Abstract

We investigate a single scalar neutrino production at the upgraded HERA with high luminosity in the framework of an R-parity violating supersymmetric model. We find that the scalar neutrino with mass around 100GeV could be observed through investigating the multilepton production process \( e^- p \rightarrow \mu^- \bar{\nu}_\tau X \rightarrow \mu^- (e^- \mu^+) X \). The signal would be characterized by \( \mu^+ \) and \( e^- \) with high transverse momentum as well as a sharp peak in the invariant mass \( M(e^- \mu^+) \) distribution.
1 Introduction

The $ep$ collider HERA is a unique accelerator because it enables us to investigate the proton structure in extremely deep region. Furthermore we can study the basic electron-quark interactions at the high energies only by HERA which provides us both baryonic and leptonic quantum numbers in the initial states. In fact HERA could set the best limit on the masses and the coupling strengths of leptoquarks via detailed analyses of the deep inelastic (DIS) neutral current (NC) and charged current (CC) processes.

It is widely known that the scalar partners of quarks (squarks : $\tilde{q}$) have similar properties to the leptoquarks in a class of the supersymmetric (SUSY) standard models, the R-parity breaking (RB) models [1]. Here the R-parity is defined by $R = (-1)^{L+3B+2S}$, where $L$, $B$ and $S$ denote the lepton number, the baryon number and the spin, respectively. The models are characterized by the R-parity violating $\tilde{L}\tilde{Q}\tilde{D}$ type superpotentials, from which the leptoquark interactions $\ell - q - \tilde{q}$ are derived. The superfields $\tilde{L}$, $\tilde{Q}$ and $\tilde{D}$ contain, respectively, the left-handed leptons, the left-handed quarks and the right-handed down-quark together with the SUSY partners $\tilde{\ell}_L$, $\tilde{q}_L$ and $\tilde{d}_R$. We could study in detail the single production of squarks as well as leptoquarks by HERA experiments.

In 1997 both H1 [2] and ZEUS [3] collaborations reported an event excess at large $x$ and high $Q^2$ in comparison with the Standard Model (SM) expectations in the DIS $e^\pm p \to e^\pm X$. The news very much excited the high energy physics community. Various ideas to understand the anomaly have extensively been examined by theoreticians since then [1, 4, 10]. We have also proposed an interpretation of the anomalous events by the scalar top quark (stop) production in the SUSY models with RB interactions [6, 7]. Contrary to initial expectation, the anomalies have gradually faded away from the whole data sample with increasing experimental data. However, this fact impressed us that HERA could have the potentiality exploring physics beyond the SM.

In this paper we consider another type of the R-parity violating SUSY model, with the $\tilde{L}\tilde{L}\tilde{E}$ type superpotential, where $\tilde{E}$ contains the right-handed leptons together with the SUSY partners $\tilde{\ell}_R$. We show that the multilepton events come from the single production of a scalar partner of the neutrinos (sneutrinos) at HERA. As the process is not an eq scattering of the resonant type, the number of events is too small to be detected at the present HERA with the integrated luminosity of around 100pb$^{-1}$. Fortunately, however, HERA has been upgraded, and experiments using polarized $e^-$ or $e^+$ beams with high luminosity will soon start [8]. Then it will be expected that we are able to search for rare events with higher statistics than before.
2 Models and constraints

In the minimal SUSY standard model (MSSM), the general RB superpotential \( W_R \) is written by

\[
W_R = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k + \lambda''_{ijk} \hat{U}_i \hat{D}_j \hat{D}_k,
\]  

(1)

where \( i, j \) and \( k \) are generation indices. The first two terms violate the lepton number \( L \) and the last term violates the baryon number \( B \). Incorporating RB interactions into the MSSM we have a possibility to unveil yet unresolved problems as (i) the cosmic baryon number violation, (ii) the origin of the masses and the magnetic moments of neutrinos and (iii) some interesting rare processes induced by the \( L \) and/or \( B \) violation. Here we consider the first \( \hat{L}_i \hat{L}_j \hat{E}_k \) term, in which we set \( (i, j, k) = (2, 3, 1) \). The Yukawa-type interaction Lagrangian

\[
L = \lambda_{231} \left( \tilde{e}_R \tilde{\nu}_\tau L - \tilde{e}_R \tilde{\nu}_\tau \mu L - \tilde{\nu}_\tau e \tilde{\mu}_L + \cdots \right) + \text{h.c.}
\]  

(2)

is derived from the superpotential from (1).

The most stringent upper bound on \( \lambda_{231} \) comes from the leptonic decay width of the tau lepton \( \bar{\nu}_\tau \)

\[
\lambda_{231} \approx 0.07 \frac{m_{\tilde{e}_R}}{100 \text{GeV}},
\]  

(3)

since the selectron exchange diagram through the first and second terms in (2) contributes to the process \( \tau \to \nu_\mu \nu_\tau \mu \). The upper limit is not so severe if we compare above bound (3) with the bounds for other RB couplings, e.g., \( \lambda_{133} \approx 0.0060 \sqrt{m_\tau/100 \text{GeV}} \) derived from the experimental limit on the electron neutrino mass \( [10, 11] \). This is the reason why we consider the \( \hat{L}_2 \hat{L}_3 \hat{E}_1 \) superpotential.

We are aware of constraints on the slepton masses from the precision measurements at LEP2 \( [12] \). The present lower mass limits at 95% C.L. are \( m_{\tilde{\nu}_\mu, \tau} \gtrsim 65 \text{GeV} \) and \( m_{\tilde{e}_R} \gtrsim 69 \text{GeV} \), which are obtained by the analyses on the pair production of the sleptons with the RB decay modes. In the following analysis we take typical input parameters \( m_{\tilde{\nu}} = 100 \text{GeV} \), \( \lambda_{231} = 0.1 \) and additionally we assume \( Br(\tilde{\nu}_\tau \to e\mu) = 1 \) for simplicity. This assumption corresponds to the case of a large SU(2) gaugino mass \( M_2 \) and a large SUSY Higgs mass \( \mu \), e.g., \( M_2 > 300 \text{GeV} \) and \( \mu > 100 \text{GeV} \).

3 Production processes

We consider the single sneutrino production as a signal process,

\[
e^- p \to \mu^- \tilde{\nu}_\tau X.
\]  

(4)

Note that the mass threshold of the process should be \( \sqrt{s_{eq}} \gtrsim m_{\tilde{\nu}} \) and it is lower than production threshold at \( e^+ e^- \) or \( pp \) colliders as far as the \( \tilde{\nu} \) pair production
is concerned. The $\tilde{\nu}_\tau$ decays into $e^-\mu^+$ via the R-parity violating interaction (4). Then we have the final state

$$e^-p \rightarrow \mu^-\mu^+e^-X.$$  \hspace{1cm} (5)

Throughout the present work whole calculations of decay widths and cross sections have been performed by using the GRACE/SUSY system, an automatic computation program for SUSY processes [13]. While the GRACE/SUSY system is originally designed to treat such elementary subprocesses as $e^+e^-$, $eq$ and $qq$ collisions, we have recently succeeded in extending it to $ep$ and $pp$ collisions. We use the extended new versions which include an interface to the PDFLIB too. For the parton distribution function we have used CTEQ4M [14]. The Feynman diagrams of the subprocesses for(4) as well as relevant SM background are shown in Figs.1 and 2, respectively.

Figure 1: Feynman diagrams for $e^-q \rightarrow \mu^-\tilde{\nu}_\tau q$ in the RB model.

4 Numerical results

We obtain the total cross section of 10fb for the signal process (4), where we take $\lambda_{231} = 0.1$, $m_{\tilde{\nu}_\tau} = 100\text{GeV}$. It is too small cross section for us to extract from the SM background with the same final states $\sigma_{SM}(e^-p \rightarrow \mu^-\mu^+e^-X) \sim 0.3\text{nb}$. Consequently we should suppress the huge background to extract the signal.

*The same final state can be expected when we take the non-zero $\lambda_{121}$ or $\lambda_{122}$ couplings. For this case $\tilde{\nu}_e$ or $\tilde{\nu}_\mu$ is singly produced with $\mu^-$ in the $eq$ collisions. However, the magnitudes of $\lambda_{121}$ and $\lambda_{122}$ are more severely constrained from the charged current universality than $\lambda_{231}$ [10].
Figure 2: Feynman diagrams for $e^-q \to \mu^-\mu^+e^-q$ in the SM.
In Fig. 3 we show the various transverse momentum ($P_T(e^-)$, $P_T(\mu^-)$ and $P_T(\mu^+)$) distributions. We find that the signal cross section is much smaller than the SM background in the $P_T(\mu^-)$ distribution in a whole kinematical region. The main contribution to the SM background comes from the two photon processes (graphs 9, 13 in Fig. 2) and the virtual photon emission processes (graphs 1, 5, 17, 21 in Fig. 2). This is reflected in the rapid increase in the $P_T$ distribution with decreasing $P_T$ as shown in Fig. 3. On the other hand, in the $P_T(e^-)$, $P_T(\mu^+)$ distributions, the signal differential cross section can be comparable to the background in a specific kinematical region, $P_T(e^-), P_T(\mu^+) \simeq 50 \text{GeV}$. This is due to the fact that the $e^-$ and $\mu^+$ are originated from the 2-body decay of the sneutrino with mass 100 GeV. We can see the similar small Jacobian peak from the Z-boson decay for the SM histograms in the $P_T(\mu^+)$ and $P_T(\mu^-)$ ($\simeq 46 \text{GeV}$) distributions.

The Monte Carlo event simulation in $(P_T(\mu^+), P_T(e^-))$ plane is displayed in Fig. 4 assuming the integrated luminosity of $1 \text{fb}^{-1}$. While the number of signal events is small compared to the backgrounds, they are characterized by the large transverse momentum. Based on the above observation, we expect that the background can be suppressed if we impose appropriate kinematical cuts on the final leptons. Specifically, we find following condition is suitable for the purpose,

\begin{align}
P_T(\mu^+) &> 20 \text{GeV}, \\
P_T(e^-) &> 20 \text{GeV}.
\end{align}

Figure 3: Transverse momentum distributions for $e^- p \rightarrow \mu^- \mu^+ e^- X$. We take $\lambda_{231} = 0.1$, $m_{\nu_e} = 100 \text{GeV}$. 

The Monte Carlo event simulation in $(P_T(\mu^+), P_T(e^-))$ plane is displayed in Fig. 4 assuming the integrated luminosity of $1 \text{fb}^{-1}$. While the number of signal events is small compared to the backgrounds, they are characterized by the large transverse momentum. Based on the above observation, we expect that the background can be suppressed if we impose appropriate kinematical cuts on the final leptons. Specifically, we find following condition is suitable for the purpose,
Figure 4: Scatter plots of $P_T$ for $e^-p \rightarrow \mu^-\mu^+e^-X$. Open triangle and closed circle respectively correspond to $e^-p \rightarrow \mu^-\tilde{\nu}_\tau X \rightarrow \mu^- (\mu^+ - e^+)X$ in the RB model and $e^-p \rightarrow \mu^-\mu^+e^-X$ in the SM. We take $\lambda_{231} = 0.1$, $m_{\tilde{\nu}_\tau} = 100\text{GeV}$ and assume $L = 1\text{fb}^{-1}$.

When we apply the $P_T$ cuts, we find that the signal can be seen as an event excess in the relevant invariant mass distributions. In Fig.5 we show $M(\mu^+\mu^-)$ and $M(e^-\mu^+)$ distributions with the $P_T$ cuts (6) and (7). The almost uniform excess for the $M(\mu^+\mu^-)$ and a sharp peak at $M(e^-\mu^+) = m_{\tilde{\nu}_\tau} = 100\text{GeV}$ can be expected.

5 Summary and conclusion

We have investigated the single scalar neutrino production at HERA in the framework of the R-parity breaking SUSY model with $\lambda_{231} \neq 0$. The signal of the process should be multilepton final states $e^-\mu^+\mu^-$ without missing energies.

The main background would be the basic QED reactions, i.e., two photon processes and the virtual photon emission from initial and final fermions. We find that the background can be suppressed by making the appropriate $P_T$ cut for for final $e^-$ and $\mu^+$. Then the signal can be clearly seen as a sharp peak at $M(e^-\mu^+) = m_{\tilde{\nu}_\tau}$ in the invariant mass distribution.

We conclude that if the R-parity violating coupling constant is $\lambda_{231} \gtrsim 0.1$ and the mass of scalar neutrino is $m_{\tilde{\nu}_\tau} \gtrsim 100\text{GeV}$, the HERA could be efficient for exploring the $\hat{L}\hat{L}\hat{E}$ type interactions in the R-parity breaking SUSY model.
Figure 5: Invariant mass distributions for $e^- p \rightarrow \mu^- \mu^+ e^- X$ with cuts $P_T(\mu^+)$, $P_T(e^-) > 20$GeV. We take $\lambda_{231} = 0.1$, $m_{\tilde{\nu}_e} = 100$GeV and assume $L = 1$fb$^{-1}$.

Acknowledgements

The work was supported in part by the Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan, No. 10440080 and No. 11206203.

References

[1] M. Besancon and E. Dudas et al., "Report of the GDR working group on the R-parity violation", hep-ph/9810232, related references will be found therein.

[2] C. Adloff et al., H1 Collab., Z. Phys. C74, 191 (1997)

[3] J. Breitweg et al., ZEUS Collab., Z. Phys. C74, 207 (1997)

[4] J. L. Hewett, "Research Directions for the Decade", Proc. of 1990 Summer Study on High Energy Physics, Snowmass, 1990, ed. E. L. Berger, (World Scientific, Singapore, 1992), p.566

[5] J. Butterworth and H. Dreiner, Proc. of the HERA Workshop : "Physics at HERA" 1991, eds. W. Buchmüller and G. Ingelman, Vol.2, p.1079 ; Nucl. Phys. B397, 3 (1993)
[6] T. Kon and T. Kobayashi, Phys. Lett. B270, 81 (1991); T. Kon, T. Kobayashi and K. Nakamura, Proc. of the HERA Workshop: "Physics at HERA" 1991, eds. W. Buchmüller and G. Ingelman, Vol.2, p.1088

[7] T. Kon and T. Kobayashi, Phys. Lett. B409, 265 (1997)

[8] K. Long, talk at Workshop on electron proton interactions with high transverse energy, KEK, 28 – 29 March 2000

[9] V. Barger, G. F. Giudice and T. Han, Phys. Rev. D40, 2987 (1989)

[10] B. C. Allanach, A. Dedes and H. K. Dreiner, Phys.Rev. D60, 075014 (1999)

[11] R. M. Godbole, R. P. Roy and X. Tata, Nucl. Phys. B401, 67 (1993)

[12] P. Achard et al., L3 Collaboration, Phys. lett. B524, 65 (2002)

[13] Minami-Tateya Collab.,
http://www-sc.kek.jp/minami/gracesusy.html

[14] H. L. Lai et al., Phys. Rev. D51, 4763 (1995)