MODERN PHYSICS

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ABOUT THE AUTHOR

FRANK J. BLATT earned B.S. and M.S. degrees in electrical engineering from M.I.T. and the Ph.D. in physics from the University of Washington. After three years as Research Associate with Professors Seitz and Bardeen at the University of Illinois, he joined the faculty of the physics department of Michigan State University. Since 1987 Dr. Blatt has been a member of the faculty of the University of Vermont. Professor Blatt spent a year at Oxford University on an N.S.F. post-doctoral fellowship and has served as visiting professor at the Swiss Federal Institute of Technology (E.T.H., Zurich), Simon Fraser University (Vancouver, B.C.), Université de Louvain (Belgium), Leeds University (England), University of North Sumatra (Indonesia), Institute of Technology (Shah Alam, Malaysia), and the United States Military Academy (West Point). Professor Blatt has written a number of books—*Physics of Electronic Conduction in Solids* (McGraw-Hill, 1968), *Thermoelectric Power of Metals* (with C. L. Foiles, D. Greig, and P. A. Schroeder, Plenum Press, 1972), and *Principles of Physics* (Allyn & Bacon, 1983, 1986, 1989)—as well as over 80 research articles in solid state physics and biophysics.

For JMB

Preface

This is a textbook for a one-semester introductory course in modern physics. The topics covered here include relativity, elementary quantum mechanics, and atomic, molecular, solid state, nuclear, and elementary particle physics, as well as a brief account of instrumentation for nuclear physics research. The text assumes that the reader has completed the standard introductory calculus-based physics course.

The primary purpose of a first course in modern physics, often the only course on the subject, is to introduce the student to the concepts and ideas of twentieth-century physics. Although the new, indeed revolutionary, approach to our understanding of nature is now widely accepted, these novel ideas met at first much skepticism and occasionally overt resistance. Understandably, students also find the concepts and axioms of relativity and quantum physics difficult to embrace. In presenting the subject, I have adopted an historical approach because the reader is better able to follow the reasoning that led physicists at the start of the twentieth century to suggest what then seemed preposterous propositions. Almost every chapter begins with a brief but succinct account of events that led to the development of the topic treated in the following pages, and throughout the text the reader will find numerous references to the original literature.

There are several reasons for including historical material and ample references to primary sources in a physics text. First, it helps students appreciate that science is an ongoing human enterprise, that whatever we may today accept as "scientific truth" is subject to question and may well have to be abandoned in light of new data. Second, historical accounts place modern science, a pervasive component of our culture, in proper perspective. And last, the occasional historical or anecdotal paragraphs provide a welcome interlude between more difficult sections of the text.

The first three chapters are devoted to the theory of relativity. Chapter 3, an innovation in an introductory modern physics text, is a largely descriptive account of the general relativity; it is included in light of recent technological advances that have allowed careful and precise experiments and have stimulated new interest in the field.

Quantum theory is the central theme of the next five chapters. Chapter 4 summarizes the experimental findings that ultimately led to broad acceptance of energy quantization. Chapter 5 is an account of the Bohr model of the hydrogen atom. The concept of cross section is introduced and illustrated in connection with Rutherford scattering. The de Broglie hypothesis and experiments that validated it are described in Chapter 6.

Elementary quantum mechanics is the subject matter of Chapters 7 and 8. The Schrödinger equation is introduced in Chapter 7 and the standard one-dimensional examples—infinite and finite square wells, barrier penetration, and the harmonic oscillator—are presented. Chapter 8 addresses primarily the quantum mechanics of the hydrogen atom. It is here that the phrase "it can be shown," studiously avoided elsewhere in the text, will occasionally be found. The formal solution of the Schrödinger equation in spherical coordinates is well beyond the mathematical sophistication of the student whose background is a one-year course in differential and integral calculus. Yet, to present the results, such as angular momentum quantization, in an ad hoc manner without at least a ''hand-waving'' justification does the student a disservice by suggesting some mystical aspect to quantization and selection rules.

Chapters 9 and 10 concern the quantum theory of atomic and molecular structure. Here intrinsic spin and the Pauli exclusion principle make their first appearance. Spin-orbit splitting, selection rules for dipole transitions, the ground state of helium, and the forces responsible for the bound state of the hydrogen molecule are presented in these chapters. Here, too, is the first of many sections on technological applications of modern physics—a discussion of the principles of maser and laser operation.

Chapter 11, Statistical Physics, reviews the concepts of classical statistical mechanics and then shows how the different counting procedures that must be employed when dealing with indistinguishable particles lead to Bose-Einstein and Fermi-Dirac distributions. The chapter concludes with a section on liquid helium, a convincing experimental demonstration of Bose-Einstein condensation.

Chapters 12 and 13 are devoted to solid state physics, the first to crystal structure, cohesive forces, and a brief survey of crystal defects and their crucial roles in diffusion, plastic flow, and crystal growth. The chapter concludes with a description of the energy states of the quasi-free electron gas in a periodic potential and introduces the concepts of energy bands, energy gaps, and effective masses.

Chapter 13 focuses on electronic properties. Electronic specific heat and conductivity of metals is followed by a discussion of electronic properties of homogeneous semiconductors. The next section is devoted to devices, including *p-n* junction diodes, tunnel diodes, *n-p-n* and field-effect transistors, photovoltaic cells, and junction lasers. In the final section of the chapter the dominant features of superconductivity are described; Josephson junctions and SQUIDs are discussed, and some applications of these sensors are presented.

Nuclear physics is the subject of Chapters 14 and 15. Chapter 14 contains a general description of the properties of nuclei, of nuclear forces, binding energy, nuclear spin and magnetic moment, and of the liquid drop model. The final section of this chapter gives a fairly detailed explanation of nuclear magnetic resonance and one of the most significant practical applications of this technique, NMR imaging.

Chapter 15 is concerned with radioactivity and nuclear reactions. Here again, several sections are devoted to practical matters—fission and fusion as energy sources, and the use of radioisotopes in archeology and medicine.

Chapter 16 contains brief descriptions of accelerators and particle detectors, instruments used in nuclear physics research. The final chapter is a brief survey of elementary particle physics and touches on the more recent theoretical advances in our understanding of the fundamental forces of nature.

In a one-semester course it is probably not possible to cover all the topics presented in the text. Some sections and chapters have been marked as optional and may be omitted without loss of continuity. For example, Chapter 3 (General Relativity) and Chapter 16 could well be omitted, depending to some extent on the interest and background of the students. Most of the ''application'' sections have also been marked as optional. Generally, in these sections I have opted for detailed and concise presentations, which has meant that to keep the text to reasonable size, some interesting technological spin-offs of modern physics had to be omitted. I have done this because in my experience students are dissatisfied with a cursory gee-whiz summary that fails to help them really understand how a device operates or a technique is employed in practice. Those applications that have been included span a broad spectrum and should appeal to most science and engineering students.

In preparing this text I have benefitted from the insight of many students whose names I no longer recall but who helped unknowingly by interrupting a lecture whenever I failed to explain a topic clearly. I am also privileged to acknowledge the assistance of the following reviewers whose comments and criticism have been most valuable: Gordon Aubrecht, Ohio State University; John Barach, Vanderbilt University; J. Birchall, University of Manitoba; Roger Clapp, University of South Florida; Maj. William E. Eichinger, U.S. Military Academy; Harry E. Grove, University of Rochester; Joseph Kiskis, University of California—Davis; Richard Kouzes, Princeton University; Patrick Labelle, Cornell University; Peter Lindenfeld, Rutgers University; A. E. Livingston, University of Notre Dame; Alan Nathan, University of Illinois; Julian V. Noble, University of Virginia; Lawrence Pinsky, University of Houston; James Trefil, George Mason University; Walter Wales, University of Pennsylvania; James K. Walker, University of Florida; James Whitmore, Pennsylvania State University; E. J. Winhold, Rensselaer Polytechnic Institute; and Tung-Mow Yan, Cornell University.

I am also indebted to John Bullock, Princeton University; David Cowan, University of Missouri; Thomas A. Kaplan, Michigan State University; David Sandison, Cornell University; and Yannis Tsamouranis, University of Houston, who solved end-of-chapter problems, called my attention to ambiguities, and suggested additional problems.

The work was initiated at the suggestion of Malvina Wassermann without whose confidence in my ability and fortitude to bring the project to successful conclusion I would not have begun to write this book. I am also grateful for the help and encouragement of McGraw-Hill Publishing, especially Anne Duffy, Holly Gordon, Jack Maisel, Safra Nimrod, Denise Schanck, and Susan Tubb.

Last, though by no means least, I wish to thank Jane Dahl-Blatt for her expert professional assistance and constant support. Without her help it is doubtful that this book could have been completed.

Frank J. Blatt

Modern Physics

Contents

(Sections marked * are optional.)

Chapter 1

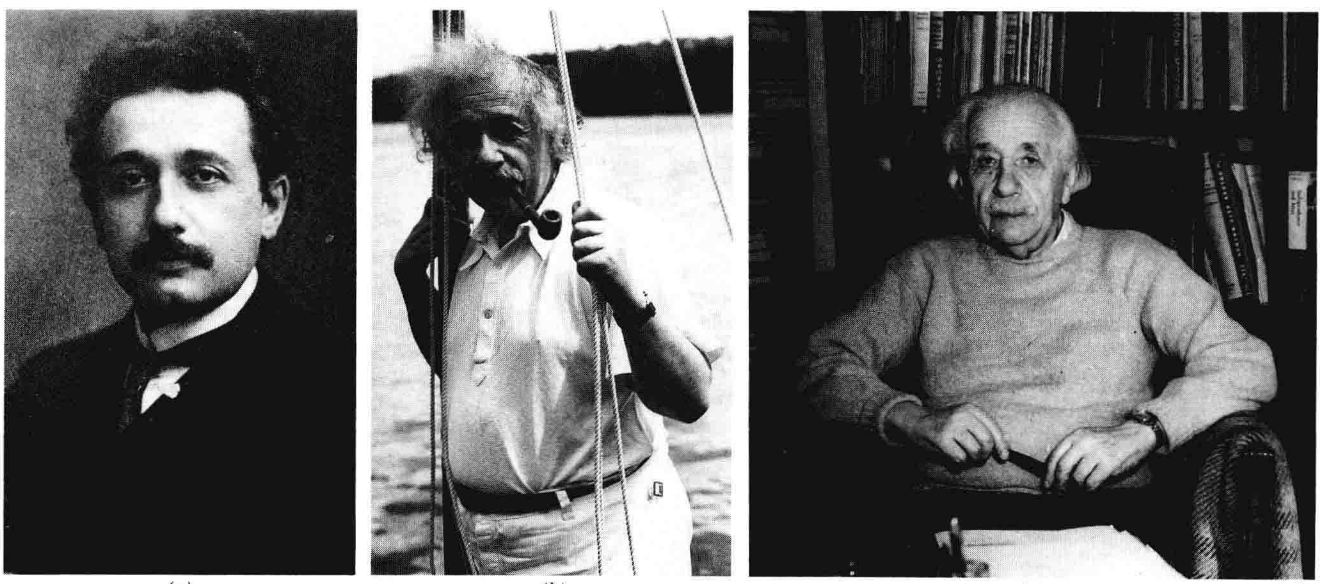
The Theory of Special Relativity I: The Lorentz Transformation

The relativity theory arose from necessity, from serious and deep contradictions in the old theory from which there seemed no escape. The strength of the new theory lies in the consistency and simplicity with which it solves all these difficulties, using only a few very convincing assumptions.

Albert Einstein and Leopold Infeld, *The Evolution of Physics* (1938)

1.1 INTRODUCTION

The year 1905 has rightly been called the *annus mirabilis* of modern physics. That year, Albert Einstein published five papers of which four have left an indelible imprint on twentieth-century science and culture.



(a) (b) (c)

Figure 1.1 Albert Einstein (*a*) in 1905 at the age of 26 (*The Bettmann Archive/Bettmann Newsphotos.*); (*b*) off Long Island, about 1935, enjoying his favorite relaxation (*AP/Wide World Photos.*); (*c*) in his later years, at his home in Princeton, New Jersey (*The Bettmann Archive/Bettmann Newsphotos.*)