Lower bounds on bilepton processes at e^-e^- and $\mu^-\mu^-$ colliders

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We show that the cross section of at least one of the s-channel processes $e^-e^-(\mu^-\mu^-)\to\ell_i^-\ell_i^-$, $i=e,\ \mu,\ \tau$, mediated by a doubly-charged scalar triplet bilepton is bounded from below and observable at a linear or muon collider provided at least one of the light neutrinos has a mass in the range where it is required to be unstable by cosmological considerations. The result applies to any model with scalar triplets and massive neutrinos which mix and is independent of further details of the models. We therefore stress the importance of the e^-e^- and $\mu^-\mu^-$ collision modes of the future colliders for discovering new physics. [S0556-2821(98)04003-X]

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The conservation of lepton flavor which has been tested with great accuracy at low energies is an important feature of the standard model. However, at energies of TeV range to be offered by electron linear [1] and muon colliders [2] lepton flavor may turn out not to be an exact symmetry. The e^-e^- and $\mu^-\mu^-$ running modes of the colliders are particularly suitable for discovering this type of new physics since the initial states carry double electron and muon number, respectively.

A very promising process which can be studied in these modes is the s-channel production of lepton pairs mediated by doubly-charged bileptons. These particles are predicted by wide range of extensions of the standard model, such as grand unified theories [3], theories with enlarged Higgs sectors [4], theories which generate neutrino Majorana masses [5] as well as technicolor theories [6] and theories of compositeness [7]. Particularly interesting among them are the theories containing scalar triplet bileptons since they provide a framework for the understanding of the smallness of the masses of the ordinary neutrinos via the see-saw mechanism [8].

In this Brief Report we consider the processes $e^-e^-(\mu^-\mu^-)\to\ell_i^-\ell_i^-$, $i=e,\ \mu,\ \tau$, [9,10] induced by a scalar triplet bilepton in wide class of models containing these particles without making further assumptions on the details of the models. We show that there are lower bounds on the cross section of the processes and at least one of them can be detected in the planned lepton colliders provided that at least one of the light neutrinos, ν_μ or ν_τ, has a mass in the range for which the constraint from the energy density of the present Universe requires it to be unstable. Should the collider experiments show the negative result then in this class of models all neutrino masses are below 90 eV or so.

We define bileptons to be bosons which couple to two leptons and which carry two units of lepton number. Their interactions need not necessarily conserve lepton flavor, but otherwise we demand the symmetries of the standard model to be respected. The most general $SU(2)_L\times U(1)_Y$ invariant renormalizable dimension four Lagrangian of this kind for triplet scalar bileptons B_3^0, B_3^+ and B_3^{++} is given by [11]

$$\mathcal{L}=\lambda_3^{ij}\Bigg(B_3^0\,\overline{\nu_i^c}P_L\nu_j-\frac{B_3^+}{\sqrt{2}}\times(\overline{\ell_i^c}P_L\nu_j+\overline{\ell_j^c}P_L\nu_i)-B_3^{++}\overline{\ell_i^c}P_L\ell_j\Bigg)+\text{H.c.},\quad (1)$$

where the indices $i,j=e,\mu,\tau$ stand for the lepton flavors and the chirality projection operators are defined as $P_{R,L}=(1\pm\gamma_5)/2$. In the following we shall drop the subscripts 3 denoting the dimension of the bilepton representation everywhere.

Because of large bilepton masses m_B the present low energy experiments can only constrain their effective couplings of a generic form $G=\lambda^2/m_B^2$. Negative results in searches for the lepton flavor violating processes $\ell_l\to3\ell_f$ and $\ell_l\to\gamma\ell_f$, where $l=\mu,\tau$, and $f=e,\mu$, put orders of magnitude more stringent bounds on off-diagonal bilepton couplings than one obtains from Møller scattering and $(g-2)_\mu$ studies as well as from the searches for muonium-antimuonium conversion for diagonal couplings λ^{ee} and $\lambda^{\mu\mu}$ [11–13]. To date there are no constraints on $\lambda^{\tau\tau}$ without involving off-diagonal elements. Following the present phenomenology we can approximate the bilepton coupling matrix λ^{ij} to be diagonal (small off-diagonal elements will not change our conclusions). Due to our ability to rotate lepton fields by a phase we can choose the couplings λ^{ii} in Eq. (1) to be real without loss of generality.

While the linear and muon colliders will probe the couplings and masses of the bileptons orders of magnitude more tightly than any of the present experiments [10,14] it is possible that due to small λ's or high bilepton masses no positive signal will be detected. However, this may not be the case if neutrinos are massive and mix as predicted by most of the extensions of the standard model.

The masses and lifetimes of the neutrinos are constrained by the requirement that the energy density of them in the present Universe does not exceed the upper limit on the total energy density of the Universe [15]. If the sum of light neutrino masses exceeds $\sim$90 eV at least one of them has to be unstable (note that the possible annihilation of the neutrinos,

$2\nu_l \leftrightarrow 2\nu_f$, has the same strength as the neutrino decay since it depends on the same coupling constants and, therefore, is negligible [16]). This may, indeed, be the case for μ or τ neutrinos since the present upper limits on neutrino masses are $m_{\nu_e} \lesssim 10$ eV, $m_{\nu_\mu} \lesssim 170$ keV [17] and $m_{\nu_\tau} \lesssim 18$ MeV [18]. The lifetime of such an unstable neutrino ν_l must satisfy the requirement [19,20]

$$\tau_{\nu_l} \lesssim 8.2 \times 10^{31}\ \mathrm{MeV}^{-1} \left(\frac{100\ \mathrm{keV}}{m_{\nu_l}} \right)^2. \tag{2}$$

The ν_l's can decay either radiatively $\nu_l \rightarrow \nu_f \gamma, \nu_f \gamma\gamma$ or at tree level $\nu_l \rightarrow 3\nu_f$ via neutral bilepton B^0 or Z' exchange. The radiative decay modes are highly suppressed [21] and cannot satisfy the constraint (2). The same is also true for Z' contribution to $\nu_l \rightarrow 3\nu_f$ decay [22]. Therefore, we are left with the decays $\nu_l \rightarrow 3\nu_f$ induced by the B^0 exchange. The effective Hamiltonian for this process is given by

$$H = \frac{G_0^{lf}}{\sqrt{2}} \overline{\nu_f} \gamma^\mu (1-\gamma_5) \nu_f \overline{\nu_f} \gamma_\mu (1-\gamma_5) \nu_l + \mathrm{H.c.}, \tag{3}$$

where $G_0^{lf} = \sqrt{2} \lambda_{ff} (\lambda_{ff} K_{fl} + \lambda_{ll} K_{lf})/(4 m_{B^0}^2)$. Note that the neutrino decays only due to the neutrino mixings presented by a mixing matrix K_{ij} and the processes $\ell_l \rightarrow 3\ell_f$ are forbidden as required by the current phenomenology.

Just from the ν_l lifetime, $\tau_{\nu_l}^{-1} = 2 G_0^2 m_{\nu_l}^5/(192\pi^3)$, and the constraint (2) we obtain a *lower* bound on the effective coupling G_0 as

$$G_0^{lf} \gtrsim 1.9 \times 10^3\ \mathrm{TeV}^{-2} \left(\frac{\mathrm{keV}}{m_{\nu_l}} \right)^{3/2}. \tag{4}$$

Numerically the minimum values of G_0 depend on whether the unstable neutrino is of μ of τ type (we assume that only one neutrino is unstable) and are given by $G_0^{\mu e} \gtrsim 8.6 \times 10^{-1}$ TeV^{-2} and $G_0^{\tau f} \gtrsim 8.0 \times 10^{-4}$ TeV^{-2}.

Let us now turn to studies of collider physics. Leptons can be pair-produced in $e^- e^-$ and $\mu^- \mu^-$ collisions via the s-channel exchange of a doubly-charged bilepton. Assuming fully left polarized incoming beams (in reality polarization rates exceeding 90% are achievable [1]) the total cross sections of the processes are given by

$$\sigma_{fi} = \frac{\lambda_{ff}^2 \lambda_{ii}^2}{2\pi} \frac{s}{(s - m_{B^{++}}^2)^2 + m_{B^{++}}^2 \Gamma_{B^{++}}^2}, \tag{5}$$

where the bilepton leptonic width is $\Gamma_{B^{++}} = \Sigma_i \lambda_{ii}^2 m_{B^{++}}/8\pi$ [9,23]. If the doubly-charged members of the multiplets turn out to be heavier than the singly-charged ones, the nonleptonic decay mode $B^{--} \rightarrow B^- W^-$ can possibly also contribute to the total width. However, only very heavy bileptons can realistically accommodate a mass splitting exceeding the mass of the W boson. Also the decay mode $B^{--} \rightarrow W^- W^-$ may contribute to the bilepton width but it is strongly suppressed by the neutral bilepton vev v_{B^0}, which is constrained to be small due to its contribution to the ρ parameter [24]. With the current constraints on the possible values of the decay width the B^{--} resonance peak at the colliders is very prominent and the resonant cross section is much larger than the off-resonance one [10]. Therefore we can study only the most conservative situation where the processes $\ell_f^- \ell_f^- \rightarrow \ell_i^- \ell_i^-$ are mediated by far off-resonance virtual bilepton. For completeness we shall later comment also on the production of $W^- W^-$ in these collisions.

If the doubly charged bilepton is very heavy, $s \ll m_{B^{++}}^2$, its interaction with leptons can be characterized by an effective Hamiltonian

$$H = \frac{G_{++}^{fi}}{\sqrt{2}} \overline{\ell_i} \gamma^\mu (1-\gamma_5) \ell_f \overline{\ell_i} \gamma_\mu (1-\gamma_5) \ell_f + \mathrm{H.c.}, \tag{6}$$

where $G_{++}^{fi} = \sqrt{2} \lambda_{ff} \lambda_{ii}/(8 m_{B^{++}}^2)$. In this formalism the cross section (5) takes a form

$$\sigma_{fi} = \frac{16\ (G_{++}^{fi})^2}{\pi} s. \tag{7}$$

The effective couplings G_{++} are related to G_0 as

$$G_{++}^{fi} = \frac{G_0^{lf}}{2} \frac{m_{B^0}^2}{m_{B^{++}}^2} \frac{\lambda_{ii}}{(\lambda_{ff} K_{fl} + \lambda_{ll} K_{lf})}. \tag{8}$$

Clearly, since some of G_0's are bounded from below also some of G_{++}'s cannot be arbitrarily small leading to nonvanishing processes at colliders. For large neutrino mass differences the present limits on the neutrino mixings are $|K_{e\mu}| = |K_{\mu e}| \lesssim 2.8 \times 10^{-2}$, $|K_{\mu\tau}| = |K_{\tau\mu}| \lesssim 3 \times 10^{-2}$ and $|K_{e\tau}| = |K_{\tau e}| \lesssim 0.2$ [17,25]. Also the mass splitting between B^{++} and B^0, which belong to the same $SU(2)_L$ multiplet, is strongly bounded from the experimental value of the parameter $\rho = 1 + \rho_\theta + \rho_B$, where ρ_θ is a correction due to the mixing of Z^0 with a new neutral gauge boson (which we are neglecting here) and ρ_B comes from the bilepton contribution to the Z^0 and $W^\pm$ mass. It is given by [24]

$$\rho_B = \frac{G_F}{4\sqrt{2}\pi^2} [f_{(B^0, B^+)} + f_{(B^+, B^{++})}] \equiv \frac{3 G_F}{8\sqrt{2}\pi^2} \Delta m^2,$$

where $f_{(x,y)} = m_x^2 + m_y^2 - 2 m_x^2 m_y^2 \ln(m_y^2/m_x^2)/(m_y^2 - m_x^2)$. Studies of the new contributions to the ρ parameter have provided the upper bounds $\Delta m^2 \leqslant (76\ \mathrm{GeV})^2$, $(98\ \mathrm{GeV})^2$, $(122\ \mathrm{GeV})^2$ [17] for the standard model Higgs masses $m_H = 60$, 300 and 1000 GeV, respectively, at 90% C.L. Therefore, for the interesting range of bilepton masses of 1 TeV and higher the ratio $m_{B^0}/m_{B^{++}}$ cannot differ from unity more than ~ 10–20 % even for $m_H = 1$ TeV.

Let us now study the implications of the bound (4) on B^{--} processes at the colliders. To estimate the discovery potential, we use the scaling relation $\mathcal{L}_{e^-e^-} = 3.25 \times 10^7 s$ for the $e^- e^-$ and $\mu^- \mu^-$ luminosities which closely corresponds to a luminosity of 25 fb^{-1} at $\sqrt{s} = 0.5$ TeV and scales like the square of the center of mass energy. This choice for the luminosity is dictated by the latest e^+e^- linear collider design report [1] and the fact that the e^-e^- mode will approximately suffer a 50% luminosity reduction because of the antipinch effect [26].

Concerning the background we have to deal with two different types of processes. While the lepton number violating processes have no background from the standard model then e^-e^- and $\mu^-\mu^-$ elastic scatterings take place also without bileptons (other standard model processes [27] can easily be discriminated on the basis of missing energy). However, due to the interference with the standard model graphs the bilepton effects are enhanced in the latter case which compensates the existence of the background. If we assume that observing one flavor violating event already constitutes a discovery, we need an average number of $-\ln(1-p)$ Poisson distributed events such that *at least* 1 event is observed with probability p. Hence, a predicted average of at least 3 events is needed to guarantee a discovery with 95% confidence. In this case the minimal testable G_{++}'s following from the cross section (7) are

$$G^{fl}_{++}(\min)=\frac{1.4\times10^{-4}}{s}\ \mathrm{TeV}^{-2}, \tag{9}$$

where $f\neq l$ and s is expressed in TeV^2. In the case a tau lepton is produced we assume its reconstruction efficiency to be 65% and this value should be divided by 0.65. The situation $f=l=e,\mu$ has been studied in [11] where the Cramer-Rao limit, $\chi^2_\infty=\mathcal{L}\int dt[d\sigma(\lambda)/dt-d\sigma(\lambda=0)/dt]^2/[d\sigma(\lambda=0)/dt]$, has been computed. At 95% confidence level $\chi^2_\infty=3.84$, and one obtains

$$G^{ff}_{++}(\min)=\frac{8\times10^{-5}}{s}\ \mathrm{TeV}^{-2}. \tag{10}$$

Independently of which neutrino has the large mass and decays to three lighter neutrinos we can always choose to study the process $\ell^-_f\ell^-_f\to\ell^-_l\ell^-_l$ at the linear or muon collider and to constrain the relevant couplings λ_{ff}, λ_{ll}, $l\neq f$, $i=l$ in Eq. (8). For the numerical estimates we choose the case if $\nu_\tau\to3\nu_e$ since the present experimental constraints on $|K_{\tau e}|$ and m_{ν_τ} give us the most conservative limits. Using the numerical quantities determined above we obtain from Eqs. (4), (8)

$$G^{e\tau}_{++}\gtrsim2\times10^{-3}\frac{\lambda_{\tau\tau}}{\lambda_{ee}+\lambda_{\tau\tau}}\ \mathrm{TeV}^{-2}, \tag{11}$$

which in comparison with Eq. (9) implies that the process $e^-e^-\to\tau^-\tau^-$ should be detected at the 1 TeV linear collider unless $\lambda_{\tau\tau}/\lambda_{ee}\lesssim10^{-1}$. On the other hand, if this is the case then

$$G^{ee}_{++}\gtrsim2\times10^{-3}\ \mathrm{TeV}^{-2}, \tag{12}$$

and Eq. (10) suggests that the excess of the electron pairs due to the s-channel bilepton production will be detected. Note that the positive signal should be seen if $\sqrt{s}\gtrsim0.3$ TeV which is below the planned initial energy of the linear collider.

Similarly, if $\nu_\tau\to3\nu_\mu$ then $\mu^-\mu^-\to\tau^-\tau^-$ should be seen unless $\lambda_{\tau\tau}/\lambda_{\mu\mu}\lesssim10^{-3}$ ($\sqrt{s}_{\mu\mu}=4$ TeV used), and if $\nu_\mu\to3\nu_e$ then $e^-e^-\to\mu^-\mu^-$ should be seen unless $\lambda_{\mu\mu}/\lambda_{ee}\lesssim10^{-5}$. Suppression of the flavor violating processes by small $\lambda_{ll}/\lambda_{ff}$ would mean that the cross sections of the flavor conserving processes $\ell^-_f\ell^-_f\to\ell^-_f\ell^-_f$ exceed the minimal observable limit (10) by orders of magnitude. Therefore, the bilepton mediated s-channel processes cannot be missed at future lepton colliders which are much more sensitive to the considered type of new physics than the low energy experiments searching for muonium-antimuonium conversion and the decay $\mu^+\to e^+\overline{\nu_e}\nu_\mu$ [20].

One should also note that at the time colliders start to operate new experimental data on neutrino mixings and masses will be available. The largest improvements in experimental sensitivity can be expected in tau neutrino physics. Proposed E803 and NAUSICAA experiments at Fermilab will respectively have about one and two orders of magnitude higher sensitivity to $|K_{e\tau}|$ and $|K_{\mu\tau}|$ than the present limits [25]. Should these experiments give negative results then, together with improvements of m_{ν_τ} determination in tau factories, the bounds on G_{++}'s will rise about a factor of hundred.

Finally, let us comment on the possibility of observing the processes $\ell^-_f\ell^-_f\to W^-W^-$ [28]. For e^-e^- collision mode there are stringent limits on this process from neutrinoless double-β decay and the cross section is vanishing [29]. However, these limits do not apply for $\mu^-\mu^-$ collisions. The $B^{++}W^-W^-$ vertex is proportional to the vacuum expectation value v_{B^0} which is experimentally constrained to be below a few GeV [24] but there is no fundamental reason that it is exactly zero. Therefore, for the energies where W pair production is not kinematically suppressed, $M_W^2\ll s\ll M_B^2$, one gets

$$\sigma(\mu^-\mu^-\to W^-W^-)\sim\sigma(\mu^-\mu^-\to\ell^-_i\ell^-_i)\frac{g^4v^2_{B^0}s}{\lambda^2_{ii}M_W^4}.$$

In the case of small λ_{ii} the cross section of $\mu^-\mu^-\to W^-W^-$ may be enhanced by a factor of $g^4v^2_{B^0}s/(\lambda^2_{ii}M^4_W)$ and provide an observable amount of lepton number violating events.

In conclusion, we have shown in the class of models under consideration that if at least one neutrino has a mass exceeding about ~90 eV and neutrinos do mix there is such a lower bound on the cross section of *at least* one of the processes $\ell^-_f\ell^-_f\to\ell^-_i\ell^-_i$, mediated by the doubly charged scalar triplet bilepton B^{--}, that the process is observable at future e^-e^- or $\mu^-\mu^-$ colliders.

We stress that this result is very general and applies to any model with scalar triplets and massive neutrinos. We have not used any model dependent relation for the bilepton couplings nor for the neutrino masses. Our conclusion is also independent of the exact values of bilepton masses since only the effective couplings G^{fi} are constrained by the analyses. For our considerations it is important that triplet bileptons and massive neutrinos do exist and mix. Therefore it appears to be difficult to avoid the lower bounds if the collider parameters will be close to the presently designed ones. Small changes in the collider parameters and cosmological bounds, small non-zero off-diagonal bilepton couplings, existence of two decaying neutrinos as well as accidental cancellations between the used parameters may change our numerical values by a factor of 2-3, or so, but not by orders of magnitude what is required to avoid our conclusions.

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