Some new aspects of supersymmetry R-parity violating interactions

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We examine R-parity-breaking interactions with lepton-number violation in the minimal supergravity model and obtain new stringent bounds on the coupling constants from low-energy processes. We discuss the decay of the lightest supersymmetric particle and analyze possible signatures for R-parity-violating interactions in W, Z, and Higgs-boson decays, and in e^+e^- collisions.

I. INTRODUCTION

The requirement of baryon- and lepton-number conservation in low-energy supergravity models[1,2] implies the existence of a discrete symmetry (R parity) which prevents the lightest supersymmetric particle (LSP) from decaying. As a consequence an excess of "missing energy" in collider experiments would be a signature for supersymmetry. However, baryon-number (B) or lepton-number (L) conservation is not ensured by gauge invariance. Even in supersymmetric models with the minimal field content, the most general superpotential contains interactions which violate B and L and simultaneously mediate the decay of the LSP.

Because of their great theoretical interest, some of the consquences of the supersymmetric models with R-parity breaking (denoted by R breaking) have been considered in the literature.[3] Some expectations resulting from R-breaking interactions in high-energy collider experiments have been systematically analyzed by Dimopoulos and Hall[4] and collaborators.[5]

In this paper, we concentrate on models which violate L but not B. We start by reconsidering the limits on R-breaking interactions from processes at low energies that do not involve the production of supersymmetric particles in the final state. If R is conserved, supersymmetry (SUSY) can contribute to these processes only at the loop level. Therefore, one can hope to find limits on supersymmetry parameters only from processes which are forbidden at the tree level in the standard model [e.g., flavor-changing neutral currents (FCNC)]. This is no longer the case if R-breaking couplings are present. In Sec. II, we examine some low-energy tree-level contributions from R-breaking interactions and we find stringent limits on the couplings. In Sec. III we first study the LSP decay via R-breaking interactions and then discuss some possible R-breaking experimental signals in W,Z and Higgs-boson decays, and in e^+e^- collisions.

II. LOW-ENERGY CONSTRAINTS ON R-BREAKING INTERACTIONS

We are considering the standard low-energy supergravity model[1,2] with the minimal content of fields. In addition to the usual Yukawa interactions, we allow the superpotential to contain the possible renormalizable L-violating couplings:

$$\lambda_{ijk} L_L^i L_L^j \bar{E}_R^k \,, \tag{1a}$$

$$\lambda'_{ijk} L_L^i Q_L^j \bar{D}_R^k \,. \tag{1b}$$

With standard notations, L_L, Q_L, $\bar{E}_R$, and $\bar{D}_R$ denote the chiral superfields containing, respectively, the left-handed lepton and quark doublets and the right-handed charged-lepton and d-quark singlets; i,j,k are generation indices. Besides the interactions of Eq. (1), the L-violating bilinear term $L_L H$ can also be introduced consistently with gauge invariance. However, this term can be rotated away through a redefinition of L_L and H', where H and H' are the superfields containing the Higgs doublets with, respectively, hypercharges $+1$ and -1. Note that λ_{ijk} in Eq. (1a) is antisymmetric in the first two indices because of the contraction of SU(2) indices. Henceforth we take λ_{ijk} nonvanishing only for $i<j$.

The interactions in Eq. (1) break R parity, giving elementary couplings involving an odd number of supersymmetric partners, unlike the R-invariant interactions where supersymmetric particles appear always in pairs. In four-component Dirac notation, the Yukawa interactions of the R-breaking Lagrangian generated by Eq. (1) are

$$\mathcal{L}=\lambda_{ijk}[\tilde{\nu}_L^i \bar{e}_R^k e_L^j + \tilde{e}_L^j \bar{e}_R^k \nu_L^i + (\tilde{e}_R^k)^* (\bar{\nu}_L^i)^c e_L^j - (i \leftrightarrow j)] + \mathrm{H.c.} \,, \tag{2a}$$

$$\mathcal{L}=\lambda'_{ijk}[\tilde{\nu}_L^i \bar{d}_R^k d_L^j + \tilde{d}_L^j \bar{d}_R^k \nu_L^i + (\tilde{d}_R^k)^* (\bar{\nu}_L^i)^c d_L^j - \tilde{e}_L^i \bar{d}_R^k u_L^j - \tilde{u}_L^j \bar{d}_R^k e_L^i - (\tilde{d}_R^k)^* (\bar{e}_L^i)^c u_L^j] + \mathrm{H.c.} \tag{2b}$$

At energies lower than the Fermi scale, the heavy supersymmetric particles can be integrated out and the net effect of the R-breaking interactions is to generate effective four-fermion operators involving the lepton and quark fields. In general, these operators will mediate L-violating and FCNC processes. The constraints on the coupling constants of the R-breaking interactions are then rather severe. However, as pointed out in Ref. 4, the situation is quite different if we assume that only one operator in Eq. (1) with a particular generation structure has a sizeable coupling constant. In this case, the effective four-fermion operators generated by $L_L^i L_L^j \bar{E}_R^k$ are of the form

$$\mathcal{L}_{\rm eff}=\frac{|\lambda_{ijk}|^2}{2}\left[\left(\frac{1}{m^2_{\tilde{e}^k_R}}\bar{\nu}^i_L\gamma^\mu\nu^i_L\bar{e}^j_L\gamma_\mu e^j_L-\frac{1}{m^2_{\tilde{e}^k_R}}\bar{e}^i_L\gamma^\mu\nu^i_L\bar{\nu}^j_L\gamma_\mu e^j_L-\frac{1}{m^2_{\tilde{\nu}^i_L}}\bar{e}^j_L\gamma^\mu e^j_L\bar{e}^k_R\gamma_\mu e^k_R-\frac{1}{m^2_{\tilde{e}^i_L}}\bar{\nu}^j_L\gamma^\mu\nu^j_L\bar{e}^k_R\gamma_\mu e^k_R\right)+(i\leftrightarrow j)\right] . \tag{3}$$

The effective operators for the $L_L^i Q_L^j \bar{D}_R^k$ case are obtained by the replacements

$$\lambda\to\lambda', \quad \begin{pmatrix}\nu^i_L\\ e^i_L\end{pmatrix}\to\begin{pmatrix}u^i_L\\ d^i_L\end{pmatrix}, \quad \text{and } e^i_R\to d^i_R$$

in Eq. (3). We note that the low-energy effective Lagrangian Eq. (3) does not lead to either L violation or FCNC despite the fact that the original Lagrangian of Eq. (2) violates L and has an arbitrary family structure.

At low energies, the L violation can arise only at the level of effective six-fermion operators, which are in general highly suppressed. From neutrinoless double-beta decay, a limit $|\lambda'_{111}|\lesssim 3\times10^{-3}$ has been inferred[6] for gluino, squark, or slepton mass $\tilde{m}\simeq 100$ GeV. However, because of the higher dimensionality of the operator, this limit scales as $(\tilde{m})^{-5/2}$, while limits on four-fermion operators scale as $(\tilde{m})^{-1}$. Limits on six-fermion R-breaking interactions can also be inferred from their contributions to neutrino masses, which depend on the value of the trilinear scalar coupling.[3,6] The least stringent bounds on the couplings will be obtained for a vanishing trilinear coupling; in that case the neutrino acquires a mass only at the two-loop level and the corresponding limits on the R-breaking interactions are less stringent than those obtained from four-fermion operator contributions to low-energy processes.

We will show in the next section that the present measurements on weak processes at low energies provide strong constraints on the existence of four-fermion operators beyond the standard model. Consequently, based on Eq. (3), we are able to set stringent limits on the coupling constants of R-breaking interactions with L violation in Eq. (1).

A. Charged-current universality constraints

One of the most important predictions of the standard electroweak gauge theory is the universality of quark and lepton couplings to W bosons. The R-breaking interactions lead in general to universality violations. Precision experimental tests of universality can thereby place stringent constraints on R-breaking couplings.

We consider first the case of the $L_L L_L \bar{E}_R$ interactions. Muon decay then receives an additional contribution from $\tilde{e}_R$ exchange, as shown in Fig. 1(b). As is apparent from Eq. (3), the R-breaking contributions have the same $(V-A)\otimes(V-A)$ structure as W exchange and the effective tree-level Fermi coupling in μ decay becomes

$$\frac{G_\mu}{\sqrt{2}}=\frac{g^2}{8M_W^2}+\frac{|\lambda_{12k}|^2}{8m^2_{\tilde{e}^k_R}}\equiv\frac{g^2}{8M_W^2}[1+r_{12k}(\tilde{e}^k_R)] . \tag{4}$$

Here and henceforth we use the notation

$$r_{ijk}(\tilde{l})=(M_W^2/g^2)(|\lambda_{ijk}|^2/m^2_{\tilde{l}}) , \tag{5}$$

with the assumption that only one of the λ_{ijk} is nonvanishing.

In the quark sector, the existence of the $L_L Q_L \bar{D}_R$ interactions gives an extra contribution to quark semileptonic decays (e.g., in nuclear β decay) of a similar form to that of μ decay and the effective tree-level weak coupling is

$$\frac{g^2}{8M_W^2}[V_{ud}+r'_{11k}(\tilde{d}^k_R)] . \tag{6}$$

The Kobayashi-Maskawa matrix elements V_{Qq} are experimentally determined from the ratio of the $Q\to qe\nu_e$ to $\mu\to\nu_\mu e\nu_e$ partial widths. The experimental value of V_{ud} is related to theoretical quantities by

$$\begin{aligned}|V_{ud}|^2_{\rm expt}&=\frac{|V_{ud}+r'_{11k}(\tilde{d}^k_R)|^2}{|1+r_{12k}(\tilde{e}^k_R)|^2}\\ &\simeq|V_{ud}|^2[1+2r'_{11k}(\tilde{d}^k_R)/V_{ud}-2r_{12k}(\tilde{e}^k_R)] ,\end{aligned} \tag{7}$$

where only one of the two R-breaking terms will be nonzero. Summing over the three generations for d_j and

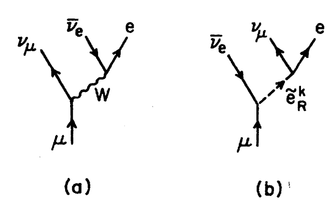

FIG. 1. Feynman diagrams for μ decay from (a) the standard model, and (b) the R-breaking interaction.

using the measured value[7] for the left-hand side we obtain

$$\sum_j |V_{ud_j}|^2_{\text{expt}} = 0.9979 \pm 0.0021$$
$$= 1 + 2V_{ud_1} r'_{11k}(\tilde{d}^k_R) - 2r_{12k}(\tilde{e}^k_R) . \quad (8)$$

Thus at the 1σ level we infer that

$$|\lambda_{12k}| < 0.04 \left[\frac{m_{\tilde{e}^k_R}}{100\ \text{GeV}} \right] \quad (9)$$

for each generation index k.

A limit $|\lambda_{12k}| \lesssim \frac{1}{6}(m_{\tilde{e}^k_R}/100\ \text{GeV})$ has been derived in Ref. 4, from a direct test of the relation $G_\mu = \pi\alpha/(\sqrt{2}\sin^2\theta_W M_W^2)$. This limit is less stringent than that obtained in Eq. (9). Future precision measurements of M_Z and $\sin^2\theta_W$ will test the validity of the relation $G_\mu = 2\sqrt{2}\pi\alpha/(\sin^2 2\theta_W M_Z^2)$, which would be modified by the λ_{12k} term in Eq. (4).

A nonvanishing λ'_{11k} is excluded by Eq. (8) at the 1σ level since there is no present experimental indication of apparent oversaturation of the unitarity condition. At the 2σ level, the limit is

$$|\lambda'_{11k}| < 0.03 \left[\frac{m_{\tilde{d}^k_R}}{100\ \text{GeV}} \right] . \quad (10)$$

B. e-μ-τ universality

Limits on the R-breaking couplings can be extracted from the present experimental constraints on deviations from e-μ-τ universality. The ratio $R_\pi \equiv \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ has been measured[8] to be

$$\frac{R_\pi(\text{expt})}{R_\pi(\text{SM})} = 0.991 \pm 0.018 , \quad (11)$$

with respect to the standard model (SM). The interaction $L_L Q_L \bar{D}_R$ gives an effective contribution to R_π:

$$R_\pi = R_\pi(\text{SM}) \left[1 + \frac{2}{V_{ud}} [r'_{11k}(\tilde{d}^k_R) - r'_{21k}(\tilde{d}^k_R)] \right] . \quad (12)$$

The experimental result of Eq. (11) yields the bounds

$$|\lambda'_{11k}| < 0.05 \left[\frac{m_{\tilde{d}^k_R}}{100\ \text{GeV}} \right] ,$$
$$|\lambda'_{21k}| < 0.09 \left[\frac{m_{\tilde{d}^k_R}}{100\ \text{GeV}} \right] , \quad (13)$$

for each generation index k. Note that the bounds in Eq. (13) are obtained under the assumption that only one of the two terms in Eq. (2) contributes. If both interactions were simultaneously present, the conditions in Eq. (13) would be weakened but then rare processses such as $\pi^0 \to \mu e$ would place even more stringent limits on the couplings. Therefore the bounds in Eq. (13) are valid in general.

The ratio $R_\tau \equiv \Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$ is experimentally measured to be[8]

$$\frac{R_\tau(\text{expt})}{R_\tau(\text{SM})} = 0.994 \pm 0.039 . \quad (14)$$

The $L_L L_L \bar{E}_R$ interaction makes the following contribution to R_τ:

$$R_\tau = R_\tau(\text{SM})\{1 + 2[r_{13k}(\tilde{e}^k_R) - r_{23k}(\tilde{e}^k_R)]\} . \quad (15)$$

The bound obtained from Eq. (14) is

$$|\lambda_{13k}| < 0.10 \left[\frac{m_{\tilde{e}^k_R}}{100\ \text{GeV}} \right] ,$$
$$|\lambda_{23k}| < 0.12 \left[\frac{m_{\tilde{e}^k_R}}{100\ \text{GeV}} \right] . \quad (16)$$

Another measure of the $L_L L_L \bar{E}_R$ interaction comes from the experimental determination[8] of the ratio $R_{\tau\mu} \equiv \Gamma(\tau \to \nu\mu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu})$:

$$\frac{R_{\tau\mu}(\text{expt})}{R_{\tau\mu}(\text{SM})} = 0.938 \pm 0.044 . \quad (17)$$

The R-breaking interactions modify $R_{\tau\mu}$ analogous to Eq. (15) for R_τ with the replacement of r_{13k} and r_{23k} by r_{23k} and r_{12k}, respectively. Equation (17) excludes nonvanishing λ_{23k} at the 1σ level and at the 2σ level,

$$|\lambda_{23k}| < 0.09 \left[\frac{m_{\tilde{e}^k_R}}{100\ \text{GeV}} \right] , \quad (18)$$

but allows λ_{12k} at the 1σ level with the value

$$|\lambda_{12k}| \left[\frac{100\ \text{GeV}}{m_{\tilde{e}^k_R}} \right] = 0.14 \pm 0.05 . \quad (19)$$

Equation (19) seems to give positive evidence for a nonzero value of λ_{12k}. However, more precise measurements are needed in order to confirm this result.

C. $\nu_\mu e$ scattering

The Lagrangian in Eq. (2) modifies neutrino-electron scattering at low energies, as shown in Fig. 2. The scattering cross section in units of $G_\mu^2 s/\pi$, where G_μ is defined in Eq. (4), can be written as

$$\sigma(\nu_\mu e) = g_L^2 + \tfrac{1}{3}g_R^2 , \quad \sigma(\bar{\nu}_\mu e) = \tfrac{1}{3}g_L^2 + g_R^2 . \quad (20)$$

The coefficients g_L and g_R receive extra contributions from the R-breaking interaction as follows:

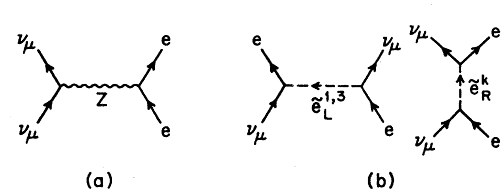

FIG. 2. Feynman diagrams for $\nu_\mu e$ scattering from (a) the standard model, and (b) the R-breaking interactions.

$$g_L = x_W - \tfrac{1}{2} - (1 + x_W - \tfrac{1}{2}) r_{12k}(\tilde{e}_R^k) ,$$
$$g_R = x_W + r_{121}(\tilde{e}_L^1) + r_{231}(\tilde{e}_L^3) - x_W r_{12k}(\tilde{e}_R^k) , \tag{21}$$

where $x_W \equiv \sin^2\theta_W$. The experimentally measured values[9] are

$$|g_L|_{\text{expt}} = 0.315 \pm 0.073 ,$$
$$|g_R|_{\text{expt}} = 0.255 \pm 0.073 . \tag{22}$$

Taking the value $x_W = 0.233 \pm 0.006$ determined from deep-inelastic scattering data,[8] Eq. (22) constrains the R-breaking couplings at the 1σ level to the ranges

$$|\lambda_{12k}| < 0.34 \left[\frac{m_{\tilde{e}_R^k}}{100\ \text{GeV}} \right] ,$$
$$|\lambda_{121}| < 0.29 \left[\frac{m_{\tilde{e}_L^1}}{100\ \text{GeV}} \right] , \tag{23}$$
$$|\lambda_{231}| < 0.26 \left[\frac{m_{\tilde{e}_L^3}}{100\ \text{GeV}} \right] .$$

D. Forward-backward asymmetry in e^+e^- collisions

The forward-backward asymmetry in e^+e^- collisions measures the axial-vector couplings ($A^f \equiv -T_3^f$) of the weak neutral current. From asymmetries in $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-, c\bar{c}, b\bar{b}$ at $\sqrt{s}$ in the range 10–40 GeV, the following results[8] have been obtained:

$$A^e A^\mu = 0.272 \pm 0.015 , \tag{24a}$$
$$A^e A^\tau = 0.232 \pm 0.026 , \tag{24b}$$
$$A^e A^c = -0.330 \pm 0.075 , \tag{24c}$$
$$A^e A^b = 0.270 \pm 0.073 . \tag{24d}$$

The R-breaking interactions modify the standard values of the product of axial-vector couplings according to

$$A^e A^\mu = \tfrac{1}{4} - \tfrac{1}{2} r_{ijk}(\tilde{\nu}), \quad ijk = 121, 122, 132, 231,$$
$$A^e A^\tau = \tfrac{1}{4} - \tfrac{1}{2} r_{ijk}(\tilde{\nu}), \quad ijk = 123, 133, 131, 231, \tag{25}$$
$$A^e A^c = -\tfrac{1}{4} - \tfrac{1}{2} r'_{12k}(\tilde{d}_R^k), \quad A^e A^b = \tfrac{1}{4} - \tfrac{1}{2} r'_{1j3}(\tilde{q}_L^j) .$$

Here we have ignored the modification of R-breaking interaction from $\tilde{e}_R^k$ contributions to G_μ given in Eq. (4), under the presumption that there are no accidental cancellations between $\tilde{e}_R$ and $\tilde{\nu}$ contributions. Here and henceforth, we drop the unnecessary subscript L for $\tilde{\nu}$.

Since the experimental result (24a) already exceeds the SM value of $A^e A^\mu = \frac{1}{4}$ and the R-breaking effect tends to decrease the SM result for $A^e A^\mu$, nonzero λ_{ijk} ($ijk = 121, 122, 132, 231$) are excluded at the 1σ level, and at the 2σ level,

$$|\lambda_{ijk}| < 0.10 \left[\frac{m_{\tilde{\nu}}}{100\ \text{GeV}} \right] . \tag{26}$$

From Eqs. (24b)–(24d) of τ, c, and b asymmetry data, we obtain the limits

$$|\lambda_{ijk}| < 0.24 \left[\frac{m_{\tilde{\nu}}}{100\ \text{GeV}} \right], \quad ijk = 123, 133, 131, 231 ,$$
$$|\lambda'_{12k}| < 0.45 \left[\frac{m_{\tilde{d}_R^k}}{100\ \text{GeV}} \right] , \tag{27}$$
$$|\lambda'_{1j3}| < 0.26 \left[\frac{m_{\tilde{q}_L^j}}{100\ \text{GeV}} \right] .$$

We note that the recent KEK TRISTAN data[10] give

$$A^e A^\mu = 0.26 \pm 0.08 , \quad A^e A^\tau = 0.32 \pm 0.09 . \tag{28}$$

One cannot set any stringent limits on λ_{ijk} from this data since the experimental errors are still rather large.

E. Atomic parity violation

The atomic parity violation and polarized eD asymmetry experiments measure the parity-violating coupling in the electron-hadron interactions, as defined in Ref. 8:

$$c_1(u) = -0.249 \pm 0.071 ,$$
$$c_1(d) = 0.381 \pm 0.064 , \tag{29}$$
$$c_2(u) - \tfrac{1}{2} c_2(d) = 0.19 \pm 0.37 .$$

Including R-breaking interactions, we obtain

$$c_1(u) = -\tfrac{1}{2} + \tfrac{4}{3} x_W - r'_{11k}(\tilde{d}_R^k) + (\tfrac{1}{2} - \tfrac{4}{3} x_W) r_{12k}(\tilde{e}_R^k) ,$$
$$c_2(u) = -\tfrac{1}{2} + 2x_W - r'_{11k}(\tilde{d}_R^k) + (\tfrac{1}{2} - 2x_W) r_{12k}(\tilde{e}_R^k) ,$$
$$c_1(d) = \tfrac{1}{2} - \tfrac{2}{3} x_W + r'_{1j1}(\tilde{q}_L^j) - (\tfrac{1}{2} - \tfrac{2}{3} x_W) r_{12k}(\tilde{e}_R^k) , \tag{30}$$
$$c_2(d) = \tfrac{1}{2} - 2x_W - r'_{1j1}(\tilde{q}_L^j) - (\tfrac{1}{2} - 2x_W) r_{12k}(\tilde{e}_R^k) .$$

Taking into account the effects of the radiative corrections, we obtain the 1σ bounds

$$|\lambda'_{11k}| < 0.30 \left[\frac{m_{\tilde{d}_R^k}}{100\ \text{GeV}} \right] ,$$
$$|\lambda'_{1j1}| < 0.26 \left[\frac{m_{\tilde{q}_L^j}}{100\ \text{GeV}} \right] . \tag{31}$$

The bounds on λ_{12k} from Eq. (30) are not as stringent as that of Eq. (9); therefore, we do not list them.

F. ν_μ deep-inelastic scattering

The ν_μ deep-inelastic scattering results provide a measurement of the vector and axial-vector couplings of the hadronic neutral current in neutrino interactions. The experimental results[8] yield

$$g_L^d = -0.429 \pm 0.014 , \tag{32a}$$
$$g_R^d = -0.011^{+0.081}_{-0.057} . \tag{32b}$$

Including R-breaking interactions, the theoretical prediction is

$$g_L^d = -\tfrac{1}{2} + \tfrac{1}{3} x_W - r'_{21k}(\tilde{d}_R^k) + (\tfrac{1}{2} - \tfrac{1}{3} x_W) r_{12k}(\tilde{e}_R^k) ,$$
$$g_R^d = \tfrac{1}{3} x_W + r'_{2j1}(\tilde{d}_L^j) - \tfrac{1}{3} x_W r_{12k}(\tilde{e}_R^k) . \tag{33}$$

TABLE I. The 1σ limits on the R-breaking couplings λ and λ' of Eqs. (2) in units of $(m_{\tilde{f}}/100\ \text{GeV})$, where $m_{\tilde{f}}$ is the appropriate sfermion mass, from (a) charged-current universality; (b) $\Gamma(\pi\to e\nu)/\Gamma(\pi\to\mu\nu)$; (c) $\Gamma(\tau\to e\nu\bar{\nu})/\Gamma(\tau\to\mu\nu\bar{\nu})$; (d) $\Gamma(\tau\to\mu\nu\bar{\nu})/\Gamma(\mu\to e\nu\bar{\nu})$; (e) $\nu_\mu e$ scattering; (f) forward-backward asymmetry in e^+e^- collisions; (g) atomic parity violation and eD asymmetry; (h) ν_μ deep-inelastic scattering. The superscript X denotes that the corresponding number is at the 2σ level, and is excluded at the 1σ level. Case (d) may indicate positive evidence for R breaking, denoted by an asterisk in the table, with λ_{ijk} values of (0.14 ± 0.05).

ijk	$\lambda_{ijk}<$	ijk	$\lambda'_{ijk}<$
121	$0.10^{(f)X}0.04^{(a)}0.29^{(e)}$ *	111	$0.03^{(a)X}0.05^{(b)}0.26^{(g)}0.30^{(g)}$
122	$0.10^{(f)X}0.04^{(a)}0.34^{(e)}$ *	112	$0.03^{(a)X}0.05^{(b)}0.30^{(g)}$
123	$0.04^{(a)}0.34^{(e)}0.24^{(f)}$ *	113	$0.03^{(a)X}0.05^{(b)}0.26^{(f)}0.30^{(g)}$
131	$0.10^{(c)}0.24^{(f)}$	211	$0.22^{(h)X}0.09^{(b)}0.11^{(h)}$
132	$0.10^{(f)X}0.10^{(c)}$	212	$0.09^{(b)}0.11^{(h)}$
133	$0.10^{(c)}0.24^{(f)}$	213	$0.09^{(b)}0.11^{(h)}$
231	$0.09^{(d)X}0.10^{(f)X}0.26^{(e)}0.12^{(c)}0.24^{(f)}$	121	$0.26^{(g)}0.45^{(f)}$
232	$0.09^{(d)X}0.12^{(c)}$	122	$0.45^{(f)}$
233	$0.09^{(d)X}0.12^{(c)}$	123	$0.26^{(f)}0.45^{(f)}$
		133	$0.26^{(f)}$
		221	$0.22^{(h)X}$
		231	$0.22^{(h)X}$
		131	$0.26^{(g)}$

No deviation from the SM result is predicted for the corresponding up-quark parameters in neutrino deep-inelastic scatterings. Equation (32a) leads to the 1σ limit

$$|\lambda'_{21k}|<0.11\left[\frac{m_{\tilde{d}_R^k}}{100\ \text{GeV}}\right], \tag{34a}$$

and Eq. (32b) excludes nonzero λ'_{2j1} at the 1σ level, but at the 2σ level

$$|\lambda'_{2j1}|<0.22\left[\frac{m_{\tilde{d}_L^j}}{100\ \text{GeV}}\right]. \tag{34b}$$

G. Summary of limits

In Table I we summarize the limits of R-breaking interactions obtained in this section. From the results of Table I we conclude that R-breaking interactions of Eq. (1), if present at all, are generally constrained to be much weaker than the ordinary electroweak interactions.

Before ending this section, two remarks are in order. First, the recent measurements[11] for Bhabha scattering at TRISTAN have set strong bounds on the composite mass scale, $\Lambda>3.3$ TeV for the $V\otimes V$ or $A\otimes A$ interaction. At first sight, one would expect a strong limit on the R-breaking coupling λ from this result, since the effective four-fermion interactions of Eq. (3) are of the same form as the composite fermion interactions.[12] Unfortunately, the above bound was obtained by assuming that only one interaction of $V\otimes V$ or $A\otimes A$ exists at a time, while the third term of Eq. (3) predicts the combination $V\otimes V-A\otimes A$. The simultaneous existence of the $V\otimes V$ and $A\otimes A$ with a relative minus sign tends to reduce the R-breaking contributions, and therefore we can only obtain a rather weak constraint, $|\lambda_{1j1}|<0.5(m_{\tilde{\nu}^j}/100\ \text{GeV})$ for $m_{\tilde{\nu}^j}\gg\sqrt{s}$. Second, we have been discussing the models with R-breaking interactions which only violate L. R-breaking interactions with B violation would be in general much less constrained than the case of L violation because of the larger measurement uncertainties of low-energy hadron processes.

III. POSSIBILITIES FOR DETECTION OF R-BREAKING SIGNALS AT COLLIDERS

In this section, we discuss the possible detection of R-breaking signals in collider experiments resulting from the $L_L L_L \bar{E}_R$ interactions. We have seen that R-breaking interactions of Eq. (1) are generally smaller than the usual electroweak interactions. Consequently, supersymmetric particles will be produced and will decay predominantly via ordinary (R-conserving) SUSY modes, except for the lightest supersymmetric particle (the lightest neutralino in our assumption), which would be stable if there are no R-breaking interactions. In Sec. III A we discuss the decays of the lightest neutralino (χ_1^0) and the lighter chargino ($\chi_1^\pm$). As a typical example, we evaluate the decay length for χ_1^0 produced via the process $Z\to\chi_1^0\chi_1^0$. In Sec. III B we discuss R-breaking signatures that may occur in W-, Z-, and Higgs-boson decays to neutralinos and charginos which subsequently decay via R-breaking interactions. In Sec. III C, we present expectations for R-breaking signals via $\tilde{\nu}$ resonance production in e^+e^- collisions. With the constraint on λ_{ijk} set in Eq. (26), sneutrino contributions modify the standard-model predictions of the e^+e^- cross sections significantly only when $\sqrt{s}$ is close to $m_{\tilde{\nu}}$; consequently we do not consider virtual sneutrino contributions. In Sec. III D we comment on R-breaking signals from neutralino or chargino pair production in e^+e^- collisions at CERN LEP II energies.

A. Decays of lightest neutralino and chargino

If R-breaking interactions exist, then the LSP χ_1^0 will not be stable and it will decay via the interactions of Eqs. (2). For the $L_L L_L \bar{E}_R$ interactions, χ_1^0 decays exclusively to charged leptons and a neutrino

$$\chi_1^0 \to \nu^i e^j e^k \tag{35}$$

via virtual sleptons. As before, the i,j,k are the generation indices. The charged leptons plus missing energy final states provide a striking signature of R breaking.

The χ_1^+ decays via

$$\chi_1^+ \to \chi_1^0 W_{\rm vir}^+ \quad \text{with} \quad \chi_1^0 \to \nu^i e^j e^k \quad \text{and} \quad W_{\rm vir}^+ \to f \bar{f}' , \tag{36}$$

which also give a distinct signature of R breaking. Here we assume the usual mass hierarchy $m(\chi_1^+) > m(\chi_1^0)$. The leptonic mode of the virtual W gives final states with three charged leptons with a χ_1^+ branching fraction of 27%.

In Table I we have shown that R-breaking interactions are severely constrained by low-energy experimental data. If coupling strengths of the R-breaking interactions are very small, then the χ_1^0 lifetime could be long enough for it to escape from detection in collider experiments. Consequently, the experimental signals for supersymmetry would then be the same as the usual discussions,[2] with a missing energy signature.

The partial width for the χ_1^0 decay mode of Eq. (35) is of a typical form for a fermion three-body decay

$$\Gamma_{\chi_1^0} = K^2 \frac{G^2 M_{\chi_1^0}^5}{192\pi^3} , \tag{37}$$

where K is an effective four-fermion coupling in χ_1^0 decays, which is proportional to both the $\chi_1^0 f \tilde{f}$ coupling[2] and the R-breaking coupling λ_{ijk}. For a large region of SUSY parameters,[2] the coupling K is ~ 0.1 $(100\ \text{GeV}/m_{\tilde{f}})^2 \lambda_{ijk}$, where $m_{\tilde{f}}$ is the mass of the virtual selectron or sneutrino exchange.

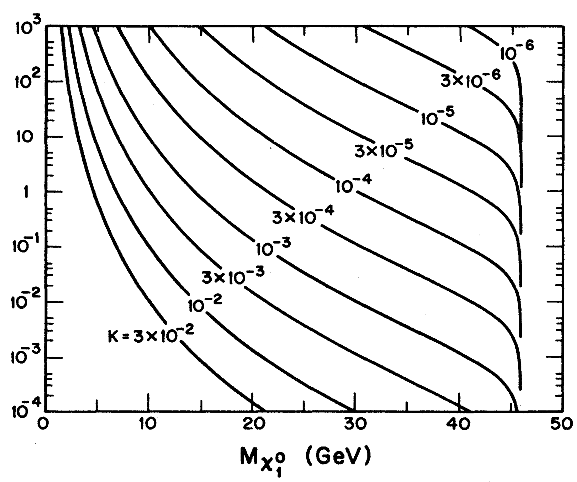

FIG. 3. The LSP χ_1^0 decay length vs its mass, evaluated in the Z rest frame for the process $Z \to \chi_1^0 \chi_1^0$ at various K values; see Eq. (37).

Figure 3 shows the χ_1^0 decay length versus its mass $M_{\chi_1^0}$ for production via $Z \to \chi_1^0 \chi_1^0$ in the Z rest frame, for various K values. For a large region of K parameter and $M_{\chi_1^0}$ values, the decay length has a value between 10^{-2} and 10 cm, which is the accessible range for a secondary vertex search at the SLAC Linear Collider (SLC) or LEP (Ref. 13). Therefore, even if the R-breaking couplings are very weak $(\lambda \sim 10^{-2})$, it is still feasible to search for χ_1^0 decays using secondary vertex detectors, provided that the sfermions are not too heavy ($\lesssim 1$ TeV).

B. Z-, W-, and Higgs-boson decays to neutralinos and charginos

In the near future large samples of Z- and W-boson events will be accumulated at e^+e^- and $p\bar{p}$ colliders. From the four LEP I detectors about 8×10^6 Z bosons are expected per year. From the CERN ACOL collider 2×10^4 Z and 6×10^4 W bosons will be produced with 10-pb^{-1} integrated luminosity. With this luminosity the Fermilab Tevatron will produce about 6×10^4 Z and 20×10^4 W bosons. Thus it may soon be possible to study rare decay modes of the Z and W bosons involving neutralinos and charginos, if the latter decay modes are kinematically accessible.

In the minimal supergravity model the masses of χ_1^0 and $\chi_1^\pm$ are typically below M_W and the decays[14]

$$Z^0 \to \chi_1^0 \chi_1^0,\ \chi_1^+ \chi_1^-, \quad W^\pm \to \chi_1^\pm \chi_1^0 , \tag{38}$$

may be realized. The branching fractions for these modes depend on supersymmetry parameters, as outlined further below, and can be sizable. For example, values up to $B(Z^0 \to \chi_1^0 \chi_1^0) \sim 5\%$, $B(Z \to \chi_1^+ \chi_1^-) \sim 15\%$, and $B(W \to \chi_1^\pm \chi_1^0) \sim 10\%$ are possible. Thus these weak boson decays are interesting for their potential in searches for R-breaking interactions.

We now give a quantitative evaluation of the decay distributions of final-state leptons and quarks from these R-breaking decays of Z and W bosons. The general coupling of a weak boson V to particles χ and χ' is of the form[2]

$$\mathcal{L} = V_\mu g \bar{\chi} \gamma^\mu (G_L P_L + G_R P_R) \chi' , \tag{39}$$

where g is the SU(2) weak coupling, $P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$ are chirality projection operators, and $G_{L,R}$ are given in terms of the elements of the mixing matrices (a 4×4 matrix N in the neutralino sector and two 2×2 matrices U and V in the chargino sector) that diagonalize the mass matrices. Following the notation of Ref. 2, the $G_{L,R}$ are given by

$$G_L=-G_R=-\frac{1}{2\cos\theta_W}(|N_{13}|^2-|N_{14}|^2)$$
$$\text{for } V=Z,\ \chi=\chi_1^0\ ,$$
$$G_L=-\frac{1}{\cos\theta_W}(|V_{11}|^2+\tfrac{1}{2}|V_{12}|^2-x_W)$$
$$\text{for } V=Z,\ \chi=\chi^+\ ,$$
$$G_R=-\frac{1}{\cos\theta_W}(|U_{11}|^2+\tfrac{1}{2}|U_{12}|^2-x_W)\ ,$$
$$G_L=-\frac{N_{14}}{\sqrt{2}}V_{12}^*+N_{12}V_{11}^*\ ,$$
$$G_R=\frac{N_{13}^*}{\sqrt{2}}U_{12}+N_{12}^*U_{11}\quad\text{for } V=W\ . \tag{40}$$

The Z or W partial widths are given by

$$d\Gamma=\left[\frac{d_2PS}{2M_V}\right]\left[\frac{d_3PS}{2M_\chi\Gamma_\chi}\right]\left[\frac{d_3PS'}{2M_{\chi'}\Gamma_{\chi'}}\right]\Sigma|\mathcal{M}|^2\ , \tag{41}$$

where $d_nPS=(2\pi)^{4-3n}\delta^4(P_i-P_f)\prod_{j=1}^{n}d^3p_j/2E_j$ denotes the phase-space factors of the sequential decays and $\mathcal{M}$ is the reduced matrix element:

$$\mathcal{M}=32K_1K_2\bar{u}(p_1)P_{\tau_1}v(p_2)\bar{u}(p_3)P_{\tau_2}v(p_4)\bar{u}(f_1)$$
$$\times(G_R\not{\chi}_1\not{\epsilon}_\alpha\not{\chi}_2-m_{\chi_1}m_{\chi_2}G_L\not{\epsilon}_\alpha)P_Lv(f_2)\ . \tag{42}$$

Here K_1 and K_2 are the effective four-fermion couplings in χ decays, as defined in Eq. (37).

To give some typical quantitative results, we evaluate the simplest and likely the most significant case $Z\to\chi_1^0\chi_1^0$. In the usual SUSY models with R-parity conservation, this decay mode gives a missing energy signature just like $Z\to\nu\bar{\nu}$. However, with R-breaking interactions under consideration here, the decay of $Z\to\chi_1^0\chi_1^0$ gives typically four charged leptons plus missing energy resulting from escaping neutrinos.

In the following discussion, we choose two representative sets of SUSY parameters:

$$\text{(a) } M=200\text{ GeV},\quad \mu=80\text{ GeV},\quad v_2/v_1=2\ ;$$
$$\text{(b) } M=80\text{ GeV},\quad \mu=150\text{ GeV},\quad v_2/v_1=2\ . \tag{43}$$

Here M and μ are, respectively, the gaugino mass parameter and Higgs-fields mixing parameter renormalized at the weak scale, and v_1 and v_2 the vacuum expectation values of the two Higgs doublets.[2] These fix the masses of the LSP χ_1^0 and the lighter chargino χ_1^+, respectively, to be 25 and 45 GeV in (a) and 12 and 34 GeV in (b).

The branching fractions of Z to four charged leptons plus missing energy for these two choices are (a) 1.7% and (b) 0.27%, which would lead to a large sample of events to test the possible existence of R-breaking interactions. Calculated $p_T(l)$, $E(l)$, and missing energy $\not{E}$ distributions in the Z rest frame for this decay mode are shown in Fig. 4. The shapes of the distributions are not sensitive to the parameter choices.

In the cases of $Z\to\chi_i^0\chi_j^0$ $(i\neq j)$, $\chi_1^+\chi_1^-$ and $W^\pm\to\chi_1^\pm\chi_1^0$, the heavier neutralinos and charginos usually decay to χ_1^0 first, and consequently there would be at least four charged leptons plus missing energy along with hadrons or more charged leptons in the events.

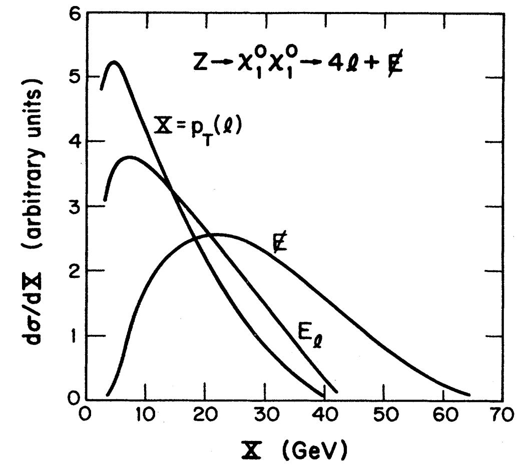

FIG. 4. Typical dynamical distributions of the energy and transverse momentum of averaged charged lepton $[E(l),p_T(l)]$, the missing energy ($\not{E}$), for the R-breaking decay of χ_1^0 from $Z\to\chi_1^0\chi_1^0$ in the Z rest frame.

Next we discuss the Higgs-boson decay signatures with the existence of the R-breaking interactions. In the minimal SUSY model, there exist five physical Higgs bosons, leading to very rich phenomenological signatures.[15] Among the five Higgs bosons, a neutral scalar H_1^0 is heavier than the Z and another neutral scalar H_2^0, which is the analogue to the one in the standard model, is lighter than the Z; the two charged Higgs bosons $H^\pm$ are heavier than the W, while the neutral pseudoscalar H_3^0 is lighter than $H^\pm$ but heavier than H_2^0. In the minimal SUSY model, all these Higgs bosons decay to the supersymmetric particles with significant branching fractions in a large region of the SUSY parameter space,[16] when the final states are kinematically accessible. These modes usually lead to events with charged leptons or hadrons from virtual W,Z decays plus large missing energy from the stable LSP χ_1^0. In some region of the parameter space, the neutral Higgs bosons can decay to $\chi_1^0\chi_1^0$ with a branching fraction of 90%, leading to the "invisible events."[17] With R-breaking interactions, the Higgs-boson signatures would be more spectacular. Instead of simply giving missing energy, the χ_1^0 manifests itself as two charged leptons plus missing energy. As an important consequence, the "invisible events" expected from $H_i^0\to\chi_1^0\chi_1^0$ would instead show up as events with four charged leptons and some missing energy from the associated neutrinos. All these $H_i\to\chi_j\chi_k$ events with multiple charged leptons and hadrons plus missing energy would provide distinctive signatures for Higgs-boson searches.

C. Sneutrino resonance production in e^+e^- collisions

In Sec. II we have concentrated on the low-energy constraints on R-breaking interactions with the assumption

$m_{\tilde{f}} \gg \sqrt{s}$. In this section we study the expectations of signals from $\tilde{\nu}$ resonance production and decay in e^+e^- collisions.

The partial width for the decay channels $\tilde{\nu}^j \to \chi_i^0 \nu_k, \chi_i^{\pm} l_k^{\mp}$ is of the form

$$\Gamma(\tilde{\nu}^j \to \chi_i^0 \nu_k, \chi_i^{\pm} l_k^{\mp}) = C \frac{g^2}{16\pi} m_{\tilde{\nu}^j} (1 - M_{\chi_i}^2 / m_{\tilde{\nu}^j}^2)^2 , \quad (44)$$

where $C = |V_{i1}|^2$ for chargino-plus-charged-lepton modes and $C = |N_{i2}|^2 / 2\cos^2\theta_W$ for neutralino-plus-neutrino modes with V_{i1} and N_{i2} the mixing matrix elements introduced in Sec. III B. M_{χ_i} is the corresponding chargino or neutralino mass. The $\tilde{\nu}$ partial width via the interaction Eq. (2) is

$$\Gamma(ee) \equiv \Gamma(\tilde{\nu}^j \to e^i e^k) = \frac{\lambda_{ijk}^2}{16\pi} m_{\tilde{\nu}^j} . \quad (45)$$

For reasonable values of the λ_{ijk} ($\lesssim 0.1$) and most of the region of SUSY parameter space, the decay modes of Eq. (44) are the dominant contributions to the $\tilde{\nu}$ total width, if kinematically accessible, as we shall assume to be the case.

Figure 5 shows the $\tilde{\nu}$ total width versus its mass, again using the two sets of parameter choices in Eq. (43) denoted by solid and dashed curves, respectively. The partial width for $\tilde{\nu}^j \to e^i e^k$ is also shown in this figure by the dotted curve [in units of $(\lambda_{1j1}/0.1)^2$ GeV]. For $m_{\tilde{\nu}} > 80$ GeV, we find $\Gamma_{\tilde{\nu}} > 100$ MeV, which is comparable to or greater than the typical expected experimental resolutions.

For an s-channel $\tilde{\nu}$ production in e^+e^- collisions, the cross section can be expressed as

$$\sigma(e^+e^- \to \tilde{\nu} \to X) = \frac{4\pi s}{m_{\tilde{\nu}}^2} \frac{\Gamma(ee)\Gamma(X)}{(s - m_{\tilde{\nu}}^2)^2 + m_{\tilde{\nu}}^2 \Gamma_{\tilde{\nu}}^2} , \quad (46)$$

where $\Gamma(X)$ generically denotes the partial width for $\tilde{\nu}$ decay to a final state X, such as those of Eqs. (44) and (45); $\Gamma_{\tilde{\nu}}$ is $\tilde{\nu}$ total width. At $\tilde{\nu}$ resonance, Eq. (46) can also be written as

$$\sigma(e^+e^- \to \tilde{\nu} \to X) = \frac{4\pi}{m_{\tilde{\nu}}^2} B(ee) B(X) , \quad (47)$$

where $B(X)$ is the branching fraction of $\tilde{\nu}$ decay to a final state X.

Figure 6 shows the calculated cross sections for $\tilde{\nu}^j \to \chi_i^0 \nu_k, \chi_i^{\pm} l_k^{\mp}$ in e^+e^- collisions at $\sqrt{s} = m_{\tilde{\nu}}$ in units of the QED point cross section, $\sigma_{pt} = 4\pi\alpha^2/(3s)$. If the χ_1^0 has an observable decay length, the final states contain at least two charged leptons with some missing energy from escaping neutrinos and the signature is spectacular.

For a narrow resonance with a total width close to the experimental resolution, as may be the case for $m_{\tilde{\nu}}$ resonance production under consideration here, it is relevant to calculate the total cross sections integrated over the resonance. Integrating Eq. (46) over $\sqrt{s}$ using the narrow-width approximation, we have

$$I \equiv \int d\sqrt{s}\, \sigma = 2\pi^2 \frac{\Gamma(ee)\Gamma(X)}{m_{\tilde{\nu}^j}^2 \Gamma_{\tilde{\nu}^j}} . \quad (48)$$

The integrated cross sections I are given on the vertical axis on the right-hand side of Fig. 5. The solid and dashed curves again correspond to the I values for Bhabha scattering with SUSY parameter sets (a) and (b), respectively; the dotted curve gives the one for $\tilde{\nu}^j \to \chi_i^0 \nu_k, \chi_i^{\pm} l_k^{\mp}$. For comparison, the J/ψ resonance gives an I value of about 0.7 nb GeV.

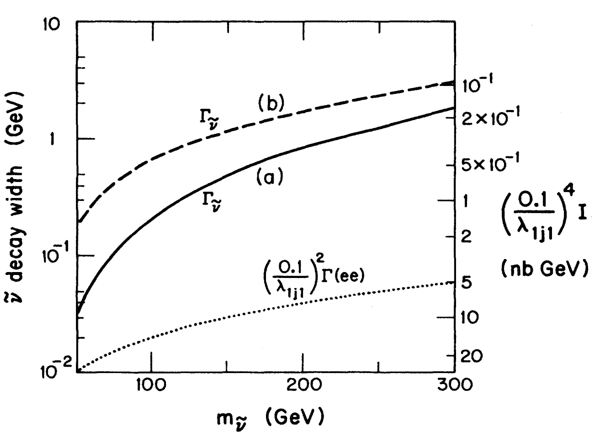

FIG. 5. the $\tilde{\nu}$ total width vs its mass for the two sets of SUSY parameters in Eq. (43), labeled by a solid curve for case (a) and a dashed curve for case (b), respectively; the dotted curve gives the partial width for $\tilde{\nu}^j \to e^i e^k$ in units of $(\lambda_{1j1}/0.1)^2$. The integrated resonance cross sections I of Eq. (48) are also shown on the vertical axis on the right-hand side, where the solid, dashed, and dotted curves again correspond to the I values of Bhabha scattering with SUSY parameters set (a) and (b), and of the processes $\tilde{\nu}^j \to \chi_i^0 \nu_k, \chi_i^{\pm} l_k^{\mp}$, respectively.

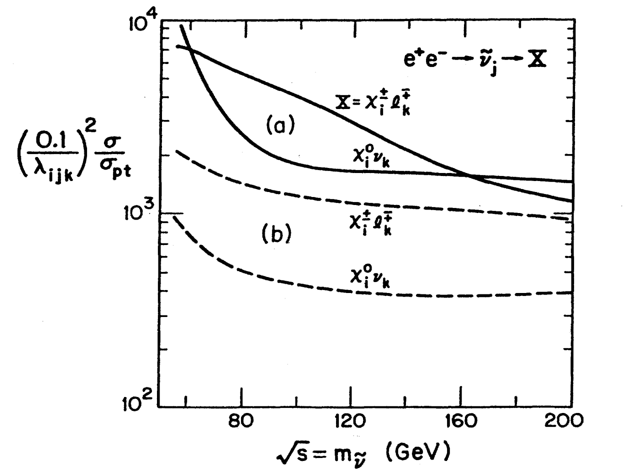

FIG. 6. The $\tilde{\nu}$ resonance cross sections for $\tilde{\nu}^i \to \chi_i^0 \nu_k, \chi_i^{\pm} l_k^{\mp}$ in e^+e^- collisions at $\sqrt{s} = m_{\tilde{\nu}}$ units of the QED point cross section $\sigma_{6pt} = 4\pi\alpha^2/(3s)$, for the two sets of SUSY parameters in Eq. (43), denoted by solid curves for case (a) and dashed curves for case (b), respectively.

Recent measurements on Bhabha scattering at TRISTAN are in good agreement with the SM predictions.[11] Considering the R-breaking contribution of Eq. (47) to Bhabha scattering and allowing 10% deviation from the SM prediction, we find that a sneutrino with a mass of 50–56 GeV is excluded for $B(ee) > 4.5\times10^{-2}$. This constraint on $B(ee)$ corresponds to (a) $|\lambda_{1j1}| \lesssim 4\times10^{-2}$ and (b) $|\lambda_{1j1}| \lesssim 0.1$, respectively, for our SUSY parameter choices of Eq. (43).

There are also no reports of events being observed at TRISTAN with two or more charged leptons plus missing energy. If we conservatively assume that there are less than 10 events for $e^+e^- \to \tilde{\nu} \to \chi^0\nu, \chi^\pm l^\mp$ with an integrated luminosity[11] 14 pb^{-1} in the AMY detector, then we exclude a sneutrino with mass in the range 50–56 GeV having $B(ee)B(\chi^0\nu,\chi^\pm l^\mp) > 2.3\times10^{-6}$. For most of the SUSY parameter space, $B(\chi^0\nu,\chi^\pm l^\mp) \simeq 1$. Therefore, we have $B(ee) \lesssim 2.3\times10^{-6}$, which corresponds to (a) $|\lambda_{1j1}| \lesssim 3\times10^{-4}$ and (b) $|\lambda_{1j1}| \lesssim 7\times10^{-4}$, respectively, for the SUSY parameter choices of Eq. (43). In this calculation, we have imposed a pseudorapidity cut on the outgoing charged leptons, $|\eta_l| < 0.93$, to simulate the AMY-detector acceptance, and require the missing energy to be larger than 5 GeV. The severe limits obtained here on λ_{1j1} are under the assumption of resonance $\tilde{\nu}$ production (i.e., $m_{\tilde{\nu}} = E_{cm}$), while the limits discussed earlier assumed $m_{\tilde{f}}$ much larger than the available energy.

Similar measurements at LEP II will easily find $\tilde{\nu}$ signals, or set more stringent limit on sneutrino mass or on the branching fractions of R-breaking decays of $\tilde{\nu}$ resonance.

D. Neutralino and chargino pair production in e^+e^- collisions

Neutralino and chargino pair productions in e^+e^- collisions provide excellent signals for SUSY searches.[18] As discussed in Sec. III B, there may be copious numbers of events at the Z resonance to study the R-breaking decays of χ's. Moreover, for energies far above the Z resonance, the cross sections for neutralino and chargino pair productions are of order 0.1–1 pb for a broad region of SUSY parameter space.[18] These cross sections correspond to 10–100 events per year at the LEP II luminosity. Since R-breaking interactions greatly change the neutralino and chargino signatures (especially for the $\chi_1^0\chi_1^0$ case) and lead to spectacular events with multiple charged leptons in the final states, it should be possible to continue the search for $\chi_i\chi_j$ production with R-breaking decays at energies above the Z resonance.

IV. CONCLUSIONS

We have investigated the phenomenology of some new aspects of R-parity violation interactions in the minimal supergravity model. From the present experimental data, stringent limits on couplings of R-breaking interactions of Eqs. (2) are obtained from low-energy data; the coupling strengths are much smaller than those of the ordinary weak interactions if the sfermions have masses of order 100 GeV. The results are summarized in Table I.

Possible R-breaking signals in future high-energy collider experiments from the $L_L L_L \bar{E}_R$ interaction have been studied. For a large region of SUSY parameter and R-breaking couplings λ, we find that it is feasible to observe the LSP decay using secondary vertex detectors. The branching fractions of W,Z decays to a neutralino or chargino pair can be of a few percent in certain regions of the SUSY parameter space. The final-state signature of the LSP decays is quite spectacular: multiple charged leptons plus substantial missing energy. It is therefore promising to search for R-breaking signals in W,Z decays since these weak bosons are produced copiously in collider experiments.

In the minimal SUSY model, it has been argued that the neutral Higgs boson may decay to $\chi_1^0\chi_1^0$ dominantly in a large region of the SUSY parameter space. If R-breaking interactions are present, then instead of simply giving missing energy, the $H \to \chi_1^0\chi_1^0$ mode would lead to distinctive four-charged-leptons-plus-missing-energy final states.

The production of a $\tilde{\nu}$ resonance in e^+e^- collisions could provide clean signals of R-breaking interactions. For 60 GeV $< m_{\tilde{\nu}} < M_Z$ $\tilde{\nu}$ resonance production could be observed in Bhabha scattering if $B(\tilde{\nu} \to e^+e^-) \gtrsim 10^{-2}$ and for $m_{\tilde{\nu}} > M_Z$ if $B(\tilde{\nu} \to e^+e^-) \gtrsim 10^{-3}$. The dominant $\tilde{\nu}$ decay modes $\tilde{\nu}_j \to \chi_i^\pm l_k^\mp, \chi_i^0\nu_k$ would give a much larger signal rate than Bhabha scattering and lead to final states with at least two charged leptons plus missing energy. Neutralino and chargino pair productions in e^+e^- collisions at energies well above the Z resonance could also provide spectacular signals from χ_1^0 decays via R-breaking interactions.

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