Dark matter in universal extra dimension models: Kaluza-Klein photon and right-handed neutrino admixture

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We show that in a class of universal extra dimension models (UED), which solves both the neutrino mass and proton decay problem, an admixture of Kaluza-Klein (KK) photon and KK right-handed neutrinos can provide the required amount of cold dark matter (CDM). This model has two parameters R^{-1} and $M_{Z'}$ (R is the radius of the extra space dimensions and Z' the extra neutral gauge boson of the model). Using the value of the relic CDM density, combined with the results from the cryogenic searches for CDM, we obtain upper limits on R^{-1} of about 400–650 GeV and $M_{Z'} \leq 1.5$ TeV, both being accessible to the LHC. In some regions of the parameter space, the dark matter-nucleon scattering cross section can be as high as 10^{-44} cm^2, which can be probed by the next round of dark matter search experiments.

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I. INTRODUCTION

The existence of dark matter is now a well established fact. The nature of the dark matter particle is however still a mystery. Its discovery is going to be a major breakthrough in the study of physics beyond the standard model of both particle physics and cosmology. One candidate that has rightly received a great deal of attention is the lightest supersymmetric particle, the neutralino, since there are many reasons to think that physics may be supersymmetric around the TeV scale. Furthermore, the Large Hadron Collider machine at CERN, which is scheduled to start operating in mid 2007, will experimentally explore physics at the TeV energy scale making it possible to have a detailed understanding of dark matter related physics.

Another class of models which leads to a very different kind of TeV scale physics and will also be explored at the LHC is one where there exist extra space dimensions with sizes of order of an inverse TeV. In particular there is a class of extra dimension models known as universal extra dimension models (UED) where all standard model particles live in either five (or six)-dimensional space-time of which one (or two) is (are) compactified with radius $R^{-1} \leq$ TeV [1]. A recently discussed cosmologically interesting point about the UED models [2,3] is that the lightest Kaluza-Klein (KK) particles of these models being stable can serve as viable dark matter candidates. This result is nontrivial due to the fact that the dark matter relic abundance is determined by the interactions in the theory which are predetermined by the standard model. It turns out that the first KK mode of the hypercharge boson is the dark matter candidate provided the inverse size of the extra dimension is less than a TeV.

A generic phenomenological problem with 5D UED models based on the standard model gauge group is that they can lead to rapid proton decay as well as unsuppressed neutrino masses. A way to cure the rapid proton decay problem is to consider six dimensions [4] where the extra space dimensions lead to a new $U(1)$ global symmetry that suppresses the strength of all baryon number nonconserving operators. On the other hand both the neutrino mass and the proton decay problem can be solved simultaneously if we extend the gauge group of the six-dimensional model to $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ [5]. With appropriate orbifolding, a neutrino mass comes out to be of the desired order due to a combination of two factors: the existence of $B-L$ gauge symmetry and orbifolding which keeps the left-handed singlet neutrino as a zero mode forbid the lower dimensional operators that could give neutrino mass. Another advantage of the 6D models over the 5D ones is that cancellation of gravitational anomaly automatically leads to the existence of the right-handed neutrinos needed for generating neutrino masses.

In this paper, we point out that the 6D UED models with an extended gauge group of Ref. [5] provide a two-component picture of dark matter consisting of a KK right-handed neutrino and a KK hypercharge boson. We do a detailed calculation of the relic abundance of both the $\nu_{R,\mathrm{KK}}$ and the B_Y^{KK} as well as the cross section for scattering of the dark matter in the cryogenic detectors in these models. The two main results of this calculation are that: (i) present experimental limits [6] on the DM-nucleon cross section and the value of the relic density [7] imply very stringent limits on the two fundamental parameters of the theory i.e. R^{-1} and the second Z'-boson associated with the extended gauge group i.e. $R^{-1} \leq 550$ GeV and $M_{Z'} \leq 1.2$ TeV and (ii) for this parameter range, where the relic density of the KK neutrino contributes significantly to the total dark matter relic density, the DM-nucleon cross section is $\geq 10^{-44}$ cm^2, a prediction that is accessible to the next round of dark matter searches. No signal in dark matter searches as well as the searches for the KK modes and Z' in the above range will rule out this class of model and alternative solutions to the neutrino mass and proton decay problem will have to be sought to keep the UED models phenomenologically viable. Discovery of two components to dark matter should also have implications for cosmology of structure formation.

II. THE BASIC FEATURES OF THE MODEL

In this section, we review the basic features of the model in Ref. [5]. The gauge group of the model is $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ with matter content per generation as follows:

$$\mathcal{Q}_{1,-}, \mathcal{Q}'_{1,-} = (3, 2, 1, \tfrac{1}{3}); \qquad \mathcal{Q}_{2,+}, \mathcal{Q}'_{2,+} = (3, 1, 2, \tfrac{1}{3}); \qquad \psi_{1,-}, \psi'_{1,-} = (1, 2, 1, -1); \qquad \psi_{2,+}, \psi'_{2,+} = (1, 1, 2, -1); \tag{1}$$

where, within parenthesis, we have written the quantum numbers that correspond to each group factor, respectively, and the subscript gives the six-dimensional chirality chosen to cancel gravitational anomaly in six dimensions. Note that there are an equal number of positive and negative six-dimensional chirality states. We denote the gauge bosons as G_M, $W^{\pm}_{1,M}$, $W^{\pm}_{2,M}$, and B_M, for $SU(3)_c$, $SU(2)_L$, $SU(2)_R$, and $U(1)_{B-L}$, respectively, where $M = 0, 1, 2, 3, 4, 5$ denotes the six space-time indices. We will also use the following short hand notations: Greek letters $\mu, \nu, \ldots = 0, 1, 2, 3$ to denote usual four dimensions indices and lower case Latin letters $a, b, \ldots = 4, 5$ for the extra space dimensions. We will also use $\vec{y}$ to denote the (x_4, x_5) coordinates of a point in the extra space.

First, we compactify the extra x_4, x_5 dimensions into a torus T^2 with equal radii R, by imposing periodicity conditions, $\varphi(x_4, x_5) = \varphi(x_4 + 2\pi R, x_5) = \varphi(x_4, x_5 + 2\pi R)$ for any field φ. This has the effect of breaking the original $SO(1, 5)$ Lorentz symmetry group of the six-dimensional space into the subgroup $SO(1, 3) \times Z_4$, where the last factor corresponds to the group of discrete rotations in the x_4-x_5 plane, by angles of $k\pi/2$ for $k = 0, 1, 2, 3$. This is a subgroup of the continuous $U(1)_{45}$ rotational symmetry contained in $SO(1, 5)$. The remaining $SO(1, 3)$ symmetry gives the usual 4D Lorentz invariance. The presence of the surviving Z_4 symmetry leads to suppression of proton decay [4] as well as neutrino mass [5].

Employing the further orbifolding conditions i.e. Z_2: $\vec{y} \to -\vec{y}$ and Z'_2: $\vec{y}' \to -\vec{y}'$ for $\vec{y} = (x_4, x_5)$; and where $\vec{y}' = \vec{y} - (\pi R/2, \pi R/2)$, we can project out the zero modes and obtain the KK modes by assigning appropriate $Z_2 \times Z'_2$ quantum numbers to the fields.

In the effective 4D theory the mass of each mode has the form: $m_N^2 = m_0^2 + \frac{N}{R^2}$; with $N = \vec{n}^2 = n_1^2 + n_2^2$ and m_0 is the Higgs vacuum expectation value (vev) contribution to mass, and the physical mass of the zero mode.

We assign the following $Z_2 \times Z'_2$ charges to the various fields:

$$\begin{gathered} G_\mu(+,+); \quad B_\mu(+,+); \quad W^{3,\pm}_{1,\mu}(+,+); \\ W^3_{2,\mu}(+,+); \quad W^{\pm}_{2,\mu}(+,-); \quad G_a(-,-); \\ B_a(-,-); \quad W^{3,\pm}_{1,a}(-,-); \quad W^3_{2,a}(-,-); \\ W^{\pm}_{2,a}(-,+). \end{gathered} \tag{2}$$

As a result, the gauge symmetry $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ breaks down to $SU(3)_c \times SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$ on the 3 + 1-dimensional brane. The $W_R^{\pm}$ pick up mass R^{-1} whereas prior to symmetry breaking the rest of the gauge bosons remain massless.

For quarks we choose

$$\begin{aligned} Q_{1,L} &\equiv \begin{pmatrix} u_{1L}(+,+) \\ d_{1L}(+,+) \end{pmatrix}; & Q'_{1,L} &\equiv \begin{pmatrix} u'_{1L}(+,-) \\ d'_{1L}(+,-) \end{pmatrix}; \\ Q_{1,R} &\equiv \begin{pmatrix} u_{1R}(-,-) \\ d_{1R}(-,-) \end{pmatrix}; & Q'_{1,R} &\equiv \begin{pmatrix} u'_{1R}(-,+) \\ d'_{1R}(-,+) \end{pmatrix}; \\ Q_{2,L} &\equiv \begin{pmatrix} u_{2L}(-,-) \\ d_{2L}(-,+) \end{pmatrix}; & Q'_{2,L} &\equiv \begin{pmatrix} u'_{2L}(-,+) \\ d'_{2L}(-,-) \end{pmatrix}; \\ Q_{2,R} &\equiv \begin{pmatrix} u_{2R}(+,+) \\ d_{2R}(+,-) \end{pmatrix}; & Q'_{2,R} &\equiv \begin{pmatrix} u'_{2R}(+,-) \\ d'_{2R}(+,+) \end{pmatrix}; \end{aligned} \tag{3}$$

and for leptons:

$$\begin{aligned} \psi_{1,L} &\equiv \begin{pmatrix} \nu_{1L}(+,+) \\ e_{1L}(+,+) \end{pmatrix}; & \psi'_{1,L} &\equiv \begin{pmatrix} \nu'_{1L}(-,+) \\ e'_{1L}(-,+) \end{pmatrix}; \\ \psi_{1,R} &\equiv \begin{pmatrix} \nu_{1R}(-,-) \\ e_{1R}(-,-) \end{pmatrix}; & \psi'_{1,R} &\equiv \begin{pmatrix} \nu'_{1R}(+,-) \\ e'_{1R}(+,-) \end{pmatrix}; \\ \psi_{2,L} &\equiv \begin{pmatrix} \nu_{2L}(-,+) \\ e_{2L}(-,-) \end{pmatrix}; & \psi'_{2,L} &\equiv \begin{pmatrix} \nu'_{2L}(+,+) \\ e'_{2L}(+,-) \end{pmatrix}; \\ \psi_{2,R} &\equiv \begin{pmatrix} \nu_{2R}(+,-) \\ e_{2R}(+,+) \end{pmatrix}; & \psi'_{2,R} &\equiv \begin{pmatrix} \nu'_{2R}(-,-) \\ e'_{2R}(-,+) \end{pmatrix}. \end{aligned} \tag{4}$$

The zero modes i.e. (+, +) fields correspond to the standard model fields along with an extra singlet neutrino which is left-handed. They will have zero mass prior to gauge symmetry breaking.

Turning now to the Higgs bosons, we choose a bidoublet, which will be needed to give masses to fermions and break the standard model symmetry and a pair of doublets $\chi_{L,R}$ with the following $Z_2 \times Z'_2$ quantum numbers:

$$\begin{gathered} \phi \equiv \begin{pmatrix} \phi_u^0(+,+) & \phi_d^+(+,-) \\ \phi_u^-(+,+) & \phi_d^0(+,-) \end{pmatrix}; \\ \chi_L \equiv \begin{pmatrix} \chi_L^0(-,+) \\ \chi_L^-(-,+) \end{pmatrix}; \qquad \chi_R \equiv \begin{pmatrix} \chi_R^0(+,+) \\ \chi_R^-(+,-) \end{pmatrix}, \end{gathered} \tag{5}$$

and the following charge assignment under the gauge group,

$$\phi = (1, 2, 2, 0), \qquad \chi_L = (1, 2, 1, -1), \qquad \chi_R = (1, 1, 2, -1). \tag{6}$$

At the zero mode level, only the SM doublet (ϕ_u^0, ϕ_u^-) and a singlet χ_R^0 appear. The vev's of these fields, namely $\langle\phi_u^0\rangle = v_{wk}$ and $\langle\chi_R^0\rangle = v_R$, break the SM symmetry and the extra $U(1)'_Y$ gauge group, respectively.

There are two classes of levels: one class corresponding to even KK number with $Z_2 \times Z'_2$ quantum numbers $(+,+)$ and $(-,-)$ and another class corresponding to odd KK number, corresponding to $Z_2 \times Z'_2$ quantum numbers $(+,-)$ and $(-,+)$. Of these only $(+,+)$ modes contain the zero mode as noted earlier. This implies that the lightest KK modes are those in $(+,-)$ or $(-,+)$ class.

As there are a large number of KK modes, one may worry whether or not electroweak precision constraints are satisfied. To our knowledge, there has been no such analysis for similar models, and it is outside the scope of the current paper to perform a complete analysis regarding the electroweak constraints. Therefore, we leave the investigation of this open issue for future work.

III. DARK MATTER CANDIDATES

In our UED model, there are the following stable KK modes: the lowest KK excitation of the hypercharge boson $B_Y^{\rm KK}$ and the lowest $(\pm,\mp)$ modes $\nu_{2,L}$ and $\nu_{2,R}$. Both the heavy neutrino states couple only the $SU(2)_R$ gauge fields. The former ($B_Y^{\rm KK}$) being a KK mode of the $(+,+)$ state has twice the mass squared of the lowest KK modes of states of $(\pm,\mp)$ type (i.e. $\nu_{2,L,R}$). The discussion of the dark matter candidate has to take this into account to see which particle really is the dark matter. We find that in general it is an admixture of both. We also include the effect of radiative corrections [8] which shift the mass levels by an amount $\sim \frac{g^2 n}{16\pi^2 R}\ln(\frac{\Lambda}{\mu})$ where n denotes the KK mode number, Λ, the fundamental scale, and μ the renormalization point. When they are included, the values of the masses differ slightly but the same lightest modes as identified here remain.

The $\nu_{2R,L}^{\rm KK}$ couple to Z'; their annihilation rate in the early universe will therefore be determined by $M_{Z'}$ which contributes in s-channel processes. There are also annihilation channels through t-channel processes mediated by $W_2^{\pm}$, whose mass has a contribution from R^{-1} as well as v_R. The discussion of the annihilation channels of $B_Y^{\rm KK}$ is similar to that in [2,3].

A. Annihilation channels of $\nu_{2L,2R}$

Since the Yukawa couplings are small, annihilations through gauge boson exchanges provide the dominant channel. Although we have two independent Dirac fermions for dark matter, $\nu^{(10)}$ and $\nu^{(01)}$, they couple the same way to Z'_μ and have the same annihilation channel. The only difference is that, for charged current processes, $\nu^{(01)}$ ($\nu^{(10)}$) couples to $W_{2,\mu}^{\pm,(01)}$ ($W_{2,\mu}^{\pm,(10)}$). The generic coupling of matter fields to Z'_μ is

$$g(\bar{f}fZ'_\mu) \equiv \tilde{g}_f = \frac{1}{2\sqrt{g_{BL}^2 + g_R^2}}(-2T_3 g_R^2 + Y_{BL} g_{BL}^2), \quad (7)$$

where $T_3 = \pm\frac{1}{2}$ for right-handed particles of the standard model and the sterile neutrino, and $T_3 = 0$ for left-handed particles. We also have $Y_{BL} = +1/3$ for quarks and $Y_{BL} = -1$ for leptons. The cross section for $\sigma(\bar{\nu}_2\nu_2 \to \bar{f}f)$ from Z' exchange can be written as

$$\sigma(\bar{\nu}_2\nu_2 \to \bar{f}f)v_{\rm rel} = a_{Z'}(f) + b_{Z'}(f)v_{\rm rel}^2, \quad (8)$$

where

$$a_{Z'}(f) = \frac{\tilde{g}_\nu^2\tilde{g}_f^2}{2\pi}\frac{M^2}{(4M^2 - M_{Z'}^2)^2},$$
$$b_{Z'}(f) = \frac{\tilde{g}_\nu^2\tilde{g}_f^2}{2\pi}\frac{M^2}{(4M^2 - M_{Z'}^2)^2}\left(\frac{1}{6} - \frac{2M^2}{4M^2 - M_{Z'}^2}\right). \quad (9)$$

For the final state of $\bar{e}_R e_R$, we have a t-channel process through charge current. The cross section therefore involves three pieces: two due to the squared amplitudes of s- and t-channel diagrams and another from their interference, denoted by σ_{ss}, σ_{tt}, and σ_{st}, respectively. Of these, σ_{ss} has the same form as Eq. (8), and we will show that σ_{tt} and σ_{st} is parametrically smaller than σ_s. Thus the main contribution to the annihilation of $\nu_{2L,R}$ comes from annihilation through s-channel processes mediated through Z'_μ.

Because of $Z - Z'$, there can also be annihilation of KK neutrino into SM Higgs charged bosons. In the limit that $v_w \ll v_R$, we can work to the leading order in the expansion of $\mathcal{O}(v_w^2/v_R^2)$, where we can estimate these processes by treating the $Z - Z'$ mixing as a mass insertion. In terms of Feynman diagrams, these annihilation channels are s-channel processes, where a pair KK neutrino annihilates into a Z'-boson, which propagates to the mixing vertex, converting Z' to Z, which then decays into h^*h (both neutral and charged) or massless W^+W^-. Compared to the amplitude of annihilation of KK neutrino into SM fermions, the annihilation to the bosons have effectively a replaced propagator

$$\frac{1}{(s - M_{Z'}^2)} \to \frac{1}{(s - M_{Z'}^2)}\delta M^2\frac{1}{(s - M_Z^2)}, \quad (10)$$

where

$$\delta M^2 \equiv \frac{g_R^2}{\sqrt{(g_L^2 + g_Y^2)(g_R^2 + g_{\rm BL}^2)}}M_Z^2, \quad (11)$$

is the off-diagonal element in the $Z - Z'$ (mass)^2 matrix. Since $s \sim 4M_\nu^2 = 4R^{-2}$, the annihilation cross section into transverse gauge bosons and the Higgs bosons are suppressed by a factor of $M_Z^4/s^2 \sim (100\ {\rm GeV})^4/16(500\ {\rm GeV})^4 \sim 10^{-4}$, and can therefore be neglected. As for the longitudinal modes, the ratio of annihilation cross sections of the longitudinal modes of the gauge bosons to the one single mode of the SM fermion-antifermion pair is roughly

$$\frac{\sigma(\nu^{\rm KK}\nu^{\rm KK}\to W^+W^-)}{\sigma(\nu^{\rm KK}\nu^{\rm KK}\to \bar{f}f)} \sim \left(\frac{\delta M^2}{m_W^2}\right)^2. \tag{12}$$

This ratio is about $\frac{1}{2}$ for $g_R = 0.7g_L$. As there is only one annihilation mode into the longitudinal modes of the charged gauge bosons, whereas there are many annihilation channels to the SM fermion-antifermion pairs, the total annihilation cross section is dominated by the SM fermion-antifermion contributions.

We note here that the annihilation channels to matter fields differ from the analysis of [2,3] in two important ways. First, in their analysis, the s-channel process is mediated by the Z-boson of the SM, whose mass can be ignored, whereas we have s-channel processes mediated by Z', whose mass is significantly higher than the mass of our dark matter candidate in the region of interest. Second, although we keep all contributions to the annihilation cross sections for the KK neutrino $\nu_{2L,2R}$ in our numerical work, to a workable approximation we can discard t, u-channel processes mediated by charged gauge bosons $W_2^{\pm}$, because $m^2_{W_2^{\pm}}$ has contributions both from R^{-1} and v_R. We have checked that excluding such processes does not affect the main conclusions of the paper. To see this, let us make the approximation $m^2_{W^{\pm}} = m^2_{Z'} + R^{-2}$, then we compare the cross section involving the product of a t or u diagram with a s-channel diagram σ_{st} with that coming from the square of a s-channel diagram σ_{ss},

$$\frac{\sigma_{ss}}{\sigma_{st}} \approx \frac{(s-m^2_{Z'})(t-m^2_{W^{\pm}})}{(s-m^2_{Z'})^2} = \frac{2(R^{-1})^2 + m^2_{Z'}}{4(R^{-1})^2 - m^2_{Z'}}. \tag{13}$$

Then $\sigma_{ss} \gg \sigma_{st}$ would require that $m^2_{Z'} > 2(R^{-1})^2$, which is satisfied in the region of interest in the parameter space. Similarly, the cross section involving two t- or u-channel diagrams, σ_{tt}, σ_{uu}, or σ_{tu} is small compared to σ_{ss}. Thus the annihilation cross section is given by

$$\sigma(\bar{\nu}_2\nu_2 \to XX)v_{\rm rel} \simeq \sum_{\rm SM}(a_{Z'}(f) + b_{Z'}(f)v^2_{\rm rel}). \tag{14}$$

B. Relic density: $\nu^{\rm KK}_{2L,2R}$ vs $B^{\rm KK}_Y$

As noted, the contribution of $B_Y^{\rm KK}$ to relic density in our case does not differ from the calculation of [2,3] since our model in the low energy limit all the $B_Y^{\rm KK}$ annihilation modes are the same as the model used there. Combining the right-handed (RH) neutrino and $B_Y^{\rm KK}$ contributions, we get the total relic density. Clearly, for different regions of parameter space, the relative fraction of the two components will be different. In Fig. 1, we combine the two contributions and plot the allowed regions in the R^{-1} and $M_{Z'}$ parameter space so that we get the $\Omega_{\nu_{L,R}}h^2 + \Omega_{\gamma^{(1)}}h^2$ to the observed value [7]. The central solid line corresponds to the central value of the dark matter contribution

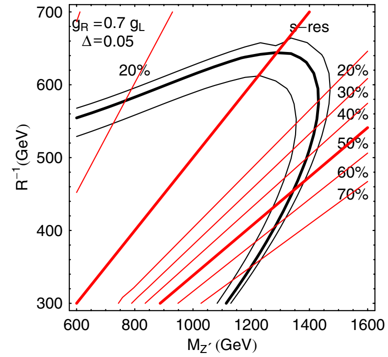

FIG. 1 (color online). The contour in the $1/R - M_{Z'}$ which corresponds to $\Omega_{\nu_{L,R}}h^2 + \Omega_{B_Y}h^2$ being the observed dark matter. The intersection of the lines with the contour indicate the fraction of KK neutrinos in the dark matter.

to Ωh^2 and the outer lines denote the one σ error range. The straight lines in Fig. 1 give the parameter range of $M_{Z'}$ and R^{-1} for which we get the noted fraction of the RH neutrino contribution to Ωh^2. For small values of $M_{Z'}$, the annihilation of $\nu^{(01)}_{2L,2R}$ is efficient and most of the dark matter is $B_Y^{\rm KK}$ having a mass of roughly $\sqrt{2}R^{-1} \sim$ 700 GeV. In fact, along the line $2M_{\nu^{(01)}} = 2R^{-1} = M_{Z'}$, the annihilation of $\nu^{(01)}_{2L,2R}$ has a s-channel resonance, and its contribution to dark matter relic density is minimal. Away from the line of s-channel resonance, the contribution of $\nu^{(01)}_{2L,2R}$ to the relic density increases, and R^{-1} decreases so as to decrease the relic density due to $B_Y^{\rm KK}$, keeping the total relic density within the allowed range. Using the present bounds on the $M_{Z'}$ of the left-right model from collider data of $M_{Z'} \geq 860$ GeV [9], we conclude that in our picture we have an interesting region in the parameter space where the KK sterile neutrinos constitute at least 30% of the dark matter density when $M_{Z'} \gtrsim 1.2$ TeV and $400 < R^{-1} < 550$ GeV.

C. Direct detection of $\nu_{2L,2R}$

As we have a two-component dark matter, the total dark matter-nucleon cross section is given by

$$\sigma_n = \kappa_{\nu_R}\sigma_{\nu_R} + \kappa_B\sigma_B, \tag{15}$$

where $\sigma_{\nu_R(B)}$ is the spin-independent KK neutrino (hypercharge boson)-nucleon scattering cross section, and

$$\kappa_{\nu_R} \equiv \frac{\Omega_{\nu_R}h^2}{\Omega_{\nu_R}h^2 + \Omega_{B_Y^{\rm KK}}h^2}, \tag{16}$$

is the fractional contribution of the KK neutrino relic density to the total relic density of the dark matter. κ_B is similarly defined. As pointed out in Ref. [2], σ_B is of the order $\sigma_B \sim 10^{-10}$ pb, and we will find that $\sigma_{\nu_R} \gg \sigma_B$. Therefore, it is a good approximation to take σ_n as

$$\sigma_n \approx \kappa_{\nu_R}\sigma_{\nu_R}. \tag{17}$$

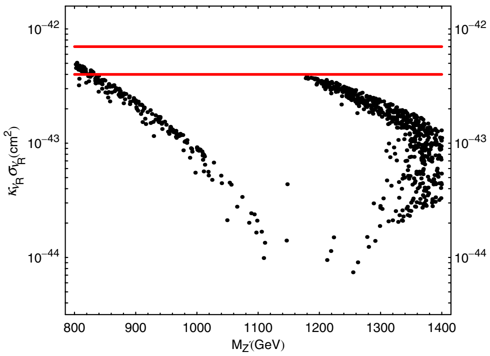

FIG. 2 (color online). The scattering plot of the scattering cross section of $\nu^{(1)}$ on the nucleon as a function of $M_{Z'}$. $\kappa_{\nu_R} \in \{0 - 0.7\}$ is the fractional contribution of the KK neutrino to the dark matter relic density. (The value $\kappa = 0$ corresponds to regions of s-channel resonance for $\nu^{\rm KK}$ annihilation.) The upper (lower) horizontal line corresponds to the CDMS II upper bound for a dark matter of mass 500 GeV (300 GeV).

The $\nu_{2L,2R}$ scattering cross section per nucleon in a nucleus $N(A, Z)$ is given by

$$\sigma_{\nu_R} = \frac{b_N^2 m_n^2}{\pi A^2}, \tag{18}$$

where $b_N = Zb_p + (A - Z)b_n$, and $b_{p,n}$ is the effective four-fermion coupling between $\nu_{2L,2R}$ and a proton or neutron. They are given by $b_p = 2b_u + b_d$ and $b_n = b_u + 2b_d$, with

$$b_q = \frac{g_{(\bar{\nu}_2\nu_2 Z')}}{2M_{Z'}^2} \sum_{i=L,R} \left[g_{(\bar{q}_i q_i Z')} - g_{(\bar{q}_i q_i Z)} \frac{\delta M^2}{M_Z^2} + \mathcal{O}\left(\frac{M_Z^2}{M_{Z'}^2}\right)\right], \tag{19}$$

so that we have taken into account the $Z - Z'$ mixing up to $\mathcal{O}(v_w^2/v_R^2)$. The contribution due to $Z - Z'$ mixing can be understood diagrammatically as a Z' propagator of $M_{Z'}^{-2}$ followed by a mass insertion of δM^2, followed by a Z-propagator of M_Z^{-2}. This is equivalent to a mixing term of $\delta M^2/M_{Z'}^2$ multiplying a Z-propagator of M_Z^{-2} at leading order in $M_Z^2/M_{Z'}^2$.

For $M_{Z'} = 1.2$ TeV, $g_R = 0.7 g_L$, $A = 73$, and $Z = 32$ (for the Ge detectors used at CDMS II), we obtain $\sigma_n = 3.87 \times 10^{-43}$ cm^2. In Fig. 2, we give the scatter plot of the predicted values of the scattering cross section between $\nu^{(1)}$ and the nucleon as a function of $M_{Z'}$ for $\kappa_{\nu_R} \in \{0 - 0.7\}$. The horizontal lines correspond to the upper bounds on σ_n from CDMS II for dark matter candidates with masses 300 and 500 GeV, which are about 4×10^{-43} cm^2 and 7×10^{-43} cm^2, respectively. We find that if this cross section is probed down to the level of 10^{-8} picobarns, the regions with large κ_{ν_R} (corresponding to $M_{Z'} \sim 1300$ GeV and 400 GeV $< R^{-1} <$ 500 GeV) can be tested. We believe that this makes this model quite interesting.

IV. CONCLUSIONS

In summary, we have proposed a new dark matter scenario which consists of an admixture of two Kaluza-Klein modes: the right-handed neutrinos of a left-right symmetric model embedded into a six-dimensional brane-bulk theory i.e. $\nu_{2L,R}^{\rm KK}$ and $B_Y^{\rm KK}$. This class of universal extra dimensional models solves naturally both the proton stability and neutrino mass problem by an extended electroweak gauge group combined with appropriate orbifold quantum numbers for fermions. Our detailed analysis of dark matter constraints i.e. Ωh^2 and DM-nucleon cross section leads us to predict the existence of an extra Z' boson with mass less than 1.4 TeV which should be accessible at the LHC. We also find that, for the region of parameter space where the relic abundance of $\nu_{2L,R}^{\rm KK}$ contributes significantly to the total relic density of dark matter, the DM-nucleon cross sections are above 10^{-8} picobarns, which can be explored in the ongoing and planned dark matter search experiments [6,10].

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