An overview of elementary particle physics around the Standard Model and its extensions

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1. Introduction

In 1995, the sixth quark, top quark was discovered by the Tevatron at Fermilab, and then precise measurements about the CKM matrix including CP violation have been carried out by KEKB at KEK and PEP2 at SLAC, called B-factories, both since 1999.

The Standard Model (SM) has been checked steadily in this way. Furthermore, the Large Hadron Collider (LHC) at CERN has been operated since 2008. It is hoped that the Higgs boson and exotic particles such as supersymmetric (SUSY) particles, which are not the members of the SM, will be discovered. On the other hand, various models have been proposed theoretically, which may unify the strong and electroweak interactions, and even gravity. In such models, the problems in the SM may be solved.

This article outlines the theoretical and experimental situations around the SM and its extensions.

2. Experimental verification of the Standard Model

2-1. Discovery of elementary particles

The SM is the local gauge theory based on the $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetries. The strong interaction is described by the $SU(3)_C$ gauge theory, Quantum Chromodynamics (QCD), and the electroweak interaction is described by the $SU(2)_L \times U(1)_Y$ gauge theory with the Higgs mechanism for spontaneous symmetry breaking. The Higgs mechanism at the same time provides the masses of elementary particles, and the Cabbibo-Kobayashi-Maskawa matrix (CKM matrix) for quark mixing (Figure 1).

Standard Model

$SU(3)_C \times SU(2)_L \times U(1)_Y$
+
Higgs mechanism
+
CKM matrix

Figure 1.Construction of the SM.

In the SM, there are six quarks, six leptons, gauge bosons and Higgs bosons. Among the gauge bosons, the photon mediates the electromagnetic interaction, the W and Z bosons mediate the weak interaction, and the gluons mediate the strong interaction (Table 1 and Table 2).

The quark model was proposed by Gell-Mann and Zweig independently in1964. Then the CKM matrix for quark mixing was presented by Kobayashi and Maskawa in1972, predicting the existence of six quarks for CP violation. The structure of nuclei was observed at SLAC in 1968, then the existence of up quark (u), down quark (d) and strange quark (s) were confirmed. The charm quark (c) was discovered independently at BNL and SLAC in 1974, and the bottom quark (b) was discovered at Fermilab in 1977. Finally, the top quark (t) was discovered at Fermilab in 1995. On the other hand, some of the leptons were discovered much earlier than the quarks. The electron (e) was observed by J. J. Thomson in 1897, the muon (μ) in 1936, the electron-neutrino (ν_e) in 1956, the mu-neutrino (ν_μ) in 1962, the tau (τ) at SLAC in 1975, and finally the tau-neutrino (ν_τ) at Fermilab in 2000. The gluons were discovered by the PETRA accelerator at DESY in 1979, and the W and Z bosons were discovered by the SPS accelerator at CERN in 1982.

Although only the Higgs boson is not discovered yet, the upper and lower limit on the Higgs mass have been currently placed by experiments at the LHC. It is hoped that the existence of Higgs will be confirmed at the LHC in near future.

Table 1 and Table 2 show summary of the particle properties.

Fermion	Electric charge	First generation	Second generation	Third generation
Quark	+2/3	u (up) 2.5MeV Discovered in 1968	c (charm) 1.27GeV Discovered in 1974	t (top) 172GeV Discovered in 1995
	−1/3	d (down) 4.95MeV Discovered in 1968	s (strange) 101MeV Discovered in 1968	b (bottom) 4.19GeV Discovered in 1977
Lepton	0	ν_e (electron neutrino) <0.000225MeV Discovered in 1956	ν_μ (mu neutrino) <0.19MeV Discovered in 1962	ν_τ (tau neutrino) <18.2MeV Discovered in 2000
	−1	e (electron) 510eV Discovered in 1897	μ (muon) 105MeV Discovered in 1937	τ (tau) 1.777GeV Discovered in 1975

Table 1. Summary of fermions.

Boson	Detail
Gauge boson	$W^{\pm}$ boson, 81GeV, Discovered in 1982 Z boson, 92GeV, Discovered in 1982 γ (photon), massless g (gluon), massless, Discovered in 1979
Higgs	H (Higgs boson), $115\text{GeV} \leqq m_H \leqq 248\text{GeV}$, Not discovered (Its discovery is hoped at the LHC.)

Table 2. Summary of bosons.

2-2. Quark and lepton flavors

There are three generations of quarks and leptons in the SM, and this variety is called "flavors".

First we describe the flavor changing interaction of quarks. The flavors of quarks are changed, mediated by the charged gauge boson $W^{\pm}$. This flavor changing process is described with the CKM matrix, which is a 3 ×3 unitary matrix containing one physical CP violating complex phase. It is represented as follows.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\sim \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}.$$

The second line is a simple expression called "Wolfenstein parameterization" [8].

No first principle is known to specify the form of this CKM matrix, but its matrix elements are determined by experiments. The experimental values up to date are given in Ref. [9]. The absolute values of the elements are given as

$$|V_{CKM}| = \begin{vmatrix} 0.97428 & 0.2253 & 0.00347 \\ 0.2252 & 0.97345 & 0.0410 \\ 0.00862 & 0.0403 & 0.999152 \end{vmatrix}.$$

It is expected that the elements V_{ub} and V_{cb} will be directly determined more precisely at the currently running B-factory. Because there is no accelerator to generate copiously top quark, the elements V_{td} and V_{ts} are determined indirectly by the neutral B meson mass differences, Δm_{B_d} and Δm_{B_s}, respectively. The element V_{tb} is directly determined by measurement of single top production, though not precise. We hope direct and precise measurements about these elements will be made at the LHC.

In order to determine the complex phase in the CKM matrix, the unitarity triangles are examined. There are six triangles which represent the unitarity conditions of the CKM matrix. We focus one of them as shown in Figure 2. The rest of the triangles are rather flat, not suitable to determine the CKM phase.

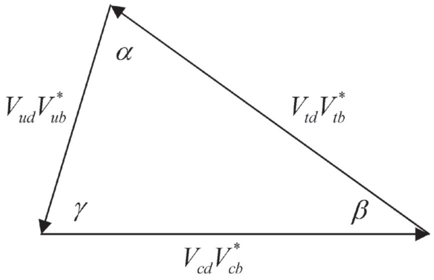

Figure 2. The unitarity triangle.

For this unitarity triangle, the lengths of sides (the absolute values of the elements in the CKM matrix) and angles (the CKM phase) are measured separately. If the triangle closes, it confirms the SM description. Otherwise, if the triangle does not close, it would indicate some New Physics (NP) beyond the SM, contributing to the flavor changing processes.

At present, the sides involving the bottom quark are measured already, but the accuracy is not good. The side involving the top quark has not been measured yet. The angle β is determined rather accurately, but the measurements of the angles α and γ still have significant uncertainties.

No lepton flavor mixing appear in the SM because the neutrinos masses are not generated by the Higgs doublet. Nonetheless, the neutrino oscillation was observed in an atmospheric neutrino measurement at the Super-Kamiokande (S-Kamiokande) in 1998, confirming the nonzero neutrino masses. This indicates that the SM should be extended for neutrino masses, providing the lepton flavor mixing matrix (MSN matrix) [10].

3. Problems on the Standard Model

In this section, we enumerate problems included in the SM [11].

(1) Gravity is not included.

There are four fundamental interactions in nature. The SM describes only three of them, the strong interaction, weak, and electromagnetic interactions, excluding the gravity.

(2) $SU(3)_C$ and $SU(2)_L \times U(1)_Y$ are not unified.

In the SM, the electroweak theory with the $SU(2)_L \times U(1)_Y$ and the QCD with the $SU(3)_C$ are described separately. The Grand Unified Theory (GUT) unifies these gauge theories, which will be explained in the next section.

(3) A lot of parameters within the SM.

The parameters contained in the SM are counted as follows.

- Gauge couplings (3 : α_s, α_1, α_2)
- Yukawa couplings (9×2 : except for the complex phases)
- The electroweak angle (1 : θ_W)
- Quark and lepton masses (9 : assuming the massless neutrinos)
- CKM matrix elements (4)
- Higgs potential (2 : Higgs mass and vacuum expectation value)

(4) No mechanism for exchange between quarks and leptons.

Why the strong interaction acts on quark, while it does not on lepton? There is no rule for exchange between quarks and leptons.

(5) No reason why there are three generations.

There is no explanation for this problem.

(6) No reason why the electric charges are quantized.

There is no rule to explain that each quark has an electric charge which is exactly a multiple of 1/3 times the electron charge.

(7) Neutrinos are massive.

Because of the absence of right-handed neutrinos in the SM, the left-handed neutrinos are regarded to be massless. However, the neutrino oscillation is observed, indicating clearly that that the neutrinos are massive.

(8) Lack of enough CP violation for the baryogenesis in the early universe.

In order to generate enough matter (baryons) to construct the present universe, the so-called Sakharov's three conditions should be realized as follows [12].

A. The baryon number conservation is broken.
B. The CP symmetry, namely the symmetry between matter and anti-matter is broken.
C. There is a derivation from thermal equilibrium.

It is well known that the CP-violating complex phase in the CKM matrix within the SM is too small to satisfy the condition B.

4. Theories beyond the SM

The SM is the gauge theory based on the $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetries. The trial to unify the three gauge couplings at a very high energy scale (GUT scale) is made by the GUTs through the renormalization-group evolution. The SU(5) proposed by Georgi and Glashow is the smallest GUT (1974) [13]. This theory was, however, denied by the measurement about the lifetime for the proton decay at the S-Kamiokande. What is worse, there are more problems in the SU(5). The three gauge couplings does not cross precisely at one point together. Furthermore, the loop correction for the Higgs mass diverges quadratically, requiring fine-tuning to make the physical Higgs mass to be the electroweak scale much below the GUT scale (hierarchy problem).

To solve these problem, the supersymmetry (SUSY) [14] is introduced in the SM or GUT. The SUSY SU(5) GUT actually solve the above two problems. Each SM particle has its superpartner, so-called SUSY particle, with the spin differing by one half. The squarks and sleptons with spin 0 are the SUSY particles for the quarks and leptons with spin 1/2, respectively. There are also SUSY particles for the gauge bosons, e.g., the wino with spin 1/2 for the W boson with spin 1. The SUSY particles have the same electric charges as their SM partners (Table 3).

The neutralino is particularly considered as a good candidate for the dark matter with which the universe is filled. However, the SUSY particles have not been discovered yet. The discovery of them is one of the main targets at the LHC.

There are several GUTs other than SU(5), including SO(10), and E_6. Furthermore, the quantum gravity theory and several superstring theories were proposed to unify even the gravity. The M theory with 11 dimensions was proposed by Witten in 1995 [15], which provide the quantum gravity and superstring theories as the low-energy limit (Figure 3).

SUSY particle	Spin
slepton ・selectron ($\tilde{e}$) ・e-sneutrino($\tilde{\tau}_e$)	0
squark ($\tilde{q}$)	0
gauginos ・wino($\tilde{W}^{\pm}$) ・zino($\tilde{Z}$) ・photino($\tilde{\gamma}$)	1/2
higgsino($\tilde{H}$)	1/2

Table 3. SUSY particles.

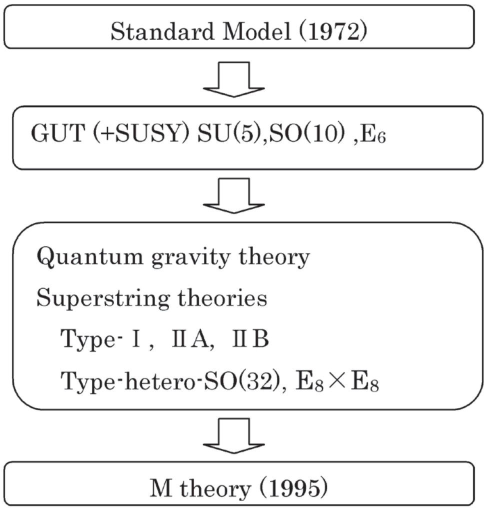

Figure 3. Evolution of unified theories.

5. Recent and future experimental status

The experiments of elementary particle physics are classified as follows.

(1) Energy frontier accelerator experiment (Primary purpose is discovery of new elementary particles.)
(2) Luminosity frontier accelerator experiment (Primary purpose is accurate measurements.)
(3) Experiment without using accelerator (The purpose is both of above two.)

Especially, (1) and (2) are complementary each other because both are required in order to validate the theory to describe elementary particle phenomena precisely.

Accordingly, accelerators are classified as follows (Table 4).

A. Type of proton-proton (antiproton) collider
B. Type of electron-positron collider
C. Type of electron (positoron)-proton collider

Electrons circulate being bent by the magnetic field in a synchrotron accelerator. Then, they lose energy emitting radiation. Hence, for circular type accelerators there is certain limitation in accelerating electrons. For this reason, there is a plan to construct a linear accelerator with straight line trajectory, the ILC (International Linear Collider).

Since a proton has 1836 times a heavy mass as an electron, the loss of energy is negligible when it is accelerated in a circular type accelerator. Hence, a proton collider can generate about ten times a large energy as an electron collider. Here, a proton is a composite particle consisting of quarks with an internal structure. In a proton collider, since protons, as the composite particles, collide with each other, the effective energy available to observe new phenomena is reduced to about 1/10 times of the energy of the accelerated protons. On the other hand, since an electron is an elementary particle without an internal structure, the energy generated by the electron collider can be used fully to observe new particles.

Therefore, the colliders of A and B are complementary each other. The colliders in operation or under a plan is listed in Table 4.

Type	Accelerator, energy, period, etc.
A. $p-p$ type	***LHC*** at CERN, 7+7TeV 2008- (Higgs?, SUSY particle?, exiotic particle?)…(1)
$p-\bar{p}$ type	***Tevatron*** at Fermilab, 1+1TeV,1987-2009 (1995: top quark)…(1)
B. $e-e^+$ type	***KEKB*** at KEK, 8.0+3.5GeV, 1999- (2001: $B \to J/\psi + K_S$ 2007: $D^0-\bar{D}^0$ mixing)…(2) ***PEP-II*** at SLAC, 9.0+3.1GeV 1999-2008 (2001: $B \to J/\psi + K_S$)…(2) ***LEP I/II*** at CERN, 100+100GeV,1989-2000 (1989: three generations of neutrinos)…(1) ***ILC*** at ? , 1TeV, under a plan…(1)
C. $e^{\pm}-p$ type	***HERA*** at DESY, 30+800GeV, 1992-2007 …(1)

Table 4. List of colliders in operation or under a plan.

The LHC is in operation now. Its experiment aims at discovery of the Higgs, the SUSY particles, exotic particles, and so on. Its highest attainment energy is 14TeV (phenomena measured at LHC is in a scale up to 1TeV). The W, Z bosons, and the top quark have been produced copiously in the LHC experiments, verifying the results of the former colliders. The running energy currently reached 7 TeV in March, 2010. At the same time, the range of the Higgs mass between 145GeV to 466 GeV has been excluded. In order to investigate phenomena in a higher energy scale than the LHC, the construction of the ILC is under a plan.

We also note experiments at the so-called B-factories as typical luminosity frontier accelerators. The operation of the PEPⅡ at SLAC had been finished. The KEKB at KEK is still in operation. The SM has been verified by precise experiments on the neutral mesons, K, D, and B at the both B-factories.

Typical experiments without using accelerators, type (3), have been performed at the Kamiokande (1983-1998) and the S-Kamiokande(1996-), which is an upgrade version of the Kamiokande. A huge amount of pure water is stored in a large tank, and tracks caused by particles from the universe are observed there. At the Kamiokande, the neutrinos emitted from a supernova in Large Magellanic Cloud were observed in 1987, and an atmospheric neutrino oscillation, $\nu_e \rightarrow \nu_\mu$, was also observed in 1989. Then, another atmospheric neutrino oscillation, $\nu_\mu \rightarrow \nu_\tau$, was observed in1998 at the S-Kamiokande. These experiments have confirmed that the neutrinos are massive particles. This oscillation was observed again at the K2K experiment (1999-2004). In this experiment the neutrinos generated by the KEK accelerator at Tsukuba were observed by the S-Kamiokande at Kamioka. Recently, the oscillation, $\nu_\mu \rightarrow \nu_e$,has been also observed at T2K experiment; neutrinos are generated by the J-PARC accelerator at Tokai, and they are detected by the S-Kamiokande. Furthermore, the KASKA experiment for sake of observing the oscillation, $\nu_e \rightarrow \nu_\tau$, is planed now.

Neutrino oscillation	Discovery year	Experiment
$\nu_e \rightarrow \nu_\mu$	1989	Kamiokande
$\nu_\mu \rightarrow \nu_\tau$	1998 1998-2004	S-Kamiokande K2K
$\nu_\mu \rightarrow \nu_e$	2011	T2K (2009-)
$\nu_e \rightarrow \nu_\tau$	Not discovered	KASKA (under a plan)

Table 5. Detection of neutrino oscillations.

6. Summary

In this article, we have surveyed the SM and its experimental verification, the problems not explained by the SM, the theories beyond the SM, and the present and future status of experiments in elementary particle physics. We hope that New Physics beyond the SM will be discovered by future experiments.

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