A new scheme for neutrino mass generation and relevant new physics

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We propose a new scheme for neutrino mass generation through a modification of the standard Higgs mechanism implemented by introducing an unconventional tiny vacuum breaking to the charged Higgs field. In this modified Higgs mechanism, with identical particle spectrum as the standard electroweak model, the lepton-Higgs Yukawa coupling Lagrangian would carry a modified lepton mass matrix. Combining the latest data of particle experiments with this modified lepton mass matrix enable us to locate the value of the parameter parametrizing the extra perturbative Higgs vacuum breaking and produce masses for neutrinos of three generations. We show that our results satisfy the constraints from current physical experiments and cosmological observations. In the new Higgs mechanism now we propose, the Higgs vacua are completely broken, such that, the very minuteness of the extra Higgs vacuum breaking explains the origin of the very minuteness of neutrino masses, while the relative greatness of the standard Higgs vacuum breaking is recognized as the origin of the relative greatness of charged lepton masses. This proposal can bring rich new physics to Higgs-relevant problems in particle physics, besides injecting new inspiration to the solution of massive neutrino problems.

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I. INTRODUCTION

Neutrino has been one type of most concerned objects among fundamental particles for various reasons such as its critical role in the evolution of universe and its thus far unexplained puzzle of the gerneration of mass. 1–4 In the standard electroweak model of particle physics, neutrinos are considered as massless particles. Over the decades, neutrino oscillations had been experimentally discovered and confirmed by several collaborations 5–10. The implication of these experiments directs to the flavor mixing between different generations of neutrinos thus the existence of nonzero neutrino masses 17–24.

Various mechanisms have been constructed to explain the fermion mass generation and flavor mixing and can roughly be classified into four types: (a) radiative mechanisms 25–28, (b) texture zeros 29–32, (c) family symmetries 33, 34, and (d) seesaw mechanisms 35–40. However, different theoretical schemes are plagued with various drawbacks, such as introducing new particle components that possess extraordinarily obscure prospects for future experimental tests, say the super heavy neutrino required in the seesaw mechanism.

In this work we propose a new scheme for the physics of massive neutrinos through a modification of the standard Higgs mechanism in which the vacuum expectation of the Higgs doublet is set to break the $SU(2)\times U(1)$ symmetry to bring the theoretical Glashow-Weinberg-Salam model into real physics. This theme of study continued to evolved into composite Higgs which is supposed to be a bound state of massive strongly interacting fermions. 32

The Higgs particle in the GellMann-Levy linear sigma model may also be a composite object as it turned out in QCD. 36 A bunch of progresses have been made in this direction over the years. 37–40 In the standard Higgs mechanism, only the neutral Higgs field is assigned with a nonzero VEV. In our modified Higgs mechanism, we introduce an additional tiny valued VEV for the charged Higgs field. It can be shown that due to the introduction of this tiny valued charged Higgs VEV, even if working with the identical particle constituents as standard electroweak model, extra terms not present in the standard Higgs mechanism will appear in the modified lepton-Higgs Yukawa coupling Lagrangian. This gives the modified lepton mass matrix from which we can produce relations between neutrino masses and the masses of charged leptons and the tiny perturbative vacuum breaking parameter. By using current neutrino experimental data, we can determine the value of the extra perturbative Higgs vacuum breaking parameter and predict the masses for neutrinos of three generations, satisfying all the constraints of current physical experiments and cosmological observations.

The article is organized as follows: in Sec. II, we layout the modified Higgs mechanism, and with identical particle constituents as standard model, derive the modified Lagrangian for lepton-Higgs Yukawa coupling that carries with a modified lepton mass matrix. In Sec. III, we solve the modified lepton mass matrix for mass eigenvalues, eigenstates and construct the lepton flavor-mass transformation matrix. In Sec. IV, we derive the dependence of neutrino masses on the masses of charged
leptons and the tiny valued charged Higgs VEV. In Sec. V, we work out the value of the extra tiny charged Higgs VEV using the latest data of neutrino experiments, then employ this result to compute the exact value of the neutrino masses of three generations, and finally, we show that the result is consistent with the constraints of current cosmological observations. Sec. VI is the conclusion and discussion.

II. YUKAWA COUPLING LAGRANGIAN FOR LEPTONS IN MODIFIED HIGGS MECHANISM

In the standard electroweak model, the breaking of the $SU_L(2) \times U_Y(1)$ symmetry is induced by the Higgs field assuming the standard vacuum expectation value,

$$\Phi_{VEV} = \frac{1}{\sqrt{2}} \begin{vmatrix} 0 \\ 1 \end{vmatrix}.$$

We now study the new physics introduced by the assumption of a very tiny perturbation $\nu_+$ to the Higgs field vacuum expectation,

$$\Phi_{VEV} = \frac{1}{\sqrt{2}} \begin{vmatrix} \nu_+ \\ \nu \end{vmatrix},$$

where $\nu_+$ may be taken as a perturbation so small that the magnitude of which should be constrained by all current particle physical experiments and cosmological observations. Then, playing similar role as the standard Higgs field, we have the modified Higgs field,

$$\Phi = \frac{1}{\sqrt{2}} \begin{vmatrix} \nu_+ \\ \nu + H \end{vmatrix}.$$  

Using this modified Higgs field, completely in parallel procedure as in the standard Higgs mechanism, we can obtain the Yukawa coupling Lagrangian for leptons,

The eigenvalues of the lepton mass matrix in Eq.(5) can be computed as follows,

$$\det(A - \lambda) = \det \left( \begin{array}{cc} -\lambda & \frac{\nu_+}{\nu} m_\xi \\ \frac{\nu_+}{\nu} m_\xi & m \end{array} \right) = 0.$$  

Eq.(9) can be expanded out as the quadratic equation,

$$\lambda^2 - \lambda m_\xi - \frac{\nu_+^2}{\nu^2} m_\xi^2 = 0,$$

with the following solutions,

$$\lambda_\pm = \frac{m_\xi}{2} \left( 1 \pm \sqrt{1 + 4 \left( \frac{\nu_+^2}{\nu^2} \right) m_\xi^2} \right).$$

Thus the Lagrangian of Eq.(3) can be written in diagonal form in the mass eigenstate representation,

$$\mathcal{L}_{\text{Yukawa}} = -\frac{g_\xi}{\sqrt{2}} H (\bar{\nu}_L \xi L - m_\xi \xi),$$

where $g_\xi$ is the Yukawa coupling constant for the $\xi$-th generation leptons, and $l^R$ and $l^L$ are, respectively, the right-hand singlet and left-hand doublet of the $\xi$-th generation lepton.

Substituting the mass of the $\xi$-th generation charged lepton after the standard Higgs vacuum breaking same as in the standard model,

$$m_\xi = \frac{g_\xi}{\sqrt{2}} v, \quad (\xi = e, \mu, \tau),$$

thus, Eq.(3) can written as

$$\mathcal{L}_{\text{Yukawa}} = -\frac{m_\xi}{v} \left[ (\nu_+)^\dagger \xi L + \nu_+ \bar{\nu}_L \xi - m_\xi \xi \right]$$

$$-\frac{m_\xi}{v} H \xi \xi$$

$$-\frac{m_\xi}{v} H \xi \xi, \quad (\xi = e, \mu, \tau).$$

It is the Yukawa coupling Lagrangian for three generations of leptons from the modified Higgs mechanism. The mass matrix is shown modified from the standard model.
\[-\frac{m_\xi}{v} H \xi, \ (\xi = e, \mu, \tau).\]

To find the mass-state eigenvectors, using Eq. (9),
\[
\begin{pmatrix}
-\lambda
\frac{v_+}{v} m_\xi
m_\xi - \lambda
\end{pmatrix}
\begin{pmatrix}
a \\
b
\end{pmatrix}
= 0,
\]
expanding out as,
\[
-\lambda a + \frac{v_+}{v} m_\xi b = 0, \quad (\Rightarrow a = \frac{v_+}{v \lambda} m_\xi b),
\]
\[
\left(\frac{v_+}{v}\right) m_\xi a + (m_\xi - \lambda)b = 0.
\]
The eigenvector up to a constant is,
\[
V = \left(\frac{v_+}{v \lambda} m_\xi b\right). \tag{13}
\]
By the normalization condition of eigenvector,
\[
V^\dagger V = \left(\frac{v_+}{v \lambda} m_\xi b\right)^\dagger \left(\frac{v_+}{v \lambda} m_\xi b\right)
= \left(\frac{v_+}{v \lambda} m_\xi b\right)^\dagger \left(\frac{v_+}{v \lambda} m_\xi b\right) + b^\dagger b = 1. \tag{14}
\]
From Eq. (14), we find
\[
b_{\lambda \pm} = \frac{e^{i \theta_{\lambda \pm}} \nu_{\lambda \pm}^2}{\sqrt{1 + \left|\nu_{\lambda \pm}^2\right|^2}}, \tag{15}
\]
where \(\theta_{\lambda \pm}\) are two arbitrary real phases. Finally we obtain the mass-state eigenvector,
\[
V_{\lambda \pm} = \begin{pmatrix}
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}}
\end{pmatrix}
\begin{pmatrix}
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}}
\end{pmatrix}^\dagger = \begin{pmatrix}
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}}
\end{pmatrix}
\begin{pmatrix}
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}}
\end{pmatrix}^\dagger.
\]
Using Eq. (10), we achieve the transformation matrix between the flavor state and the mass state,
\[
U = \begin{pmatrix}
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}}
\end{pmatrix}
\begin{pmatrix}
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}}
\end{pmatrix}^\dagger

= \frac{1}{\sqrt{1 + \left|\nu_{\lambda \pm}^2\right|^2}} \begin{pmatrix}
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}}
\end{pmatrix}
\begin{pmatrix}
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}} \\
\frac{v_+}{v \lambda} m_\xi e^{i \theta_{\lambda \pm}}
\end{pmatrix}^\dagger.
\]

Transforming the flavor state to mass state,
\[
\begin{pmatrix}
\nu_{\xi \ell L}' \\
\nu_{\xi \ell L}
\end{pmatrix}
= U \begin{pmatrix}
\nu_{\xi \ell L} \\
\bar{\nu}_{\xi \ell L}
\end{pmatrix}
= \frac{1}{\sqrt{1 + \left|\nu_{\lambda \pm}^2\right|^2}} \begin{pmatrix}
\nu_{\xi \ell L} \\
\bar{\nu}_{\xi \ell L}
\end{pmatrix}. \tag{18}
\]
Further making a transformation on \(\nu_{\xi \ell L}'\), we have
\[
\nu_{\xi \ell L}' = i \gamma^5 \nu_{\xi \ell L}, \quad \bar{\nu}_{\xi \ell L}' = \bar{\nu}_{\xi \ell L} \gamma^0 = \bar{\nu}_{\xi \ell L} i \gamma^5. \tag{19}
\]
Consequently, the Lagrangian of Eq. (9) can be rewritten in the standard mass-state form,
\[
L_{Yukawa} = -\frac{m_\xi}{2} \left(\sqrt{1 + 4 \left|\nu_{\lambda \pm}^2\right|^2} - 1\right) \bar{\nu}_{\xi \ell L}' \nu_{\xi \ell L}'
= -\frac{m_\xi}{2} \left(1 + \sqrt{1 + 4 \left|\nu_{\lambda \pm}^2\right|^2}\right) \bar{\xi}^\dagger \xi', \tag{20}
\]

IV. RELATIONS BETWEEN LEPTON MASSES

Eq. (21) and the leptonic dynamic terms same as in the standard model together make up the total Lagrangian relevant to leptons, not losing generality, neglecting the interaction terms with Higgs field \(H\),
\[
L_{Yukawa} = \bar{\nu}_{\xi \ell L}' i \gamma^\mu \partial_\mu \nu_{\xi \ell L}' + \bar{\xi} i \gamma^\mu \partial_\mu \xi'.
\]
Then the Euler-Lagrange equations can be found,
\[
i \gamma^\mu \partial_\mu \nu_{\xi \ell L}' - \frac{m_\xi}{2} \left(\sqrt{1 + 4 \left|\nu_{\lambda \pm}^2\right|^2} - 1\right) \nu_{\xi \ell L}' = 0, \tag{22}
\]
\[
i \gamma^\mu \partial_\mu \xi' - \frac{m_\xi}{2} \left(1 + \sqrt{1 + 4 \left|\nu_{\lambda \pm}^2\right|^2}\right) \xi' = 0, \tag{23}
\]
(\(\xi = e, \mu, \tau\)). Thus, we can read the masses of leptons,
\[
m_{\nu_{\xi \ell L}'} = \frac{m_\xi}{2} \left(\sqrt{1 + 4 \left|\nu_{\lambda \pm}^2\right|^2} - 1\right), \ (\xi = e, \mu, \tau). \tag{24}
\]
\[ m_{\xi} = \frac{m_\nu}{2} \left( 1 + \sqrt{1 + 4 \frac{|v_\nu|^2}{v^2}} \right), \quad (\xi = e, \mu, \tau). \]  

In the modified Higgs mechanism, \( v_\nu \) is assumed to be very small compared to the standard Higgs VEV \( v \). Then Eq. \((24)\) and Eq. \((25)\) can be expanded in small quantity,

\[ m_{\nu e_L} = m_\xi \frac{|v_\nu|^2}{v^2}, \quad (\xi = e, \mu, \tau), \]

\[ m_{\xi e} = m_\xi \left( 1 + \frac{|v_\nu|^2}{v^2} \right), \quad (\xi = e, \mu, \tau). \]  

By Eq. \((24)\) and Eq. \((25)\), we can also get

\[ m_{\nu e_L} = m_\xi \frac{|v_\nu|^2}{v^2} - 1 \left( 1 + \frac{|v_\nu|^2}{v^2} + 1 \right), \quad (\xi = e, \mu, \tau). \]  

This is a relation of neutrino masses depending on the known value of the charged lepton masses, with only a single new parameter originating from our newly proposed modified Higgs mechanism.

**V. NEUTRINO MASSES CONSISTENT WITH CURRENT EXPERIMENTAL CONSTRAINTS**

We show that the value of the single new parameter in the modified Higgs mechanism can be determined by the current experimental data on the neutrino mass-squared differences by using Eq. \((28)\) so that the exact value of the neutrino masses could eventually be predicted. To fulfil this purpose, performing the neutrino mass-squared differences on Eq. \((28)\),

\[ \Delta M^2_{21} = m_{\nu e_L}^2 - m_{\nu e_L}^2 = \left[ m_\mu \frac{\sqrt{1 + 4 \frac{|v_\nu|^2}{v^2}} - 1}{\sqrt{1 + 4 \frac{|v_\nu|^2}{v^2}} + 1} \right]^2 - \left[ m_\xi \frac{\sqrt{1 + 4 \frac{|v_\nu|^2}{v^2}} - 1}{\sqrt{1 + 4 \frac{|v_\nu|^2}{v^2}} + 1} \right]^2, \]

\[ \Delta M^2_{32} = m_{\nu e_L}^2 - m_{\nu e_L}^2 = \left[ m_\mu \frac{\sqrt{1 + 4 \frac{|v_\nu|^2}{v^2}} - 1}{\sqrt{1 + 4 \frac{|v_\nu|^2}{v^2}} + 1} \right]^2 - \left[ m_\xi \frac{\sqrt{1 + 4 \frac{|v_\nu|^2}{v^2}} - 1}{\sqrt{1 + 4 \frac{|v_\nu|^2}{v^2}} + 1} \right]^2. \]

Slightly massaging Eq. \((29)\),

\[ \Delta M^2_{21} = (m_\mu^2 - m_\xi^2) \left[ \frac{\sqrt{1 + 4 \frac{|v_\nu|^2}{v^2}} - 1}{\sqrt{1 + 4 \frac{|v_\nu|^2}{v^2}} + 1} \right]^2 = (m_{\mu e}^2 - m_{\xi e}^2) \left[ 1 - \frac{2}{\sqrt{1 + 4 \frac{|v_\nu|^2}{v^2}} + 1} \right]^2, \]

gives the parameter of the vacuum perturbation,

\[ \frac{|v_\nu|^2}{v^2} = \frac{1}{4} \left( \frac{2}{1 - \sqrt{\frac{\Delta M^2_{21}}{m_\mu^2 - m_\xi^2}}} - 1 \right) - 1. \]  

Similarly massaging Eq. \((30)\) gives,

\[ \frac{|v_\nu|^2}{v^2} = \frac{1}{4} \left( \frac{2}{1 - \sqrt{\frac{\Delta M^2_{32}}{m_\mu^2 - m_\xi^2}}} - 1 \right) - 1. \]

We cite here the current experimental data on the charged lepton masses and the neutrino mass-squared differences \([53, 54]\),

\[ m_\mu^\prime = 0.5109989461 \times 10^6 \text{eV}, \]
\[ m_\tau^\prime = 1776.86 \times 10^6 \text{eV}, \]
\[ \Delta M^2_{21} = 7.53 \times 10^{-5} \text{eV}^2, \]
\[ \Delta M^2_{32} = 2.54 \times 10^{-3} \text{eV}^2. \]

Substituting these data into Eq. \((31)\) and Eq. \((32)\) gives,

\[ \frac{|v_\nu|^2}{v^2} \approx 8.21294 \times 10^{-11}, \]
\[ \frac{|v_\nu|^2}{v^2} \approx 2.84140 \times 10^{-11}. \]

They agree with each other in the order of magnitude and are satisfactorily close in the numerics, at the early stage of our theoretical attempt, and also at the consideration of inevitable experimental errors. We thus adopt the average of them in the following calculations.

\[ \frac{|v_\nu|^2}{v^2} = \frac{1}{2} (8.21294 \times 10^{-11} + 2.84140 \times 10^{-11}) \approx 5.52717 \times 10^{-11}. \]  

Taylor expanding Eq. \((28)\) and keep only the first order in the tiny ratio \( \frac{|v_\nu|^2}{v^2} \), we have

\[ m_\xi e = m_\xi \sqrt{1 - \frac{2}{\sqrt{1 + 4 \frac{|v_\nu|^2}{v^2}} + 1}}, \quad (\xi = e, \mu, \tau). \]

With the common ratio between neutrino mass and the mass of the corresponding charged lepton, our final prediction of the neutrino masses are listed:

\[ m_{\nu e_L} = 2.82438 \times 10^{-5} \text{eV}, \]
\[ m_{\nu^\prime \nu_L} = 583.992 \times 10^{-5} \text{eV}, \quad (40) \]
\[ m_{\nu^\prime \nu_L} = 9821.01 \times 10^{-5} \text{eV}. \quad (41) \]

The summation of these values is,
\[ m_{\nu^\prime \nu_L} + m_{\nu^\prime \nu^\prime L} + m_{\nu^\prime \nu^\prime L} \approx 0.104078 \text{eV}. \quad (42) \]

This result satisfies the constraint from the current cosmological observations [55], which we cite here:
\[ \Sigma (\nu) m_\nu < 0.176 \text{eV}. \quad (43) \]

This presents a very positive signal to the consistency and soundness of our proposal of neutrino mass generation.

VI. CONCLUSION AND DISCUSSION

Symmetry has been found a fundamental principle in the theory of particle physics. But afterwards many of the symmetries in theory have been found broken in reality, or had to be so to account for the physics in the reality. The so-called Higgs mechanism proposes a new scalar field with symmetry breaking in the vacuum state to interact with fermions and non-abelian gauge bosons so that the massiveness of non-abelian gauge bosons and most of the fermions receives excellent explanation. The standard electroweak model is then rendered a practically complete structure. However, the massiveness of neutrinos was mainly realized after the completion of the standard model and is not explained by the standard model. This article proposes a modified version of the standard Higgs mechanism by extending the standard Higgs field vacuum breaking to one with an extra but tiny breaking in the vacuum of the charged Higgs field. This modification to the standard Higgs mechanism provides an simplistic, natural and physical inspiring explanation for the mechanism of neutrino mass generation.

The effectiveness, simplicity and naturalness of our scheme of neutrino mass generation could be considered as solidly reasonable due to three reasons: firstly, the tiny vacuum breaking parameter is the only new parameter of our model; secondly, our model assigns a common Yukawa coupling constant to the neutrino and its corresponding charged lepton in the same family rather than introducing two separate Yukawa coupling constants for each of them as typical models of massive neutrinos do; and thirdly, the physical picture of our model originates from natural extension of the standard Higgs mechanism.

The only new independent parameter we introduce is a quantity parametrizing the new physics of extra Higgs vacuum breaking, the existence of which is compatible with current physical experiments, and the validity of the relevant new physics is to be verified in the physical experiments or cosmological observations. The fact that the neutrino masses we predicted in this work by using the particle experimental data could sum up to satisfy the constraint of current cosmological observations presents very positive signal to the soundness of this new scheme of neutrino physics and of the relevant new physics.

In summary, in this article we have proposed a completely broken Higgs mechanism in a way consistent with the constraints of all current experiments. Maintaining the identical particle constituents and the full set theoretical symmetries of the standard electroweak model but working in the completely broken Higgs mechanism allows us to obtain the new physics that is fundamental for the solution of the massive neutrino problems. In the view of the completely broken Higgs mechanism, the very minuteness of the charged Higgs vacuum breaking explains the origin of the very minuteness of neutrino masses, while the relative greatness of the standard Higgs vacuum breaking is recognized as the origin of the relative greatness of charged lepton masses. This proposal can bring rich new physics to Higgs-relevant problems in particle physics, besides injecting new inspiration to the solution of massive neutrino problems.

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