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On symmetry-extended SM and neutrino masses

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An abelian symmetry extension of the SM and its possible implicaton for the neutrino sector is considered. The symmetry breaking by a new scalar vev is described and the resulting suppressed neutrino mass terms are determined. From the known data, the strenghts of the corresponding suppressing effect are derived and the associated new scales are approached.

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With the recent observation of the Higgs boson, a large amount of experimental data is now said to be in an excellent agreement with the Standard Model of particle physics (SM) [1, 2]; it describes successfully low-energy phenomena for the elementary particles and the fundamental interactions. However, the SM includes no fundamental explanation for the gaps among the masses of the particles. The masses and the Yukawa terms which determine them, are spread across five orders of magnitude. This is the problem of flavor in the SM. Although the large hierarchy between the fermion masses may be understood in their coupling constants, it is difficult to be accepted in the case of neutrinos, which besides they were considered massless in the SM, they are actually known to have tiny $\sim$ eV masses and, say, twelve ordres of magnitude less than the top quark mass [3–5]. This neutrino problem requests an explanation from an extension of the SM. Important proposals in terms of extra dimensions, symmetries, and scalars have been proposed to explain partially the suppressed neutrino masses [6–9]. As neutrinos are known to be the lightest fermions, it makes sense to take a highly suppressing effect in the model to describe such tiny scale. A natural way to explain this pattern, is in terms of symmetry and a symmetry breaking order parameter. This would explain the smallness of neutrino masses by having different operators in the model transform under different representations of the symmetry group. If the symmetry is continuous, such a symmetry breaking would lead to a massless Goldstone boson as a low-energy remnant. This possible remnant can be identified with postulated bosons and it is interesting to find models where such hypothetical particle is related to this symmetry breaking.

This work aims to join in these works by presenting an extended SM involving two abelian gauge factors $\mathrm{U}(1)_{b,c}$. An associated singlet scalar field ϕ breaks this extended symmetry down to the electroweak one and hence contributes to its mediation to the neutrino sector, resulting in a highly suppressed neutrino mass terms. We then refer to the SM data with the known neutrino masses scale, we derive the corresponding suppressing effect and approach the scales of the associated symmetry breaking and the new physics, new particles and scales M_s, behind the underlying effective theory by refering to the known data.

As we discussed in the introduction, we want to make the SM richer by adding new symmetries that will in particular affect the neutrino sector. The simplest option is to enlarge the SM hypercharge by more abelian gauge factors,

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_b \times \mathrm{U}(1)_c. \tag{1}$$

This enlarged symmetry is assumed to be broken above the electroweak scale by the vev of a new scalar field ϕ, leading to the hypercharge combination

$$Y = \sum_{b,c} \alpha_{b,c} Q_{b,c}, \tag{2}$$

where the $\alpha_{b,c}$ are such that the combinations correspond to the right fermion hypercharges. So, we deal with an extended SM where only the neutrino sector is affected. At this level, we need to fit the charges of the

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leptonic sector ℓ_L^i , Higgs h and the scalar ϕ under the extended symmetry. Based on these requirements, we assign the following needed quantum numbers (Table).

The neutrino and scalar content corresponding to the hypercharge combination $Y = 0.5(Q_b + Q_c)$. The index $i = 1, 2, 3$ denotes the family index

Charges/Fields	Q_b	Q_c	Y
ℓ_i	0	-1	$-1/2$
h	1	0	$1/2$
ϕ	-1	1	0

These quantum numbers contain enough information to say about the scale of the neutrino masses. In fact, although a Yukawa coupling for the neutrino sector with h will be prevented unlike the other SM fermions, and hence is not directly connected to the electroweak symmetry breaking, it may be connected via the complex scalar field ϕ having a non-vanishing vev and carrying appropriate charges. In this picture, neutrinos are distinguished by their Q_c charge. This symmetry together with Q_b under which the Higgs h is charged forbid the lowest order term made out of the SM fields [10],

$$Q_{b,c}\left(\overline{\ell_{iL}}\widetilde{h}\widetilde{h}^t\ell_{jL}^c\right) \neq 0, \quad (3)$$

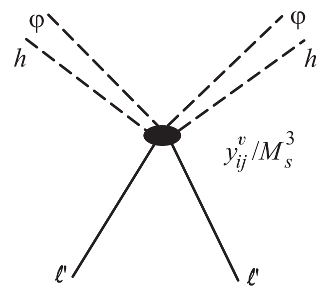
where $\widetilde{h}$ is related to the standard Higgs doublet by $\widetilde{h} = i\sigma_2 h^*$, but would allow it through the effective seven-dimensional couplings,

$$Q_{b,c}\left(\phi^{*2}\overline{\ell_{iL}}\widetilde{h}\widetilde{h}^t\ell_{jL}^c\right) = 0, \quad (4)$$

leading to the corresponding effective Yukawa Lagrangian,

$$\zeta_{\text{Yuk}}^v = y_{ij}^v \frac{\phi^{*2}}{M_s^3}\overline{\ell_{iL}}\widetilde{h}\widetilde{h}^t\ell_{jL}^c + \text{h.c.}, \quad (5)$$

with y_{ij}^v correspond to the coupling constants, M_s is a high scale corresponding to the lepton number violation. For a clear exhibition, we illustrate this effective term in the following figure.



Higher couplings of neutrinos to Higgs sector with effective strenghts y_{ij}^v/M_s^3 through the new scalar ϕ

Upon spontaneous breaking down to the electroweak symmetry $\text{SU}(2)_L \times \text{U}(1)_b \times \text{U}(1)_c \overset{\langle\phi\rangle}{\to} \text{SU}(2)_L \times \text{U}(1)_Y$ by the non-vanishing vev of the new scalar ϕ, the corresponding effective Lagrangian (5) becomes

$$\zeta_{\text{Yuk}}^v = y_{ij}^v \frac{\langle\phi\rangle^2}{M_s^3}\overline{\ell_{iL}}\widetilde{h}\widetilde{h}^t\ell_{jL}^c + \text{h.c.} \quad (6)$$

After the electroweak symmetry breaking $\text{SU}(2)_L\times\text{U}(1)_Y \overset{\langle h\rangle}{\to}\text{U}(1)_{Q_{em}}$ by the vev of the SM higgs h, and accepting the approximation,

$$\varepsilon^3 = \langle\phi\rangle^2\langle h\rangle/M_s^3 \sim (\langle\phi\rangle/M_s)^3, \quad (7)$$

where ε is a small dimensionless parameter, the Lagrangian (6) becomes,

$$\zeta_{\text{mass}}^v = y_{ij}^v\varepsilon^3\langle h\rangle\,\ell_i\ell_j. \quad (8)$$

Within this approach, even with a fundamental Yukawas y_{ij}^v of order 1, a high suppression effect is realized due to the suppressing parameter $\varepsilon^3 \ll 1$. Indeed, after the electroweak symmetry breaking at the usual scale $\langle h\rangle \sim 10^2$ GeV, according to the neutrino mass scale $m_v \sim 10^{-4}$ eV [3–5], we estimate the suppressing factor,

$$\varepsilon \sim \sqrt[3]{\frac{m_v}{\langle h\rangle}} \sim 10^{-5}. \quad (9)$$

Having fixed the value of ε, we finally turn to the associated breaking symmetry $\langle\phi\rangle$ and the mass parameter M_s behind neutrino masses (8). According to (7) and with the fact that $\langle\phi\rangle > \langle h\rangle$, we derive lower bounds of the involved high scales,

$$M_s > \frac{\langle h\rangle}{\varepsilon} \sim 10^7\,\text{GeV}, \quad \langle\phi\rangle > \varepsilon M_s \sim 10^2\,\text{GeV}. \quad (10)$$

In addition to the extra SM singlet scalar ϕ, which is heavier than its SM counterpart, the model also contains an extra particle corresponding to the broken extended symmetry. This particle is a gauge boson similar to the Z' boson which we are looking for at LHC. Here in this model, one could expect its mass as well as its coupling to SM fields. The kinetic term for the field ϕ generates the Z' mass through the covariant derivative,

$$D_\mu\phi = \left[\partial_\mu + i\left(g_bQ_b + g_cQ_c\right)Z'_\mu\right]\phi, \quad (11)$$

with the constants $g_{b,c}$ are the corresponding $\text{U}(1)_{b,c}$ couplings. Roughly, with the non-vanishing vacuum expectation value, $\langle\phi\rangle \neq 0$, Eq. (11) produces the following mass term for the Z' boson,

$$\zeta_{\text{mass}}^{Z'} \sim (g_c - g_b)^2\langle\phi\rangle^2 Z_\mu'^2, \quad (12)$$

where the Z' mass reads,

$$M_{Z'} \sim (g_c - g_b)\langle\phi\rangle. \quad (13)$$

In general, the scale of the extended symmetry breaking is unknown, ranging from $\sim 10^2$ GeV to much higher scales. However, a TeV scale is predicted in many new physics scenarios [11, 12]. In this picture, the first implication of such U(1) extensions for the LHC is a new gauge boson Z' at TeV scale. Although there are other discovery goals at the LHC, after the discovered Higgs boson, such as Dark Matter and Supersymmetry, Z' is very likely to be the next discovery at the LHC if it exists. Indeed, Z' can be a factory of new and old particles, especially clean lepton signals revealing the effect of new particles between the Z' and final leptons.

In this work, we were interested in the connection between neutrino masses and possible extensions of the SM. We have presented a symmetry extension consisting of four abelian gauge factors whose a linear combination of them is the SM hypercharge. We have studied in detail how this extension could explain the known tiny neutrino masses. For that, we have in particular investigated the breaking of this symmetry down to the electroweak one through the vev of an introduced singlet scalar ϕ, and showed how this leads to the neutrino mass terms $m_v = y_{v^i}\varepsilon^3 \langle h\rangle$. In particular, the model involves a higher order coupling generated by through the scalar ϕ, so as without dealing with the structure of the Yuakwa constants and the investigation of their strengths, the allowed four-dimensional couplings give rise to a highly suppressed neutrino mass term compared to other SM fermions $m_v = y^v\varepsilon^3 \langle h\rangle \ll m_f = y_f \langle h\rangle$ with $\varepsilon \sim \langle\phi\rangle / M_s \ll 1$. Then, we have based on the neutrinos $\sim$eV scale data to approach the supressing effetcs, the associated scales $M_s \sim 10^7$ GeV, $\langle\phi\rangle > 10^2$ GeV and the resulting Z'-like boson of the model.

This work comes up with many questions related to possible extended models. A concrete one concerns the link with string theory, particularly with D-branes where N coincident piece of them typically generates a unitary group $\mathrm{U}(N) \sim \mathrm{SU}(N) \times \mathrm{U}(1)$ supplying the model with extra abelian factors U(1)'s in the gauge group which have clear interpretations in terms of globale symmetries of the SM, i.e., baryon, lepton, and isospin numbers [13–15].

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