Exploring Fundamental Particles

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CRC Press
Taylor & Francis Group
A TAYLOR & FRANCIS BOOK

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Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
A TAYLOR & FRANCIS BOOK

Taylor & Francis
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Version Date: 20140515

International Standard Book Number-13: 978-1-4398-3613-2 (eBook - PDF)

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Preface

A fundamental goal of science from the earliest times has been a search for the elementary constituents of the physical universe and the interactions between them. In the last half of the twentieth century, this has been the goal of a field of physics called elementary particle physics.

In the early 1930s, three particles had been identified as the constituents of matter: electrons, protons, and neutrons. Today, of these, only the electron is considered elementary, since it is believed that the protons and neutrons are made up of quarks. On the other hand, we have a list of 16 elementary particles, although most of them are not constituents of ordinary matter. In the early 1930s there were two fundamental interactions: gravity and electromagnetism. Today we have two more: the weak and strong interactions. This book is intended to explain the development of this new picture through the combined effort of theoreticians and experimentalists.

The picture that we will present in Part A of the book is called the standard model. As each aspect of it was developed, it usually took many years before it became accepted. Sometimes a new theory that became part of the standard model was ignored for several years because it had little or no experimental validation. Sometimes difficult experiments done in different laboratories gave conflicting results. New theoretical ideas often seemed too strange to believe.

The problem anyone faces in trying to explain aspects of this standard model is that, on the one hand, it should be easy to understand, but, on the other hand, the reader should realize that these ideas were only accepted after years of struggle. If you find some of the theories presented here somewhat weird, you will be in the same position as most physicists when the theories were first developed.

Although there is so much we have learned in the twentieth century, there is no reason to believe that now we have all the answers. Rather than speaking of *the* standard model, we should perhaps speak of the 2000 model of the physical universe. There may be many surprises ahead. There is a big new accelerator, the Large Hadron Collider (LHC) beginning operation in Geneva, as well as a large number of smaller important experiments in many different countries. There are many new astronomical observations being planned. In Parts B, C, and D we consider three parts of the standard model where there have been important developments in the last 20 years and which present challenges for the coming years.

In Part B, we discuss the violation of the symmetry between matter and antimatter, which goes under the name CP violation. The first small violation of this symmetry was discovered in 1964, and it took 30 years before a second different small violation was found. Only in the last dozen years have large violations of this symmetry been discovered in studies of the decay of a particle called the B meson. Experiments in progress and being planned are needed to determine whether all the violations of this symmetry are consistent with the standard model.

In Part C, experimental results involving the once-mysterious neutrino are presented. They lead to the conclusion that neutrinos have mass, which provides the first direct evidence for something beyond the standard model. New neutrino experiments are starting in Japan, China, France, and the United States. Furthermore, neutrino astronomy may offer a new window on stars and galaxies.

In Part D, we turn to the Higgs particle, the one constituent of the standard model that has not been detected. The Higgs particle plays a very central role in the standard model, and thus its detection is essential for the validation of the model. The analysis of experiments in the last 15 years has put important constraints on the mass of the Higgs particle. A major goal of the LHC accelerator is the discovery of the Higgs.

The success of human endeavors discovering fundamental new features of the physical universe is exciting and thrilling. This excitement should not be limited to a small group of scientists but should be shared with everyone. That is a major goal of this book.

Acknowledgments

The Feynman diagrams of this book were initially drawn with Freeware JaxoDraw v1.3. We are very grateful to Lukas Theussl for building a program to convert our original figures into v2.0 of JaxoDraw.

We thank our colleagues Augusto Barroso and António Silvestre, who have read the whole book and made numerous suggestions. Needless to say, ours is the blame for any inadequacies that might remain.

Stan Wakefield acted as our discerning agent, and John Navas of Taylor & Francis accepted to become our editor. We are indebted to both for their guidance and friendly advice.

Lincoln Wolfenstein wishes to acknowledge the many discussions related to this book with the late Darwin Chang, who died too young. He dedicates the book to his patient wife, Wilma, and their four children and nine grandchildren. João Silva thanks his family for their unfailing support and dedicates the book to Ana and Sara.

The Authors

The authors are professional particle physicists.

Lincoln Wolfenstein got his PhD at the University of Chicago and is professor emeritus at Carnegie Mellon University. He made landmark contributions to most of the subjects presented in this book. He is a member of the American National Academy of Sciences, and has been awarded the 1992 J. J. Sakurai Prize by the American Physical Society and the 2005 Bruno Pontecorvo Prize by the Scientific Council of the Joint Institute for Nuclear Research (Dubna, Russia). The discovery of neutrino masses, which forced a revision of the standard model, hinges on his prediction and study of the influence of matter on neutrino oscillations, now known as the Mikheyev–Smirnov–Wolfenstein effect.

João P. Silva got his PhD at Carnegie Mellon University, was a Fulbright scholar at Stanford University's SLAC, and is on the faculty at ISEL–Lisbon, Portugal. He is a coauthor of the book *CP Violation*, edited by Oxford University Press, increasingly involved in science awareness and in the interplay between science and art.

PART A

Genesis of the Standard Model

CHAPTER 1

The Foundation of Modern Physics

The Legacy of Newton

THE BEGINNING OF MODERN science most clearly is dated by the work of Isaac Newton in the second half of the seventeenth century. Much of the framework of modern physics follows from his formulations. In this introductory section we illustrate how Newton's work planted seeds that yielded many of the theories discussed in this book.

1.1 SIMPLE QUANTITATIVE LAWS

The triumph of Newton is that one can make precise quantitative predictions of observations starting from a couple of equations. Given Newton's second law and the universal laws of gravitation, one can calculate the motion of the planets around the sun, and the moon around the earth. More than that, once you see a comet come into view, you can predict its motion, and you can calculate the motion of artificial satellites that we put in orbit around the earth. All this follows from two simple equations.

To be precise, what Newton's laws tell us is that given the position and velocity of all the masses relevant to the problem, you can in principle calculate their future positions and velocities. The laws do not explain these initial conditions; they do not answer Kepler's question as to why there are six (or now eight) planets, or why they are in particular orbits around a medium-size star, our sun. The laws also allow us to extrapolate backward in time, and we can tell where the planets were a million years ago.

However, there are limits to this simple picture; we now know that the solar system is only 4.5 billion years old: we cannot extrapolate backwards indefinitely just using Newton's laws. Similarly, we now believe that in another 4.5 billion years the sun will turn into a red giant star and expand over the planets. Eventually, we must understand the internal structure of the sun and not just consider it as a massive sphere.

The calculation using Newton's laws can be done in principle, but in practice the mathematical solutions of the equations may not be easy. If we consider just one planet going around the sun, then it is easy with the calculus developed by Newton to calculate the possible elliptical orbits. When you consider several planets and include in the calculation the forces that each planet exerts on the others, in addition to the force of the sun, the calculation becomes very complicated. The problem that Adams and LeVerrier faced in determining the unknown orbit of Neptune from its effect on the motion of Uranus is even harder. But the fundamental equations that govern it all are amazingly simple.

The Newtonian world picture has sometimes been called the mechanical universe. The entire future is determined by physical laws from the initial conditions. This does not mean that in practice we can predict the future, because the more detail we want to know and the further in the future we want to see, the greater and greater the details we must know about the present. A well-known example is weather predictions. Modern quantum physics provides limits to this predictability, yet prediction from quantitative laws remains the model for physics today.

Since the time of Newton, the goal of physicists has been to discover these quantitative laws. Thus, in the nineteenth century, James Clerk Maxwell produced four differential equations that govern the phenomena of electricity and magnetism. In the twentieth, Erwin Schrödinger produced a differential equation in quantum mechanics that determines the energy states of any atom. The apparent fact that the physical world is governed by simple mathematical equations is a continual source of wonder and amazement.

1.2 FUNDAMENTAL INTERACTIONS

Newton's first law states that an object moving at a certain speed will continue to move with the same speed and in the same direction unless it is acted on by a force. If you want to speed up an object, you will have to give it a push in the direction of motion; if you want to change the direction, you have to give a push to one side or another.

In the absence of forces the universe consists of particles all moving at a constant velocity. Everything of interest that happens has to do with forces that change the motion, that may cause particles to stick together or rotate around each other.

In fact, we believe that forces act between particles; that is, the force on one particle results from the presence of other particles. Thus, the most fundamental laws of physics are the laws governing the forces between particles or fundamental interactions. This point of view continues to the present day. A major goal of elementary particle physics has been to discover the laws of interaction between particles. Today, we identify four fundamental interactions: (1) gravitational, (2) electromagnetic, (3) strong nuclear, and (4) weak nuclear.

It is the first of these force laws that was discovered by Newton. The universal law of gravitation states that every particle attracts every other particle in the universe with a force that is inversely proportional to the square of the distance between them and proportional to the product of the two masses. The proportionality constant is known as Newton's constant and is usually represented by the letter G. It is this force that determines the motion of the apple that falls from the tree and the motion of the moon around the earth.

The forces other than gravity that we are most familiar with are forces like friction or those of springs. None of these are considered fundamental forces; they depend on the details of the different materials involved. We believe that in principle, all these forces can be derived from fundamental forces acting at the atomic level, although in practice we usually use semiempirical descriptions involving parameters determined by experiment, like the Young's modulus or the coefficient of friction.

At the atomic level, by far the most important force is the electrical force. This force can be observed when combing your hair on a very dry day. You find that your hairs "become electrified" and tend to repel each other while the comb attracts your hairs. This illustrates a crucial difference between electrical forces and gravitational forces. Electrical forces can be both repulsive and attractive. In order to obtain an electrical force between two ordinary objects, it is necessary to prepare them (as by rubbing a comb against your hair) so they have a net electrical charge. There are two possibilities: positive charge or negative charge. The rule then is: like charges repel, unlike charges attract. Thus, the individual hairs with positive charge repel each other while the comb with a negative charge attracts the hairs. In 1785, by accurate measurements, Coulomb established the electrostatic law of force. For two stationary small charged objects the electrostatic force decreases with the square of the distance, just like the gravitational force. The force is proportional to the electric charge on one object multiplied by the charge on the other.

The electrostatic force law is only one component of the more general electromagnetic force laws. When the charges are moving, there is additional magnetic force. There are also magnetic forces between magnets. A complete theory of electric and magnetic forces came only with the work of James Clerk Maxwell in 1865.

On the atomic level, the electrical force is overwhelmingly larger than the gravitational force. However, on a larger scale, big objects contain about equal numbers of positive and negative charges so that electrical attraction and repulsion cancel out. Thus, on a large scale the gravitational force dominates because all particles in a large object attract other particles.

At the subatomic level, two additional interactions become important that fall off very quickly with distance. The strong force is the dominant one within the atomic nucleus and is responsible for holding the nucleus together. The weak interaction was originally formulated to explain certain radioactive decays of nuclei and now plays a very important role in the physics of elementary particles.

1.3 FIELDS

A concept that has played a major role in physics is that of the field. The simplest example is the gravitational field, for example, that of the earth. We define the field at a point in space as the force that would act on a unit mass if the mass were at that point. Thus, the field at a point outside the earth is directed toward the center of the earth with a magnitude that falls off with the square of the distance. Similarly, one can define the electric field, E, in terms of the force that would act on a unit positive charge.

At first the introduction of the field seems to add nothing to the original interaction law. However, in more complex situations it becomes essential. Given a set of moving charges Maxwell's equations allow you to calculate the electric and magnetic fields at any point. The most striking feature was that at a large distance from an oscillating charge the electric and magnetic fields varied in space like a wave, and this wave pattern moved outward with a velocity given by c, the velocity of light. These are the electromagnetic waves that vary from radio waves to light waves, to x-rays as the wavelength gets shorter.

In analyzing the photoelectric effect, Einstein pointed out that light, when it was absorbed or emitted, behaved like a particle with energy, given by hf, where f is the frequency and h is Planck's constant. Thus, there arose the wave-particle duality; one had to accept that light had both aspects. The particle is called the photon, and the probability of observing the particle at a point is proportional to the magnitude of the field.

With the development of quantum mechanics it became clear that the electron behaved like a wave, as dramatically illustrated by electron diffraction. Thus, here too there was a wave-particle duality, but the electron has a mass while the photon is massless. It became necessary to describe the electron as a field.

The fundamental equations that describe the electromagnetic interactions, called quantum electrodynamics (QED), involve electron fields and photon fields. Given the time-dependent electron field, a time-dependent photon field (or electromagnetic field) is determined, and if enough energy is available, this can correspond to the emission of a photon. On the other hand, lacking enough energy, the electromagnetic field can affect another electron; this is sometimes referred to as a virtual photon.

In the 1930s and 1940s there were a large number of successful predictions based on QED in experiments involving the emission and the annihilation of electrons and positrons as well as atomic physics. Thus, it served as the model for the development of theories of the weak and strong interactions.

1.4 COSMOLOGICAL PRINCIPLES

The story of Newton and the apple leads to the concept that the same laws of physics hold on earth and in the heavens. There is nothing special about our own time and place. We may formalize this in terms of what we will call cosmological principles:

> Cosmological principle 1: The same laws of physics hold everywhere in the universe.
>
> Cosmological principle 2: The same laws of physics hold for all times.

Perhaps it would be better to call these working hypotheses, which allow us to try to understand the astronomical universe. So far they have served us very well.

The first cosmological principle is the foundation of modern astrophysics. The laws of physics we know seem to work far beyond the solar system. We find two stars with one rotating about the other in accordance with the same law of gravity that governs our solar system. We see the same sequence of spectral lines (colors of light) coming from distant stars as those we see in our laboratory, indicating that the laws of atomic physics are the same.

Nevertheless, there is a problem of which we must be constantly aware. There may be laws of physics that we have not yet discovered. Today as we contemplate the universe, we try to apply the laws we know, but we also look at the universe as a laboratory from which we may find clues to physics not yet known.

This is wonderfully illustrated by the story of Lord Kelvin and the age of the earth and the solar system. Using the then known laws of physics, he asked for the source of the sun's energy and how long it could have been shining. If the sun were burning up by normal combustion, it could not continue more than 100,000 years. A much larger source of energy was available from gravitational collapse as the sun fell in on itself from a large size to its present radius. But even this led to a lifetime of much less than 100 million years. Such a short time seemed to contradict the theories of biological and geological evolution. The answer came only with the discovery of nuclear reactions and nuclear energy.

With the discovery of nuclear fusion reactions, it was proposed that the stellar energy was produced by nuclear reactions that fused hydrogen into helium. There was enough energy for the sun to shine for 10 billion years. Nuclear physics also brought with it natural radioactivity, which provides "clocks" that determine the age of the earth and of meteorites. A number of such clocks coincide in dating the solar system at 4.5 billion years.

The second principle is the basis of cosmology, our attempt to reconstruct the history of the universe. It has much less evidence, particularly the farther we go back in time. However, it has led to some remarkable successes over the last 40 years.

It has been proposed by some physicists that what we call physical constants are actually varying with time. Thus, Dirac had a theory in which Newton's constant, G, was not constant. Studies of the motion of the moon place a limit on the change in G of less than 1 part in 10^{10} per year, which actually disproved Dirac's specific proposal.

1.5 WAS NEWTON WRONG? THE RELATION OF NEW THEORIES TO OLD

It is often said that Einstein's theories overthrew Newton's. Was Newton wrong after all? The idea of scientific revolutions was popularized by the very interesting work of Thomas Kuhn.[1] While it correctly describes the difficulty of acceptance of new theories, it gives the incorrect impression that the old theory is to be thrown out.

The point is that, from Newton's time on, theories have been accepted only when they have been verified by empirical data. Newton's laws of motion and of gravity have described the motion of the planets and the moons and much more. How could they be wrong?

Einstein's theories of special and general relativity provide laws of motion and of gravity that look quite different from Newton's. But they do not overthrow Newton's laws; they encompass them. The new laws reduce to the old laws in appropriate limits.

Special relativity modifies the laws of motion when velocities become very large. In the limit when velocities are much less than the speed of light (3×10^8 meters per second) they reduce to Newton's laws. For ordinary motions, including those of the planets, Newton's laws will do fine. On the other hand, physicists often are concerned with electrons and other particles that are moving with speeds close to that of light.

General relativity modifies the law of gravity when the gravitational force gets very strong. In fact, it was discovered in the 1800s that there was a slight deviation of the motion of the planet Mercury, the planet closest to the sun, from the predictions of Newton's laws. (It is called the precession of the perihelion of Mercury.) No one figured out how to solve this problem, but of course they didn't say Newton was wrong; after all, his laws worked so very well and this was a small deviation. However, when Einstein developed his general theory of relativity, based on rather abstract theoretical principles, he showed that he could now explain the small problem with Mercury. For the other planets farther away, Newton will do just fine. On the other hand, we believe there exist collapsed stars and galaxy centers where gravity is so large that one must use general relativity; indeed, these may be "black holes" from which nothing can escape, no matter how fast it is moving.

Quantum mechanics becomes important at very small distances. As the distances get larger, the results become more and more the same as the results of Newton's classical mechanics. Niels Bohr called this the correspondence principle.

For new theories to be accepted today, they must encompass the old; there must be a correspondence principle.

1.6 THE ROLE OF PROBABILITY

A major distinction between Newtonian physics and physics today is that we now often talk of probabilities in contrast to the exact predictability of the mechanical world picture. There are at least three different ways in which probability enters.

1. Chaotic motion: As we have mentioned, often the outcome from an initial condition depends on the exact details. For example, if we add a planet to a given planetary system, it may stay bound or it may move away from the other planets after some time. However, even if we cannot specify the initial condition accurately enough to make a precise prediction, we may be able to give the probability of certain outcomes. A whole mathematical theory, called chaos theory, has been developed for this purpose.

2. Statistical mechanics: We often are dealing with billions of billions of particles, such as the air molecules in a room. We cannot specify all their initial positions and velocities, and we do not want to know about each individual molecule. What we can do and what we want to know is the probability that a molecule has some velocity or, on average, the fraction of the molecules that have a speed greater than some given speed. Thus, even though the motion may be deterministic, we end up talking about probabilities. This is the subject of statistical mechanics.

3. Quantum mechanics: At the atomic level the fundamental laws are not deterministic. A simple example is a radioactive atom with a half-life of a day. This means there is a 50% probability it will decay during the next 24 hours. There is no observation on it you can make that will tell when it will decay. Nevertheless, if you have a large number of atoms, you can predict with great accuracy that half of them will have decayed after 24 hours.

NOTE

1. T. S. Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1962).

CHAPTER 2

Waves That Are Particles; Particles That Are Waves

A MAJOR REVOLUTION IN OUR understanding of nature took place in the early twentieth century; we learned that light can have particle-like properties and that particles can have wave-like properties. This is deeply ingrained into the standard model of particle physics.

2.1 PARTICLES VERSUS WAVES

This book tells the exhilarating recent history of the search for the fundamental building blocks of all things and their interactions. When physicists mention "point particles," they may not be talking about fundamental particles at all. Point particles might have some internal structure, but they are so named because, whatever their internal structure might be, it has no bearing on the phenomenon under study. For example, consider a rigid ball sliding down an inclined plane without rolling and without friction. If this experiment is performed in a vacuum (that is, with all the air sucked out), the velocity that the ball has after it slides for 1 in. can be calculated ignoring what the ball is made of. It is even independent of the ball's mass; it depends exclusively on the slope of the inclined plane.

There is an interesting way to describe how this happens. When the ball is placed in a high position, we say that it has the potential to gain speed and we ascribe to it some *potential* energy. As it accelerates down the inclined plane, we say that it transforms this potential energy into *kinetic* energy, from the Greek word *kinesis*, which means motion. That is, the potential energy the ball had because it was placed in a high position is transformed into the kinetic energy associated with its speed as it moves down the plane.[1]

Another interesting quantity is the momentum of this particle. Momentum is an arrow (so-called vector) that has a size equal to the product of mass with velocity, and it has the direction of the particle's movement. Intuitively, the momentum is related to the particle's ability to push things placed in its path. Why this ability should be proportional to the velocity and also to the mass is easy to understand. Imagine that a car is sliding out of control toward you down an inclined street. If the car has a small speed as it hits you, it will push you in the direction in which it is moving and will hurt you, but you might end up okay. However, if the car has a large speed, you expect to be hurled through the air for quite a distance. It is obvious to you that the push you get goes in the direction in which the car is moving and that it increases with the car's velocity. Similarly, you expect a heavier car (say, a truck) to hurt you more than a lighter car. In accordance, momentum is proportional to mass and to velocity.

When two fundamental particles collide, the total energy in the system remains the same. That is, if you sum the energies of each particle before the collision, you get the same result as you get by summing the energies of each particle after the collision. We call this the principle of energy conservation. It is a sacrosanct law that no physicist is eager to part with. Similarly, if you sum the arrows corresponding to each particle's momentum before the collision, you get the same result as you get by summing their momenta after the collision. This is known as the principle of momentum conservation.

When you collide two particles with some internal structure, you may find that the total kinetic energy before and after the collision is the same. This is an *elastic collision*. But there are collisions for which this is not the case. Because there is conservation of energy, the only explanation is that some energy must have gone into a reorganization of the internal structure of one or even both particles. This is known as an *inelastic collision*. This idea can be used to probe the internal structure of particles. Accordingly, some experimental facilities are known as particle colliders.

We have mentioned particles. Now we turn to something completely different: waves. One can get intuition about waves by performing an experiment on a tub filled with water. Immersing a hand in the water and