Vol. 40 (2009) *ACTA PHYSICA POLONICA B* No 1

INVISIBLE TECHNICOLOR

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(Received March 10, 2008; revised version received July 1, 2008)

We propose a scenario of dynamical electroweak symmetry breaking which is applicable to the model with no tree-level potential for the elementary Higgs doublet field. An example of such a model is the gauge-Higgs unification model. The strong coupling "technicolor" dynamics can provide the scale of the electroweak symmetry breaking in the potential of the Higgs doublet field. The negative mass squared and quartic coupling can be generated through the Yukawa couplings among heavy and light "technifermions" and the Higgs doublet field. Since the massless "technifermion" is singlet under the electroweak gauge symmetry, no large corrections to the electroweak observables arise. As a prediction of this scenario, there must be a pseudo-Nambu–Goldstone boson which couple with the Higgs field in a specific way, though it is singlet under the standard model gauge symmetry.

PACS numbers: 12.60.Nz, 12.60.Rc, 11.30.Qc, 12.60.Fr

1. Introduction

The dynamics of the electroweak symmetry breaking is still unknown. In the standard model the electroweak symmetry is spontaneously broken by the vacuum expectation value of an elementary scalar field, the Higgs doublet field. The energy scale of the symmetry breaking is set by hand as the mass of the Higgs doublet field. This scenario may be true, but it is probable that some unknown dynamics determine the energy scale of the symmetry breaking.

Technicolor theory has been proposed as a scenario in which the energy scale is dynamically given by the pair condensation of the technifermion due to the strong coupling technicolor gauge interaction [1, 2]. The technicolor theory has a beautiful concept: all the matter are fermion fields and all the interactions are originated from gauge symmetry. But, it is well known that some special dynamics or mechanisms are required so that this scenario is consistent with the precision electroweak measurements [3–7]. The problem is that the strong coupling technicolor dynamics directly affects the electroweak interaction.

Gauge-Higgs unification is a scenario which has the similar concept of the technicolor theory [8–12]. The Higgs doublet field is originated from a gauge boson in the five-dimensional space-time, and no elementary scalar fields are required. Because of the gauge symmetry, there is no Higgs potential at tree level, and the finite radiative correction may give non-trivial potential and trigger electroweak symmetry breaking [13, 14].

In this letter we propose a scenario of the electroweak symmetry breaking in the model in which the tree-level potential of the Higgs doublet field is suppressed by some mechanism. Gauge-Higgs unification models are good example of such models[1]. We introduce a strong coupling gauge interaction, "technicolor", but the resultant fermion pair condensation does not directly break the electroweak symmetry, since the fermion, "technifermion", is singlet under the standard model gauge group. The strong coupling gauge dynamics delivers electroweak symmetry breaking scale to the potential of the Higgs doublet field through the Yukawa couplings among Higgs doublet field and technifermions[2]. Since the scale is determined by the technicolor dynamics, it is natural to have small electroweak breaking scale in comparison with the Planck scale. Some composite states, especially a pseudo-Nambu–Goldstone bosons, may couple to the Higgs field through the Yukawa couplings and may give some observable effects in future high-energy colliders.

In the following we discuss the scenario based on gauge-Higgs unification models for concreteness, though it is applicable to any models with no tree-level potential of the Higgs doublet field.

[1] Little Higgs models [17] also can be good examples.

[2] The similar mechanism of the dynamical electroweak symmetry breaking through the vacuum misalignment by the Yukawa coupling has been proposed in Ref. [15]. The combination of the massive (effectively) elementary Higgs doublet field and the dynamical electroweak symmetry breaking by the usual technicolor has been considered in Ref. [16].

2. The dynamics

In the gauge-Higgs unification scenario, some appropriate large gauge symmetry which includes standard model gauge symmetry is assumed in five-dimensional space-time. The gauge symmetry is broken to the standard model gauge symmetry through the compactification of the fifth dimension. The fifth component of some gauge boson of the original gauge symmetry can be a Higgs doublet field which is a scalar field in our non-compact four-dimensional space-time. There is no tree-level scalar potential for such Higgs doublet field due to the original gauge symmetry. Since the original gauge symmetry is broken by the compactification of the fifth dimension, quantum corrections give a non-trivial potential to the Higgs doublet field. In fact, the one-loop contribution of gauge bosons to the potential has been calculated in some concrete models [13,14], and typically the potential is bounded from below around zero vacuum expectation value of the Higgs doublet field. It means that the gauge boson one-loop contribution to the Higgs mass squared is typically positive, and some physics is required to have electroweak symmetry breaking. One of such physics is to introduce appropriate number of (massive) matter fields in the five-dimensional space-time (bulk), which gives additional contribution to the Higgs potential. Typically, the contribution to the Higgs mass squared s negative for bulk fermions and positive for bulk bosons[3]. Therefore, by arranging the field contents in the bulk it is possible to realize the electroweak symmetry breaking. Of course, we also have to take care of the higher power terms of the Higgs potential to have realistic value of the vacuum expectation value of the Higgs doublet field.

Now we point out that another contribution is possible in case that we have strong coupling gauge interactions. Suppose $SU(N_{TC})$ gauge symmetry ($N_{TC} > 2$), "technicolor", in the bulk with appropriate fermion field contents which give the following field contents in four-dimensional effective theory[4].

	$SU(N_{TC})$	$SU(2)_L$	$U(1)_Y$
$\chi_{L,R}$	N_{TC}	2	$-1/2$
$\psi_{L,R}$	N_{TC}	1	0

[3] It it interesting to note that the one-loop contribution of the top quark with large Yukawa coupling solely can give realistic value of the Higgs mass squared.

[4] Although it is beyond the scope of this article to construct some specific models, we point out the Yukawa coupling of Eq. (1) can be produced in a specific model. In five-dimensional SU(6) model ($SU(6) \supset SU(3)_c \times SU(2)_L \times U(1)_Y$) [11,12], where the field contents and the Yukawa coupling of Eq. (1) can be obtained by introducing two bulk fermion fields which belong to the fundamental representation of SU(6) and also to the fundamental representation of $SU(N_{TC})$. The $\mathbf{Z}_2$ orbifold parity should be opposite in these two fermion fields. For the origin of M, it can be produced in SU(6) model through the brane localized mass term. Since the gauge symmetry is reduced on the brane, the brane localized field does not need to be SU(6) multiplet, and χ can have Dirac mass term, while ψ is assumed to remain massless.

Suppose also that the field χ has Dirac mass M which is smaller than the compactification scale $1/R \equiv \Lambda$. It is possible that these "technifermions" interact with Higgs doublet field Φ through the following Yukawa couplings.

$$\mathcal{L}_{\rm TC}^{\rm Yukawa} = g_2 \left(\bar{\psi}\chi\Phi + \bar{\chi}\psi\Phi^\dagger \right) , \tag{1}$$

where g_2 is the $\mathrm{SU(2)_L}$ gauge coupling constant. The $\mathrm{SU}(N_{\rm TC})$ interaction is asymptotically free in the four-dimensional effective theory and the coupling becomes strong at the scale $\Lambda_{\rm TC}$. Suppose the case that $\Lambda_{\rm TC} \ll M \ll \Lambda$. Then a chiral condensate $\langle \bar{\psi}\psi \rangle \simeq \Lambda_{\rm TC}^3$ forms and a global $\mathrm{U}(1)_A$ symmetry (anomalous) is spontaneously broken, where $\mathrm{U}(1)_A$ transformation is the axial phase transformation of ψ. We have a pseudo-Nambu–Goldstone boson $\eta_{\rm TC} \sim \bar{\psi} i \gamma_5 \psi$.

The effect of this technicolor dynamics to the Higgs potential can be estimated in several ways. The most intuitive understanding is obtained by considering technifermion one-loop contribution in four-dimensional effective theory. The contribution to the Higgs mass squared is given by

$$\begin{aligned} m_\Phi^2 &= N_{\rm TC} {\rm tr} \int \frac{d^4k}{(2\pi)^4 i} g_2 \frac{\Sigma(-k^2) + k^\mu \gamma_\mu}{\Sigma(-k^2)^2 - k^2} g_2 \frac{M + k^\nu \gamma_\nu}{M^2 - k^2} \\ &= 4 N_{\rm TC} g_2^2 \int \frac{d^4 k_{\rm E}}{(2\pi)^4} \frac{\Sigma(k_{\rm E}^2) M}{(\Sigma(k_{\rm E}^2)^2 + k_{\rm E}^2)(M^2 + k_{\rm E}^2)} \\ &\quad - 4 N_{\rm TC} g_2^2 \int \frac{d^4 k_{\rm E}}{(2\pi)^4} \frac{k_{\rm E}^2}{(\Sigma(k_{\rm E}^2)^2 + k_{\rm E}^2)(M^2 + k_{\rm E}^2)} , \end{aligned} \tag{2}$$

where Σ is the mass function of ψ which is generated through the technicolor dynamics, and the subscript E denotes Euclidean momentum. The quadratically divergent contribution of the second term becomes finite correction in five-dimensional theory by virtue of the gauge symmetry. In the language of the four-dimensional effective theory, it is "regularized" by infinite Kaluza–Klein modes. The magnitude of this contribution is the same order of the contribution by gauge field, but the sign is opposite. The first term is the contribution of the technicolor dynamics. The mass function $\Sigma(k_{\rm E}^2)$ roughly takes constant value of the order of $\Lambda_{\rm TC}$ in the region of $k_{\rm E}^2 < \Lambda_{\rm TC}^2$, and quickly decays to zero in the region of $k_{\rm E}^2 > \Lambda_{\rm TC}^2$, because of the asymptotically free nature of technicolor. It is easily understood that the sign of the mass function is negative in our case due to the effect of the Yukawa interaction of Eq. (1) by using Cornwall–Jackiw–Tomboulis effective action [18]. In case of $\Lambda_{\rm TC} \ll M$, the integral can be estimated as

$$m_\Phi^2|_{\rm TC}^{\rm one-loop} \simeq -\frac{g_2^2 N_{\rm TC}}{8\pi^2} \frac{\Lambda_{\rm TC}^3}{M} \tag{3}$$

up to some logarithmic correction. The same result is obtained through the mean field approximation in the induced higher-dimensional interaction by the tree-level exchange of the heavy technifermion χ:

$$\mathcal{L}_{\rm eff} = \frac{g_2^2}{M}\bar{\psi}\psi\Phi^\dagger\Phi \;\to\; \frac{g_2^2}{M}\Lambda_{\rm TC}^3\Phi^\dagger\Phi\,, \tag{4}$$

where we define $\Lambda_{\rm TC}$ by $\Lambda_{\rm TC}^3 \equiv \langle\bar{\psi}\psi\rangle$. The induced Higgs mass by the technicolor dynamics is now

$$m_\Phi^2|_{\rm TC} = -g_2^2\frac{\Lambda_{\rm TC}^3}{M}\,. \tag{5}$$

This contribution of the technicolor dynamics should be considered with other one-loop contributions of gauge bosons and other matter fields in the bulk. The absolute magnitude of the contribution of the bulk fields (including technifermions) are typically larger than the technicolor contribution of Eq. (5). In usual gauge-Higgs unification models the appropriate value of Higgs mass is expected to be generated through the cancellations among the contributions of the order of $\Lambda^2 \sim 1\,{\rm TeV}^2$ from many bulk fields. It is expected that nature has chosen an appropriate field contents and their orbifold parities to realize electroweak symmetry breaking at the weak scale. Although this is certainly a general problem in gauge-Higgs unification model, solving this problem and constructing some realistic models without this difficulty are not the aim of this paper. Here, we simply imagine a model in which these contributions to the Higgs mass are canceled out or smaller than weak scale due to some special fields contents. In this case the electroweak symmetry breaking scale is determined by the dynamics of technifermions. The actual Higgs vacuum expectation value is determined by the Higgs mass squared and the Higgs quartic coupling constant λ as $v = \sqrt{-m^2/\lambda} \simeq 250\,{\rm GeV}$. The quartic coupling is also induced by one-loop quantum effect of gauge bosons (negative contributions) and fermions (positive contributions) in the bulk. Note that the one-loop positive contribution of the technifermion is roughly proportional to $N_{\rm TC}$, though some non-perturbative correction by strong coupling technicolor is expected. Therefore, large $N_{\rm TC}$ results heavy Higgs. This may give a solution to the general problem of too light Higgs boson in usual gauge-Higgs unification models.

In case that the technicolor contribution is not dominant in Higgs mass squared, the electroweak symmetry breaking scale should be determined by the collaboration of the gauge and matter fields in the bulk [13, 14] as well as the technicolor contribution. In this case technicolor is not necessary, but if it exists there must be a extra field, a pseudo-Nambu–Goldstone boson, which couples with the Higgs particle in a specific way. For large $N_{\rm TC}$ the Higgs mass in case with technicolor can be heavier than that in case without technicolor.

3. Phenomenology

Since the technicolor dynamics breaks $\mathrm{U}(1)_A$ symmetry, which is explicitly broken by the technicolor anomaly, there appears massive pseudo-Nambu–Goldstone boson $\eta_{\mathrm{TC}} \sim \bar{\psi} i \gamma_5 \psi$. The scalar resonances which couple with the operator $\bar{\psi}\psi$ (σ_{TC}, for example) can couple with two η_{TC}. Therefore, through the interaction of Eq. (4), we expect the effective interaction

$$\mathcal{L}_{\mathrm{eff}}^{HH\eta\eta} \sim \frac{g_2^2}{M \Lambda_{\mathrm{TC}}} \Phi^\dagger \Phi \partial^\mu \eta_{\mathrm{TC}} \partial_\mu \eta_{\mathrm{TC}}, \tag{6}$$

where derivative coupling is required by chiral $\mathrm{U}(1)_A$ symmetry [19]. If η_{TC} is lighter than the half of the Higgs mass, Higgs can decay into two η_{TC} through the following characteristic interaction

$$\mathcal{L}_{\mathrm{eff}}^{h\eta\eta} \sim \frac{g_2^2 v}{M \Lambda_{\mathrm{TC}}} h \partial^\mu \eta_{\mathrm{TC}} \partial_\mu \eta_{\mathrm{TC}}\,, \tag{7}$$

where h is the physical Higgs field. If η_{TC} is heavy, it is associatively produced in pair through the Higgs and weak gauge boson production processes.

The precise estimation of the mass of η_{TC} is not easy, since we have to quantitatively understand the instanton effect [20]. The very naive scaling-up of QCD gives

$$\frac{m_{\eta_{\mathrm{TC}}}}{\Lambda_{\mathrm{TC}}} \simeq \frac{m_\eta}{\Lambda_{\mathrm{QCD}}} \simeq 2.5\,, \tag{8}$$

where we used the result of "naive dimensional analysis" [21, 22], $\Lambda_{\mathrm{QCD}}^3 \equiv \langle \bar{q} q \rangle \simeq 4\pi f_\pi^3$, with $f_\pi \simeq 93\mathrm{MeV}$ and $m_\eta \simeq 550\,\mathrm{MeV}$. The value of Λ_{TC} is model dependent. In case that the technicolor effect dominates the electroweak symmetry breaking, $\Lambda_{\mathrm{TC}} > 1\mathrm{TeV}$ and η_{TC} is heavy. Note that a larger value of Λ_{TC} means a larger value of M (see Eq. (5)). In case that the technicolor effect is subdominant, η_{TC} can be lighter.

Since η_{TC} is the lightest "technihadron" and singlet under the standard model gauge group (the constituent technifermions are also singlet), it is almost stable. It can decay into two photons only through the three loop effect. Therefore, η_{TC} can be a candidate of the cold dark matter (further analysis, which is model dependent, is required).

There should be a heavy "technimeson" $\Theta \sim \bar{\psi}\chi$, which can mix with Higgs doublet fields through the interaction of Eq. (1). The mixing mass matrix can be roughly estimated as

$$\mathcal{L}_{\Phi\Theta} = -\begin{pmatrix} \Phi^\dagger & \Theta^\dagger \end{pmatrix} \begin{pmatrix} 0 & g_2 \Lambda_{\mathrm{TC}} \sqrt{M \Lambda_{\mathrm{TC}}} \\ g_2 \Lambda_{\mathrm{TC}} \sqrt{M \Lambda_{\mathrm{TC}}} & M^2 \end{pmatrix} \begin{pmatrix} \Phi \\ \Theta \end{pmatrix} \tag{9}$$

using the technique of the heavy quark effective theory. Precisely saying, we have two Higgs doublet fields. In case $\Lambda_{\mathrm{TC}} \ll M$, the mixing angle is small and the heavy Higgs doublet field decouples. It is interesting to note that we have negative mass squared of the Higgs doublet field of the order of $-g_2^2 \Lambda_{\rm TC}^3/M$ from this mass matrix of "bosonic see-saw" form [23, 24]. Since Θ is much heavier than $\Lambda_{\rm TC}$, this result in the low-energy effective theory may be thought as the same result of Eq. (5) in the high-energy fundamental theory.

4. Conclusions

We have proposed a scenario of electroweak symmetry breaking which is applicable in the case when there is no tree-level potential of Higgs doublet field. The gauge-Higgs unification model is an example, in which the tree-level potential of Higgs doublet field is forbidden by gauge symmetry. The strong coupling "technicolor" dynamics can play a role to set electroweak symmetry breaking scale through the Yukawa couplings among heavy and light "technifermions" and elementary Higgs doublet field. The prediction of this scenario is a pseudo-Nambu–Goldstone boson, which is a singlet under the standard model gauge symmetry, but interacts with the Higgs doublet field in a specific way. We leave concrete model buildings and phenomenological analysis for future works.

N.H. and N.K. thank the theory division of KEK for hospitality. N.H. is supported in part by the Grand-in-Aid for Scientific Research number 16028214 and 16540258. N.K. and N.O. are supported in part by the Grand-in-Aid for Scientific Research 16340078 and 15740164, respectively.

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