Introduction to Elementary Particle Physics

The third edition of this successful textbook has been redesigned to reflect the progress of the field in the last decade, including the latest studies of the Higgs boson, quark–gluon plasma, progress in flavour and neutrino physics and the discovery of gravitational waves. It provides undergraduate students with complete coverage of the basic elements of the Standard Model of particle physics, assuming the reader has done only introductory courses in nuclear physics, special relativity and quantum mechanics. Examples of fundamental experiments are highlighted before discussions of the theory, giving students an appreciation of how experiment and theory interplay in the development of physics. The author examines leptons, hadrons and quarks, before presenting the dynamics and the surprising properties of the charges of the different forces, concluding with a discussion on neutrino properties beyond the Standard Model. This title is also available as Open Access on Cambridge Core.

Alessandro Bettini is Emeritus Professor of Physics at the University of Padua, Italy, and a research associate of the Italian National Institute for Nuclear Physics (INFN). He has served the INFN as Director of the Padova section, as Vice-president and as Director of the Gran Sasso Laboratory (LNGS). He has also served the International Union of Pure and Applied Physics (IUPAP) as Chair of the Particle and Nuclear Astrophysics and Gravitation International Committee and the Spanish Government as Director of the Canfranc Underground Laboratory (LSC). He is the author of more than 200 scientific publications, 8 university textbooks and 2 books for the general public. He is a fellow of the European Physical Society, 'Socio Benemerito' of the Italian Physical Society (SIF) and a member of the Accademia Galileiana di Scienze, Lattere e Arti.

‘Lecturers who use this book for their courses will love this new edition even more. The balance between theory, descriptions of detectors, and experimental results remains unique to this book. The abundant choice of exercises and the appendices enrich it even more. From g-2 and lattice QCD and a much expanded part on Higgs physics, to neutrinos and CP violation, and by adding gravitational waves, the author updates us with the newest topics in the field, providing a very modern textbook at the bachelor’s and master’s level.’

Professor Elisabetta Gallo, University of Hamburg and DESY

‘Bettini successfully bridges the gap between the textbooks for the first modern physics courses and graduate-level textbooks. Bettini’s book, like Donald Perkins’ famous textbook, weaves in experimental data and discoveries, detectors and quantum field theory, but it is more up to date. Bettini’s third edition has a number of new sections such as gravitational waves and the g-2 experiment, and many other chapters and parts of the text are improved.’

Professor Tom Browder, University of Hawai’i at Mānoa

‘Alessandro Bettini is to be thanked for such a wonderful book. I am totally amazed by the depth of the theoretical contents across all subjects. The author endeavours to bring readers the experimental and observational bases from both logical descriptions and a historical point of view. This makes this book more than just a textbook of particle physics, but a complete handbook of the whole field over the last century. I’ll certainly recommend this book as an essential reference in my classes on cosmic ray physics.’

Professor Zhen Cao, Institute of High Energy Physics,
Chinese Academy of Sciences

‘Bettini’s is one of the most popular and comprehensive textbooks in particle physics for university degree courses as it appeals to students and readers of various levels. Its greatest asset is that it manages to combine theory and experiment so beautifully, through elegant writing coupled to a remarkable spirit of synthesis that never allows the reader to lose the thread of the argument. This third edition’s updates are concise and effective, aiming directly at the core of the subject and highlighting the many still open issues at the very roots of contemporary research in physics.’

Professor Luisa Cifarelli, University of Bologna

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Third Edition

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Preface

This textbook is a presentation of subnuclear physics, at an introductory level, for undergraduate physics students, including those not specializing in the field. The first edition was published in 2008 and the second in 2014. This third edition, while keeping the design principles, is fully updated with the latest experimental and theoretical results, including on Higgs boson physics and on CP violation in the quark and the neutrino sectors. The reader will find presentations of the relativity principle, of the Dirac and Majorana equations and of quantum chromodynamics calculations on the lattice. The electron and muon magnetic moments as extreme precision tests of the Standard Model are also discussed, as is the quark–gluon plasma as a laboratory tool to study the Universe soon after the Big Bang; there is also a new chapter on gravitational waves outlining the information they provide on the graviton.

The Standard Model is the theory of the fundamental constituents of matter, describing all the fundamental interactions (excluding gravitation) as gauge quantum field theories. The reader is assumed to have already taken, at an introductory level, nuclear physics, special relativity and quantum mechanics. Knowledge of angular momentum, its composition rules and the underlying group theoretical concepts is also assumed at a working level. No prior knowledge of elementary particles or of quantum field theories is assumed. While the book will not lead to an in-depth knowledge of these theories, it will convey the basic physics elements and their beauty at an elementary level. ‘Elementary’ means that only knowledge of elementary concepts (in relativistic quantum mechanics) is assumed. However, it does not mean a superficial discussion. In particular, I have tried not to cut corners and I have avoided hiding difficulties, whenever they arise, following the Einstein dictum: ‘make everything as simple as possible, but not simpler’. As in the previous editions, I have included only well-established elements with the exception of the final outlook, in which I survey the main challenges of the present frontier.

The text now contains more material than can be accommodated in a single undergraduate course. However, several chapters are quite independent from one another, leaving the instructor a range of choices.

The majority of the texts on elementary particles place special emphasis on theoretical aspects. However, physics is an experimental science and only experiment can decide which of the possible theoretical schemes has been chosen by Nature. Moreover, the progress of our understanding is often due to the discovery of unexpected phenomena. I have tried to select examples of basic experiments first, and then to go on to the theoretical picture.

A direct approach to the subject would start from leptons and quarks and their interactions and explain the properties of hadrons as consequences. A historical approach would also discuss the development of ideas. The former is shorter, but is lacking in depth. I tried to arrive at a balance between the two views.

The necessary experimental and theoretical tools are presented in the first chapter. Even if the students have already met special relativity, the theory is presented here from a more advanced point of view, independent of electromagnetism. Indeed, the laws of all the interactions, not only those of electromagnetism, must respect the relativity principle. In addition, students are guided to practical exercises in the use of relativistic invariants and Lorentz transformations. Chapter 1 also contains a summary of the artificial and natural sources of high-energy particles and of detectors. In Chapter 2, I present the Dirac Lagrangian and derivations of the Dirac equation, which had been assumed to be known in the previous editions. The Majorana equation for completely neutral fermions is also introduced here. As in the previous editions, the symmetries of elementary particles are discussed in Chapter 3.

The elementary fermions fall into two categories: the leptons, which can be found free, and the quarks, which always live inside the hadrons. Hadrons are non-elementary, compound structures, rather like nuclei. The 'oldest' elementary particles are presented in Chapter 2, with a partly historical approach, while the hadron 'zoo', and how hadrons are described by the quark model, is discussed in Chapter 4.

There is a fundamental difference between hadrons on the one hand and atoms and nuclei on the other. While the electrons in atoms and nucleons in nuclei move at non-relativistic speeds, the quarks in the nucleons move almost at the speed of light. Actually, their rest energies are much smaller than their total energies. Subnuclear physics is fundamentally relativistic quantum mechanics.

The second part of the book is dedicated to the fundamental interactions and to the Standard Model. The approach is substantially more direct, but the main historical steps are recalled. The most important experiments that prove the crucial aspects of the theory are discussed in some detail.

Chapter 5 deals with quantum electrodynamics (QED), the prototype of all the relativistic gauge theories. I show how the concept of gauge invariance evolves from classical electromagnetism, where it plays a secondary role, to the quantum theory in which it becomes dominant. I introduce the Feynman diagram at a non-quantitative level as a tool to analyse scattering and decay probabilities; I discuss the experiments that led to QED and test its main aspects. New to this edition, the magnetic moments of the electron and the muon are discussed from both the experimental and the theoretical points of view, as examples of the extreme precision reached by both.

Chapter 6 presents quantum chromodynamics (QCD), its analogies and its radical differences from QED, entering into the magic 'coloured' world. New to this edition is a discussion of QCD on the lattice, a theoretical tool enabling calculations at low energies where the perturbative approach fails, and of how the most powerful supercomputers that recently became available allow precise predictions to be obtained. Amongst these, I discuss the hadron mass spectrum and the deconfinement phase transition to the quark–gluon plasma, the phase of matter 1 μs after the Big Bang.

In Chapter 7 the weak interaction is described. I start with the Fermi theory, before discussing the experiments that showed that parity and charge conjugation are violated and that led to the *V*–*A* theory of the 'charged currents'. We continue with lepton universality and quark mixing. The chapter ends with the discovery of the weak neutral currents. Chapter 8 discusses in detail the neutral meson oscillations and the *CP* violation in quark interactions. The recent discoveries in the beauty and charm sectors are included for the first time.

In Chapter 9, electroweak unification is discussed in detail, both in its theoretical principles and in the experimental proofs: from the measurements of the weak mixing angle, to the discovery of the vector bosons, to the precision tests at the electron–positron (Large Electron–Positron (LEP)) and proton–antiproton (Tevatron) colliders. Finally, after introducing the Brout–Englert–Higgs (BEH) theory, the long search for the Higgs boson and how it was discovered are discussed. The measurements of its principal properties, determined after the previous edition of this book, are now presented.

In Chapter 10, we turn to physics beyond the Standard Model (SM). Neutrinos are massive and can change their lepton flavour, which is different from what is assumed in the SM. Actually neutrino mixing, masses, oscillations and adiabatic flavour conversion in matter make a beautiful set of phenomena that can be properly described at an elementary level, using only the basic concepts of quantum mechanics. Possible *CP* violation in the neutrino sector is also presented.

Chapter 11 is new. Even though we do not have a quantum theory of gravitation, after the discovery in 2016 of gravitational waves (GW) and the subsequent great progress of the field, we now know elements close to particle physics. I discuss the measurement of the velocity of GW and of a limit on the graviton mass.

Chapter 12 contains a short discussion on the limits of the Standard Model and on facts beyond it. I briefly discuss gravity, dark matter, dark energy, supersymmetry, strong *CP* violation, absence of antimatter in the universe and structural theoretical problems.

Problems

Numbers in physics are important; the ability to calculate a theoretical prediction on an observable or an experimental resolution is a fundamental characteristic of any physicist. More than 260 numerical examples and problems are presented. The simplest ones are included in the main text under the form of questions. Other problems covering a range of difficulty are given at the end of the chapters. In every case the student can arrive at the solution without studying further theoretical material. Physics rather than mathematics is emphasized.

The physical constants and the principal characteristics of the particles are not given explicitly in the text of some problems. The student is expected to look for them in the tables given in the Appendices. Solutions to about half of the problems are given at the end of the book.

Appendices

One appendix contains the dates of the main discoveries in particle physics, both experimental and theoretical. It is intended to give a bird's-eye view of the history of the field. However, keep in mind that the choice of the discoveries is partially arbitrary and that history is always a complex non-linear phenomenon. Discoveries are seldom due to a single person and never happen instantaneously.

Tables of the Clebsch–Gordan coefficients, of the spherical harmonics and of the rotation functions in the simplest cases are included in the appendices. They are needed for some of the problems. Other tables give the main properties of gauge bosons, of leptons, of quarks and of the ground levels of the hadronic spectrum.

The principal source of the data in the tables is the most recent edition of 'Review of Particle Physics' (Workman *et al.* 2022), PDG for short. Its website, http://pdg.lbl.gov/, is a very useful resource for the reader. It includes not only the complete data on elementary particles, but also short reviews of topics such as tests of the Standard Model, searches for hypothetical particles, particle detectors and probability and statistical methods.

Reference Material on the Internet

The URLs cited in this work were correct at the time of going to press, but the publisher and the author make no undertaking that the citations remain live or accurate or appropriate.

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