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Low mass pseudoscalar dark matter in an extended $B-L$ model

E. C. F. S. Fortes and M. D. Tonasse*

Instituto de Física Teórica, Universidade Estadual Paulista, Rua Dr. Bento Teobaldo Ferraz 271, 01140-070 São Paulo, São Paulo, Brazil

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We study an extended $B-L$ model, which has in its structure four neutral scalars. In this model, a representative set of parameters enable us to conclude that one of these scalars is a promising candidate for low-mass dark matter. We introduce a Z_2 symmetry, which ensures the stability of the dark matter. The dominant annihilation process will be through the s channel of the Scalar boson exchange in $b\bar{b}$. So, this is also a Higgs-portal dark matter model, but the Higgs decay to dark matter is suppressed and meets the constraints from invisible decays of the Higgs boson. The model is also in agreement with the constraints established by the XENON100, CoGeNT, and CDMS experiments, matching the relic abundance and the cross section with the nucleon.

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I. INTRODUCTION

Recent research in dark matter (DM) has evolved rapidly. This is due mainly to improvements in the techniques of astronomical observations, which have revealed a wealth of information about galaxies and the structure of galactic clusters. Moreover, a greater sensitivity of underground and spatial experiments has been reached. Recent data about the composition of the Universe include that from the WMAP satellite [1] and the SDSS Collaboration [2]. They have shown that approximately 73% of the matter-energy composition of the Universe is dark energy, approximately 4% is baryonic matter, and nearly 23% is DM. The DM density is $\Omega h^2 = \rho h^2/\rho_c = 0.1196 \pm 0.0031$ [3], where $\rho_c = 3H_0^2/(8\pi G)$ is the critical density of the Universe, and H_0 is the Hubble constant [4].

Nowadays there are a number of experiments that could detect possible manifestations of DM. Some of these are based on astronomical observations [5,6]. The others come from the DAMA [7], CoGeNT [8], CDMS [9], and XENON [10,11] detectors. These experiments measure the recoil energy of nuclei when they scatter with DM. DAMA and CoGeNT events rates present a clear annual modulation. They could be interpreted as the scattering of DM on atomic nuclei, taking into account the translational motion of the Earth around the Sun. However, some others detectors—such as CDMS [9], XENON10 [10], and XENON100 [11]—have presented null results related to this modulation. On the other hand, the results of the CoGeNT [12] and CDMS [13] collaborations are consistent with a component of DM with a mass in the range (7–10) GeV and a spin-independent cross section of $(2-6)\times 10^{-41}$ cm^2. Furthermore, these results are consistent with the observations of gamma rays from the Galactic center [6,14] and other regions of the inner Galaxy [15]. Recently the LUX Collaboration announced its first results about light WIMP limits [16]. LUX is a more sensitive experiment and it is suitable for detecting low-mass dark matter. Again, the results of LUX are not compatible with the DAMA, CDMS, and CoGeNT for analyses that take into account isospin conservation. If isospin is violated, the results of LUX disagree with those of DAMA and CoGeNT. On the other hand, the results of LUX remain consistent with a dark matter mass of 10 GeV, but with a cross section for proton scattering that is two orders of magnitude smaller.

Many attempts have been made to make these results compatible amongst themselves and to interpret them as DM signals. Despite the difficulties of interpreting the present data set as DM evidence, the facts suggest that it is composed of one or more types of elementary particles that do not interact or interact very weakly with ordinary matter, except for the gravitational interaction, for which it is believed that these particles behave canonically [17]. Thus, a good model of electroweak interactions must include a candidate with sufficient properties to play the role of DM. The supersymmetric models present the most popular candidate: the neutralino [18]. It is a typical candidate, since it is the lightest supersymmetric particle and the R parity prevents it from interacting with the standard model (SM). The neutralino is an example of what we call *cold* DM (CDM), namely a kind of DM that is not relativistic at the time of decoupling between radiation and matter.

Besides the neutralino there are other possibilities, including Kaluza-Klein states in models with universal [19,20] or warped [21] extra dimensions, stable states in little Higgs theories [22], and a number of models with extra neutrinos. Other alternative scenarios consider self-interacting DM and warm DM due to the possibility of solving some of the challenges presented by CDM at the scale of dwarf galaxies without affecting the successes

*On leave from Campus Experimental de Registro, Universidade Estadual Paulista, Rua Nelson Brihi Badur 430, 11900-000 Registro, SP, Brazil.

of CDM at larger scales [23]. In order to be consistent with the properties of structure formation, our Universe must be of the ΛCDM type, i.e., a flat universe with CDM supplemented with a cosmological constant. The models of cold DM of the ΛCDM type are in excellent agreement with astronomical observations at scales above a few Mpc. On small scales, however, N-body simulations do not faithfully reproduce the structure of galaxies and clusters of galaxies [24,25].

The models that propose scalar DM normally extend the SM by introducing a scalar singlet [26,27]. However, we know that the SM must be extended not only because of the DM problem, but also in order to explain many other problems regarding its context. Therefore, it becomes interesting to investigate the DM problem in the context of an extended electroweak model that is simple and phenomenologically well motivated. An electroweak model that satisfies these requirements is the $B-L$ model. Here we propose a Higgs pseudoscalar as dark matter, but we work in the context of the $B-L$ model [28], which has a well-studied phenomenology [29,30].

The original motivation for the $B-L$ model was to find an explanation for the pattern of neutrino masses and leptonic mixing angles while giving meaning to the accidental $B-L$ symmetry of the SM. In these models, the $B-L$ quantum number (which forbids the neutrino masses) in the SM is gauged, yielding an extra neutral gauge boson Z'. In order to cancel anomalies, three right-handed neutrinos are added to the model. Thus, the $B-L$ model can provide a small neutrino mass naturally through the $B-L$ spontaneous symmetry breaking. In order to break $B-L$, an $\mathrm{SU}(2)_L$ complex Higgs singlet is introduced. In this paper, to have a scalar DM candidate we introduce a second complex scalar singlet. This singlet, which obeys a Z_2 symmetry, leads to a pseudoscalar which interacts with ordinary matter mainly through the Higgs boson of 746 GeV, satisfying the requirements to be a candidate for DM.

II. THE MODEL

The minimal $B-L$ model was developed in detail in Ref. [30]. As already mentioned, the SM $B-L$ accidental symmetry is promoted to a $\mathrm{U}(1)_{B-L}$ local symmetry. Thus, this symmetry must be broken, since it does not manifest at low energies. To this end, an $\mathrm{SU}(2)_L$ scalar singlet χ_1 with $B-L=2$ is added to the SM, which develops a vacuum expectation value (VEV) x and whose vacuum representation is $\chi_1 = x + \xi_1 + i\zeta_1$. The breaking of $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ to the $\mathrm{U}(1)_Q$ of electromagnetism remains governed by an $\mathrm{SU}(2)_L$ doublet as in the SM, i.e.,

$$\phi = \begin{pmatrix} i\omega^+ \\ h^0 \end{pmatrix}, \tag{1}$$

with $B-L=0$. In the symmetry-breaking process, h^0 is shifted to $v+\xi+i\zeta$, with v being its VEV. Here, in order to have a scalar DM candidate we add another singlet which also has $B-L=2$, obeying the reflection symmetry $Z_2{:}\,\chi_2 \to -\chi_2$ (the other fields transform trivially under Z_2), which is shifted as $\chi_2 = \xi_2 + i\zeta_2$, conserving Z_2. The Higgs potential is given by

$$\begin{aligned} V(\varphi,\chi_1,\chi_2) = {} & \mu^2\Phi^\dagger\Phi + \mu_1^2\chi_1^*\chi_1 + \mu_2^2\chi_2^*\chi_2^2 + \lambda_1(\Phi^\dagger\Phi)^2 \\ & + \lambda_2(\chi_1^*\chi_1)^2 + \lambda_3(\chi_2^*\chi_2)^2 + \lambda_4[(\chi_1^*\chi_2)^2 + \mathrm{H.c.}] \\ & + \lambda_5\chi_1^*\chi_2\chi_2^*\chi_1 + \lambda_6(\chi_1^*\chi_2 + \mathrm{H.c.})^2 \\ & + \Phi^\dagger\Phi(\lambda_7\chi_1^*\chi_1 + \lambda_8\chi_2^*\chi_2). \end{aligned} \tag{2}$$

In the potential (2), the constants μ, μ_1, and μ_2 have dimension of mass, while $\lambda_{1,\ldots,8}$ are dimensionless. From the real part of the potential (2) we get the square masses,

$$m_{h_1}^2 = \mu_2^2 + \lambda_8 v^2 + (2\lambda_4 + \lambda_5 + 4\lambda_6)x^2, \tag{3a}$$

$$m_{h_2}^2 = 2\left[\lambda_1 v^2 + \lambda_2 x^2 - \sqrt{(\lambda_1 v^2 + \lambda_2 x^2)^2 + \lambda_7^2 v^2 x^2}\right], \tag{3b}$$

$$m_{h_3}^2 = 2\left[\lambda_1 v^2 + \lambda_2 x^2 + \sqrt{(\lambda_1 v^2 + \lambda_2 x^2)^2 + \lambda_7^2 v^2 x^2}\right]. \tag{3c}$$

From the imaginary sector we have a Higgs boson with mass

$$m_{h_4}^2 = \mu_2^2 + \lambda_8 v^2 + (-2\lambda_4 + \lambda_5)x^2, \tag{3d}$$

and two Goldstone bosons which are eaten by the neutral gauge bosons Z and Z'.

The respective eigenstates are

$$h_1 = \xi, \quad h_2 = c_\xi\xi_1 + s_\xi\xi_2, \quad h_3 = -s_\xi\xi_1 + c_\xi\xi_2, \quad h_4 = \zeta_2, \tag{4a}$$

$$G_1 = \zeta, \quad G_2 = \zeta_1, \tag{4b}$$

where h_i ($i = 1,\ldots,4$), G_1 and G_2 are physical eigenstates, with G_1 and G_2 being the Goldstone bosons. The mixing $c_\xi^2 = 1 - s_\xi^2 = \cos^2\theta_\xi$ is defined by

$$\theta_\xi = \arctan\frac{\lambda_7 v x}{\lambda_2 x^2 - \lambda_1 v^2 - \sqrt{(\lambda_2 x^2 - \lambda_1 v^2)^2 + \lambda_7^2 v^2 x^2}}. \tag{5}$$

In Tables I and II we present the relevant couplings for the scalars of the model. Equation (3a) and Table I suggest that h_1 is the Higgs boson of 125 GeV. The scalar we propose as a DM candidate is h_4. Hence, it is important that $m_{h_4} \approx 10$ GeV, that is, it is in the region suggested by most of the experiments (see Sec. I).

TABLE I. Trilinear Higgs interactions.

$h_1h_1h_1$	$4\lambda_1 v$
$h_1h_1h_2$	$2\lambda_7 c_\xi x$
$h_1h_1h_3$	$2\lambda_7 s_\xi x$
$h_1h_2h_2$	$2(\lambda_7 c_\xi^2 + \lambda_8 s_\xi^2)v$
$h_1h_2h_3$	$4(\lambda_7 - \lambda_8)c_\xi s_\xi v$
$h_1h_3h_3$	$2(\lambda_7 s_\xi^2 + \lambda_8 c_\xi^2)v$
$h_1h_4h_4$	$2\lambda_8 v$
$h_2h_2h_2$	$2[2\lambda_2 c_\xi^2 + (2\lambda_4 + \lambda_5 + 4\lambda_6)s_\xi^2]c_\xi x$
$h_2h_2h_3$	$2[2(3\lambda_2 - 2\lambda_4 - \lambda_5 - 4\lambda_6)c_\xi^2 + (2\lambda_4 + \lambda_5 + 4\lambda_6)s_\xi^2]s_\xi x$
$h_2h_3h_3$	$2[(2\lambda_4 + \lambda_5 + 4\lambda_6)c_\xi^2 + 2(3\lambda_2 - 2\lambda_4 - \lambda_5 - 4\lambda_6)s_\xi^2]c_\xi x$
$h_2h_4h_4$	$-2(2\lambda_4 - \lambda_5)c_\xi x$
$h_3h_3h_3$	$2[(2\lambda_4 + \lambda_5 + 4\lambda_6)c_\xi^2 + 2\lambda_2 s_\xi^2]s_\xi x$
$h_3h_4h_4$	$-2(2\lambda_4 - \lambda_5)s_\xi x$

TABLE II. Neutrino couplings to scalars.

	$\bar{\nu}_\ell \nu_\ell$	$\bar{\nu}_\ell \nu_h$	$\bar{\nu}_h \nu_h$
h_1	$2y_\nu c_\nu s_\nu$	$-y_\nu(c_\nu^2 - s_\nu^2)$	$-2y_\nu c_\nu s_\nu$
h_2	$-2y_M s_\nu^2 c_\xi$	$2y_M c_\nu s_\nu s_\xi$	$2y_M c_\nu^2 c_\xi$
h_3	$2y_M s_\nu^2 s_\xi$	$-2y_M c_\nu s_\nu s_\xi$	$2y_M c_\nu^2 s_\xi$

From the gauge sector, the masses of the gauge bosons Z and Z' are given by

$$m_Z^2 = \frac{1}{4}(g^2 + g_1^2)v^2, \qquad m_{Z'}^2 = {g'_1}^2 x^2, \tag{6}$$

where g, g_1, and g'_1 are the coupling constants of the SU(2), $\mathrm{U}(1)_Y$, and $\mathrm{U}(1)_{B-L}$ groups, respectively. The limits imposed by LEP and Tevatron establish that $m_{Z'}/g'_1 \geq 7$ TeV [31], and the LEP experiments also provided a lower bound of $x \geq 3.5$ TeV [31].

The lepton Yukawa interactions are given by

$$-\mathcal{L} = y_{jk}^e \overline{\ell'_{jL}} e'_{kR}\phi + y_{jk}^\nu \overline{\ell'_{jL}} N'_{kR}\sigma_2\phi^* + y_{jk}^M \overline{(N'_R)^c_j} N'_{kR}\chi_1 + \mathrm{H.c.}, \tag{7}$$

where $\ell_{iL} = (\nu_i \;\; e_i)_L^T$, N_{iR} are heavy neutrinos, y_{jk}^e, y_{jk}^ν, y_{jk}^M are Yukawa constants, and i, j, k are family indexes. We are not assuming interfamily mixing for the neutrinos, so we assume $y_{jk}^e = y_e$, $y_{jk}^\nu = y_\nu$, and $y_{jk}^M = y_M$ [30]. Therefore, from the Lagrangian (7) we obtain the neutrino masses

$$m_{\nu_i} = \frac{1}{2}\left(y_M x_1 - \sqrt{y_\nu^2 v^2 + y_M^2 x_1^2}\right), \tag{8a}$$

$$m_{N_i} = \frac{1}{2}\left(y_M x_1 + \sqrt{y_\nu^2 v^2 + y_M^2 x_1^2}\right), \tag{8b}$$

with the eigenstates

$$\nu_i = c_\nu \nu_{\ell_i} + s_\nu \nu_{h_i}, \qquad N_i = -s_\nu \nu_{\ell_i} + c_\nu \nu_{h_i}, \tag{9}$$

where $c_\nu = \cos\theta_\nu$, $s_\nu = \sin\theta_\nu$, and $\tan^2\theta_\nu = -m_{N_i}/m_{\nu_i}$.

III. DARK MATTER ABUNDANCE

To study the evolution of the numerical density n of h_4 (the DM candidate) at temperature T in the early Universe the Boltzmann equation can be written in a simplified form,

$$\frac{dY}{dy} = -\sqrt{\frac{\pi g_*}{45G}}\frac{m_{h_4}}{y^2}\langle\sigma_{\mathrm{ann}}|\mathrm{v}|\rangle(Y^2 - Y_{\mathrm{eq}}^2), \tag{10}$$

where $Y = n/s$, s is the entropy per unit of volume, Y_{eq} is the Y value at thermal equilibrium, and $y = m_{h_4}/T$. The parameter G is the universal constant of gravitation, σ_{ann} is the cross section for annihilation of the particle h_4 and v is the relative velocity. In Eq. (10), the symbol $\langle\rangle$ represents the thermal average. The term g_* is a parameter that measures the effective number of degrees of freedom at freeze-out, which is expressed as

$$g_* = \sum_{i=\mathrm{bosons}} g_i\left(\frac{T_i}{T}\right)^4 + \frac{7}{8}\sum_{i=\mathrm{fermions}} g_i\left(\frac{T_i}{T}\right)^4. \tag{11}$$

Note that g_* is a function of T, and the sums in Eq. (11) run over only those species with masses $m_i \ll T$ [32]. Considering $T \gtrsim 300$ GeV, in this model $g_* = 113$ and (because of the assignment of values to the parameters in Sec. IV) the particles included in this calculation will be all the species of the standard model plus one extra Higgs and three right-handed neutrinos. In this case, the Z' and the other two scalars, which are also contained in the model, did not appear in the calculation of g_* since they are heavier than 300 GeV.

To find Y_0, the present value of Y, Eq. (10) must be integrated between $y = 0$ and $y_0 = m_{h_4}/T_0$. Once this value is found, the contribution of h_4 to the DM density is

$$\Omega_{h_4} = \frac{m_{h_4} s_0 Y_0}{\rho_c}. \tag{12}$$

Considering the model studied here and the set of parameters, the annihilation cross section mediated by h_2 is dominant over the one mediated by h_1. The DM annihilates mainly in $b\bar{b}$, $c\bar{c}$, and $\tau^+\tau^-$. The cross section for the annihilation of h_4 into fermions f is given by

$$\sigma(h_4h_4 \to f\bar{f}) = \frac{N_c}{64\pi s}\sqrt{\frac{s - 4m_f^2}{s - 4m_{h_4}^2}}\frac{g_{244}^2 g^2 s_\xi^2 m_f^2}{m_W^2} \times \frac{s - 4m_f^2}{(s - m_{h_2}^2)^2 + m_{h_2}^2\Gamma_{h_2}^2}, \tag{13}$$

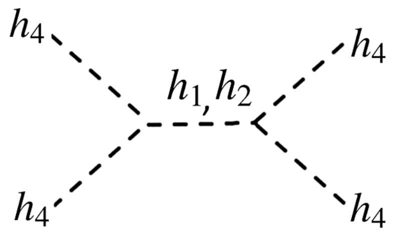

FIG. 1. Feynman diagrams involved in the process $h_4 h_4 \to h_4 h_4$.

where N_c denotes the color number, g is the coupling constant of $SU(2)_L$, m_f is the fermion mass, and g_{244} is the strength of the interaction $h_2 h_4 h_4$ (Table I).

If there are no resonances and coannihilations, it is required that the thermal average annihilation cross section is $\langle \sigma_{\rm ann} |{\rm v}| \rangle \sim 3 \times 10^{-26}$ cm^3/s at the temperature of freeze-out ($T_f \simeq m_{h_4}/x_f$), with $x_f \simeq 20$ to 30 in order to have a relic abundance $\Omega_{h_4} = 0.1196 \pm 0.0031$.

In this paper we use the MICROMEGAS package, which employs the Runge-Kutta method to numerically solve the Boltzmann equation (10) [33]. All the interactions of the minimal $B-L$ model are given in Ref. [30]. We have implemented all the interactions in the CALCHEP package [34] and in MICROMEGAS.

In Fig. 1 we present the Feynmann diagrams that contribute to the scattering of h_4.

IV. RESULTS AND COMMENTS

In this section we present the parameter choices for the model. In order to have h_4 as the DM candidate we use the following inputs: $\mu_2 = 3170.19$, $\lambda_1 = 2.3$, $\lambda_2 = 4 \times 10^{-2}$, $\lambda_3 = 1$, $\lambda_4 = -9.9 \times 10^{-2}$, $\lambda_5 = -6 \times 10^{-1}$, $\lambda_6 = 9.916 \times 10^{-2}$, $\lambda_7 = 3 \times 10^{-4}$, $\lambda_8 = 10^{-7}$, $v = 246$ GeV, and $x = 5000$ GeV. These particular choices will result in the following masses for the scalars: $m_{h_1} = 126.8$ GeV, $m_{h_2} = 746.15$ GeV, $m_{h_3} = 2000$ GeV, and the DM candidate will have a mass $m_{h_4} = 10.2$ GeV. For the neutrino sector we have chosen $y_M = 10^{-6}$ and $y_\nu = 10^{-8}$, so the masses for the light and heavy neutrinos will be, respectively, $m_{\nu_1} = m_{\nu_2} = m_{\nu_3} \simeq 3 \times 10^{-10}$ GeV and $m_{N_1} = m_{N_2} = m_{N_3} = 5 \times 10^{-3}$ GeV.

These parameter choices lead to $\sigma |{\rm v}| = 2.63 \times 10^{-26}$ cm^3/s, $\Omega = 0.11$, and the dominant annihilation channels for h_4 will be in fermions, with 87% in $b\bar{b}$, 7% in $\tau\bar{\tau}$, and 6% in $c\bar{c}$. In addition, our spin-independent elastic cross sections are close to $\sigma_I \simeq (2-5) \times 10^{-41}$ cm^2, the value established by XENON100 constraints for low-mass DM [11]. We obtain $\sigma_{I,p} = 1.17 \times 10^{-41}$ cm^2 and $\sigma_{I,n} = 1.19 \times 10^{-41}$ cm^2 for collisions with the proton and neutron, respectively. It is interesting to notice that there are other parameter region that can also lead to the right experimental results.

Our DM candidate is light. Global fits put limits on the resulting invisible decay of the Higgs boson such that $B(H \to \text{invisible}) < 0.19(0.38)$ at 95% C.L. [35,36]. But in the scenario chosen here, the Higgs decay into the DM is suppressed. The coupling of the Higgs to DM is presented in Table I and depends essentially on the parameters λ_8 and v. The Higgs coupling to DM should be smaller than the SM bottom Yukawa coupling, considering the fact that our parameter choice for the branching is $B(H \to DM) = 2.9 \times 10^{-8}$, which is very safe.

V. CONCLUSION

We have proposed a scenario where the $B-L$ model has a potential low-mass DM candidate. The model has four scalar bosons, two of which are heavy, one of which plays the role of the Higgs with a mass of 125 GeV, and one which plays the role of the DM candidate. The DM candidate is a pseudoscalar and the dominant annihilation processes are via scalar exchanges in the s channel.

The model's motivation is to develop a Higgs portal to DM without spoiling the present constraints for invisible Higgs decays. Besides, the spin-independent elastic cross section is in good agreement with the results of the CoGeNT and CDMS experiments discussed in Sec. I for DM with a mass of the order of (7–10) GeV [11]. On the other hand, the LUX experiment presented results that are not fully compatible with those of CoGeNT and CDMS. With our parameter choices the results of CoGeNT and CDMS are reproduced. The results of LUX can also be reproduced with another set of parameters for the model. As the experiments disagree amongst themselves, it is not possible to reach all the results at the same time.

We have shown here that the minimal $B-L$ model with the addition of a singlet complex scalar is a theoretically self-consistent model for dark matter. So, the model is a good candidate to be detected in the future experiments at the LHC and with direct DM searches. As opposed to the 125 GeV Higgs, the other scalar h_2—which dominates the annihilation processes—decays predominantly through invisible DM decays.

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