Freeze-in dark matter from a minimal B – L model and possible grand unification

Nobuchika Okada  
(okadan@ua.edu)  
University of Alabama

In collaboration with Rabi Mohapatra (U. of Maryland)

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1. Problems of the Standard Model

Although the **Standard Model (SM)** is the best theory so far, **New Physics beyond SM** is strongly suggested by various experimental & theoretical points of view

**What is missing?**

Two major missing pieces

1. Neutrino masses and flavor mixings
2. Dark matter candidate

New Physics **must** supplement the missing pieces
2. Minimal gauged B-L extension of the SM

Based on $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

|       | $SU(3)_C$ | $SU(2)_L$ | $U(1)_Y$ | $U(1)_{B-L}$ |
|-------|-----------|-----------|----------|---------------|
| $q^i_L$ | 3         | 2         | 1/6      | 1/3           |
| $u^i_R$ | 3         | 1         | 2/3      | 1/3           |
| $d^i_R$ | 3         | 1         | -1/3     | 1/3           |
| $l^i_L$ | 1         | 2         | -1/2     | -1            |
| $N^i_R$ | 1         | 1         | 0        | -1            |
| $e^i_R$ | 1         | 1         | -1       | -1            |
| $H$    | 1         | 2         | -1/2     | 0             |
| $\Phi$ | 1         | 1         | 0        | 2             |

3 right-handed neutrinos (RHNs)

B-L Higgs field for the B-L breaking
Properties of gauged B-L extended SM

➢ It is easy (well-motivated) to gauge the global B-L symmetry in the SM
➢ All the gauge anomalies cancel in the presence of 3 RHNs
➢ New B-L gauge boson mass & RHNs’ Majorana masses are generated by the B-L gauge symmetry breaking
➢ The seesaw mechanism for generating tiny neutrino masses is implemented automatically.

Seesaw mechanism

\[
\begin{align*}
m_\nu &= \frac{(Y_D \langle H \rangle)^2}{M_R} \\
&= Y_D \langle H \rangle \left( \frac{Y_D \langle H \rangle}{M_R} \right) \ll Y_D \langle H \rangle
\end{align*}
\]
DM candidate is still missing in the minimal B-L model

Many proposal for introduction of DM particles

Concise model: no extension of the particle content

Example: parity-odd right-handed neutrino DM
RHN DM + Minimal Seesaw

In this talk, we consider another possibility:
the B-L Higgs boson = DM

$$\Phi = \frac{1}{\sqrt{2}} \left( v_{BL} + \sigma + i\chi \right)$$
Challenges to realize the B-L Higgs boson DM

1. Stability & Cosmic Ray constraints: \( \tau_\sigma \gtrsim 10^{25} \text{ sec} \)

Suppression for a single DM coupling & mixing

\[
\sigma - N_R - N_R : \text{related to the oscillation data via Seesaw}
\]

\[
\sigma - Z_{BL} - Z_{BL} : \text{related to } g_{BL} & M_{Z_B}
\]

\[
\sigma - h_{SM} \text{ mixing : simply dropped}
\]

It turns out that the most severe constraint is from the decay mode with off-shell B-L gauge bosons: \( \sigma \rightarrow Z_{BL}Z_{BL} \rightarrow f\bar{f}f\bar{f} \)

\[
g_{BL} \leq 4.2 \times 10^{-8} \left( \frac{M_{Z_B}}{1 \text{ GeV}} \right) \left( \frac{1 \text{ GeV}}{m_\sigma} \right)^{7/6}
\]
Challenges to realize the B-L Higgs boson DM

2. Observed DM relic density: \( \Omega_{DM} h^2 = 0.12 \)

- Due to the lifetime constraint, the DM particle must be very weakly coupling with the SM sector

- Freeze-out mechanism results in overabundance

- We consider Freeze-in mechanism

Two cases can be considered: for \( T \geq M_{Z_{BL}} \),

(i) \( Z_{BL} \) was in thermal equilibrium with the SM plasma

\[
g_{BL} > 2.7 \times 10^{-8} \left( \frac{M_{Z_{BL}}}{1 \text{ GeV}} \right)^{1/2}
\]

(ii) or not
Evaluation of the DM relic density

by solving the Boltzmann equation with DM creation cross section

The main DM creation processes

Case (i): $Z_{BL}Z_{BL} \rightarrow \sigma\sigma$

Case (ii): $f\bar{f} \rightarrow Z_{BL}\sigma$

The resultant DM relic density is controlled by only three parameters: $g_{BL}, M_{Z_{BL}}, m_{\sigma}$
Results for Case (i)

\[ \Omega_{DM} h^2 = 0.12 \] along the red lines

Freeze-out region (overabundance)

Relevant to Lifetime Frontier Experiments

Allowed

\[ \sigma \gg 10^{25} \text{ sec} \]

\[ g_{BL} > 2.7 \times 10^{-8} \left( \frac{M_{BL}}{1 \text{ GeV}} \right)^{1/2} \]

\[ \tau_\sigma \gtrsim 10^{25} \text{ sec} \]
We now comment on the $\sigma$-Higgs mixing effect on the DM lifetime. To keep the lifetime above the limit $\tau_\sigma > 10^{25}$ seconds, we set the tree-level $H^- - \Delta$ coupling in the Higgs potential to zero so that $\sigma$ and the SM Higgs field $h$ do not mix at the tree level. This will, for example, be true if the model becomes supersymmetric at a high scale. The $\sigma$-Higgs mixing in this case is loop induced as shown in Ref. [11] and for the parameter range of interest to us, can be small enough to satisfy the DM lifetime constraint as we show below.

For the case when $m_\sigma \leq m_h$, the dominant contribution to the loop induced mixing comes from an RHN fermion box diagram. This contribution is logarithmically divergent. Using the Planck mass as the cutoff, we can estimate the mixing angle to be

$$\theta \sim f^2 h^2 v_{16} \pi^2 v_{EW} v_{BL} m_h^2.$$  

Through this mixing, the DM particle can decay to a pair of SM fermions with a partial decay width of

$$\Gamma_{\sigma \rightarrow f \bar{f}} \sim \theta^2 4 \pi \left(\frac{m_f}{v_{EW}}\right)^2 m_\sigma.$$  

The lifetime constraint then translates to a limit on $g_{BL}$ as follows:

$$g_{BL} < 2 \times 10^{-8} \times \frac{1}{C_{18}} \frac{v_{EW}}{m_f} \frac{1}{C_{19}} \frac{1}{M_{3N}} \frac{1}{M_Z}.$$  

With a suitable choice of $M_{3N}$ ($> m_\sigma$), we can see that this limit is quite compatible with our results shown in the right panel of Figs. 1 and 2.

For the case when $m_\sigma > m_h$, on the other hand, the DM particle can decay to a pair of Higgs doublets through the mixing, and we find that the loop induced mixing is not

![Graph](image-url)
Results for Case (ii)

\[ \Omega_{DM} h^2 = 0.12 \text{ along the red lines} \]

\[ g_{BL} > 2.7 \times 10^{-8} \left( \frac{M_{ZBL}}{1 \text{ GeV}} \right)^{1/2} \]

\[ M_{ZBL} [\text{GeV}] \]

\[ g_{BL} \]

\[ \Omega_{DM} h^2 = \frac{\rho_{DM}}{H_0^2} \text{ (observed dark matter density)} \]

\[ M_{BL} \]

\[ \tau_{\sigma} \gtrsim 10^{25} \text{ sec} \]

\[ n_{BL} > M_P \]

\[ 10^6 \quad 10^8 \quad 10^{10} \quad 10^{12} \quad 10^{14} \quad 10^{16} \]

\[ 10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 0.1 \]

\[ 100 \text{ keV} \quad 10 \text{ MeV} \]

\[ 1 \text{ GeV} \quad 100 \text{ GeV} \quad 10 \text{ TeV} \quad 1 \text{ PeV} \quad 100 \text{ PeV} \]

\[ \sigma \]

\[ Z \]

\[ M_{ZBL} \]

\[ M_P \]
Prospects for SO(10) embedding

Generalization of the minimal B-L model: the minimal U(1) _X model

➢ The structure of the model is essentially the same
➢ SU(5) x U(1) GUT embedding is possible
➢ Then, SO(10) embedding

|      | SU(3) _c | SU(2) _L | U(1) _Y | U(1) _X | SU(5) | SO(10) |
|------|----------|----------|----------|----------|--------|--------|
| q_L  | 3        | 2        | 1/6      | 1/5      |        |        |
| u^c_L| 3*       | 1        | 2/3      | 1/5      |        |        |
| e^c_L| 1        | 1        | +1       | 1/5      |        |        |
| d^c_L| 3*       | 1        | −1/3     | −3/5     | 5*     |        |
| ℓ_L  | 1        | 2        | −1/2     | −3/5     |        |        |
| N^c_L| 1        | 1        | 0        | +1       |        | 1      |
| H    | 1        | 2        | −1/2     | 2/5      |        |        |
| Φ    | 1        | 1        | 0        | +2       |        |        |

Table 4: The particle content of the minimal U(1) _X extended SM with Z_2-parity. In addition to the SM particle content (i=1,2,3), the three RHNs (N_j^R (j=1,2)) and N^R and the U(1) _B−L Higgs field (Φ) are introduced. The unification into SU(5) x U(1) _X is achieved only for x_H = −4/5, and x_H is quantized in our model.
Successful gauge coupling unification?

➢ With a suitable set of extra matters, SU(5) gauge coupling unification is possible

➢ But, the U(1) gauge coupling is much smaller than the SM ones in our Freeze-In DM scenario

How can we realize the successful gauge coupling unification?

5D extension of the model

• $S^1/Z_2$ compactification with a brane at $y=0$
• $1/R = SU(5)$ GUT scale
5D SO(10) GUT

Extra matters (color adjoint + SU(2) adjoint scalars) @ 5 TeV

SM gauge group —> SU(5) x U(1) —> SO(10) in 5D

\[ M_{SU(5)} = 6.8 \times 10^{15} \text{ GeV} \]

\[ \frac{1}{\alpha_X} = \frac{1}{R} \equiv M_{KK} \]

SO(10) unification

SU(5) gauge boson’s KK mode contributions
5. Summary

- We have considered the minimal B-L model where the B-L Higgs boson play the role of a decaying DM

- Lifetime & observed relic density constraints require freeze-in DM scenario

- We have identified the allowed parameter region

- For a low DM mass region, the long-lived B-L gauge boson can be explored by FASER etc in the future

- SO(10) GUT embedding has been considered in 5D