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Partially Broken Seesaw Mechanism

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In a class of models with global SU(n) family symmetry, the possibility naturally exists that $n-1$ generations have light neutrinos and the remaining generation has a medium-heavy neutrino, of the order of the charged-lepton mass or the quark mass, as a consequence of an incomplete action of the seesaw mechanism. We discuss as applications two possibilities: (i) The heavy neutrino is identified with the neutral particle of mass 17 keV suggested by Simpson from β-decay experiments, and (ii) there may exist a fourth generation and the associated neutrino has a heavy mass, probably of the order of a hundred GeV.

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The seesaw mechanism is one of the most attractive ways to understand why neutrinos have masses much smaller than those of the charged leptons and quarks.[1] With the concept of unification of particle interactions, it is not unreasonable to suppose there is a right-handed Majorana neutrino with a mass M_R much heavier than the ordinary mass scale. If there is a Dirac mass term for the neutrino of the order of that for the charged lepton or the quark, the left-handed neutrino acquires a small mass of the order of $M_L \simeq m_D^2/M_R$ through the ν_L-ν_R mixing caused by the Dirac mass m_D. This is easily seen by diagonalizing the matrix

$$\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \tag{1}$$

with the two rows (and columns) referring to left- and right-handed sectors. For n generations it is usually supposed that the similar structure repeats for n times, i.e.,

$$M_{Li} \simeq m_{Di}^2/M_{Ri}, \quad i=1,\ldots,n, \tag{2}$$

with $M_{Ri} \gg m_{Di}$.

In this Letter we point out that there exists naturally a class of family models in which only $n-1$ generations have light neutrinos by virtue of the seesaw mechanism, while the remaining one has a medium-heavy neutrino of the order of the Dirac mass. We do not know where this mechanism is to be applied. We would like to point out, however, that the present possibility may provide motivation to search for a heavy neutrino (with a mass of the order of a hundred GeV) associated with a fourth generation. Another possibility in the case of $n=3$ is that one of the three neutrinos has a mass considerably heavier than the others. We discuss how the scheme proposed here would accommodate the "heavy neutrino" with mass of 17 keV suggested by Simpson[2] some time ago. This is a particle which, while it needs confirmation, has not yet been excluded.

The standard idea in considering the family problem is to start with the assumption of family symmetry,[3] which we suppose to be global $\mathrm{SU}(n)_F$ in this Letter. Let the left-handed leptons and quarks,

$$l_L \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}_L, \quad q_L \equiv \begin{pmatrix} u \\ d \end{pmatrix}_L, \tag{3}$$

take the $[n]$ representation of $\mathrm{SU}(n)_F$, and let the right-handed ν_R, e_R, u_R, and d_R also take $[n]$ of $\mathrm{SU}(n)_F$. We then assume this $\mathrm{SU}(n)_F$ symmetry is broken completely by Higgs scalars ξ in the fundamental representation $[n^*]$ of $\mathrm{SU}(n)_F$ [we assume ξ to be an $\mathrm{SU}(2)_L$ singlet]. For this aim, it is sufficient to have $n-1$ such Higgs particles, the vacuum expectation values of which can generally be written

$$\langle \xi^{(1)} \rangle = \begin{pmatrix} v_1^{(1)} \\ 0 \\ \vdots \\ 0 \end{pmatrix}, \ldots, \langle \xi^{(n-1)} \rangle = \begin{pmatrix} v_1^{(n-1)} \\ \vdots \\ v_{n-1}^{(n-1)} \\ 0 \end{pmatrix}. \tag{4}$$

The lowest-dimension couplings of $\xi^{(a)}$ and ν_R take the form

$$\frac{f_{ab}}{M}(\xi_i^{(a)} \nu_R^i)(\xi_j^{(b)} \nu_R^j), \tag{5}$$

where i and j denote the generation, and M is an effective mass corresponding to some higher unification.[4] The Majorana mass term

$$M_R = \frac{f_{ab}}{M} \langle \xi^{(a)} \rangle \langle \xi^{(b)} \rangle \tag{6}$$

then has vanishing matrix elements for either the row $i=n$ or the column $j=n$.

There are also the Dirac mass terms

$$\bar{e}_R^j (G_e^{(1)} \tilde{\phi}_j^i + G_e^{(2)} \tilde{\phi} \delta_j^i) l_{Li} + \bar{\nu}_R^j (G_\nu^{(1)} \phi_j^i + G_\nu^{(2)} \phi \delta_j^i) l_{Li} + \text{H.c.}, \tag{7}$$

where the $SU(2)_L$ doublet fields ϕ^i_j and ϕ are, respectively, an adjoint and a trivial representation of $SU(n)_F$, and the tilde means the $SU(2)_L$ conjugate. The Dirac mass of the neutrino is then

$$[m_D]^i_j = G^{(1)}_\nu \langle \phi^i_j \rangle + G^{(2)}_\nu \langle \phi \rangle \delta^i_j \, . \tag{8}$$

Now the seesaw mechanism works between (6) and (8) for the generation $i=1,\ldots,n-1$ to give a left-handed neutrino mass

$$m_L = m_D M^{-1} m_D \, . \tag{9}$$

For the neutrino of the nth generation, however, the seesaw mechanism does not work and its mass is given by the Dirac mass.

We note that there is left a U(1) symmetry which is a linear combination of $U(1)_\xi$ (the phase rotation of the ξ field) and the U(1) subgroup of $SU(n)$ at low energies. This U(1) protects one of the ν_R's from acquiring a large Majorana mass. When the ϕ^i_j develop vacuum expectation values at the weak-interaction scale,[5] this global U(1) is also broken spontaneously, yielding a dangerous Nambu-Goldstone boson. This problem, however, is easily avoided, if the following term that explicitly breaks $U(1)_\xi$ is put in the Higgs potential:

$$V(\phi,\xi) = \frac{1}{M^{n-2}} \epsilon_{ikl\cdots} \bar{\epsilon}_{abc\cdots} \phi^i_j \phi^* \xi^{*j}_{(a)} \xi^{*k}_{(b)} \xi^{*l}_{(c)} \cdots \, , \tag{10}$$

where $\epsilon_{ikl\cdots}$ and $\bar{\epsilon}_{abc\cdots}$ are nth- and $(n-1)$th-rank antisymmetric tensors, respectively. Note that this is perfectly consistent with $SU(n)$ symmetry. The Nambu-Goldstone boson acquires a mass

$$\langle \xi \rangle (\xi/M)^{(n-2)/2} \tag{11}$$

[which is $\sim 10^6$ GeV for the case of SU(3) with $\langle \xi \rangle \simeq 10^{10}$ GeV and $M \simeq 10^{19}$ GeV, see the example below], and it no longer appears at low energies. Higher-order corrections would lead to ν_R-ξ couplings of the form

$$\frac{\alpha_Y^2}{M^{n-1}} \epsilon_{ikl\cdots} \bar{\epsilon}_{bc\cdots} \nu^i_R \nu^j_R \xi^{(a)}_j \xi^{*k}_{(b)} \xi^{*l}_{(c)} \cdots$$

and

$$\frac{\alpha_Y^2}{M^{2n-3}} \epsilon_{ikl\cdots} \epsilon_{jmn\cdots} \bar{\epsilon}_{ab\cdots} \bar{\epsilon}_{cd\cdots} \nu^i_R \nu^j_R \xi^{*k}_{(a)} \xi^{*l}_{(b)} \cdots \xi^{*m}_{(c)} \xi^{*n}_{(d)} \, , \tag{12}$$

which give a small Majorana mass to ν^i_R of the order to $\langle \xi \rangle (\langle \xi \rangle / M)^{2n-3}$.

In summary, we have $n-1$ small-mass Majorana neutrinos, and one ordinary mass neutrino with predominantly the Dirac character. We emphasize that no global symmetry is left at low energies; yet one zero-mass particle that appears in the right-handed neutrinos cripples the conventional seesaw mechanism.

Application to the Simpson neutrino.— Let us now see whether the heavy neutrino found by Simpson some time ago would fit into the scheme considered here. In 1985 Simpson[2] reported evidence for a heavy "neutrino" with a mass of 17 keV emitted in the β decay of tritium. The mixing with ν_e ($\sin^2\theta = 0.01$–0.03) was surprisingly large. Since then a number of experiments have been carried out to confirm or refute its existence. The situation does not yet seem quite clear in spite of the negative claim made by many authors.[6] More recently, Sur *et al.*[7] have presented positive evidence for this particle in their ^{14}C experiment.

One of the main reasons why many people are not apt to take this "particle" seriously lies in the fact that it does not seem to fit the scheme expected in a simple picture. In particular, besides its unusual mass, it is not easy to understand (i) why the mixing with ν_e is so large compared with the constraint from neutrino-oscillation experiments for the ν_e-ν_μ mixing, (ii) why the heavy neutrino should be of the Dirac type, or otherwise it strongly violates the constraint from double-β decay, $\langle m_\nu \rangle_{ee} <$ (a few eV), since $\langle m_\nu \rangle_{ee}$ receives a Majorana mass of the order of (17 keV)$\times \sin^2\theta \approx 0.2$ keV, and (iii) why such a neutrino should undergo fast ($\tau \leq 10^5$ yr) nonradiative decay, to avoid the constraint from standard cosmology. The situation becomes even more difficult if one tries to reconcile this neutrino with very small, but finite masses for ν_e and ν_μ, as strongly suggested from the recent solar-neutrino experiments.[8,9]

Let us turn to the model ($n=3$) proposed in this Letter. It would be natural to suppose[10] that the family symmetry is broken at around $v \sim 10^{10}$ GeV. The mass of ν_R is thus $M_R \sim 10$ GeV with M in the denominator of (6) set equal to the Planck mass. Let us suppose a crude hierarchy $m_D(\nu_\mu):m_D(\nu_\tau) \simeq m_\mu:m_\tau$ and set $m_D(\nu_\tau) \simeq 17$ keV (this requires $G_\nu \sim 10^{-5} G_l$; the present model does not explain this hierarchy in the Yukawa coupling, however). By the seesaw mechanism we then obtain $m_{\nu_\mu} \simeq 10^{-4}$ eV, which is the value required to explain the solar-neutrino problem with the aid of the Mikheyev-Smirnov-Wolfenstein mechanism. The mass of the τ neutrino is dominantly the Dirac mass and does not contribute to double-β decay. [The Majorana-mass contribution from higher-dimensional operators (11) would lift the degeneracy of ν_τ, but it is of the order of 10^{-8} eV, and is negligible.] In the present model, the neutrino counting from the Z^0 decay width should give $N_\nu = 3$.

Another important point is that ν_τ is necessarily unstable in our model due to the existence of a familon. The lifetime of $\nu_\tau \to \nu_e + \chi$ is $\sim (2\times 10^4 \text{ yr})[v/(10^{10} \text{ GeV})]^2$. Hence the cosmological constraint is satisfied if $v < 4 \times 10^{10}$ GeV. Let us remark that familon emission is the only mechanism proposed so far that causes the decay of ν_τ with a mass of 17 keV within the required lifetime. The right-handed ν_R's of the first and the second generations decay into three ν_i's through ν_L-ν_R mixing. Since the lifetimes $\tau \sim 1-10^{-2}$ sec, these particles do not cause significant effects in cosmology.

Possibility of a heavy neutrino in a fourth generation.—The belief that the number of generation is three comes from the Z^0 width that allows only three species of light neutrinos. The possibility of a heavy fourth-generation neutrino has not been given serious attention, because it requires a huge jump in the mass hierarchy of the neutrinos from ν_τ to ν_X.

In the model proposed in the present Letter we naturally have three light neutrinos and one heavy neutrino, the mass of which is expected to be of the order of the heavy lepton mass or the quark mass of the fourth generation. Let us suppose that the family symmetry is broken at $\sim 10^{15}$ GeV. Then $m_{\nu R} \sim 10^{11}$ GeV, with M set equal to the Planck mass again. If the Dirac masses of the neutrinos are of the order of their corresponding quark masses of charge $\frac{2}{3}$, we expect $m(\nu_e) \simeq 10^{-8}$ eV, $m(\nu_\mu) \simeq 10^{-4}$ eV, and $m(\nu_\tau) \simeq 1-10$ eV. On the other hand, the fourth-generation neutrino perhaps has a mass of the order of a few hundred GeV. With this possibility the search for a fourth generation should be given more serious consideration in experiments to be made in future high-energy accelerators.

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[1] Y. Yanagida, in *Proceedings of the Workshop in the Unified Theory and the Baryon Number in the Universe,* edited by O. Sawada and A. Sugamoto (KEK Report No. 79-18, 1979), p. 95; M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity*, edited by P. van Nieuwenhuizen and D. Freedman (North-Holland, Amsterdam, 1979), p. 315.

[2] J. J. Simpson, Phys. Rev. Lett. **54**, 1891 (1985).

[3] F. Wilczek, Phys. Rev. Lett. **49**, 1549 (1982); G. B. Gelmini, S. Nussinov, and T. Yanagida, Nucl. Phys. **B219**, 31 (1983).

[4] S. Weinberg, in *Proceedings of the First Workshop on the Grand Unification,* edited by P. H. Frampton, S. L. Glashow, and A. Yildiz (Math Sci, Brookline, MA, 1980), p. 347.

[5] In our model one out of the n^2-1 Higgs scalars ϕ^i_j in an adjoint representation and a singlet ϕ have a light mass, and develop a vacuum expectation value at the weak-interaction scale. We can hereby avoid the unwanted flavor-changing neutral current.

[6] Negative reports were given by T. Altzitzoglou *et al.* [Phys. Rev. Lett. **55**, 799 (1985)], T. Ohi *et al.* [Phys. Lett. **160B**, 322 (1985)], V. M. Datar *et al.* [Nature (London) **318**, 547 (1985)], J. Markey and F. Boehm [Phys. Rev. C **32**, 2215 (1985)], A. Apalikov *et al.* (Pis'ma Zh. Eksp. Teor. Fiz. **42**, 233 (1985) [JETP Lett. **42**, 289 (1985)]), and D. W. Hetherington *et al.* [Phys. Rev. C **36**, 1504 (1987)]. Simpson, however, argued that these claims were not quite conclusive, and moreover reinterpreted the result by Ohi *et al.* as rather giving supporting evidence for this heavy neutrino [J. J. Simpson, Phys. Lett. **174B**, 113 (1986)]. Simpson has also repeated experiments and claims the existence of this neutrino [J. J. Simpson and A. Hime, Phys. Rev. D **39**, 1825 (1989); A. Hime and J. J. Simpson, *ibid.* **39**, 1837 (1989)].

[7] B. Sur *et al.*, Phys. Rev. Lett. **66**, 2444 (1991).

[8] The results of the recent solar-neutrino experiments at Homestake [K. Lande, in Proceedings of "Neutrino 90," Geneva, 1990 (to be published)] and at Kamioka [K. S. Hirata *et al.*, Phys. Rev. Lett. **65**, 1297 (1990)], if these two data sets are combined, strongly suggest some unusual neutrino properties rather than the modification of the astrophysical model of the Sun [see J. Bahcall, Princeton University Report No. IASSNS-AST 90/30, 1990 (to be published); M. Fukugita and T. Yanagida, Institute for Theoretical Physics, Santa Barbara, Report No. NSF-ITP-91-07, 1991 (to be published)]. In this view, we consider that a model of neutrinos should include the possibility of explaining the solar-neutrino problem.

[9] See also M. J. Dugan *et al.* [Phys. Rev. Lett. **54**, 2303 (1985)]. In this model the heavy neutrino is of the pseudo Dirac type and one neutrino remains strictly massless. There is also a possibility that the constraint from neutrinoless double-β decay is satisfied within the simple Majorana-neutrino model. In this case we necessarily have $m_{\nu_e} < m_{\nu_\tau} \simeq 17$ keV $< m_{\nu_\mu}$ [M. Fukugita and T. Yanagida, Prog. Lett. (Kyoto) **85**, L437 (1991)]. Both of these models are unattractive from the solar-neutrino-problem viewpoint.

[10] M. Fukugita and T. Yanagida, Phys. Rev. Lett. **55**, 2645 (1985). In this paper, the constraints $v \geq 4\times10^9$ GeV and $v \geq 3\times10^{10}\delta$ GeV were derived from $\mu \rightarrow e+\chi$ and $K \rightarrow \pi+\chi$ decays, where δ is an unknown parameter $(0 \leq \delta \leq 1)$. Since then the experimental situation has changed little, and these constraints still apply to the family-symmetry-breaking scale v.