RECEIVED: January 8, 2021

REVISED: May 24, 2021

ACCEPTED: June 8, 2021

PUBLISHED: June 18, 2021

Vector dark matter from a gauged SU(2) symmetry

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ABSTRACT: We propose a scenario of dark sector described by a hidden SU(2) gauge symmetry which is broken by a vacuum expectation value (VEV) of a scalar multiplet. We discuss a general mass relation among SU(2) gauge bosons after spontaneous symmetry breaking which is determined by weight of gauge group representation associated with a scalar multiplet developing VEV. Then a model with quintet and triplet scalar fields is discussed in which hidden gauge boson can be dark matter (DM) stabilized by remnant discrete Z_2 symmetry and resonant dark matter annihilation is realized by mass relation between DM and mediator. We estimate relic density and spin independent DM-nucleon scattering cross section searching for allowed parameter region.

KEYWORDS: Beyond Standard Model, Gauge Symmetry

ARXIV EPRINT: [2012.11377](https://arxiv.org/abs/2012.11377)

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1 Introduction

Explanation of dark matter(DM) nature is one of the outstanding issues which requires physics beyond the standard model(SM). One promising candidate of DM is a stable particle weakly interacting with the SM particles where its relic density in current Universe can be explained by thermal production. Interactions among DM and the SM particles have been tested by direct detection, indirect detection and collider experiments. However we have no clear signal of DM in such experiments indicating that interaction among DM and the SM particle would be sufficiently weak to escape these searches.

In describing DM physics, one attractive scenario is introduction of dark sector that is described by hidden gauge symmetry as the SM sector is also described by gauge symmetry; here we indicate hidden gauge symmetry under which the SM fields are neutral. In such a scenario we can explain stability of DM by a remnant of hidden gauge symmetry after spontaneous symmetry breaking [1, 2]. In particular a case of non-Abelian group is interesting since an unbroken discrete symmetry can be naturally preserved; in Abelian case we might need to tune charge assignment since its choice is more arbitrary compared to non-Abelian case. Moreover hidden gauge boson(s) can be DM candidate depending on a structure of remnant symmetry. Here we focus on the simplest non-Abelian gauge group $SU(2)$ as hidden gauge symmetry. In fact, various approaches applying a hidden $SU(2)$ gauge symmetry have been discussed in literatures, for examples, a remaining $Z_{2,3,4}$ symmetry with a quadruplet(quintet) in refs. [3–7], $Z_2 \times Z'_2$ symmetry [8], a custodial symmetry in refs. [9, 10], an unbroken $U(1)$ from $SU(2)$ in refs. [11–13], a model adding hidden $U(1)_h$ [14], other DM scenarios [15–18], a model with classical scale invariance [19], Baryogenesis [20] and electroweak phase transition [21].

In this paper, we consider a scenario of dark sector described by hidden $SU(2)$ gauge symmetry which is broken by a vacuum expectation value(VEV) of scalar multiplet(s).

Then we show general mass relation among SU(2) gauge bosons after spontaneous symmetry breaking which is determined by weight of gauge group representation associated with a scalar multiplet developing VEV. It is found that hidden gauge bosons can be DM and mediator Z' with mass ratio of 1 : 2 realizing resonant DM annihilation when SU(2) is broken by scalar quintet VEV. In our scenario Z' from hidden SU(2) can interact with SM particles via kinetic mixing coming from higher dimensional operator with triplet VEV. Note that we consider mass mixing between hidden SU(2) and U(1)_{B-L} gauge bosons to realize interactions between DM and SM particles in ref. [3] where resonant annihilation of DM occurs by the similar mechanism. In our model discussed in this work we simplify the structure of gauge sector without U(1)_{B-L} and thus interactions between DM and SM particles via Z' exchange differs from ref. [3]. We then discuss relic density and DM-nucleon scattering cross section in our model.

This paper is organized as follows. In section 2, we show general relation among SU(2) gauge bosons after spontaneous symmetry breaking. In section 3 we consider a model realizing resonant annihilation of DM and estimate relic density of DM and spin independent nucleon-DM scattering cross section. We then conclude and discuss in section 4.

2 General aspect

In this section we discuss SU(2) gauge symmetry which is spontaneously broken by a VEV of a scalar field, and show relation among massive gauge boson masses after symmetry breaking in general way.

Let us start from the definition of a scalar field Φ belonging to SU(2) multiplet whose components are described by ℓ, m , where numbers ℓ and m respectively correspond to the highest weight and weight (eigenvalue of diagonal generator T_3). Then, we symbolize it as

$$\Phi \equiv \left[\phi_{\ell, \ell}^{(2\ell)}, \dots, \phi_{\ell, m+1}^{(\ell+m+1)}, \phi_{\ell, m}^{(\ell+m)}, \phi_{\ell, m-1}^{(\ell+m-1)}, \dots, \phi_{\ell, -\ell}^{(0)} \right]^T, \quad (2.1)$$

where the number of component is $2\ell + 1$; $-\ell \leq m \leq \ell$, which corresponds to the dimension of representation of our gauged SU(2) symmetry, and the upper indices represent an order of components from 0 to 2ℓ .

Here, we show several examples in the SU(2)_L × U(1)_Y case. If Φ is Higgs field in the SM; $\ell = \frac{1}{2}$ and hypercharge $Y = \frac{1}{2}$, one writes it to $\Phi = \left[\phi_{\frac{1}{2}, \frac{1}{2}}^{(1)}, \phi_{\frac{1}{2}, -\frac{1}{2}}^{(0)} \right]^T$. Here upper indices coincide with electric charge since it is defined by $Q = T_3 + Y$ and $Y = \ell$; each of the charges is 1 and 0. As another example, let us consider the Higgs triplet with $\ell = 1$ and $Y = 1$, which is often used to explain the active Majorana neutrino mass matrix via type-II seesaw mechanism. In this case, we have $\Phi = \left[\phi_{1,1}^{(2)}, \phi_{1,0}^{(1)}, \phi_{1,-1}^{(0)} \right]^T$. The upper indices coincide with electric charge again due to $Y = \ell$ and then each of the charges is found to be 2, 1 and 0 that are consistent with the component of Higgs triplet. Notice here that we consider SU(2) is a hidden symmetry, thus nonzero VEV can be found in the components with nonzero charge.

Next, let us consider the kinetic term of $\Phi_{\ell,m}$, which is written by

$$\mathcal{L}_{kin} = (D_\mu \Phi_{\ell,m})^\dagger (D^\mu \Phi_{\ell,m}), \quad (2.2)$$

$$D_\mu = \partial_\mu - i \frac{g_X}{\sqrt{2}} (T^+ X_\mu^+ + T^- X_\mu^-) - ig_X T_3 X_\mu^3, \quad (2.3)$$

where $X_\mu^\pm \equiv (X_\mu^1 \mp i X_\mu^2)/\sqrt{2}$ and the following relations are found

$$\begin{aligned} T^+ & \left[\phi_{\ell,\ell}^{(2\ell)}, \dots, \phi_{\ell,m+1}^{(\ell+m+1)}, \phi_{\ell,m}^{(\ell+m)}, \phi_{\ell,m-1}^{(\ell+m-1)}, \dots, \phi_{\ell,-\ell}^{(0)} \right]^T \\ &= \left[C_{\ell,\ell-1}^+ \phi_{\ell,\ell-1}^{(2\ell-1)}, \dots, C_{\ell,m}^+ \phi_{\ell,m}^{(\ell+m)}, C_{\ell,m-1}^+ \phi_{\ell,m-1}^{(\ell+m-1)}, C_{\ell,m-2}^+ \phi_{\ell,m-2}^{(\ell+m-2)}, \dots, 0 \right]^T, \end{aligned} \quad (2.4)$$

$$\begin{aligned} T^- & \left[\phi_{\ell,\ell}^{(2\ell)}, \dots, \phi_{\ell,m+1}^{(\ell+m+1)}, \phi_{\ell,m}^{(\ell+m)}, \phi_{\ell,m-1}^{(\ell+m-1)}, \dots, \phi_{\ell,-\ell}^{(0)} \right]^T \\ &= \left[0, \dots, C_{\ell,m+2}^- \phi_{\ell,m+2}^{(\ell+m+2)}, C_{\ell,m+1}^- \phi_{\ell,m+1}^{(\ell+m+1)}, C_{\ell,m}^- \phi_{\ell,m}^{(\ell+m)}, \dots, C_{\ell,-\ell+1}^- \phi_{\ell,-\ell+1}^{(1)} \right]^T, \end{aligned} \quad (2.5)$$

$$\begin{aligned} T_3 & \left[\phi_{\ell,\ell}^{(2\ell)}, \dots, \phi_{\ell,m+1}^{(\ell+m+1)}, \phi_{\ell,m}^{(\ell+m)}, \phi_{\ell,m-1}^{(\ell+m-1)}, \dots, \phi_{\ell,-\ell}^{(0)} \right]^T \\ &= \left[\ell \phi_{\ell,\ell}^{(2\ell)} \dots, (m+1) \phi_{\ell,m+1}^{(\ell+m+1)}, m \phi_{\ell,m}^{(\ell+m)}, (m-1) \phi_{\ell,m-1}^{(\ell+m-1)}, \dots, -\ell \phi_{\ell,-\ell}^{(0)} \right]^T, \end{aligned} \quad (2.6)$$

where we defined $C_{\ell,m}^+ \equiv \sqrt{(\ell-m)(\ell+m+1)}$ and $C_{\ell,m}^- \equiv \sqrt{(\ell+m)(\ell-m+1)}$.

Then, we find the following mass terms for vector bosons when only $\langle \phi_{\ell,m}^{(\ell+m)} \rangle = v_\Phi/\sqrt{2} \neq 0$

$$\begin{aligned} & \frac{g_X^2}{4} \left[(C_{\ell,m}^+)^2 + (C_{\ell,m}^-)^2 \right] v_\Phi^2 X_\mu^+ X^{-\mu} + \frac{g_X^2}{2} m^2 v_\Phi^2 X_\mu^3 X^{3\mu} \\ & \equiv m_{X^\pm}^2 X_\mu^+ X^{-\mu} + \frac{1}{2} m_{X^3}^2 X_\mu^3 X^{3\mu}. \end{aligned} \quad (2.7)$$

Taking the mass ratio between $X_\mu^\pm$ and X_μ^3 , one finds

$$\frac{m_{X^3}^2}{m_{X^\pm}^2} = \frac{4m^2}{(C_{\ell,m}^+)^2 + (C_{\ell,m}^-)^2} = \frac{4m^2}{(\ell-m)(\ell+m+1) + (\ell+m)(\ell-m+1)}. \quad (2.8)$$

Here we consider only one scalar field develops a VEV but it is straitforward to extend more general cases in which multiple scalar fields and/or more than one components in a multiplet develop non-zero VEVs.

In case of $\ell = |m| = 2$, especially, one finds the mass ratio of gauge bosons as follows:

$$\frac{m_{X^3}^2}{m_{X^\pm}^2} = 4. \quad (2.9)$$

Here $\ell = 2$ case corresponds to a quintet scalar field $\Phi = [\phi_{2,2}^{(4)}, \phi_{2,1}^{(3)}, \phi_{2,0}^{(2)}, \phi_{2,-1}^{(1)}, \phi_{2,-2}^{(0)}]^T$, where only $\phi_{2,2}^{(4)}$ has non-vanishing VEV.¹ Remarkably eq. (2.9) indicates that $X_\mu^\pm$ annihilates into pairs of SM particles around the resonant point when $X_\mu^\pm$ is DM and X_μ^3 is mediator decaying into SM fields. Note also that a component with even and odd m have respectively Z_2 parity even and odd where this remnant Z_2 can stabilize $X^\pm$ since it has $m = \pm 1$. We discuss a model with a quintet scalar field realizing resonant DM annihilation scenario in next section.

¹This relation is pointed out in ref. [3].

3 A model with resonant dark matter annihilation

In this section we consider a model with hidden $SU(2)_X$ gauge symmetry introducing real quintet and triplet scalar fields denoted by Φ and $\Phi' = [\phi'_{1,1}, \phi'_{1,0}, \phi'_{1,-1}]^T$, respectively. In this setup resonant DM annihilation is realized by mass relation between DM and mediator gauge boson, and interaction between dark sector and the SM sector is obtained via kinetic mixing between $SU(2)_X$ and $U(1)_Y$ gauge fields. In our model scalar potential is written by

$$V = \frac{1}{2}M_\Phi^2\Phi^2 + \frac{1}{2}M_{\Phi'}^2\Phi'^2 + \mu_1\Phi\Phi'\Phi' + \mu_2\Phi\Phi\Phi + \lambda_1(\Phi^4) + \lambda_2(\Phi'^4) + \lambda_{H\Phi}|H|^2\Phi^2 + \lambda_{H\Phi'}|H|^2\Phi'^2 + V(H), \quad (3.1)$$

where H is the SM Higgs, $V(H)$ is scalar potential including only H , each term is contracted to be $SU(2)_X$ singlet implicitly, and we assume invariant contraction of $SU(2)_X$ representation indices for each term. Here we discuss how to obtain $SU(2)_X$ gauge invariant contraction where we use symmetric tensor notation of triplet and quintet given in the appendix A. Non-zero three point interactions are given by

$$\Phi^3 = \Phi_{ijkl}\Phi_{mn}^{ij}\Phi^{klmn} = -\frac{8}{3}\left(\sqrt{6}(\phi_{2,0}^{(2)})^3 + 9\phi_{2,2}^{(4)}(\phi_{2,-1}^{(1)})^2 + 9\phi_{2,-2}^{(4)}(\phi_{2,1}^{(3)})^2 + 3\sqrt{6}\phi_{2,0}^{(2)}(\phi_{2,1}^{(3)}\phi_{2,-1}^{(1)} - 2\phi_{2,2}^{(4)}\phi_{2,-2}^{(0)})\right) \quad (3.2)$$

$$\Phi\Phi'\Phi' = \Phi_{ijkl}\Phi^{ij}\Phi'^{kl} = -\sqrt{\frac{2}{3}}\phi_{2,0}^{(2)}(\phi'_{1,0}^{(1)})^2 + i\sqrt{2}\phi_{2,-1}^{(1)}\phi'_{1,1}^{(2)}\phi'_{1,0}^{(1)} - i\sqrt{2}\phi_{2,1}^{(3)}\phi'_{1,-1}^{(0)}\phi'_{1,0}^{(1)} + \sqrt{\frac{2}{3}}\phi_{2,0}^{(2)}\phi'_{1,1}^{(2)}\phi'_{1,-1}^{(0)} + \phi_{2,-2}^{(0)}(\phi'_{1,1}^{(2)})^2 + \phi_{2,2}^{(4)}(\phi'_{1,-1}^{(0)})^2. \quad (3.3)$$

Four point interactions are also given by

$$\Phi'^4 = (\Phi'_{ij}\Phi'^{ij})^2 = \frac{1}{2}(\phi'_{1,0}^{(1)})^4 + 2(\phi'_{1,0}^{(1)})^2\phi'_{1,1}^{(2)}\phi'_{1,-1}^{(0)} + 2(\phi'_{1,1}^{(2)}\phi'_{1,-1}^{(0)})^2 \quad (3.4)$$

$$\Phi^4 = (\Phi_{ijkl}\Phi^{ijkl})^2 = \frac{1}{2}(\phi_{2,0}^{(2)})^4 + 2(\phi_{2,0}^{(2)})^2\phi_{2,1}^{(3)}\phi_{2,-1}^{(1)} + 2(\phi_{2,1}^{(3)}\phi_{2,-1}^{(1)})^2 + 2(\phi_{2,0}^{(2)})^2\phi_{2,2}^{(4)}\phi_{2,-2}^{(0)} + 4\phi_{2,1}^{(3)}\phi_{2,-1}^{(1)}\phi_{2,2}^{(4)}\phi_{2,-2}^{(0)} + 2(\phi_{2,2}^{(4)}\phi_{2,-2}^{(0)})^2. \quad (3.5)$$

We find only one non-zero contraction for (Φ'^4) and other non-zero contractions for (Φ^4) give same one.² The other terms such as $|H|^2\Phi^2$ can be trivially obtained. In our analysis we do not discuss details of scalar potential and assume our VEV alignments are obtained by turning parameters in potential.

3.1 Mass spectrum and relevant interactions

Firstly, we discuss our gauge symmetry breaking pattern when $\phi_{2,2}^{(4)}$ and $\phi'_{1,0}^{(0)}$ develop non-zero VEVs. The quintet VEV $\langle\Phi\rangle$ is invariant under the unitary transformation of $U_{T_3} = e^{i\pi T_3}$; $U_{T_3}\langle\Phi\rangle = \langle\Phi\rangle$, where $T_3 \equiv \text{diag}(2, 1, 0, -1, -2)$. Then, each of the components of Φ and Φ' has parity odd and even; $\text{Parity}(\phi_{2,2}^{(4)}, \phi_{2,1}^{(3)}, \phi_{2,0}^{(2)}, \phi_{2,-1}^{(1)}, \phi_{2,-2}^{(0)}) = (+, -, +, -, +)$ and

²Other contractions such as $\Phi_{ijkl}\Phi_{mn}^{ij}\Phi_{ab}^{kl}\Phi^{abmn}$ give the same terms as eq. (3.5).

Parity($\phi'_{1,1}{}^{(2)}, \phi'_{1,0}{}^{(1)}, \phi'_{1,-1}{}^{(0)}$) = $(-, +, -)$ under U_{T_3} transformation. It suggests that we have a remnant Z_2 symmetry that plays a role in stabilizing the DM candidate with odd parity as discussed below. Note also that if we introduce a field having half integer ℓ (without developing a VEV), a remnant symmetry becomes Z_4 ; for example a ($\ell = 1/2$) doublet field $\eta = (\eta_1, \eta_2)^T$ transform as $U_{T_3}\eta = (i\eta_1, -i\eta_2)^T$.

Next step is to find how X_μ^3 interacts with the SM fields. In order to realize the interaction, we introduce an $SU(2)_X$ triplet scalar field φ which is given by

$$\varphi = \varphi_a \frac{\sigma^a}{2} = \begin{pmatrix} \frac{1}{2}\phi'_{1,0}{}^{(1)} & \frac{1}{\sqrt{2}}\phi'_{1,1}{}^{(2)} \\ \frac{1}{\sqrt{2}}\phi'_{1,-1}{}^{(0)} & -\frac{1}{2}\phi'_{1,0}{}^{(1)} \end{pmatrix}, \quad (3.6)$$

where the elements in the most right side correspond to our standard form.³ Then we can write the following term: the relevant term for these kinetic mixing is dim-5 operator [7, 22]:

$$\mathcal{L}_{XB} = \frac{C_\varphi}{\Lambda} X_{\mu\nu}^a \tilde{B}^{\mu\nu} \varphi^a \quad (3.7)$$

where Λ indicates the cut off scale and $X_{\mu\nu}^a = \partial_\mu X_\nu^a - \partial_\nu X_\mu^a + \epsilon^{abc} g_X X_\mu^b X_\nu^c$ and $\tilde{B}^{\mu\nu}$ are the gauge field strength for $SU(2)_X$ and $U(1)_Y$, respectively (g_X and ϵ^{abc} are $SU(2)_X$ gauge coupling and anti-symmetric tensor). After φ developing VEV,

$$\langle \varphi \rangle = \begin{pmatrix} \frac{1}{2\sqrt{2}}v_\varphi & 0 \\ 0 & -\frac{1}{2\sqrt{2}}v_\varphi \end{pmatrix}, \quad (3.8)$$

we obtain the following kinetic mixing term:

$$\mathcal{L}_{KM} = -\frac{1}{2} \sin \chi X_{\mu\nu}^3 \tilde{B}^{\mu\nu}, \quad (3.9)$$

where we define $\sin \chi \equiv \sqrt{2}C_\varphi v_\varphi / \Lambda$ as a new kinetic mixing parameter.

The kinetic terms for X_μ^3 and $\tilde{B}_\mu$ can be diagonalized by the following transformations (we neglect refractive phenomena contributed by a forwardly scattering off the thermal bath, i.e. plasma effect [23–28]):

$$\tilde{B}_\mu = B_\mu - \tan \chi X_\mu^3, \quad (3.10)$$

$$\tilde{X}_\mu^3 = \frac{1}{\cos \chi} X_\mu^3. \quad (3.11)$$

In our analysis, we take a limit of $\chi \ll 1$ and gauge fields are approximately written by

$$\tilde{B}_\mu \simeq B_\mu - \chi X_\mu^3, \quad \tilde{X}_\mu^3 \simeq X_\mu^3. \quad (3.12)$$

Here we denote dark gauge bosons associated with $X_\mu^{1,2,3}$ field as $X_{1,2,3}$ henceforth. After quintet and triplet scalar fields develop nonzero VEVs, we obtain mass terms for $SU(2)_X$

³The relations between φ_a and components in our standard form; $\phi'_{1,m}{}^{(\ell+m)}$, are given by $\phi'_{1,1}{}^{(2)} = (\varphi_1 - i\varphi_2)/\sqrt{2}$, $\phi'_{1,-1}{}^{(0)} = (\varphi_1 - i\varphi_2)/\sqrt{2}$ and $\phi'_{1,0}{}^{(1)} = \varphi_3$.

Figure 1. $\sin \theta_{ZZ'}$ as a function of $m_{X^\pm}$ for $\chi = 10^{-2}$ and 10^{-3} where we fix $2v_\varphi^2/v_\Phi^2 = 0.01$.

gauge fields and SM Z boson field including kinetic mixing effect such that

$$L_M = \frac{1}{2}m_{Z_{\text{SM}}}^2 \tilde{Z}_\mu \tilde{Z}^\mu + m_{Z_{\text{SM}}}^2 \chi \sin \theta_W \tilde{Z}_\mu X^{3\mu} + \frac{1}{2}m_{X^3}^2 X_\mu^3 X^{3\mu} + m_{X^\pm}^2 X_\mu^+ X^{-\mu}, \quad (3.13)$$

$$m_{Z_{\text{SM}}}^2 = \frac{v^2}{4}(g^2 + g_B^2), \quad m_{X^3}^2 = 4g_X^2 v_\Phi^2, \quad m_{X^\pm}^2 = g_X^2 v_\Phi^2 \left(1 + \frac{v_\varphi^2}{v_\Phi^2}\right), \quad (3.14)$$

where $\tilde{Z}$ is Z boson field in the SM, g and g_B are gauge couplings of SU(2) and U(1)_Y, and v is the SM Higgs VEV. Diagonalizing $\tilde{Z}$ and X^3 mass terms, mass eigenstate and mixing angles are given by

$$m_{Z,Z'}^2 = \frac{1}{2}(m_{X^3}^2 + m_{Z_{\text{SM}}}^2) \mp \frac{1}{2}\sqrt{(m_{X^3}^2 - m_{Z_{\text{SM}}}^2)^2 + 4\chi^2 \sin^2 \theta_W m_{Z_{\text{SM}}}^4}, \quad (3.15)$$

$$\tan 2\theta_{ZZ'} = \frac{2 \sin \theta_W \chi m_{Z_{\text{SM}}}^2}{m_{Z_{\text{SM}}}^2 - m_{X^3}^2}, \quad (3.16)$$

where we approximate $m_Z \simeq m_{Z_{\text{SM}}}$ and $m_{Z'} \simeq m_{X^3}$ for tiny χ , and we take $0 \leq \theta_{ZZ'} \leq \frac{\pi}{2}$. The mass eigenstates are written by

$$\begin{pmatrix} Z \\ Z' \end{pmatrix} = \begin{pmatrix} \cos \theta_{ZZ'} & -\sin \theta_{ZZ'} \\ \sin \theta_{ZZ'} & \cos \theta_{ZZ'} \end{pmatrix} \begin{pmatrix} \tilde{Z} \\ X^3 \end{pmatrix}. \quad (3.17)$$

In figure 1, we show $\sin \theta_{ZZ'}$ as a function of $m_{X^\pm}$ for $\chi = 10^{-2}$ and 10^{-3} where we fix $2v_\varphi^2/v_\Phi^2 = 0.01$. We find that $\sin \theta_{ZZ'} \lesssim 10^{-3}$ for $\chi \leq 10^{-2}$ and $m_{X^\pm} \geq 100$ GeV, and thus it is safe from current constraints [29].

Finally interactions among dark gauge fields are also given by

$$\mathcal{L} \supset -g_X \epsilon^{abc} \partial_\mu X_\nu^a X^{b\mu} X^{c\nu} - \frac{1}{4} g_X^2 \epsilon^{abc} \epsilon^{ade} X_\mu^b X_\nu^c X^{d\mu} X^{e\nu}, \quad (3.18)$$

where ϵ^{abc} is the structure constants of $SU(2)_X$ and $a = 1, 2, 3$. Since $m_{Z'} \simeq m_{X^3} \gtrsim m_{X^\pm}$ the four point gauge interaction in eq. (3.18) does not provide dominant contribution to DM annihilation process. We thus focus on the three point interaction which is given by $X^\pm$ and Z' such that

$$\begin{aligned} \mathcal{L} \supset & ig_X C_{ZZ'} \left[(\partial_\mu X_\nu^+ - \partial_\nu X_\mu^+) X^{-\mu} Z'^\nu - (\partial_\mu X_\nu^- - \partial_\nu X_\mu^-) X^{+\mu} Z'^\nu \right. \\ & \left. + \frac{1}{2} (\partial_\mu Z'_\nu - \partial_\nu Z'_\mu) (X^{+\mu} X^{-\nu} - X^{-\mu} X^{+\nu}) \right], \end{aligned} \quad (3.19)$$

where $C_{ZZ'} \equiv \cos \theta_{ZZ'}$. Then Z' interacts with the SM particles via Z - Z' mixing. The Z' interaction with SM fermions f is given by

$$\mathcal{L}_{Z' \bar{f} f} = \sum_{X=L,R} \frac{g}{\cos \theta_W} Z'_\mu \bar{f}_X \gamma^\mu \left[S_{ZZ'} (T_3 - Q \sin^2 \theta_W) + C_{ZZ'} \chi Y \sin \theta_W \right] f_X, \quad (3.20)$$

where T_3 is diagonal generator of $SU(2)_L$, Q is the electric charge, $S_{ZZ'} \equiv \sin \theta_{ZZ'}$, and $C_{ZZ'} \equiv \cos \theta_{ZZ'}$. Note that we reproduce dark photon interaction for $m_{Z'} \ll m_Z$ such that

$$\mathcal{L}_{Z' \bar{f} f} \sim Z'_\mu \left[\chi \cos \theta_W e J_{\text{EM}}^\mu + \sum_{X=L,R} \frac{m_{Z'}^2}{m_Z^2} \frac{\chi g \sin \theta_W}{\cos \theta_W} \bar{f}_X (T_3 - Q \sin^2 \theta_W) \gamma^\mu f_X \right], \quad (3.21)$$

where we used $S_{ZZ'} \simeq \chi \sin \theta_W (1 + m_{Z'}^2/m_Z^2)$ and J_{EM}^μ is the electromagnetic current of the SM.

3.2 Dark matter physics

Here we discuss dark matter physics such as relic density and direct detection by carrying out numerical analysis. In our analysis we write Z' mass by

$$m_{Z'} \simeq 2m_{X^\pm} (1 + R_M)^{-\frac{1}{2}} \quad (3.22)$$

where we ignored tiny kinetic mixing effect and $R_M \equiv v_\phi^2/v_\Phi^2$ representing deviation from the relation $m_{Z'} = 2m_{X^\pm}$. We expect $R_M \ll 1$ so that we can explain the sizable relic density by resonant enhancement. Note that if the hidden gauge coupling g_X is very large around order 1, the resonant point would not be needed to explain the correct relic density. Performing numerical analysis, we search for parameter region satisfying observed relic density of $\Omega h^2 \sim 0.12$ [30].

We calculate relic density of DM with *micrOMEGAs 5* [31] implementing relevant interactions. In our analysis, we randomly scan parameters $\{m_{X^\pm}, g_X, R_M\}$ within the following region

$$m_{X^\pm} \in [100, 5500] \text{ GeV}, \quad g_X \in [0.001, 1.0], \quad R_M \in [0.001, 0.1], \quad (3.23)$$

where we consider two values of kinetic mixing parameter as $\chi = 10^{-2}$ and 10^{-3} . Each point in figure 2 shows parameter sets which realize relic density of DM in approximated observed region of $0.11 \leq \Omega h^2 \leq 0.13$; here we fix $\chi = 10^{-3}$ but the behavior will be the same if we choose $\chi = 10^{-2}$ since only Z' width is affected by the change. Here color

Figure 2. The parameter points which realize relic density of DM as $0.11 \leq \Omega h^2 \leq 0.13$; we fix $\chi = 10^{-3}$ here. The color gradient indicates the value of R_M .

gradient in the figure indicates the value of R_M as shown in color bar. We find that observed relic density can be explained by $0.01 \lesssim g_X \lesssim 1.0$ for DM mass range $[100, 5500]$ GeV where g_X tends to be larger for large R_M since resonant enhancement becomes smaller.

Next we discuss direct detection of DM calculating nucleon-DM scattering cross section for allowed parameter sets which explain observed relic density. In our case nucleon and DM interact via Z and Z' exchanging process due to Z - Z' mixing effect. Spin independent nucleon-DM scattering cross section is obtained by

$$\sigma_{NX} = \frac{2g_X^2 g^2}{\pi \cos^2 \theta_W} \left(\frac{m_{X\pm} m_N}{m_X + m_N} \right)^2 \left(\frac{S_{ZZ'} C_{NNZ}^V}{m_Z^2} + \frac{C_{ZZ'} C_{NNZ'}^V}{m_{Z'}^2} \right)^2, \quad (3.24)$$

where m_N is nucleon mass ($N = p, n$). The nucleon- $Z(Z')$ vector coupling $C_{NNZ(Z')}^V$ is given by

$$\begin{aligned} C_{ppZ}^V &= C_{ZZ'} \left(\frac{1}{4} - \sin^2 \theta_W \right), & C_{nnZ}^V &= C_{ZZ'} \left(-\frac{1}{4} \right), \\ C_{ppZ'}^V &= -S_{ZZ'} \left(\frac{1}{4} - \sin^2 \theta_W \right) + \frac{3}{2} C_{ZZ'} \sin \theta_W \delta, & C_{nnZ'}^V &= \frac{1}{4} S_{ZZ'} + \frac{1}{2} C_{ZZ'} \sin \theta_W \delta. \end{aligned} \quad (3.25)$$

In figure 3, we show $\bar{\sigma}_{NX} \equiv (\sigma_{pX} + \sigma_{nX})/2$ as a function of DM mass for allowed parameter sets where left and right plots show DM mass range $[100, 1000]$ GeV and $[1000, 5500]$ GeV respectively. We also compare our result with experimental constraints by XENON1T [32, 33] and neutrino scattering limit [34]. For $\chi = 10^{-3}$, the scattering cross sections are much less than current bound. They are even smaller than neutrino scattering limit except for light DM region $m_{X\pm} \lesssim 250$ GeV. For $\chi = 10^{-2}$, the scattering cross sections are above current bound in $m_{X\pm} \lesssim 150$ GeV region, between neutrino scattering limit and current bound in

Figure 3. Spin independent DM-nucleon scattering cross section for allowed parameter sets where dashed curve corresponds to XENON1T constraint and dotted curve corresponds to neutrino scattering limit.

$150 \text{ GeV} \lesssim m_{X^\pm} \lesssim 1200 \text{ GeV}$, and below neutrino scattering limit in $m_{X^\pm} \gtrsim 1200 \text{ GeV}$. Thus DM signal could be detected for $\chi = 10^{-2}$ and $m_{X^\pm} \lesssim 1200 \text{ GeV}$ in future experiments while it is difficult to test DM signal by direct detection for small kinetic mixing parameter χ .

Before closing this section we comment on DM production at collider experiments. Our DM candidate $X^\pm$ can be produced at collider via Z' and/or scalar portal when we have Z - Z' mixing and/or mixing between new scalar from $\Phi^{(\prime)}$ and SM Higgs. From Z - Z' mixing, we would have $q\bar{q} \rightarrow Z' \rightarrow X^+X^-$ process where we need extra jet/photon to detect at collider experiments. From scalar mixing, we would have $gg \rightarrow \phi \rightarrow X^+X^-$ process where ϕ is a scalar boson which is mixture of SM Higgs and a new scalar boson. Detailed study of collider signal is beyond the scope of this paper and it will be given in future works.

4 Conclusions and discussions

We have proposed a scenario of dark sector described by hidden $SU(2)$ gauge symmetry which is broken by a VEV of scalar multiplet. Firstly we have discussed general mass relation among $SU(2)$ gauge bosons after spontaneous symmetry breaking which is determined by weight of gauge group representation associated with a scalar multiplet developing VEV. Interestingly, when $SU(2)$ is broken by scalar quintet VEV, hidden gauge bosons can be DM and mediator with mass ratio of 1 : 2 which realizes resonant DM annihilation. In addition Z_2 symmetry stabilizing DM is naturally obtained in this case.

Then we have discussed a model introducing hidden $SU(2)_X$ quintet and triplet scalar fields in which resonant DM annihilation is realized. In this model dark sector and the SM sector interact through kinetic mixing between $SU(2)_X$ and $U(1)_Y$ gauge fields obtained from higher dimensional operator through the VEV of $SU(2)_X$ triplet scalar. We have shown the kinetic mixing term and formulated Z - Z' mixing to give interaction between

DM and the SM particles. After formulating interactions, we estimated DM relic density and DM-nucleon scattering cross section. We have found that DM relic density can be explained for $SU(2)_X$ gauge coupling in the range of $\sim [0.01, 1]$. In addition, most of parameter sets giving observed relic density is safe from direct detection constraints and some region can be tested in future experiment.

Acknowledgments

This research was supported by an appointment to the JRG Program at the APCTP through the Science and Technology Promotion Fund and Lottery Fund of the Korean Government. This was also supported by the Korean Local Governments - Gyeongsangbuk-do Province and Pohang City (H.O.). H. O. is sincerely grateful for the KIAS member, and log cabin at POSTECH to provide nice space to come up with this project. The work of S.Y. is supported by the research grant “The Dark Universe: A Synergic Multi-messenger Approach” number 2017X7X85K under the program PRIN 2017 funded by the Ministero dell’Istruzione Università e della Ricerca (MIUR).

A Symmetric tensor notation of $SU(2)_X$ representations

The scalar quintet Φ is represented as

$$\Phi = \left[\phi_{2,2}^{(4)}, \phi_{2,1}^{(3)}, \phi_{2,0}^{(2)}, \phi_{2,-1}^{(1)}, \phi_{2,-2}^{(0)} \right]^T, \quad \text{or} \quad \Phi_{ijkl}, \quad (\text{A.1})$$

where Φ_{ijkl} is the symmetric tensor notation with index $i, j, k, l = 1, 2$ corresponding to fundamental representation of $SU(2)$. These elements are explicitly given by

$$\Phi_{[1111]} = \phi_{2,2}^{(4)}, \quad \Phi_{[1112]} = \phi_{2,1}^{(3)}/\sqrt{4}, \quad \Phi_{[1122]} = \phi_{2,0}^{(2)}/\sqrt{6}, \quad \Phi_{[1222]} = -\phi_{2,-1}^{(1)}/\sqrt{4}, \quad \Phi_{[2222]} = \phi_{2,-2}^{(0)}. \quad (\text{A.2})$$

Here coefficients in right hand sides are chosen so that we obtain canonical kinetic term as

$$\frac{1}{2}\Phi^2 = \frac{1}{2}\Phi_{ijkl}\Phi_{i'j'k'l'}\epsilon^{ii'}\epsilon^{jj'}\epsilon^{kk'}\epsilon^{ll'} = \frac{1}{2}\Phi_{ijkl}\Phi^{ijkl} = \frac{1}{2}(\phi_{2,0}^{(2)})^2 + \phi_{2,2}^{(4)}\phi_{2,-2}^{(0)} + \phi_{2,1}^{(3)}\phi_{2,-1}^{(1)}, \quad (\text{A.3})$$

where ϵ^{ij} is anti-symmetric tensor and summation over repeated indices is imposed. Note that superscript and subscript are related by ϵ^{ij} as $\Phi_{ijkl}^i = \epsilon^{ii'}\Phi_{i'jkl}$, and gauge invariance is satisfied by contracting superscript and subscript. Similarly we write the triplet Φ' as

$$\Phi' = \left[\phi_{1,1}'^{(2)}, \phi_{1,0}'^{(1)}, \phi_{1,-1}'^{(0)} \right]^T, \quad \text{or} \quad \Phi'_{ij}, \quad (\text{A.4})$$

These elements are explicitly given by

$$\Phi'_{[11]} = \phi_{1,1}'^{(2)}, \quad \Phi'_{[12]} = i\phi_{1,0}'^{(1)}/\sqrt{2}, \quad \Phi'_{[22]} = \phi_{1,-1}'^{(0)}, \quad (\text{A.5})$$

where we chose convention to obtain canonical kinetic term

$$\Phi'^2 = \Phi'_{ij}\Phi'^{ij} = (\phi_{1,0}'^{(1)})^2 + 2\phi_{1,1}'^{(2)}\phi_{1,-1}'^{(0)}. \quad (\text{A.6})$$

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References

- [1] P. Ko, *Particle, Astroparticle Physics and Cosmology in Dark Matter Models with Dark Gauge Symmetries*, *J. Korean Phys. Soc.* **73** (2018) 449.
- [2] L.M. Krauss and F. Wilczek, *Discrete Gauge Symmetry in Continuum Theories*, *Phys. Rev. Lett.* **62** (1989) 1221 [[INSPIRE](#)].
- [3] C.-W. Chiang, T. Nomura and J. Tandean, *Nonabelian Dark Matter with Resonant Annihilation*, *JHEP* **01** (2014) 183 [[arXiv:1306.0882](#)] [[INSPIRE](#)].
- [4] C.-H. Chen and T. Nomura, *SU(2)_X vector DM and Galactic Center gamma-ray excess*, *Phys. Lett. B* **746** (2015) 351 [[arXiv:1501.07413](#)] [[INSPIRE](#)].
- [5] C.-H. Chen and T. Nomura, *Searching for vector dark matter via Higgs portal at the LHC*, *Phys. Rev. D* **93** (2016) 074019 [[arXiv:1507.00886](#)] [[INSPIRE](#)].
- [6] C.-H. Chen, C.-W. Chiang and T. Nomura, *Dark matter for excess of AMS-02 positrons and antiprotons*, *Phys. Lett. B* **747** (2015) 495 [[arXiv:1504.07848](#)] [[INSPIRE](#)].
- [7] P. Ko, T. Nomura and H. Okada, *Dark matter physics in dark SU(2) gauge symmetry with non-Abelian kinetic mixing*, *Phys. Rev. D* **103** (2021) 095011 [[arXiv:2007.08153](#)] [[INSPIRE](#)].
- [8] C. Gross, O. Lebedev and Y. Mambrini, *Non-Abelian gauge fields as dark matter*, *JHEP* **08** (2015) 158 [[arXiv:1505.07480](#)] [[INSPIRE](#)].
- [9] T. Hambye, *Hidden vector dark matter*, *JHEP* **01** (2009) 028 [[arXiv:0811.0172](#)] [[INSPIRE](#)].
- [10] C. Boehm, M.J. Dolan and C. McCabe, *A weighty interpretation of the Galactic Centre excess*, *Phys. Rev. D* **90** (2014) 023531 [[arXiv:1404.4977](#)] [[INSPIRE](#)].
- [11] S. Baek, P. Ko and W.-I. Park, *Hidden sector monopole, vector dark matter and dark radiation with Higgs portal*, *JCAP* **10** (2014) 067 [[arXiv:1311.1035](#)] [[INSPIRE](#)].
- [12] V.V. Khoze and G. Ro, *Dark matter monopoles, vectors and photons*, *JHEP* **10** (2014) 061 [[arXiv:1406.2291](#)] [[INSPIRE](#)].
- [13] R. Daido, S.-Y. Ho and F. Takahashi, *Hidden monopole dark matter via axion portal and its implications for direct detection searches, beam-dump experiments, and the H_0 tension*, *JHEP* **01** (2020) 185 [[arXiv:1909.03627](#)] [[INSPIRE](#)].
- [14] H. Davoudiasl and I.M. Lewis, *Dark Matter from Hidden Forces*, *Phys. Rev. D* **89** (2014) 055026 [[arXiv:1309.6640](#)] [[INSPIRE](#)].
- [15] B. Barman, S. Bhattacharya, S.K. Patra and J. Chakraborty, *Non-Abelian Vector Boson Dark Matter, its Unified Route and signatures at the LHC*, *JCAP* **12** (2017) 021 [[arXiv:1704.04945](#)] [[INSPIRE](#)].
- [16] B. Barman, S. Bhattacharya and M. Zakeri, *Multipartite Dark Matter in SU(2)_N extension of Standard Model and signatures at the LHC*, *JCAP* **09** (2018) 023 [[arXiv:1806.01129](#)] [[INSPIRE](#)].
- [17] B. Barman, S. Bhattacharya and M. Zakeri, *Non-Abelian Vector Boson as FIMP Dark Matter*, *JCAP* **02** (2020) 029 [[arXiv:1905.07236](#)] [[INSPIRE](#)].

- [18] B. Barman, S. Bhattacharya and B. Grzadkowski, *Feebly coupled vector boson dark matter in effective theory*, *JHEP* **12** (2020) 162 [[arXiv:2009.07438](#)] [[INSPIRE](#)].
- [19] A. Karam and K. Tamvakis, *Dark matter and neutrino masses from a scale-invariant multi-Higgs portal*, *Phys. Rev. D* **92** (2015) 075010 [[arXiv:1508.03031](#)] [[INSPIRE](#)].
- [20] E. Hall, T. Konstandin, R. McGehee, H. Murayama and G. Servant, *Baryogenesis From a Dark First-Order Phase Transition*, *JHEP* **04** (2020) 042 [[arXiv:1910.08068](#)] [[INSPIRE](#)].
- [21] T. Ghosh, H.-K. Guo, T. Han and H. Liu, *Electroweak Phase Transition with an SU(2) Dark Sector*, [arXiv:2012.09758](#) [[INSPIRE](#)].
- [22] C.A. Argüelles, X.-G. He, G. Ovanessian, T. Peng and M.J. Ramsey-Musolf, *Dark Gauge Bosons: LHC Signatures of Non-Abelian Kinetic Mixing*, *Phys. Lett. B* **770** (2017) 101 [[arXiv:1604.00044](#)] [[INSPIRE](#)].
- [23] E. Braaten and D. Segel, *Neutrino energy loss from the plasma process at all temperatures and densities*, *Phys. Rev. D* **48** (1993) 1478 [[hep-ph/9302213](#)] [[INSPIRE](#)].
- [24] H. An, M. Pospelov and J. Pradler, *New stellar constraints on dark photons*, *Phys. Lett. B* **725** (2013) 190 [[arXiv:1302.3884](#)] [[INSPIRE](#)].
- [25] J. Redondo and G. Raffelt, *Solar constraints on hidden photons re-visited*, *JCAP* **08** (2013) 034 [[arXiv:1305.2920](#)] [[INSPIRE](#)].
- [26] J. Redondo and M. Postma, *Massive hidden photons as lukewarm dark matter*, *JCAP* **02** (2009) 005 [[arXiv:0811.0326](#)] [[INSPIRE](#)].
- [27] E. Hardy and R. Lasenby, *Stellar cooling bounds on new light particles: plasma mixing effects*, *JHEP* **02** (2017) 033 [[arXiv:1611.05852](#)] [[INSPIRE](#)].
- [28] D.K. Hong, C.S. Shin and S. Yun, *Cooling of young neutron stars and dark gauge bosons*, [arXiv:2012.05427](#) [[INSPIRE](#)].
- [29] P. Langacker, *The Physics of Heavy Z' Gauge Bosons*, *Rev. Mod. Phys.* **81** (2009) 1199 [[arXiv:0801.1345](#)] [[INSPIRE](#)].
- [30] PARTICLE DATA GROUP collaboration, *Review of Particle Physics*, *Prog. Theor. Exp. Phys.* **2020** (2020) 083C01.
- [31] G. Bélanger, F. Boudjema, A. Pukhov and A. Semenov, *MicrOMEGAs4.1: two dark matter candidates*, *Comput. Phys. Commun.* **192** (2015) 322 [[arXiv:1407.6129](#)] [[INSPIRE](#)].
- [32] XENON collaboration, *First Dark Matter Search Results from the XENON1T Experiment*, *Phys. Rev. Lett.* **119** (2017) 181301 [[arXiv:1705.06655](#)] [[INSPIRE](#)].
- [33] XENON collaboration, *Dark Matter Search Results from a One Ton-Year Exposure of XENON1T*, *Phys. Rev. Lett.* **121** (2018) 111302 [[arXiv:1805.12562](#)] [[INSPIRE](#)].
- [34] J. Billard, L. Strigari and E. Figueroa-Feliciano, *Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments*, *Phys. Rev. D* **89** (2014) 023524 [[arXiv:1307.5458](#)] [[INSPIRE](#)].