Over the two decades since this book was first published, many outstanding questions in particle physics have been answered, but our increasingly sophisticated level of understanding has led to even deeper questions. In 1983, the discovery of the W and Z bosons provided firm evidence of the correctness of the Standard Model. This marked the beginning of the end of the phase of particle physics which extended the methods of quantum electrodynamics, formulated at the end of the 1940s, to both the weak and strong nuclear forces. But a quantum theory of the other known force, gravity, was lacking.

By the second edition in 1991, the increasingly well-observed structure of quarks, leptons and gauge bosons had established the Standard Model beyond reasonable doubt. But the 'first string revolution' of 1984 had opened up the possibility that a whole class of string theories could be candidates for a more fundamental theory incorporating gravity.

Since that time, another decade of experiment has confirmed the Standard Model and its generation structure with impressive accuracy. But the recently confirmed phenomenon of neutrino oscillations (and so neutrino mass) is definitely beyond its scope. Also, cosmological observations now indicate that as much as 96 percent of the Universe is made up of unknown sources of 'dark matter' and 'dark energy'. Furthermore, yet another string revolution has resulted in a new understanding of string theories as the limit of 'M-theory', whose exact structure is not yet known.

The next few years will see the operation of the Large Hadron Collider at CERN which promises an eventful decade of both confirmation and, perhaps, surprise. The main goal of observing the Higgs boson would provide the final piece in the Standard Model jigsaw. But there is also a very likely possibility of finding evidence of supersymmetric particles (the missing dark matter of the Universe?) or other new physics beyond the Standard Model. Either of these will herald the dawn of a new era in particle physics.

On the basis of the advances described in this third edition, the physics of the current century may be as profoundly exciting as that of the last.

# The Ideas of Particle Physics

An Introduction for Scientists

*G. D. Coughlan, J. E. Dodd and B. M. Gripaios*

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Frontmatter
More information

# *Contents*

# Preface

The last thirty years have seen an enormous advance in our understanding of the microscopic world. We now have a convincing picture of the fundamental structure of observable matter in terms of certain point-like elementary particles. We also have a comprehensive theory describing the behaviour of and the forces between these elementary particles, which we believe provides a complete and correct description of nearly all non-gravitational physics.

Matter, so it seems, consists of just two types of elementary particles: quarks and leptons. These are the fundamental building blocks of the material world, out of which we ourselves are made. The theory describing the microscopic behaviour of these particles has, over the past decade or so, become known as the 'Standard Model', providing as it does an accurate account of the force of electromagnetism, the weak nuclear force (responsible for radioactive decay), and the strong nuclear force (which holds atomic nuclei together). The Standard Model has been remarkably successful; up until a year or two ago all experimental tests have verified the detailed predictions of the theory.

The Standard Model is based on the principle of 'gauge symmetry', which asserts that the properties and interactions of elementary particles are governed by certain fundamental symmetries related to familiar conservation laws. Thus, the strong, weak and electromagnetic forces are all 'gauge' forces. They are mediated by the exchange of certain particles, called gauge bosons, which are, for example, responsible for the interaction between two electric charges, and for the nuclear processes taking place within the sun. Unsuccessful attempts have been made to fit the only other known force – gravity – into this gauge framework. However, despite our clear understanding of certain macroscopic aspects of gravity, a microscopic theory of gravity has so far proved elusive. Moreover, recent experiments in neutrino physics cannot be explained within the Standard Model, showing beyond doubt that there must be a theory beyond the Standard Model, and that the Standard Model itself is only an approximation (albeit a very good one) to the true theory.

The above picture of the microworld has emerged slowly since the late 1960s, at which time only the electromagnetic force was well understood. It is the story of the discoveries which have been made since that time to which this book is devoted. The telling of the story is broadly in chronological order, but where appropriate this gives way to a more logical exposition in which complete topics are presented in largely self-contained units. The advances described in Parts 6–9, for example, were made more or less simultaneously, but no attempt is made here to relate an accurate history. Instead, we focus on the logical development of the individual topics and give only the main historical interconnections.

Our main concern in writing this book has been to communicate the central ideas and concepts of elementary particle physics. We have attempted to present a comprehensive overview of the subject at a level which carries the reader beyond the simplifications and generalisations necessary in popular science books. It is aimed principally at graduates in the physical sciences, mathematics, engineering, or other numerate subjects. But we must stress that this is *not* a textbook. It makes no claim whatsoever to the precision and rigour required of a textbook. It contains no mathematical derivations of any kind, and no complicated formulae are written down (other than for the purpose of illustration). Nevertheless, simple mathematical equations are frequently employed to aid in the explanation of a particular idea, and the book does assume a familiarity with basic physical concepts (such as mass, momentum, energy, etc.).

This book is organised in ten parts each consisting of four or five short chapters. However, Part 10 is more substantial. Dealing with the most exciting of current research topics, it consists of ten chapters which are rather longer than average and which will require more time and concentration on the part of the reader. We draw the reader's attention to the Glossary (Appendix 2), which gives concise definitions of the most important of particle physics nomenclature. It should prove useful as a memory prompt, as well as a source of supplementary information.

The story begins in Part 1 at the turn of the century when physicists were first beginning to glimpse the remarkable nature of ordinary matter. Out of this period came the two elements essential for the understanding of the microworld: the theories of special relativity and quantum mechanics. These are the unshakeable foundations upon which the rest of the story is based.

Part 2 introduces the four known fundamental forces, and is followed by a more detailed discussion of the physics of the strong and weak (nuclear) forces in Parts 3–5. It was the desire to understand the weak force, in particular, which led eventually to recognition of the role of gauge symmetry as a vital ingredient in theories of the microworld. Gauge theory is the subject of Part 6, which introduces the Glashow–Weinberg–Salam theory of the electromagnetic and weak forces. This theory, often called the 'electroweak model', has been spectacularly verified in many experiments over the past two decades. The most impressive of these was the discovery at CERN in 1983 of the massive $W^{\pm}$ and $Z^0$ gauge bosons which mediate the weak force.

At about the same time as the electroweak model was being developed, physicists were using 'deep inelastic scattering' experiments to probe the interior of the proton. These experiments, which are described in Part 7, provided the first indication that the proton was not truly elementary, but composed of point-like objects (called quarks). As the physical reality of quarks gained wider acceptance, a new gauge theory was formulated in an attempt to explain the strong forces between them. This theory is called 'quantum chromodynamics' and attributes the strong force to the exchange of certain gauge bosons called gluons. It is described in Part 8. Together, quantum chromodynamics and the Glashow–Weinberg–Salam electroweak theory constitute the 'Standard Model' of elementary particle physics.

Part 9 describes early experiments involving collisions between electrons and positrons. These experiments were instrumental in confirming the physical reality of quarks and in testing many of the predictions of quantum chromodynamics and the electroweak theory.

Part 10 begins by summarizing the Standard Model and describes the many tests of the model performed in electron–positron colliders over the past two decades. The recent neutrino experiments, which show that there must be a theory beyond the Standard Model, are then discussed. Finally, we address the question of what this theory may be, using ideas from current research, such as grand unification, supersymmetry and string theory.