

## Scalar fields as dark matter candidates in the modified left-right symmetry model

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### ABSTRACT

Dark matter is about 25% of the universe, but it is still a mystery. The Modified Left-Right Symmetry Model with the scalar field, extension is expected to explain dark matter candidate. The dark matter candidates were analyzed using the Higgs Potential and Lagrangian Yukawa to obtain information on decay and scattering interactions. The generation of dark matter can be determined by analyzing the temperature evolution of the universe, which is divided into three stages post-inflation reheating, symmetry breaking first step, and symmetry breaking second step. The analysis results show that the right-sector scalar field  $\Delta_R$  can be Cold Dark Matter (CDM), candidate, because it has non-relativistic characteristics, is stable, does not interact with fermions, and has an abundance of 0.004. The right-sector atom can also be a CDM candidate because it has non-relativistic characteristics, is neutral, and consists of the right nucleons and right electrons. The singlet scalar field  $\eta$  can be the Warm Dark Matter (WDM) candidate because it can decay into fermion, interact in the left and right sectors, is neutrally charged and does not interact with other particles electromagnetically and has an abundance of 0.003. Thus, based on the modified left-right symmetry model, the particle that can be a candidate for dark matter is the scalar field.

### Keywords:

Left Right Symmetry; Standard Model; Dark Matter; Particle Physics; Scalar Field

### Introduction

The elementary particles that make up the universe interact with each other through four fundamental interactions, namely electromagnetic, strong, weak, and gravitational interactions (Collins et al., 1989). The theory that can explain the dynamics of particles based on the four interactions has yet to be found. However, there is a theory that can combine the three fundamental interactions, namely the Standard Model of Particle Physics. This model is based on the gauge group  $SU(3) \otimes SU(2) \otimes U(1)$ .  $SU(3)$  Groups describe particles that experience strong interactions,  $SU(2)$  groups describe particles that experience weak interactions, and  $U(1)$  groups describe particles that experience electromagnetic interactions (Hariwangsa & Satriawan, 2016).

The success of this model is indicated by the results of its predictions that are by the experimental results. The mass of the gauge and Bosons predicted in this model is relevant to the results of experiments conducted at CERN (Griffiths, 2008). Another success, the Higgs hypothesis of the particle responsible for giving the mass of the Standard Model particle, was discovered in 2012 (The ATLAS Collaborations, 2013). However, this model has drawbacks, including being unable to neutrino masses, interactions, being unable to explain matter-antimatter asymmetry, and dark matter (Levy et al., 2021). Thus, it is necessary to expand the Standard Model to compensate for these weaknesses. Several expansions of the Standard Model are the Grand Unified Theory (Dutta et al., 2010), the Minimal Left-Right Supersymmetry Model (Huitu, 2020), the Minimal Extension of the Standard Model (Haniah et al., 2020), and Modified Left-Right Symmetry Model (Istikomah, 2020).

The Modified Left-Right Symmetry Model has advantages such as predicting the mass formulation of the Higgs boson and the mass of the gauge boson, which follows the Standard

Model (Istikomah, 2020). This model can compensate for one of the Standard Model's weaknesses, namely the presence of dark matter. The existence of dark matter is one of the solutions to cosmological phenomena that many scientists believe. Natural phenomena that indicate the presence of dark matter include observing of the Coma galaxy cluster, which has a mass-to-luminosity ratio of 50 times greater than that of each member of the galaxy cluster (Majumdar, 2015). The observations of collisions between two galaxies (bullet clusters) in the constellation Carina show that the center of mass of the gravitational equipotential surfaces of the two galaxies is not at the center of mass of the baryon. This observation indicates the existence of other matter, namely dark matter, which fills the universe. The existence of dark matter itself fills the universe about 25%; the other composition is baryons and dark energy. Dark matter must be neutrally charged so it does not interact electromagnetically. It is a relativistic particle with a massive mass and a long-lived (Rubakov & Gorbunov, D., 2011).

Theoretically, dark matter candidates are divided into three types. Hot Dark Matter (HDM) is a relatively small-mass, relativistic dark matter candidate. Examples of HDM candidates are the three types of neutrinos in the Standard Model of Particle physics. Secondly, a dark matter candidate with a large mass and non-relativistic motion is known as Cold Dark Matter (CDM). CDM candidates are particles introduced to Standard Model extensions such as Weakly Interacting Massive Particles (WIMPs), axions, super-partner particles of Supersymmetric particles and non-baryonic particles of other Standard Model expansions. New scalar fields introduced in the expansion of the Standard Model that interacts only with the Englert–Brout–Higgs scalar field and remains stable can also be candidates for CDM (Rubakov & Gorbunov, D., 2011). The third type of candidate is Warm Dark Matter (WDM), whose mass and velocity are between the mass and velocity intervals of the HDM and CDM candidate types (Luminet, 2002). This WDM model can explain several problems on a small scale, such as the missing satellite problem (Simon & Geha, 2021). The hypothetical particle included in the WDM candidate is a sterile neutrino. Unlike the Standard Model neutrino particle, sterile neutrinos do not interact in an electromagnetic way and are, therefore, very difficult to detect (Rubakov & Gorbunov, D., 2011).

Previous research on dark matter candidates in the Mirror Model showed that the mirror electron abundance of around 0.174 and a mass of 3.55 MeV could potentially be CDM candidates (Setyadi & Satriawan, 2014). Another study showed the lightest sneutrino and neutralino particles in the Minimal Left-Right Supersymmetry Model (Huitu, 2020). In the B-L Minimal Model, with the addition of right-handed neutrino particles, the gauge boson  $A'_\mu$  from the gauge symmetry  $U(1)_{B-L}$  is identified as a candidate for dark matter. Yukawa coupling between the scalar field and neutrinos is required to produce a dark sector with a scale of about keV. Based on Yukawa's interaction strength, there are two ways of evolution of the dark sector system: with a dark thermal bath and without a dark thermal bath (Choi et al., 2021). In other studies, the scalar field could be a candidate for dark matter to explain the speed curve problem. The rotation in spiral galaxies is almost the same as the halo curve in spiral galaxies (Guzmán & Matos, 2000; Matos et al., 2000). The scalar field can become a communicator with dark matter, so the scalar field is a dark matter candidate (Lebedev et al., 2012).

Based on the description, dark matter is interesting to study because of its role as one of the compositions of the universe. The Modified Left-Right Symmetry Model has been analyzed related to the symmetry-breaking process of the gauge group. This interaction process occurs while the dark matter candidate particles are in kinetic equilibrium and the interaction process after decoupling from the equilibrium temperature. The interaction studied and analyzed is the interaction of decay and scattering that occurs based on the Yukawa lagrangian and the Scalar Field potential. Based on the processes that occur, the mass, abundance of dark matter, and its characteristics as a candidate for dark matter can be known.

## Methods

This research is theoretical. The generation of dark matter can be determined by analyzing the temperature evolution of the universe. The temperature evolution is divided into three stages: after post-inflation reheating, symmetry breaking first step, and symmetry breaking second step. Each step analyzes the possibility of interactions contributing to entropy by reviewing based on Higgs Potential and Yukawa's Lagrangian. It is assumed that massive particles in the comoving volume released from thermal equilibrium experience decay and that they affect the entropy. Following the method (Kolb & Turner, 1990), the entropy difference before and after the process, as shown by equation (1)

$$\frac{S_f}{S_i} = \left[ 1 + \frac{4}{3} \left( \frac{45}{2\pi^2 g_*(T_i)} \right)^{\frac{1}{3}} \frac{mY_i}{T_i} \tau^{-1} \int_0^\infty \left( \frac{2\pi^2 g_*}{45} \right)^{\frac{1}{3}} \frac{R(t)}{R_i} e^{(-\frac{t}{\tau})} dt \right]^{\frac{3}{4}} \quad (1)$$

Where  $g_*$  is the relativistic degree of freedom,  $T_i$  is the initial temperature before the decay process,  $R_i$  is the cosmological scale at this initial time and initial abundance  $Y_i$ . The integral in equation (1) depends on the scale factor  $R(t)$ . If the particle under consideration dominates the energy density of the universe before it decays, then the integral can be evaluated numerically so can be written as (Kolb & Turner, 1990)

$$\frac{S_f}{S_i} \cong 1.83 \frac{(g_*^{1/3})^{\frac{3}{4}} mY_i \tau^{\frac{1}{2}}}{m_{pl}^{1/2}} \quad (2)$$

It is assumed that the massive particle's lifetime  $\tau$  is very long, so the entropy change in equation (1) is only affected by the particle's lifetime, which is reciprocal of the particle's total decay rate,  $\tau = 1/\Gamma$  Suppose there is a process that causes a change in entropy in the left sector and the right sector. Thus, the change in entropy causes the two sectors to heat up; the comparison of temperature changes can be approximated by equation (3)(Satriawan, 2018)

$$\frac{T_{fR}}{T_{fL}} = \left( \frac{S_{fR}}{S_{fL}} \right)^{1/3} \approx \left( \frac{\Gamma_R}{\Gamma_L} \right)^{1/4} \quad (3)$$

The decay rate is obtained by analyzing the Feynman diagram using the Golden Rule(Griffiths, 2008). The density of the number of particles uses the Maxwell-Boltzmann distribution as shown by equation (4)

$$n_i = g_i \left( \frac{m_i T}{2\pi} \right)^{3/2} e^{-\frac{\mu_i - m_i}{T}} \quad (4)$$

If the density of the number of particles is known, then the abundance of particles can be known by the relation  $Y_i = n_i/s_i$ . Thus, once the interactions and particle abundances are known, it can be predicted which particles can be used as dark matter candidates.

## Scalar Field

The Modified Left-Right Symmetry Model is built based on the gauge group  $SU(3) \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_Y$  and consists of two: left and right sectors (Istikomah, 2020). This model has six scalar fields with assumptions,

1. The two primary doublet scalar fields represented by equation (5)

$$\phi_L = \begin{pmatrix} \phi_L^0 \\ \phi_L^- \end{pmatrix} \sim (\mathbf{1}, \mathbf{2}, \mathbf{1}, -1), \quad \phi_R = \begin{pmatrix} \phi_R^0 \\ \phi_R^- \end{pmatrix} \sim (\mathbf{1}, \mathbf{1}, \mathbf{2}, -1) \quad (5)$$

The Dirac mass of the fermion and gauge boson masses are generated by the Vacuum Expectation Value (VEV) of the scalar field  $\phi_L$  and  $\phi_R$ .

2. The two new doublet scalar fields represented by equation (6)

$$\Delta_L \sim \left( \mathbf{1}, \mathbf{2}, \mathbf{1}, \frac{1}{3} \right), \quad \Delta_R \sim \left( \mathbf{1}, \mathbf{1}, \mathbf{2}, \frac{1}{3} \right) \quad (6)$$

These two new scalar field roles are necessary for breaking the symmetry phenomenologically from a gauge group  $SU(3) \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_Y$  to  $SU(3) \otimes SU(2)_L \otimes U(1)_Y$ . The scalar field  $\Delta_L$  is a doublet but a singlet  $SU(2)_L$ , so it cannot interact with ordinary fermions. Interactions between scalar fields  $\Delta_L$  or scalar fields  $\Delta_R$  can produce the primary scalar fields,  $\phi_L$  and  $\phi_R$ .

3. The two singlet scalar fields are represented by equation (7)

$$\eta \sim (\mathbf{1}, \mathbf{1}, \mathbf{1}, 0), \quad \xi \sim (\mathbf{1}, \mathbf{1}, \mathbf{1}, -2) \quad (7)$$

The scalar field  $\eta$  and  $\xi$  are introduced as fields that can be carrier particles for the interaction between sectors. In addition, this singlet scalar field can also interact with the primary and new doublet scalar fields.

## Evolution Of Universe Temperature

The process of dark matter generation is assumed to occur when the universe is dominated by the radiation energy density of the two sectors. The interactions in the two sectors affect the temperature evolution of the universe, especially the process of decay of massive particles into relativistic particles. It is these relativistic particles that contribute to the radiation energy of the universe, thereby affecting the temperature of the universe. There are three stages to observing the evolution of the universe's temperature. According to (Tenkanen, 2019)research, dark matter in the form of a massive scalar field did exist during the pre-Big Bang period or when cosmic inflation occurred. While in this study analyzed the occurrence of post-reheating inflation.

### Stage I: Period After Reheating Post-inflation

It is assumed that the temperature of the two sectors is the same,  $T_L = T_R \sim 10^{13}$  GeV, during the post-inflation reheating period. The energy of the two sectors is dominated by non-relativistic massive particles (Istikomah, 2015). These particles are the left-sector neutrino  $\nu_R$  and the right-sector neutrino  $N_L$ . Yukawa's Lagrangian describing the coupling between scalar fields and neutrinos is shown by equation (8)

$$L_Y \supset -G_4(\bar{\ell}\phi_L P_R \nu' + \bar{L}\phi_R P_L N') - G_5(\bar{\nu}'\xi^\dagger P_L E + \bar{N}'\xi^\dagger P_R e) + h.c. \quad (8)$$

Based on equation (8), the possibility of massive neutrino decay illustrated by The Feynman diagram is shown in Figure 1.

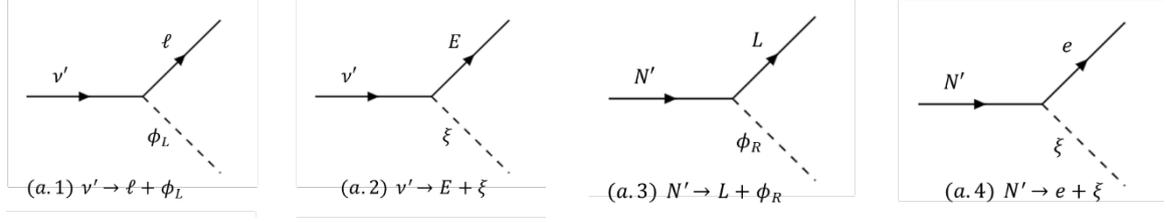


Figure 1. Decays Particle of  $\nu'$  and  $N'$

Crossing processes (a.1) – (a.4) modes in Figure 1 efficiently happen in two sectors if  $T_{L,R} > m_{\nu',N'}$ . When the temperature of sectors is less than the mass of the neutrino mass  $T_{L,R} < m_{\nu',N'}$ , the four decay modes only take place in one direction. The decay process (a.1) – (a.4) will be released from thermal equilibrium when the rate of the interaction process is slower than the expansion rate of the universe,  $\sum_i \Gamma_i < H$ .

The decay modes (a.1) and (a.4) produce left-sector sector particles that contribute entropy to the left sector. The total decay rate is shown by equation (9)

$$\Gamma_{L_1} = \frac{1}{16\pi} (G_4^2 m_{\nu'} + G_5^2 m_{N'}) \quad (9)$$

Processes (a.2) and (a.4) contribute additional entropy in the right sector. The total decay rate that produces particles in the right sector is shown by equation (10)

$$\Gamma_{R_1} = \frac{1}{16\pi} (G_5^2 m_{\nu'} + G_4^2 m_{N'}) \quad (10)$$

The decay rate of the two sectors can be related to the ratio of entropy and temperature before and after the process. If it is assumed that the initial temperature between the left sector and the right sector is the same ( $T_{iL_1} = T_{iR_1}$ ), then a temperature comparison between the two sectors is obtained, which is shown by equation (11)

$$\frac{T_{fR_1}}{T_{fL_1}} \approx \left( \frac{S_{fR_1}}{S_{fL_1}} \right)^{1/3} \approx \frac{(G_5^2 m_{\nu'} + G_4^2 m_{N'})^{1/4}}{(G_4^2 m_{\nu'} + G_5^2 m_{N'})^{1/4}} \quad (11)$$

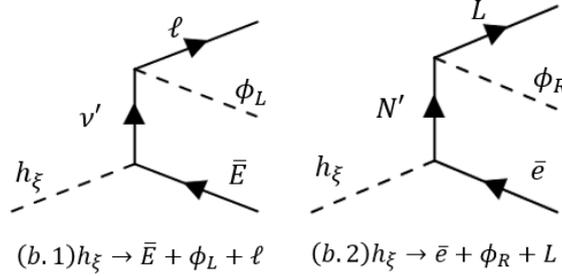
Suppose that the coupling constants  $G_4 \approx G_5$  and the neutrino masses  $m_{\nu'} = m_{N'}$ , Based on Equation (11), the temperature between the left sector is the same as the rate of the right sector during the post-inflation reheating period.

#### Stage ii: Spontaneous Symmetry Breaking First Step

In the second stage, symmetry breaks spontaneously when the universe's temperature is around  $10^4$  GeV (Istikomah, 2015). The scalar field  $\Delta_L, \Delta_R, \eta$ , and  $\xi$  takes its zero VEV, resulting in the scalar field obtaining its mass. The scalar field  $\xi$  which has mass undergoes decay mediated by  $\nu'$  and  $N'$  based on the combination of Yukawa's Lagrangian shown by Equation (12)

$$L_Y \supset -G_4 (\bar{\ell} \phi_L P_R \nu' + \bar{L} \phi_R P_L N') - G_5 (\bar{\nu}' h_\xi P_L E + \bar{N}' h_\xi P_R e) + hc \quad (12)$$

The Feynman diagram illustrating the possible process based on equation (12) is shown in Figure 2. The decay process (b.1) is a scalar field decay process  $\xi$  mediated by the neutrino mass  $\nu'$ ; the decay results are two particles in the left sector, namely  $\bar{\ell}$  and  $\phi_L$  and one particle E in the right sector. The decay process (b.2) is the decay of the scalar field  $\xi$  mediated by a massive neutrino  $N'$ ; the decay results are in the form of two right-sector particles, namely  $\bar{L}$  and  $\phi_R$  and one particle in the left sector, namely electrons  $e$ .



**Figure 2.** The neutrino mass  $\nu'$  mediates the decay of the  $\xi$  Scalar Field

The  $\eta$  scalar field gains mass and then decays into two  $\phi_L$  scalar fields on the left sector via mode (b.3)  $\eta \rightarrow \phi_L + \phi_L$  and into two  $\phi_R$  scalar fields on the right sector through mode (b.4)  $\eta \rightarrow \phi_R + \phi_R$ . The scalar fields  $\Delta_L$  and  $\Delta_R$  do not have a decay process, only a scattering process mediated by the scalar field  $\eta$ . The scatter mode is indicated in Table 1.

<b>Table 1.</b> Scalar Field $\Delta_L$ and $\Delta_R$ Scattering via $\eta$	
<b>Potential Higgs Terms</b>	<b><math>\Delta_L</math> and <math>\Delta_R</math> Scattering modes via <math>\eta</math></b>
$\alpha_1 h_\eta  \phi_L ^2 + \frac{1}{2} \alpha_3 h_{\Delta_L}^2 h_\eta$	(b.5) $h_{\Delta_L} + h_{\Delta_L} \rightarrow \phi_L + \phi_L^\dagger$
$\alpha_4 h_\eta  \phi_R ^2 + \frac{1}{2} \alpha_3 h_{\Delta_L}^2 h_\eta$	(b.6) $h_{\Delta_L} + h_{\Delta_L} \rightarrow \phi_R + \phi_R^\dagger$
$\alpha_1 h_\eta  \phi_L ^2 + \frac{1}{2} \alpha_5 h_{\Delta_R}^2 h_\eta$	(b.7) $h_{\Delta_R} + h_{\Delta_R} \rightarrow \phi_L + \phi_L^\dagger$
$\alpha_4 h_\eta  \phi_R ^2 + \frac{1}{2} \alpha_5 h_{\Delta_R}^2 h_\eta$	(b.8) $h_{\Delta_R} + h_{\Delta_R} \rightarrow \phi_R + \phi_R^\dagger$

Relativistic scalar field  $\eta$  and  $\xi$  decaying into relativistic particles via mode (b.1) – b(4), When the temperature of both sectors is  $T_L \leq m_{\Delta_L}$  and  $T_R \leq m_{\Delta_R}$ . Suppose that the decay product  $\xi$ , namely the scalar field  $\phi_L$ , moves in the opposite direction to the other two particles, namely  $\bar{E}$  and  $\ell$ . The scalar field  $\phi_L$  gets  $\frac{1}{2} m_\xi$  kinetic energy, while the other two particles get the rest. Thus, the decay product of process (b.1) contributes significantly to the change in entropy in the left sector compared to that in the right sector. The same assumption also applies to the case of the  $\xi$  decay process through mode (b.2).

The decay processes (b.1) and (b.3) contribute significantly to the change in entropy of the left sector. In contrast, processes (b.2) and (b.4) contribute significantly to the right sector. The rate of process decay in both sectors is shown by equations (13) and (14)

$$\Gamma_{L_2} = \Gamma_{(b.1)} + \Gamma_{(b.3)} = \frac{\alpha_1^2}{128 \pi \hbar m_\eta^2} + \frac{11 G_4^2 G_5^2 m_\xi^5}{12 (8\pi)^3 m_\nu^4} \quad (13)$$

$$\Gamma_{R_2} = \Gamma_{(a.24)} + \Gamma_{(a.19)} = \frac{\alpha_4^2}{128 \pi \hbar m_\eta} + \frac{11 G_4^2 G_5^2 m_\xi^5}{12 (8\pi)^3 m_N^4} \quad (14)$$

It is assumed that process (b. 5) – (b. 8) does not significantly affect the entropy change of the two sectors because it has the same probability. Thus, the temperature of the two sectors after the scalar field  $\Delta_L, \Delta_R, \eta$ , and  $\xi$  gain mass is compared shown by equation (15)

$$\frac{T_{fR_2}}{T_{fL_2}} \approx \left( \frac{S_{fR_2}}{S_{fL_2}} \right)^{\frac{1}{3}} \approx \frac{\left( \frac{\alpha_4^2}{128\pi\hbar m_\eta} \frac{12(8\pi)^3 m_{N'}^4}{11G_4^2 G_5^2 m_\xi^5} + 1 \right)^{\frac{1}{4}}}{\left( \frac{\alpha_1^2}{128\pi\hbar m_\eta} \frac{12(8\pi)^3 m_{\nu'}^4}{11G_4^2 G_5^2 m_\xi^5} + 1 \right)^{\frac{1}{4}}} \quad (15)$$

In this stage, there is a temperature difference between the two sectors. The temperature of both sectors is affected by the coupling constant  $\alpha_1 > \alpha_4$  so the left sector temperature is greater than the right one.

### Stage III: Symmetry Breaking Second Step

Scalar fields  $\phi_L$  and  $\phi_R$  take their VEV when symmetry gauge group  $SU(3) \otimes SU(2)_L U(1)_Y$  breaks to  $SU(3) \otimes U(1)_{em}$ . Yukawa's Lagrangian, which shows the decay of the massive scalar fields  $\phi_L$  and  $\phi_R$  shown by equation (16)

$$L_Y \supset -\frac{G_1}{\sqrt{2}} \bar{e} h_{\phi_L} P_R e' - \frac{G_1}{\sqrt{2}} \bar{E} h_{\phi_R} P_L E' - \frac{G_2}{\sqrt{2}} \bar{u} h_{\phi_L} P_R u' - \frac{G_2}{\sqrt{2}} \bar{U} h_{\phi_R} P_L U' - \frac{G_3}{\sqrt{2}} \bar{d} h_{\phi_L} P_R d' - \frac{G_3}{\sqrt{2}} \bar{D} h_{\phi_R} P_L D' - \frac{G_4}{\sqrt{2}} \bar{\nu} h_{\phi_L} P_R \nu' - \frac{G_4}{\sqrt{2}} \bar{N} h_{\phi_R} P_L N' \quad (16)$$

The Feynman diagram, which describes the decay process shown in Figure 3. The scalar field  $\phi_L$  decays into left-sector fermions through decay modes (c. 1), (c. 3), (c. 5) and (c. 7). The scalar field  $\phi_R$  also decays into a right fermion via (c. 2), (c. 4), (c. 6) and (c. 8) modes. Whose total decay rate is shown by equation (17) and equation (18) respectively.

$$\Gamma_{L_3} = \frac{m_{\phi_L}}{64\pi} (G_1^2 + G_2^2 + G_3^2 + G_4^2) \quad (17)$$

$$\Gamma_{\phi_R} = \frac{m_{\phi_R}}{64\pi} (G_1^2 + G_2^2 + G_3^2 + G_4^2) \quad (18)$$

The final temperature in stage II will be the initial temperature in stage III,  $T_{fL_2} = T_{iL_3}$ . So the entropy contribution comes from processes (c. 1) – (c. 8) as shown by equation (19)

$$\frac{T_{fR_3}}{T_{fL_3}} = \left( \frac{m_{\phi_R}}{m_{\phi_L}} \right)^{1/4} \frac{\left( \frac{\alpha_4^2}{128\pi\hbar m_\eta} \frac{12(8\pi)^3 m_{N'}^4}{11G_4^2 G_5^2 m_\xi^5} + 1 \right)^{1/4}}{\left( \frac{\alpha_1^2}{128\pi\hbar m_\eta} \frac{12(8\pi)^3 m_{\nu'}^4}{11G_4^2 G_5^2 m_\xi^5} + 1 \right)^{1/4}} \approx \left( \frac{m_{\phi_R} \alpha_4^2}{m_{\phi_L} \alpha_1^2} \right)^{\frac{1}{4}} \quad (19)$$

The final temperature difference between sectors affected by the mass of the scalar fields and neutrino. Suppose, the mass of the neutrino mass is massif  $m_{\nu'} = m_{N'}$ , the mass of scalar field  $m_{\phi_L} < m_{\phi_R}$  coupling constant  $\alpha_4 < \alpha_1$  so that it dramatically affects the final temperature ratio of the two sectors. Thus, the temperature of the left sector is greater than that of the right sector.

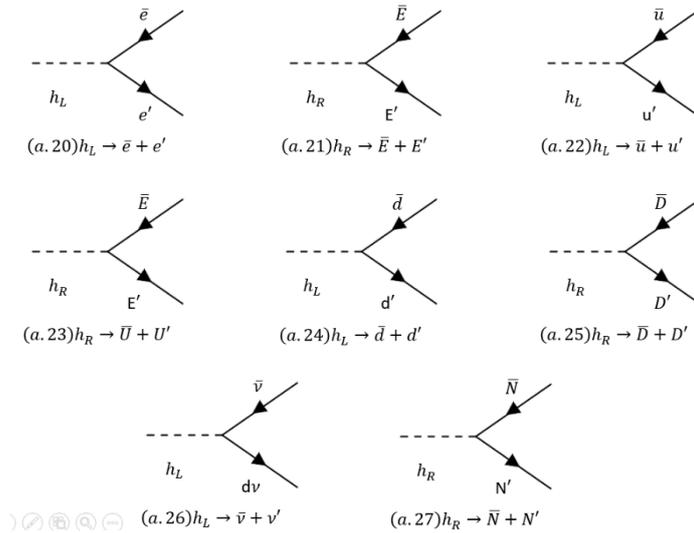


Figure 3. Scalar Field Decay  $\phi_L$  and  $\phi_R$

### The Dark Matter Generation Scenario

When the universe's temperature begins to decrease, the interaction that occurs is that massive particles  $\nu'$  and  $N'$  decay into lighter relativistic fermion particles. There is fermion scattering and scalar field scattering, which can still occur in both directions. At the end of stage I, both sectors have the same temperature. The relativistic degrees of freedom in both sectors is 112.75, so The abundance of neutrinos  $\nu'$  and  $N'$  in both sectors is the same as shown by equation (10)

$$Y_{\nu',N'} = \frac{n_{\nu',N'}}{S_{L_1,R_1}} = \frac{g_{\nu',N'} \left( \frac{m_{\nu',N'} T_{iL_1,R_1}}{2\pi} \right)^{\frac{3}{2}} e^{-\frac{\mu_{\nu',N'} - m_{\nu',N'}}{T_{iL_1,R_1}}}}{g_{*S_{L_1,R_1}} \frac{2\pi^2}{45} T_{iL_1,R_1}^3} = 0,001 \quad (10)$$

The symmetry breaks spontaneously when the universe's temperature is around  $10^4$  GeV. The scalar fields  $\Delta_L, \Delta_R, \eta$  dan  $\xi$  take the expected values of the vacuum and obtain their masses. he relativistic two-sector degrees of freedom has been reduced to 108.75 because the scalar fields  $\Delta_L$  and  $\Delta_R$  have a non-relativistic characteristic. The abundance of this scalar field is shown by equation (11)

$$Y_{\Delta_L,\Delta_R} = \frac{n_{\Delta_L,\Delta_R}}{S_{L_2,R_2}} = \frac{g_{\Delta_L,\Delta_R} \left( \frac{m_{\Delta_L,\Delta_R} T_{iL_2,R_2}}{2\pi} \right)^{\frac{3}{2}} e^{-\frac{\mu_{\Delta_L,\Delta_R} - m_{\Delta_L,\Delta_R}}{T_{iL_2,R_2}}}}{g_{*S_{L_2,R_2}} \frac{2\pi^2}{45} T_{iL_2,R_2}^3} = 0,004 \quad (11)$$

The scalar fields  $\Delta_L$  and  $\Delta_R$  scatter into another scalar field but do not decay into another particle; These scalar fields do not interact with other fermion particles electromagnetically. These results are consistent with Peebles' research, showing that dark matter does not interact with other matter. He only interacts gravitationally and with himself (Vilenkin, 1999). Thus, this scalar field can be a dark matter candidate for the Cold Dark Matter (CDM) category.

The scalar field  $\eta$  includes particles that can interact in the left and right sectors. These particles are neutrally charged and do not interact with other particles electromagnetically. However, the scalar field  $\eta$  is relativistic and almost stable because it decays into  $\phi_L$  and  $\phi_R$  scalar fields, making it a candidate for dark matter. The scalar field abundance  $\eta$  is shown by equation

(12).

$$Y_\eta = \frac{45\zeta(3)}{2\pi^4} \frac{g_{\text{eff}}}{g_{*sL2}} \approx 0.003 \quad (12)$$

The abundance of  $\eta$  is 0.003 in each sector—this  $\eta$  singlet scalar field is a candidate for Warm Dark Matter (WDM). The singlet scalar field as a candidate for dark matter is also consistent with the results of research conducted by (Bøehm et al., 2021; Hara et al., 2022). Research conducted by Hara et al. (2022) adding two additional singlet scalar extensions from MS, which could be candidates for dark matter. Dark matter was assumed to be in thermal equilibrium with SM particles in the early universe. Due to the universe's expansion, the density of dark matter began to decrease, and dark matter began to move out of thermal equilibrium with SM particles, called freeze out. The decrease in DM density can be explained by eradicating the singlet scalar field into fermions or other scalar fields. In accordance with the results of research conducted by Ruiz (2021) regarding scalar field as a WDM candidates.

The singlet scalar field  $\xi$  can interact with both sectors in the same way as the scalar field  $\eta$ . This scalar field can interact with fermions such as right sector Up and Down quarks. The scalar field  $\eta$  decays into a relativistic fermion. The scalar field abundance  $\xi$  in the right sector is 0.003. Thus, the scalar field  $\xi$  cannot be a candidate for dark matter. When the universe's temperature is around  $10^2$  GeV, the scalar fields  $\phi_L$  and  $\phi_R$  acquire their vacuum expectancy values. Moreover, these two scalar fields are gaining mass and starting to decay into relativistic fermions. The decay results of these two scalar fields contribute heat to both sectors. The final temperature in the third stage shows that the temperature of the left sector is greater than that of the right sector. The scalar field  $\phi_R$  decay results in the right sector become  $U\bar{U}, D\bar{D}, N\bar{N}$  and  $E\bar{E}$  fermions. The quarks in the right sector combine to form a right meson and a right baryon. A right meson, such as a right pawn, will be annihilated into a fundamental particle in the right sector. The right baryon formed is like the r-neutron and r-proton, which has a mass that is more massive than the left proton and left neutron. The suitable proton and right neutron form the right nucleon, and the light nucleus and the right E sector electrons form the r-atom. The right-hand sector atoms are neutral and non-relativistic, so they can potentially become candidates for the category of Cold Dark Matter (CDM) dark matter following the research results (Satriawan, 2018), (Foot, 2014).

## Conclusion

In the Modified Left-Right Symmetry Model, the scalar field  $\Delta_R$  can be a candidate for Cold Dark Matter because it has non-relativistic characteristics does not decay into other particles, experiences scattering interactions between scalar fields, does not interact with other fermion particles electromagnetically and has an abundance of 0.004. The scalar field  $\eta$  can be a candidate for Warm Dark Matter, has relativistic characteristics, can decay, can interact in the left and right sectors, has a neutral charge, does not interact with other particles electromagnetically and has an abundance of 0.003.

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## Conflicts of interest

The authors declare that there are no conflicts of interest.

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