1
Introduction

1.1
An Overview of the Standard Model

1.1.1
What is an Elementary Particle?

Particle physics, also known as high-energy physics, is the field of natural science that pursues the ultimate structure of matter. This is possible in two ways. One is to look for elementary particles, the ultimate constituents of matter at their smallest scale, and the other is to clarify what interactions are acting among them to construct matter as we see them. The exploitable size of microscopic objects becomes smaller as technology develops. What was regarded as an elementary particle at one time is recognized as a structured object and relinquishes the title of "elementary particle" to more fundamental particles in the next era. This process has been repeated many times throughout the history of science.

In the 19th century, when modern atomic theory was established, the exploitable size of the microscopic object was $\sim 10^{-10}$ m and the atom was "the elementary particle". Then it was recognized as a structured object when J.J. Thomson extracted electrons in 1897 from matter in the form of cathode rays. Its real structure (the Rutherford model) was clarified by investigating the scattering pattern of α-particles striking a golden foil. In 1932, Chadwick discovered that the nucleus, the core of the atom, consisted of protons and neutrons. In the same year, Lawrence constructed the first cyclotron. In 1934 Fermi proposed a theory of weak interactions. In 1935 Yukawa proposed the meson theory to explain the nuclear force acting among them.

It is probably fair to say that the modern history of elementary particles began around this time. The protons and neutrons together with their companion pions, which are collectively called hadrons, were considered as elementary particles until ca. 1960. We now know that they are composed of more fundamental particles, the quarks. Electrons remain elementary to this day. Muons and τ-leptons, which were found later, are nothing but heavy electrons, as far as the present technology can tell, and they are collectively dubbed leptons. Quarks and leptons are the fundamental building blocks of matter. The microscopic size that can be explored

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by modern technology is nearing 10^{-19} m. The quarks and leptons are elementary at this level. They may or may not be at a smaller level. The popular string theory regards the most fundamental matter constituent not as a particle but as a string at the Planck scale ($\sim 10^{-35}$ m), but in this book we limit ourselves to treating only experimentally established facts and foreseeable extensions of their models.

1.1.2
The Four Fundamental Forces and Their Unification

Long-Range Forces: Gravity and the Electromagnetic Force There are four kinds of fundamental forces in nature, the strong, electromagnetic, weak and gravitational forces. The strong force, as the name suggests, is the strongest of all; it is a thousand times stronger, and the weak force a thousand times weaker, than the electromagnetic force. The gravitational force or gravity is negligibly weak (that between the proton and electron is 10^{-42} times the electromagnetic force) at elementary particle levels. Its strength becomes comparable to the others only on an extremely small scale (Planck scale $\sim 10^{-35}$ m), or equivalently at extremely high energy (Planck energy $\sim 10^{19}$ GeV), not realizable on the terrestrial world. Despite its intrinsic weakness, gravity controls the macroscopic world. Indeed, galaxies hundred millions of light years apart are known to be mutually attracted by the gravitational force. The strength of the force decreases (only) inversely proportional to the distance squared, but it also scales as the mass, and the concentration of the mass more than compensates the distance even on the cosmic scale. We refer to it as a long-range force. The behavior of the electromagnetic force is similar to and far stronger than gravity, but, in general, the positive and negative charges compensate each other. However, its long-distance effect manifests itself in the form of the galactic magnetic field, which spans hundreds or possibly millions of light years. It binds nuclei and electrons to form atoms, atoms to form molecules and molecules to form matter as we observe them. Namely, it is the decisive force in the microworld where the properties of matter are concerned. Atomic, molecular and condensed matter physics need only consider the electromagnetic force. A mathematical framework, called quantum electrodynamics (QED), is used to describe the dynamical behavior of point-like charged particles, notably electrons, the electromagnetic field and their interactions. Mathematically, it is a combination of quantized Maxwell equations and relativistic quantum mechanics.

Short-Range Forces: The Strong and Weak Forces In the ultramicroscopic world of the nuclei, hadrons and quarks (at scales less than $\sim 10^{-15}$ m), both the strong and the weak force come in. The reason why they are important only at such a small scale is that they are short ranged reaching only a few hadron diameters, and accumulation of the mass does not help to make it stronger. They are referred to as short-range forces. The strong force (referred to as the color force at the most fundamental level) acts between quarks to bind them to form hadrons. Historically, the strong force was first discovered as the nuclear force to bind protons and neutrons. But as they were found to be composites of the quarks, the nuclear force is recognized as a kind of molecular force (van der Waals force) that can be derived from the more fundamental color force. In 1935, Yukawa predicted the existence of the π meson as the carrier of the nuclear force. The idea that the force is transmitted by a "force carrier particle" was revolutionary and laid the foundation for present-day gauge theories. Later, it was clarified that the pion was a composite and cannot be a fundamental force carrier, but the basic idea remains valid. The weak force is known to act in the decay of hadrons, notably in nuclear β decays. It is also known to control the burning rate of the sun and to play a decisive role to in the explosion of type II supernovae.

The electromagnetic force, though playing an essential role at the microscopic level, can also act at the macroscopic distance. We observe electromagnetic phenomena in daily life, for example electrically driven motors or the reaction of a tiny magnet to the earth's magnetic field. The reason is that its strength is proportional to the inverse square of the distance (Coulomb's law). In general, a long-range force decreases only as the inverse power of the distance ($\sim r^{-n}$) and can act on an object no matter how far away it is if there is enough of the force source. A short-range force, on the other hand, is a force whose strength diminishes exponentially with the distance. The nuclear force, for instance, behaves like $\sim e^{-r/r_0}/r^2(r_0 \sim 10^{-15}\,\text{m})$ and reaches only as far as $r \lesssim r_0$. The range of the weak force is even shorter, of the order of $\sim 10^{-18}$ m. Because of this, despite their far greater strength than gravity, their effects are not observed in the macroscopic world. However, if one can confine enough matter within the reach of the strong force and let it react, it is possible to produce a large amount of energy. Nuclear power and nuclear fusion are examples of such applications.

When a Long-Range Force Becomes a Short-Range Force The above description emphasizes the difference between the properties of the forces. Modern unified theories tell us, however, that all the fundamental forces, despite their variety of appearances, are essentially long-range forces and can be treated within the mathematical framework of gauge theories. The seemingly different behavior is a result of metamorphosis caused by environmental conditions. We introduce here one example of a long-range force becoming short range under certain circumstances. A train with a linear induction motor, the next generation supertrain, uses a phenomenon called the Meissner effect to magnetically levitate its body in the air. There, the magnetic field is completely repelled from the superconductor. This happens because, at very low temperatures near absolute zero, electron pairs in a special configuration called the "Cooper pair" collectively react to the magnetic field to form a strong eddy current to cancel the invading magnetic flux. The cancellation is complete except for a shallow depth at the surface, into which the flux can invade. In other words, the electromagnetic force, which is originally long range, becomes short range in the superconductor. This example inspired Nambu [287] to formulate an important concept known as "spontaneous symmetry breaking", which played a crucial role in forming the Standard Model.

Higgs Mechanism The essence of modern unified theory is to recognize that "the vacuum in which we live is in a sort of superconducting phase". What corresponds to the Cooper pair in the superconductor is called the Higgs particle, unseen by us but thought to permeate everywhere in the universe. The weak force is long range originally, but because of the ultracold vacuum that surrounds us becomes short range, owing to the pseudo-Meissner effect caused by the Higgs particles. The short-range force translates to a finite mass of the force carrier particle in quantum field theory, as we shall see in the following sections. The Higgs particle condenses at the ultracold temperature and causes a phase transition of the vacuum, a phenomenon similar to the vapor-to-water phase transition. Elementary particles, which have zero mass originally, acquire mass because of the dragging effect caused by swimming through the condensed sea of the Higgs particle. This mass-generating scheme is called the Higgs mechanism. It is thought that at high temperature (such as at the hot Big Bang) and before the Higgs condensation the weak force was a long-range force, just like the electromagnetic force, and both were just different aspects of the same force. The relation between them is similar to that between magnetic and electric forces. They are unified in the sense they are described by a single mathematical framework, just like the electric and magnetic forces are described by the Maxwell equations. After Glashow, Weinberg and Salam, who constructed the unified theory of the electromagnetic and the weak forces, it is often called as GWS theory or simply the electroweak theory.

Confinement and Screening of Color Contrary to the weak force, the strong force becomes short range for a different reason. A group of quarks bind together by the color force to become hadrons. Protons and pions are examples. At short distances, the color force between the quarks is inversely proportional to the square of the distance, just like any long-distance forces but at long distances, its behavior is different and has a component that does not diminish as the distance increases. Therefore, stored potential energy between them increases with distance, hence an infinite energy is required to separate them to a macroscopic distance. The quarks are, in a sense, connected by a string and, like the north and south poles of a magnet, cannot be isolated individually, a phenomenon called "confinement". They tend not to separate from each other by more than $\sim 10^{-15}$ m, which is the typical size of hadrons. When the string is stretched beyond its limit, it is cut into many pieces, producing more hadrons. The color charges of the quarks come in three kinds dubbed "R, G, B", for red, green and blue, but only a neutral color combination can form hadrons.[1] In the vicinity of the hadron, quarks of different color are located at different distances and hence the effect of individual color can be felt. But from far away the color looks completely neutralised and the strong force between the hadrons vanishes, making it a short-range force. The force between the hadrons, including the nuclear force, is an action of partially compensated residual

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[1] The name "color" is used as a metaphor for three kinds of force-generating charge. We may equally call them by a number or any other index. Only a certain mixture of R, G, B, or color with anticolor (complementary color) that makes white can form hadrons. Hence in the color terminology we can conveniently say hadrons are color-neutral.

colors and is therefore secondary in its nature, like the van der Waals force acting between molecules. The action of color forces is, mathematically, almost identical to that of the electromagnetic force and is also described by a gauge theory, the difference being only in the number of charges (three).[2] This is the reason for the name quantum chromodynamics (QCD) to describe the mathematical framework of the strong force dynamics.

1.1.3
The Standard Model

The weak force can be described by a gauge theory that contains two kinds of charge. General relativity, the theory of gravity, was also recognized as a kind of gauge theory. Considering that the electromagnetic and weak forces are unified and all four fundamental forces work in the same mathematical framework, it is natural to consider that all the forces are unified but show different aspects in different environments. The Grand Unified Theory (GUT), to unify the electroweak and strong interactions, and the Super Grand Unified Theory,[3] to combine all the forces, including gravity, are currently active research areas. Among them "supergravity" and "superstring theories" are the most popular. But only the electroweak theory and QCD are experimentally well established and are called collectively "the Standard Model" (SM) of elementary particles. The history and current situation of force unification are shown in Fig. 1.1.

The essence of the Standard Model can be summarized as follows:

1. The elementary particles of matter are quarks and leptons.
2. The mathematical framework for the force dynamics are gauge theories.
3. The vacuum is in a sort of superconducting phase.

Particle species in the Standard Model are given in Table 2.1 of Sect. 2.1. Matter particles, the quarks and leptons, are fermions having spin 1/2, and the fundamental force carriers, also called gauge particles, are spin 1 bosons. The Higgs boson is a spin 0 particle and is the only undiscovered member. Whether it is elementary or a dynamical object remains to be seen. The Standard Model was proposed around 1970 and was firmly established experimentally by the end of the 1970s. The Standard Model was constructed on the torrent of data from the 1960s to 1980s, when large accelerators become operational (see Table 1.1). It marked the end of the era of the 80-year quest for the fundamental building blocks of matter that started with Rutherford at the beginning of the 20th century, and opened a new epoch. The effect on our consciousness (material view) was revolutionary and comparable to that of relativity and quantum mechanics at the beginning of the 20th century. The

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[2] Gluons, the equivalent of photons in electromagnetism, come in eight colors, which are combinations of the three basic colors, excluding white.

[3] The prefix "super" is attached for theories that contain the supersymmetry that combines fermions and bosons to form one family. They are examples of theories beyond the Standard Model and are briefly described in Chap. 19.

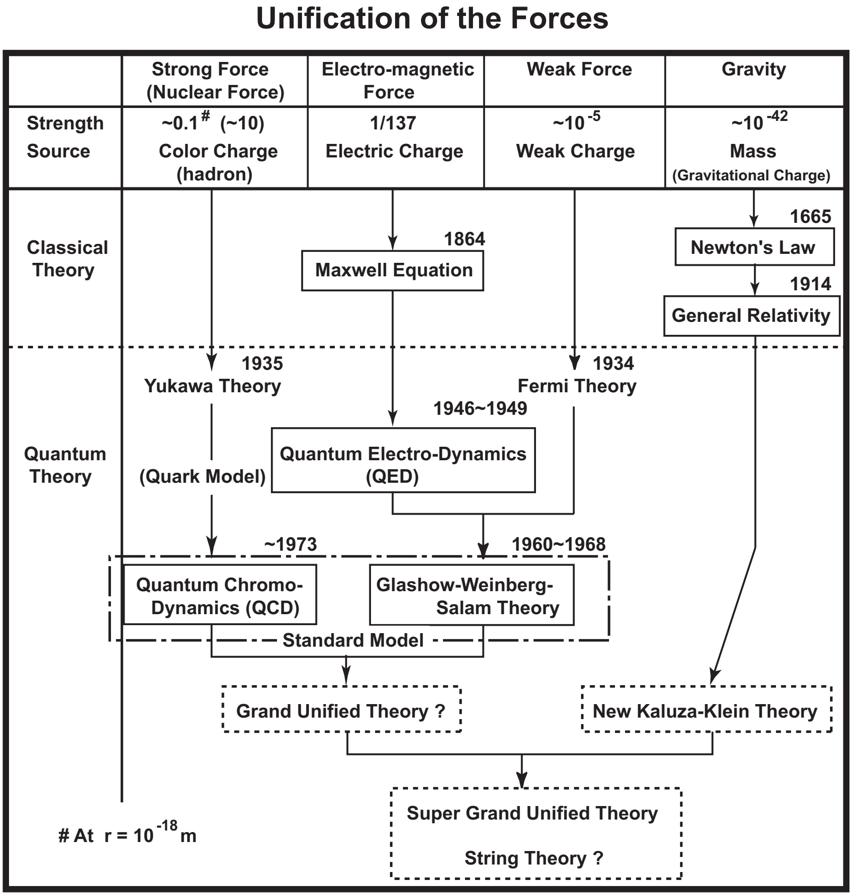

Figure 1.1 Unification of the forces. Those enclosed in dashed lines are not yet established. Only the strong force changes its strength appreciably within currently available energy ranges or, equivalently, distances. This is why the distance of the strong force is specified.

Standard Model is very powerful and can explain all the phenomena in the microworld of particles in a simple and unified way, at least in principle. Forty years have passed since the Standard Model was established, yet there has appeared only one phenomenon that goes beyond the Standard Model. Neutrino oscillation in which a neutrino of one kind is transformed to another while it propagates, does not happen if the mass of the neutrino vanishes, as is assumed in the Standard Model. But it is fair to say it only needs a small stretch and is not a contradiction to the Standard Model. The model is so powerful to the extent that it is not easy to think of an experiment with currently available accelerators that could challenge the Standard Model in a serious way. A quantum jump in the accelerator energy and/or intensity is required to find phenomena that go beyond the Standard Model and explore new physics.

Table 1.1 Chronicle of particle physics. Important discoveries and contributing accelerators. Items in parentheses (···) are theoretical works.

Year	Names	Discovered or proposed	Accelerator
1897	J.J. Thomson	Electron	Cathode tube
1911	E. Rutherford	Atomic model	α Isotope
1929	W. Heisenberg W. Pauli	(Quantum field theory)	
1930	P.A.M. Dirac	(Dirac equation)	
1930	W. Pauli	(Neutrino)	
1932	J. Chadwick	Neutron	α Isotope
"	C.D. Anderson	Positron	Cosmic ray
"	E.O. Lawrence	Cyclotron	Cyclotron
1934	E. Fermi	(Weak interaction theory)	
1935	H. Yukawa	(Meson theory)	
1937	C.D. Anderson S.H. Neddermyer	Muon	Cosmic ray
1947	G.F. Powell	Pion	Cosmic ray
"	G.O. Rochester C.C. Butler	Strange particles	Cosmic ray
1946–1949	S. Tomonaga J. Schwinger R. Feynman	(QED)	
1950–1955		Strange particle production	Cosmotron
1953	K. Nishijima M. Gell-Mann	(Nishijima–Gell-Mann law)	
1954	C.N. Yang R.L. Mills	(non-Abelian gauge theory)	
1955	E. Segre O. Chamberlain	Antiproton	Bevatron
1956	C.L. Cowan F. Reines	Neutrino	Reactor
1956	C.N. Yang T.D. Lee	(Parity violation)	
1958	R. Feynman and others	(V-A theory)	
1960	Y. Nambu	(Spontaneous breaking of symmetries)	
1960–1970	L.W. Alvarez et al.	Resonance production by bubble chambers	Bevatron Cosmotron
1962	L. Lederman M. Schwarz J. Steinberger	2-neutrinos	BNL/AGS

Table 1.1 (continued)

Year	Names	Discovered or proposed	Accelerator
1964	M. Gell-Mann G. Zweig	(Quark model)	
"	V. Fitch J. Cronin	CP violation	BNL/AGS
"	P. Higgs	(Higgs mechanism)	
"	N. Samios et al.	Ω	BNL/AGS
1961–1968	S. Glashow S. Weinberg A. Salam	(Electro-weak unification)	
1969	J.I. Friedman H.W. Kendall R.E. Taylor	Parton structure of the nucleon	SLAC/Linac
$\sim$ 1971	G. 't Hooft M.J.G. Veltman	(Renormalization of EW theory)	
1972–1980		Neutrino experiments	Fermilab/PS CERN/SPS
1973	M. Kobayashi T. Maskawa	(KM model on CP)	
1973	H.D. Politzer D.J. Gross F. Wilczek	(Asymptotic freedom and QCD)	
"	A. Lagarrigue et al.	Neutral current	CERN/PS
1974	C.C. Ting B. Richter	J/ψ (charm quark)	BNL/AGS SPEAR
1974–1980		Charm spectroscopy	SPEAR, DORIS
1975	M. Pearl	τ lepton	SPEAR
1978	L. Lederman	Υ (bottom quark)	Fermilab/PS
1978–1979		Bottom spectroscopy Gluon	CESR/SPS DESY/PETRA
1983	C. Rubbia van de Meer	W, Z^0	S$\bar{p}$pS
1990–2000		$N_\nu = 3$ Precision test of EW theory	LEP LEP, TEVATRON
1994		Top quark	TEVATRON
1998	Y. Totsuka et al.	Neutrino oscillation	Cosmic rays
2000	SLAC/BaBar KEK/BELLE	Kobayashi–Maskawa model confirmed	SLAC/B KEK/B

The fact that the kinetic energy of particles in particle physics far exceeds the mass energy makes special relativity an indispensable tool to describe their behavior. Understanding the mathematical formalism that is built on the combination of special relativity and quantum mechanics, also known as quantum field theory, requires a fair amount of effort, and the ensuing results very often transcend human common sense. The only other fields that need both disciplines are cosmology and extreme phenomena in astrophysics, such as supernovae and black-hole dynamics.

1.2
The Accelerator as a Microscope

In order to investigate the microscopic structure of matter, we need a tool, a microscope, that magnifies the object so that we can see it, or more generally recognize it using our five senses. What corresponds to the light-collecting device in the microscope is a particle accelerator. Shining light on the object corresponds to making high-energy particles collide with target particles whose structure we want to investigate. The scattered light is collected by objective lenses and focused to an image, which we observe through an eyepiece. In the accelerator experiment, we use a radioisotope detector to measure patterns of the scattered particles. By computer processing they can be transformed to a pattern that we can recognize as a magnified image. The magnification of a microscope is determined by a combination of lenses, but they merely transform the image to help human eyes to recognize the scattered pattern of light. The resolution, the ability of the optical microscope to discriminate, is largely determined by the wavelength of the light. The more powerful electron microscope uses an electron beam and instead of optical lenses, quadrupole magnets to focus the beam. The scattered electrons are illuminated on a fluorescent board to make an image that human eyes can recognize. In other words, the electron microscope is a mini accelerator–detector complex.

The quantum principle dictates that particles have a dual wave/particle property and the wavelength is given by the Planck constant divided by the particle momentum (the de Broglie wavelength $\lambda = h/p$). Therefore, the resolving power is directly proportional to the momentum or the energy of the incoming particle. This is why we need high-energy accelerators to explore the structure of matter. The smaller the scale, the higher the energy. Therefore, to explore elementary particles, the highest energy technologically realizable at the era is required. This is why particle physics is often called high-energy physics.

Figure 1.2, commonly referred to as the Livingston chart, shows the history of major accelerators and their energy. On the right are indicated the approximate ranges of energy that are suitable for the investigation of the particle structure at the specified level. We summarize important discoveries and tools used for them in the history of particle physics in Table 1.1. We can see that the most effective tools for particle physics are accelerators of the highest energy available at the time. The one with the highest energy currently is the LHC (Large Hadron Collider; a proton–

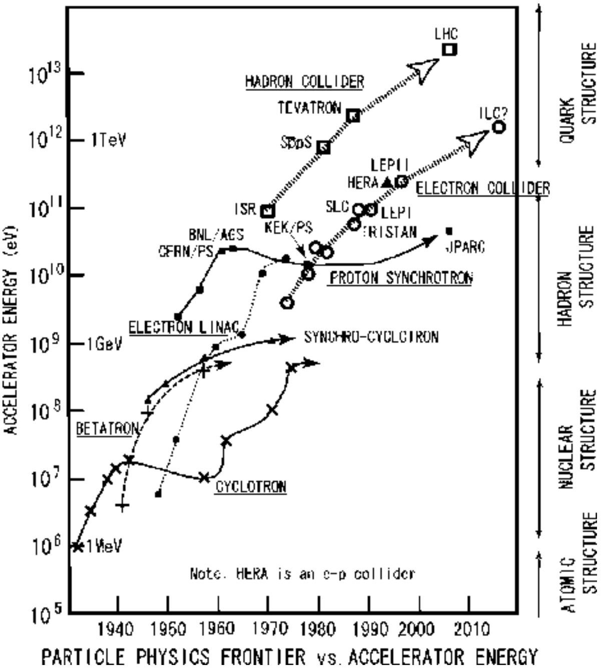

Figure 1.2 The Livingstone chart showing development of accelerators and the investigated constituent particles.

proton colliding accelerator of total energy 14 TeV) in Europe. It started operation in 2009. The LHC can explore a micro-size of $\sim 10^{-20}$ m and is expected to discover the Higgs particle.