revised Chapter 14 (“Astrophysics and Cosmology”) examines the current observations of stars and galaxies and qualitatively integrates our discussions of quantum mechanics, atoms, nuclei, particles, and relativity to explain our present

understanding of the universe. It includes several new EXPLORING sections. Located with deliberate and symbolic intent on the book's Web site, this location enables us to include some of the beautiful color imagery available from today's remarkable telescopes and to update the chapter's contents between revisions.

New Coverage

Research over the past quarter century has added abundantly to our understanding of our world, enhanced the links from physics to virtually every other discipline, and measurably improved the tools and devices that enrich life. Here are just a few of the new topics covered in *Modern Physics*, Fourth Edition, that reflect 25 years of physics research.

- **The search for the Higgs boson** has shifted into high gear at Brookhaven's Relativistic Heavy Ion Collider and at CERN with construction of the Large Hadron Collider. (Chapter 13)
- **The neutrino mass problem** appears to be solved by measurements from the Super Kamiokande and SNO neutrino detectors. (Chapters 2 and 11)
- **The spin of the proton** may include contributions from virtual strange quarks. (Chapter 11)
- **The Bose-Einstein condensates**, that suggest that atomic lasers and super-atomic clocks are in our future, have been joined by **Fermi-Dirac condensates**. (Chapter 8)
- It now appears that a mysterious **dark energy** accounts for as much as 70 percent of the mass of the universe. (Chapter 14)
- **Scanning tunneling and atomic force microscopes** can image individual atoms, and probes can put the atoms where we want them. (Chapter 10)
- **High-temperature superconductors have reached $> 130\text{ K}$ with doped fullerenes now competing with cuprates for high- T_c records**, but we still don't know why they work. (Chapter 10)
- **Gravity waves from space** may soon be detected by the Large Interferometric Gravitational Observatory. (Chapter 2)
- **Adaptive-optics telescopes, large baseline arrays, and the improved Hubble telescope** are providing new views of deeper into space of the very young universe, revealing that the expansion is speeding up. (Chapter 14)
- **Giant Rydberg atoms**, made accessible by research on tunable dye lasers, are now of high interest and may provide the first direct test of the correspondence principle. (Chapter 4)
- **The search for new elements has reached $Z = 114$ and possibly 116**, tantalizingly near the edge of the "island of stability." (Chapter 11)

Many more new discoveries and developments are to be found throughout the fourth edition of *Modern Physics*.

Some Teaching Suggestions

This book is designed to serve well in either one- or two-semester courses. The chapters in Part 2 are independent of one another and can be covered in any order, with the exception that Chapter 12 is best preceded by Chapter 11. Some possible one-semester courses might consist of:

- Part 1, Chapters 1, 3, 4, 5, 6, 7; and Part 2, Chapters 11, 13
- Part 1, Chapters 3, 4, 5, 6, 7, 8; and Part 2, Chapters 9, 10

- Part 1, Chapters 1, 2, 3, 4, 5, 6, 7; and Part 2, Chapter 9
- Part 1, Chapters 1, 3, 4, 5, 6, 7; and Part 2, Chapters 11, 13, 14

Possible two-semester courses might be made up of:

- Part 1, Chapters 1, 3, 4, 5, 6, 7; and Part 2, Chapters 9, 10, 11, 12, 13, 14
- Part 1, Chapters 1, 2, 3, 4, 5, 6, 7, 8; and Part 2, Chapters 9, 10, 11, 12

There is tremendous potential for individual student projects and extra-credit assignments based on the EXPLORING or, in particular, the MORE sections. The latter will encourage students to search for related sources on the web.

Acknowledgments

Many people contributed to the success of the earlier editions of this book and many more have helped with the development of the fourth edition. We owe our thanks to them all. Those who reviewed all or parts of this book, offering suggestions for the fourth edition, include the following:

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Paul A. Tipler, Berkeley, California
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MODERN PHYSICS

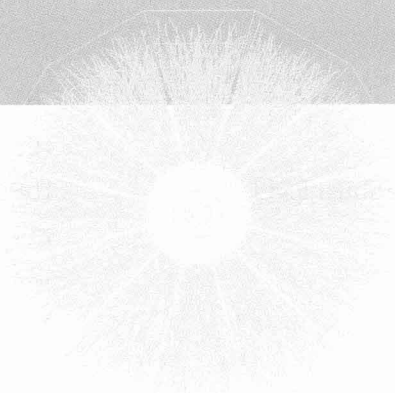
Part 1

Relativity and Quantum Mechanics: The Foundations of Modern Physics

The earliest recorded systematic efforts to assemble knowledge about motion as a key to understanding natural phenomena were those of the ancient Greeks. Set forth in sophisticated form by Aristotle, theirs was a natural philosophy (i.e., physics) of explanations deduced from assumptions rather than experimentation. For example, it was a fundamental assumption that every substance had a “natural place” in the universe. Motion then resulted when a substance was trying to reach its natural place. Time was given a similar absolute meaning, as moving from some instant in the past (the creation of the universe) toward some end goal in the future, its natural place. The remarkable agreement between the deductions of Aristotelian physics and motions observed throughout the physical universe, together with a nearly total absence of accurate instruments to make contradictory measurements, enabled acceptance of the Greek view for nearly 2000 years. Toward the end of that time a few scholars had begun to deliberately test some of the predictions of theory, but it was the Italian scientist Galileo Galilei who, with his brilliant experiments on motion, established for all time the absolute necessity of experimentation in physics and, coincidentally, initiated the disintegration of Aristotelian physics. Within 100 years Isaac Newton had generalized the results of Galileo’s experiments into his three spectacularly successful laws of motion, and the natural philosophy of Aristotle was gone.

With the burgeoning of experimentation, the following 200 years saw a multitude of major discoveries and a concomitant development of physical theories to explain them. Most of the latter, then as now, failed to survive increasingly sophisticated experimental tests, but by the dawn of the twentieth century Newton’s theoretical explanation of the motion of mechanical systems had been joined by equally impressive laws of electromagnetism and thermodynamics as expressed by Maxwell, Carnot, and others. The remarkable success of these laws led many scientists to believe that description of the physical universe was complete. Indeed, A. A. Michelson, speaking to scientists near the end of the nineteenth century, said, “The grand underlying principles have been firmly established . . . the future truths of physics are to be looked for in the sixth place of decimals.”

Such optimism (or pessimism, depending on your point of view) turned out to be premature, as there were already vexing cracks in the foundation of what we now refer to as classical physics. Two of these were described by Lord Kelvin, in his famous Baltimore Lectures in 1900, as the “two clouds” on the horizon of twentieth-century physics: the failure of theory to account for the radiation spectrum emitted by a blackbody and the inexplicable results of the Michelson-Morley experiment. Indeed, the breakdown of classical physics occurred in many




Contents

Part 1











Relativity and Quantum Mechanics: The Foundations of Modern Physics














1


<i>Chapter 1</i>	Relativity I	2
1-1	The Experimental Basis of Relativity	3
	 The Michelson-Morley Experiment	14
1-2	Einstein's Postulates	14
1-3	The Lorentz Transformation	21
	 Exploring Calibrating the Spacetime Axes	32
1-4	Time Dilation and Length Contraction	33
1-5	The Doppler Effect	46
	 Exploring Transverse Doppler Effect	50
1-6	The Twin Paradox and Other Surprises	50
	 The Case of the Identically Accelerated Twins	53
	 Exploring Superluminal Speeds	57
 <i>Chapter 2</i>	 Relativity II	 69
2-1	Relativistic Momentum	70
2-2	Relativistic Energy	74
	 Exploring Another Surprise!	85
2-3	Mass/Energy Conversion and Binding Energy	87

The  icon indicates material that appears only on the Web site: www.whfreeman.com/modphysics4e

The  icon indicates material of high interest to students.

2-4	Invariant Mass	91
2-5	General Relativity	105
	 Exploring Deflection of Light in a Gravitational Field	108
	 Exploring Gravitational Redshift	111
	 Perihelion of Mercury's Orbit	114
	 Delay of Light in a Gravitational Field	115
<i>Chapter 3</i>	Quantization of Charge, Light, and Energy	125
3-1	Quantization of Electric Charge	125
	 Millikan's Oil-Drop Experiment	132
3-2	Blackbody Radiation	132
3-3	The Photoelectric Effect	141
3-4	X Rays and the Compton Effect	147
	 Derivation of Compton's Equation	153
<i>Chapter 4</i>	The Nuclear Atom	162
4-1	Atomic Spectra	163
4-2	Rutherford's Nuclear Model	165
	 Rutherford's Prediction and Geiger & Marsden's Results	172
4-3	The Bohr Model of the Hydrogen Atom	175
	 Exploring Giant Atoms	185
4-4	X-Ray Spectra	186
4-5	The Franck-Hertz Experiment	191
4-6	Critique of Bohr Theory and the "Old" Quantum Mechanics	194
<i>Chapter 5</i>	The Wavelike Properties of Particles	203
5-1	The de Broglie Hypothesis	203
5-2	Measurements of Particle Wavelengths	204
5-3	Wave Packets	215
5-4	The Probabilistic Interpretation of the Wave Function	223
5-5	The Uncertainty Principle	225
	 Exploring The Gamma Ray Microscope	227
5-6	Some Consequences of the Uncertainty Principle	229
5-7	Wave-Particle Duality	233
	 Two-Slit Interference Pattern	234



Chapter 6	The Schrödinger Equation	242
6-1	The Schrödinger Equation in One Dimension	243
6-2	The Infinite Square Well	250
6-3	The Finite Square Well	260
	 Graphical Solution of the Finite Square Well	263
6-4	Expectation Values and Operators	264
	 Transitions Between Energy States	268
6-5	The Simple Harmonic Oscillator	268
	 Exploring Parity	272
6-6	Reflection and Transmission of Waves	272
	 Exploring Alpha Decay	280
	 Exploring NH ₃ Atomic Clock	282
	 Tunnel Diodes	283
Chapter 7	Atomic Physics	291
7-1	The Schrödinger Equation in Three Dimensions	291
7-2	Quantization of Angular Momentum and Energy in the Hydrogen Atom	294
7-3	Hydrogen Atom Wave Functions	304
7-4	Electron Spin	308
	 Exploring Stern-Gerlach Experiment	311
7-5	Total Angular Momentum and the Spin-Orbit Effect	314
7-6	The Schrödinger Equation for Two (or More) Particles	318
7-7	Ground States of Atoms: The Periodic Table	320
7-8	Excited States and Spectra of Atoms	324
	 Multielectron Atoms	326
	 The Zeeman Effect	327
	 Exploring Frozen Light	327
Chapter 8	Statistical Physics	338
8-1	Classical Statistics	339
	 Kinetic Theory: A Brief Review	339
	 Temperature and Entropy	342
	 A Derivation of the Equipartition Theorem	350
8-2	Quantum Statistics	354

8-3	The Bose-Einstein Condensation	362
	Exploring Liquid Helium	363
8-4	The Photon Gas: An Application of Bose-Einstein Statistics	371
8-5	Properties of a Fermion Gas	379








Part 2














<i>Applications</i>	389
---------------------	-----






<i>Chapter 9</i>	Molecular Structure and Spectra	390
------------------	---------------------------------	-----

9-1	The Ionic Bond	391
9-2	The Covalent Bond	395
	Other Covalent Bonds	402
	9-3 Exploring Other Bonding Mechanisms	403
9-4	Energy Levels and Spectra of Diatomic Molecules	406
9-5	Absorption, Stimulated Emission, and Scattering	416
9-6	Lasers and Masers	423

<i>Chapter 10</i>	Solid-State Physics	439
-------------------	---------------------	-----

10-1	The Structure of Solids	439
10-2	Classical Theory of Conduction	449
	Thermal Conduction—The Classical Model	455
10-3	Free-Electron Gas in Metals	456
10-4	Quantum Theory of Conduction	460
	Thermal Conduction—The Quantum Model	464
10-5	Magnetism in Solids	464
10-6	Band Theory in Solids	467
	Energy Bands in Solids—An Alternate Approach	475
10-7	Impurity Semiconductors	475
	Exploring Hall Effect	478
10-8	Semiconductor Junctions and Devices	481
	How Transistors Work	486
10-9	Superconductivity	486
	Exploring Flux Quantization	492
	Exploring Josephson Junctions	496

<i>Chapter 11</i>	Nuclear Physics	506
11-1	Composition of the Nucleus	507
11-2	Ground-State Properties of Nuclei	508
	 Liquid-Drop Model and the Semiempirical Mass Formula	519
11-3	Radioactivity	522
	 Production and Sequential Decays	525
11-4	Alpha, Beta, and Gamma Decay	525
	 Energetics of Alpha Decay	529
	 Exploring Mössbauer Effect	537
11-5	The Nuclear Force	540
	 Exploring Probability Density of the Exchange Mesons	546
11-6	The Shell Model	547
	 Exploring Finding the “Correct” Shell Model	550
 <i>Chapter 12</i>	 Nuclear Reactions and Applications	 562
12-1	Nuclear Reactions	563
12-2	Fission, Fusion, and Nuclear Reactors	573
	 Safety Issues of Fission Reactors	586
	 Interaction of Particles and Matter	593
12-3	Applications	594
	 Radiation Dosage	607
 <i>Chapter 13</i>	 Particle Physics	 615
13-1	Particles and Antiparticles	616
13-2	Fundamental Interactions and the Classification of Particles	622
	 Exploring A Further Comment About Interaction Strengths	630
13-3	Conservation Laws and Symmetries	633
	 When Is a Physical Quantity Conserved?	636
	 Resonances and Excited States	642
13-4	The Standard Model	643
	 Exploring Where Does the Proton Get Its Spin?	649
13-5	Beyond the Standard Model	658

	Chapter 14	Astrophysics and Cosmology	
		Chapter 14 appears only on the Web site: www.whfreeman.com/modphysics4e	
	14-1	The Sun	
		 Exploring Is There Life Elsewhere?	
	14-2	The Stars	
	14-3	The Evolution of Stars	
	14-4	Cataclysmic Events	
	14-5	The Final States of Stars	
	14-6	Galaxies	
		 Exploring Telescopes	
	14-7	Gravitation and Cosmology	
	14-8	Cosmogenesis	
		 Exploring “Natural” (Planck) Units	
	<i>Appendix A</i>	Table of Atomic Masses	AP-1
	<i>Appendix B</i>	Mathematical Aids	AP-16
		B1 Probability Integrals	AP-16
		B2 Distribution Functions	AP-18
		B3 Derivation of the Boltzmann Distribution	AP-21
		B4 Binomial and Exponential Series	AP-22
	<i>Appendix C</i>	Electron Configurations	AP-23
	<i>Appendix D</i>	Fundamental Physical Constants	AP-28
	<i>Appendix E</i>	Conversion Factors	AP-32
	<i>Appendix F</i>	Nobel Laureates in Physics	AP-33
	<i>Answers</i>		AN-1
	<i>Index</i>		I-1