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## A Model for Neutrino Warm Dark Matter and Neutrino Oscillations (Postprint)

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### Abstract

The muon- and tau-neutrinos with the mass in the keV range, which are allowed in a low reheating temperature cosmology, can compose the warm dark matter of the universe. A model of four light neutrinos including the keV scale  $\mu$  and  $\nu$ ; is studied, which combines the seesaw mechanism and the Abelian flavor symmetry. The atmospheric neutrino anomaly is due to the  $\mu$  – oscillation. The solar neutrino problem is answered by the oscillation into the light sterile neutrino, where the SMA, LMA, and LOW-QVO solutions can be accommodated in our scenario.

### Full Text

### Preamble

#### A Model for Neutrino Warm Dark Matter and Neutrino Oscillations

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### Abstract

The muon- and tau-neutrinos with masses in the keV range, which are allowed in a low reheating temperature cosmology, can compose the warm dark matter of the universe. We study a model of four light neutrinos including the keV-scale  $\mu$  and  $\nu$ , which combines the seesaw mechanism and the Abelian flavor symmetry. The atmospheric neutrino anomaly is explained by  $\mu$  – oscillation. The solar neutrino problem is solved by oscillation into a light sterile neutrino,

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Cosmological studies show increasing evidence that dark matter is in fact warm—neither cold nor hot—so as to explain the observed structure and behavior of the expanding universe [1]. In particle physics, gravitinos or sterile neutrinos with masses in the keV range have been proposed as candidates for warm dark matter (WDM). In this paper, we consider the possibility that ordinary active neutrinos constitute the WDM.

Experiments have provided various constraints on the neutrino mass spectrum. From direct experimental searches, we have  $m_{\nu_1} < 2.5$  eV,  $m_{\nu_2} < 170$  keV, and  $m_{\nu_3} < 18$  MeV [2]. Additional information comes from neutrino oscillation experiments. The Super-Kamiokande (Super-K) data for the atmospheric neutrino anomaly suggest that  $\nu_\mu$  is maximally mixed with  $\nu_x$  ( $x = e$ ) with  $\Delta m^2 \sim 10^3$  eV<sup>2</sup> strongly favored [3,4]. The solar neutrino deficit [5] may imply oscillation of  $\nu_e$  into  $\nu_y$ . There are several allowed parameter regions. For example, if  $\nu_y$  is a sterile neutrino, the currently favored solution is the small mixing angle (SMA) with  $\Delta m^2 \sim 10$  eV<sup>2</sup> and  $\tan^2 \theta_{ey} \sim 10^3$ . If one experiment among Super-K, Ga, and Cl is removed from the global analysis, the large mixing angle (LMA) solution with  $\Delta m^2 \sim 10^{-10}$  eV<sup>2</sup> and the low-mass and quasi-vacuum oscillation (LOW-QVO) solution with  $\Delta m^2 \sim 10^{-10}$  eV<sup>2</sup> are also allowed. The LSND experiment has reported positive appearance results for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations, which implies  $\Delta m^2 \sim 1$  eV<sup>2</sup> and  $\sin^2(2\theta_{e\mu}) \sim 10^{-2}$  [6]. However, a large part of its parameter space is excluded by the null results of the KARMEN data [7].

One of the most stringent constraints on neutrino mass comes from cosmological considerations to avoid over-closing the universe. In standard cosmology [8], stable neutrinos should be no heavier than about 20 eV. Recently, it has been shown that if the reheating temperature  $T_{RH}$  is low, the densities of neutrinos can become much smaller than usually assumed [9,10], greatly relaxing the cosmological constraint. Indeed, for  $1$  MeV  $< T_{RH} < 3$  MeV, the abundance of tau- and muon-neutrinos is [11]

$$\Omega_{\nu_\tau} h^2 = \Omega_{\nu_\mu} h^2 = \frac{4 \text{ keV}}{m_{\nu_{\tau,\mu}}} \left( \frac{1 \text{ MeV}}{T_{RH}} \right)$$

This leads Ref. [11] to consider  $\nu_\mu$  and  $\nu_\tau$  as the WDM.

The above WDM consideration makes the neutrino mass pattern quite unique. First, the Super-K results constrain the masses of both  $\nu_\mu$  and  $\nu_\tau$  to be around the keV scale [4]. Their mass-squared difference of order  $10^3$  eV<sup>2</sup> implies that the masses of  $\nu_\mu$  and  $\nu_\tau$  are highly degenerate. In this case, the solar neutrino problem can only be understood by introducing a light sterile neutrino,  $\nu_s$ . The  $\nu_e$  (and in the large mixing case, the  $\nu_s$ ) should be lighter than of order

eV for consistency with laboratory experiments on  $m_{\nu_e}$ . The LSND result, however, cannot be compatible with the presence of keV-scale muon-neutrinos. Instead, the mixing between  $\nu_\mu$  and  $\nu_e$  must be very small, as expected from the keV-scale mass of  $\nu_\mu$  and the sub-eV-scale mass of  $\nu_e$ .

In this paper, we construct a four-light-neutrino model that yields the aforementioned neutrino mass pattern. How to construct the mass spectrum of four light neutrinos with hierarchies is a theoretically challenging problem. We extend a method proposed in Ref. [12] that simply incorporates the seesaw mechanism [13] with flavor symmetry [14]. By introducing three right-handed neutrinos and assuming singularity in both the Dirac and Majorana mass matrices, the neutrino mass matrix has approximately a block structure with two heavy neutrinos of masses  $\sim M$ , two light neutrinos of masses  $\sim m^2/M$ , and two massless neutrinos. Three mass scales— $M$ ,  $m^2/M$ , and 0—characterize this model. Thus the four light neutrinos are naturally divided into two pairs with a mass gap of  $m^2/M$ , and each pair consists of two degenerate mass eigenstates.

Abelian flavor symmetry [14] can be used to generate such a neutrino mass matrix. Furthermore, this symmetry should also provide the maximal mixing for the atmospheric neutrino anomaly, which is not guaranteed in the form of Eq. (2). A soft breaking of the symmetry is necessary to generate small masses for the two massless neutrinos and to lift the degeneracy in each pair. In the following discussion, supersymmetry is implied. The flavor symmetry is spontaneously broken by a vacuum expectation value (VEV) of an electroweak singlet field  $X$ . As long as the flavor charges balance under the symmetry, the following interactions are allowed:

$$\mathcal{L} \supset \frac{1}{\Lambda^{m_{\alpha\beta}}} L_\alpha H N_\beta + \frac{1}{\Lambda^{n_{\alpha\beta}}} M N_\alpha N_\beta$$

where  $L_\alpha$  ( $\alpha = e, \mu, \tau$ ),  $H$ , and  $N_\alpha$  denote the lepton doublets, a Higgs field, and the right-handed neutrino fields, respectively.  $\Lambda$  is the flavor symmetry breaking scale, and  $m_{\alpha\beta}$  and  $n_{\alpha\beta}$  are non-negative integers required for the holomorphy of the superpotential.

The order parameter for this new symmetry is defined by  $\langle X \rangle = X/\Lambda$ , which is typical order of the Cabibbo angle. The assignment of the Abelian flavor charges relevant to Eq. (2) and to maximal  $\nu_\mu$ - $\nu_e$  mixing is assumed to be

$$L_e(z + \frac{1}{2}), L(a), L_\tau(z + \frac{9}{2}), E_e^c(a+3), E_\tau^c(a+2), H(\frac{1}{2}), N(a), N_\tau(a), X(-1)$$

with positive integers  $a$  and  $x$  ( $x > a > 1$ ). The sign of the integer  $z$  is to be set later. The  $\hat{E}_\alpha^c$  in Eq. (5) are the anti-particle fields of the SU(2) singlet charged leptons. To obtain the physical mixing angles of neutrinos, the charged lepton mass matrix should be simultaneously taken into account. The gauge and Higgs bosons possess vanishing flavor charges. Note that the flavor charges for the first

generation are half-integers while those for the second and third generations are integers expressed by a single parameter  $a$ . Compared to analogous analyses for three-light-neutrino scenarios, the choice of flavor charges here is more limited. One tricky point is that one of the right-handed neutrino masses is made to be vanishingly small ( $\sim m^2/M$ ).

The flavor charge assignment in Eq. (5) produces the Dirac and Majorana mass matrices of neutrinos as

$$M_D = m \begin{pmatrix} Y_{11}\lambda^{x+z} & 0 & 0 \\ 0 & Y_{22}\lambda^{2a} & Y_{23}\lambda^{2a} \\ 0 & Y_{32}\lambda^{2a} & Y_{33}\lambda^{2a} \end{pmatrix}$$

and

$$M_M = M \begin{pmatrix} \zeta_1\lambda^{2x-1} & 0 & 0 \\ 0 & \zeta_2\lambda^{2a} & \zeta_3\lambda^{2a} \\ 0 & \zeta_4\lambda^{2a} & \zeta_5\lambda^{2a} \end{pmatrix}$$

and the mass matrix of charged leptons as

$$M_l = m \begin{pmatrix} \eta_{11}\lambda^5 & \eta_{12}\lambda^3 & \eta_{13}\lambda^{2a+2} \\ \eta_{21}\lambda^3 & \eta_{22}\lambda^3 & \eta_{23}\lambda^2 \\ \eta_{31}\lambda^{2a+2} & \eta_{32}\lambda^2 & \eta_{33}\lambda^2 \end{pmatrix}$$

where  $Y$ 's,  $\zeta$ 's, and  $\eta$ 's are order-one coefficients.  $M_D$  is almost diagonal, while  $M_M$  is mainly off-diagonal. Therefore, to leading order, the mass matrix of four light neutrinos in the  $(\nu_s, \nu_e, \nu_\mu, \nu_4)$  basis is obtained as

$$M_\nu \simeq \begin{pmatrix} 0 & \lambda^x/\epsilon & \lambda^{2\beta-1} & \lambda^{\beta+z} \\ \lambda^x/\epsilon & 0 & \lambda^{\beta+z} & \lambda^{\beta+z} \\ \lambda^{2\beta-1} & \lambda^{\beta+z} & 0 & 1 \\ \lambda^{\beta+z} & \lambda^{\beta+z} & 1 & 0 \end{pmatrix}$$

where the charged lepton mixing effects are incorporated so that the charged lepton fields have been rotated into mass eigenstates. In Eq. (12), combinations of order-one parameters such as  $Y_{ij}$ ,  $\zeta_i$ , and  $\eta_i$  are omitted for simplicity.

In our scenario, there is no mixing between the two pairs due to our assignment of half-integer charges for the first generation and integer charges for the second and third generations. The absence of  $\nu_e$ - $\nu_\mu$  mixing predicts null results in future laboratory searches for  $\nu_e$ - $\nu_\mu$  oscillation and has no influence on astrophysical processes [16]. The  $\nu_\mu$ - $\nu_4$  mixing is compatible with the KARMEN data, and  $M_\nu$  is automatically factorized into  $M_\nu\{\nu_s$ - $\nu_e\}$  and  $M_\nu\{\nu_\mu$ - $\nu_4\}$ .

The requirement of Super-K data determines the value of  $a$  as  $\Delta m_{23}^2 = 10^{-3} \text{ eV}^2$ , for  $a = 4$ . The effective mass matrix of  $\nu_e$  and  $\nu_s$  (in units of eV) can be written as

$$M_{\nu_s-\nu_e} \simeq m_0 \begin{pmatrix} \lambda^{2\beta-4} & \lambda^{\beta+z-3} \\ \lambda^{\beta+z-3} & 1 \end{pmatrix}$$

The case of  $\beta < z$  ( $\beta > z$ ) corresponds to the small (large) mixing angle solution for the solar neutrino problem. Some possible solutions are listed in the following table.

Solution	(x)	$m_{\nu_e}$ (eV)	$\Delta m_{23}^2$ (eV <sup>2</sup> )	$\sin^2 \theta_{23}$
SMA	3.5 (12)	–	10	$10^{-3}$
LMA	4.5 (13)	–	10	0.8
LOW-QVO	5.5 (14)	–	$10^{-1}$	0.8

These solutions will be tested in the SNO [17] and KamLAND experiments. For one of the LOW-QVO solutions, the mass of the electron neutrino is just an order of magnitude lower than the current experimental limit, making it possible to probe this value directly in future experiments. In addition, it may have observable effects in cosmic microwave background anisotropies. The  $\nu_e$  and  $\nu_s$  compose a Dirac neutrino that does not produce any observable neutrinoless double  $\beta$  decay in relevant next-generation experiments.

In summary, it would be simple if the muon- and tau-neutrinos are indeed the WDM. We have presented a neutrino model that generates keV-scale  $\nu_\mu$  and  $\nu_\tau$  while simultaneously providing neutrino oscillation solutions for solar and atmospheric neutrino experiments. The model combines the seesaw mechanism and the Frogatt-Nielsen mechanism. The key point is that the neutrino mass matrix has a singular form, and a light sterile neutrino is obtained due to the flavor symmetry.

Finally, some remarks should be mentioned. Compared to the model in Ref. [12], the light neutrino spectrum is similar to the ordinary 2+2 light neutrino scheme [18], but the two neutrino pairs are more widely separated (by keV). For the solar neutrino problem, the SMA, LMA, or LOW-QVO oscillation solutions into light sterile neutrinos can be accommodated in our scenario. This is achieved by taking the U(1) flavor charges to be half-integers for the first generation and integers for the second and third generations. Of course, the LSND results cannot be accommodated in this model, but our results are compatible with the KARMEN data.

The LMA and LOW-QVO solutions have been obtained in fact due to the singular seesaw mechanism. The singular seesaw mechanism was applied to the atmospheric neutrino anomaly in Ref. [15]; however, the current Super-K data do not favor  $\nu_s$  oscillation. What we have done in Ref. [12] and in this paper

for the LMA and LOW-QVO scenarios is to obtain a singular seesaw mechanism for solar neutrinos.

It may seem a drawback to introduce both the seesaw and Frogatt-Nielsen mechanisms to make neutrinos light. However, the seesaw mechanism itself cannot predict the neutrino flavor structure, especially the maximal  $\mu$ - $\tau$  mixing. Another motivation is to make the four-light-neutrino scenario easier to understand within the underlying framework of grand unification theories, which will be studied further.

Other interesting aspects of keV neutrinos have been discussed previously. Such neutrinos may be responsible for the large velocities of pulsars [19]. Because the neutrino densities in the early universe are much smaller than assumed in standard cosmology, the cosmological constraints on neutrinos from big bang nucleosynthesis differ from those in the standard scenario [20]. This requires more detailed study. In addition to keV active neutrinos, certain amounts of other keV sterile neutrinos [21] may also contribute to the WDM.

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