Introduction to Elementary Particle Physics

The second edition of this successful textbook is fully updated to include the discovery of the Higgs boson and other recent developments, providing undergraduate students with complete coverage of the basic elements of the Standard Model of particle physics for the first time.

Physics is emphasised over mathematical rigour, making the material accessible to students with no previous knowledge of elementary particles. Important experiments and the theory linked to them are highlighted, helping students appreciate how key ideas were developed.

The chapter on neutrino physics has been completely revised, and the final chapter summarises the limits of the Standard Model and introduces students to what lies beyond. Over 250 problems, including 60 that are new to this edition, encourage students to apply the theory themselves. Partial solutions to selected problems appear in the book, with full solutions provided at www.cambridge.org/9781107050402.

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Second Edition

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Preface to the second edition

While keeping the same target and the same design principles as the first edition, the second edition results from a complete review (more precise definition of the parity of the spinors, further clarification of the concepts of helicity versus chirality, description of the GIM mechanism extended to loop order, gauge dependence of the colour charge, etc.) and is completely updated to take into account the progress of the field in the past six years (on the mass differences and lifetimes of the neutral mesons, limit on proton decay lifetime, quark masses values, in particular, for the light ones, $\mathcal{CP}$ violation in charged mesons, etc.).

A very important element of the Standard Model, the origin of all the masses, had not been experimentally proven at the time of the first edition, and as such it had not been included. The spontaneous symmetry breaking mechanism of Englert & Brout, Higgs and Gularnik, Hagen & Kibble is now discussed at the introductory level of the textbook. The CERN LHC collider, the ATLAS and CMS experiments and their discovery of the Higgs boson are now discussed, as well as the available measurements of its characteristics. I also include the precision tests of the Standard Model and the Higgs search at the Fermilab.

In the above mechanism, massless Goldstone bosons do not appear, but rather are absorbed in the non-physical degrees of freedom of the gauge fields. The way to the understanding of these rather difficult concepts is prepared with the following three elements, which are introduced in the preceding chapters.

(1) A more complete discussion of the different types of symmetries and of their breaking mechanisms is now included in Chapter 3.
(2) The chiral symmetry of the strong interaction (QCD) Lagrangian is both explicitly and spontaneously broken. As such it is a very interesting, and not too difficult, example to discuss. Moreover, chiral symmetry has a very important physical relevance *per se*. Its breaking explains why the pion mass squared is two orders of magnitude smaller of its scalar, rather than pseudoscalar, chiral partner. I discuss this now in Chapter 7, after the vector and axial vector currents have been introduced. Moreover, the spontaneous breakdown of the chiral symmetry points to aspects of the QCD vacuum, which are now qualitatively discussed, together with the relations between light quark masses resulting from perturbative chiral expansion.
(3) The gauge invariance of classical electrodynamics, the corresponding non-physical degrees of freedom of the potentials and the gauge fixing procedures (gauge choices in magnetostatics and electrodynamics) are recalled from the elementary courses of electromagnetism, as a help for understanding the analogous procedures in quantum field theories.

Chapter 10 is now completely dedicated to neutrino physics. The established new evidence since the first edition has been included: (1) the measurement of θ_{13}, the mixing angle for which only an upper limit existed; (2) the first direct evidence for the appearance of electron neutrinos in T2K and tau neutrinos in OPERA on the CNGS beam from CERN, by detecting electrons and taus respectively.

A new section is dedicated to the discussion of the nature of neutrinos. Indeed, neutrinos may be completely neutral spinors, obeying Majorana rather than the Dirac equation. This very basic issue, considering that neutrinos are already showing physics beyond the Standard Model, can be treated without difficulty, but is not present in any other text book at this level. Majorana neutrinos imply lepton number violation, but we show how the V–A character of the charge current weak interaction is sufficient to explain the experimental observations without invoking lepton number conservation. Neutrino-less double-beta decay is then shown to be the available experimental way to check whether neutrinos are completely neutral.

In the first edition, the running of the coupling constants is already included. A section is now presented on the running of the quark masses, discussing in particular the bottom-quark. This is because, on one side, it has been experimentally observed at LEP; on the other, it is relevant for the branching ratio of the Higgs in $b\bar{b}$.

The new Chapter 11 contains a short discussion on the limits of the Standard Model and on facts beyond it. I mention and briefly discuss: neutrino mass, dark matter, dark energy, the problem of the vacuum energy, grand unification, SUSY, gravitation, absence of anti-matter in the universe, strong CP violation, and 'aesthetical' 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, of which 60 are new. 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 each chapter (except the last one). In every case the student can arrive at the solution without studying further theoretical material. Physics rather than mathematics is emphasised.

The physical constants and the principal characteristics of the particles are not given explicitly in the text of the 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 issues 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. 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 'Review of Particle Properties' (Yao *et al.* 2006). This 'Review', with its website http://pdg.lbl.gov/, may be very useful to the reader too. 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, probability and statistical methods, etc. However, it should be kept in mind that these 'mini reviews' are meant to be summaries for the expert and that a different literature is required for a deeper understanding.

Reference material on the Internet

There are several URLs present on the Internet that contain useful material for further reading and data on elementary particles. 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.

Preface to the first edition

This book is mainly meant to be a presentation of subnuclear physics, at an introductory level, for undergraduate physics students, not necessarily for those specialising in the field. The reader is assumed to have already taken, at an introductory level, nuclear physics, special relativity and quantum mechanics, including the Dirac equation. 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.

The Standard Model is the theory of the fundamental constituents of matter and of the fundamental interactions (excluding gravitation). A deep understanding of the 'gauge' quantum field theories that are the theoretical building blocks of this model requires skills that the readers are not assumed to have. However, I believe it to be possible to convey the basic physics elements and their beauty even 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 was the case. I have included only well established elements with the exception of the final chapter, in which I survey the main challenges of the present experimental frontier.

The text is designed to contain the material that may be accommodated in a typical undergraduate course. This condition forces the author to hard, and sometimes difficult, choices. The chapters are ordered in logical sequence. However, for a short course, a number of sections, or even chapters, can be left out. This is achieved at the price of a few repetitions. In particular, the treatments of oscillation and of the *CP* violation phenomena are given in an increasingly advanced way first for the *K* mesons, then for the *B* mesons and finally for neutrinos.

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. From my experience, students have a sufficient knowledge of special relativity, but need practical exercise in the use of relativistic invariants and Lorentz transformations. In the first chapter I also include a summary of the artificial and natural sources of high-energy particles and of detectors. This survey is far from being complete and is limited to what is needed for the understanding of the experiments described in the following chapters.

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. Three chapters are dedicated to the ground-level hadrons (the S-wave nonets of pseudoscalar and vector mesons and the S-wave octet and decimet of baryons), to their symmetries and to the measurement of their quantum numbers (over a few examples). The approach is partly historical.

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 mass of a system can be measured if it is free from external interaction. Since the quarks are never free, for them the concept of mass must be extended. This can be done in a logically consistent way only within quantum chromodynamics (QCD).

The discoveries of an ever-increasing number of hadrons led to a confused situation at the beginning of the 1960s. The development of the quark model suddenly put hadronic spectroscopy in order in 1964. An attempt was subsequently made to develop the model further to explain the hadron mass spectrum. In this programme the largest fraction of the hadron mass was assumed to be due to the quark masses. Quarks were supposed to move slowly, at non-relativistic speeds inside the hadrons. This model, which was historically important in the development of the correct description of hadronic dynamics, is not satisfactory however. Consequently, we will limit the use of the quark model to classification.

The second part of the book is dedicated to the fundamental interactions and to the Standard Model. The approach is substantially more direct. The most important experiments that prove the crucial aspects of the theory are discussed in some detail. I try to explain at an elementary level the space-time and gauge structure of the different types of 'charge'. I have included a discussion of the colour factors giving examples of their attractive or repulsive character. I try to give some hint of the origin of hadron masses and of the nature of vacuum. In the weak interaction chapters the chiralities of the fermions and their weak couplings are discussed. The Higgs mechanism, the theoretical mechanism that gives rise to the masses of the particles, has not been tested experimentally yet. This will be done at the new high-energy collider, LHC, now becoming operational at CERN. I shall only give a few hints about this frontier challenge.

In the final chapter I give a hint of the physics that has been discovered beyond the Standard Model. Actually neutrino mixing, masses, oscillations and flavour transitions in matter make a beautiful set of phenomena that can be properly described at an elementary level, namely using only the basic concepts of quantum mechanics. Other hints of physics beyond the Standard Model are already under our eyes. They are due mainly to the increasing interplay between particle physics and cosmology, astrophysics and nuclear physics. The cross fertilisation between these sectors will certainly be one of the main elements of fundamental research over the next few years. I limit the discussion to a few glimpses to give a flavour of this frontier research.

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