Influence of the left-handed part of the neutrino mass matrix on the lepton number violating $e^-e^-\to W^-W^-$ process

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The influence of the neutrino mass submatrix M_L on the $e^-e^-\to W^-W^-$ process is discussed. Taking into account various possible CP signatures of heavy neutrinos it is shown that, in some cases, a nonzero M_L substantially changes predictions for maximum possible values of the $e^-e^-\to W^-W^-$ cross section. The direct role of the ω^2 parameter (coming from neutrinoless double-beta decay) is clarified. The consequences of doubly charged Higgs particles (δ^{--}) with resonances still far away from energies of the future linear lepton collider ($\sqrt{s}=0.5$–1 TeV) are studied. [S0556-2821(98)02717-9]

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I. INTRODUCTION

The e^-e^- option of the future $\sqrt{s}=0.5$–2 TeV linear collider is a very interesting area for investigating new physics [1]. Processes such as $e^-e^-\to l_i^-l_j^-$, $W^-W^-(l_{i(j)}=e,\mu,\tau)$ could be studied, indicating that lepton number (flavor or total) is not a global symmetry of the electroweak interactions. In this paper we would like to examine the $e^-e^-\to W^-W^-$ process. This reaction violates the total lepton number by two units, $\Delta L=2$. Its potential importance and hopes connected with it are based on two facts. First, the standard model (SM) background is very small and under control [2], and so with the planed luminosity of 10 fb^{-1}/yr [1] a cross section as small as 0.1 fb could give a visible effect. Second, its occurrence would indicate that there exist massive neutrinos of Majorana type. These neutrinos must be heavy (with masses $M_N>M_Z$) as known neutrinos cannot give any substantial signal [3]. Many papers have been devoted to this process during the last decade [4–7]. For the first time this reaction was proposed and examined in 1982 by Rizzo [4]. Additional interest has come with Ref. [5] where it was shown that the process is enhanced for heavy neutrino masses in the vicinity of the collider's c.m. energy. Then optimism returned in [6], where constraints on heavy neutrinos coming from neutrinoless double-β decay were taken into account. It has been shown that an observable signal requires fine-tuning among different heavy neutrino couplings. However, as shown in [8], these cancellations can be in a natural manner connected with CP parities of heavy neutrinos. All other papers cited in [7] give many interesting details connected with the process.

This paper brings another such a detail which can, however, appears to be crucial for the magnitude of the cross section. In the last paper concerning the $e^-e^-\to W^-W^-$ where all relevant constraints on the heavy neutrinos have been taken into account [8] we have assumed that the neutrino mass submatrix M_L generated by left-handed neutrinos,

$$M=\begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}, \tag{1}$$

is exactly zero (M_D is the submatrix of Dirac-type masses, and M_R is the submatrix of right-handed Majorana masses). This means that we have considered the class of models beyond the standard model where only right-handed neutrinos were introduced. Then, to get an observable magnitude of the cross section, at least three heavy neutrinos with appropriate CP signatures and masses were necessary. However, there are models where M_L does not vanish. Such a nonzero M_L changes the relations which restrict the space of parameters of possible (i.e., allowed by experimental data) heavy neutrino couplings and masses.

The full phenomenological discussion of nonzero M_L has been given lately [9] in the context of heavy neutrino production in $e^-e^+(e^-e^+\to\nu N)$ and $e^-\gamma(e^-\gamma\to W^-N)$ reactions. Here we will restrict ourselves to two nonstandard models with possible nonzero M_L: the standard model with both additional right-handed (RH) neutrinos and Higgs triplets and the left-right (LR) symmetric model. Details of these models can be found in literature (e.g., in [3,10]). As we are going to find the largest possible values of the cross section, we consider models where CP is conserved in the lepton sector.

II. INFLUENCE OF M_L ON $e^-e^-\to W^-W^-$

The leading helicity amplitudes for the $e^-e^-\to W^-W^-$ process can be written in the following, simplified, way:

$$M=\sum_a \{K_{ae}^2 m_a[f_t(m_a)+f_u(m_a)+f_s^L]+(K_R)_{ae}^2 m_a f_s^R\}. \tag{2}$$

The matrices K,K_R are part of the unitary matrix $U=(K^*,K_R)^T$ which diagonalizes the 6×6 neutrino mass matrix M in Eq. (1); the index $L(R)$ is connected with the left (right) doubly charged Higgs particle which is exchanged in the s channel. For details see, e.g., [3,10].

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The sum in Eq. (2) runs over all light (ν) and heavy (N) neutrinos. Let us note that the kinematical factors in the t and u channels, $f_{t,u}$, depend on m_a, but the $f_s^{L(R)}$ ones in the s channel do not. First we will examine the t and u channels, assuming only that the influence of the s channel is negligible (heavy $\delta^{--}_{L,R}$). At the end we will comment on the effect of nonzero M_L on the s-channel contribution.

The experimental bounds on the elements of the matrix, $K_{\nu e}$ and K_{Ne}, describing the mixing of electrons with light and heavy neutrinos can be summarized as follows:

$$\sum_{N(heavy)} |K_{Ne}^2| \leq \kappa^2 = 0.0054, \tag{3}$$

$$\sum_{\nu(light)} |K_{\nu e}^2 m_\nu| \leq \kappa_{light}^2 = 0.65 \ \text{eV}, \tag{4}$$

$$\left| \sum_{N(heavy)} K_{Ne}^2 \frac{1}{m_N} \right| \leq \omega^2 = 6\times10^{-3} - 5\times10^{-5} \ \text{TeV}^{-1}. \tag{5}$$

The first relation [Eq. (3)] comes from low energy experiments [11]; the other ones can be derived from the fact that neutrinoless double-β decay $(\beta\beta)_{0\nu}$ has not been detected yet.[1]

Diagonalization of the matrix (1) together with Eq. (4) yields the following relation $[m_L = (M_L)_{\nu_e \nu_e}]$:

$$\left| m_L - \sum_N K_{Ne}^2 m_N \right| < \kappa_{light}^2 . \tag{6}$$

However, κ_{light}^2 is very small and can be neglected; then from Eq. (6) we get

$$\sum_N m_N K_{Ne}^2 = m_L . \tag{7}$$

Similar to the analysis given in [8,9] let us discuss the influence of m_L on the magnitude of the cross section for different CP parities of heavy neutrinos.

If we have only one heavy neutrino state (or more but with the same CP parities), then from Eqs. (3), (5), and (7) we get restrictions on m_L [9]:

$$0 \leq m_L \leq \min(\kappa^2 M, \omega^2 M^2), \tag{8}$$

where M is the mass of the lightest of heavy neutrinos. It gives, for instance, $m_L \leq 5\times10^{-4}$ GeV for $M = 100$ GeV($\omega^2 = 5\times10^{-5}$ TeV^{-1}). For the above values of m_L the mixing angle K_{Ne} is limited to [9]

$$K_{Ne}^2 \leq \min(\omega^2 M, \kappa^2). \tag{9}$$

Figure 1 shows the maximum value of the cross section $\sigma(e^- e^- \to W^- W^-)$ where the parameters are restricted by relation (9) for three different values of ω^2 and $\sqrt{s} = 0.5(1)$ TeV. We can see that for various ω^2 there are different masses M_0 for which the cross section reaches maximum value, e.g., $M_0 \simeq 1$ (100) TeV for $\omega^2 = 6\times10^{-3}(5\times10^{-5})$ TeV^{-1}. For $M \leq M_0$ the maximum value of the cross section increases with increasing $M[(K_{Ne})^2_{max}$ in Eq. (9) increases]; for masses larger than M_0 the cross section decreases with $M[(K_{Ne})^2_{max} = \kappa^2 = \text{const}]$. We can see that only for $\omega^2 > 5\times10^{-4}$ TeV^{-1} and $\sqrt{s} \geq 1$ TeV is there a small region of masses where $\sigma_{max} > 0.1$ fb. If there is only one heavy neutrino or more but with the same CP parities, then the value of ω^2 crucially determines σ_{max}. Much effort is devoted to find the bound on ω^2 parameters [12].

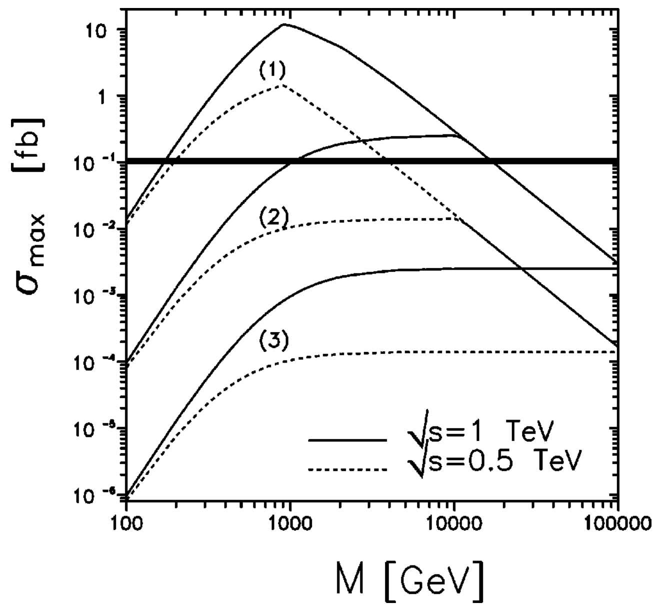

FIG. 1. The largest cross section for the $e^- e^- \to W^- W^-$ process with any number of heavy neutrinos with the same CP parities. Dashed (solid) line is for $\sqrt{s} = 0.5$ (1) TeV energy, (1), (2), (3) stand for different ω^2 values: $\omega^2 = 6\times10^{-3}$ TeV^{-1} (1), $\omega^2 = 5\times10^{-4}$ TeV^{-1} (2), $\omega^2 = 5\times10^{-5}$ TeV^{-1} (3). Doubly solid line in this and next figures denotes a background level of this process.

For the case of two heavy neutrinos with opposite CP parities we get the following inequalities ($K_{N_1 e} = x_1$, $K_{N_2 e} = i x_2$, $m_1 = M$, $m_2 = AM$):

$$x_1^2 + \left| \frac{x_1^2}{A} - \frac{m_L}{AM} \right| \leq \kappa^2, \tag{10}$$

$$\left| x_1^2 \left(1 - \frac{1}{A^2} \right) + \frac{m_L}{A^2 M} \right| \leq \omega^2 M. \tag{11}$$

When $m_L = 0$, to remove the bound given by ω^2 [Eq. (11)], we have to assume that two neutrinos are almost degenerate: $A \to 1$. But then we have practically one Dirac neutrino (two Majorana neutrinos with opposite CP values) and the cross section approaches zero. This was actually shown in [8] where the $m_L = 0$ case was examined.

[1]As we can see there exist large discrepancies in the limit on ω^2. For arguments on lower (upper) limits, see [12,13].

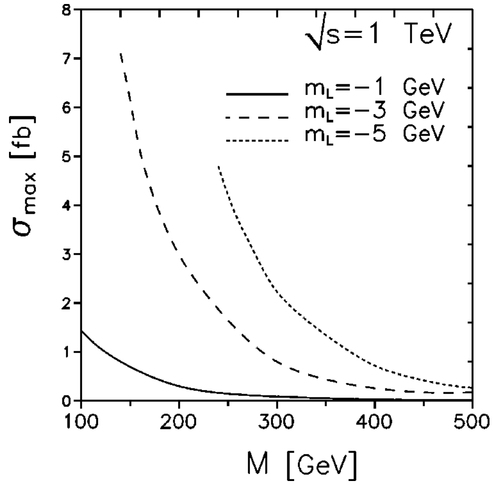

FIG. 2. Influence of the m_L on σ_{max} for two heavy neutrinos with opposite CP parities for $\sqrt{s}=1$ TeV and $A=5$ as function of M. Only negative m_L values give substantial results in this case.

However, for $m_L \neq 0$ the situation is different. The inequalities (10) and (11) can be satisfied only for the confined region of m_L [9]:

$$-\max(AM\kappa^2,(A-1)M\kappa^2+A^2\omega^2M^2) \leqslant m_L \leqslant \min(\omega^2M^2,\kappa^2M). \tag{12}$$

Positive values of m_L are strongly restricted but the space of negative m_L values is wider and depends on the values of M and A. In Fig. 2 we plot the results for $m_L=-1(-3,-5)$ GeV and $A=5$ as a function of neutrino mass. As we can see lines start from different masses. This is because Eq. (12) must hold. Similar results can be obtained for a larger spectrum of $A(=3\text{–}15)$. For positive m_L the situation is similar to the case with $n_R=1$ [compare Eqs. (8),(12)]. Results given in Fig. 2 describe also the case of three heavy neutrinos with the following CP signatures:

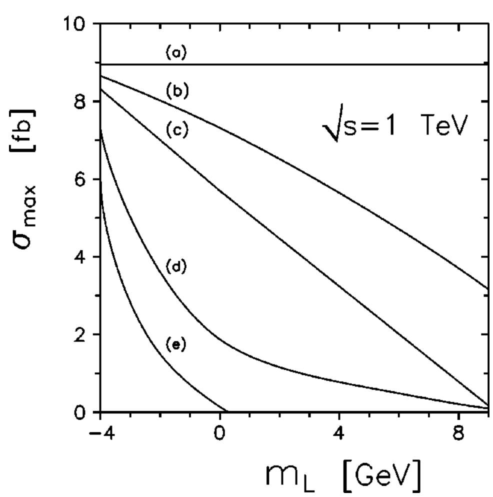

FIG. 3. The case of three heavy neutrinos with $\eta_{CP}(N_1)=\eta_{CP}(N_2)=-\eta_{CP}(N_3)$. The cross section as a function of m_L for different A, $B=10$ and $M=100$ GeV is given. (a),(b),(c),(d),(e) are for $A=10^6$,100,50,20,10, respectively.

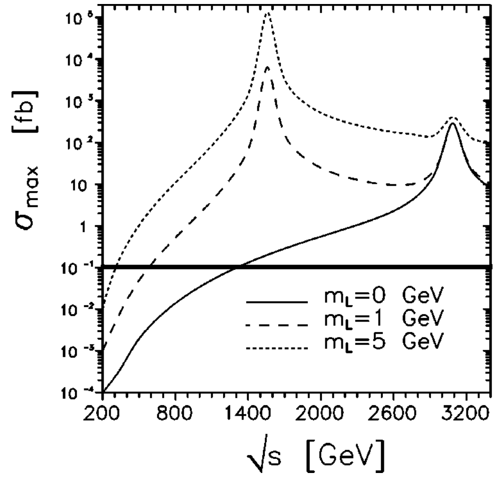

FIG. 4. Influence of the m_L parameter on the s-channel δ_L^{--} resonance. Solid, dashed, and dotted lines are for $m_L=0$, 1, and 5 GeV, respectively. The t- and u-channel contributions are calculated for the same η_{CP} eigenvalues of heavy neutrinos and $\omega^2=5\times10^{-5}$ TeV^{-1}.

$\eta_{CP}(N_1)=-\eta_{CP}(N_2)=-\eta_{CP}(N_3)$. Then two heavy neutrinos (N_2,N_3) contribute in the same way to the amplitude [Eq. (2)] and can be effectively treated as one.

The last quantitatively distinguishable possibility which is left for three heavy neutrinos is the case $\eta_{CP}(N_1)=\eta_{CP}(N_2)=-\eta_{CP}(N_3)$. Then the initial inequalities (3), (5) and (7) are satisfied if m_L is confined to the following region $(m_1=M,\ m_2=AM,\ m_3=BM)$ [9]:

$$-\min\{BM\kappa^2,\max\{B^2\omega^2M^2,(B-1)M\kappa^2+B\omega^2M^2\}\} \leqslant m_L \leqslant \min\{AM\kappa^2,(A-B)M\kappa^2+AB\omega^2M^2\}. \tag{13}$$

By fixing $B=10$ and $M=100$ GeV for different values of A we have found mixing angles $K_{N_1e}=x_1$, $K_{N_2e}=x_2$, $K_{N_3e}=ix_3$ such that the cross section is maximal. The result is given in Fig. 3 for $\sqrt{s}=1$ TeV. For larger masses $(M>100\ \text{GeV})\sigma_{max}$ decreases; e.g., for $M=200$ GeV, $\sigma_{max}\leqslant 4$ fb. Let us note that the largest results are possible for large A and then we can always find a space of allowed mixings for which $\sigma_{max}\simeq 9$ fb independently of m_L. Similar plots can be made for other energies 0.5 TeV $\leqslant\sqrt{s}\leqslant 2$ TeV with the result $\sigma_{max}\leqslant 1(25,40)$ fb and $\sqrt{s}=0.5(1.5,2)$ TeV, respectively (see [8] for the $m_L=0$ case).

Finally, in Fig. 4 we describe the s-channel contribution to the $e^-e^-\to W^-W^-$ process. We present the contribution of two doubly charged Higgs particles δ_L^{--} and δ_R^{--} which exist, for example, in the LR model.[2] Masses of the $\delta_{L,R}^{--}$

[2]Other aspects of doubly charged Higgs boson physics at an e^-e^- collider can be found in [14].

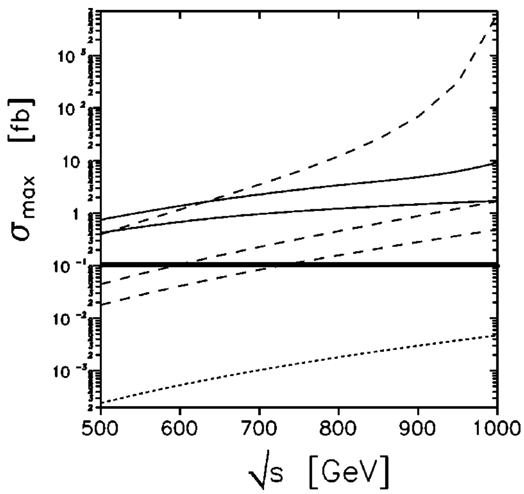

FIG. 5. Contribution of the δ_L^{--} resonance to the $e^-e^- \to W^-W^-$ process in the range of energies of the future linear lepton collider. Dashed lines are for $m_L = 1$ GeV and the same CP parities of heavy neutrinos (case A); solid lines are for $m_L = -1$ GeV and $\eta_{CP}(N_1) = -\eta_{CP}(N_2)$ (case B). To show the s-channel effect we present σ_{max} for t and u channels only (short dashed line for the A case and lower solid line for the B case) and for the full cross section with s, t, and u channels altogether (long dashed lines for the A case and upper solid line for the B case). Long dashed lines are for $M_{\delta_L^{--}} = 1000, 1600, 2000$ GeV, respectively. The upper solid line is for $M_{\delta_L^{--}} = 1600$ GeV.

particles depend on M_{W_2} [15] and for $M_{W_2} = 1$ TeV we have (without fine-tuning between parameters in the Higgs potential) $M_{\delta_L^{--}} \simeq 1600$ GeV and $M_{\delta_R^{--}} \simeq 3000$ GeV. As $m_{\delta_R^{--}} \gg m_{\delta_L^{--}}$ the effect of δ_R^{--} is negligible. In such circumstances our considerations are also valid for the SM enlarged by additional Higgs triplet and right-handed neutrinos. Let us note that the contribution of the δ_L^{--} resonance to the helicity amplitudes [Eq. (2)] is directly proportional to $m_L (m_L = \Sigma_a K_{ae}^2 m_a$; see, e.g., [10]) and is invisible if only light neutrinos exist. If we take $m_L = 0$, then the resonance disappears (solid line in Fig. 4). If however $m_L \neq 0$, then its effect can be large. This is shown in Fig. 4 where we take doubly charged Higgs' widths to be $\Gamma_{\delta_{L,R}^{--}} = \Gamma_{M_W} M_{\delta_{L,R}^{--}} / M_W$. Lines in this figure present the cross sections for the case when all heavy neutrinos have the same CP eigenvalues. As has already been discussed, σ_{max} depends strongly on ω^2 in this case. We take $\omega^2 = 5 \times 10^{-5}$ TeV^{-1}, and so t- and u-channel contributions to the cross section are very small (see Fig. 1). This means that the large cross sections in Fig. 4, even for energies far away from the resonance region, are due to the δ_L^{--} resonance. For example, for $m_L = 5$ GeV and $\sqrt{s} = 1$ TeV, $\sigma_{max} \simeq 40$ fb and the effect is caused almost exclusively by $\delta_L^{--}(1600)$ Higgs resonance. As the contribution of δ_R^{--} to the cross section is not proportional to m_L its effect can be large even for $m_L = 0$, especially if its mass is around the c.m. energy. This case has been considered in [16].

We present directly in Fig. 5 the influence of δ_L^{--} resonance on the $e^-e^- \to W^-W^-$ process as a function of energy. To extract the effect of the δ_L^{--} resonance we compare the cross section σ_{max} for t and u channels only (short-dashed line) with the total cross section where t, u, and s channels are added altogether (long-dashed lines) for $m_L = 1$ GeV and $\eta_{CP}(N_1) = \eta_{CP}(N_2)$. We can see the huge influence of the δ_L^{--} resonance on the total cross section. Even for a very high mass of $\delta_L^{--} (M_{\delta_L^{--}} = 2000$ GeV, $\sqrt{s} = 1$ TeV) σ_{max} is above the "discovery limit."

The solid lines in Fig. 5 describe another case with $\eta_{CP}(N_1) = -\eta_{CP}(N_2)$. The upper one corresponds to the full cross section (s,t,u channels); the lower one is for a cross section without the s channel. As we can see for $m_L = -1$ GeV, contributions of the s and t+u channels are now comparable. The influence of δ_L^{--} on the cross section depends on the δ_L^{--} mass and width, and the value of the m_L parameter. For the same mass and the same width of δ_L^{--} its contribution to $\sigma_{max}(e^-e^- \to W^-W^-)$ can be very small, comparable or much bigger than the t+u channels' part, depending on the value of m_L.

III. CONCLUSIONS

We have analyzed the predictions for maximum possible values of the $e^-e^- \to W^-W^-$ cross section in models with nonzero m_L. If we have only one heavy neutrino or more but with the same CP parities, then the value of ω^2 is crucial for the maximum of the cross section and m_L does not have any visible influence. For the smallest value of $\omega^2 (\leq 5 \times 10^{-5}$ TeV$^{-1})$ predicted by some existing estimations (e.g., [13]) the cross section σ_{max} is too small to be measured in future e^-e^- linear colliders unless $\delta_{L,R}^{--}$ exist in the model.

However, for all other cases, the $m_L \neq 0$ changes substantially the $e^-e^- \to W^-W^-$ cross section. Negative m_L values move the limits on experimentally allowed neutrino mixings and masses. If there are two heavy neutrinos with opposite CP parities (or any number of them but with the lightest one having opposite CP parity with respect to all other ones), the value of σ_{max} can be substantial, much above the background level (e.g., for $M = 150$ GeV, $A = 5$, $\sigma_{max} \simeq 7$ fb).

In another configuration of CP parities of heavy neutrinos $[\eta_{CP}(N_1) = \eta_{CP}(N_2) = -\eta_{CP}(N_3)]$ the largest $\sigma(e^-e^- \to W^-W^-)$ is obtained for $m_L = 0$.

The most dramatic influence of the nonzero m_L on $e^-e^- \to W^-W^-$ is connected with the δ_L^{--} resonance. For $m_L = 0$ the contribution of this resonance to the process disappears. The $m_L \neq 0$ values cause δ_L^{--} to give a large contribution even far away from on-peak energies. The contribution of δ_R^{--} to the cross section does not depend on the m_L value.

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