Light Z’ and Dark Matter from U(1)x Gauge Symmetry

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Introduction

**Dark Matter**

= One of the most exciting puzzles of cosmology and particle physics

Required properties of DM:
1. electric charge neutral
2. lifetime > age of the Universe
3. cold

There is **NO** dark matter candidate in the Standard Model!

Need theories **beyond the SM**

In this talk, I’ll discuss

**the minimal U(1)x model with a dark matter candidate**
1. U(1)x gauge extension of the SM

Minimal B–L model

J. C. Pati and A. Salam, Phys. Rev. D8 (1973) 1240
A. Davidson, Phys. Rev. D20 (1979) 776
1. U(1)x gauge extension of the SM

Minimal B–L model

generalization

Minimal U(1)x extended SM


U(1)x charge of a field is given by a linear combination of hypercharge and B–L charge

\[ Q_{B-L} \rightarrow Q_X = x_H Q_Y + Q_{B-L} \]
**Particle content of the minimal U(1)\(_x\) model**

\[
Q_X = x_H Q_Y + Q_{B-L}
\]

<table>
<thead>
<tr>
<th>SU(3)(_c)</th>
<th>SU(2)(_L)</th>
<th>U(1)(_Y)</th>
<th>U(1)(_X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(q^i_L)</td>
<td>3</td>
<td>2</td>
<td>(1/6)</td>
</tr>
<tr>
<td>(u^i_R)</td>
<td>3</td>
<td>1</td>
<td>(2/3)</td>
</tr>
<tr>
<td>(d^i_R)</td>
<td>3</td>
<td>1</td>
<td>(-1/3)</td>
</tr>
<tr>
<td>(\ell^i_L)</td>
<td>1</td>
<td>2</td>
<td>(-1/2)</td>
</tr>
<tr>
<td>(e^i_R)</td>
<td>1</td>
<td>1</td>
<td>(-1)</td>
</tr>
<tr>
<td>(H)</td>
<td>1</td>
<td>2</td>
<td>(-1/2)</td>
</tr>
<tr>
<td>(N^j_R)</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(N_R)</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(\Phi)</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

- \(i = 1, 2, 3\)
- \(j = 1, 2\)

\(x_H = 0\) : minimal B–L model

\(|x_H| \gg 1\) : hyper–charge oriented \(U(1)_x\)

N. Okada, SO and D. Raut, Phys. Rev. D95 (2017) 055030
The particle content of the minimal U(1)\textsubscript{X} model is listed in Table I. The U(1)\textsubscript{X} charge of a particle is defined as a linear combination of its U(1)\textsubscript{Y} and U(1)\textsubscript{B−L} charges with a real parameter $x_H$. Note that the minimal B−L model is realized by setting $x_H = 0$, while the U(1)\textsubscript{X} gauge interaction becomes similar (up to a sign) to the SM hyper-charge interaction for $|x_H| \gg 1$ ("hyper-charge oriented" U(1)\textsubscript{X}). All the gauge and mixed gauge-gravitational anomalies are canceled by the presence of three RHNs. The parity-odd $N_R$ is stable and a unique DM candidate (RHN DM) in the model.

<table>
<thead>
<tr>
<th>Particle</th>
<th>SU(3)\textsubscript{c}</th>
<th>SU(2)\textsubscript{L}</th>
<th>U(1)\textsubscript{Y}</th>
<th>U(1)\textsubscript{X}</th>
<th>Z\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q^i_L$</td>
<td>3</td>
<td>2</td>
<td>$\frac{1}{6}$</td>
<td>$\frac{1}{6}x_H + \frac{1}{3}$</td>
<td>+</td>
</tr>
<tr>
<td>$u^i_R$</td>
<td>3</td>
<td>1</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{2}{3}x_H + \frac{1}{3}$</td>
<td>+</td>
</tr>
<tr>
<td>$d^i_R$</td>
<td>3</td>
<td>1</td>
<td>$-\frac{1}{3}$</td>
<td>$-\frac{1}{3}x_H + \frac{1}{3}$</td>
<td>+</td>
</tr>
<tr>
<td>$\ell^i_L$</td>
<td>1</td>
<td>2</td>
<td>$-\frac{1}{2}$</td>
<td>$-\frac{1}{2}x_H + (-1)$</td>
<td>+</td>
</tr>
<tr>
<td>$e^i_R$</td>
<td>1</td>
<td>1</td>
<td>$-1$</td>
<td>$-x_H + (-1)$</td>
<td>+</td>
</tr>
<tr>
<td>$H$</td>
<td>1</td>
<td>2</td>
<td>$-\frac{1}{2}$</td>
<td>$-\frac{1}{2}x_H$</td>
<td>+</td>
</tr>
<tr>
<td>$N^j_R$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>$-1$</td>
<td>+</td>
</tr>
<tr>
<td>$N_R$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>$-1$</td>
<td>−</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>$+2$</td>
<td>+</td>
</tr>
</tbody>
</table>

TABLE I. The particle content of the minimal U(1)\textsubscript{X} model with $Z\textsubscript{2}$ symmetry (parity). In addition to the SM particle content ($i=1,2,3$), three RHNs ($N^j_R$ ($j=1,2$) and $N_R$) and the U(1)\textsubscript{X} Higgs field ($\Phi$) are introduced. Due to its $Z\textsubscript{2}$-parity assignment, the $N_R$ is a unique DM candidate. The U(1)\textsubscript{X} charge of a field is defined as a linear combination of its U(1)\textsubscript{Y} and U(1)\textsubscript{B−L} charges with a real parameter $x_H$. The minimal B−L model is defined as a limit of $x_H \to 0$.
Gauge invariant Yukawa coupling

\[ \mathcal{L}_Y \supset - \sum_{i=1}^{3} \sum_{j=1}^{2} Y_D^{ij} \bar{\ell}_L^{i} H N_R^{j} - \frac{1}{2} \sum_{k=1}^{2} Y_N^{k} \Phi \bar{N}_R^{k} C N_R^{k} - \frac{1}{2} Y_N \Phi \bar{N}_R C N_R + \text{h.c.} \]

<table>
<thead>
<tr>
<th>Dirac Yukawa coupling for RHNs</th>
<th>Majorana Yukawa coupling for RHNs</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ Y_D^{ij} \bar{\ell}_L^{i} H N_R^{j} ]</td>
<td>[ Y_N^{k} \Phi \bar{N}_R^{k} C N_R^{k} ]</td>
</tr>
</tbody>
</table>
Gauge invariant Yukawa coupling

\[ \mathcal{L}_Y \supset - \sum_{i=1}^{3} \sum_{j=1}^{2} Y^{ij}_{D} \bar{\ell}^{i}_{L} H N^{j}_{R} - \frac{1}{2} \sum_{k=1}^{2} Y^{k}_{N} \Phi \bar{N}^{k}_{R} C N^{k}_{R} - \frac{1}{2} Y^{k}_{N} \Phi \bar{N}^{k}_{R} C N^{k}_{R} + \text{h.c.} \]

**U(1)x symmetry breaking**

**EW symmetry breaking**

**Minimal seesaw**

with only two RHNs

T. Yanagida, Conf. Proc. C7902131 (1979) 95
2. Freeze-in RHN Dark Matter

DM relic density is evaluated by solving the Boltzmann equation

\[
\frac{dY}{dx} = - \frac{s(m_{DM})}{H(m_{DM})} \frac{\langle \sigma v_{\text{rel}} \rangle}{x^2} (Y^2 - Y_{\text{EQ}}^2)
\]

\(Y\) : yield
\(x \equiv \frac{m}{T}\)

Initial condition (freeze-in DM case): \(Y(x_{\text{RH}}) = 0\)

\(x_{\text{RH}} = \frac{m_{DM}}{T_{\text{RH}}}\)

Reheating temperature \(T_{\text{RH}}\) after inflation

DM relic density at present universe

\[
\Omega_{DM} h^2 = \frac{m_{DM} Y(\infty) s_0}{\rho_c / h^2} = 0.12 \text{ (Planck 2018)}
\]
2. Freeze-in RHN Dark Matter

\[ m_{Z'} \ll m_{DM} \quad 10 \text{ MeV} \lesssim m_{Z'} \lesssim 1 \text{ GeV} \]

Main process for the DM pair creation from the SM thermal plasma

\[ f \quad Z' \quad \bar{f} \quad \longrightarrow \quad N_R \quad N_R \]

\[ \sigma(s) = \frac{g_X^4}{48\pi} \frac{\sqrt{s(s - 4m_{DM}^2)}}{(s - m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2} F(x_H) \]

\[ F(x_H) = 13 + 16x_H + 10x_H^2 \]

\[ m_{Z'} \ll m_{DM} \]

\[ \sigma(s) \approx \frac{g_X^4}{48\pi} \frac{\sqrt{s(s - 4m_{DM}^2)}}{s^2} F(x_H) \]

Z’-portal RHN DM
We numerically solve the Boltzmann equation \((x_{RH} = 10^{-10})\)

\[ g_X = 3.11 \times 10^{-6} \quad m_{DM} = 1 \text{ TeV}, \text{ and } x_H = 0 \]

\[ x = m_{DM}/T \]

We numerically solve the Boltzmann equation \((x_{RH} = 10^{-10})\)

- \(g_X = 3.11 \times 10^{-6}\)
- \(m_{DM} = 1\) TeV, and \(x_H = 0\)

Resultant \(Y(\infty) = 4.36 \times 10^{-13}\)
reproduces the observed DM relic density \(\Omega_{DM} h^2 = 0.12\)
We numerically solve the Boltzmann equation \((x_{RH} = 10^{-10})\)

\[ g_X = 3.11 \times 10^{-6} \quad m_{DM} = 1 \text{ TeV}, \text{ and } x_H = 0 \]

\[ Y(\infty) \text{ is independent of } x_{RH} \ll 1 \]

\[ Y(\infty) \propto \frac{1}{m_{DM}} \]

\[ H \]

\[ \Omega_{DM} h^2 \text{ is independent of } m_{DM} \]
We numerically solve the Boltzmann equation ($x_{RH} = 10^{-10}$)

$g_X = 3.11 \times 10^{-6}$, $m_{DM} = 1$ TeV, and $x_H = 0$

Resultant $Y(\infty) \simeq Y(x = 1)$ since production of DM particles from the thermal plasma stops around $x \sim 1$ ($T \sim m_{DM}$) due to kinematics
that the 2 can search for a long-lived to interpret the analysis result for the B particularly interested in the hyper-charge oriented case of the results for the U(1) gauge coupling is found to be very small as shown in Eq. (16). This fac

To obtain the prospect of our operation at the LHC Run-3 and its upgraded version (FASER 2) at t experiments. The recently approved ForwArd Search Experiment that the observed DM relic density is reproduced by the cross section in Eq. (9) is proportional to the value to be close to what we have obtained by the numerical analysis, while it is controlled by the gauge boson search at FASER is summarized in Ref. [43]. FASER Z’ boson is long-lived. Such a long-lived particle can be explored at Lifetime Frontier. In t indicates that the Lifetime Frontier will cover a parameter region complementary to FASER.

Thus, we find

Substituting this into Eq. (12), we integrate the Boltzmann equation for the DM creation cross section:

Realizing that the cross section in Eq. (9) is proportional to the value. Hence, this rough estimate leads to

Very small + Z’ boson is light

Z’ boson is long-lived
3. Future experiments at the Lifetime Frontier

How to test the scenario in the future experiments at the Lifetime Frontier?

- FASER
- LHCb
- FASER 2
- SHiP
- Belle II
- LDMX
3. Future experiments at the Lifetime Frontier

How to test the scenario in the future experiments at the Lifetime Frontier?

- FASER
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We need to interpret the analysis result for the B–L gauge boson to the U(1)x model case.

Results for the $|x_H| \lesssim 1$ are expected to be similar to the one for the B–L case.

$\rightarrow$ Hyper-charge oriented case in $|x_H| \gg 1$

- B–L case: $Z'$ boson coupling with the SM fermions is controlled by $g_{BL}$
- Hyper-charge oriented case: controlled by $g_X|x_H|$

$g_{BL} \leftrightarrow g_X|x_H|$
3. Future experiments at the Lifetime Frontier

Gauge coupling to reproduce the observed DM relic density $\Omega_{DM}h^2 = 0.12$

\[
g_X = 3.11 \times 10^{-6} \left( \frac{F(0)}{F(x_H)} \right)^{1/4}
\]

\[
g_X \simeq \frac{3.32 \times 10^{-6}}{\sqrt{|x_H|}} \quad \text{for } |x_H| \gg 1
\]

$g_{BL}$ value in the analysis of the prospective search for the B–L gauge boson can be inferred to be

Inferred $g_{BL}$: $g_{BL} \rightarrow g_X |x_H| \simeq 3.32 \times 10^{-6} \sqrt{|x_H|}$
Inferred $g_{BL}$ to reproduce DM relic abundance


Current excluded region
- Searches for long-lived particle
- Anomalous neutrino interactions

Inferred $g_{BL}$ value shifts upward as $|x_H|$ increases
If a long-lived $Z'$ boson is observed in the future,

we can determine $|x_H|$ and $Z''!!$
4. Conclusion and discussion

We consider a $U(1)_X$ gauge symmetry extension of the SM with a $Z'$–portal Majorana fermion DM that allowed for a relatively light gauge boson $Z'$ with mass of 10 MeV–a few GeV and a much heavier DM through the freeze–in mechanism.

Motivated by the future Lifetime Frontier experiments, we have focused on the parameter space where the DM particle very weakly couples to the light $Z'$ boson. In this case, the $Z'$ boson is long–lived.

For $m_{Z'} \ll m_{DM}$ case, we have identified the model parameter regions to reproduce the observed DM relic density $\Omega_{DM} h^2 = 0.12$.

We have discussed how our scenario can be tested by various future Lifetime Frontier experiments. We found that the $U(1)_X$ model with a large $|x_H|$ (hyper–charge oriented case) dramatically alters the parameter region to be explored by the future experiments compared to that for B–L mode.
Back Up
**mz' >> mDM case**

\[ x_{RH} = 10^{-10} \]

Here, we have set \( g_X = 1.80 \times 10^{-9} \), \( m_{DM} = 10 \) keV, \( m_{Z'} = 10 \text{ GeV} \), and \( x_H = 0 \).

The resultant \( Y(\infty) \) reproduces the observed DM density of \( \Omega_{DM} h^2 = 0.12 \).

**B. Case (ii):**

\( m_{Z'} \gg m_{DM} \)

We next consider the case \( m_{Z'} \gg m_{DM} \). Although the basic formulas that we employ in our analysis are the same as in Case (i), the RHN DM is dominantly produced through the \( Z' \) boson resonance in Case (ii).

Note that for \( m_{Z'} > m_{DM} \), the DM pair creation/annihilation cross section of Eq. (9) includes the resonance point at \( s = m_{Z'}^2 \) for \( s \geq 4 m_{DM}^2 \). Since the gauge coupling is very small, we use the narrow width approximation,

\[
\frac{d \Gamma}{ds} \left( s - m_{Z'}^2 \right)^2 + m_{Z'}^2 \gamma_{Z'}^2 = \frac{d \pi}{m_{Z'} \Gamma_{Z'}} \delta \left( s - m_{Z'} \right),
\]

in calculating the thermal-averaged cross section, where the total decay width is given by

\[
\Gamma_{Z'} = g_X^2 \frac{24}{\pi m_{Z'} \left( F(x_H) + 1 \right)}.
\]

\( F(x_H) \) in the total decay width formula depends on \( m_{Z'} \) since only the kinematically allowed final states are involved in the formula. For example, if a \( Z' \) boson is lighter than the top quark, Eq. (10) must be modified.

However, \( F(x_H) \gg 1 \) is satisfied in our analysis, and our result is almost independent of \( F(x_H) \). See Eq. (21) and the discussion below.
mz' >> m_{DM} case

FIG. 4. Inferred g_{BL} values to reproduce the observed DM relic density for various |x_H| values along with the search reach of various planned/proposed experiments at the Lifetime Frontier and the current excluded region (gray shaded and light green shaded from the SN1987A observation). Here, we have set m_{DM} = 10 \text{ keV}. The diagonal lines from top to bottom, along which \Omega_{DM} h^2 = 0.12 is reproduced, correspond to |x_H| = 10^5, 10^4, 10^3, 100, and 0 (B − L limit), respectively.

In Fig. 4, we show our results for the inferred g_{BL} gauge coupling as a function of m_{Z'} to reproduce the observed DM relic density, along with the search reach of various planned/proposed experiments at the Lifetime Frontier. The current excluded region from the combination of the searches for a long-lived particle and anomalous neutrino interactions is gray shaded (see Ref. [50] for details). The observation of Supernova 1987A (SN1987A) [51, 52] excludes the green shaded region, which causes an extra energy release for the supernova explosion via Z' boson emissions [53, 54]. The diagonal lines from top to bottom, along which \Omega_{DM} h^2 = 0.12 is reproduced, correspond to |x_H| = 10^5, 10^4, 10^3, 100, and 0 (B − L limit), respectively. The inferred g_{BL} value shifts upward as |x_H| increases. If a long-lived Z' boson is observed in the future, we can determine |x_H| and m_{Z'}.

IV. CONCLUSION AND DISCUSSION

The minimal gauged U(1)_{X} extension of the SM is a simple, well-motivated framework to incorporate the neutrino masses in the SM, where the U(1)_{X} charge of a field is defined as a