Signatures of left-right symmetry at high energies\footnote{Invited talk in \textit{The 2nd Tallinn Symposium on Neutrino Physics}, October 5-8, 1993}

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Abstract

We discuss various experimental tests of the left-right symmetric $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model possible to perform in the next generation linear colliders. We consider processes which provide sensitive probes of the basic ingredients of the model: right-handed gauge bosons, right-handed Majorana neutrinos, lepton number violating interactions and triplet Higgs scalars. A supersymmetric version of the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model is also studied and some distinctive experimental tests for it is proposed. One of the main messages of this talk is to emphasize the usefulness of the collision modes $e^-e^-$, $e^−\gamma$ and $\gamma\gamma$ for the tests of the left-right symmetric model.

1 Introduction

The left-right symmetric model based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$\cite{1} is the simplest extension of the standard electroweak theory involving extra charged gauge bosons. Apart from its original motivation of providing a dynamical explanation for the parity violation observed in low-energy weak interactions, this model differs from the Standard Model in another important respect: it can explain the observed lightness of neutrinos in a natural way. Neutrino masses are created through the see-saw mechanism \cite{2}, according to which there are in each family a light neutrino, much lighter than the charged fermions of the family, and a heavy neutrino. The anomalies measured in the solar \cite{3} and atmospheric \cite{4} neutrino fluxes seem to indicate that neutrinos indeed should have a small but non-vanishing mass. Furthermore, the recent observations of the COBE satellite \cite{5}
may indicate that there exists a hot neutrino component in the dark matter of the Universe. The see-saw mechanism can account for all these phenomena, while in the Standard Model neutrinos are massless.

Several authors [6], [7] have investigated indirect implications of the left-right symmetry on the various low-energy phenomena to set constraints on the parameters of the model, such as the mixings between the new gauge bosons $W^+_R$ and $Z_R$ associated with $SU(2)_R$ and their $SU(2)_L$ counterparts $W^+_L$ and $Z_L$. In the case the gauge coupling constants $g_L$ and $g_R$ of $SU(2)_L$ and $SU(2)_R$, as well as the CKM-matrix and its equivalent in $V + A$ charged current interactions, are kept unrelated, one obtains from the charged current data the bounds $g_L M_{W_2}/g_R \gtrsim 300$ GeV and $g_L \zeta/g_R \lesssim 0.013$, where $\zeta$ is the $W_L - W_R$ mixing angle. From neutral current data one can derive the lower bound $M_{Z_2} \gtrsim 400$ GeV for the mass of the new $Z$-boson and the upper bound of 0.008 for the $Z_1, Z_2$ mixing angle. CDF experiment at Tevatron one has recently obtained the mass limits $M_{W_2} > 520$ GeV and $M_{Z_2} > 310$ GeV [8].

In this talk I will consider various direct tests of the left-right symmetric model, which one could perform in the high energy linear colliders. The collision energies in these accelerators (CLIC, NLC, TESLA, JLC) are planned to be in the range $\sqrt{s} = 0.5 - 2$ TeV [9]. If the masses of the new gauge bosons are close to their present lower limits, it would be possible to produce them and directly investigate their properties. Similarly it would be possible to search for the heavy Majorana neutrinos, or right-handed neutrinos, predicted by the model. The masses of these neutrinos are, if one believes in the see-saw mechanism, in the most simple case of the order of the masses of the new weak bosons. One would also be able to probe the symmetry breaking sector of the theory by looking for the new type of Higgs bosons, in particular doubly charged triplet scalars which are assumed to set the large mass scale of the model.

The organization of this talk will be as follows. We first give a short account of the basic structure of the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model. In Section 3 the pair production of weak bosons in $e^+e^-$ collisions will be considered. It is pointed out that the cross section of these processes may be quite sensitive to the mass of heavy neutrinos. In Section 4 we will discuss processes where the lepton number violating couplings associated with the triplet Higgses and the Majorana neutrinos play role. In Section 5 we will introduce a supersymmetric version of the left-right symmetric model and investigate its tests in $e^+e^-, e^-\gamma$ and $\gamma\gamma$ collisions. Some conclusions are made in Section 6.
2 Structure of the left-right symmetric model

The left-right symmetric models are characterized by the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The left- and right-handed fermions are set into doublet representations of $SU(2)_L$ and $SU(2)_R$, respectively. In the following we will deal with leptons only, which are assigned according to

$$
\Psi_L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \quad \Psi_R = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix},
$$

and similarly for other families. The $U(1)$ quantum number is normalized in such a way that the electric charge $Q$ is given by

$$
Q = T^3_L + T^3_R + (B - L)/2,
$$

where $T^3_L = T^3_R = \sigma_3/2$ are the doublet representations of the neutral generators of the $SU(2)$ subgroups.

In order to generate masses for fermions one requires at least one Higgs bidoublet of the form

$$
\Phi = \begin{pmatrix} \phi^0_1 & \phi^+_1 \\ \phi^-_2 & \phi^0_2 \end{pmatrix} = (2, 2, 0),
$$

whose vacuum expectation value (VEV) is given by

$$
<\Phi> = \frac{1}{\sqrt{2}} \begin{pmatrix} \kappa_1 & 0 \\ 0 & \kappa_2 \end{pmatrix}.
$$

In order to break the symmetry to the electromagnetic group $U(1)_{em}$ additional higgs multiplets with $B - L \neq 0$ are needed. To introduce at the same time Majorana mass terms for the neutrinos we add to theory the triplet Higgses

$$
\Delta_L = \begin{pmatrix} \Delta^+_L & \sqrt{2}\Delta^0_L \\ \sqrt{2}\Delta^0_L & -\Delta^+_L \end{pmatrix} = (3, 1, 2),
$$

$$
\Delta_R = \begin{pmatrix} \Delta^+_R & \sqrt{2}\Delta^0_R \\ \sqrt{2}\Delta^0_R & -\Delta^+_R \end{pmatrix} = (1, 3, 2)
$$

with the VEV’s given by

$$
<\Delta_{L,R}> = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}.
$$

The left-handed triplet scalar $\Delta_L$ does not play any role in the dynamics of the model. Its vacuum expectation value $v_L$ is tightly constrained by the measurements of the mass ratio of the ordinary weak bosons which implies $v^2_L \ll \kappa_1^2 + \kappa_2^2$. On the other hand, $v^2_R \gg \kappa_1^2 + \kappa_2^2$ in order to satisfy the lower mass limits of the new weak bosons.
The Yukawa couplings between the leptons and the scalars are the following:

\[ \mathcal{L}_Y = f \bar{\Psi}_R \Phi \Psi_L + g \bar{\Psi}_R \tilde{\Phi} \Psi_L + i h_L \Psi_L^T C \sigma_2 \Delta L \Psi_L + i h_R \Psi_R^T C \sigma_2 \Delta R \Psi_R + h.c. \],

where \( \Delta_{L,R} = \Delta_i \sigma_i \) and \( \tilde{\Phi} = \sigma^2 \Phi^* \sigma^2 \). As one can see from this the triplet Higgses \( \Delta_L \) and \( \Delta_R \) carry lepton number \(-2\), and on the other hand the \( B - L \) symmetry forbids their coupling to quarks.

There are all together seven vector bosons: \( W_{L,R}^\pm = \frac{1}{\sqrt{2}} (V_{1L,R} \pm i V_{2L,R}), V_{2L} \), and \( B \). We define the physical states of the bosons by the equations

\[
\begin{pmatrix}
W_L^+ \\
W_R^+
\end{pmatrix} =
\begin{pmatrix}
\cos \zeta & -\sin \zeta \\
\sin \zeta & \cos \zeta
\end{pmatrix}
\begin{pmatrix}
W_1^+ \\
W_2^+
\end{pmatrix},
\]

\[
\begin{pmatrix}
V_L^2 \\
V_R^2 \\
B
\end{pmatrix} = (R_{ij}) \begin{pmatrix}
Z_1 \\
Z_2 \\
Z_3 = \gamma
\end{pmatrix} \quad (i = L, R, B).
\]

The mixing matrix \( R \) can be parametrized in terms of three rotation angles. One can determine [10] their values for example by using the experimental results for the electron vector and axial vector neutral current couplings and the low-energy constraint for the \( W_L - W_R \) mixing angle \( \zeta \lesssim 0.005 \).

From the left-handed and right-handed neutrino states one can form three types of Lorentz-invariant mass terms: Dirac term \( \bar{\nu}_L \nu_R \) and Majorana terms \( \bar{\nu}_L^c \nu_R \) and \( \bar{\nu}_R^c \nu_L \). All these terms are realized in the left-right symmetric model with the Yukawa coupling (6) and the VEVs given in eqs. (3) and (5). By assuming \( v_L \approx 0 \) one ends up with the famous see-saw mass matrix

\[ M = \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}. \]

The eigenstates of this matrix are two Majorana neutrinos \( \nu_1 \) and \( \nu_2 \) with approximate masses \( m_1 \approx m_D/m_R \) and \( m_2 \approx m_R \). The left-handed and the right-handed neutrinos are related to the mass eigenstates according to

\[
\begin{align*}
\nu_L &= (\nu_{1L} \cos \eta - \nu_{2L} \sin \eta), \\
\nu_R &= (\nu_{1R} \sin \eta + \nu_{2R} \cos \eta).
\end{align*}
\]

where the mixing angle \( \eta \) is given by

\[ \tan 2\eta = \frac{2m_D}{m_R}. \]
The masses of $W_2$ and $\nu_2$ are related as

$$m_2 \simeq \frac{h_R}{g_R} M_{W_2}.$$  \hspace{1cm} (12)

Most naturally the heavy neutrino and the heavy weak boson would have roughly the same mass, but depending on the actual value of the Yukawa coupling constant $h_R$ the neutrino may be much lighter or somewhat heavier than $W_2$.

3 Production of heavy weak bosons

The pair production reactions

$$e^+ e^- \rightarrow W_2^+ W_2^-$$

$$\rightarrow W_1^+ W_2^-, W_1^- W_2^+$$  \hspace{1cm} (13)

proceed through the s-channel exchange of the photon, $Z_1, Z_2$ or the neutral Higgses (there are altogether six physical neutral Higgs states in the model), and through the t-channel exchanges of the neutrinos $\nu_1$ and $\nu_2$. Although favoured kinematically, the cross section of the latter reaction is much smaller than that of the former because it is possible only through the neutrino and/or weak boson mixing. The Higgs contribution is in general negligible in both reactions [12].

Of a special interest is dependence of the cross sections of the reactions (13) on the heavy neutrino mass $m_2$. Since there is no lepton number violation, this process does not directly probe the large Majorana mass term of $\nu_R$, and hence the mass effect is not that dramatic. Nevertheless, just above the threshold the cross section behaves quite differently as a function of collision energy depending on the value of $m_2$ [10] (see Fig. 1). This is a quite significant effect and may be experimentally detectable.

4 Lepton number violation in $e^- e^-$ collision

The lepton number violation associated with the triplet Higgs couplings and Majorana neutrinos gives rise to many distinctive signals of left-right symmetry. One interesting process is ”inverse neutrinoless double beta decay” [13], [10], [14]

$$e^- e^- \rightarrow W_2^- W_2^-. $$  \hspace{1cm} (14)

The main contributions to this reaction comes from the $\Delta^- \Delta^-$ exchange in s-channel and heavy Majorana neutrino $\nu_2$ exchange in t-channel. One should note that any
model having only one of these particles would violate unitarity; the unitarity is saved by a destructive interference of the $\Delta^{--}$ exchange and $\nu_2$ exchange amplitudes.

The reaction (14) offers a probe of the symmetry breaking sector of the theory, as well as of the nature of the neutrinos. The most clean signal is obtained through the decay chain $W_2 \rightarrow W_1 Z_1 \rightarrow 3l + \text{missing energy}$, for which there is no significant background from the Standard Model processes. Generally the cross section of (14) can be quite large, of the order of 1 pb, as shown in Fig. 2. This would correspond to event rates of $10^4$ for an integrated luminosity in the range of 0.1 pb$^{-1}$. The rate is about the same as that of the $W^+W^-$ production in the Standard Model.

Even more clear signature would have the processes (15)

$$e^-e^- \rightarrow \mu^-\mu^-, \tau^-\tau^-.$$  

The two leading contributions to these reactions come from the $\Delta^{--}$ exchange in the s-channel and box-diagrams with virtual Majorana neutrinos and charged gauge bosons. Although the total lepton number is conserved in the processes, the lepton numbers $L_e$ and $L_\mu$ or $L_\tau$ are violated by two units. Also these processes have practically no background from the Standard Model phenomena. (The background opposite-sign muon pairs, produced via two-photon processes, can be separated from the signal by having a magnetic field in detector.)

The cross section, which depends on the unknown masses of $\Delta^{--}$ and $\nu_2$, can be as high as 0.1 –1 pb, i.e., comparable with that of the $WW$ production. It would be possible to explore quite a large range of mass values $m_N$, $M_\Delta$ and $M_{WR}$ by using this process (13).

5 Tests of a susy left-right model

The left-right symmetric model has a naturality problem similar to that of the Standard Model: the masses of the Higgs scalars diverge quadratically. As in the Standard Model, the supersymmetry (susy) can be used to cure this hierarchy problem. To be theoretically satisfactory left-right symmetric model should be supersymmetrized (see e.g. [16], [17]).

Apart from the existence of the supersymmetric particles, the most significant difference between the ordinary and the supersymmetric left-right model concerns the Higgs sector. In supersymmetrization, the cancellation of chiral anomalies among the fermionic partners of the triplet Higgs fields requires that the Higgs triplet $\Delta$ is accompanied by another triplet, $\delta$, with opposite $U(1)_{B-L}$ quantum number. Due to the conservation of the $B-L$ symmetry, $\delta$ does not couple with leptons and
quarks. Also another bidoublet should be added to avoid trivial Kobayashi-Maskawa matrix for quarks. This comes about because supersymmetry forbids the Yukawa coupling in which the bidoublet appears as conjugated, so that the \(u\)-type quarks and \(d\)-type quarks should have bidoublets of their own (denoted by \(\phi_u\) and \(\phi_d\)).

In [18] we have investigated a model described by the superpotential

\[
W = h_u^Q \hat{Q}_L^T \hat{\phi}_u \hat{Q}_R + h_d^Q \hat{Q}_L^T \hat{\phi}_d \hat{Q}_R
+ f_u^L \hat{L}_L^T \hat{\phi}_u \hat{L}_R
+ f_d^L \hat{L}_L^T \hat{\phi}_d \hat{L}_R
+ h_R \hat{L}_R^T \bar{i} \tau_2 \hat{\Delta}_R \hat{L}_R
+ \mu_1 \text{Tr}(\tau_2 \hat{\phi}_d^T \bar{i} \tau_2 \hat{\phi}_d)
+ \mu_2 \text{Tr}(\hat{\Delta}_R^T \hat{\delta}_R).
\]

(16)

Here \(\hat{Q}_{L(R)}\) stands for the doublet of left(right)-handed quark superfields, \(\hat{L}_{L(R)}\) stands for the doublet of left(right)-handed lepton superfields, \(\hat{\phi}_u\) and \(\hat{\phi}_d\) are the two bidoublet Higgs superfields, and \(\hat{\Delta}_R\) and \(\hat{\delta}_R\) the two right-handed triplet Higgs superfields. The generation indices of the quark and lepton superfields are not shown. It should be noticed that the mass matrix of the doubly charged higgsinos, following from the last term of the superpotential, is particularly simple, because the doubly charged higgsinos do not mix with gauginos.

The next generation linear electron colliders will, besides the \(e^+e^-\) and \(e^-e^-\) reactions, be able to operate also in the photon modes \(e^-\gamma\) and \(\gamma\gamma\). The high energy photon beams can be obtained by back-scattering of intensive laser beam on high energy electrons. It turns out that all these collision modes may provide useful processes for investigation of the susy left-right model [18] (like it does for the susy version of the Standard Model [19]). Among these are the reactions

\[
e^+e^- \rightarrow \hat{\Delta}^{++}\hat{\Delta}^{--}
\]  
(17)

\[
e^-e^- \rightarrow \tilde{l}^-\tilde{l}^-
\]  
(18)

\[
\gamma e^- \rightarrow \tilde{e}^+\tilde{\Delta}^{--}
\]  
(19)

\[
\gamma\gamma \rightarrow \hat{\Delta}^{--}\hat{\Delta}^{++},
\]  
(20)

which have the common feature of the appearance of the doubly charged higgsino(s) \(\hat{\Delta}^{\pm\pm}\) in the final or intermediate state. The fact that this particle carries two units of electric charge and two units of lepton number and that it does not couple to quarks makes the processes most suitable and distinctive test of the susy left-right model.

In large regions of the parameter space, the kinematically favoured decay mode of the triplet Higgsino is \(\hat{\Delta}^{++} \rightarrow \tilde{\ell}^+\tilde{\ell}^+\). The simplest decay mode of the slepton \(\tilde{\ell}\) is
into an electron and the lightest neutralino (presumably the lightest supersymmetric particle):
\[ \tilde{l} \rightarrow l\tilde{\chi}^0. \]  

(21)

If kinematically allowed, the decays into final states with leptons accompanied with heavier neutralinos or charginos can take place in addition, but also then the end-product of subsequent cascade decays often is electrons plus invisible energy. The doubly charged triplet higgsino would thus have the following decay signature:
\[ \tilde{\Delta}^{--} \rightarrow l^-l^- + \text{missing energy}, \]  

(22)

where \( l \) can be any of \( e, \mu \) and \( \tau \) with practically equal probabilities. Accordingly, the signature of the pair production reaction (L7), as well as of the two photon reaction (P9), would be the purely leptonic final state associated with missing energy. The missing energy is carried by neutrinos, sneutrinos or neutralinos. Conservation of any separate lepton number may be broken in the visible final state. Such final states are not possible in the Standard Model or in the minimal susy model. The total cross section for the total collision energy \( \sqrt{s} = 1\text{TeV} \) and the slepton and higgsino masses in the range of 100–400 GeV is about 0.5 pb. The cross section of the reaction (P9) decreases with increasing mass of \( \tilde{\Delta} \), but may be as large as 10 pb [18].

Purely leptonic final states accompanied with missing energy form also the signals of the reactions (L8) and (L9).

6 Conclusions

The phenomenologically interesting characteristics of left-right symmetric model are the new charged weak bosons, heavy right-handed Majorana neutrinos and doubly charged Higgses and higgsinos. The triplet Higgses (and higgsinos) mediate \( \Delta L = 2 \) interactions, which give rise to clean and low-background signals. These features would be best benefitted in the \( e^-e^- \), \( \gamma e^- \) and \( \gamma\gamma \) collision modes feasible at a linear collider facility.

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FIGURE CAPTION

Figure 1. The total cross section of the process $e^+e^- \rightarrow W^-_2W^+_2$ as a function of the total collision energy for various values of heavy neutrino mass $m_2$ and with $M_{W_2} = 0.5$ TeV, $M_{Z_2} = 0.5$ TeV.

Figure 2. The total cross section of the process $e^-e^- \rightarrow W^-_2W^-_2$ as a function of the total collision energy for various values of heavy neutrino mass $m_2$ and with $M_{W_2} = M_{Z_2} = M_{\Delta} = 0.5$ TeV.
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9310295v1