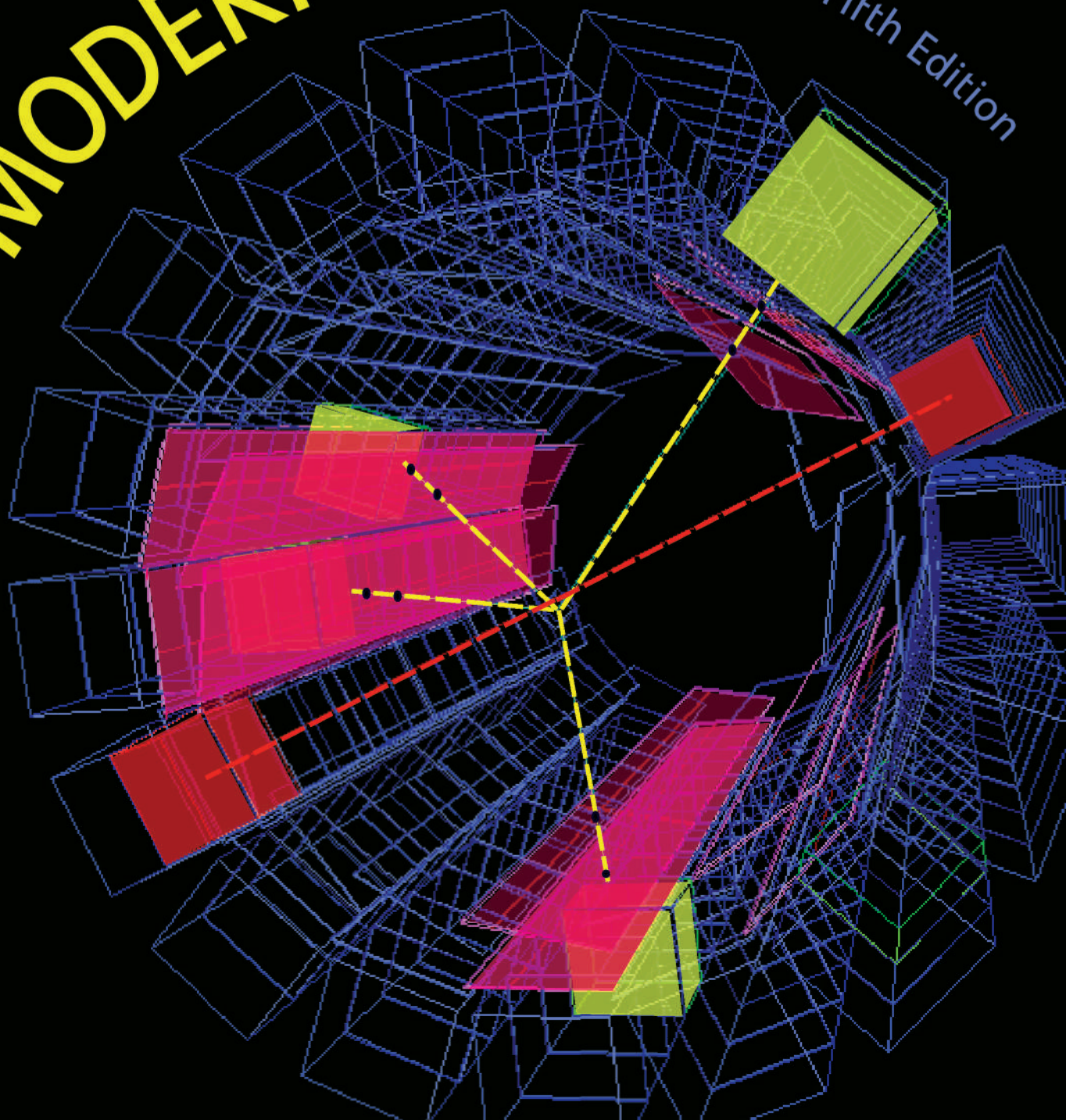
Paul A. Tipler
Ralph A. Llewellyn

MODERN PHYSICS

Fifth Edition



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Fifth Edition

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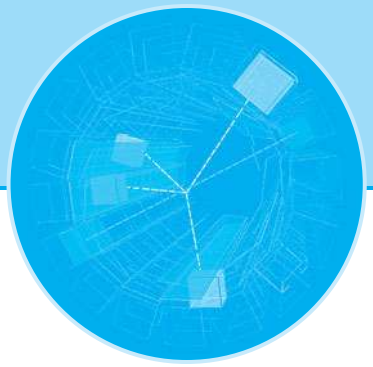

Preface

In preparing this new edition of *Modern Physics,* we have again relied heavily on the many helpful suggestions from a large team of reviewers and from a host of instructor and student users of the earlier editions. Their advice reflected the discoveries that have further enlarged modern physics in the early years of this new century and took note of the evolution that is occurring in the teaching of physics in colleges and universities. As the term *modern physics* has come to mean the physics of the modern era—relativity and quantum theory—we have heeded the advice of many users and reviewers and preserved the historical and cultural flavor of the book while being careful to maintain the mathematical level of the fourth edition. We continue to provide the flexibility for instructors to match the book and its supporting ancillaries to a wide variety of teaching modes, including both one- and two-semester courses and media-enhanced courses.

Features

The successful features of the fourth edition have been retained, including 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 many reviewers and instructors.
- As in the earlier editions, the end-of-chapter problems are separated into three sets based on difficulty, with the least difficult also grouped by chapter section. More than 10 percent of the problems in the fifth edition are new. The first edition's *Instructor's Solutions Manual* (*ISM*) 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 ISM is available in print or on CD for those adopting *Modern Physics,* fifth edition, for their classes. As with the previous edition, a paperback *Student's Solution Manual* containing one-quarter of the solutions in the ISM is also available.
- We have continued to include many examples in every chapter, a feature singled out by many instructors as a strength of the book. As before, we frequently use combined quantities such as hc, $\hbar c$, and ke^2 in eV · nm to simplify many numerical calculations.
- The summaries and reference lists at the end of every chapter have, of course, been retained and augmented, including the two-column format of the summaries, which improves their clarity.

- We have continued the use of real data in figures, photos of real people and apparatus, and short quotations from 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.
- More than two dozen Exploring sections, identified by an atom icon and dealing with text-related topics that captivate student interest such as superluminal speed and giant atoms, are distributed throughout the text.
- The book's Web site includes 30 MORE sections, which expand in depth on many text-related topics. These have been enthusiastically endorsed by both students and instructors and often serve as springboards for projects and alternate credit assignments. Identified by a laptop icon , each is introduced with a brief text box.
- More than 125 questions intended to foster discussion and review of concepts are distributed throughout the book. These have received numerous positive comments from many instructors over the years, often citing how the questions encourage deeper thought about the topic.
- Continued in the new edition are the Application Notes. These brief notes in the margins of many pages point to a few of the many benefits to society that have been made possible by a discovery or development in modern physics.

New Features

A number of new features are introduced in the fifth edition:

- The "Astrophysics and Cosmology" chapter that was on the fourth edition's Web site has been extensively rewritten and moved into the book as a new Chapter 13. Emphasis has been placed on presenting scientists' current understanding of the evolution of the cosmos based on the research in this dynamic field.
- The "Particle Physics" chapter has been substantially reorganized and rewritten focused on the remarkably successful Standard Model. As the new Chapter 12, it immediately precedes the new "Astrophysics and Cosmology" chapter to recognize the growing links between these active areas of current physics research.
- The two chapters concerned with the theory and applications of nuclear physics have been integrated into a new Chapter 11, "Nuclear Physics." Because of the renewed interest in nuclear power, that material in the fourth edition has been augmented and moved to a MORE section of the Web.
- Recognizing the need for students on occasion to be able to quickly review key concepts from classical physics that relate to topics developed in modern physics, we have added a new Classical Concept Review (CCR) to the book's Web site. Identified by a laptop icon in the margin near the pertinent modern physics topic of discussion, the CCR can be printed out to provide a convenient study support booklet.
- The *Instructor's Resource* CD for the fifth edition contains all the illustrations from the book in both PowerPoint and JPEG format. Also included is a gallery of the astronomical images from Chapter 13 in the original image colors.
- Several new MORE sections have been added to the book's Web site, and a few for which interest has waned have been removed.

Organization and Coverage

This edition, like the earlier ones, is divided into two parts: Part 1, "Relativity and Quantum Mechanics: The Foundation 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 12. The two-chapter format for relativity provides instructors with the flexibility to cover only the basic concepts or to go deeper into the subject. Chapter 1 covers the essentials 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 a mostly qualitative section on general relativity that emphasizes experimental tests. Because the relation $E^2 = p^2c^2 + (mc^2)^2$ is the result most needed for the later applications chapters, it is possible to omit Chapter 2 without disturbing continuity. Chapters 1 through 8 have been updated with a number of improved explanations and new diagrams. Several classical foundation topics in those chapters have been moved to the Classical Concept Review or recast as MORE sections. 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), and the excited states and spectra of two-electron atoms (Chapter 7). The comparisons of classical and quantum statistics are illustrated with several examples in Chapter 8, and unlike the other chapters in Part 1, Chapter 8 is arranged to be covered briefly and qualitatively if desired. This chapter, like Chapter 2, is not essential to the understanding of the applications chapters of Part 2 and may be used as an applications 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 bonding in metals, magnetism, and superconductivity. Chapter 11 ("Nuclear Physics") is an integration of the nuclear theory and applications that formed two chapters in the fourth edition. It focuses on nuclear structure and properties, radioactivity, and the applications of nuclear reactions. Included in the last topic are fission, fusion, and several techniques of age dating and elemental analysis. The material on nuclear power has been moved to a MORE section, and the discussion of radiation dosage continues as a MORE section. As mentioned above, Chapter 12 ("Particle Physics") has been substantially reorganized and rewritten with a focus on the Standard Model and revised to reflect the advances in that field since the earlier editions. The emphasis is on the fundamental interactions of the quarks, leptons, and force carriers and includes discussions of the conservation laws, neutrino oscillations, and supersymmetry. Finally, the thoroughly revised Chapter 13 ("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 origin and evolution of the universe from the Big Bang to dark energy.

The Research Frontier

Research over the past century has added abundantly to our understanding of our world, forged strong links from physics to virtually every other discipline, and measurably improved the tools and devices that enrich life. As was the case at the beginning of the last century, it is hard for us to foresee in the early years of this century how scientific research will deepen our understanding of the physical universe and enhance the quality of life. Here are just a few of the current subjects of frontier research included in *Modern Physics,* fifth edition, that you will hear more of in the years just ahead. Beyond these years there will be many other discoveries that no one has yet dreamed of.

- **The Higgs boson**, the harbinger of mass, may now be within our reach at Brookhaven's Relativistic Heavy Ion Collider and at CERN with completion of the Large Hadron Collider. (Chapter 12)
- **The neutrino mass question** has been solved by the discovery of neutrino oscillations at the Super-Kamiokande and SNO neutrino observatories (Chapters 2, 11, and 12), but the magnitudes of the masses and whether the neutrino is a Majorana particle remain unanswered.
- **The origin of the proton's spin**, which may include contributions from virtual strange quarks, still remains uncertain. (Chapter 11)
- **The Bose-Einstein condensates**, which suggest atomic lasers and super–atomic clocks are in our future, were joined in 2003 by **Fermi-Dirac condensates,** wherein pairs of fermions act like bosons at very low temperatures. (Chapter 8)
- **It is now clear that dark energy** accounts for 74 percent of the mass/energy of the universe. Only 4 percent is baryonic (visible) matter. The remaining 22 percent consists of as yet unidentified **dark matter** particles. (Chapter 13)
- **The predicted fundamental particles of supersymmetry (SUSY)**, an integral part of grand unification theories, will be a priority search at the Large Hadron Collider. (Chapters 12 and 13)
- **High-temperature superconductors reached critical temperatures greater than 130 K a few years ago and doped fullerenes compete with cuprates for high-T_c records,** but a theoretical explanation of the phenomenon is not yet in hand. (Chapter 10)
- **Gravity waves from space** may soon be detected by the upgraded Laser Interferometric Gravitational Observatory (LIGO) and several similar laboratories around the world. (Chapter 2)
- **Adaptive-optics telescopes, large baseline arrays, and the Hubble telescope** are providing new views deeper into space of the very young universe, revealing that the expansion is speeding up, a discovery supported by results from the Sloan Digital Sky Survey and the Wilkinson Microwave Anisotropy Project. (Chapter 13)
- **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 $Z = 118$,** tantalizingly near the edge of the "island of stability." (Chapter 11)

Many more discoveries and developments just as exciting as these are to be found throughout *Modern Physics,* fifth edition.

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. Some possible one-semester courses might consist of

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

Possible two-semester courses might consist of

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

There is tremendous potential for individual student projects and alternate credit assignments based on the Exploring and, 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 fifth edition. We owe our thanks to them all. Those who reviewed all or parts of this book, offering suggestions for the fifth edition, include

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Oviedo, Florida

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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, led to 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 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 different areas: the Michelson-Morley null result contradicted Newtonian relativity, the blackbody radiation spectrum contradicted predictions of thermodynamics, the photoelectric effect and the spectra of atoms could not be explained by electromagnetic theory, and the exciting discoveries of x rays and radioactivity seemed to be outside the framework of classical physics entirely. The development of the theories of quantum mechanics and relativity in the early twentieth century not only dispelled Kelvin's "dark clouds," they provided answers to all of the puzzles listed here and many more. The applications of these theories to such microscopic systems as atoms, molecules, nuclei, and fundamental particles and to macroscopic systems of solids, liquids, gases, and plasmas have given us a deep understanding of the intricate workings of nature and have revolutionized our way of life.

In Part 1 we discuss the foundations of the physics of the modern era, relativity theory, and quantum mechanics. Chapter 1 examines the apparent conflict between Einstein's principle of relativity and the observed constancy of the speed of light and shows how accepting the validity of both ideas led to the special theory of relativity. Chapter 2 discusses the relations connecting mass, energy, and momentum in special relativity and concludes with a brief discussion of general relativity and some experimental tests of its predictions. In Chapters 3, 4, and 5 the development of quantum theory is traced from the earliest evidences of quantization to de Broglie's hypothesis of electron waves. An elementary discussion of the Schrödinger equation is provided in Chapter 6, illustrated with applications to one-dimensional systems. Chapter 7 extends the application of quantum mechanics to many-particle systems and introduces the important new concepts of electron spin and the exclusion principle. Concluding the development, Chapter 8 discusses the wave mechanics of systems of large numbers of identical particles, underscoring the importance of the symmetry of wave functions. Beginning with Chapter 3, the chapters in Part 1 should be studied in sequence because each of Chapters 4 through 8 depends on the discussions, developments, and examples of the previous chapters.