Fermi National Accelerator Laboratory

FERMILAB-Conf-89/167-T

August, 1989

R-PARITY BREAKING IN LOW ENERGY SUPERGRAVITY MODELS*

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Abstract

The existence of R-parity violating interactions in supersymmetric models leads to various rare processes at low energies, deviations from the standard model predictions on weak interactions and new signals in collider experiments. The present limits on R-violating couplings in the minimal low energy supergravity model are derived. The effects of R-parity violation on the experimental search for supersymmetry are also briefly discussed.

*Talk given at the XII Warsaw Symposium on Elementary Particle Physics, Kazimierz, Poland, May 29 - June 2, 1989.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

I. R-Parity Violation

Violations of baryon (B) and lepton (L) number in elementary particle interactions can play an important role in nature, providing an explanation for the cosmic baryon asymmetry, for non-vanishing neutrino masses and for some rare processes. An understanding of B and L violation requires necessarily new physics beyond the Standard Model (SM). In fact, aside from possible non-perturbative effects, the SM interactions conserve automatically B and L, once gauge invariance is imposed. This is no longer true in the minimal supersymmetric extension of the SM[1)], where B and L are not accidental symmetries of the Lagrangian. Nevertheless, B and L are related to the R-parity,[2)] defined as

$$R \equiv (-)^{3B+L+2S} \tag{1.1}$$

for a particle with baryon number B, lepton number L and spin S. In the minimal supersymmetric extension of the SM, R is conserved if and only if B and L are both conserved. Moreover, the R-parity has a precise physical meaning: it is even for all SM particles and odd for their supersymmetric partners. R-parity conservation implies that the lightest supersymmetric particle (LSP) is stable, thus leading to "missing energy" as characteristic signature in collider experiments and providing an attractive explanation for the dark matter in galactic halos. However, the requirement of B and L conservation does not seem, at this stage, deeply motivated, and the study of low energy supergravity models with R-parity breaking deserves attention[†].

A first option is to start with the minimal supersymmetric model and allow spontaneous R-parity breaking through a non-vanishing sneutrino vacuum expectation value, $< \tilde{\nu} >$. This is possible, although rather difficult to achieve in the minimal model[4)], and generally leads to the prediction of light sleptons, close to the present experimental bounds. Moreover, the spontaneous breaking of L yields a massless Goldstone boson, the Majoron, which has an axial coupling to fermions (f) of order

[†] Phenomenological consequences of R-parity breaking have been studied in refs. 3-7.

$G_F m_f < \tilde{\nu} >$. The requirement that helium ignition occurs in stars limits the energy loss via Majorons and therefore implies that their axial coupling to electrons should be smaller than 10^{13} (see ref. 8). Consequently, this leads to $< \tilde{\nu} > \lesssim 20\ KeV$. This unnaturally small vacuum expectation value, seven orders of magnitude smaller than the Fermi scale, is very unattractive. In order to give mass to the dangerous massless Majoron, one is lead to introduce explicit L violation. Therefore, let us consider the general structure of the R–parity (and consequently of L, B) breaking.

With the minimal choice of superfields consistent with the SM, the following R–violating gauge invariant interactions can be introduced in a renormalizable superpotential:

$$\lambda_{ijk}\, L_L^i\, L_L^j\, \overline{E}_R^k, \quad \lambda'_{ijk}\, L_L^i\, Q_L^j\, \overline{D}_R^k, \quad m_i\, L_L^i\, H, \quad \rho_{ijk}\, \overline{U}_R^i\, \overline{D}_R^j\, \overline{D}_R^k \qquad (1.2)$$

Following the standard notation, $L_L, Q_L, \overline{E}_R, \overline{D}_R$ and $\overline{U}_R$ denote the chiral superfields containing respectively the left–handed lepton and quark weak doublets and the right–handed charged lepton and quark $SU(2)$ singlets; i, j, k are generation indices. Due to the contraction of the gauge group indices, the coupling constants λ and ρ are antisymmetric in the first two and last two generation indices respectively. Therefore, I will assume λ_{ijk} nonvanishing only for $i < j$ and ρ_{ijk} nonvanishing only for $j < k$. The first three operators in eq. (2) violate L and the last one violates B. In the presence of the trilinear L–violating interactions, the bilinear term mL_LH can be rotated away through a redefinition of L_L and H', where H and H' are the superfields containing the Higgs doublets with hypercharges $+1$ and -1 respectively.

II. Low Energy Constraints on R-Breaking

How large can the R–violating interaction coupling constants λ, λ' and ρ be? First notice that, when R–parity is conserved, supersymmetric particles always appear in pairs at each interaction vertex and new physics contributions to SM low energy processes can occur only at the loop level. This is the reason why the supersymmetric models are generally compatible with low energy phenomenology, even if they introduce a large number of particles with masses below the Fermi scale. One can hope to find reasonable limits on the parameters of the supersymmetric models only from processes which are forbidden at the tree level in the SM, e.g. flavor changing neutral currents (FCNC). This is no longer the case if R-violating couplings are present: supersymmetric particles can now mediate SM processes at tree level.

In order to avoid proton decay, L and B violating interactions cannot be both present. If all supersymmetric particles are heavier than 1 GeV, L conservation will prevent the proton from decaying, even in presence of B violation. If the coupling constants ρ are non-vanishing, λ and λ' should be zero and vice versa. Of course, one should still worry about L-violating or FCNC processes like $K_L^0 \to \mu e$, $\pi^0 \to \mu e$, $\mu \to eee$, $\mu \to e\gamma$, $K^0 - \overline{K}^0$ mixing, etc. For instance, from $\mu \to eee$, one infers a limit on the following combination of coupling constants λ:

$$\lambda_{122}\,\lambda_{121},\ \lambda_{132}\,\lambda_{131},\ \lambda_{231}\,\lambda_{131}\ < 7\cdot 10^{-7}\left(\frac{m_{\tilde{f}}}{100\ GeV}\right)^2 , \tag{2.1}$$

where $m_{\tilde{f}}$ is the mass of the exchanged slepton. Even if the bounds obtained from L-violating and FCNC processes, like eq. (3), are rather stringent, they always involve the products of couplings with different generation indices. Since it is plausible to assume a hierarchy in the R-violating couplings (similar to the case of the SM Yukawa couplings), we are more interested in absolute limits on each different λ, λ' and ρ in eq. (2). Therefore, let us assume that only one interaction in eq. (2) with a single entry ijk in generation indeces is present. At low energy, the effects of the new interaction are best discussed in terms of effective operators. The scalar quark or lepton exchange mediates four-fermion interactions which, in the case of the $L_L L_L \overline{E}_R$ operator, have the form:

$$\mathcal{L}_{eff} \;=\; -\frac{|\lambda_{ijk}|^2}{4}\Bigg[\frac{1}{\widetilde{m}^2_{e_R^{(k)}}}\left(\bar{\ell}_L^{(i)}\,\gamma^\mu\,\vec{\sigma}\,\ell_L^{(i)}\,\bar{\ell}_L^{(j)}\,\gamma_\mu\,\vec{\sigma}\,\ell_L^{(j)} - \bar{\ell}_L^{(i)}\,\gamma^\mu\,\ell_L^{(i)}\,\bar{\ell}_L^{(j)}\,\gamma_\mu\,\ell_L^{(j)}\right) +$$

$$+ \quad 2\left(\frac{1}{\tilde{m}^2_{\ell_L^{(i)}}}\bar{\ell}_L^{(j)}\,\gamma^\mu\,\ell_L^{(j)}\,\bar{e}_R^{(k)}\,\gamma_\mu\,e_R^{(k)} + (i\leftrightarrow j)\right)\Bigg] \tag{2.2}$$

where ℓ_L and e_R are respectively the lepton left-handed doublet and right-handed singlet; $\vec{\sigma}$ are the Pauli matrices. Effective four-fermion interactions analagous to eq. (4) can be derived in the case of the other trilinear operators of eq. (2). Note that the gauge-invariant interactions in eq. (4) conserve L and do not induce FCNC. Even so, the existence of four-fermion interactions beyond the SM in the leptonic and semi-leptonic sectors is constrained by the low energy precise measurements on weak processes. In particular, note that the interactions in eq. (4) break universality of the weak force. The corresponding limits on the R-violating coupling constants λ, λ', in units of $(m_{\tilde{f}}/100\ GeV)$, where $m_{\tilde{f}}$ is the appropriate sfermion mass, are summarized in the following table[7]:

ijk	$\lambda_{ijk} <$	ijk	$\lambda'_{ijk} <$
121	$0.10.^{(f)X}$ $0.04^{(a)}$ $0.08^{(c)}$ *	111	$0.03^{(a)X}$ $0.05^{(b)}$ $0.26^{(g)}$ $0.30^{(g)}$
122	$0.10^{(f)X}$ $0.04^{(a)}$ $0.10^{(e)}$ *	112	$0.03^{(a)X}$ $0.05^{(b)}$ $0.30^{(g)}$
123	$0.04^{(a)}$ $0.15^{(e)}$ $0.24^{(f)}$ *	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	$0.09^{(d)X}$ $0.10^{(f)X}$ $0.08^{(e)}$ $0.11^{(c)}$ $0.24^{(f)}$	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	$0.45^{(f)}$
		133	$0.26^{(f)}$
		221	$0.22^{(h)X}$
		231	$0.22^{(h)X}$
		131	$0.26^{(g)}$

The limits are derived from: (a) quark-lepton weak universality, assuming 3 generations; (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 limits are given at the 1σ level. However, the superscript X indicates that the coupling is excluded at the 1σ level and the limit at the 2σ level is given. Case (d) may indicate positive evidence for R-violation, denoted by * in the table, with λ_{ijk} values of 0.14 ± 0.05. For more details, see ref. 7. It is much more difficult to constraint the coupling constants ρ of eq. (2) from low energy measurements, because of the large uncertainties involved in hadronic processes. This is particularly interesting because the existence of this B-violating interactions could provide ways to generate the cosmic baryon asymmetry at very low temperature[9)].

In the presence of a single R-violating operator, the L or B violation, although absent at the four-fermion interaction level, will appear in effective six-fermion operators. Contributions to neutrino masses and to $n - \bar{n}$ oscillations can be expected. However, no absolute bound on the R-violating interaction can be extracted, since the contribution will generally depend on the trilinear scalar couplings or the squark mixing parameters[3,5)]. From the contribution to neutrinoless double beta decay, one infers[5)]:

$$|\lambda'_{111}| \lesssim 3 \cdot 10^{-3} \left(\frac{\widetilde{m}}{100\ GeV}\right)^{5/2} \tag{2.3}$$

where $\widetilde{m}$ is the typical mass of the exchanged supersymmetric particles.

In conclusion, from leptonic and semi-leptonic processes we can conclude that R-parity breaking interaction with L violations are constrained to be much weaker than the weak force. If several couplings are simultaneously present, the limits are considerably more stringent. R-breaking interaction with B violation are much less constrained. In the next section, the possibility of detecting R-breaking effects is briefly discussed.

III. Signals of R-Breaking

The first drastic difference in the phenomenology of supersymmetric models with R-breaking is the decay of the LSP and therefore the absence of large "missing energy" signals. It is important to note that even very small R-violating couplings would allow the LSP to decay with a rate observable in collider experiments. Unlike the ordinary case, the LSP is not forced to be charge and color neutral by cosmological arguments. In most models a weakly interacting spin 1/2 particle (χ) turns out to be the LSP. Both a neutral or charged χ as LSP will decay into three SM fermions with lifetime of order

$$\tau_{LSP} \simeq \frac{1}{\lambda_R^2} \left(\frac{m_{\tilde{f}}}{100\ GeV}\right)^4 \left(\frac{20\ GeV}{m_\chi}\right)^5 10^{-15}\ sec, \tag{3.1}$$

where λ_R is the relevant R-violating coupling constants ($\lambda_R = \lambda, \lambda', \rho$). The R-violating interaction is testable if the LSP decays inside the detector, i.e.:

$$\lambda_R \gtrsim 5 \cdot 10^{-4} \left(\frac{m_{\tilde{f}}}{100\ GeV}\right)^2 \left(\frac{20\ GeV}{m_\chi}\right)^{5/2} \tag{3.2}$$

Therefore, even coupling constants as small as eq. (7) can give observable effects in the search for supersymmetry. In particular, the range of small couplings λ_R giving rise to decay lengths between 10^{-2} cm and 10 cm could be experimentally very interesting, since the LSP decays would then be accessible for secondary vertex detection at LEP. If a scalar quark or lepton is the LSP, it decays into a pair of SM fermions with lifetime

$$\tau_{LSP} \simeq \frac{1}{\lambda_R^2} \left(\frac{50\ GeV}{\widetilde{m}_{LSP}}\right) 3 \cdot 10^{-18}\ sec \tag{3.3}$$

Now, an observable LSP decay is achieved for R-violating coupling λ_R as small as

$$\lambda_R \gtrsim 3 \cdot 10^{-5} \left(\frac{50\ GeV}{\widetilde{m}_{LSP}}\right)^{1/2} \tag{3.4}$$

If R-breaking is present, the usual supersymmetric experimental signals should be revisited. Depending on the particular LSP decay channel, the new signatures will show characteristic multi-lepton or multi-jet events or even an excess of "missing energy" events, if neutrinos are among the LSP decay products.

The existence of R-violating interactions could also play an interesting role in the processes of supersymmetric particle production. However, unlike the case of the LSP decay, now they have to compete with strong and electroweak interactions. At least in the case of R-breaking with L-violation, the limits prresented in the previous section represent a serious constraint on the observability of new production mechanisms. Nevertheless, some interesting signals from single supersymmetric particle production could still be within reach of future experiments. For instance, there exists the possibility of a "sneutrino resonance" in e^+e^- collisions through the first operator in eq. (2)[6] (see also ref. 7). The cross section at resonance is:

$$\sigma\left(e^+e^- \to \tilde{\nu} \to X\right) = \frac{4\pi}{m_{\tilde{\nu}}^2}\ BR(ee)\,BR(X) \tag{3.5}$$

where $BR(X)$ is the branching ratio for $\tilde{\nu} \to X$. Generally, we expect $\tilde{\nu} \to \chi^0\nu$ or $\tilde{\nu} \to \chi^{\pm}\ell^{\mp}$ to be the dominant channels, both yielding a spectacular signal. If the sneutrino is the LSP, it will decay back into e^+e^-, producing a striking peak in Bhabha scattering.

In conclusion, R-parity breaking can give new insights in the origin of L and B violation, can predict a variety of interesting processes and deviations from SM physics at low energy, and can drastically modify the experimental signals for supersymmetry. Moreover, an understanding of the origin of R-violating interactions and a good explanation for either the smallness or vanishing of the relative coupling constants could introduce new theoretical ideas.

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