Chapter 19 discussed the structure and the formal properties of non-abelian gauge theories. This chapter applies this formalism to the description of some general properties of the Standard Model of Weak, Electromagnetic and Strong Interactions. In particular, it calculates the RG β-function of the strong sector (Quantum Chromodynamics or QCD) and verifies the property of asymptotic freedom.

“We do not really know what energy is”. This was the conclusion of Richard Feynman, who in the 20th century contributed so much to our understanding of the nature of energy. The first chapter deals in particular with its role in establishing the expression “elementary particle” – or what in various phases of our growing knowledge was so termed. Theory and experiment are described with equal emphasis. Theory includes Einstein’s special and general relativity, the two approaches to quantum mechanics by Heisenberg and Schrödinger, as well as some fundamental expansions of the theory in the second half of the 20th century, including the quantum electrodynamics “created” by Sin-Itiro Tomonaga, Julian Schwinger, Richard Feynman and Freeman Dyson, and quantum chromodynamics, a brain-child of (in particular)
Murray Gell-Mann. Other new insights, up to the standard model of particle physics, are mentioned here. Some are described in depth, though without mathematical detail. Experiments that have led to fundamentally important results are described in balance with theory. All this is discussed in the context of the title of the book. A comparison with living systems shows that animate matter needs to have more complex properties than do the “strangely simple” building-blocks of inanimate matter.

Weak interactions
G. Barr, R. Devenish, R. Walczak, and T. Weidberg

in Particle Physics in the LHC Era

This chapter starts with a recap of both the weak interaction model from Fermi’s theory of beta decay (with no spin) and the pictorial way of understanding interactions using Feynman diagrams. An introduction is given to both this use of Feynman diagrams and the formal method of calculating matrix elements with Feynman rules. The weak interaction is then considered using the Dirac equation to include spin-half fermion effects, using the decay of the tau lepton as an example. Weak interactions with quarks, including Cabibbo mixing, the Glashow–Iliopoulos–Maiani (GIM) mechanism, and the Cabibbo–Kobayashi–Maskawa (CKM) matrix, are then covered. The chapter then gives a step-by-step approach to the unification of the electromagnetic and weak forces in the Glashow–Salam–Weinberg (GSW) model of electroweak unification, leading to the predictions of the Standard Model on the properties of the weak neutral current and to the existence of W and Z bosons.

The weakly interacting Bose gas at the critical temperature
Jean Zinn-Justin

in From Random Walks to Random Matrices

Chapter 20 examines effects of weak repulsive interactions in a Bose–Einstein condensate and the transition from Bose–Einstein condensate
to superfluid phase transition. Renormalization group methods are used and a universal amplitude is calculated by non-perturbative methods. After the discovery of the predicted Bose-Einstein condensation, which is a property of free bosons, an interesting issue was the effects of weak repulsive interactions. In this chapter, it is shown that, near the transition temperature, the initial non-relativistic field theory can be replaced by a relativistic effective Euclidean field theory known to describe a superfluid phase transition (a dimensional reduction). These theoretical considerations are illustrated by an evaluation of the universal variation of the transition temperature at weak coupling. For this purpose, the O(2) symmetry of the model is generalized to O(N) symmetry, and large N techniques are used.

Particle physics I
Ian R. Kenyon

in Quantum 20/20: Fundamentals, Entanglement, Gauge Fields, Condensates and Topology

Published in print: 2019 Published Online: November 2019
Item type: chapter

Particle families (quarks and leptons), their properties and their interactions are introduced. The exchange mechanism and the Yukawa potential are discussed. Natural units are explained. The cross-section for $e^- + e^+ \rightarrow \mu^- + \mu^+$ is calculated using a first order Feynman diagram. Comparison with data reveals the existence of the Z0-boson and makes a link between electroweak processes. Higher orders diagrams give divergences and their removal by renormalization is described. Neutrino properties are outlined and the determination of the number of light neutrinos related. The weak interaction is discussed: parity and charge parity are seen to be maximally violated in W-boson exchange, but the product is approximately conserved. Handedness is pursued in an appendix using Dirac spinors. The neutrino mass and weak eigenstates differ and this leads to oscillations between weak eigenstates in flight. Measurements of the neutrino flux from the sun revealing this behaviour are described. Weak and strong eigenstates of quarks also differ by a unitary transformation, the CKM matrix. This difference leads to oscillations of certain neutral mesons from particle to antiparticle. This behaviour is explored for neutral K-mesons and for B0d mesons. CP violation is observed, which is required for the survival of matter in the universe.
The Current-Current Model of the Weak Interaction
Michael E. Peskin

This chapter discusses the representation of the weak interaction as a current-current interaction that violates parity and charge conjugation invariance. It describes the experiments that demonstrate that this violation is maximal. The resulting theory is called the V-A theory of the weak interaction. The chapter works out the predictions of the V-A theory for muon and pion decay and high-energy neutrino scattering and shows the comparison to experiment.

The Standard Theory
John Iliopoulos

All ingredients of the previous chapters are combined in order to build a gauge invariant theory of the interactions among the elementary particles. We start with a unified model of the weak and the electromagnetic interactions. The gauge symmetry is spontaneously broken through the BEH mechanism and we identify the resulting BEH boson. Then we describe the theory known as quantum chromodynamics (QCD), a gauge theory of the strong interactions. We present the property of confinement which explains why the quarks and the gluons cannot be extracted out of the protons and neutrons to form free particles. The last section contains a comparison of the theoretical predictions based on this theory with the experimental results. The agreement between theory and experiment is spectacular.
This is a textbook of elementary particle physics whose goal is to explain the Standard Model of particle interactions. Part I introduces the basic concepts governing high-energy particle physics: elements of relativity and quantum field theory, the quark model of hadrons, methods for detection and measurement of elementary particles, methods for calculating predictions for observable quantities. Part II builds up our understanding of the strong interaction from the key experiments to the formulation of Quantum Chromodynamics and its application to the description of events at the CERN Large Hadron Collider. Part III builds up our understanding of the weak interaction from the key experiments to the formulation of spontaneously broken gauge theories. It then describes the tests and extensions of this theory, including the precision study of the W and Z bosons, CP violation, neutrino mass, and the Higgs boson.

Dynamics I: The physical ingredients of quantum field theory: dynamics, symmetries, scales
Anthony Duncan

in The Conceptual Framework of Quantum Field Theory
Published in print: 2012 Published Online: January 2013
Publisher: Oxford University Press
Item type: chapter

This chapter introduces the basic principles from which relativistic quantum field theory can be constructed. Local relativistic quantum field theory is based on three basic principles which in combination lead to a powerful and elegant formalism, which appears to allow a remarkably accurate description (the so-called ‘Standard Model’) of at least three of the four fundamental forces in Nature: the strong, weak, and electromagnetic interactions. An overview of Chapters 4 to 19 is also presented.

The Existence of Field Theories beyond the Perturbation Expansion
Laurent Baulieu, John Iliopoulos, and Roland Sénéor

in From Classical to Quantum Fields
Published in print: 2017 Published Online: May 2017
Publisher: Oxford University Press
Item type: chapter

A Problem of Mass
John Iliopoulos

in The Origin of Mass: Elementary Particles and Fundamental Symmetries
Published in print: 2017 Published Online: December 2017

This chapter examines the constraints coming from the symmetry properties of the fundamental interactions on the possible values of the masses of elementary particles. We first establish a relation between the range of an interaction and the mass of the particle which mediates it. This relation implies, in particular, that long-range interactions are mediated by massless particles. Then we argue that gauge invariant interactions are long ranged and, therefore, the associated gauge particles must have zero mass. Second, we look at the properties of the constituents of matter, the quarks and the leptons. We introduce the notion of chirality and we show that the known properties of weak interactions, combined with the requirement of gauge invariance, force these particles also to be massless. The conclusion is that gauge symmetries appear to be incompatible with massive elementary particles, in obvious contradiction with experiment. This is the problem of mass.

The Laws of Thermodynamics Tell You What Is and What Is Not Possible
Avelino Corma and Adolfo Plasencia

in Is the Universe a Hologram?: Scientists Answer the Most Provocative Questions
Published in print: 2017 Published Online: January 2018
Avelino Corma, the distinguished research chemist explains why scientific discovery is difficult. He then explains how ‘molecular recognition’ is achieved in nanochemistry, how molecular design and creating nanoreactors with zeolites is carried out in the laboratory to trap nanoparticles and make them react selectively, and what is meant by the ‘sociology of nanoparticles’. The relationship of chemistry with brain function or genome evolution is also considered. He then reflects on the role of chemistry from ancient times, when the discovery and synthesis of ammonia enabled the development of agriculture and societies, to the world as we know it today. The reason why chemistry is a fundamental discipline for balancing our ‘energy basket’ is also discussed, particularly with regard to achieving sustainable development of our planet.

A First, Fast Visit to the Universe
Alvaro De Rújula

in Enjoy Our Universe: You Have No Other Choice

Published in print: 2018 Published Online: February 2020
Publisher: Oxford University Press
DOI: 10.1093/oso/9780198817802.003.0006
Item type: chapter

This initial visit to the Universe is fast but not short. The fact that looking far away is looking into the past is recalled. There are a lot of things in our Universe, which are introduced here in order of diminishing size: The entire visible universe, cosmic background radiation (CBR), clusters of galaxies, galaxies, stars and planets, living beings, molecules, atoms, atomic nuclei, nucleons, electrons, quarks The fundamental forces holding these various objects together as well as antimatter, neutrinos, and Feynman diagrams make their first appearance here.