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Implications of neutrino mass generation from QCD confinement

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Abstract

We consider the possibility that the quark condensate formed by QCD confinement generates Majorana neutrino masses m_ν via dimension seven operators. No degrees of freedom beyond the Standard Model are necessary, below the electroweak scale. Obtaining experimentally acceptable neutrino masses requires the new physics scale $\Lambda \sim$ TeV, providing a new motivation for weak-scale discoveries at the LHC. We implement this mechanism using a Z_3 symmetry which leads to a massless up quark above the QCD chiral condensate scale. We use non-helicity-suppressed light meson rare decay data to constrain Λ. Experimental constraints place a mild hierarchy on the flavor structure of dimension seven operators and the resulting neutrino mass matrix.

Non-zero neutrino masses m_ν provide the simplest and most robust explanation of neutrino oscillation data from a multitude of experiments. However, generically, models of neutrino mass require physics beyond the Standard Model (SM) either far above or well-below the electroweak scale $m_W \sim 100$ GeV. Most of these models are based on the seesaw mechanism [1], in which Majorana mass terms of the order $\Lambda_S \sim 10^{14}$ GeV for the right-handed neutrinos are present in addition to the usual electroweak Dirac mass terms, such that the tiny values of m_ν are obtained from the ratio m_W^2/Λ_S.

Recently, classes of models have been proposed in which neutrino masses arise from higher-dimensional operators suppressed by lower scales $\Lambda \ll \Lambda_S$ (e.g. $\Lambda \sim 10$ TeV) [2–4]. A key ingredient is the inclusion of new physics in the infrared, typically well-below 1 GeV. The new IR sector gives rise to novel astrophysical signatures that have been recently studied [5,6].

Given the typical scales involved in this class of models, it is interesting to consider using the natural SM electroweak scale $\Lambda \sim$ TeV and the scale $\Lambda_\chi \sim 100$ MeV of chiral symmetry breaking in quantum chromo-dynamics (QCD) to generate m_ν of $\mathcal{O}(0.1)$ eV. In what follows, we explore this possibility and outline the requirements that yield a consistent scenario.

We first note that this general framework has also been considered by Ref. [7], using a similar line of reasoning and based on new global $U(1)$ symmetries. Although we share the general features of the scenarios put forward in Ref. [7], we construct a simple model that satisfies the necessary requirements via a new Z_3 discrete symmetry. We also consider additional constraints on these models from meson decay data, not considered in Ref. [7], which lead to stronger bounds on the scale of new physics Λ. If the active neutrinos have Majorana masses, no new degrees of freedom beyond the minimal SM are required below the electroweak scale.

This scenario predicts that the mass of the up quark is zero above the scale of chiral symmetry breaking in QCD. We will later comment on the consistency of a massless up quark in light of the recent lattice results [8,9] and its implications for the strong CP problem.

Let us begin by outlining our theoretical framework. In an effective theory below $\Lambda \sim$ TeV, suppression of lepton number violation, and hence Majorana neutrino masses, requires that we forbid the dimension 5 operator[1]

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[1] We assume $\mathcal{O}(1)$ coefficients for operators in our discussion, unless otherwise specified.

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$$\mathcal{O}_H \sim \frac{(HL)(HL)}{\Lambda}, \tag{1}$$

where generation indices are suppressed. Given this assumption, a simple way to do this is to impose a discrete Z_3 symmetry [4], under which the lepton doublet L has charge $+1$ and the Higgs doublet H is neutral.

At this point, we would like to make a comment regarding the nature of the scale Λ. In our work, we will only assume that Λ is a scale of new physics and not necessarily a cutoff scale where quantum gravity effects appear. Thus, we do not expect a breakdown of all global symmetries at or above Λ. However, if Λ is treated as a cutoff scale, then one must impose additional symmetries to suppress baryon number violation and other experimentally forbidden processes, as well [4].

The SM fermions get their mass from Yukawa interactions of the form

$$\mathcal{O}_Y \sim H \bar{f}_L f_R, \tag{2}$$

which couple the left- and the right-handed fermions f_L and f_R, respectively. We assign Z_3 charge $+1$ to all right-handed charged lepton fields e^i_R, $i = 1, 2, 3$, in the SM, so that the Yukawa interactions (2) are allowed for them.

Schematically, we are interested in generating Majorana masses $m_\nu \sim 0.1$ eV from the dimension-7 operator $\mathcal{O}_q$ of the form[2]

$$\mathcal{O}^M_q \sim \frac{[(\bar{Q}_L q_R) \cdot L](HL)}{\Lambda^3}, \tag{3}$$

in which Q_L is a left-handed quark doublet and q_R is a right-handed up-type quark. The combination $\bar{Q}_L q_R$ is a $\bar{2}$ of $\mathrm{SU}(2)_L$ and has $\mathrm{U}(1)_Y$ hypercharge $+1/2$. We must arrange for $\mathcal{O}^M_q$ to be Z_3 neutral if it is to be allowed in our theory. A simple way to achieve this is to endow q_R with Z_3 charge $+1$. However, this will forbid writing down the Yukawa term (2) for q_R and hence this quark remains massless at scale Λ. Since the lightest quark in the SM is the up quark, we will hereafter assume that $q_R = u_R$ and thus the up quark remains massless at the cutoff scale: $m_u(\Lambda) = 0$.

So far, we have succeeded in forbidding $\mathcal{O}_H$ in Eq. (1) and allowing the operator

$$\mathcal{O}^M_u = y_{ijk} \frac{[(\bar{Q}^i_L u_R) \cdot L^j](HL^k)}{\Lambda^3}, \tag{4}$$

where $y_{ijk} \sim 1$. As a result of QCD confinement, the light quarks (u, d) in the SM form a condensate that breaks the global $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ chiral symmetry of strong interactions. In particular, $\langle \bar{u}_L u_R \rangle \neq 0$, which implies that below the electroweak scale, Eq. (4) contains a term

$$\mathcal{O}^M_{\nu\nu} = y_{1jk} \frac{[\langle \bar{u}_L u_R \rangle \langle H \rangle]}{\Lambda^3} \nu^j \nu^k. \tag{5}$$

We thus require

$$m_\nu \sim \frac{\langle \bar{u}_L u_R \rangle \langle H \rangle}{\Lambda^3}. \tag{6}$$

For $\langle \bar{u}_L u_R \rangle \simeq (200\ \mathrm{MeV})^3$, $\langle H \rangle \equiv v/\sqrt{2} \simeq 174$ GeV, as required by the SM, and $m_\nu = \sqrt{\Delta m^2_{\mathrm{atm}}} \simeq 0.06$ eV, we get $\Lambda \simeq 3$ TeV. Since established data only allow small variations in the 3 input parameters that set Λ, our prediction for the scale of new physics is unambiguous.

We saw that our simple construct forbids the usual up quark mass term, and hence this mechanism appears to require $m_u(\Lambda) = 0$. A massless up quark has long been invoked as a possible resolution of the strong CP problem. This is because the CP violating angle θ in the QCD Lagrangian is only defined up to the phase of the quark-mass-matrix determinant. With a zero eigenvalue, the phase becomes undefined and the θ-angle can be rotated away. However, recent lattice QCD calculations [8,9] seem to show that the up quark is not massless, in apparent conflict with our construct. Next, we will argue that this is not necessarily the case.

What has been shown by lattice calculations is that setting $m_u = 0$ at a scale of order $\Lambda_{\mathrm{QCD}} \sim 100$ MeV cannot be compensated by a contribution from the next to leading order chiral Lagrangian. This contribution was shown by Kaplan and Manohar [11] to induce an effective up quark mass and originates in a redundancy of the chiral Lagrangian formulation [12]. Nonetheless, there is an additive non-perturbative contribution to m_u [12], due to QCD instantons, that generate $m_u \neq 0$ at Λ_{QCD}, even if we set $m_u = 0$ at the cutoff scale $\Lambda \sim 1$ TeV. This contribution has a form similar to that of the Kaplan–Manohar ambiguity, but is physically of a different origin [12,13]. Therefore, we hold that the requirement $m_u(\Lambda) = 0$ is not necessarily in conflict with the lattice results.

Here, we would like to add that the operator in Eq. (4) contributes to the up-quark mass at 1-loop level.[3] The size of this contribution can be estimated and is of order $\delta m_u \sim \langle H \rangle m_\nu / \Lambda$. In this estimate, we have used $m_\nu \Lambda^2$ as the size of the neutrino loop. The θ-angle in QCD is constrained by the electric dipole moment (EDM) of the neutron which is proportional to m_u [14,15]. Since the contribution δm_u is suppressed by $\sim 10^{-8}$–10^{-10} compared to the usual value of $m_u \sim 1$ MeV, the neutron experimental EDM bound does not require a significant fine-tuning θ and hence the strong CP problem is resolved for all practical purposes. Note that the much larger instanton-generated mass of order 100 MeV, mentioned above, is a real contribution to the non-perturbative renormalization of the light quark masses and does not affect the resolution of the strong CP problem [13].

We now examine the quantum stability of the Z_3 symmetry we have employed in the above framework. To this end, we inquire whether this symmetry is anomaly-free in the SM. The fermions that are charged under Z_3 are L^i, e^i_R, and u_R. As both the number of leptonic generations and the number of QCD colors are equal to 3, all triangle anomalies related to $\mathrm{SU}(2)_L$,

[2] The possibility of generating Dirac masses via the quark condensate was considered in Refs. [7,10], using an operator of the form $O^D_q \sim (\bar{Q}_L q_R) \cdot LN/\Lambda^2$, where N is a sterile neutrino. This possibility leads to overcooling of Supernova 1987A, unless $\Lambda \gtrsim 10$ TeV, leading to $m_\nu < 5 \times 10^{-2}$ eV [7], which is disfavored by current neutrino data. Given that introducing sterile particles is a departure from minimal model building in any case, we concentrate on Majorana masses in our work.

[3] We thank C. Thorn for pointing out this feature.

$U(1)_Y$, and gravity are zero *mod* 3. The only anomaly is from the triangle with two $SU(3)_c$ gluons and one Z_3 vertex, since only u_R has Z_3 charge.

We see that the Z_3 symmetry is not exact at the quantum level and cannot be imposed as a *gauge* symmetry at scale Λ. In principle, the anomaly can be canceled by introducing new fermions near the cutoff scale. This possibility will lead to the presence of new massless $SU(3)_c$ charged fermions in the theory. These fermions stay massless as long as the Z_3 we have imposed is not broken and can only have masses of order m_ν from chiral symmetry breaking of QCD. This is in stark conflict with nearly all experimental data. Thus, the only way to have these fermions in our theory is to push their masses above $\sim$100 GeV, where they decouple from present data. However, this would require Z_3 to be spontaneously broken at $\sim$100 GeV, which means that m_ν would no longer be protected down to Λ_{QCD}, negating the purpose of having this symmetry in the first place.

In our treatment, we will not attempt to resolve the issue of anomaly cancellation. In 4-d, the anomaly of our Z_3 symmetry suggests that it must be thought of as an accidental symmetry. That is, like baryon number symmetry in the SM, it arises from gauge invariance and renormalizability of the underlying theory. Thus, we expect that a new gauge symmetry beyond the SM to exist above scale Λ in a UV completion of our framework.

Another interesting possibility could be provided by anomaly cancellation in extra-dimensional models. One could entertain a scenario in which the Z_3 anomaly of the "visible sector" is canceled by contributions from other fields that are localized on various defects in extra dimensions. For example, a 5-d theory with three identical 3-branes containing the same field content as our framework will have no Z_3 anomaly. Depending on the details of compactification and the underlying geometry of the extra dimensions, this scenario could result in the appearance of collider and other high energy experimental signatures. We will not attempt to construct a UV complete theory that induces our Z_3 at low energies; this is beyond the scope of this work which focuses on the phenomenological implications of neutrino mass generation from QCD confinement.

The central features of the mechanism studied here are encoded in Eqs. (4) and (5): the QCD chiral-condensate and $\langle H\rangle$, all SM ingredients, can be incorporated into an effective suppressed mass term which yields acceptable neutrino masses. We emphasize that because this operator is exclusively constructed out of SM fields, *the size of the scale where new physics emerges is not arbitrary and must be at a few TeV*. Therefore, the above mechanism for neutrino mass generation motivates new physics near the electroweak scale, *independently* of the gauge hierarchy problem. Examples of specific scenarios with new scalars at TeV energies have been presented in Ref. [7], using a U(1) global symmetry. Consequently, we expect such new physics, relating neutrino masses to QCD, will be accessible at the LHC.

Here, we turn to the question of experimental constraints on this mechanism. The operator $\mathcal{O}_u^M$ in (4) can also lead to new decay channels for charged pseudoscalar mesons, with $Q_L^i = d_L^i$:

$$\mathcal{O}_{du} = \left(\frac{\langle H\rangle}{\Lambda}\right)\frac{(\bar{d}_L^i, u_R)e^j\nu^k}{\Lambda^2}, \tag{7}$$

where we have set $y_{ijk} = 1$ for simplicity and consider bounds on the effective value of Λ, taking all the relevant coefficients to be unity. Ref. [7] considered this possibility for the lepton number violating decay $\pi^+ \to \mu^+\bar{\nu}$, for which the helicity of the μ^+ has the wrong sign compared to the SM decay $\pi^+ \to \mu^+\nu$. The total muon polarization depends on the scale Λ as: $1 - |P_\mu| \propto 1/\Lambda^6$. It was found that $\Lambda \gtrsim 1$ TeV, given the available data [7]: $|P_\mu| > 0.9959$. One can easily verify that using the most recent 90% C.L. bound from PDG, $|P_\mu| > 0.9968$, would only provide a tiny improvement, resulting in effectively the same bound as before.

However, we can achieve much stronger bounds on the cutoff scale if we consider the contribution of the $\mathcal{O}_{du}$ to the partial decay width of a light pseudoscalar $P_i \to e^+\bar{\nu}_x$, where $P_i^+ = \pi^+, K^+, B^+$, for $i = 1, 2, 3$, respectively; ν_x is an active neutrino. Note that the decay channels including $e^\pm$ are severely helicity suppressed in the SM. However, lepton number violating decays mediated by $\mathcal{O}_{du}$ are not helicity suppressed. The current Particle Data Group (PDG) [16] bounds are on the SM processes $P_i^+ \to e^+\nu_e$. However, since the quantum numbers of the final state neutrino is not measured, these bounds constrain $P_i^+ \to e^+\nu_x$, where ν_x is any type of neutrino. Thus, the helicity unsuppressed processes mediated by $\mathcal{O}_{du}$ will contribute to the measured branching fractions $\mathrm{Br}(P_i^+ \to e^+\nu_e)$.

The partial width Γ_i for $P_i \to e^+\bar{\nu}_x$ mediated by $\mathcal{O}_{du}$ is given by

$$\Gamma_i = 3\left(\frac{v^2}{128\pi\Lambda^6}\right) f_i^2\mu_i^2 m_i. \tag{8}$$

In the above, m_i is the mass of P_i^+, the factor 3 refers to the contribution of 3 diagrams corresponding to the unobserved neutrino flavors, and $v = 246$ GeV ($\langle H\rangle \equiv v/\sqrt{2}$). We also have $\mu_1 = m_\pi^2/(2\bar{m})$, with $\bar{m} = (m_u + m_d)/2 \simeq 5$ MeV; m_u and m_d are the up and down quark masses, respectively. Hence $\mu_1 = 14m_\pi$. For the $i = 2$, $\mu_2 = m_K^2/(m_s + \bar{m})$, with $m_s \simeq 100$ MeV the strange quark mass; $\mu_2 \simeq 5m_K$. We also get $\mu_3 \simeq m_B$, for the B^+ meson, where the b quark mass $m_b \simeq m_B$. The f_i are the pseudoscalar meson decay constants: $f_1 = 130$ MeV, $f_2 = 160$ MeV, and $f_3 = 180$ MeV.

From PDG [16], we have

$$\mathrm{Br}\big(\pi^+ \to e^+\nu_e\big) = (1.230 \pm 0.004) \times 10^{-4}, \tag{9}$$

$$\mathrm{Br}\big(K^+ \to e^+\nu_e\big) = (1.55 \pm 0.07) \times 10^{-5}, \tag{10}$$

and

$$\mathrm{Br}\big(B^+ \to e^+\nu_e\big) < 1.5 \times 10^{-5} \quad (90\%\ \text{C.L.}). \tag{11}$$

We require that the contribution to the above branching fractions from Eq. (8) is smaller than the 1-σ uncertainty on the measured branching fraction, or smaller than the bound, in the case of B^+. The following bounds

$$\Lambda > 8.6, 9.8, 2.7\ \text{TeV} \tag{12}$$

are obtained for the π^+, K^+, and B^+, respectively. Note that these bounds are weaker than those obtained from usual (pseudo)scalar leptoquarks, which are typically of $\mathcal{O}(100\ \text{TeV})$ for $\mathcal{O}(1)$ coefficients [17,18]. The bounds derived here are weaker because these operators do not interfere with SM processes, which is not the case for the operators considered in [17,18].

The strongest bound arises from K mesons; $\Lambda \simeq 10$ TeV. This constraint leads to neutrino masses which are too small to account for the observed atmospheric neutrino mass-squared difference. However, this bound was obtained by assuming all coefficients y_{ijk} of $\mathcal{O}(1)$. In practice, such coefficients should have an intrinsic flavor dependence. The meson decays $P_i \to e^+\bar{\nu}_x$ constrain the coefficients y_{i1k}, with $i = 1$ for the pions, $i = 2$ for the kaons, and $i = 3$ for the B mesons, while the neutrino mass matrix involves the coefficients y_{1jk} (see Eq. (4)). Therefore, the bound from the K mesons can be alleviated if there is a flavor-dependent hierarchy between the $i = 1$ and $i = 2$ operators of $\mathcal{O} \sim (3\ \text{TeV}/10\ \text{TeV})^3 \approx (1/30)$, where 3 TeV is the mass scale required for realistic neutrino masses as derived above. However, we still have the bound from the pions, which is similar and cannot be addressed by flavor hierarchy amongst the operators. To see this, note that the operator which contributes to π^+ decay also contributes to the neutrino mass matrix up to an $SU(2)_L$ transformation, so gauge invariance does not allow further tuning of coefficients.

To have a consistent framework, we thus require that the coefficient y_{11k} in Eq. (4) be suppressed at the level $(3/9)^3 \approx 1/30$, similar to the suppression required from the K decay data. This, given the above discussion, also leads to suppression of neutrino mass matrix elements M_{1k}. Therefore, the consistency of our framework seems to suggest hierarchical neutrino masses. Hence, we see that the meson decay data provide some guidance for constructing a UV completion of our effective theory at scale Λ. Since the scale of new physics is in the TeV regime, this framework could provide an interesting avenue of exploration for weak scale model building.

In conclusion, we studied the consequences of generating neutrino masses from QCD confinement via higher-dimensional operators. Neutrino masses are suppressed by the ratio of the QCD chiral condensate to the scale of new physics. The higher dimension operators consist only of SM fields. Consequently, the scale of new physics cannot be larger than a few TeV, in order to generate acceptable neutrino masses. This strongly suggests that the LHC will probe the new physics that relates non-perturbative QCD dynamics and neutrino masses. We considered a model that requires a massless up quark above the QCD confinement scale. We argued that this is not necessarily in conflict with lattice results and may resolve the strong CP problem. Below the electroweak scale, the model reduces to the field content of the minimal SM. We used rare decays of light pseudo-scalar mesons to place bounds on the effective scale of new physics. The experimental constraints suggest a quark and lepton flavor-dependent $\mathcal{O}(10^{-1})$ hierarchy among the coefficients of the higher dimension operators. Since the neutrino mass matrix is generated from these higher dimensional operators, a generic consistency condition for our framework is a hierarchical pattern of neutrino masses and mixings.

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