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Spontaneous dark matter stability from a fermiophobic U(1)' gauge symmetry

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In model building, discrete symmetries cannot only play an important role in preserving the structure of Yukawa interactions but also provide a pathway to stabilise dark matter candidates. However, such discrete symmetries are not necessarily be imposed directly by hand. Instead, they can arise from the spontaneous symmetry breaking (SSB) of continuous symmetries. As an example, we study the type Ib seesaw model, where the effective neutrino mass operator involves two different Higgs doublets and two right-handed (RH) neutrinos forming a single heavy Dirac pair. The heavy neutrino, together with the Higgs doublets, is charged under a $U(1)'$ gauge symmetry which helps to preserve the special structure of the type Ib seesaw mechanism. After the SSB, the $U(1)'$ symmetry turns into a Z_2 symmetry which stabilises a dark matter candidate. The dark matter candidate interacts with the other particles in the thermal bath through the massive boson resulting from the $U(1)'$ symmetry breaking. We explore how the correct dark matter relic abundance can be produced thermally in both a low energy effective model and a renormalisable model with a complete fourth family of vector-like fermions.

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	$q_{L\alpha}$	$u_{R\beta}$	$d_{R\beta}$	$\ell_{L\alpha}$	$e_{R\beta}$	Φ_1	Φ_2	$N_{\rm R1}$	$N_{\rm R2}$	$\chi_{L,R}$	ϕ
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**2**	**2**	**1**	**1**	**1**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	$-\frac{1}{2}$	0	0	0	0
$U(1)'$	0	0	0	0	0	1	-1	-1	1	$\frac{1}{2}$	1

Table 1: Irreducible representations of the fields of the model under the electroweak $SU(2)_L \times U(1)_Y \times U(1)'$ gauge symmetry. The fields $q_{L\alpha}, \ell_{L\alpha}$ are left-handed SM doublets while $u_{R\beta}, d_{R\beta}, e_{R\beta}$ are right-handed SM singlets where α, β label the three families of quarks and leptons. The fields $N_{\rm R1,2}$ are the two right-handed neutrinos.

1. Introduction

Although discrete symmetries have a wide application in model building, including stabilising dark matter candidates in dark matter models and constraining Yukawa interactions in two Higgs doublet models (2HDMs), the SM only contains gauge symmetries and accidental (approximate) global symmetries without any discrete symmetry. This fact provided us a good motivation to seek the origin of discrete symmetries.

In general, discrete symmetries can arise from subgroups of gauge symmetries. As a typical example, we consider the possibility that dark matter is stabilised by a discrete Z_2 symmetry which arises from a subgroup of a $U(1)'$ gauge symmetry in the framework of type Ib seesaw mechanism [1], where the light neutrino masses are obtained from a Weinberg-like operator involving two Higgs doublets and a Dirac heavy neutrino mediator [2–4]. Due to the different seesaw structures, the type Ib seesaw model can realise large Yukawa coupling and light mediator spontaneously and therefore can provide a stronger link between neutrino physics and dark matter when extended by a neutrino portal [3], different from the traditional type I seesaw model [5–7]. Under the $U(1)'$ gauge symmetry, the chiral quarks and leptons are uncharged, while a chiral fermion χ with a half-integer charge is odd under the preserved Z_2 and hence becomes a stable dark matter candidate. The dark matter candidate χ can be produced through couplings to right-handed neutrinos with vector-like $U(1)'$ charges, as in the type Ib seesaw mechanism. In this model, no discrete symmetries are required to be added by hand. Instead, the $U(1)'$ is broken into a Z_2 symmetry spontaneously by the vacuum expectation value (VEV) of an integer charged scalar singlet, together with integer charged Higgs doublets.

2. Extension of the minimal type Ib seesaw model as an effective model

Here, we introduce the $U(1)'$ extension of minimal type Ib seesaw model with a Majorana fermion singlet. The charges of the fields in the model are summarised in Tab.1. The $U'(1)$ gauge symmetry, rather than any discrete Z_3 or Z_4 symmetries [3, 4], is responsible for making the two Higgs doublets distinguishable and ensuring the type Ib seesaw structure. However, the $U(1)'$ symmetry does not completely take over the function of the discrete symmetries. In fact, the Yukawa interaction between charged fermions and Higgs doublets is forbidden by the $U(1)'$ symmetry. To preserve the fermion mass, a new scalar singlet ϕ is introduced with which dimension-5 interaction is allowed in the form of $\overline{q_L}_\alpha \Phi_2 u_{R\beta}\phi$, $\overline{q_L}_\alpha \tilde{\Phi}_1 d_{R\beta}\phi$ and $\overline{\ell}_\alpha \tilde{\Phi}_1 e_{R\beta}\phi$. The

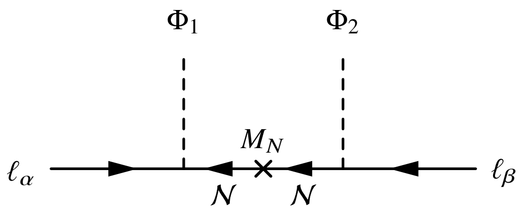

Figure 1: Light neutrino masses generated by the type Ib seesaw mechanism

dimension-5 operators $\overline{q_L}_\alpha \Phi_1 u_{R\beta}\phi^*$, $\overline{q_L}_\alpha \tilde{\Phi}_2 d_{R\beta}\phi^*$ and $\overline{\ell}_\alpha \tilde{\Phi}_2 e_{R\beta}\phi^*$ are also allowed by the $U(1)'$ gauge symmetry but are forbidden when a more complete renormalisable theory is considered [1], which helps to avoid flavour-changing neutral currents and keep the structure of the 2HDM. After ϕ gains a VEV $\langle\phi\rangle = v_\phi/\sqrt{2}$, the Yukawa interactions generating fermion mass after spontaneous symmetry breaking (SSB) of Higgs doublets are

$$\mathcal{L}_{\text{2HDM}} \supset -Y^u_{\alpha\beta}\overline{q_L}_\alpha \Phi_2 u_{\text{R}\beta} - Y^d_{\alpha\beta}\overline{q_L}_\alpha \tilde{\Phi}_1 d_{\text{R}\beta} - Y^e_{\alpha\beta}\overline{\ell}_\alpha \tilde{\Phi}_1 e_{\text{R}\beta} + \text{h.c.}\,, \tag{1}$$

which is referred to as the type II two Higgs doublet model. The Yukawa interactions allowed in the type Ib seesaw sector take the form

$$\mathcal{L}_{\text{seesawIb}} = -Y_{1\alpha}\overline{\ell_L}_\alpha \Phi_1 N_{\text{R1}} - Y_{2\alpha}\overline{\ell_L}_\alpha \Phi_2 N_{\text{R2}} - M\overline{N^c_{\text{R1}}} N_{\text{R2}} + \text{h.c.}\,, \tag{2}$$

The two "right-handed" Weyl neutrinos can actually form a four component Dirac spinor $\mathcal{N} = (N^c_{R1}, N_{R2})$ with a Dirac mass M. The $U(1)'$ Dirac spinor $\mathcal{N}$ can be easily read as 1 from Tab.1. Notice that any Majorana mass terms of the RH neutrinos break the $U(1)'$ symmetry and therefore the classical type Ia seesaw is forbidden in this model. The type Ib seesaw Lagrangian can be rewritten in $\mathcal{N}$ as

$$\mathcal{L}_{\text{seesawIb}} = -Y^*_{1\alpha}\overline{\ell^c_L}_\alpha \Phi^*_1 \mathcal{N}_{\text{L}} - Y_{2\alpha}\overline{\ell_L}_\alpha \Phi_2 \mathcal{N}_{\text{R}} - M_N \overline{\mathcal{N}_{\text{L}}}\mathcal{N}_{\text{R}} + \text{h.c.}\,. \tag{3}$$

The light neutrino masses are generated by dimension-5 Weinberg-like operators as shown in Fig.1.

In Tab.1, the SM fermions are uncharged under $U(1)'$ to avoid chiral anomalies while the two Higgs doublets $\Phi_{1,2}$, the heavy neutrino $\mathcal{N}$, the dark fermion singlet $\chi_{L,R}$ and ϕ are charged. The kinetic terms of those particles are

$$\begin{aligned}\mathcal{L}_{\text{U}'(1)} = {} & \left(D'_\mu \Phi_1\right)^\dagger D'^\mu \Phi_1 + \left(D'_\mu \Phi_2\right)^\dagger D'^\mu \Phi_2 + i\overline{\mathcal{N}}\not{D}'\mathcal{N} \\ & + i\overline{\chi_L}\not{D}'\chi_L + i\overline{\chi_R}\not{D}'\chi_R + D'_\mu\overline{\phi}D'^\mu\phi\end{aligned} \tag{4}$$

with the covariant derivative $D'_\mu = \partial_\mu + i\frac{1}{2}g_2\,\boldsymbol{\sigma}\cdot\boldsymbol{W}_\mu + ig_1 Y B_\mu + ig'_1 Y' B'_\mu$. In addition to the kinetic terms, the dark fermion can only couple to ϕ through interaction

$$y^L_\chi \overline{\phi}\,\overline{\chi^c_L}\chi_L + y^R_\chi \overline{\phi}\,\overline{\chi^c_R}\chi_R + h.c.\,. \tag{5}$$

After the $U(1)'$ is broken, the dark fermion χ gains a Majorana mass $m_{L,R} = \sqrt{2}y^{L,R}_\chi v_\phi$ and become stable due to its half-integer charge under $U(1)'$. For simplicity, we focus on the case where the

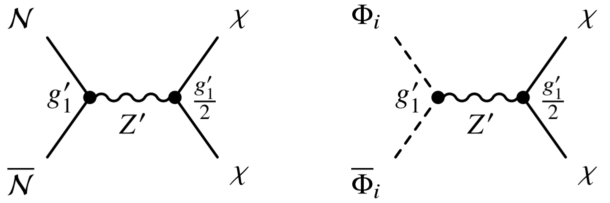

Figure 2: The processes responsible for DM production

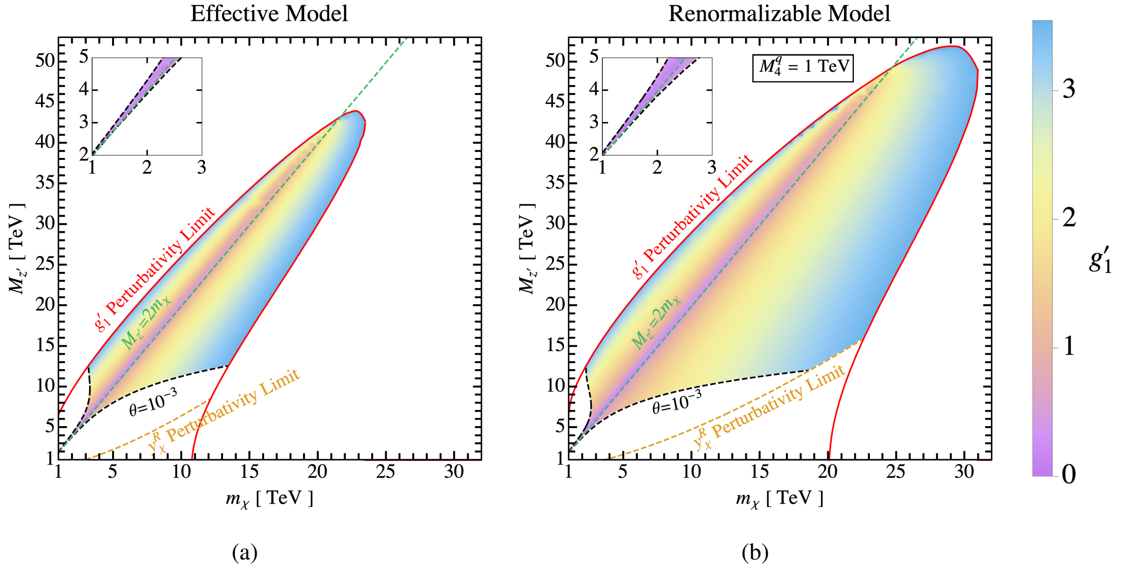

Figure 3: Allowed values of the $U(1)'$ gauge coupling for different masses of dark fermion and $U(1)'$ gauge boson in the effective model. The upper limits of g_1' and y_χ^R that required by the validity of perturbative expansion are both $\sqrt{4\pi}$.

dark fermion masses are hierarchical and only χ_R is considered during the freeze-out production of dark matter and adopt χ and m_χ for the dark matter candidate χ_R and its mass.

Constrained by the mixing between massive neutral gauge bosons, the dark matter candidate and $U(1)'$ gauge boson are likely to be TeV scale. Therefore the neutrino mass is neglectable in dark matter production when it is GeV scale. Then there are only three parameters affecting the dark matter freeze-out production through the processes in Fig.2: the dark fermion mass m_χ, the $U(1)'$ gauge boson mass $M_{Z'}$ and the $U(1)'$ gauge coupling g_1'. The allowed value of g_1' in the $m_\chi - M_{Z'}$ plane is shown in Fig.3(a). Constrained by the perturbativity limit of g_1', m_χ and $M_{Z'}$ cannot exceed 24 TeV and 44 TeV respectively. A resonance appears along the line $M_{Z'} = 2m_\chi$ due to the stability of Z' in the propagator.

	$q_{L\alpha}$	$u_{R\beta}$	$d_{R\beta}$	$\ell_{L\alpha}$	$e_{R\beta}$	q_4	u_4	d_4	ℓ_4	e_4	Φ_1	Φ_2	$\mathcal{N}$	$\chi_{L,R}$	ϕ
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**2**	**1**	**1**	**2**	**1**	**2**	**2**	**1**	**1**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	$-\frac{1}{2}$	0	0	0
$U(1)'$	0	0	0	0	0	-1	1	1	-1	1	1	-1	1	$\frac{1}{2}$	1

Table 2: Irreducible representations of the fields of the model under the electroweak $SU(2)_L \times U(1)_Y \times U(1)'$ gauge symmetry. The fields $q_{L\alpha}, \ell_{L\alpha}$ are left-handed SM doublets while $u_{R\beta}, d_{R\beta}, e_{R\beta}$ are right-handed SM singlets where α, β label the three families of quarks and leptons. The two right-handed neutrino fields $N_{\mathrm{R}1,2}$ are written as a Dirac pair $\mathcal{N}$.

3. Renormalisable model with fourth family vector-like fermions

A renormalisable theory that preserves the structure of type II 2HDM can be achieved by introducing a fourth family of vector-like fermions as shown in Tab.2. With new vector-like fermions, the allowed Yukawa interactions between charged fermions and scalars are

$$\begin{aligned}\mathcal{L}_{\text{Yuk}} \supset\; & -Y^{qu}_{\alpha 4}\overline{q_L}_\alpha \Phi_2 u_4 - Y^{qd}_{\alpha 4}\overline{q_L}_\alpha \tilde{\Phi}_1 d_4 - Y^{u}_{\beta 4}\overline{u_{\mathrm{R}}}_\beta \Phi_2^\dagger q_4 - Y^{d}_{\beta 4}\overline{d_{\mathrm{R}}}_\beta \tilde{\Phi}_1^\dagger q_4 \\ & -Y^{\ell}_{\alpha 4}\overline{\ell}_\alpha \tilde{\Phi}_1 e_4 - Y^{e}_{\beta 4}\overline{e_{\mathrm{R}}}_\beta \tilde{\Phi}_1^\dagger \ell_4 - y^{q}_{\alpha 4}\phi\, \overline{q_L}_\alpha q_4 - y^{u}_{\beta 4}\overline{\phi}\, \overline{u_{\mathrm{R}}}_\beta u_4 \\ & -y^{d}_{\beta 4}\overline{\phi}\, \overline{d_{\mathrm{R}}}_\beta d_4 - y^{\ell}_{\alpha 4}\phi\, \overline{\ell_L}_\alpha \ell_4 - y^{e}_{\beta 4}\overline{\phi}\, \overline{e_{\mathrm{R}}}_\beta e_4 + \text{h.c.}\,. \end{aligned} \tag{6}$$

The mass terms of the fourth family fermions are also imposed as

$$\mathcal{L}_{\text{mass}} \supset M_4^q \overline{q_4} q_4 + M_4^u \overline{u_4} u_4 + M_4^d \overline{d_4} d_4 + M_4^\ell \overline{\ell_4} \ell_4 + M_4^e \overline{e_4} e_4\,. \tag{7}$$

Like the Weinberg operator in the seesaw mechanism, the non-renormalisable dimension-5 operators in the effective model can be generated by diagrams similar to Fig.4. After ϕ gains a VEV, the resulting interactions are coincident with the Lagrangian in Eq.(1) with Yukawa couplings

$$\begin{aligned} Y^u_{\alpha\beta} &= \frac{Y^{qu}_{\alpha 4}(y^u_{\beta 4})^* \langle\phi\rangle}{M_4^u} + \frac{y^q_{\alpha 4}(Y^u_{\beta 4})^*\langle\phi\rangle}{M_4^q}\,, \\ Y^d_{\alpha\beta} &= \frac{Y^{qd}_{\alpha 4}(y^d_{\beta 4})^* \langle\phi\rangle}{M_4^d} + \frac{y^q_{\alpha 4}(Y^d_{\beta 4})^*\langle\phi\rangle}{M_4^q}\,, \\ Y^e_{\alpha\beta} &= \frac{Y^{\ell}_{\alpha 4}(y^u_{\beta 4})^* \langle\phi\rangle}{M_4^e} + \frac{y^\ell_{\alpha 4}(Y^u_{\beta 4})^*\langle\phi\rangle}{M_4^\ell}\,. \end{aligned} \tag{8}$$

The lightest one in the fourth family fermions, q_4, can make an extra contribution to the amplitude during the freeze-out in addition to the processes in Fig.2, which enlarges the allowed parameter space as shown in Fig.3(b).

4. Conclusion

We have considered the possibility that dark matter is stabilised by a discrete Z_2 symmetry which arises from a subgroup of a $U(1)'$ gauge symmetry, spontaneously broken by integer charged

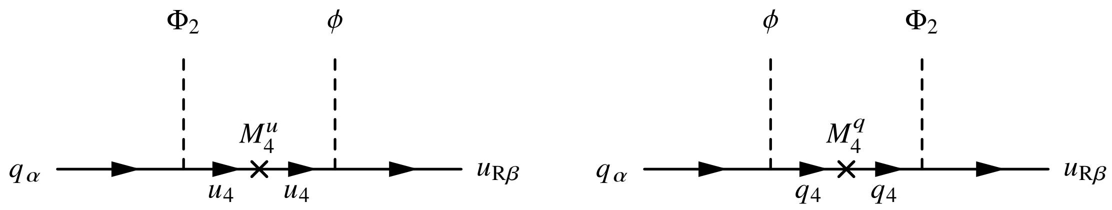

Figure 4: Effective interaction between quark doublets and up-type quarks

scalars, and under which the chiral quarks and leptons do not carry any charges. A four-component fermion χ with half-integer charge is odd under the preserved Z_2, and hence becomes a stable dark matter candidate, being produced through couplings to heavy neutrinos with vector-like $U(1)'$ charges. The model accounts for both dark matter and neutrino mass and mixing, without requiring the addition of discrete symmetries to stabilise the dark matter mass. As a concrete example, the model shows how a discrete symmetry can arise from a subgroup of a gauge symmetry through spontaneous symmetry breaking.

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