Majorana Neutrinos and the Production of the Right-Handed Charged Gauge Boson

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A possibility of a very clean signature for the production of $W_R^\pm$ is pointed out. If the right-handed neutrino is lighter than $W_R^\pm$, left-right symmetric gauge theory predicts the decay $W_R^+ \to \mu^+\mu^+ + 2$ hadronic jets, with the branching ratio $\simeq 3\%$. The lack of neutrinos in the final state and the absence of a sizable background make $W_R^\pm$ rather easy to detect (if it exists). Detailed predictions regarding the production and decay rates of W_R^+ are presented.

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In recent years left-right symmetric models[1] have emerged as a popular extension (or alternative) of the standard electroweak theory. Parity nonconservation, being due to the spontaneous symmetry breaking, in these models becomes a low-energy phenomenon which ought to disappear at energies sufficiently above the mass M_R of the right-handed charged gauge boson W_R^+. Although some possible indirect low-energy tests of this idea do exist, the only clear and unambiguous confirmation of left-right symmetry would be the production and identification of the right-handed gauge bosons. In this Letter we point out the possibly unusually clean signal for the production of the right-handed charged boson, which would also directly test the Majorana nature of the neutrinos. As we show below, a nontrivial fraction of W_R^+'s possibly decay into the final state consisting of two antimuons and two hadronic jets, without neutrinos so that there is no loss of energy whatsoever. Furthermore, such a process is almost free from any background and could therefore serve as a direct and clean test of W_R^+ production.

The model.—In order to be more specific we briefly review the main features of the theory. The gauge group is $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$, which requires the existence of the heavier gauge bosons $W_R^\pm$ and Z_2, besides the usual ones: $W_L^\pm$ and Z_1. To the lowest order in $(M_L/M_R)^2$, one has the following relation, given here only for illustration, between the neutral and charged gauge boson masses[2]:

$$M_{Z_1}{}^2 \simeq \frac{M_L{}^2}{\cos^2\theta_W}; \quad M_L{}^2 = \frac{\pi\alpha}{G_F\sqrt{2}\sin^2\theta_W}; \qquad (1)$$
$$M_{Z_2}{}^2 = 2\,\frac{\cos^2\theta_W}{\cos 2\theta_W} M_R{}^2.$$

Clearly the properties of $W_L^\pm$ and Z_1 are not dramatically changed compared with the standard model; furthermore, relation (1) guarantees the right-handed charged gauge boson $W_R^\pm$ to be substantially lighter than Z_2. For example, for $\sin^2\theta_W \simeq 0.25$, $M_R \simeq (1/\sqrt{3})M_{Z_2}$.

As shown by Mohapatra and one of us (G.S.), the smallness of the neutrino mass is related to the maximality of parity nonconservation in weak interactions. Namely, ν_R becomes a heavy Majorana neutral lepton N with $m_N \sim M_R$ and ν_L is the light Majorana neutrino ν with $m_\nu \sim 1/M_R$. As a result of negligible mixings between ν_L and ν_R and very small W_L-W_R mixing ($< 10^{-3}$), the *right-handed gauge boson is coupled only to the heavy lepton N,* and *not to the neutrino.* This is the crucial feature, responsible for our main result discussed below.

Although the scale of parity restoration, i.e., M_R, cannot be predicted by the theory, current experimental data allow M_R to be quite low,[3-5] thus encouraging the direct search for W_R and Z_2. Let us now discuss the production and decay rates for these particles, with the emphasis on the more interesting case of W_R^+.

Neutral gauge boson Z_2.—The signature is not spectacular. Take $M_{Z_2} = 300$ GeV, $\sin^2\theta_W = 0.25$. The computation gives for the total decay width[3]

$$\Gamma_{Z_2} \simeq 9\text{–}10 \text{ GeV}, \qquad (2)$$

with the decay branching ratios

$$B(Z_2 \to \nu\nu) \simeq 1\%, \quad B(Z_2 \to NN) \simeq 9\%,$$
$$B(Z_2 \to \mu^+\mu^-) \simeq 2\%, \quad B(Z_2 \to \bar{u}u) \simeq 7\%, \qquad (3)$$
$$B(Z_2 \to \bar{d}d) \simeq 14\%,$$

where we assume $2m_N < M_{Z_2}$ and ignore the phase-space corrections. The cross section for the production of Z_2 in the pp collider is found to be[3]

$$B(Z_2 \to \mu^+\mu^-)\sigma \simeq 3\times 10^{-38} \text{ cm}^2 \qquad (4)$$

at $\sqrt{s} = 800$ GeV. Thus, under optimal luminosity of 10^{33} cm^{-2} sec^{-1} at the future Collider Beam Accelerator (CBA), it would imply a few events per day.

The right-handed charged gauge boson $W_R^\pm$.—Its decay patterns and signatures depend crucially on whether N is lighter than $W_R^\pm$ or not.[6] We make, what we believe, a reasonable assumption: $m_N < M_R$ (it is equivalent to a commonly used premise $m_t < m_W$ in the standard model).

In this case, ignoring the phase-space corrections, we obtain for three generations of fermions

$$B(W_R^+ \to N_\mu \mu^+) \simeq 8\%.$$

We have also assumed that the charged and doubly charged Higgs bosons are not lighter than W_R; relaxing this would change the branching fraction $B(W \to Nl)$ by at most 1%.

A few words are needed here regarding mass differences and mixings among different N's. The combined limit on the product of mixings and mass differences comes from lepton flavor-changing processes, such as $\mu \to e\gamma$. Namely, one estimates[2]

$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} \simeq \frac{\alpha}{\pi}\left(\frac{M_L}{M_R}\right)^4 \left(\sin\theta_R \cos\theta_R \frac{m_{Ne}^2 - m_{N\mu}^2}{M_R^2}\right)^2, \quad (5)$$

where for simplicity we specify to two generations only; θ_R is the Cabibbo leptonic mixing angle in the right-handed sector. Taking $(M_L/M_R)^2 \gtrsim \frac{1}{10}$, as to make W_R accessible to direct production, we get

$$\sin(2\theta_R)\Delta m_N^2/M_R^2 \lesssim 10^{-5}, \quad (6)$$

a rather stringent limit. It means that we can safely ignore intergenerational mixings in the production and decay of W_R^+.

Now, N's being Majorana leptons they decay equally often into leptons or antileptons. Therefore[7]

$$B(N_\mu \to \mu^+ X^-) = B(N_\mu \to \mu^- X^+) \simeq 50\% \quad (7)$$

and so, with the branching ratio of about 4%, W_R^+ decays into

$$W_R^+ \to \mu^+\mu^+\bar{q}q', \quad (8)$$

where the quarks in the final state form hadronic jets ($\bar{q}q' = \bar{u}d$ or $\bar{c}s$ or $\bar{t}b$). The above process would serve as a very clean signal for W_R^+ production and, simultaneously, would be a direct test of the Majorana character of neutrinos. As a result of the absence of neutrinos, there is no energy loss in the final state, and so it is possible to reconstruct the W_R invariant mass. Furthermore, it is almost free from the background (see below).

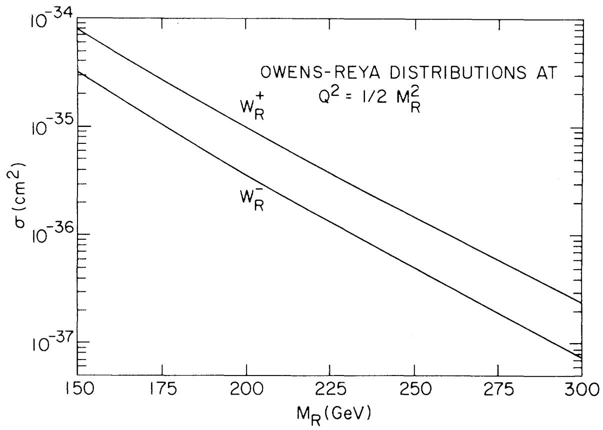

FIG. 1. Total $pp \to W_R^\pm$ cross sections vs M_R at $\sqrt{s}$ = 800 GeV. $\sin^2\theta_W$ is chosen to be 0.25.

Assume for the moment $M_R = 200$ GeV, expected approximately if $M_{Z_2} \simeq 300$ GeV or so; let us also take $m_{N\mu} \simeq 100$ GeV. Then one μ^+ has the energy of 75 GeV, and the other three particles have approximately $E_i \simeq 42$ GeV, a perfectly clean signature of W_R^+ production. In the rest of this paper we quantify the above point by presenting the results of the detailed calculation of production rates of W_R^+, transverse momentum distributions of the primary and secondary leptons, and invariant mass distribution of the final lepton pair. To be as complete as possible we vary the $W_R^\pm$ mass in the range of experimental interest: 150 GeV $\lesssim M_R \lesssim$ 300 GeV; we keep $m_N = 100$ GeV and at the end display the dependence on m_N.

We calculate the W_R production in the simple Drell-Yan picture. The rates for the relevant subprocesses are

$$\hat{\sigma}(u\bar{d} \to W^+) = \tfrac{1}{3}(\pi^2\alpha/\sin^2\theta_W)\delta(\hat{s} - M_R^2), \quad (9)$$

and

$$\frac{d\hat{\sigma}}{d\hat{t}}(u\bar{d} \to \mu^+ N) = \frac{1}{3}\frac{\alpha\pi^2}{4\sin^4\theta_W\,\hat{s}^2}\frac{\hat{t}(\hat{t} - m_N^2)}{(\hat{s} - M_R^2)^2 + M_R^2\Gamma^2}. \quad (10)$$

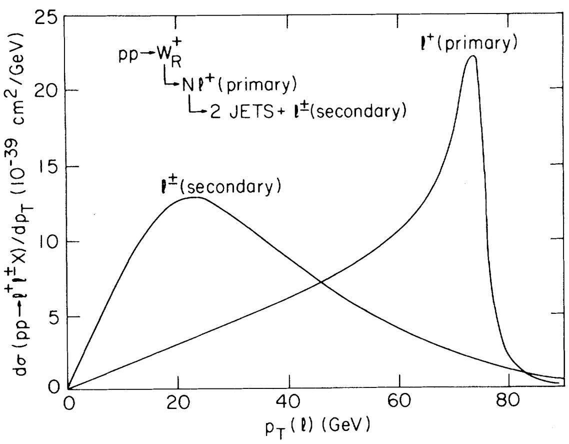

FIG. 2. Transverse momentum distributions of the primary and secondary leptons from W_R production for pp collision at $\sqrt{s} = 800$ GeV. The case $M_R = 200$ GeV, $m_N = 100$ GeV, and $\sin^2\theta_W = 0.25$ is illustrated.

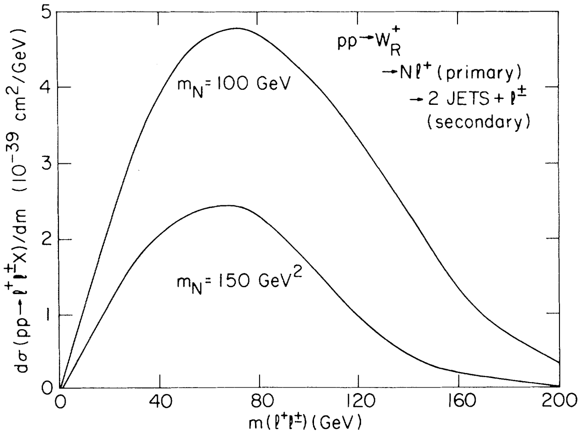

FIG. 3. Invariant-mass distribution of the lepton pair from the W_R cascade decays for a pp colliding beam at $\sqrt{s} = 800$ GeV. The cases $m_N = 100$ GeV and 150 GeV with $M_R = 200$ GeV and $\sin^2\theta_W = 0.25$ are illustrated.

Here the width Γ is given by the sum of partial widths for decays into fermion pairs,

$$\Gamma(W_R \to f_1\bar{f}_2) = (\tfrac{1}{12}C\alpha\,\sin^2\theta_W M_R)\lambda^{1/2}(M_R^2, m_1^2, m_2^2)\left[1 - \frac{1}{2}\frac{m_1^2 + m_2^2}{M_R^2} - \frac{1}{2}\frac{(m_1^2 - m_2^2)^2}{M_R^4}\right], \tag{11}$$

with $C = 1$ for leptons and $C = 3$ for quarks, and $\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$. For the choice of $M_R = 200$ GeV, $m_N = 100$ GeV, and $m_t = 20$ GeV, the total width is about 5.3 GeV and the branching fraction for $W_R \to Nl$ is slightly reduced by kinematics from 8% to 6%. In calculating the inclusive production rates, the subprocess cross section, $\hat{\sigma}$, in Eqs. (9) and (10) must be convoluted with the momentum distributions of the quarks in the initial hadrons. We use the parametrization of Owens and Reya[8] for the parton distributions evaluated at the mass scale $Q^2 = \frac{1}{2}\hat{s}$. For the secondary decay $N \to l + 2$ jets, the momentum distribution of the lepton l in the rest frame of N is simply given by $dn/dp \propto p^2(3m_N - 4p)$ for $p < \frac{1}{2}M_R$. Figure 1 shows the $W_R^\pm$ production cross sections versus M_R for the pp collider at $\sqrt{s} = 800$ GeV. At an integrated luminosity 10^{39} cm^{-2} accumulated approximately over one year for the future CBA, 10^4 W_R events could be produced for $M_R \approx 200$ GeV. These then give hundreds of same-sign dilepton events per year as discussed above for a reasonable branching fraction $B(W \to Nl) \approx 6\%$. In Fig. 2, useful p_T distributions for both primary and secondary leptons are illustrated. High invariant mass for the lepton pair is also expected as shown in Fig. 3.

A few words are in order regarding the background for this process. Previous calculations[9] indicate that in the case of opposite-sign dimuons, the background turns out to be at least an order of magnitude below the W_R^+ signal. In our case, the only conceivable background would be from the heavy-quark decays and so, if anything, it should be lower for same-sign dimuons. Furthermore, because of small generational mixing we do not expect a lepton flavor-changing final state, such as μ^+e^+, which should be equally present in the background. Therefore, an additional nice feature of this process is the absence of the competing background.

In conclusion, a reasonable assumption, $m_N \leq M_R$, allows for the exciting possibility of a very clean signal for the production of $W_R^\pm$, which crucially depends on the Majorana character of both left-handed and right-handed neutrinos. This offers a simultaneous possibility of confirming the idea of parity restoration at soon achievable energies and of directly testing the Majorana nature of neutrinos.

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[5]Recently, G. Beall, M. Bander, and A. Soni, Phys. Rev. Lett. 48, 848 (1982), have argued the existence of the lower bound on M_R: $M_R \gtrsim 1.6$ TeV from the K_L-K_S mass difference. Their result is, however, applicable only to the special class of left-right symmetric theories characterized by the same left and right Cabibbo rotations. Even then, this bound is a function of the top-quark and Higgs-boson masses and could be quite lower. See R. N. Mohapatra, G. Senjanović, and M. D. Tran, to be published.

[6]The production of $W_R^{\pm}$ was discussed before in Ref. 3. The clean signature we are stressing here was, however, not emphasized.

[7]Here we assume a small mass difference between N_i's as to suppress processes such as $N_\mu \rightarrow N_e e \mu^+$ and as suggested by Eq. (6).

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