Dark Matter in Minimal $U(1)_{B-L}$ Model

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We study the $B-L$ gauge extension of the Standard Model which contains a singlet scalar and three right-handed neutrinos. The third generation right-handed neutrino is qualified as the dark matter candidate, as an artifact of Z_2-charge assignment. Relic abundance of the dark matter is consistent with WMAP9 and PLANCK data, only near scalar resonances. Requiring correct relic abundance, we restrict the parameter space of the scalar mixing angle and mass of the heavy scalar boson of this model.

1 Gauged $U(1)_{B-L}$ Model

The minimal $U(1)_{B-L}$ extension of the SM [1, 2, 3, 4] contains in addition to SM : a SM singlet S with $B-L$ charge +2, three right-handed neutrinos $N_R^i (i = 1, 2, 3)$ having $B-L$ charge -1. The assignment of $\mathbb{Z}_2$-odd charge ensures the stability of N_R^3 [5, 4] which qualified as a viable DM candidate. Scalar Lagrangian of this model can be written as,

$$\mathcal{L}_s = (D^\mu \Phi)^\dagger D_\mu \Phi + (D^\mu S)^\dagger D_\mu S - V(\Phi, S)\,, \tag{1}$$

where the potential term is,

$$V(\Phi, S) = m^2 \Phi^\dagger \Phi + \mu^2 |S|^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 |S|^4 + \lambda_3 \Phi^\dagger \Phi |S|^2\,,$$

with Φ and S as the SM-scalar doublet and singlet fields, respectively. After spontaneous symmetry breaking (SSB) the singlet scalar field can be written as, $S = \frac{v_{B-L}+\phi'}{\sqrt{2}}$ with v_{B-L} real and positive. The mass eigenstates (H_1, H_2) are linear combinations of ϕ and ϕ' with mixing angle α. We identify H_2 as the SM-like Higgs boson with mass 125.5 GeV.

The RH neutrinos interact with the singlet scalar field S through interaction term of the lagrangian:

$$\mathcal{L}_{int} \;=\; \sum_{i=1}^{3} \frac{y_{n_i}}{2} \overline{N_R^i} S N_R^i. \tag{2}$$

Here we define, λ_{DM} as the coupling between DM candidate and the SM Higgs boson, which is effectively the Yukawa coupling of the N_R^3. Thus, the mass of dark matter is given by, $m_{DM} = m_{N_R^3} = \frac{y_{n_3}}{\sqrt{2}} v_{B-L}$.

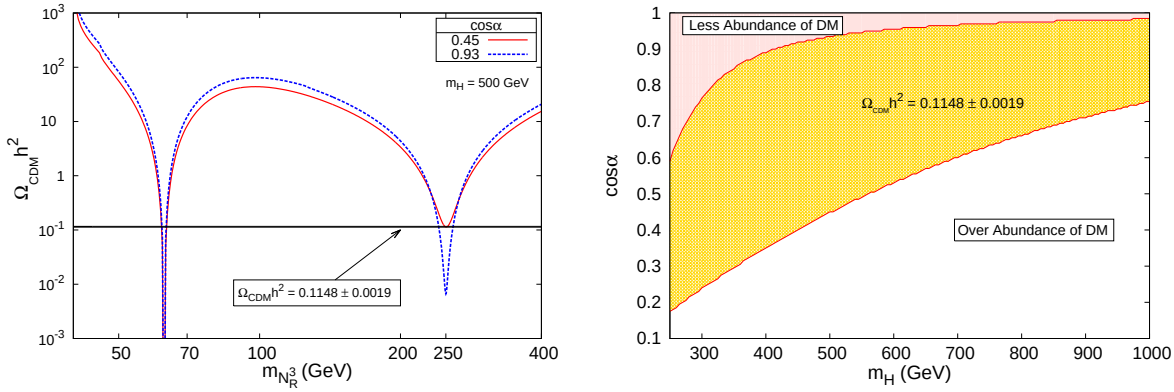

Figure 1: Left : Plot of relic abundance as a function of DM mass for $m_H = 500$ GeV with specific choices of scalar mixing angle $\cos\alpha = 0.935$ (blue-dashed), 0.45 (red-solid). The straight line shows the WMAP9 value, $\Omega_{CDM}h^2 = 0.1148 \pm 0.0019$. Right : Yellow region (in the middle) shows the allowed range of $\cos\alpha$ and m_H consistent with correct relic abundance as reported by WMAP9. The above-pink (below-white) region is disallowed due to under-abundance (over-abundance) of dark matter.

2 Dark Matter Observations

2.1 Relic Abundance

m_h	Γ_h	v_{B-L}	g_{B-L}
125 GeV	4.7×10^{-3} GeV	7 TeV	0.1

Table 1: Choice of Parameters

A specific set of benchmark values chosen is shown in Table.1. The relic abundance of DM can be formulated as [6],

$$\Omega_{CDM}h^2 = 1.1 \times 10^9 \frac{x_f}{\sqrt{g^*}m_{Pl}\langle\sigma v\rangle_{ann}}\text{GeV}^{-1} \ , \tag{3}$$

where $x_f = m_{N_R^3}/T_D$ with T_D as decoupling temperature. m_{Pl} is Planck mass $= 1.22 \times 10^{19}$ GeV, and, g^* is effective number of relativistic degrees of freedom. $\langle\sigma v\rangle_{ann}$ is the thermal averaged value of DM annihilation cross-section times relative velocity. DM interacts with the SM particles via Z'-boson and h, H. But, Z'-boson being heavy ($m_{Z'} \geq 2.33$ TeV [7]), the annihilation of DM into the SM particles takes place via h and H only. Thus, effectively we

obtain a Higgs-portal DM model. $\langle\sigma v\rangle_{ann}$ can be obtained using the well known formula [8],

$$\langle\sigma v\rangle_{ann} = \frac{1}{m^2_{N^3_R}} \left\{ w(s) - \frac{3}{2}\Big(2w(s) - 4m^2_{N^3_R} w'(s)\Big)\frac{1}{x_f} \right\}\Bigg|_{s=\left(2m_{N^3_R}\right)^2} , \tag{4}$$

where prime denotes differentiation with respect to s ($\sqrt{s}$ is the center of mass energy). Here, the function $w(s)$ depends on amplitude of different annihilation processes,

$$N^3_R N^3_R \longrightarrow b\bar{b},\, \tau^+\tau^-,\, W^+W^-,\, ZZ,\;\; hh. \tag{5}$$

In Figure. 1 the relic density is plotted against DM mass for two specific choices of scalar mixing angles. The resultant relic abundance is found to be consistent with the reported value of WMAP-9 and PLANCK experiment only near resonance when, $m_{N^3_R} \sim (1/2)\; m_{h,H}$. The reason for the over abundance of DM except at the resonance can be understood in the following way : The annihilation cross-section of DM, being proportional to $y^2_{n_3}$ (where, $y_{n_3} = (\sqrt{2}m_{N^3_R})/v_{_{B-L}}$), is heavily suppressed due to large value of $v_{_{B-L}}$.

Relic abundance near the second resonance depends on the following model parameters (unknown) : scalar mixing angle (α), heavy scalar mass (m_H) and decay width (Γ_H). For large mixing angle, the total decay width of heavy scalar is large and hence the annihilation cross-section $\langle\sigma v\rangle_{ann}$ is less compared to that with minimal mixing scenario. This behavior is observed in Figure. 1, where $\Omega_{_{CDM}}h^2$ is large for smaller value of $\cos\alpha$ (at $m_{N^3_R} \sim (1/2)\; m_H$) and vice-versa. We therefore perform a scan over the entire parameter range of m_H (300-1000 GeV) and $\cos\alpha$ (shown in Fig. 1) to find the allowed region consistent with the 9-year WMAP data [9].

2.2 Spin-independent scattering cross-section

The effective Lagrangian describing the elastic scattering of the DM off a nucleon is given by,

$$L_{eff} = f_p \bar{N^3_R} N^3_R \bar{p}p + f_n \bar{N^3_R} N^3_R \bar{n}n \;, \tag{6}$$

We obtain the scattering cross-section (spin-independent) for the dark matter off a proton or neutron as,

$$\sigma^{SI}_{p,n} = \frac{4m^2_r}{\pi} f^2_{p,n} \tag{7}$$

where, $f_{p,n}$ is the hadronic matrix element and m_r is the reduced mass.

We observe that, $\sigma^{SI}_{p,n} \propto (\sin 2\alpha)^2 f(m_H)$, which is maximum at $\alpha = \pi/4$ (or $\cos\alpha = 0.707$) irrespective of the choice of m_H. Figure. 2 shows the maximum value of spin-independent scattering cross-section (i.e, with $\cos\alpha = 0.707$) of the DM off proton (σ^{SI}_p) as a function of DM mass. We observe that the value of the resultant cross-section with two different values of m_H for the entire range 6 GeV $\leq m_{N^3_R} \leq$ 500 GeV lies much below the XENON100 and latest LUX exclusion limits. But, as the value of m_H is increased, the spin-independent cross-section becomes larger at higher values of DM mass and approaches the limits as reported by LUX and XENON100. As shown in Figure. 2, in future XENON1T data might severely restrict the choice of allowed m_H.

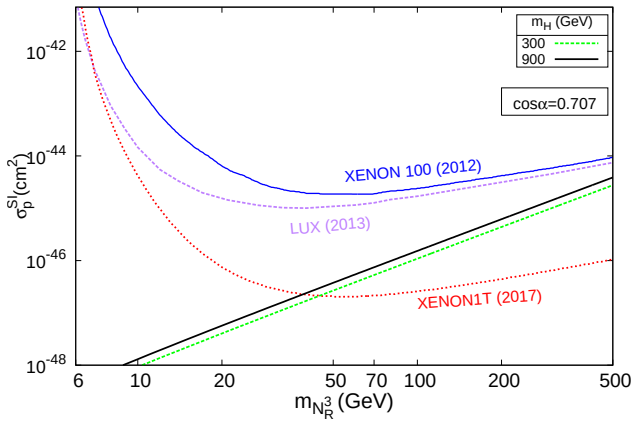

Figure 2: Variation of σ_p^{SI} with $m_{N_R^3}$ for $m_H = 300$ GeV (green-dashed) and 900 GeV (black-solid) with $\cos\alpha = 0.707$. The blue and violet curves show the bound from XENON100 [10] and LUX [11] data respectively. Red curve shows the projected limits for XENON1T [12] .

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