Singlet scalar Dark matter in a $U(1)_{B-L}$ model without right-handed neutrinos

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$B - L$ models and anomaly cancellation

$B - L$ gauge extension of SM is the simplest model where the difference between baryon and lepton number is promoted to local gauge symmetry. SM fermion content don't cancel the triangle gauge anomalies giving

$$\mathcal{A}^{\rm SM}\left[{\rm grav}^2 U(1)_{B-L}\right] = -3 \quad \mathcal{A}^{\rm SM}\left[U(1)^3_{B-L}\right] = -3$$

Motivated by type-I seesaw mechanism, the solution is to add three right-handed neutrinos with $B - L$ charge -1 in the conventional $B - L$ models. Other possible solution is to add three exotic fermions with charges namely -4, -4, +5 [1, 2].

$$\begin{aligned}
\mathcal{A}\left[U(1)^3_{B-L}\right] &= \mathcal{A}_1^{\rm SM}\left(U(1)^3_{B-L}\right) + \mathcal{A}_1^{\rm New}\left(U(1)^3_{B-L}\right) \\
&= -3 + (4)^3 + (4)^3 + (-5)^3 = 0\,, \\
\mathcal{A}\left[\text{gravity}^2 \times U(1)_{B-L}\right] &\propto \mathcal{A}_1^{\rm SM}\left(U(1)_{B-L}\right) + \mathcal{A}_1^{\rm New}\left(U(1)_{B-L}\right) \\
&= -3 + (4) + (4) + (-5) = 0\,.
\end{aligned}$$

1. J. C. Montero and V. Pleitez, Phys. Lett. B675 (2009) 64–68.
2. E. Ma and R. Srivastava, Phys. Lett. B741 (2015) 217–222.

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Model description

	Field	$SU(2)_L \times U(1)_Y$	$U(1)_{B-L}$
Fermions	$Q_L \equiv (u, d)_L^T$	$(\mathbf{2}, 1/6)$	$1/3$
	u_R	$(\mathbf{1}, 2/3)$	$1/3$
	d_R	$(\mathbf{1}, -1/3)$	$1/3$
	$\ell_L \equiv (\nu,\ e)_L^T$	$(\mathbf{2}, -1/2)$	-1
	e_R	$(\mathbf{1}, -1)$	-1
	N_{1R}	$(\mathbf{1}, 0)$	-4
	N_{2R}	$(\mathbf{1}, 0)$	-4
	N_{3R}	$(\mathbf{1}, 0)$	5
Scalars	H	$(\mathbf{2}, 1/2)$	0
	$\phi_{\rm DM}$	$(\mathbf{1}, 0)$	$n_{\rm DM}$
	ϕ_1	$(\mathbf{1}, 0)$	-1
	ϕ_8	$(\mathbf{1}, 0)$	8

Table : Particle spectrum and their charges of the proposed $U(1)_{B-L}$ model.

Scalar potential and Yukawa terms

The scalar potential and the scalar interaction lagrangian of this model are

$$V = \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_1^2 \phi_1^\dagger \phi_1 + \lambda_1 (\phi_1^\dagger \phi_1)^2 + \mu_8^2 \phi_8^\dagger \phi_8 + \lambda_8 (\phi_8^\dagger \phi_8)^2$$
$$+ \mu_{\mathrm{DM}}^2 \phi_{\mathrm{DM}}{}^\dagger \phi_{\mathrm{DM}} + \lambda_{\mathrm{DM}} (\phi_{\mathrm{DM}}{}^\dagger \phi_{\mathrm{DM}})^2 + \lambda_{H1} (H^\dagger H)(\phi_1^\dagger \phi_1) + \lambda_{H8} (H^\dagger H)(\phi_8^\dagger \phi_8)$$
$$+ \lambda_{18} (\phi_1^\dagger \phi_1)(\phi_8^\dagger \phi_8) + \lambda_{HD} (H^\dagger H)(\phi_{\mathrm{DM}}^\dagger \phi_{\mathrm{DM}}) + \lambda_{D1} (\phi_{\mathrm{DM}}^\dagger \phi_{\mathrm{DM}})(\phi_1^\dagger \phi_1) + \lambda_{D8} (\phi_{\mathrm{DM}}^\dagger \phi_{\mathrm{D}}$$

$$\begin{aligned} \mathcal{L}_{\mathrm{scalar}} &= (\mathcal{D}_\mu H)^\dagger (\mathcal{D}^\mu H) + (\mathcal{D}_\mu \phi_{\mathrm{DM}})^\dagger (\mathcal{D}^\mu \phi_{\mathrm{DM}}) + (\mathcal{D}_\mu \phi_1)^\dagger (\mathcal{D}^\mu \phi_1) \\ &\quad + (\mathcal{D}_\mu \phi_8)^\dagger (\mathcal{D}^\mu \phi_8) - V(H, \phi_{\mathrm{DM}}, \phi_1, \phi_8), \end{aligned}$$

where the covariant derivatives are

$$\begin{aligned} \mathcal{D}_\mu H &= \partial_\mu H + i\, g \vec{W}_{\mu L} \cdot \frac{\vec{\tau}}{2} H + i \frac{g'}{2} B_\mu H, \\ \mathcal{D}_\mu \phi_{\mathrm{DM}} &= \partial_\mu \phi_{\mathrm{DM}} + i\, n_{\mathrm{DM}} g_{\mathrm{BL}} Z'_\mu \phi_{\mathrm{DM}}, \\ \mathcal{D}_\mu \phi_1 &= \partial_\mu \phi_1 - i g_{\mathrm{BL}} Z'_\mu \phi_1, \\ \mathcal{D}_\mu \phi_8 &= \partial_\mu \phi_8 + 8 i g_{\mathrm{BL}} Z'_\mu \phi_8. \end{aligned}$$

The relevant terms in the Lagrangian for fermions in the present model is given by

$$\mathcal{L}^{\rm fermion}_{\rm Kin.} = \overline{N_{1R}} i\gamma^{\mu} \left(\partial_{\mu} - 4i\, g_{\rm BL}\, Z'_{\mu}\right) N_{1R} + \overline{N_{2R}} i\gamma^{\mu} \left(\partial_{\mu} - 4i\, g_{\rm BL}\, Z'_{\mu}\right) N_{2R} + \overline{N_{3R}} i\gamma^{\mu} \left(\partial_{\mu} + 5i\, g_{\rm BL}\, Z'_{\mu}\right) N_{3R}\ .$$

The Yukawa interaction for the present model is given by

$$\begin{aligned} \mathcal{L}_{\rm Yuk} &= Y_u\, \overline{Q_L} \widetilde{H} u_R + Y_d \overline{Q_L} H\, d_R + Y_e\, \overline{\ell_L} H e_R \\ &+ \sum_{\alpha=1,2} h_{\alpha 3} \phi_1 \overline{N^c_{\alpha R}} N_{3R} + \sum_{\alpha,\beta=1,2} h_{\alpha\beta} \phi_8 \overline{N^c_{\alpha R}} N_{\beta R}\ , \end{aligned}$$

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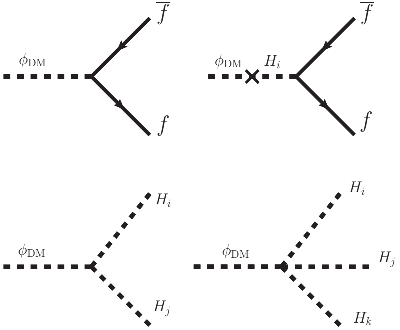
Stability of scalar dark matter

In the present model, we do not assume any ad-hoc discrete symmetry as such which can stabilize the dark matter(DM). Rather the model structure itself stabilizes the dark matter particle, say the values of n_{DM} such as $\pm 4, \pm 5$ and fractional charges forbid the decay of scalar dark matter.



Relic abundance

The relevant interaction term playing a dominant role in relic density with Z' being a connector between the visible and dark sector is given by

$$\mathcal{L}_I \supset -n_{\rm DM} i g_{\rm BL} Z'_\mu (S\partial^\mu A - A\partial^\mu S) - n^f_{\rm BL} g_{\rm BL} \bar{f}\gamma^\mu f Z'_\mu,$$

here $n^f_{\rm BL}$ denotes the $B-L$ charge for the SM fermion f and the corresponding expression for the annihilation channel is

$$\hat{\sigma}_{ff} = \sum_f \frac{n^2_{\rm DM}(n^f_{\rm BL})^2 g^4_{\rm BL} c_f}{12\pi s} \frac{(s-4M^2_{\rm DM})(s+2M^2_f)}{\left[(s-M^2_{Z'})^2 + M^2_{Z'}\Gamma^2_{Z'}\right]} \frac{(s-4M^2_f)^{\frac{1}{2}}}{(s-4M^2_{\rm DM})^{\frac{1}{2}}},$$

where c_f denotes the color charge of the fermion f with mass M_f. $M_{Z'}$ is the mass of Z' with the decay width $\Gamma_{Z'}$. We have implemented the model in LanHEP, micrOMEGAs packages to compute the relic abundance of scalar dark matter.

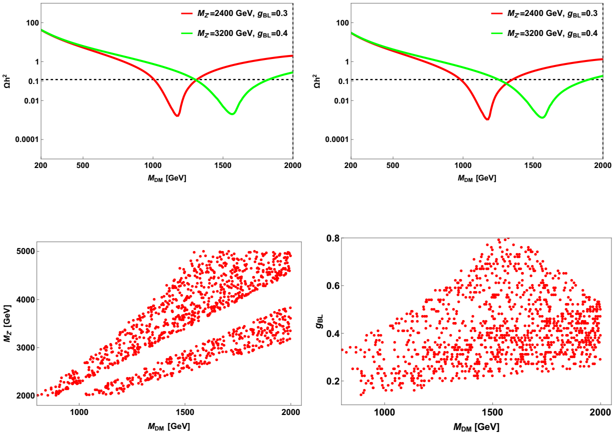


Figure : Variation of relic abundance with the mass of DM for $\frac{M_{Z'}}{g_{\rm BL}}$ values consistent with LEP-II, $n_{\rm DM} = 4$ (left panel) and $n_{\rm DM} = 5$ (right panel). Allowed region of $M_{Z'}$ and $g_{\rm BL}$ with the mass of dark matter $M_{\rm DM}$ consistent with 3σ in relic constraint for $n_{\rm DM} = 4$.

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Z' mediated contribution

The spin-independent(SI) direct detection cross-section is found to get contributions from the h and Z'-portal channels. The effective Lagrangian for Z'-mediated processes is

$$i\mathcal{L}_{\rm eff} \supset -\frac{n_{\rm DM} g_{\rm BL}^2}{3M_{Z'}^2}\left(S\partial^\mu A - A\partial^\mu S\right)\bar{u}\gamma_\mu u - \frac{n_{\rm DM} g_{\rm BL}^2}{3M_{Z'}^2}\left(S\partial^\mu A - A\partial^\mu S\right)\bar{d}\gamma_\mu d.$$

The Z' mediated DM-nucleon SI contribution is given by [3]

$$\sigma_{Z'} = \frac{\mu^2}{16\pi}\frac{n_{\rm DM}^2 g_{\rm BL}^4}{M_{Z'}^4}.$$

where $\mu = \left(\frac{M_n M_{\rm DM}}{M_n + M_{\rm DM}}\right)$ is the reduced mass of DM-nucleon system.

S. Khalil, H. Okada, and T. Toma, JHEP 07 (2011) 026 .

Higgs mediated contribution

Moving to h-portal SI contribution, the effective Lagrangian is given as

$$\mathcal{L}_{\rm eff} = \left(\frac{m_q}{v}\right)(\lambda_{HD} v)\frac{1}{m_h^2} SS\bar{q}q, \quad q = (u\ ,\ d).$$

The h-portal DM-nucleon SI contribution is given by

$$\sigma_h = \frac{\lambda_{HD}^2 f_n^2 \mu^2}{\pi} \frac{M_n^2}{M_{\rm DM}^2 M_h^4}.$$

where $f_n = 0.3 \pm 0.03$. The h-portal contribution is dependent on mass of dark matter $M_{\rm DM}$ while Z'-portal contribution is insensitive to it. It is convenient to write the individual contributions (in cm^2) with $r_{\rm BL} = \frac{M_{Z'}}{g_{\rm BL}}$ as

$$\sigma_{Z'} = 7.75 \times 10^{-42} \left(\frac{\mu}{1\ \rm GeV}\right)^2 \times {n_{\rm DM}}^2 \times \left(\frac{1\ \rm TeV}{r_{\rm BL}}\right)^4,$$

$$\sigma_h = 4.577 \times 10^{-44} \left(\frac{\mu}{1\ \rm GeV}\right)^2 \times \lambda_{HD}^2 \times \left(\frac{M_n}{1\ \rm GeV}\right)^2 \times \left(\frac{1\ \rm TeV}{M_{\rm DM}}\right)^2.$$

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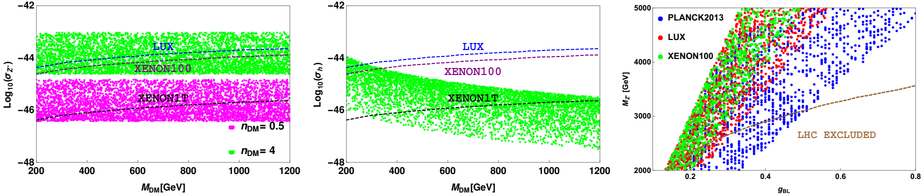

Figure : DM-Nucleon Spin independent cross section versus the mass of the DM with the ratio $r_{\rm BL} = \frac{M_{Z'}}{g_{\rm BL}}$ value varied in the range $6 - 15$ TeV. The first panel depicts Z'-mediated cross section and middle panel shows the contribution from h-mediated channels with λ_{HD} varied in the range $0.01 \to 0.1$. Third panel scattered plot in the plane of $g_{\rm BL}$ and $M_{Z'}$ where the blue, red and green points represent the values consistent with the current abundance in 3σ range, LUX and XENON100 bounds for $n_{\rm DM} = 4$. The brown dashed line denotes the LHC bound [4,5] on $B - L$ model.

4. ATLAS Collaboration, Phys. Lett. B 761 (2016) 372-392.
5. M. Klasen, F. Lyonnet, and F. S. Queiroz, arXiv:1607.06468.

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Semi annihilation

For $n_{\rm DM} = 1/3$ there is a quartic term in the Lagrangian is of the form

$$\mathcal{L}_{1/3} = \frac{\lambda'_{\rm DM}}{3}\phi_{\rm DM}^3\phi_1 + \text{h.c.}$$

With this interaction term, there is a semi-annihilation channel $\phi_{\rm DM}\phi_{\rm DM} \to \phi_{\rm DM} H_1$ whose cross section is given by

$$\hat{\sigma}_{1/3} = \frac{{\lambda'_{\rm DM}}^2}{64\pi s}\frac{\left[(s-(M_{\rm DM}+M_{H_1})^2)(s-(M_{\rm DM}-M_{H_1})^2)\right]^{\frac{1}{2}}}{[s(s-4M_{\rm DM}^2)]^{\frac{1}{2}}}.$$

Similarly for $n_{\rm DM} = 8/3$, the cross section for the semi annihilation channel $\phi_{\rm DM}\phi_{\rm DM} \to \phi_{\rm DM} H_8$

$$\mathcal{L}_{8/3} = \frac{\lambda''_{\rm DM}}{3}\phi_{\rm DM}^3\phi_8 + \text{h.c.}$$

$$\hat{\sigma}_{8/3} = \frac{{\lambda''_{\rm DM}}^2}{64\pi s}\frac{\left[(s-(M_{\rm DM}+M_{H_2})^2)(s-(M_{\rm DM}-M_{H_2})^2)\right]^{\frac{1}{2}}}{[s(s-4M_{\rm DM}^2)]^{\frac{1}{2}}}.$$

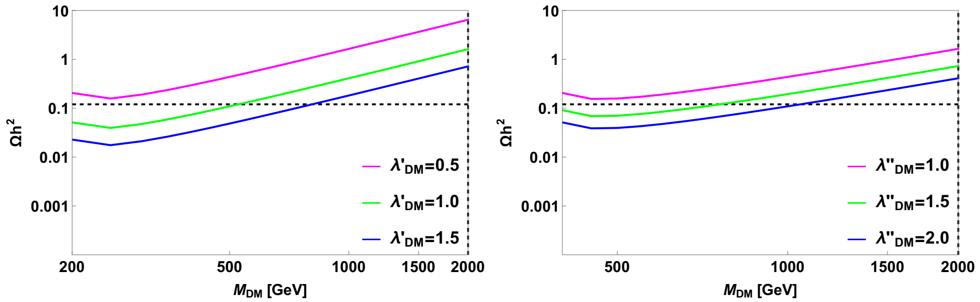

Figure : Variation of relic abundance Ωh^2 with the mass of DM for three different sets of quartic couplings $\lambda'_{\rm DM}$ and $\lambda''_{\rm DM}$ fixing $M_{H_1} = 200$ GeV and $M_{H_2} = 400$ GeV.

W. Rodejohann and C. E. Yaguna, JCAP 1512 (2015) no. 12, 032.

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Conclusion

- In this article, we have presented in detail the scalar dark matter phenomenology in the context of $U(1)_{B-L}$ extension of SM where three heavy exotic fermions with $B-L$ charges $-4, -4$ and $+5$ are added to make the model anomaly free.
- A scalar singlet $\phi_{\rm DM}$ is introduced such that the $U(1)_{B-L}$ symmetry takes care of making it a stable dark matter candidate. A viable parameter space is shown consistent with the current dark matter experimental limits and collider bounds in the light of gauge and scalar mediated channels.
- The explored model is quite consistent with current bounds of recent and ongoing DM experiments and a testable framework built based on the well-tested local gauge principles of standard model.

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Thank you

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