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The Simplest Scheme With Massive Neutrinos

C. Jarlskog

CERN - Geneva

and

Department of Physics, University of Stockholm
Stockholm, Sweden

ABSTRACT

The simplest possible extension of the "Minimal Three-Family Standard Model", where a single right-handed neutrino is added to the matter content of the Model, is analyzed in some detail. The scheme has two massless and two massive Majorana neutrinos. A convenient parametrization of the lepton mixing matrix is proposed and all couplings of the neutrinos are calculated. It is found that the effective number of neutrinos, as determined by neutrino counting at the Z-peak, is bounded by three.

Dedicated to Torleif Ericson, on the occasion of
his and the neutrino hypothesis sextennial anniversaries

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1. Introduction

One of the most interesting questions in physics is: are the neutrinos massive or not? If they are massless, we would like to know the reason and if not we would like to know and understand their masses. Indeed the question of neutrino mass is as old as the neutrino hypothesis itself, i.e., 60 years old. In his revolutionary letter, dated Dec. 4, 1930, where Pauli [1] introduced the neutrino (then called the neutron) hypothesis, he noted that it cannot have a large mass: "the mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass". In 1933, Perrin [2] realized that the neutrino is small and that the data were consistent with neutrino mass being zero. Fermi [3], in his monumental paper of 1934, came to the same conclusion. He noted that "the theoretical curve for vanishing neutrino mass shows the greatest resemblance to the experimental curves". (Of course, zero mass, at that time, was very different from what we would call consistent with zero. In fact, Bethe and Bacher [4], in their extended review article of 1936, concluded that "a very small mass of the neutrino, up to about $1/5$ of the electron mass, would, however, seem tolerable in the light of the present evidence". The first "precision measurements" of the neutrino mass, using tritium decay, were done much later, in the late 1940's, and established [5] the upper limit of about 1 KeV.

The issue of the neutrino mass was an open one until the discovery [6] of violations of parity and C-conjugation symmetries in 1956-1957. Subsequently, one began to strongly favour the hypothesis [7] of massless neutrino. The reason was that the observed maximal violations of P and C symmetries, in β -decay, could easily be understood if the neutrino were a two-component and thereby a massless object. It was also argued that the requirement of simplicity called for massless neutrinos because then the allowed structure of operators responsible for β -decay greatly simplified. In addition, the two-component hypothesis could easily explain the absence of double β -decay. What was not clear was why the hadronic currents (which did not at all involve the neutrino) were

also maximally P and C violating.

Much has happened since the 1950's. In a nutshell, the most important development, relevant to the issues to be discussed here, is that we now have a "Standard Model" [8] which we take very seriously. Furthermore, we know that there are at least three different kinds of neutrinos in Nature. The recent "neutrino-counting" measurements at the Z-peak are consistent with the existence of only 3 neutrino species, provided that one assumes the validity of the minimal version of the Standard Model, which, by definition, excludes right-handed neutrinos.

It is interesting to note that, in the Standard Model, the issues of maximal violations of P and C symmetries and the neutrino mass are separate. The charged currents are, by assumption, purely left-handed. The neutrino could be massless or massive, depending on whether one "introduces" right-handed neutrinos or not. Again, by invoking simplicity, one could argue that there should be no right-handed neutrinos in nature, whereby the neutrinos would be massless. However, by making such an assumption, one is giving up any hope of ever understanding the neutrino mass and its nature. After all, neutrino, being a neutral lepton, is the only known fermion which could be truly neutral, i.e., its own antiparticle (Majorana neutrino [9]).

The question of neutrino mass has been much studied in the past, both experimentally and theoretically. The experimental investigations have involved direct measurement of the mass, looking for neutrino oscillations which were proposed [10] long ago, in analogy with $K^0 - \bar{K}^0$ oscillations [11], and for double β -decay [12]. The observations of neutrinos from the supernova, SN1987A, and solar neutrinos have also provided a great deal of information. On the theoretical side, there is a wealth of literature on models for neutrino masses. Many of these models were inspired by the Grand Unified Theories. For an extensive list of references the reader may consult the review articles listed under [13] as well as the Proceedings of the Neutrino Conferences and of the Moriond Meetings on neutrinos. In this paper, we consider the simplest possible extension of the

2. The Simplest Scheme and its Lagrangian

The scheme to be studied in this paper is based on the following assumptions

1. We shall assume the validity of the Standard Model with three families of quarks and leptons (with usual quantum numbers, i.e., left-handed doublets and right-handed singlets) supplemented with the usual Higgs doublet.

2. We shall assume that, in addition to the above matter fields, there exists just a *single* right-handed neutrino.

Note that right-handed neutrinos (i.e., particles which are singlets, under both the SU(2) and the U(1) symmetry groups of the Standard Model) are common inhabitants in many models. Often, one introduces three right-handed neutrinos because of the "prejudice" that the number of the left-handed and right-handed neutrinos should be equal. The analysis then becomes very complicated and one must make further assumptions to be able to compare with data. The most popular assumption, in the past, has been the effective one-family see-saw model, where the interfamily cross-talk is neglected. The present status of these models is reviewed, for example, in [1-4]. However, one should keep in mind that in the Standard Model the right-handed neutrinos are not at all related to the left-handed neutrinos. There is a priori no reason why the number of right-handed and left-handed neutrinos should be equal. In principle, there is nothing wrong with having, e.g., three left-handed neutrinos and an arbitrary number of right-handed ones. In the absence of a compelling dynamical model, for massive neutrinos, one should take the above simplest scheme very seriously. The above scheme is, also of pedagogical value, because one can work out the details explicitly and gain a good understanding of what is going on. It turns out that, for example, one of the most interesting features of the scheme, concerning neutrino-counting at the Z-peak, can be generalized to an arbitrary number of families and of right-handed neutrinos [15].

The matter fields, in the leptonic sector of the scheme to be discussed, are

$$\begin{pmatrix} \nu'_{jL} \\ l'_{jL} \end{pmatrix}, \quad l'_{jR}, \quad \nu'_{jR}, \quad j = 1, 2, 3 \quad (1)$$

The primes, on the matter fields, denote that these fields are not yet the physical ones. The leptonic Lagrangian is of the form

$$L = L(W) + L(Z) + L(H, l) + L(H, \nu) + L(l - mass) + L(\nu - mass) \quad (2)$$

Here $L(W)$ is the charged current piece. It is proportional to the factor

$$C.C. \equiv \sum_{j=1}^3 \bar{\nu}'_{jL} \gamma^\lambda l'_{jL} W_\lambda + h.c. \quad (3)$$

The piece in $L(Z)$ which contains the neutrino fields is proportional to

$$N.C. \equiv \sum_{j=1}^3 \bar{\nu}'_{jL} \gamma^\lambda \nu'_{jL} Z_\lambda \quad (4)$$

The quantity $L(H)$ will be discussed later. The next term, in Eq. (2), contains the mass matrix for the charged leptons. We do not know what it looks like but we know that it can be gedanken diagonalized by unitary transformations, viz.,

$$l' \equiv \begin{pmatrix} l'_1 \\ l'_2 \\ l'_3 \end{pmatrix} = U \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} \equiv U E \quad (5)$$

where we have suppressed the helicity indices, l, and R. U denotes a unitary matrix. Substituting Eq. (5) into Eq. (3) gives

$$C.C. = \sum_{j=1}^3 \sum_{k=1}^3 \bar{\nu}'_{jL} (U^\dagger)_{jk} \gamma^\lambda E_{kL} W_\lambda + h.c. \quad (6)$$

Thus, we may redefine the left-handed neutrino fields by taking

$$\nu''_{jL} = \sum_{k=1}^3 U_{jk} \nu'_{kL}, \quad j = 1, 2, 3 \quad (7)$$

Again the double prime indicates that the neutrino fields are still not the physical ones.

We can now rewrite every term in the Lagrangian of Eq. (2) in the above basis, where the charged lepton mass matrix is diagonal and the leptonic mixing matrix is just unity, i.e., $\nu_{1L}^{\prime\prime}$ couples only to the electron, $\nu_{2L}^{\prime\prime}$ couples only to the muon, and so on. The neutral current factor, N^C , in Eq. (4), has the same form in the new bases as in the old basis, i.e., it is diagonal in neutrino flavours. Now we turn to the neutrino mass term $I(\nu - mass)$. The most general form of this term, in the new basis, is

$$I(\nu - mass) = - \sum_{j=1}^3 \overline{a_j \nu_{jL}^{\prime\prime}} \nu_R^{\prime} - \frac{M}{2} \overline{\nu_R^{\prime C}} \nu_R^{\prime} + h.c. \quad (8)$$

Note that the a_j come from the non-diagonal interactions of the left-handed and the right-handed neutrinos with the Higgs doublet. M is the self-coupling of the right-handed neutrino. It is there because we have no right to forbid it. The right-handed neutrino is a singlet and does not need the Higgs to acquire mass. This term is similar to the electron mass term in QED or the quark mass terms in QCD. Mass terms of the kind $\overline{\nu_L^{\prime\prime}} \nu_R^{\prime C}$ are, on the other hand, forbidden in the Standard Model. All the four arbitrary constants, appearing in Eq. (8), may be taken to be real and positive, by appropriate choices of the phases of the four neutrino fields. Of course, in order to keep the charged current factor and the charged lepton mass matrices in their previous form we must also replace the left-handed and the right-handed charged lepton fields. Equation (8) can be rewritten in the form

$$I(\nu - mass) = - \frac{1}{2} \overline{N} \begin{pmatrix} 0 & 0 & 0 & a_1 \\ 0 & 0 & 0 & a_2 \\ 0 & 0 & 0 & a_3 \\ a_1 & a_2 & a_3 & M \end{pmatrix} N^C + h.c. \quad (9)$$

Here

$$N = \text{col}(\nu_{1L}^{\prime\prime}, \nu_{2L}^{\prime\prime}, \nu_{3L}^{\prime\prime}, \nu_R^{\prime C})$$

and we have used the identity $\overline{\nu_{jL}^{\prime\prime}} \nu_R = \overline{\nu_R^{\prime C}} \nu_{jL}$. Finally, the term $I(H, \nu)$, in Eq. (2),

is given by

$$I(H, \nu) = - \frac{H}{2v} \overline{N} \begin{pmatrix} 0 & 0 & 0 & a_1 \\ 0 & 0 & 0 & a_2 \\ 0 & 0 & 0 & a_3 \\ a_1 & a_2 & a_3 & 0 \end{pmatrix} N^C + h.c. \quad (10)$$

3. Neutrino Masses and Mixings

The mass matrix, in Eq. (9), is real and symmetric. Hence it is easily diagonalized. We shall denote the four physical states by ν_1 , ν_2 , ν_P and ν_F , respectively. The first two are massless [16] and the other two, ν_P and ν_F are massive Majorana neutrinos. Their masses are given by

$$m(\nu_P) = \frac{1}{2}(\sqrt{M^2 + 4a^2} - M), \quad m(\nu_F) = \frac{1}{2}(\sqrt{M^2 + 4a^2} + M) \quad (11)$$

where

$$a^2 = a_1^2 + a_2^2 + a_3^2 \quad (12)$$

Rewriting the term C^C , Eq. (6), in terms of the physical fields yields the lepton mixing matrix, V , which we will take to be 4 by 4 [see after Eq. (15)]. This matrix is of the form

$$V = \Phi R \quad (13)$$

where Φ is a diagonal phase matrix and R is an orthogonal matrix. The matrix Φ can be taken to be

$$\Phi = \text{diag}(1, 1, i, 1) \quad (14)$$

The presence of the i , in the above equation, may look strange but it is not. Such phases have been known to appear in models and their physical significance is understood [17]. The technical reason for its appearance is simply because one of the eigenvalues of the mass matrix, in Eq. (9), is negative ($-m(\nu_P)$). However, we are used to working with positive masses. Therefore, we remove the negative sign, in the mass, by multiplying our diagonalized mass matrix with the phase matrix Φ both from the left and the right.

Then all masses are non-negative but the matrix Φ will appear as a factor in the lepton mixing matrix. For most processes, when we compute the rates, only the moduli of the elements of the lepton mixing matrix enter and the i in Φ is irrelevant. However, that is not always true. For example, in double β -decay, the amplitudes due to ν_P and ν_F exchanges interfere. Then we are not allowed to leave out the relative phase of the two amplitudes, as we shall see below.

The next essential point to note is that ν_1 and ν_2 are massless and indistinguishable. We may rotate in the "space" spanned by the two massless neutrinos as we wish and define arbitrary orthogonal linear combinations of them as our new fields. For example, we may define the linear combination of ν_1 and ν_2 which couples to the electron as our new ν_1 . Then, by definition, the neutrino carrying index 2 does not couple to the electron. For some phenomenological considerations it may be more convenient to define the ν_1 such that it does not couple to the muon or to the tau. Such definitions will amount to permutations of the columns of the lepton mixing matrix adopted below. Defining ν_1 to be the linear combination which does not couple to the electron we find that the lepton mixing matrix V appears in the charged currents in the following form

$$C.C. = (\overline{\nu_1}, \overline{\nu_2}, \overline{\nu_3}) \gamma^\lambda \Phi \begin{pmatrix} c_\beta & -s_\beta s_\gamma & -s_\beta c_\gamma & 0 \\ 0 & c_\gamma & -s_\gamma & 0 \\ c_\alpha s_\beta & c_\alpha c_\beta s_\gamma & c_\alpha c_\beta c_\gamma & -s_\alpha \\ s_\alpha s_\beta & s_\alpha c_\beta s_\gamma & s_\alpha c_\beta c_\gamma & c_\alpha \end{pmatrix} \begin{pmatrix} c_L \\ \mu_L \\ \tau_L \\ 0 \end{pmatrix} W_\lambda \quad (15)$$

where the matrix Φ was defined in Eq. (14) and c and s stand for the cosine and sine of their respective arguments. The angles α , β and γ lie in the first quadrant and are related to the parameters of the mass matrix through [see Eqs. (9) and (11)]

$$\begin{aligned} s_\alpha &= \sqrt{m(\nu_P)/[m(\nu_P) + m(\nu_F)]} \\ s_\beta &= a_1/a \\ c_\beta s_\gamma &= a_2/a \\ c_\beta c_\gamma &= a_3/a \end{aligned} \quad (16)$$

Note that we have four neutrinos but only three charged leptons. Therefore, we have extended the charged lepton column matrix, through the zero on the fourth row, in order to be able to manifestly exhibit the unitarity property of the four by four lepton mixing matrix. Thus the four parameters of this minimal scheme are three angles and one scale parameter, with the dimension of a mass, e.g., one of the two Majorana masses. If the reader would prefer to have a parametrization where, instead, one of the neutrinos does not couple to the tau, all she/he has to do is to permute the first and the third columns. Then, of course, the meaning of the angles β and γ changes, i.e., $a_3 = a s_\beta$, etc.

4 Lepton Universality and Neutrino Counting

From the above leptonic mixing matrix, it follows that the $e - \mu - \tau$ universality of the charged currents is not exact, in this scheme. For example the leptonic widths of the W are proportional to

$$\begin{aligned} R_e &= c_\beta^2 + (c_\alpha^2 x_{eP} + s_\alpha^2 x_{eF}) s_\beta^2 \\ R_\mu &= c_\gamma^2 + s_\beta^2 s_\gamma^2 + (c_\alpha^2 x_{\mu P} + s_\alpha^2 x_{\mu F}) c_\beta^2 s_\gamma^2 \\ R_\tau &= s_\gamma^2 + s_\beta^2 c_\gamma^2 + (c_\alpha^2 x_{\tau P} + s_\alpha^2 x_{\tau F}) c_\beta^2 c_\gamma^2 \end{aligned} \quad (17)$$

where the R 's denote the relative branching ratios and the x_{IP} and x_{IF} are the phase space suppression factors due to the non-vanishing masses of ν_P and ν_F , and the charged leptons,

$$x_{I\alpha} = \sqrt{\lambda(M_\alpha^2, m_I^2, m_\alpha^2)}/M_\alpha^2 \quad (18)$$

Here λ is the triangular function defined by

$$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + bc + ca) \quad (19)$$

Note that if both ν_P and ν_F are very light, universality will be automatic, due to unitarity of the lepton mixing matrix. Also, in the limit $\alpha \rightarrow 0$, ν_P becomes massless and ν_F decouples, whereby one gets the Minimal Standard Model supplemented with a non-interacting additional neutrino. Universality will also hold, again if the neutrino masses are very small, in the "democratic" configuration, i.e., when $a_1 = a_2 = a_3$. The effective one-family see-saw models are also special cases of the scheme discussed here, where one puts two of the a_j 's equal to zero and assumes the remaining one, say a_3 , is much smaller than M . In the leptonic mixing matrix, Eq. (15) that corresponds to $\beta = \gamma = 0$ and α being very small.

Now we turn to the neutral currents. The quantity N.C., Eq. (4), written in the physical basis, reads

$$N.C. = (\bar{\nu}_{1L}, \bar{\nu}_{2L}, \bar{\nu}_{PL}, \bar{\nu}_{FL}) \gamma^\lambda \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c_\alpha^2 & i c_\alpha s_\alpha \\ 0 & 0 & -i c_\alpha s_\alpha & s_\alpha^2 \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{PL} \\ \nu_{FL} \end{pmatrix} Z_\lambda \quad (20)$$

A very important property of the neutral current coupling coefficients is that

$$\sum_{\rho, \sigma} |N_{\rho\sigma}|^2 = 3 \quad (21)$$

Here $N_{\rho\sigma}$, the indices ρ and σ running from one to four, denote the elements of the above matrix. The point is that the 3, on the right hand side of Eq. (21), is simply the number of leptonic doublets. Thus, Eq. (21) conveys a very important message. Due to unitarity of the leptonic mixing matrix, the "invisible" width of the Z , in this minimal scheme, is always smaller than predicted in the Minimal Standard Model. The

introduction of the right-handed neutrino can only decrease the invisible width. In fact, the invisible width of the Z is given by

$$\Gamma(Z \rightarrow \nu's) = \Gamma_0 [1 + 1 + c_\alpha^4 x_{PF} + 2c_\alpha^2 s_\alpha^2 x_{PF} + s_\alpha^4 x_{FF}] \quad (22)$$

where the ones, in Eq. (22), represent the contributions of the massless neutrinos and the x 's are, as before, the phase space suppression factors due to nonzero neutrino masses [see Eq. (18)]. The latter are bounded by unity. Hence $\Gamma(Z \rightarrow \nu's) \leq 3\Gamma_0$. Note that since the ν_P and ν_F are Majorana neutrinos their diagonal vector couplings to the Z vanish. As is well known, that does not affect the width. In the V-A case, the V and A give equal contributions, say $1^2 + 1^2 = 2$. In the Majorana case, the magnitude of the transition is twice as large giving $2^2 = 4$, but one must divide by two because the neutrinos in the final state are identical. Finally, in the non-diagonal transition $Z \rightarrow \nu_P + \nu_F$, the axial coupling vanishes. The factor of two in front of the non-diagonal contribution, in Eq. (22), arises because there are two such terms in Eq. (20).

5. Couplings to the Higgs, CP Properties and double β -decay

Finally, we must rewrite Eq. (10) in terms of the physical fields. Doing so, we find that, as expected, the massless states decouple from the Higgs and the massive ones interact via

$$I(H, \nu) = \frac{-aH}{2v} [\sin 2\alpha (\bar{\nu}_P \nu_P + \bar{\nu}_F \nu_F) + i \cos 2\alpha (\bar{\nu}_P \gamma_5 \nu_F + \bar{\nu}_F \gamma_5 \nu_P)] \quad (23)$$

In fact, the two terms in the second parenthesis are equal, due to the Majorana nature of the neutrinos. Here, we see again that there is an i in front of the non-diagonal terms. Also in the charged currents, C.C., and the neutral currents, N.C., the non-diagonal couplings involving ν_P are purely imaginary. One sees immediately that it is possible to choose the CP phases of ν_P and ν_F such that the Lagrangian, Eq. (2), is invariant

under CP. In fact all that is needed is to assign opposite parities to the two neutrinos (for definition of the transformation properties under these symmetries see, for example [18]).

Finally, in double β -decay, in the case where the neutrinos have very small masses, the matrix element is proportional to a quantity called the effective neutrino mass, $\langle m_\nu \rangle$, defined by

$$\langle m_\nu \rangle = \left| \sum_j m_\nu V_{\nu e}^2 \right| \quad (24)$$

Using Eqs. (15), we find

$$\langle m_\nu \rangle = s_\beta^2 |c_\alpha^2 m_P - s_\alpha^2 m_F| = 0 \quad (25)$$

where we have used the first relation in Eq. (16). Evidently, similar results will hold also for double-muon and double-tau decays.

Conclusions

In this paper, we examined the simplest possible extension of the Three-Family Minimal Standard Model which gives massive neutrinos, by simply adding a right-handed neutrino to the matter fields of the Minimal Model. We believe that (in the absence of a compelling dynamical model for neutrino masses) the proposed scheme should be taken very seriously simply because it is the simplest. In this simplest scheme there are four additional parameters (three mixing angles in the lepton mixing matrix and one mass parameter). A convenient parametrization of the lepton mixing matrix was given and all the couplings of the neutrinos were computed. It was shown that the effective number of neutrinos, determined by the "invisible width" of the Z_ν , is bounded by three (the number of lepton doublets). The double β -decay is much suppressed due to the vanishing of the leading order contributions of the two massive neutrinos, if both are assumed to be very light. Furthermore, the model is CP conserving and the two massive neutrinos have opposite CP parities, as expected from general considerations

[17]. Phenomenological and cosmological restrictions, on the parameters of this scheme will be discussed elsewhere.

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