Constraints on the R-parity- and lepton-flavor-violating couplings from B^0 decays to two charged leptons

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We derive the upper bounds on certain products of R-parity- and lepton-flavor-violating couplings from the decays of the neutral B meson into two charged leptons. These modes of B^0 decays can constrain the product combinations of the couplings with one or more heavy generation indices. We find that most of these bounds are stronger than the previous ones. [S0556-2821(97)03711-9]

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In the standard model (SM), there are no couplings which violate baryon number B and lepton number L. The failures of experimental searches to find B- and/or L-violating processes show that this feature of the SM is a good one. But one notes that this feature of the SM is not the result of gauge invariance. In the supersymmetric standard models, there are gauge invariant interactions which violate B and L generally. To prevent occurrences of these B- and L-violating interactions in the supersymmetric standard models, an additional global symmetry is required. This requirement leads to the consideration of the so-called R parity. R parity is given by the relation $R_p=(-1)^{(3B+L+2S)}$ where S is the intrinsic spin of a field. According to this definition, R_p of the ordinary SM particles is $+1$ and R_p of the superpartners is -1. Even though the requirement of R_p conservation gives a theory consistent with present experimental searches, there is no good theoretical justification for this requirement. Therefore, the models with explicit R_p violation have been considered by many authors [1]. If we discover a sign of R_p violations in future experiments, it may provide us with some hints of the existence of supersymmetry.

In the model without R_p, the supersymmetric particles can decay into the ordinary particles alone. So the couplings which violate R_p can be detected by using usual particle detectors. To discover the R_p violation in future experiments, we need to know what kinds of couplings are severely constrained by present experimental data. Therefore, it is important to constrain the R_p-violating couplings from the present data, especially data on the processes forbidden or highly suppressed in the SM. Usually, the bounds on the R_p-violating couplings with heavy fields are not stronger than those with at most one heavy field.

In this paper, we try to derive the upper bounds on certain products of R_p- and lepton-flavor-violating couplings from the decays of the neutral B meson into two charged leptons in the minimal supersymmetric standard model (MSSM) with explicit R_p violation. These modes of B^0 decays can constrain the product combinations of the couplings with one or more heavy generation indices. We find that most of these bounds are stronger than the previous ones.

In the MSSM, the most general R_p-violating superpotential is given by

$$W_{\not{R}_p}=\lambda_{ijk}L_iL_jE_k^c+\lambda'_{ijk}L_iQ_jD_k^c+\lambda''_{ijk}U_i^cD_j^cD_k^c. \tag{1}$$

Here i,j,k are generation indices and we assume that possible bilinear terms $\mu_iL_iH_2$ can be rotated away. L_i and Q_i are the SU(2)-doublet lepton and quark superfields, and E_i^c,U_i^c,D_i^c are the singlet superfields, respectively. λ_{ijk} and λ''_{ijk} are antisymmetric under the interchange of the first two and the last two generation indices, respectively; $\lambda_{ijk}=-\lambda_{jik}$ and $\lambda''_{ijk}=-\lambda''_{ikj}$. So the number of couplings is 45 (9 of the λ type, 27 of the λ' type, and 9 of the λ'' type). Among these 45 couplings, 36 couplings are related with the lepton-flavor violation.

The simultaneous presence of the B- and L-violating couplings leads to the squark-mediated proton decay. To avoid a too rapid proton decay we should constrain these couplings very strongly:

$$|\lambda'\cdot\lambda''|\leqslant 10^{-24} \tag{2}$$

for squark masses around 1 TeV [2]. Note that this bound does not affect certain products of couplings with heavy generations at the tree level. Therefore, one can expect the possibility of large R_p-violating couplings with heavy generation indices. But recently, the authors of Ref. [3] studied the one-loop structure. They showed that, choosing whichever pair of couplings λ' and λ'', there is always at least one diagram relevant for the proton decay at one-loop level. This means there are upper bounds on *all* products of λ' and λ'' from the proton decay. The less-suppressed pair of couplings has the bound

$$|\lambda'\cdot\lambda''|\leqslant 10^{-9}. \tag{3}$$

It is known that the bounds from the proton decay are better than those from B-meson decays unless branching ratios of 10^{-8} or better are obtained [4]. To constrain R_p-violating couplings from the B-meson decays, therefore, we should avoid the simultaneous presence of B- and L-violating couplings.

In this paper we assume that B-violating couplings of the λ'' type are vanishing. For example, one can construct a grand unified model which has only lepton number noncon-

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serving trilinear operators in the low-energy superpotential when R_p is broken only by bilinear terms of the form L_iH_2 [5]. We observe that many additional and stronger upper bounds on $\lambda\lambda'$ and $\lambda'\lambda'$ involving heavy generations can be derived from the experimental upper bounds on the pure leptonic decays of the B meson; $B^0\to e^+e^-$ or $e^\pm\mu^\mp$ or $e^\pm\tau^\mp$ or $\mu^\pm\tau^\mp$ or $\mu^+\mu^-$.

The exchange of the sleptons and squarks leads to the four-fermion interactions in the effective Lagrangian at the scale of B-meson mass. Among these four-fermion operators, there is a term relevant for B^0 decays into two charged leptons. This effective term has 2 down-type quarks and 2 charged leptons. From Eq. (1) we obtain

$$\mathcal{L}^{\rm eff}_{2d-2l}=\sum_{n=1}^{3}\frac{2}{m^2_{\tilde{l}_n}}[\lambda^*_{njk}\lambda'_{nlm}(\overline{e_j}P_Re_k)(\overline{d_m}P_Ld_l)+\text{H.c.}]$$
$$-\sum_{n,r,s=1}^{3}\frac{1}{2m^2_{\tilde{Q}_n}}K_{nr}K^*_{ns}\lambda'^*_{jrk}\lambda'_{lsm}(\overline{e_j}\gamma^\mu P_Le_l)$$
$$\times(\overline{d_m}\gamma_\mu P_Rd_k), \tag{4}$$

where K is the Cabibbo-Kobayashi-Maskawa (CKM) matrix and we assume the matrices of the soft mass terms are diagonal.

The effective term $\mathcal{L}^{\rm eff}_{2d-2l}$ is also related with the pure leptonic decay modes of the neutral K meson [6]. From these decays of K^0 meson one can derive upper bounds on $\lambda\lambda'$ between 10^{-7} and 10^{-8}. But for some λ', which include at least one heavy generation index, the product combinations of the $\lambda\lambda'$-type are not constrained from K-meson decays. B-meson decays can constrain certain product combinations of $\lambda\lambda'$-type which are not constrained from K-meson decays. But, the upper bounds from B decays are less stringent than those from K decays since the experimental upper bounds on B-meson decays are weaker than those on K-meson decays.

There are upper bounds on *single* R_p-violating coupling from several different sources [7–10]. Among these, upper bounds from neutrinoless double β decay [8], ν mass [9], and K^+, t-quark decays [10] are strong. Neutrinoless double β decay gives $\lambda'_{111}<4\times10^{-4}$. The bounds from ν mass are $\lambda_{133}<10^{-3}$ and $\lambda'_{133}<10^{-3}$. From K^+-meson decays one obtains $\lambda'_{ijk}<0.012$ for $j=1$ and 2. Here all masses of scalar partners which mediate the processes are assumed to be 100 GeV. Any cosmological bounds can be avoided by assuming the smallest lepton-number-violating coupling λ' is less than 10^{-7} [11]. Fully reviewed and updated limits on single R_p-violating coupling can be found in [12,13].

The measurements of the branching ratios of the B^0-meson decays to two charged leptons give the upper bounds (at 90% C.L.) [14]

$$\mathcal{B}(B_d\to e^+e^-)<5.9\times10^{-6}, \tag{5}$$
$$\mathcal{B}(B_d\to e^\pm\mu^\mp)<5.9\times10^{-6},$$
$$\mathcal{B}(B_d\to e^\pm\tau^\mp)<5.3\times10^{-4},$$
$$\mathcal{B}(B_d\to \mu^\pm\tau^\mp)<8.3\times10^{-4},$$

and [15]

$$\mathcal{B}(B_d\to\mu^+\mu^-)<1.6\times10^{-6},$$
$$\mathcal{B}(B_s\to\mu^+\mu^-)<8.4\times10^{-6}. \tag{6}$$

In the SM, the processes which have different lepton species as decay products are forbidden due to the conservation of each lepton-flavor number. On the other hand, the processes with the same lepton species are highly suppressed; $\mathcal{B}(B_s\to e^+e^-)\simeq(8.0\pm3.5)\times10^{-14}$, $\mathcal{B}(B_s\to\mu^+\mu^-)\simeq(3.5\pm1.0)\times10^{-9}$ [16]. The pure leptonic decays of B_d meson are more suppressed by the smaller CKM angle. So we neglect the SM contributions to the processes under considerations. But in the MSSM under considerations, all processes are possible through $\mathcal{L}^{\rm eff}_{2d-2l}$ at the tree level.

Using the PCAC (partial conservation of axial-vector current) relations

$$\langle 0|\overline{b}\gamma^\mu\gamma_5 q|B_q(p)\rangle=if_{B_q}p^\mu_{B_q},$$
$$\langle 0|\overline{b}\gamma_5 q|B_q(p)\rangle=-if_{B_q}\frac{M^2_{B_q}}{m_b+m_q}\cong-if_{B_q}M_{B_q}, \tag{7}$$

the decay rate of the processes $B_q\to e^-_ie^+_j$ reads

$$\Gamma(B_q\to e^-_ie^+_j)$$
$$=\frac{f^2_{B_q}M^3_{B_q}}{64\pi\tilde{m}^4}\sqrt{1+(\kappa_i^2-\kappa_j^2)^2-2(\kappa_i^2+\kappa_j^2)}$$
$$\times\{(|\mathcal{A}^q_{ij}|^2+|\mathcal{B}^q_{ij}|^2)(1-\kappa_i^2-\kappa_j^2)+|\mathcal{C}^q_{ij}|^2[(\kappa_i^2+\kappa_j^2)$$
$$-(\kappa_i^2-\kappa_j^2)^2]+4\text{Re}(\mathcal{A}^q_{ij}\mathcal{B}^{q*}_{ij})\kappa_i\kappa_j+2\kappa_j\text{Re}(\mathcal{A}^q_{ij}\mathcal{C}^{q*}_{ij})$$
$$\times(1+\kappa_i^2-\kappa_j^2)+2\kappa_i\text{Re}(\mathcal{B}^q_{ij}\mathcal{C}^{q*}_{ij})(1+\kappa_j^2-\kappa_i^2)\}, \tag{8}$$

where $q=1(B_d)$ or $2(B_s)$, $\kappa_i\equiv m_{e_i}/M_{B_q}$. We assume the universal soft mass $\tilde{m}$. M_{B_q} is the mass of B_q meson and f_{B_q} is the usual leptonic decay constant of the B_q meson. The constants $\mathcal{A}^q_{ij}$, $\mathcal{B}^q_{ij}$, and $\mathcal{C}^q_{ij}$ which depend on the generations of leptons and the type of decaying neutral B meson are given by

$$\mathcal{A}^q_{ij}=2\sum_{n=1}^{3}\lambda^*_{nij}\lambda'_{nq3},$$
$$\mathcal{B}^q_{ij}=2\sum_{n=1}^{3}\lambda_{nji}\lambda'^*_{n3q},$$
$$\mathcal{C}^q_{ij}=\frac{1}{2}\sum_{n,p,s=1}^{3}K_{np}K^*_{ns}\lambda'^*_{ipq}\lambda'_{js3}=\frac{1}{2}\sum_{n=1}^{3}\lambda'^*_{inq}\lambda'_{jn3}. \tag{9}$$

Note that $\mathcal{A}^q_{ij}\neq\mathcal{A}^q_{ji}$, etc. and we assume the universal soft mass. The values of κ_i are the followings: $\kappa_1=10^{-4}$, $\kappa_2=2\times10^{-2}$, and $\kappa_3=0.34$. So we neglect the effects of lepton masses if there is no τ in the decay products.

Neglecting lepton masses, the decay rate becomes simple and has terms which depend only on $\mathcal{A}^q_{ij}$ and $\mathcal{B}^q_{ij}$. Numerically, we obtain

$$\Gamma(B_q \to e_i^- e_j^+) \approx 2.93\times 10^{-10}[|\mathcal{A}^q_{ij}|^2 + |\mathcal{B}^q_{ij}|^2] \times \left(\frac{f_{B_q}}{0.2\ \text{GeV}}\right)^2 \left(\frac{M_{B_q}}{5.28\ \text{GeV}}\right)^3 \times \left(\frac{100\ \text{GeV}}{\tilde{m}}\right)^4 \text{GeV}. \tag{10}$$

For example, let us think about the decay of B_d into e^+e^-. In this case, $i=1$, $j=1$, and $q=1$. Combining the above equation with Eq. (5), we obtain

$$|\mathcal{A}^1_{11}|^2 + |\mathcal{B}^1_{11}|^2 < 8.5\times 10^{-9}. \tag{11}$$

From Eq. (9), $\mathcal{A}^1_{11} = 2(-\lambda^*_{121}\lambda'_{213} - \lambda^*_{131}\lambda'_{313})$ and $\mathcal{B}^1_{11} = 2(-\lambda_{121}\lambda'^*_{231} - \lambda_{131}\lambda'^*_{331})$. Under the assumption that only one product combination is not zero, we obtain the same upper bound 4.6×10^{-5} on the magnitudes of four coupling products; $\lambda_{121}\lambda'_{213}$, $\lambda_{121}\lambda'_{231}$, $\lambda_{131}\lambda'_{313}$, and $\lambda_{131}\lambda'_{331}$. In a similar way, other upper bounds can be obtained in the cases of B_d decays into $e^-\mu^+ + e^+\mu^-$, $\mu^+\mu^-$ and B_s decay into $\mu^+\mu^-$, see Table I.

We have two decay modes of B meson which have τ in the decay products; $B^0 \to e^\pm \tau^\mp$ or $\mu^\pm\tau^\mp$. In this case,

$$\begin{aligned}\Gamma(B_q \to \tau^- e_i^+) + \Gamma(B_q \to e_i^- \tau^+) &\approx 2.93\times 10^{-10}\times 0.88\times\{0.88\times(|\mathcal{A}^q_{3i}|^2 + |\mathcal{B}^q_{3i}|^2 + |\mathcal{A}^q_{i3}|^2 \\ &\quad + |\mathcal{B}^q_{i3}|^2) + 0.10\times(|\mathcal{C}^q_{3i}|^2 + |\mathcal{C}^q_{i3}|^2) \\ &\quad + 0.60\times \mathrm{Re}(\mathcal{B}^q_{3i}\mathcal{C}^{q*}_{3i} + \mathcal{A}^q_{i3}\mathcal{C}^{q*}_{i3})\} \\ &\quad \times\left(\frac{f_{B_q}}{0.2\ \text{GeV}}\right)^2\left(\frac{M_{B_q}}{5.28\ \text{GeV}}\right)^3\left(\frac{100\ \text{GeV}}{\tilde{m}}\right)^4 \text{GeV}.\end{aligned} \tag{12}$$

One obtains the most stringent bounds on $|\mathcal{A}^q_{i3}|^2$ and $|\mathcal{B}^q_{i3}|^2$ or on product combinations of the $\lambda\lambda'$-type. The bounds on $\mathcal{B}^q_{3i}\mathcal{C}^{q*}_{3i}$ and $\mathcal{A}^q_{i3}\mathcal{C}^{q*}_{i3}$ are slightly weaker than those on $|\mathcal{A}^q_{i3}|^2$ and $|\mathcal{B}^q_{i3}|^2$. These constrain the product combinations of the type of $\lambda\lambda'\lambda'\lambda'$. We will not consider these kinds of bounds on $\lambda\lambda'\lambda'\lambda'$ since these bounds seem to be less important. The bounds on $|\mathcal{C}^q_{i3}|^2$ and $|\mathcal{C}^q_{3i}|^2$ are the weakest ones. For the case of B_d decay into electron and τ, $i=1$ and $q=1$. Neglecting the terms of $\mathrm{Re}[(\mathcal{A},\mathcal{B})^q_{3i}\mathcal{C}^{q*}_{3i}]$,

$$\begin{aligned}&0.88\times(|\mathcal{A}^1_{31}|^2 + |\mathcal{B}^1_{31}|^2 + |\mathcal{A}^1_{13}|^2 + |\mathcal{B}^1_{13}|^2) \\ &+ 0.10\times(|\mathcal{C}^1_{31}|^2 + |\mathcal{C}^1_{13}|^2) < 8.5\times 10^{-7}.\end{aligned} \tag{13}$$

Under the assumption that only one product combination is not zero, we obtain the same upper bound 4.9×10^{-4} on the magnitudes of eight coupling products of the $\lambda\lambda'$-type. We also obtain the same upper bound 5.8×10^{-3} on the magnitudes of six coupling products of the $\lambda'\lambda'$-type; $\lambda'_{311}\lambda'_{113}$, $\lambda'_{321}\lambda'_{123}$, $\lambda'_{331}\lambda'_{133}$, $\lambda'_{111}\lambda'_{313}$, $\lambda'_{121}\lambda'_{323}$, and $\lambda'_{131}\lambda'_{333}$. Among these, only the bound on $\lambda'_{131}\lambda'_{333}$ is stronger than the previous one. In a similar way, the bounds coming from B_d decay into $\mu^-\tau^+ + \mu^+\tau^-$ can be obtained, see Table I. In the case of B_d decay into μ and τ, only two bounds on $\lambda'_{231}\lambda'_{333}$ and $\lambda'_{233}\lambda'_{331}$ are stronger than previous ones.

The previous bounds are calculated from the bounds on

TABLE I. Upper bounds on the magnitudes of products of couplings derived from B^0 decays into two charged leptons.

Decay mode	Combinations constrained	Upper bound	Previous bound
$B_d \to e^+e^-$	$\lambda_{121}\lambda'_{213}$	4.6×10^{-5}	4.8×10^{-4}
	$\lambda_{121}\lambda'_{231}$	4.6×10^{-5}	8.8×10^{-3}
	$\lambda_{131}\lambda'_{313}$	4.6×10^{-5}	1.2×10^{-3}
	$\lambda_{131}\lambda'_{331}$	4.6×10^{-5}	2.6×10^{-2}
$B_d \to e^+\mu^- + e^-\mu^+$	$\lambda_{121}\lambda'_{113}$	4.6×10^{-5}	4.8×10^{-4}
	$\lambda_{121}\lambda'_{131}$	4.6×10^{-5}	1.0×10^{-2}
	$\lambda_{121}\lambda'_{231}$	4.6×10^{-5}	8.8×10^{-3}
	$\lambda_{122}\lambda'_{213}$	4.6×10^{-5}	4.8×10^{-4}
	$\lambda_{132}\lambda'_{313}$	4.6×10^{-5}	1.2×10^{-3}
	$\lambda_{132}\lambda'_{331}$	4.6×10^{-5}	2.6×10^{-2}
	$\lambda_{231}\lambda'_{313}$	4.6×10^{-5}	1.1×10^{-3}
	$\lambda_{231}\lambda'_{331}$	4.6×10^{-5}	2.3×10^{-2}
$B_d \to e^+\tau^- + e^-\tau^+$	$\lambda_{123}\lambda'_{213}$	4.9×10^{-4}	4.8×10^{-4}
	$\lambda_{123}\lambda'_{231}$	4.9×10^{-4}	8.8×10^{-3}
	$\lambda_{131}\lambda'_{113}$	4.9×10^{-4}	1.2×10^{-3}
	$\lambda_{131}\lambda'_{131}$	4.9×10^{-4}	2.6×10^{-2}
	$\lambda_{133}\lambda'_{313}$	4.9×10^{-4}	1.2×10^{-5}
	$\lambda_{133}\lambda'_{331}$	4.9×10^{-4}	2.6×10^{-4}
	$\lambda_{231}\lambda'_{213}$	4.9×10^{-4}	1.1×10^{-3}
	$\lambda_{231}\lambda'_{231}$	4.9×10^{-4}	2.0×10^{-2}
	$\lambda'_{131}\lambda'_{333}$	5.8×10^{-3}	6.8×10^{-2}
$B_d \to \mu^+\tau^- + \mu^-\tau^+$	$\lambda_{123}\lambda'_{113}$	6.0×10^{-4}	4.8×10^{-4}
	$\lambda_{123}\lambda'_{131}$	6.0×10^{-4}	1.0×10^{-2}
	$\lambda_{132}\lambda'_{113}$	6.0×10^{-4}	1.2×10^{-3}
	$\lambda_{132}\lambda'_{131}$	6.0×10^{-4}	2.6×10^{-2}
	$\lambda_{232}\lambda'_{213}$	6.0×10^{-4}	1.1×10^{-3}
	$\lambda_{232}\lambda'_{231}$	6.0×10^{-4}	2.0×10^{-2}
	$\lambda_{233}\lambda'_{313}$	6.0×10^{-4}	1.1×10^{-3}
	$\lambda_{233}\lambda'_{331}$	6.0×10^{-4}	2.3×10^{-2}
	$\lambda'_{231}\lambda'_{333}$	7.4×10^{-3}	5.7×10^{-2}
	$\lambda'_{233}\lambda'_{331}$	7.4×10^{-3}	1.1×10^{-1}
$B_d \to \mu^+\mu^-$	$\lambda_{122}\lambda'_{113}$	2.4×10^{-5}	4.8×10^{-4}
	$\lambda_{122}\lambda'_{131}$	2.4×10^{-5}	1.0×10^{-2}
	$\lambda_{232}\lambda'_{313}$	2.4×10^{-5}	1.1×10^{-3}
	$\lambda_{232}\lambda'_{331}$	2.4×10^{-5}	2.3×10^{-2}
$B_s \to \mu^+\mu^-$	$\lambda_{122}\lambda'_{123}$	5.5×10^{-5}	4.8×10^{-4}
	$\lambda_{122}\lambda'_{132}$	5.5×10^{-5}	1.6×10^{-2}
	$\lambda_{232}\lambda'_{323}$	5.5×10^{-5}	1.1×10^{-3}
	$\lambda_{232}\lambda'_{332}$	5.5×10^{-5}	2.3×10^{-2}

single R_p-violating coupling, see Table I of Ref. [13].[1] We observe that the bounds on the product combinations of the $\lambda\lambda'$-type, which are between 10^{-4} and 10^{-5}, are stronger than the previous bounds or comparable except those on $\lambda_{133}\lambda'_{313}$, $\lambda_{133}\lambda'_{331}$. This is because there exists a strong upper bound (10^{-3}) on λ_{133} from ν mass. We find that only 3 of 12 bounds on the product combinations of the $\lambda'\lambda'$-type are stronger than previous ones.

There are bounds on certain product combinations of the $\lambda\lambda'$-type from the K-meson decays into pure lepton pairs: $K_L \to e^+e^-$, $K_L \to \mu^+\mu^-$, and $K_L \to e^+\mu^- + e^-\mu^+$ [6]. The bounds from K-meson decays are more stringent than those from B-meson decays. They are between 10^{-7} and 10^{-8}. We observe that even though the bounds on $\lambda\lambda'$ from B-meson decays are weaker than those from K-meson decays, B-meson decays can constrain the product combinations of the $\lambda\lambda'$-type which K-meson decays cannot constrain.

To conclude, we have derived the upper bounds on certain products of R_p- and lepton-flavor-violating couplings from the decays of the neutral B-meson into two charged leptons. These modes of B^0 decays can constrain the product combinations of the couplings with one or more heavy generation indices which the similar decay modes of K meson cannot constrain. We find that most of the bounds on products of the $\lambda\lambda'$-type are stronger than the previous ones. For the bounds on products of the $\lambda'\lambda'$-type, we find three stronger bounds than previous ones.

[1]We use $\lambda'_{11k} < 0.012$ and $\lambda'_{132} < 0.4$ from [10] instead of the values shown in Table I of Ref. [13].

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