Dirac neutrinos, dark matter stability and flavour predictions from Lepton Quarticity

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Abstract. We propose to relate dark matter stability to the possible Dirac nature of neutrinos. The idea is illustrated in a simple scheme where small Dirac neutrino masses arise from a type-I seesaw mechanism as a result of a Z₄ discrete lepton number symmetry. The latter implies the existence of a viable WIMP dark matter candidate, whose stability arises from the same symmetry which ensures the Diracness of neutrinos. The symmetry groups Δ₂₇ and A₄ are then used to extract a rich variety of flavour predictions.

Keywords: Dirac neutrinos, Dark Matter, Flavour predictions, Quarticity

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INTRODUCTION

Amongst the major shortcomings of the Standard Model are the neutrino mass and the dark matter stability problem. Underpinning the origin of neutrino mass and elucidating the nature of dark matter would constitute a gigantic step forward in particle physics. Here we focus on the possibility that the neutrino nature and dark matter stability problem may be closely interconnected. Concerning neutrinos a major unknown is whether they are their own anti-particles, an issue which has remained an open challenge ever since Ettore Majorana had his pioneering idea on the quantum mechanics of spin [1]. On the other hand, since many years, physicists have pondered about what is the dark matter made of, and what makes it stable, a property usually assumed in an ad-hoc fashion. Indeed, although the existence of non-baryonic dark matter is well established by using cosmological and astrophysical probes, its nature has otherwise remained elusive.

Recently it has been argued in [2] that the Dirac or Majorana nature of neutrinos is intimately connected to the breaking pattern of U(1)ₑ Lepton number symmetry, which is accidentally conserved in the Standard Model, to its residual conserved Zₙ subgroups. Interestingly enough, neutrinos can only be Majorana for specific Zₙ groups and even within these specific Zₙ groups, only for special choices of the charges, while they will be Dirac in any other case. Here we focus on the U(1)ₑ → Z₄ scenario, which we call Quarticity. We show that a WIMP dark matter candidate can naturally emerge, stabilized by Quarticity, the same symmetry associated to the Diracness of neutrinos. Moreover, the smallness of neutrino masses can be understood through the Dirac analogue of type-I seesaw. We also show that many different symmetry groups can be used to give the flavour structure of neutrino mixings and therefore a rich variety of models arise, showing different features and predictions but all maintaining the principal result, the connection between Dark Matter and the Dirac nature of neutrinos.

THE MODEL

The general structure of the model is given in [3]. Concerning the particle content of the model, we need to introduce some new fields in addition to those in the Standard Model. In the fermionic sector we introduce 3 generations of right handed neutrinos, νᵢ,ₑ, to obtain neutrino masses, as well as 3 more generations of heavy neutral leptons with the two chiralities, ψᵢ,ₑ and ψᵢ,ₑ, in order to have a seesaw mechanism. We also have to introduce a new scalar, χ, which has a non-zero vev. In addition there are two other scalars carrying non-trivial Z₄ charges, a real scalar η, and a complex scalar ζ, which is the DM candidate. All of them are gauge singlets. The set of transformation rules under Z₄ for the fields in the model is:
TABLE 1. Charge assignments for leptons, quarks, scalars ($\Phi^u_i, \Phi^d_i$ and $\chi_i$) as well as “dark matter sector” ($\zeta$ and $\eta$). Here $z$ is the fourth root of unity, i.e. $z^4 = 1$.

| Fields | $Z_4$ | Fields | $Z_4$ |
|--------|-------|--------|-------|
| $\bar{L}_{i,L}$ | $z^3$ | $\nu_{i,R}$ | $z$ |
| $l_{i,R}$ | $z$ | $\bar{N}_{i,L}$ | $z^3$ |
| $\bar{N}_{i,R}$ | $z$ |       |       |
| Scalars (vev $\neq 0$) |       | Scalars (vev=0) |       |
| $\Phi$ | $1$ | $\chi$ | $1$ |
| $\zeta$ | $z$ | $\eta$ | $z^2$ |

The only requirement for the flavour structure of the model is that the flavour symmetry group $G$ forbids the tree level neutrino mass, this is, $L\Phi^c v_R$. Then neutrino masses are generated via a type-I seesaw.

Neutrino Diracness

The symmetry rules under $Z_4$ ensures that neutrinos are Dirac particles by forbidding all the possible Majorana terms at all orders. Note that the scalars which have a non-zero vev, $\Phi$ and $\chi$, transform trivially under $Z_4$, thus implying that the Quarticity symmetry $Z_4$ is not spontaneously broken. Moreover

$$(\Phi^\dagger \Phi)^n \chi^m \sim 1$$  \hspace{1cm} (1)

This implies that if all the Majorana mass terms are forbidden at tree level, then they are forbidden at all orders. This is indeed the case, because all neutral fermionic field transform as $z$ under $Z_4$. Therefore, all the Majorana masses at tree level are forbidden. For example

$$\bar{\nu}_{R} v_R \sim z^2$$  \hspace{1cm} (2)

The higher order mass terms -via non-zero vevs of the scalars $\Phi$ and $\chi$- also transform non-trivially under the quarticity symmetry

$$\bar{\nu}_{R} v_R (\Phi^\dagger \Phi)^n \chi^m \sim z^2$$  \hspace{1cm} (3)

Therefore, these terms are forbidden and neutrinos remain Dirac particles at all orders, while the symmetry $Z_4$ is not broken after spontaneous symmetry breaking.

A stable Dark Matter candidate

To ensure that neutrinos remain Dirac particles, the $Z_4$ quarticity symmetry should remain exact, so that no scalar carrying a $Z_4$ charge should acquire any vev. Thus both $\zeta$ and $\eta$ which carry $Z_4$ charge can potentially be stable as a result of the unbroken quarticity symmetry. However, owing to the $Z_4$ charge assignments, the $\eta$ field has cubic couplings to both scalars and fermions. These couplings lead to the decay of $\eta$ and thus, despite carrying a $Z_4$ charge, $\eta$ is not stable. On the other hand, in the lagrangian there is no term of the form $\zeta \rho \rho$, where $\rho$ is a generic scalar, nor of the form $\zeta \psi \psi$, where $\psi$ is a generic fermion. This implies that $\zeta$ is an stable particle, thus it is a viable dark matter candidate.

The detection could be direct, via nuclear recoil. The WIMP particle will also contribute to the invisible decay of the Higgs. Both features are shown in the following diagrams 1

The constraints from LHC for invisible decay and the for direct searches coming from LUX experiment rules out part of the parameter space regarding the higgs-dark matter quartic coupling $\lambda_{h\zeta}$ and mass of dark matter $m_\zeta$, which can be seen in the figure 2.
FLAVOUR PREDICTIONS

The model includes, apart from the Standard Model gauge group, a global symmetry $Z_4 \otimes G$, where $Z_4$ is the Quarticity symmetry already discussed while $G$ is the flavour symmetry. Its role is to forbid the tree level coupling between left and right handed neutrinos and this can be trivially done using $Z_2$, as done in [3]. However, one can use non-abelian discrete symmetries to extract very interesting flavour predictions.

$\Delta_{27}$ as flavour symmetry

This model was discussed in [4]. **When we take $\Delta(27)$ as the flavour symmetry**, $G$, an interesting structure appears in the neutral fields mass matrix, which can then be diagonalized and the masses and mixing parameters can be extracted. The parameters in the model have enough freedom to **fit all the mixing angles and neutrino masses constraints**. The charged assignments are shown in Table 2.

The interesting scenario arises when we consider the following alignment for the vevs of the scalars

$$
\langle \Phi_i \rangle = v \; (1,1,1) \quad \text{(4)}
$$

$$
\langle \chi_i \rangle = u \; (1,1+\epsilon,1+\alpha) \quad \text{(5)}
$$

Where $\epsilon \ll 1$. In this limit, one can find a **correlation between the CP violation parameter, $\delta_{CP}$, and the deviation from the alignment limit which is parametrized by $\epsilon$**. This is shown in the figure 3.
TABLE 2. The $\Delta(27)$ and $Z_4$ charge assignments for leptons, the Higgs scalars ($\Phi_i$, $\chi_i$) and the dark matter sector scalars ($\zeta$ and $\eta$). Here $z$ is the fourth root of unity, i.e. $z^4 = 1$.

| Fields | $\Delta(27)$ | $Z_4$ | Fields | $\Delta(27)$ | $Z_4$ |
|--------|--------------|-------|--------|--------------|-------|
| $L_e$  | 1            | $z^3$ | $\nu_{e,R}$ | 1            | $z$   |
| $L_{\mu}$ | 1$''$    | $z^3$ | $\nu_{\mu,R}$ | 1$'$        | $z$   |
| $L_{\tau}$ | 1$'$    | $z^3$ | $\nu_{\tau,R}$ | 1$''$      | $z$   |
| $l_i,R$ | 3          | $z$   | $\zeta_{i,L}$ | 3          | $z^3$ |
| $N_{i,R}$ | 3$'$    | $z$   | $\chi_i$ | 3$'$        | 1     |
| $\Phi_i$ | 3$'$    | 1     | $\zeta$  | 1          | $z^2$ |

FIGURE 3. Leptonic CP violation phase $\delta_{CP}$ versus $\epsilon$, the deviation from the reference alignment. We have taken $\alpha = 1.2$. See text.

$A_4$ as flavour symmetry

This realization of the quarticity model was done in [5]. Taking $A_4$ as the flavour symmetry $G$ gives very different results. On the one hand, the model gives some strong predictions

$$
\theta_{12}^\nu = 45^\circ, \quad \delta^\nu = \pm 90^\circ \\
\theta_{13}^\nu = \text{arbitrary} \quad \theta_{13}^\nu = \text{arbitrary}
$$

(6)

While $\theta_{12}^\nu$ and $\theta_{13}^\nu$ are strongly correlated. However, this correlation does not allow the fitting of the experimental constraints for these two angles. The model can be minimally extended to include another set of Higgs doublet, which only couples to the up quarks and the neutrinos, while the other Higgs doublet only couples to the d-type quarks and the charged leptons. This way, not only the mixing parameters can be fitted but also a series of interesting predictions arise. The charged assignments are

\[
\begin{align*}
\bar{L}_e & \sim (1, z^3) \\
\bar{L}_\mu & \sim (1'', z^3) \\
\bar{L}_\tau & \sim (1', z^3) \\
l_{i,R} & \sim (3, z) \\
N_{i,R} & \sim (3', z) \\
\Phi_i & \sim (3', 1) \\
\zeta & \sim (1, z) \\
\eta & \sim (1, z^2) \\
\end{align*}
\]
TABLE 3. Charge assignments for leptons, quarks, scalars ($\Phi^u_i$, $\Phi^d_i$ and $\chi_i$) as well as “dark matter sector” ($\zeta$ and $\eta$). Here $z$ is the fourth root of unity, i.e. $z^4 = 1$.

| Fields  | $SU(2)_L$ | $A_4$ | $Z_4$ | Fields  | $SU(2)_L$ | $A_4$ | $Z_4$ |
|---------|-----------|-------|-------|---------|-----------|-------|-------|
| $L_i$   | 2         | 3     | $z^3$ | $\bar{N}_i$ | 1         | 1     | $z$  |
| $\bar{N}_i$ | 1     | 3     | $z^3$ | $\nu_{e,R}$ | 1         | 1     | $z$  |
| $N_i$   | 1         | 3     | $z$  | $\nu_{\mu,R}$ | 1         | 1     | $z$  |
| $l_{i,R}$ | 1     | 3     | $z$  | $d_{i,R}$ | 1         | 3     | $z$  |
| $\bar{Q}_{i,L}$ | 2     | 3     | $z^3$ | $\nu_{\tau,R}$ | 1         | 3     | $z$  |
| $\Phi^u_i$ | 2     | 1     | 1     | $\zeta$ | 1         | 3     | 1    |
| $\Phi^d_i$ | 2     | 1''   | 1     | $\eta$ | 1         | 1     | $z^2$ |
| $\Phi^u_i$ | 2     | 1''   | 1     | $\zeta$ | 1         | 1     | $z$  |
| $\Phi^d_i$ | 2     | 3     | 1     | $\zeta$ | 1         | 1     | $z$  |

A strong correlation between $\delta_{CP}$ and $\delta_{23}$ appears as shown in figure 4.

FIGURE 4. CP violation and $\theta_{23}$ predictions within the model. Left panel: $\delta_{CP}$ vs $\theta_{23}$. The green regions are the 1$\sigma$ (dark) and 3$\sigma$ (light) regions for $\theta_{23}$ from current oscillation fit. Right panel: Same correlation, now showing $J_{CP}$ vs $\sin^2 \theta_{23}$ and zooming in the region allowed by the model, fully consistent in the 2$\sigma$ experimental range.

Also, only normal hierarchy of neutrinos is realized. Moreover, an interesting relation between the masses of the quarks and the charged leptons is also present in the model.

$$\frac{m_b}{\sqrt{m_dm_s}} \approx \frac{m_\tau}{\sqrt{m_e m_\mu}}$$

(7)

In this case, the flavour symmetry predicts (i) a generalized bottom-tau mass relation involving all families, (ii) small neutrino masses are induced via a type-I seesaw, (iii) CP must be significantly violated in neutrino oscillations, (iv) the atmospheric angle $\theta_{23}$ lies in the second octant while showing a strong correlation with $\delta_{CP}$ and (v) only the normal neutrino mass ordering is realized. A more detailed phenomenological analysis of the oscillation predictions of the model has been recently done in [6].

CONCLUSIONS

We have shown a very rich family of predictive models which can accommodate many different setups while conserving the central features of the model, this is

- The quarticity symmetry $Z_4$ ensures that neutrinos are Dirac particles and the stability of the DM candidate.
- Naturally small neutrino masses are generated via a type-I seesaw.

Then, the freedom to select the flavour symmetry $G$ leads to a whole variety of models with rich predictions, not only in the neutrino sector but also in the quark and charged lepton sector.
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