Review of the extended Standard Model with quark singlets

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Abstract

Almost all particle phenomena have been explained cleanly by the Standard Model. There, however, remain some problems about the fermion mass hierarchy, the electroweak angle, neutrino oscillation, baryogenesis, and so on, which are not explained in the framework of the Standard Model. The extended Standard Model with quark singlets is one of promising theories which may resolve some of these problems. A notable feature of this extended model is the appearance of flavor changing neutral processes at the tree level.

1. Introduction

So far most of the behavior of elementary particles is well described by the Standard Model (SM) [1]. This is a gauge theory with three types of interactions, namely, the strong, electromagnetic and the weak interactions, based on the internal symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$. The $SU(3)_C$ gauge symmetry describes the dynamics of the strong interaction, QCD (quantum chromodynamics). The $SU(2)_L \times U(1)_Y$ gauge symmetry describes the dynamics of the electromagnetic and weak interactions through the spontaneous symmetry breaking by the Higgs field.

Quarks and leptons couple to the Higgs field, namely the Yukawa couplings, and they acquire masses with the vacuum expectation value of the Higgs field developed by the spontaneous breaking of the $SU(2)_L \times U(1)_Y$ symmetry. The current experimental value of the these fermion masses are as follows [2]:

$m_u = 1.5 - 3.3\,\text{MeV}$, $m_c = 1.16 - 1.34\,\text{GeV}$, $m_t = 169.0 - 173.6\,\text{GeV}$,

$m_d = 3.5 - 6.0\,\text{MeV}$, $m_s = 70 - 140\,\text{MeV}$, $m_b = 4.13 - 4.37\,\text{GeV}$,

$m_e = 0.5110\,\text{MeV}$, $m_\mu = 105.66\,\text{MeV}$, $m_\tau = 1.777\,\text{GeV}$,

$m_{\nu_e} < 0.225\,\text{MeV}$, $m_{\nu_\mu} < 0.19\,\text{MeV}$, and $m_{\nu_\tau} < 18.2\,\text{MeV}$.

Recently, it has been also confirmed that the neutrino masses are nonzero. Since the right-handed neutrinos are not present in the SM, some extension of the SM is required for the neutrino mass generation. Here, we note certain hierarchy about the quark and lepton masses. That is,

$m_u \ll m_c \ll m_t, m_d \ll m_s \ll m_b$,

$m_e \ll m_\mu \ll m_\tau$, and $m_{\nu_e} = m_{\nu_\mu} = m_{\nu_\tau} \sim 0$.

In addition to the fermion mass generation, the Yukawa couplings provide mixing among the quarks or leptons with the same electric charge. In general, this causes flavor changing processes in the weak interaction. In the SM, they appear at the tree level in the coupling of the quarks with the charged gauge bosons (W), which are described with the Cabbibo-Kobayashi-Maskawa (CKM) matrix [3]. Such flavor changing interactions, for instance, induce the β decays of the charged π and K mesons. On the other hand, in the limit of zero neutrino masses, such mixing among the leptons is physically ineffective.

The SM has steadily been validated by the discovery of the W bosons, Z boson and top quark. However, some parameters have not been checked fully in experiments such as the elements of the CKM matrix including the third generation. Moreover, it has been confirmed by the experiment at K2K in2004 that neutrinos have nonzero masses. Its experimental limit is given as $0.04\,\mathrm{eV}<(\mathrm{Mass})[\mathrm{Heviest}\ \nu]<(0.07\sim 0.7)\,\mathrm{eV}$. Hence the SM should be extended for the neutrino mass generation. Then, the lepton flavor changing processes may occur. Besides the problem of the neutrino masses, there remain some problems to be solved, including the value of the electroweak angle θ_W, the quark and lepton mass hierarchy, and the explanation for the shape of the CKM matrix (specifically, the small off-diagonal elements). Furthermore, there are more problems in the SM, e.g., the baryogenesis at electroweak phase transition cannot be explained [4]. At present there is no principle to solve these problems.

In order to resolve these problems, various extensions for the SM have been considered. The grand unified theory (GUT), which unifies $SU(3)_C$ and $SU(2)_L \times U(1)_Y$ into $SU(5)$ [5], SO (10) or E_6 [6], can potentially explain these problems to some extent. For example, in the E6 model the quarks, leptons and Higgs bosons in each generation are combined in a unified way as a 27-dimensional representation. Then, it is noteworthy that $SU(2)_L$ singlet quarks, leptons and Higgs bosons as well as the ordinary ones are contained in the 27-dimensional representation of E6. Although these new particles have not yet been discovered directly, they might already show their presence in the electroweak scale through the quark mixing, the lepton mixing, and so on. By examining these effects in detail, important information may hopefully be obtained about the microscopic physical world which is much smaller than the electroweak scale. The presence of these particles are also suggested by the super string theory which is a unified theory including the gravity.

In this article, we review the SM and its extension with quark singlets, specifically considering the flavor changing processes.

2. The Standard Model

2-1. Outline

The Standard Model (SM) is the gauge theory based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$. In the $SU(3)_C$ (QCD), the strong interaction among the quarks is mediated by the gauge bosons called gluons. The $SU(2)_L$ and $U(1)_Y$ symmetries introduce the gauge bosons W and B, respectively. The corresponding gauge couplings are g_s, g and g'. The weak gauge bosons get their masses from the spontaneous symmetry breaking of the electroweak $SU(2)_L \times U(1)_Y$ to the electromagnetic

$U(1)_{em}$, which is caused by the Higgs mechanism. Specifically, the four gauge bosons mix each other to form the mass eigenstates $W^{\pm}$, Z, and A^0. The massless photon is given by $A^0=W^{(3)}\sin\theta_W + B\cos\theta_W$. The massive charged and neural weak bosons are given by $W^{\pm}=(W^{(1)}\mp iW^{(2)})/\sqrt{2}$ and $Z=W^{(3)}\cos\theta_W - B\sin\theta_W$, respectively, where $\theta_W=\tan^{-1}(g'/g)$ is the electroweak angle. The generator of $U(1)_{em}$, namely the electric charge, is given by $Q=Y/2+I_3$, where Y is the generator of $U(1)_Y$ (the weak hypercharge), and I_3 is one of the $SU(2)_L$ generators (the weak isospin). In this article, we will concentrate on the phenomenology concerning the electroweak interaction of $SU(2)_L\times U(1)_Y$, thus almost omitting the strong interaction of $SU(3)_C$.

2-2. Particle contents

The SM contains spin-1/2 particles as fermions, spin-1 particles as gauge bosons, and spin-0 particles Higgs bosons.

In the fermion group, there are six quarks (up, down, charm, strange, top, and bottom) and six leptons (electron, electron neutrino, muon, mu neutrino, and tauon, tauneutrino). They are classified into three generations, as shown in Table. 1. Each member of one generation has the grater mass than the corresponding member of the lower generations. This hierarchy cannot be explained in the SM. While the quarks with color charges of $SU(3)_C$ interact with each other via the strong interaction mediated by the gluons, the leptons as $SU(3)_C$ singlet do not have the strong interaction.

The boson group include the four gauge bosons ($W^{\pm}$, Z, and A^0) mediating the weak and electromagnetic interactions, and one Higgs boson (H^0) generating the masses of particles via the spontaneous breaking of $SU(2)_L\times U(1)_Y$ (Table 2). The charged W bosons and neutral Z boson (weak bosons) mediate the weak interaction. The neutral A^0 boson is the massless photon mediating the electromagnetic interaction. The weak bosons get their masses via the spontaneous breaking of $SU(2)_L\times U(1)_Y$. The Higgs boson (H), though has not been observed so far, is expected to be discovered at the large hadron collider (LHC).

The quantum numbers of the respective particles in the SM are shown in Table 3.

2-3. The masses and mixings of quarks and leptons

The Yukawa couplings are given by

$$L_{Yukawa}=y_u\overline{L_q^0}\tilde{\Phi}u_R^0+y_d\overline{L_q^0}\Phi d_R^0+y_e\overline{L_l^0}\Phi e_R^0+h.c.$$

in thems of the weak eigenstates with subscript "0" (eigenstates of the gauge interactions). After the spontaneous breaking of $SU(2)_L\times U(1)_Y$ the quarks and leptons acquire the mass terms through the Yukawa coupling with the Higgs field. The quark mass matrix is diagonalized by unitarity transformations as

$$\begin{aligned}\overline{q_L{}^0}M_q q_R{}^0 &= \overline{q_L{}^0}V_{qL}V_{qL}{}^{\dagger}M_q V_{qR}V_{qR}{}^{\dagger}q_R{}^0\\ &=\overline{q_L}M_{q-diag}q_R\end{aligned}$$

where q without subscript "0" represents the mass eigenstates, as given by

$$q_\chi = V_{qR}{}^{\dagger} q_\chi{}^0,\ M_{q-diag} = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix}.$$

The masses and mixings of the leptons are described in a similar fashion.

The characteristic features of the SM are summarized as follows:

1. The quark and lepton mixings induce flavor changing charged processes mediated by the $W^{\pm}$ bosons. However, flavor changing neutral processes mediated by the Z boson or the Higgs boson H are absent at the tree level.
2. There is a small CP violating phase in the CKM matrix V_{CKM}, which will be described in detail later.

Table 1. Fermion group

Fermions	Electric charge	First generation	Second generation	Third generation
Quarks	+2/3	Up(u)	Charm(c)	Top(t)
	-1/3	Down(d)	Strange(s)	Bottom(b)
Leptons	+2/3	Electron(e)	Muon(μ)	Tauon(τ)
	-1/3	Electron eutrino(ν_e)	Mu neutrino(ν_μ)	Tau neutrino(ν_τ)

Table 2. Boson group

Bosons	Charged bosons	Neutral bosons
Gauge bosons	$W^{\pm}$ (weak interaction)	Z(weak interaction) A^0(electromagnetic interaction)
Higgs boson	-	H

Table 3. The quantum numbers of the respective particles

Particles	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Quarks $L_q = (u_L, d_L)$	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
Leptons $L_l = (\nu_L, e_L)$	1	2	-1/2
e_R	1	1	-1
Higgs bosons $\Phi = (\phi^+, \phi^0)$	1	2	1/2
Gauge bosons W	1	3	0
B	1	1	0

3. The extended SM with quark singlets

3-1.Outline

Extension of the SM may be motivated in various points of view toward the discovery of new physics. Among many intriguing possibilities, the presence of isosinglet quarks is suggested in certain models such as the E6 type unified model. Specifically, there are two types of singlet quarks, U with electric charge Q_{em}=2/3 and D with Q_{em}=-1/3, which may mix with the ordinary quarks. Then, various novel features arise through the mixing between the ordinary quarks ($q=u,d$) and the singlet quarks ($Q=U,D$). The unitarity of the CKM matrix within the ordinary quark sector is violated, and the flavor changing neutral currents (FCNC's) appear at the tree level. These flavor changing interactions are actually described in terms of the q-Q mixing parameters and the quark masses. This may be viewed as an interesting extension of the natural flavor conservation proposed in the early literature. Furthermore, the q-Q mixing may involve CP violating phases. Hence, it is fairly expected that the q-Q mixing provides significant effects on various physical processes. It is also noted that the so-called seesaw mechanism even works for generating the ordinary quark masses through q-Q mixing.

The q-Q mixing effects on the Z boson mediated neutral currents have been investigated so far extensively in the literature. These analyses show, in particular, that there is a good chance to find singlet quark effects in B physics. Some contributions of the neutral couplings mediated by the Higgs scalar particles have also been considered on the neutral meson mixings.

The singlet quarks may even provide important contributions in cosmology. In fact, for the electroweak baryogenesis the CP violating q-Q mixing through the coupling with a complex singlet Higgs field S can be efficient to generate the chiral charge fluxes through the bubble wall. This possibility is encouraging, since the CP asymmetry induced by the conventional CKM phase is far too small to account for the observed baryon to entropy ratio. Furthermore, the singlet Higgs field S, which provides the singlet quark mass term and the q-Q mixing term, is preferable for realizing the strong enough first order electroweak phase transition.

3-2.Particle contents

The quantum numbers of the respective exotic particles beyond the SM are shown in Table 4. These particles are expected to be observed at the LHC.

The characteristic features introduced by the singlet quarks are summarized as follows:

1. Flavor changing neutral currents mediated by the Z and Higgs bosons appear at the tree level.
2. The unitarity of the CKM matrix is violated in the ordinary quark sector.
3. The new CP violating phases in the q-Q mixing may provide significant effects for various processes, including the electroweak baryogenesis.

Table 4. The quantum numbers of the respective exotic particles

Particles	Electric charge	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Singlet quarks				
U_L	2/3	3	1	2/3
U_R	-2/3	3	1	-2/3
D_L	-1/3	3	1	-1/3
D_R	1/3	3	1	1/3
Singlet Higgs boson S	0	1	1	0

4. Flavor changing process

Flavor changing process is one of the most interesting issues in particle physics. In the SM, there is the flavor changing charged current (FCCC) mediated by the gauge boson $W^{\pm}$. The CKM matrix for the W mediated FCCC is given by a 3×3 unitary matrix,

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

Its magnitude is determined xperimentally as

$$|V_{CKM}| = \begin{bmatrix} 0.9752 & 0.2213 & 0.0032 \\ 0.2210 & 0.9745 & 0.0391 \\ 0.0117 & 0.0375 & 0.9992 \end{bmatrix}$$

On the other hand, no flavor changing neutral current (FCNC) is present at the tree level in the SM.

New physics, however, may be observed beyond the SM, as experiments are improved more precisely at the B factory etc., and in the higher energy region at the LHC etc. Especially, it is very fascinating to focus on the FCNC's that may arise beyond the SM. In the extended SM with quark singlets, the FCNC's are mediated by the Z boson and singlet Higgs field S. They will hopefully provide interesting phenomenology in future experiments.

5. Summary

We have reviewed the SM and its extension with quark singlets. Specifically, we have considered the flavor changing neutral current processes at the tree level, which are absent in the SM. They may be observed in experiments at the LHC.

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