Physics Letters B 734 (2014) 64–67

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

A predictive model of Dirac neutrinos

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ARTICLE INFO

Article history:
Received 13 March 2014
Received in revised form 9 May 2014
Accepted 14 May 2014
Available online 20 May 2014
Editor: M. Cvetič

Keywords:
Dirac neutrino
Inverse hierarchy
μ–τ symmetry

ABSTRACT

Assuming lepton number conservation, hermiticity of the neutrino mass matrix and ν_μ–ν_τ exchange symmetry, we show that we can determine the neutrino mass matrix completely from the existing data. Comparing with the existing data, our model predicts an inverted mass hierarchy (close to a degenerate pattern) with the three neutrino mass values, 9.16×10^{-2} eV, 9.21×10^{-2} eV and 7.80×10^{-2} eV, a large value for the CP violating phase, $\delta = 109.63°$, and of course, the absence of neutrinoless $\beta\beta$ decay. All of these predictions can be tested in the forthcoming or future precision neutrino experiments.

1. Introduction

In the past 20 years, there has been a great deal of progress in neutrino physics from the atmospheric neutrino experiments (Super-K [1], K2K [2], MINOS [3]), solar neutrino experiments (SNO [4], Super-K [5], KamLAND [6]) as well as reactor/accelerator neutrino experments (Daya Bay [7], RENO [8], Double Chooz [9], T2K [10], NOνa [11]). These experiments have pinned down three mixing angles – θ_{12}, θ_{23}, θ_{13} and two mass squared differences $\Delta m^2_{ij} = m^2_i - m^2_j$ with reasonable accuracy [12]. However there are several important parameters yet to be measured. These include the value of the CP phase δ which will determine the magnitude of CP violation in the leptonic sector and the sign of Δm^2_{32} which will determine whether the neutrino mass hierarchy is normal or inverted. We also don't know yet if the neutrinos are Majorana or Dirac particles.

On the theory side, the most popular mechanism for neutrino mass generation is the see-saw [13]. This requires heavy right handed neutrinos, and this comes naturally in the $SO(10)$ grand unified theory (GUT) [14] in the 16 dimensional fermion representation. The tiny neutrino masses require the scale of these right handed neutrinos close the GUT scale. The light neutrinos generated via the see-saw mechanism are Majorana particles. However, the neutrinos can also be Dirac particles just like ordinary quarks and lepton.This can be achieved by adding right handed neutrinos to the Standard Model. The neutrinos can get tiny Dirac masses via the usual Yukawa couplings with the SM Higgs. In this case, we have to assume that the corresponding Yukawa couplings are very tiny, $\sim 10^{-12}$. Interesting works in Dirac neutrinos can be found in these references [15]. Alternatively, we can introduce a 2nd Higgs doublet and a discrete Z_2 symmetry so that the neutrino masses are generated only from the 2nd Higgs doublet. The neutrino masses are generated from the spontaneous breaking of this discrete symmetry from a tiny vev of this 2nd Higgs doublet in the eV or keV range, and then the associated Yukawa couplings need not be so tiny [16]. At this stage of neutrino physics, we cannot determine which of these two possibilities are realized by nature.

In this work, we show that with the three known mixing angles and two known mass difference squares, we find an interesting pattern in the neutrino mass matrix if the neutrinos are Dirac particles. With three reasonable assumptions: (i) lepton number conservation, (ii) hermiticity of the neutrino mass matrix, and (iii) ν_μ–ν_τ exchange symmetry, we can construct the neutrino mass matrix completely. It is important to note that the assumption of hermiticity is somewhat ad hoc i.e., hermiticity of neutrino mass matrix is not an outcome of symmetry argument. However, we have shown in the following that with this assumption, the existing neutrino data can completely deteirimine the mass matrix for the Dirac neutrinos with particular predictions for the neutrino masses and the CP violating phase which can be tested at the ongoing and future neutrino experiments. Therefore, in our analysis, the assumption of hermiticity of neutrino mass matrix is a purely phenomenological assumption. However, in the future, there might be some compelling theoretical framework which requires the hermiticity of neutrino mass matrix. The resulting mass

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http://dx.doi.org/10.1016/j.physletb.2014.05.036

matrix satisfies all the constraints implied by the above three assumptions, and gives an inverted hierarchy (IH) (very close to the degenerate) pattern. We can now predict the absolute values of the masses of the three neutrinos, as well as the value of the CP violating phase δ. We also predict the absence of neutrinoless double $\beta\beta$ decay.

2. The model and the neutrino mass matrix

Our model is based on the Standard Model (SM) Gauge symmetry, $SU(3)_C \times SU(2)_L \times U(1)_Y$, supplemented by a discrete Z_2 symmetry [16]. In addition to the SM particles, we have three SM singlet right handed neutrinos, N_{Ri}, $i = 1, 2, 3$, one for each family of fermions. We also have one additional Higgs doublet ϕ, in addition to the usual SM Higgs doublet χ. All the SM particles are even under Z_2, while the N_{Ri} and the ϕ are odd under Z_2. Thus while the SM quarks and leptons obtain their masses from the usual Yukawa couplings with χ with vev of ~ 250 GeV, the neutrinos get masses only from its Yukawa coupling with ϕ for which we assume the vev is $\sim$ keV to satisfy the cosmological constraints which we will discuss later briefly. Note that even with as large as a keV vev for ϕ, the corresponding Yukawa coupling is of order 10^{-4} which is not too different from the light quarks and leptons Yukawa coupling in the SM. The Yukawa interactions of the Higgs fields χ and ϕ and the leptons can be written as,

$$L_Y = y_l \bar{\Psi}_L^l l_R \chi + y_{\nu l} \bar{\Psi}_L^l N_R \tilde{\Phi} + \text{h.c.}, \tag{2.1}$$

where $\bar{\Psi}_L^l = (\bar{\nu}_l, \bar{l})_L$ is the usual lepton doublet and l_R is the charged lepton singlet, and we have omitted the family indices. The first term gives rise to the masses of the charged leptons, while the second term gives tiny neutrino masses. The interactions with the quarks are the same as in the Standard Model with χ playing the role of the SM Higgs doublet. Note that in our model, the tiny neutrino masses are generated from the spontaneous breaking of the discrete Z_2 symmetry with its tiny vev of $\sim$ keV. The left handed doublet neutrino combine with its corresponding right handed singlet neutrino to produce a massive Dirac neutrino. Since we assume lepton number conservation, the Majorana mass terms for the right handed neutrinos, having the form, $M\nu_R^T C^{-1} \nu_R$ are not allowed.

The model has a very light neutral scalar σ with mass of the order of this Z_2 symmetry breaking scale. Detailed phenomenology of this light scalar σ in context of $e + e-$ collider has been done previously [16] and also some phenomenological works have been done on the chromophobic charged Higgs of this model at the LHC whose signal are very different from the charged Higgs in the usual two Higgs doublet model [17]. There are bounds on v_ϕ from cosmology, big bang nucleosynthesis, because of the presence of extra degree of freedom compared to the SM; puts a lower limit on $v_\phi \geq 2$ eV [18], while the bound from supernova neutrino observation is $v_\phi \geq 1$ keV [19].

In this paper, we study the neutrino sector of the model using the input of all the experimental information regarding the neutrino mass difference squares and the three mixing angles. Our additional theoretical inputs are that the neutrino mass matrix is hermitian and also has ν_μ–ν_τ exchange symmetry. We find that in order for our model to be consistent with the current available experimental data, the neutrino mass hierarchy has to be inverted type (with neutrino mass values close to degenerate case). We also predict the values of all three neutrino masses, as well as the CP violating phase δ.

Table 1
The best-fit values and 1σ allowed ranges of the 3-neutrino oscillation parameters. The definition of Δm^2 used is $\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2$. Thus $\Delta m^2 = \Delta m_{31}^2 - m_{21}^2/2$ if $m_1 < m_2 < m_3$ and $\Delta m^2 = \Delta m_{32}^2 + m_{21}^2/2$ for $m_3 < m_1 < m_2$.

Parameter	best-fit ($\pm\sigma$)
$\Delta m_{21}^2 [10^{-5}\ \text{eV}^2]$	$7.53^{+0.26}_{-0.22}$
$\Delta m^2 [10^{-3}\ \text{eV}^2]$	$2.43^{+0.06}_{-0.10}$
$\sin^2\theta_{12}$	$0.307^{+0.018}_{-0.016}$
$\sin^2\theta_{23}$	$0.392^{+0.039}_{-0.022}$
$\sin^2\theta_{13}$	$0.0244^{+0.0023}_{-0.0025}$

With the three assumptions stated in the introduction, namely, lepton number conservation, hermiticity of the neutrino mass matrix, and the ν_μ–ν_τ exchange symmetry, the neutrino mass matrix can be written as

$$M_\nu = \begin{pmatrix} a & b & b \\ b^* & c & d \\ b^* & d & c \end{pmatrix}. \tag{2.2}$$

The parameters a, c and d are real, while the parameter b is complex. Thus the model has a total of five real parameters. The important question at this point is whether the experimental data is consistent with this form. Choosing a basis in which the Yukawa couplings for the charged leptons are diagonal, the PMNS matrix in our model is simply given by U_ν, where U_ν is the matrix which diagonalizes the neutrino mass matrix. Since the neutrino mass matrix is hermitian, it can then be obtained from

$$M_\nu = U_\nu \boldsymbol{M}_\nu^{diag} U_\nu^\dagger \tag{2.3}$$

where

$$\boldsymbol{M}_\nu^{diag} = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}. \tag{2.4}$$

The matrix U_ν is the PMNS matrix for our model (since U_l is the identity matrix from our choice of basis), and is conventionally written as:

$$U_\nu = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}, \tag{2.5}$$

where, $c_{ij} = \text{Cos}\,\theta_{ij}$ and $s_{ij} = \text{Sin}\,\theta_{ij}$.

3. Results

The values of three mixing angles and the two neutrino mass squared differences are now determined from the various solar, reactor and accelerator neutrino experiments with reasonable accuracy (the sign of Δm_{32}^2 is still unknown). The current knowledge of the mixing angles and mass squared differences are given by [20] Table 1.

It is not at all sure that the data will satisfy our model given by Eq. (2.2), either for the direct hierarchy or the indirect hierarchy. We first try the indirect hierarchy. In this case, the diagonal neutrino mass matrix, using the experimental mass difference squares, can be written as

$$\boldsymbol{M}_\nu^{diag} = \begin{pmatrix} \sqrt{m_3^2 + 0.002315} & 0 & 0 \\ 0 & \sqrt{m_3^2 + 0.00239} & 0 \\ 0 & 0 & m_3 \end{pmatrix}, \tag{3.1}$$

where we have used the definition of Δm^2 in the inverse hierarchy mode as referred in Table 1.

Taking these experimental values in the best-fit ($\pm\sigma$) region from Table 1, for the PMNS mixing matrix, we get from Eq. (2.5)