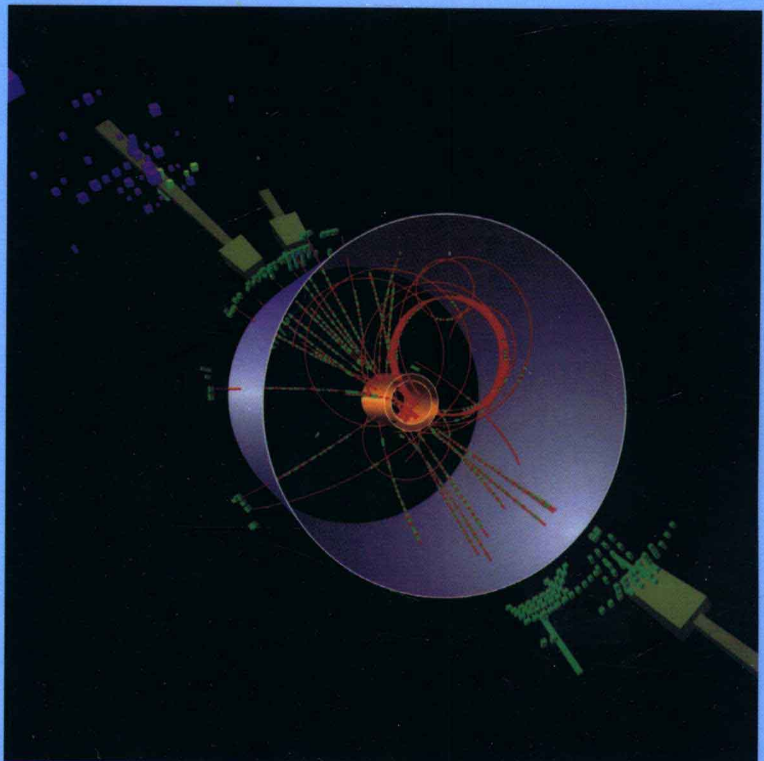
Christopher G. Tully

Elementary Particle Physics in a Nutshell

基本粒子物理学



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Preface

The 21st century is a time of great change in particle physics. A new energy frontier recently opened up at the Large Hadron Collider (LHC) at CERN. It's a time of great excitement with the anticipation of unexpected outcomes. At the same time, the most widely used university-level texts on high-energy physics date back to the time leading up to the W and Z boson discoveries. Since then, the Standard Model of particle physics has been thoroughly explored at the Large Electron Positron (LEP) collider at CERN, the Tevatron at Fermilab, HERA at DESY and at two B-factories, KEKB and PEP-II. A decade of neutrino physics has brought an exciting new view on these elementary and light, but massive, particles. This text is an attempt to capture the modern understanding of particle physics in a snapshot of time leading up to the start-up of the LHC. I believe that the pause in the development of texts has been due in part to the anticipated discovery of the Higgs boson and the implications that the observed Higgs field properties will have in defining the high-energy unification of the fundamental interactions. However, it is difficult for a new generation of high-energy physics to prepare for the challenge of the LHC without having the perspective needed to look beyond the limitations of the current Standard Model. In this text, I attempt to introduce a complete working knowledge of the $SU(3)_C \times SU(2)_L \times U(1)_Y$ Standard Model as early as possible and then focus on the many experimental confirmations in the context of the full theory. Ultimately, this will lead us to the next generation of high-energy experiments with a focus on what we hope to learn.

The final editing of this book was completed while on sabbatical at the Institute for Advanced Study with support from the IBM Einstein Fellowship Fund.

Chris Tully
Princeton, 2010

E lementary Particle Physics in a Nutshell

Contents

1 Particle Physics: A Brief Overview

Particle physics is as much a science about today's universe as it is of the early universe. By discovering the basic building blocks of matter and their interactions, we are able to construct a language in which to frame questions about the early universe. What were the first forms of matter created in the early universe? What interactions were present in the early universe and how are they related to what we measure now? While we cannot return space-time to the initial configuration of the early universe, we can effectively turn back the clock when it comes to elementary particles by probing the interactions of matter at high energy. What we learn from studying high-energy interactions is that the universe is much simpler than what is observed at "room temperature" and that the interactions are a reflection of fundamental symmetries in Nature. An overview of the modern understanding of particle physics is described below with a more quantitative approach given in subsequent chapters and finally with a review of measurements, discoveries, and anticipated discoveries, that provide or will provide the experimental facts to support these theories.

We begin with the notion of a fundamental form of matter, an elementary particle. An elementary particle is treated as a pointlike object whose propagation through space is governed by a relativistically invariant equation of motion. The equation of motion takes on a particular form according to the intrinsic spin of the particle and whether the particle has a nonzero rest mass. In this introduction, we begin by assuming that elementary particles are massless and investigate the possible quantum numbers and degrees of freedom of elementary particle states.

1.1 Handedness in the Equation of Motion

A massless particle with nonzero intrinsic spin travels at the speed of light and has a definite handedness as defined by the sign of the dot product of the momentum and spin. The handedness of a massless particle, of which there are two possible values, is invariant and effectively decouples the elementary particles into two types, left-handed and right-handed. However, the association of handedness to a degree of freedom has to be extended to all solutions of the relativistic equation of motion. The time evolution of a solution to a wave equation introduces a time-dependent complex phase, where for a plane-wave solution of ordinary matter, we have

$$\exp(-i\mathcal{H}t/\hbar)\,\Psi_{\text{matter}} = \exp(-iEt/\hbar)\,\Psi_{\text{matter}} = \exp(-i\omega t)\,\Psi_{\text{matter}}. \tag{1.1}$$

Relativistic invariance and, in particular, causality introduces solutions that propagate with both positive and negative frequency. Relative to the sign of the frequency for "matter" solutions, a new set of solutions, the "antimatter" solutions, have the opposite sign of frequency, $\exp(i\omega t)$, so as to completely cancel contributions of the relativistic wave function outside the light cone. Therefore, in the relativistic equation of motion, there is always an antiparticle solution that is inseparable from the particle solution. In terms of handedness, an antiparticle solution has the sign of the dot product of momentum and spin reversed relative to the corresponding particle solution. We define a new quantity, called the chirality, that changes sign for antiparticles relative to particles. Therefore, a particle solution with left-handed chirality is relativistically linked through the equation of motion to an antiparticle solution that also has left-handed chirality. We can now separate in a relativistically invariant way two types of massless particles, left-handed and right-handed, according to their chirality.

1.2 Chiral Interactions

The existence of an interaction is reflected in the quantum numbers of the elementary particles. We introduce here a particular type of chiral interaction, one in which left-handed particle states can be transformed into one another in a manner similar to a rotation. However, unlike a spatial rotation, the chiral interaction acts on an internal space termed isospin, in analogy to a rotation of intrinsic spin. The smallest nontrivial representation of the isospin interaction is a two-component isospin doublet with three generators of isospin rotations. Left-handed particles interact under the chiral interaction, and, therefore, the symmetry associated with this interaction imposes a doubling of the number of left-handed elementary particles. There is an "up" and "down" type in each left-handed isospin doublet of elementary particles. If we further tailor our chiral interaction, we can begin to construct the table of known elementary particles. Namely, we do not introduce a right-handed chiral interaction. Furthermore, elementary particles that have right-handed chirality are not charged under the left-handed chiral interaction and are therefore singlets of the left-handed chiral symmetry group.

The evidence for the left-handed chiral interaction was initially observed from parity violation in the radionuclear decay of unstable isotopes emitting a polarized electron and an undetected electron antineutrino in the final state. While we have not introduced mass or an interaction for electric charge as would be expected for the electron, we can ignore these properties for now and construct a left-handed doublet from the elementary particles consisting of the electron (down-type) and the electron neutrino (up-type). The electron and neutrino are part of a general group of elementary particles known as the leptons.

1.3 Fundamental Strong Interaction

We now consider the force that leads to the formation of protons and neutrons, and is ultimately responsible for nuclear forces. This force is the fundamental strong interaction and, similar to the chiral interaction, is an interaction that acts on an internal space. In this case, the internal space is larger and has a smallest nontrivial representation given by a triplet with a set of eight generators of rotation. The triplet is referred to as a triplet of color, with components denoted red, green, and blue. As with the electron and electron neutrino, a left-handed triplet of color is also a doublet of the chiral interaction. The lightest down-type color triplet is called the down-quark. Correspondingly, the lightest up-type color triplet is called the up-quark. In contrast to the quarks, leptons are charge neutral with respect to the strong interaction.

1.4 Table of Elementary Particles

The chiral and fundamental strong interactions are a sufficient starting point to introduce the table of elementary particles, shown in figure 1.1. The quarks and leptons, shown on the left, have an intrinsic spin of $\hbar/2$. In the leftmost column, the up- and down-quarks and the electron and electron neutrino form what is known as the first generation of matter. The second and third generations are carbon copies of the first, ordered from left to right by the measured masses of the fermions. On the right-hand side of figure 1.1 are the particles that carry the forces or, according to our symmetry-based description of interactions, they are the "generators of rotation" for the internal spaces of color and isospin, called the eight gluons and the three weak bosons ($W^{\pm}$ and Z), respectively.

The properties of the elementary particles not explained by the chirality and color interactions are the electric charges and masses, and so too the unexplained presence of the photon. In order to explain the properties of mass and charge, here we look to a predicted and yet still elusive element in the particle table, the particle shown in the center of figure 1.1, the Higgs boson.

1.5 Mass and Electric Charge

While mass and electric charge are second nature from classical physics, they are highly nonobvious quantities in the elementary particles. In other words, their origin is believed to be linked to the properties of the physical vacuum rather than an inherent quantity that one would assign based on first principles, as explained below.

The "poor assumption" in the above discussions on elementary particles is the requirement of indistinguishability of the components of the particle doublets that represent the internal space of the chiral interaction. For the strong interaction, the components of the triplet of color are indistinguishable and hence are not explicitly labeled in figure 1.1. However, the electron and electron neutrino are different in their mass and in their

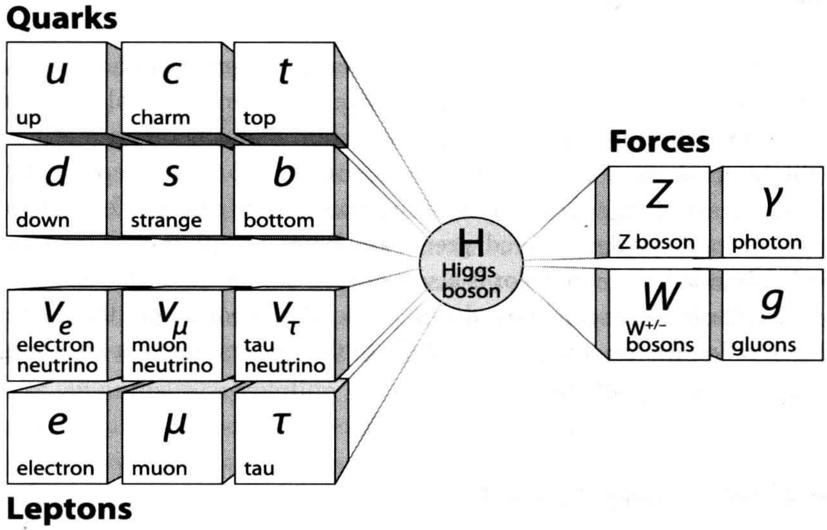

FIGURE 1.1. Elementary particles of the Standard Model. Leptons and quarks (spin-$\hbar/2$) are shown to the left. The gauge bosons (spin-$\hbar$) are on the right. The central particle, the Higgs boson (spin-0), has yet to be observed (Credit: Fermilab).

electric charge, similarly for the up- and down-quarks. The chiral interaction is therefore not an observed symmetry of Nature. Nevertheless, the chiral symmetry is or was clearly present in some form; otherwise, the particles would not interact with the $W^{\pm}$ and Z bosons in the way that they do. Moreover, for the chiral interaction to be based on an exact symmetry, the masses of elementary particles would have to be identically zero; otherwise, particles of left-handed chirality and right-handed chirality could be transformed into each other through a relativisitic transformation, changing the quantum numbers.

1.6 Hypercharge Interaction of the Standard Model

The Standard Model is a theory that solves the paradox of the "hidden symmetry" of the chiral interaction. To restore the indistinguishability of components of a chiral doublet, the Standard Model eliminates electromagnetism as an elementary interaction of massless fermions. The road to reintroducing electomagnetism as an interaction of massive fermions begins by postulating an alternative elementary interaction for massless fermions, called the hypercharge interaction. Hypercharge has every similarity to electric charge with the exception of the charge assignments to the elementary particles. A left-handed electron and electron neutrino are assigned the same hypercharge, and similarly for left-handed up- and down-quarks. Hypercharge assignments preserve the indistinguishability of the components of isospin doublets. The right-handed chiral particles are singlets in the chiral interaction and hence a right-handed up-quark can be assigned a different hypercharge than the left-handed up-quark or the right-handed down-quark without breaking the chiral symmetry. Thus, the critical step in constructing the Standard Model is to throw out mass and electric charge as a starting point for building a table of elementary particles. However, of what purpose is the hypercharge interaction in explaining the physically observed masses and charges of elementary particles and from where does the photon of electromagnetism originate? This brings us to the heart of the Standard Model theory, the electroweak symmetry breaking.

1.7 Higgs Mechanism

The central concept of the Standard Model is that the properties of the physical vacuum do not have the same symmetries as the fundamental interactions. This notion seems absurd at first, but physical examples of such systems, such as low-temperature superconductivity, clearly demonstrate such behavior in nonvacuous environments. Indeed, in a superconductor, the vacuum symmetry of zero electric charge is no longer present and photons do not propagate as massless particles in the space of a superconductor. The space of a low-temperature superconductor is filled with charge $2e$ electron pairs, known as Cooper pairs, that behave as a condensate of bosons. The photon is unable to propagate freely in a superconductor as it encounters nonzero electric charge at every point in space. The same type of mechanism can be postulated in the physical vacuum if there exists a condensate with nonzero hypercharge everywhere in space. Furthermore, the lack of an observed chiral symmetry in Nature would imply that a condensate of nonzero isospin is present in the vacuum ground state.

If there is a condensate in the ground state of the physical vacuum, what is it? One possible mechanism of electroweak symmetry breaking is known as the Higgs mechanism. The Higgs mechanism predicts the existence of a new type of elementary matter, called the Higgs bosons. The Higgs bosons are a set of spin-0 particle states with nonzero isospin and nonzero hypercharge quantum numbers. Similar to the Cooper pairs of superconductivity, the Higgs bosons interact with each other and do so in such a way so as to prefer a nonzero expectation value in the ground state. In other words, the Higgs condensate is present everywhere in space. Such an occurrence completely redefines our concept of the elementary particles and interactions. The table of elementary particles are those mass eigenstates that arise from particles interacting with the Higgs condensate. Similarly, the particles mediating the elementary interactions are hindered from propagating freely, resulting in a transformation of the elementary particle interactions. The photon of electromagnetism is the zero-mass eigenstate that propagates in the electrically neutral physical vacuum. It is in this way that the physical vacuum imposes the definition of electric charge and mass eigenstates in the elementary particles—these are not properties that come directly from the fundamental hypercharge and chiral interactions.

1.8 Program of Study

The Higgs mechanism of the Standard Model is a great leap beyond the notion of an empty vacuum and symmetry-preserving interactions. Indeed, the timeline of when the universe developed a vacuum filled with a symmetry-breaking condensate is not clear. Perhaps the most trying part of studying elementary particle physics is the lack of direct evidence to prove the existence of the Higgs mechanism or alternative electroweak symmetry-breaking mechanisms. Nevertheless, the experimental verification of the Standard Model is extensive with no apparent deviations with respect to all known predictions. Many internal consistencies of the Standard Model overwhelmingly support the concept of a symmetry-breaking physical vacuum, whether the fundamental source is the Higgs mechanism or something else. It is this predicament that has brought elementary particle physics into its most challenging and potentially the most revolutionary stage in its development. The energy scale that will confirm or refute the Higgs mechanism will be fully explored by the Large Hadron Collider (LHC) at the CERN laboratory in Geneva, Switzerland. The LHC experiments will be able to detect evidence for the Higgs bosons and probe possible extensions to the known physical symmetries in the elementary particles that would explain what stabilizes the electroweak scale.

The purpose of this text is to bring students a full understanding of the Standard Model, from relativistic kinematics and the Dirac equation through the concept of gauge interactions, and then to review in the context of the full theory the many areas of experimental investigation that have tested and subsequently confirmed the validity of the Standard Model predictions. Each chapter is concluded with a section that lists references that provide detailed background on the topics discussed. These references contain a wealth of interesting perspectives and lessons that were invaluable in the development of the Standard Model. In contrast, this book teaches the Standard Model as an established theory and applies the predictions to directly explain the mountain of experimental evidence that in retrospect was intended to challenge its validity. By presenting a fresh look at the Standard Model outside of the historically important questions that led to its creation, the intention is to prepare the ground for the next generation of exploration of elementary particle physics at the LHC.

1.9 Exercises

1. Fundamental interactions.

(a) What are the interactions described by the Standard Model in a symmetry-preserving vacuum? Ignore the Higgs interactions.

(b) What Standard Model interactions in part (a) are unaffected by the reduced symmetries of the physical vacuum?