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Small Dirac Neutrino Masses and Fast Decay of The 17-KeV Neutrino

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ABSTRACT

We construct an invisible Axion model which naturally explains the smallness of Dirac neutrino masses by generating the neutrino masses at the two-loop level. This model also provides a qualitative explanation for the fermion mass hierarchy $m_t \gg m_b, m_\tau \gg m_\nu$. The implications of a possible 17-KeV neutrino are discussed. In particular a 17-KeV heavy neutrino can have a cosmologically safe fast decay through $\nu_{heavy} \rightarrow \nu_{light} + Axion$.

A very interesting question of particle physics is whether neutrinos have non zero masses. The experimental bounds from particle physics on the masses of different neutrinos are [1] $m_{\nu_e} < 17$ eV, $m_{\nu_\mu} < 270$ KeV, and $m_{\nu_\tau} < 35$ MeV. There are more stringent bounds from SN1987A [2]. If neutrinos have masses, do they have Dirac- or Majorana-type masses or both? It was claimed in 1985 by Simpson [3] that the study of the β decay of tritium indicates that the electron neutrino is mixed with a heavy neutrino of mass around 17-KeV and a mixing angle θ of approximately 0.1. Several other groups gave negative results [4]. However, there are new experiments [5] which support Simpson's claim. If the interpretation of the experimental data is correct, there are interesting constraints on neutrino properties. The 17-KeV neutrino cannot be the muon neutrino according to experiments on neutrino oscillations [6]. Experimental results from LEP [7] and constraints from ^4He abundance of the universe [8] have determined the number of neutrinos whose masses are small, compared with $m_Z/2$, to be 3. The heavy neutrino must be the τ neutrino. The properties of this 17-KeV neutrino would be a indication that neutrinos should have Dirac masses. This is because if the neutrinos are Majorana ones, it is possible to have neutrinoless double β decay and the decay rate is proportional to the effective electron neutrino mass $|U_{ee}^2 m_{\nu_e} + U_{e\mu}^2 m_{\nu_\mu} + U_{e\tau}^2 m_{\nu_\tau}|$, where U_{ij} are the mixing matrix elements. Experiments have put the upper limit for the effective electron neutrino mass to be less than 5.6 eV [9], while the data from the 17-KeV neutrino would imply an effective mass of 170 eV for the electron neutrino. This is an order of magnitude larger than the experimental upper bound. It may be that there are two 17-KeV neutrinos with opposite CP parities such that their contributions to the effective electron neutrino mass cancels. This possibility has been studied in Ref. [10]. This model offers no solution to the solar neutrino problem either by the MSW mechanism [11] or the VVO mechanism [12]. It may be that there are right handed neutrinos. In this case it is possible to have Majorana neutrino masses for the first two generations of neutrinos while the 17-KeV neutrino is almost a Dirac neutrino. The first two neutrinos have a suitable range of masses and mixings for the MSW solution to the solar neutrino problem. This has been investigated in Ref. [13]. One needs to understand why some of the neutrinos are almost Majorana neutrinos and others are almost Dirac ones. This has been further studied in Ref [14]. If the neutrinos are not purely Majorana neutrinos, the next simplest possibility is that all neutrinos are Dirac ones. In this letter, we consider the scenario that all neutrinos are Dirac neutrinos. The discussion in the following can be independent of the 17-KeV neutrino. However we find the properties of the 17-KeV neutrino to be very interesting and we will discuss its implications in our model. It is natural to ask why, if the neutrinos are Dirac

ones, their masses are so much smaller than the masses of their charged lepton partners. For Majorana neutrinos, the 'See-Saw' mechanism provides a natural explanation which is not possible for Dirac neutrinos. To explain the smallness of Dirac neutrino masses, one is led to propose that neutrino masses are generated by loop corrections [15]. In fact, there is a hierarchical structure in the fermion spectrum, namely $Mass(up - quark) \gg Mass(down - quark, charged - lepton) \gg mass(neutrinos)$ (except for d and u quark masses). Are there reasons for this hierarchy? Is this hierarchy related to the small Dirac neutrino masses? The hierarchy of $Mass(up - quark) \gg Mass(down - quark)$ has been discussed in Ref. [16]. This hierarchical structure can be qualitatively explained by the following: the up-quarks obtain their masses at the tree level, the down-quarks and the charged leptons obtain their masses at the one loop level whereas neutrinos obtain their masses at the two loop level. In this way the small Dirac neutrino masses are related to the fermion mass hierarchical pattern mentioned above. If there is a neutrino which has a mass of order 17-KeV, it must decay fast enough such that it would not contradict the cosmological bound on unstable neutrinos which requires a 17-KeV neutrino to have a lifetime τ less than $10^{14}(s)$ [17]. It is well known that the photon decays of heavy neutrinos are not fast enough to satisfy the cosmological bound [18]. Some other decay mechanisms must be explored. Since neutrinos are much lighter than other ordinary fermions in the theory, the neutrino must decay into some new particles which are massless or almost massless. There are two well known such particles, the Majoron and the Axion. Since the neutrinos are Dirac particles in our theory, there is no spontaneous global lepton number breaking and therefore no Majoron. This leaves the possibility that the heavy neutrino must decay with an Axion in the final state. In the following we will construct a model which accommodates the above ideas.

The gauge symmetry of the model is $SU(3)_C \times SU(2)_L \times U(1)_Y$. On top of this we impose the Peccei-Quinn symmetry [19] which is necessary to supply an Axion. Of course we have the bonus of solving the strong CP problem. In order not to contradict experimental constraints on Axion properties, the Axion must be an invisible one. It is also well known[19] that if there is only one Higgs doublet in a theory with PQ symmetry, not all particles can receive masses at the tree level from spontaneous symmetry breaking. This can be used to incorporate the idea that at tree level only up-quarks obtain their masses. Of course we have to find a mechanism which will generate other fermion masses. In our model, this is achieved by the introduction of a pair of di-quark scalars η_1, η_2 and a pair of lepto-quark scalars ω_1, ω_2 . The particle contents and their quantum numbers under the symmetry group are given as follows:

Fermions:

$$Q_L : (3, 2, 1/6)(-1), \quad u_R : (3, 1, 2/3)(1), \quad d_R : (3, 1, -1/3)(1), \\ l_L : (1, 2, -1/2)(2), \quad e_R : (1, 1, -1)(-2), \quad \nu_R^e, \nu_R^\mu : (1, 1, 0)(-2), \quad \nu_R^\tau : (1, 1, 0)(0).$$

Scalars:

$$H : (1, 2, -1/2)(-2), \quad S : (1, 1, 0)(2), \quad \eta_1 : (3, 1, -1/3)(2), \quad \eta_2 : (3, 1, -1/3)(-2), \\ \omega_1 : (\bar{3}, 1, 1/3)(-1), \quad \omega_2 : (\bar{3}, 1, 1/3)(1).$$

where the numbers in the first bracket are the gauge group quantum numbers corresponding to $SU(3)_C$, $SU(2)_L$, and $U(1)_Y$ respectively and the numbers in the second bracket are the quantum numbers for the $U(1)_{PQ}$ global symmetry. Notice the different assignments of PQ charges for different neutrinos. This is crucial for fast neutrino decays. The point is that in order for the Axion to have off-diagonal couplings to neutrinos, it is necessary that the vacuum expectation values (VEVs) which break the PQ symmetry should also break the generational neutrino numbers. The Yukawa couplings consistent with the symmetry group are given by

$$L_Y = -\lambda_{ui} \bar{Q}_{Li} u_{Ri} H + \lambda_{ij}^{QQ} \bar{Q}_L^C Q_L \eta_1 + \lambda_{ij}^{UD} \bar{u}_{Ri}^C d_{Rj} \eta_2 + \lambda_{ij}^{QL} \bar{Q}_L^C l_{Lj} \omega_1 \\ + \lambda_{ij}^{Ue} \bar{u}_{Ri}^C e_{Rj} \omega_2 + \lambda_{ie}^{D\nu} \bar{d}_{Ri}^C \nu_R^e \omega_2 + \lambda_{i\mu}^{D\nu} \bar{d}_{Ri}^C \nu_R^\mu \omega_2 + \lambda_{i\tau}^{D\nu} \bar{d}_{Ri}^C \nu_R^\tau \omega_1, \quad (1)$$

and the scalar potential is

$$V = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + H^\dagger H (\lambda_S S^\dagger S + \lambda_{\eta_\alpha} \eta_\alpha^\dagger \eta_\alpha + \lambda_{\omega_\alpha} \omega_\alpha^\dagger \omega_\alpha) \\ - \mu_S^2 S^\dagger S + \delta_S (S^\dagger S)^2 + S^\dagger S (\delta_{\eta_\alpha} \eta_\alpha^\dagger \eta_\alpha + \delta_{\omega_\alpha} \omega_\alpha^\dagger \omega_\alpha) \\ + \mu_{\eta_\alpha}^2 \eta_\alpha^\dagger \eta_\alpha + \gamma_{\eta_{\alpha\beta}} (\eta_\alpha^\dagger \eta_\beta) (\eta_\beta^\dagger \eta_\alpha) + \gamma_\eta \eta_1^\dagger \eta_2 S^2 + H.C. + \gamma_{\eta\omega_{\alpha\beta}} \eta_\alpha^\dagger \eta_\alpha \omega_\beta^\dagger \omega_\beta \\ + \mu_{\omega_\alpha}^2 \omega_\alpha^\dagger \omega_\alpha + \gamma_{\omega_{\alpha\beta}} (\omega_\alpha^\dagger \omega_\beta) (\omega_\beta^\dagger \omega_\alpha) + \gamma_\omega \omega_1^\dagger \omega_2 S^\dagger + H.C., \quad (2)$$

where $i, j = 1, 2, 3$ are flavour indices and $\alpha, \beta = 1, 2$. We have written the Yukawa couplings in the basis where the couplings of the up-quarks to the Higgs H are diagonal. Notice that the coupling λ_{ij}^{QQ} is symmetric under exchange of i and j . H and S can develop VEV's v and v_1 , $H^T = (v + \frac{Re H^0 + i Im H^0}{\sqrt{2}}, H^-)$ and $S = v_1 + \frac{Re S + i Im S}{\sqrt{2}}$. The symmetry is broken by the VEV's down to $U(1)_{em}$. $Im H^0$ is the Goldstone boson "eaten" by Z^0 and $Im S$ becomes the Axion field A . It is clear that after symmetry breaking, at the tree level only the up-quarks have obtained masses while other fermions are still massless. The down quark and the charged lepton masses will be generated at the one loop level. The diagrams responsible for the down-quark and charged lepton mass generations are shown in Figs. 1

and 2. Neutrino masses are generated by two two loop diagrams which are shown in Fig. 3. In the basis $\bar{F}_R M_F F_L$, we have for the mass matrices,

$$M_u = \lambda_{ui} v ;$$

$$M_d = \frac{2\gamma_\eta v_1^2}{m_{\eta_1}^2 - m_{\eta_2}^2} \ln(m_{\eta_1}^2/m_{\eta_2}^2) \frac{\lambda_{lj}^{*UD} m_l^u \lambda_{li}^{QQ}}{8\pi^2} ,$$

$$M_l = \frac{2\gamma_\omega v_1}{m_{\omega_1}^2 - m_{\omega_2}^2} \ln(m_{\omega_1}^2/m_{\omega_2}^2) \frac{\lambda_{lj}^{*Ul} m_l^u \lambda_{li}^{Ql}}{32\pi^2} , \quad (3)$$

$$M_\nu = M_1 + M_2 ,$$

where M_1 and M_2 are due to Figs. 3a and 3b respectively and are given by,

$$M_1 = \frac{2\gamma_\omega v_1}{m_{\omega_1}^2 - m_{\omega_2}^2} \frac{\ln(m_{\omega_1}^2/m_{\omega_2}^2)}{32\pi^2} \lambda_{k(e,\mu)}^{*D\nu} M_{dlk}^* \lambda_{li}^{Ql} = \begin{pmatrix} x_{11} & x_{12} & x_{13} \\ x_{21} & x_{22} & x_{23} \\ 0 & 0 & 0 \end{pmatrix} ,$$

$$M_2 = \frac{I(2)_l - I(1)_l}{\ln(m_{\eta_1}^2/m_{\eta_2}^2)} \frac{\lambda_{k\tau}^{*D\nu} M_{dlk}^* \lambda_{li}^{Ql}}{16\pi^2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ x_{31} & x_{32} & x_{33} \end{pmatrix} , \quad (4)$$

with

$$I(i)_l = \int_0^1 dx \int_0^x dy \frac{\ln(m_{\eta_i}^2(y-y^2)/[(x-y)m_{\omega_1}^2 + ym_{\omega_l}^2])}{(y-y^2)m_{\eta_i}^2 - (x-y)m_{\omega_1}^2 - ym_{\omega_l}^2}.$$

In the small-mixing approximation, we can parametrize the mixing of the neutrinos, in the basis where the charged leptons are diagonalized, as

$$\begin{aligned} \nu_L^{em} &= \nu_L^e + \alpha \nu_L^\mu + \theta \nu_L^\tau , \\ \nu_L^{\mu m} &= -\alpha \nu_L^e + \nu_L^\mu + \beta \nu_L^\tau , \\ \nu_L^{\tau m} &= -\theta \nu_L^e - \beta \nu_L^\mu + \nu_L^\tau , \end{aligned} \quad (5)$$

where ν_L^{im} are the neutrino mass eigenstates and ν_L^i are the weak eigenstates. The value for θ is fixed from the data on the 17-KeV neutrino to be about 0.1 and the values for α and β are not fixed. However from $\nu_\mu - \nu_\tau$ neutrino oscillation experiments, $|\beta|$ is constrained to be smaller than 0.03[6]. Assuming the MSW mechanism as the solution of the solar

neutrino problem, we require the electron and muon neutrinos to have the correct masses and mixings which satisfy $|m_{\nu_e}^2 - m_{\nu_\mu}^2| \sin^2 2\alpha \approx 3 \times 10^{-8} eV^2$ and $|\alpha| > 0.03$ [20]. Although this mode does not predict the above-mentioned range of parameters, it is possible to adjust the parameters to do so. The Yukawa couplings need not be extremely small to obtain small neutrino masses. For example, assuming $\lambda_{33}^{QQ}, \lambda_{33}^{Ql}, \lambda_{33}^{UD}$, and λ_{33}^{Ue} to be of order $O(1)$, we typically require $\lambda_{i(e,\mu,\tau)}^{D\nu}$ to be of order $O(10^{-3})$.

If the τ neutrino is indeed the 17-KeV neutrino, then it must decay fast enough in order not to be in conflict with the cosmological bound. For this we have to study the Axion-neutrino interactions. The Axion A is massless at the classical level but acquires a finite mass of order $m_A \approx m_\pi f_\pi / f_A$ through the colour anomaly. Here $f_A = \sqrt{2}v_1$ and is constrained to be in the range $10^9 - 10^{12} GeV$ from cosmological and astrophysical considerations [21]. The colour anomaly will generate the familiar quark-Axion couplings which are flavour diagonal. In addition there are new Axion-fermion couplings in this model. The calculation of these couplings is not difficult once we have obtained the mass matrices. One simply replaces the mixing parameters $\gamma_\eta v_1^2$ of the $\eta_1^\dagger \eta_2$ vertex and $\gamma_\omega v_1$ of the $\omega_1^\dagger \omega_2$ vertex in the diagrams by $2iA/\sqrt{2}v_1$ and $-iA/\sqrt{2}v_1$ respectively. The new Axion-quark and -charged lepton interactions are also diagonal. However there are off-diagonal elements in the Axion-neutrino couplings, and we have

$$L_{int} = \bar{\nu}_R(-3M_\nu + M_2)\nu_L \frac{iA}{f_A} + H.C.. \quad (6)$$

This interaction is phenomenologically important because it is the off-diagonal couplings of the Axion to neutrinos which will enable the heavy neutrino to decay fast enough. Let U_R and U_L be the unitary matrices which diagonalize the neutrino mass matrix, so that $M_\nu = U_R^\dagger \hat{M}_\nu U_L$ where $\hat{M}_\nu$ is the diagonalized neutrino mass matrix. The off-diagonal Axion-neutrino couplings are then given by

$$L_{int} = \bar{\nu}_R U_R M_2 U_L^\dagger \nu_L \frac{iA}{f_A} + H.C.. \quad (7)$$

If we assume M_ν to be Hermitian, we find that the biggest off-diagonal element is given by $(U_R M_2 U_L)_{13} \approx m_{\nu_\tau} \theta$. From this we obtain the lifetime of the decay of the 17-KeV neutrino into Axion and electron neutrino to be

$$\tau \approx 10^{13} \left(\frac{f_A}{10^{10} GeV} \right)^2 \left(\frac{0.1}{\theta} \right)^2 (s). \quad (8)$$

We thus find that in our model the 17-KeV neutrino has a lifetime τ which can be as short as $10^{11}(s)$ and hence can satisfy the cosmological bound on the 17-KeV neutrino lifetime $\tau < 10^{14}(s)$.

The introduction of various scalars into the theory may induce new interactions. There are three physical neutral spin-zero particles in this model, the Axion and two scalar particles. The Axion is ImS . Its properties are very similar to the KSVZ [22] invisible Axion which has been studied extensively and we will not discuss this here. One of the neutral scalars corresponds to the standard Higgs scalar in the minimal standard model. In this model this Higgs scalar is flavour-diagonal to the lowest non-trivial order. Its properties are the same as the one in the minimal standard model. The other neutral scalar is ReS which has a mass of order v_1 and therefore has a negligible effect on low-energy physics. There are also charged spin-zero particles η_1, η_2 and ω_1, ω_2 . They all have masses of order v_1 . These particles play important roles in providing radiative masses for down-quarks, charged leptons and neutrinos. However their other effects are small due to their super-heavy masses. In particular these new interactions are too small to enable the right handed neutrinos to be in equilibrium with other fermion particles and the right handed neutrinos in this theory will not affect the 4He abundance in the universe.

In conclusion, we have constructed a simple invisible Axion model which qualitatively explains the smallness of Dirac neutrino masses and the fermion mass hierarchy. In this model, heavy neutrinos can decay into Axions and can easily satisfy the cosmological bound on the heavy neutrino lifetime. The consequences of the 17-KeV neutrino in this model were discussed and found to be consistent with all experimental data.

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FIGURES

Fig. 1: The one loop diagram which generates the down-quark masses.

Fig. 2: The one loop diagram which generates the charged lepton masses.

Fig. 3: The two loop diagrams which generate the neutrino masses.

Fig. 1

Fig. 2

(a)

(b)

Fig. 3