INVERSE NEUTRINOLESS DOUBLE $\beta$-DECAY AT THE NLC?

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ABSTRACT

The NLC may allow us to search for the 'inverse' process to neutrinoless double-$\beta$ decay, $e^-e^- \rightarrow W^-W^-$, which probes the existence of Majorana masses for neutrinos. Expectations for the observation of this process in both the Standard Model and its extension, the Left-Right Symmetric Model, are examined.

Within the framework of extended electroweak models (EEM) one of the most attractive scenarios for explaining the apparently small size of neutrino masses is to invoke the see-saw mechanism. This scheme naturally predicts that neutrino masses are of the Majorana type and that new heavy isosinglet leptons ($N$), which can mediate $\Delta L=2$ interactions, must exist. At low energies, such models can be probed indirectly by looking for rare processes such as neutrinoless double-$\beta$ decay. The lack of observation of these processes implies additional constraints on model building.

High energy $e^-e^-$ collisions, a possible option at the NLC, may provide a new window into the $\Delta L=2$ sector of these models via the process $e^-e^- \rightarrow W^-W^-$, where the $W$ is either the conventional gauge boson of the Standard Model (SM) or that of some EEM. By forcing the reconstructed final state $W$ pairs to have large invariant masses and by imposing missing energy and rapidity cuts, the SM backgrounds for such a process can be reduced to a level substantially below 0.1 fb for a 1 TeV $e^-e^-$ collider. However, if we try to calculate the cross-section ($\sigma$) for this process assuming that only a single $N$ is exchanged in the $t$- and $u$-channels, one is immediately faced with the prospect of unitarity violation which can be cured only by the exchange of additional particles. There are potentially two distinct approaches: (i) in the single-generation SM, where $N$ is identified with $\nu^c$, the weak eigenstates $\nu$ and $\nu^c$ mix, by an angle $\theta$, to form the two Majorana mass eigenstates $N_{1,2}$ which are now both exchanged in the $e^-e^- \rightarrow W^-W^-$ process. By noting the relationships between the mass matrix entries, $\theta$, and the mass eigenvalues, we find that the leading high $s$ term in the amplitude is indeed cancelled resulting in the restoration of unitarity. However, as a consequence of this, $\sigma$ is very small, as shown in Fig. 1, due to the enormous mixing angle suppression. (This suppression occurs since $\sigma$ is now proportional to $\theta^4$, and we would suspect that $\theta < O(10^{-2})$). Although we can imagine that in a multi-generational model there may be sufficient parameter freedom to conspire to overcome some of this suppression, we can anticipate that within the SM this will be somewhat difficult to achieve and that
the value of $\sigma$ will likely remain small. We note, however, that $N$’s may also make their existence known indirectly by a slight degradation of the forward peak arising from the $t$–channel amplitude in $e^+e^- \rightarrow W^+W^-$ of order a few percent. Unfortunately, this will tell us nothing about their Dirac vs. Majorana nature. Of course, if $N$’s can be directly produced at a collider, their decays will tell us whether they are Dirac or Majorana particles.

(iii) A second scenario to cure the unitarity problem is the $s$–channel exchange of a doubly-charged Higgs scalar ($\Delta$) which couples to $e^-e^-$. This possibility is phenomenologically excluded in the SM due both to $\rho$-parameter and neutrino counting constraints but can be realized naturally in some EEM such as the Left-Right Symmetric Model (LRM) [1]. (We can, of course, introduce a $\Delta$ that couples to isosinglet right-handed electrons without violating these constraints in the SM context but then $\Delta$ will not couple to $WW$ and so will not cure the unitarity problem.) In the LRM case, the sum of the asymptotic $\nu$ and $\nu^c$ contributions to the amplitude no longer cancel and a $\Delta$ exchange is required in order to restore unitarity. Of course, the $W$’s in the final state are now to be identified with $W_R$’s, the right-handed gauge bosons of the LRM. For purposes of the analysis presented here we will assume that $W_R$’s have a mass of 480 GeV and are thus kinematically accessible at a 1 TeV $e^-e^-$ collider. We will also assume that $\kappa = g_R/g_L = 0.9$, consistent with $SO(10)$ renormalization group analyses [1] and that $N$ has a mass in the 100 GeV and above range thus avoiding the $W_R$ mass bounds from $\mu$ decay as well as Tevatron collider searches. (Similar constraints arising from the $K_L - K_S$ mass difference can also be avoided but will not be discussed here.) Unitarity for $\sigma$’s in various channels is maintained so long as $N(\Delta)$ has a mass less than about 2(10) TeV. Generally the cross section for $e^-e^- \rightarrow W^+_R W^-_R$ can be quite large, as shown in Figs. 2a and 2b, with very sizeable event rates $> 10^{4-5}$ fb$^{-1}$ for integrated luminosities in the 100 $fb^{-1}$ range. (For most values of the parameters, the $\cos \theta$ distribution of the produced $W_R$’s is fairly flat implying that kinematic cuts will not significantly reduce these rates.) Figs. 2a and 2b show that for small $M_N$ the cross section tends to zero because the amplitude is proportional to the Majorana mass itself since it is the source of the explicit lepton number violation. For larger $M_N$, there is found to be a trade off between the proportionality to $M_N$ in the numerator of the amplitude and the $M_R^2$ factor appearing in $u$– and $t$–channel propagators. Except near the narrow $\Delta$ resonance, the production cross section is relatively insensitive to $M_\Delta$ as shown explicitly in Fig. 2b. Clearly, if the $W_R$ pair final state is kinematically accessible at the NLC and if the $N$ and $W_R$ masses are at all comparable, then the process $e^-e^- \rightarrow W^-_R W^-_R$ should be observable with a significant rate. We remind the reader that $\sigma$ scales as $\kappa^4$ so that results for other values of $\kappa$ can be easily obtained from the figures.

If this LRM scenario is indeed realized, one can imagine that a small amount of $W - W_R$ mixing (by an angle $\phi$) will naturally be present and thus could result in the feeding of the large $W^-_R W^-_R$ rate into other channels. $\phi$ is essentially given by $\phi \simeq f \nu M_L^2/M_R^2$, with $M_L(M_R)$ being the SM $W(W_R)$ mass and, in the minimal model, $f < 1$ is a ratio of squares of vev’s so that numerically $\phi \simeq 0.01$. The most obvious channel to examine in this connection is to see whether this non-zero mixing can induce a significant SM $W^- W^-$ rate. Unfortunately, as shown in Fig. 3a, unless the $W - W_R$
mixing angle is very large, the induced $W^-W^-$ cross section will remain quite small.

Mixing in the $\nu-\nu^c$ mass matrix, while not significantly contributing to $W^R_W^-$ production, could induce the mixed final state $W^-W^R$ even in the absence of $W^-W^R$ mixing. This process will proceed only via $t-$ and $u-$channel exchanges when $\phi = 0$ (since $\Delta$ does not couple to the weak eigenstate $WW^R$ combination) but will still obey unitarity due to the opposite helicity structures at the two vertices. The cross section for this mixed final state is shown in Fig. 3b and is seen to be reasonably small but perhaps still observable depending on the value of the $\nu-\nu^c$ mixing angle, $\theta$, introduced above. If both $\phi$ and $\theta$ are simultaneously non-zero then the possibility of feed down becomes quite complicated and we refer the reader to the very detailed analysis presented in Ref. 7. Clearly, if $W^-W^-$ production is indeed observed, all possible channels must be examined in order to pin down the nature of the lepton number violating interaction.

In scenario (ii), realized in the LRM example above, other new physics must also be present. An example of this is the process $e^+e^- \rightarrow \mu^+\mu^-$ which can occur via $s-$channel $\Delta$ exchanged. For a $\Delta$ of mass 2 TeV and an $e^+e^-$ center of mass energy of $\sqrt{s} = 1$ TeV, one finds a cross section, $\sigma \approx 620(\kappa M_N/M_R)^4$ fb, which yields a very large event rate with a flat angular distribution for integrated luminosities in the 10-100 $fb^{-1}$ range. Such a process would be quite difficult to miss especially if a $\Delta$ resonance exists with a mass less than the NLC’s center of mass energy.

In conclusion we have found that $e^-e^-$ collisions at a center of mass energy near 1 TeV may provide a useful probe of the neutrino mass generating mechanism, in both the SM as well as EEM’s, via the process $e^-e^- \rightarrow W^-W^-$. Other new physics signatures may also be present in the $e^-e^-$ channel.

References

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4. Generic cross section formulae are given in Ref. 1.
5. For a review and original references, see R.N. Mohapatra, Unification and Supersymmetry, (Springer, New York, 1986).
6. N.G. Deshpande, E. Keith, and T.G. Rizzo, Phys. Rev. Lett. 70, 3189 (1993).
7. For general formulae, see J. Maalampi et al., Ref. 2.
8. See, for example, T.G. Rizzo, Phys. Rev. D25, 1355 (1982).
Fig. 1: Total cross section for $e^- e^- \rightarrow W^- W^-$ in the SM as a function of the heavy neutrino mass with $\sqrt{s}= 500$(solid) or 1000(dash-dot) GeV. Results should be scaled by 4 powers of the mixing angle $\theta$.

Fig. 2: Cross section for $e^- e^- \rightarrow W^-_R W^+_R$ with $\sqrt{s}=1$ TeV as a function of (a) $M_N$ and (b) $M_\Delta$ for the parameter choices discussed in the text. In[(a),(b)], the curves on the right(left)-hand side correspond, from top to bottom, to $M_\Delta=800, 1200, 500, 1500, 200$, and $2000$ GeV [$M_N=1500, 1200, 800, 500, 200$ GeV].

Fig. 3: (a) $W^- W^-$ production via $W^- W_R$ mixing as a function of $M_N$ with $M_\Delta=300, 150,$
800, 1200, 1500, 2000 GeV for the curves from top to bottom on the right-hand side assuming √s=500 GeV. (b) $W^- W_R$ production as a function of $M_N$ with $\sqrt{s}=1$ TeV. This result must be rescaled by 2 powers of the mixing angle ratio $\theta/0.01$. 