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Light active and sterile neutrinos from compositeness

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Abstract

Neutrinos can have naturally small Dirac masses if the Standard Model singlet right-handed neutrinos are light composite fermions. Theories which produce light composite fermions typically generate many of them, three of which can marry the left-handed neutrinos with small Dirac masses. The rest can serve as sterile states which can mix with the Standard Model neutrinos. We present explicit models illustrating this idea.

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There are strong experimental hints that suggest that the neutrino sector is more complicated than it is in the Standard Model (SM). The solar [1] and atmospheric [2] neutrino puzzles, the LSND results [3], models of mixed (hot and cold) dark matter [4] and other phenomena [5] seems to require massive neutrinos with $m_\nu \sim 10^{-5} - 10^{7}\,\mathrm{eV}$ and mixing angles of order 10^{-2} or larger. Moreover, these anomalies require different masses or mass-squared differences. Therefore, these results cannot be accommodated simultaneously in an extended three generation SM with small neutrino masses [5,6]. It is well known that SLD and LEP data excludes the existence of a fourth light sequential neutrino [7]. The way out is to postulate light sterile neutrinos: SM singlets that mix with the standard active neutrinos. Then, there would be more than three neutrino masses, and the different sets of masses required can be obtained. Although the ad hoc addition of these sterile neutrinos can accommodate all existing neutrino data, this solution has one bothering feature: unlike the active neutrinos, which can be naturally light due to the see-saw mechanism, there is no good reason why a SM singlet should be so light; being a gauge singlet, it could have a mass much above the weak scale.

Indeed, several ideas of how to get naturally light sterile neutrinos have been proposed. They can be light due to extra discrete [8] or continuous [9] symmetries, or due to the way GUT E_6 is implemented [10]. Supersymmetry also provides singlets that may be light due to an R symmetry [11], or because they are quasi Nambu-Goldstone bosons [12] or Modulinos [13]. String models with higher dimensional operators are another possibility [14]. Also, the light sterile neutrinos may be neutrinos from a mirror world [15].

Here we suggest an alternative mechanism to explain the lightness of the sterile neutrinos, which can also simultaneously provide a small Dirac mass for the active ones. The idea is to imagine a new sector, isolated from the SM where strong dynamics at a scale Λ produces massless composite fermions required to match the anomalies of an unbroken chiral symmetry of the strong dynamics. We assume that the only interaction between the "preons" of the new sector and the SM fields is via higher dimension operators suppressed by a scale $M \gg \Lambda$. After the confining dynamics occurs, some of these higher dimension operators turn into relevant operators connecting the massless composites to the SM fields, with couplings naturally suppressed by powers of the small ratio (Λ/M). Since the unbroken chiral symmetries can be quite large, many massless composites will typically be generated, which can furnish us both active and sterile neutrinos.

Some of the earliest examples of chiral gauge theories producing massless composite fermions were considered in [16]. The models are based on an $SU(n+4)$ gauge group with a single antisymmetric tensor A and n antifundamentals ψ_i (with $i = 1..n$). This particle content is anomaly free and completely chiral. In [16], it was argued that after confinement, this theory produces $n(n+1)/2$ massless composite "baryons" $B_{ij} = \psi_i A \psi_j = B_{ji}$. If we suppose that all these fields are SM singlets which can communicate with the SM only through higher dimension operators suppressed by a scale M, the lowest dimension operator of interest is

$$\mathcal{L} \supset \lambda^{ij,\alpha} \frac{(\psi_i A \psi_j) L_\alpha H^*}{M^3} = \lambda^{ij,\alpha} \left(\frac{\Lambda}{M}\right)^3 \hat{B}_{ij} L_\alpha H^*, \tag{1}$$

where $\alpha = 1,2,3$ runs over the three SM generations, Λ is the dynamical scale of the theory, and

$$\hat{B}_{ij} = \frac{\psi_i A \psi_j}{\Lambda^3}, \tag{2}$$

are the canonically normalized baryon fields. For $n \geq 2$, there are at least 3 massless baryons, which we can consider as being right-handed neutrinos with Yukawa couplings to left-handed neutrinos naturally suppressed by $(\Lambda/M)^3$. The mass spectrum then depends on whether or not lepton number is preserved by the mass matrix, i.e. whether higher dimension operators are allowed which turn into Majorana mass terms for the neutrinos after confinement or electroweak symmetry breaking.

First, imagine a situation where lepton number (L) is conserved, and $L(\hat{B}_{ij}) = -1$. Then, a linear combination of three of the baryons can marry the three left-handed neutrinos, while the orthogonal baryons decouple and remain massless. After the Higgs acquires its vev, this gives neutrino masses

$$m_\nu \sim v\epsilon^3, \tag{3}$$

where v is the Higgs vev and

$$\epsilon \equiv \frac{\Lambda}{M}. \tag{4}$$

Here and in what follows we suppress unknown Yukawa couplings and assume them to be of $O(1)$ (of course, if the neutrino sector exhibits flavor structure, these Yukawa couplings may be hierarchical). This model generates naturally small Dirac masses and non-trivial mixings. The extra $n(n+1)/2 - 3$ baryons are sterile states which however decouple and do not mix with the active neutrinos.

Next, we consider a model without lepton number. By this we mean that in addition to Eq. (1) also operators of the form

$$\mathcal{L} \supset h^{ij,kl} \frac{(\psi_i A \psi_j)(\psi_k A \psi_l)}{M^5} + y^{\alpha\beta} \frac{L_\alpha H^* L_\beta H^*}{M} = h^{ij,kl} M \epsilon^6 \hat{B}_{ij} \hat{B}_{kl} + y^{\alpha\beta} \frac{L_\alpha H^* L_\beta H^*}{M}, \tag{5}$$

are present. The mass matrix is now a square $(n(n+1)/2+3)$ matrix, which in the $\{L_\alpha, \hat{B}_{ij}\}$ basis is of the form

$$m_\nu \sim \begin{pmatrix} v^2/M & \epsilon^3 v \\ \epsilon^3 v & \epsilon^6 M \end{pmatrix}. \tag{6}$$

Diagonalizing this mass matrix we find

$$m_a \sim \frac{v^2}{M}, \qquad m_s \sim \epsilon^6 M, \qquad \theta_{as} \sim \min\left(\sqrt{\frac{m_a}{m_s}}, \sqrt{\frac{m_s}{m_a}}\right), \tag{7}$$

where m_a, m_s and θ_{as} are the masses of the mainly active and sterile states and their mixing angles, respectively. The active–active and sterile–sterile mixing angles are determined by the unknown Yukawa couplings. Note that as long as ϵ^3 and v/M are within two order of magnitudes of each other, Eq. (7) exhibits an interesting pattern. For $M \sim 10^6 - 10^{18}$ GeV we obtain $m_\nu \sim 10^7 - 10^{-5}$ eV and $\theta \gtrsim 10^{-2}$. Both the masses and mixing angles are in the ranges indicated by the data.

While we gave two explicit examples, it is clear that there are many models with the same basic idea. In particular, SUSY models exhibiting confinement without chiral symmetry breaking [17] can be used to furnish the sterile states. Furthermore, the composites can be made of different number of constituents, leading to different powers of ϵ in the mass matrices we have considered.

It is also possible to have active–sterile mixing in theories with conserved lepton number, and thus without Majorana masses. For instance, suppose we have $N > 3$ composites B_i with $L = 1$ and $\bar{B}_j$ with $L = -1$. For simplicity we assume that both $B, \bar{B}$ are made of n_f fermionic and n_b bosonic preons. The most general lepton-number conserving mass matrix involving these fields and the left-handed neutrinos is an $(N+3) \times N$ matrix, that in the $\{\nu_{L_\alpha}, B_j\} \times \{\bar{B}_j\}$ basis reads

$$m_\nu \sim \left(\epsilon^p v \quad \epsilon^{2p} M \right) \tag{8}$$

where $p = (n_f - 1)3/2 + n_b$. This mass matrix generates three massless and N massive states. We emphasize that there are active neutrino components in all the states. Thus, in this model there are effectively N sterile neutrinos that mix with the standard three active neutrinos. When $v/M \ll \epsilon^p$, the three mainly active neutrinos are massless, while the N mainly sterile neutrinos have a mass $m_s \sim \epsilon^{2p} M$. In the opposite limit $v/M \gg \epsilon^p$, three mainly sterile neutrinos are massless, and the remaining states have masses

$$m_a \sim \epsilon^p v, \quad m_s \sim \epsilon^{2p} M. \tag{9}$$

In both cases the mixing angles between the three mainly active neutrinos and the N mainly sterile neutrinos are given by

$$\theta_{as} \sim \min\left(\frac{m_a}{m_s}, \frac{m_s}{m_a}\right) \tag{10}$$

where $m_{a,s}$ are given in Eq. (9). As before, also in this model one can get masses and mixing angles in the relevant ranges. Note that in the previous model the mixing angles were of the order of the square root of the neutrino mass ratios, while in this model they are linear in this ratio.

We did not specify the high energy model where the non-renormalizable terms arise. This high energy theory can be a string theory with $M \sim 10^{18}$ GeV, a GUT with $M \sim 10^{16}$ GeV, or another intermediate scale theory. Such theory has to provide connection between the two sectors of the low energy theory, namely, the SM and the strong gauge theory providing massless composite fermions. Note that since we have not made any connection between v and Λ, our models simply allow but do not predict active and sterile neutrinos with similar masses. Such a connection may arise if the composite dynamics also triggers SUSY breaking while keeping massless composite fermions (examples of such models may be found in [18]). Furthermore, we did not address the issue of how the flavor structure in the neutrino sector is generated. In the simple models we presented, the required flavor structure must come from a different source, for example a horizontal symmetry [19].

As an aside, the lepton number conserving models we considered can also be useful to generate neutrino masses in a recently proposed scenario to solve the hierarchy problem by lowering the fundamental Planck scale to the weak scale [20]. In that scenario, it is difficult to generate small neutrino masses through the usual $(LH^*)^2/M$ operator since M cannot be far above the weak scale. However, we can still generate small Dirac masses suppressed by powers of (Λ/M) if $\Lambda \ll$ TeV.

To conclude, we presented a scheme for generating light active and sterile neutrinos with either no or possibly realistic active–sterile mixing. Both active and sterile neutrinos are light because they are protected by chiral symmetries. The sterile states are massless composite fermions at the renormalizable level, and higher dimension operators linking them to the SM fields can produce dimensionless couplings naturally suppressed by powers of $\epsilon = (\Lambda/M)$. Moreover, in general one finds many sterile neutrinos. This is a welcome feature since sterile neutrinos may help in solving the known neutrino anomalies [5]. While we have presented some simple models, it is clear that many variations are possible.

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REFERENCES

[1] See *e.g.*, J.N. Bahcall and P.I. Krastev, Phys. Rev. **D 53** (1996) 4211; N. Hata and P. Langacker, Phys. Rev. **D 56** (1997) 6107.

[2] See *e.g.*, C. Giunti, C.W. Kim and M. Monteno, hep-ph/9709439.

[3] C. Athanassopoulos *et al.*, LSND Collaboration, Phys. Rev. Lett. **77** (1996) 3082; nucl-ex/9709006; nucl-ex/9706006.

[4] See *e.g.*, J.R. Primack, astro-ph/9707285.

[5] J.T. Peltoniemi, hep-ph/9506228;

[6] See e.g., S. Goswami, Phys. Rev. **D 55** (1997) 2931; N. Okada and O. Yasuda, Int. J. Mod. Phys. **A 12** (1997) 3669; S.M. Bilenky, C. Giunti and W. Grimus, Eur. Phys. J. **C 1** (1998) 247; hep-ph/9805368.

[7] R.M. Barnett *et al.*, the Particle Data Group, Phys. Rev. **D 54** (1996) 1.

[8] E. Ma and P. Roy, Phys. Rev. **D 52** (1995) 4780.

[9] E. Ma, Mod. Phys. Lett. A **11** (1996) 1893.

[10] E. Ma, Phys. Lett. **B 380** (1996) 286.

[11] E.J. Chun, A.S. Joshipura and A.Yu. Smirnov, Phys. Lett. **B 357** (1995) 608.

[12] E.J. Chun, A.S. Joshipura and A.Yu. Smirnov, Phys. Rev. **D 54** (1996) 4654.

[13] K. Benakli and A.Yu. Smirnov, Phys. Rev. Lett. **79** (1997) 4314.

[14] P. Langacker, hep-ph/9805281.

[15] Z.G. Berezhiani and R.N. Mohapatra, Phys. Rev. **D 52** (1995) 6607; B. Brahmachari and R.N. Mohapatra, hep-ph/9805429.

[16] S. Dimopoulos, S. Raby and L. Susskind, Nucl. Phys. **B 173** (1980) 208.

[17] C. Csaki, M. Schmaltz and W. Skiba, Phys. Rev. **D 55** (1997) 7840.

[18] N. Arkani-Hamed, M. Luty and J. Terning, hep-ph/9712389, to appear in Phys. Rev. **D**.

[19] See *e.g.*, Y. Grossman and Y. Nir, Nucl. Phys. **B 448** (1995) 30.

[20] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, hep-ph/9803315, to appear in Phys. Lett. **B**; I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali, hep-ph/9804398.