Neutrino masses in superstring theories

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The problem of neutrino masses is analyzed in a supersymmetric SO(10) model obtained from a (2,0) compactification of an $E_8 \times E_8$ heterotic string. The estimates found for the neutrino masses explain experimental data on the flux of solar neutrinos.

Recent measurements of the flux of solar neutrinos provide evidence that neutrinos have a nonzero mass.[1,2] The deficiency of solar neutrinos can be explained in terms of long-wave oscillations of neutrinos in vacuum if the difference between the squares of the neutrino masses is, in order of magnitude, $\Delta m^2 \sim 10^{-10}$ eV^2. Alternatively, it can be explained[3–5] in terms of neutrino oscillations in the sun if $\Delta m^2 \sim (0.3\text{–}5.0) \times 10^{-5}$ eV^2.

As we know, in the SO(10) grand unified model it is possible to generate small neutrino masses by the so-called seesaw mechanism.[6] If mixing is ignored in this case, the mass of the electron neutrino is $m_\nu = m^2/M_R$, where m is the mass of the u quark, and M_R is on the order of the scale of the breaking of the SO(10) subgroup $G = SU(4) \times SU(2)_L \times SU(2)_R$, if this breaking is carried out with the help of the vacuum expectation value of the scalar field in the $\underline{126}$ SO (10) representation. There is a corresponding case for the second and third generations. For models found from superstrings, however, there are no scalar fields in the $\underline{126}$ representation. In this case G can be broken with the help of a vacuum expectation value of the scalar field in the $\underline{16}$ SO(10) representation. Again in this case it is possible to obtain small masses for neutrinos by incorporating radiation corrections.[7] A problem arises for supersymmetric models, since the radiative corrections are small in this case.[8] Here we need to take into account the terms stemming from unrenormalizable interactions, which can arise in superstring theories.[9]

A supersymmetric SO(10) model with three generations of fermions was proposed in Refs. 10 and 11. It was obtained from a (2, 0) compactification of a heterotic string. In this model, massless chiral superfields are classified in terms of the SO(10) representations. These superfields are of the form

$$n \cdot \underline{16} + \delta(\underline{16} + \underline{\overline{16}} + \epsilon \cdot \underline{10} + \delta \cdot \underline{1}, \qquad (1)$$

where n is the number of generations of fermions ($n=3$), and δ and ϵ are natural numbers satisfying $\delta, \epsilon \geqslant 1$. The breaking of SO(10) to G occurs dynamically here (the Osotani mechanism).[11]

Let us examine the problem of neutrino masses in this model. In the simplest case, $\epsilon = \delta = 1$, we have only a single SO(10) singlet. The 7×7 mass matrix for the three left-hand neutrinos (ν_e, ν_μ, ν_τ), the three right-hand neutrinos (ν_e^c, ν_μ^c, ν_τ^c), and the singlet is of the form

$$\mathscr{M}=\begin{pmatrix} M_L & M_D & 0 \\ M_D & R & V_G \\ 0 & V_G & M_x \end{pmatrix}. \tag{2}$$

Here M_L is the 3×3 mass matrix of the left-hand neutrinos, R is the 3×3 mass matrix of the right-hand neutrinos, V_G is a column vector of dimensionality 3 corresponding to the mixing of the right-hand neutrinos and the singlet, M_x is the mass of the singlet, and M_D is a 3×3 Dirac mass matrix, which is assumed to be equal to the mass matrix of the up quarks. The terms in V_G, M_X, and M_D arise from terms in the superpotential:[8,9]

$$\lambda_1 FF'h+\lambda_2 HF'X+\lambda_3 X^3, \tag{3}$$

where F is the (4, 2, 1) representation of G and includes, for the first generation of fermions, a left-hand neutrino, the electron, and the u and d quarks; F' is the ($\bar{4}$, 1, 2) representation and includes a right-hand neutrino, $\bar{u}$, $\bar{d}$, and the positron; H is a Higgs field in the (4, 1, 2) representation, whose vacuum expectation value is associated with the breaking of G to $G_0=\mathrm{SU}(3)_C\times\mathrm{SU}(2)_L\times\mathrm{U}(1)_Y$; and, finally, h is the (1, 2, 2) representation, which is associated with the breaking of G_0 to $\mathrm{SU}(3)_C\times\mathrm{U}(1)_{e,m}$.

The mass matrices M_L and R could arise only from unrenormalizable interactions, which are possible in superstring theories. Specifically, M_L could arise from an $FFHHhh/M_S^3$ interaction, and R from an $F'F'HH/M_S$ interaction,[8,9,12,13] where M_S is a scale associated with the strings.

An analysis of the equations of the renormalization group carried out in Ref. 11 for the set of chiral superfields in (1) yields an estimate of the scale of the breaking of G: $M_G\sim(2\times 10^{15}–2.2\times 10^{16})$ GeV. The scale associated with grand unification, in contrast, in close to the string scale, $M_S\sim 2.4\times 10^{18}$ GeV. Consequently, SO(10) is not a real symmetry of grand unification.[11]

After diagonalizing matrix (2), we obtain seven Majorana neutrinos, three of which must be light. We can estimate the masses of the light neutrinos without fixing the form of mass matrix (2). Our sole assumption is as follows: All the matrix elements of matrix (2) are on the same order of magnitude. The same assertion must hold for the matrix R and for V_G separately. These quantities are given in order of magnitude by

$$(M_L)_{ij}\sim m_L\sim M_W^2 M_G^2/M_S^3\sim(3\times 10^{-21}–3.5\times 10^{-19})\ \text{GeV},$$

$$R_{ij}\sim M_R\sim M_G^2/M_S\sim(1.6\times 10^{12}–2.0\times 10^{14})\ \text{GeV},$$

$$V_i\sim M_G\sim(2.0\times 10^{15}–2.2m\sim 10^{16})\ \text{GeV},$$

$$M_X\sim M_W;\quad i,j=1,2,3. \tag{4}$$

In this case it is a simple matter to derive estimates for the determinant of matrix (2) and also for the largest determinants of its 6×6, 5×5, and 4×4 submatrices:

$$\det M \sim m_C^2 m_t^2 m_L^2 M_G^2, \quad \det M_6 \sim m_C^2 m_t^2 M_G^2,$$

$$\det \mathscr{M}_5 \sim m_t^2 M_R^2 M_G^2, \quad \det \mathscr{M}_4 \sim M_G^2 M_R^2. \tag{5}$$

Clearly, two heavy neutrinos have a mass on the order of M_G, and two others have a mass on the order of M_R.

For the light neutrinos we find

$$m_{\nu1} \sim \det \mathscr{M} / \det \mathscr{M}_6 \sim m_L \sim (3\times10^{-12}\text{–}3.5\times10^{-10}) \text{ eV},$$

$$m_{\nu2} \sim \det \mathscr{M}_6 / \det \mathscr{M}_5 \sim m_C^2/M_R \sim (10^{-5}\text{–}1.4\times10^{-3}) \text{ eV},$$

$$m_{\nu3} \sim \det \mathscr{M}_5 / \det \mathscr{M}_4 \sim m_t^2/M_R \sim (0.1\text{–}14) \text{ eV}.$$

These estimates are of course valid only in order of magnitude. We see that the difference between the squares of the masses of the two lightest neutrinos is on the order of 10^{-10}–2×10^{-6} eV^2. On the other hand, as we have already mentioned, the deficiency of solar neutrinos can be explained in terms of long-wave oscillations of neutrinos in vacuum if the difference between the squares of the neutrino masses is on the order of 10^{-10} eV^2. That conclusion agrees with our results. The largest difference between square masses, 2×10^{-6} eV^2, is close to the value which would be required in order to explain the deficiency in terms of neutrino oscillations in the sun,[3-5] $\Delta m^2 \sim (3\times10^{-6}\text{–}5\times10^{-5})$ eV^2.

The estimates of the neutrino masses found in the model of this letter thus make it possible to explain the deficiency of solar neutrinos in a natural way. Questions associated with the mixing of neutrinos and mass renormalization effects will be discussed in another paper.

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