Purely Leptonic $B$ decays at High Luminosity $e^+e^-$ $B$ factories

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Abstract

High Luminosity upgrades of the KEK–B collider are being discussed. We consider the role of the purely leptonic decays $B^\pm \rightarrow l^\pm \nu$ and $B^0 \rightarrow l^+l^-$ in motivating such an upgrade. These decays are very sensitive to $R$ parity violating extensions of the MSSM, and we show that future runs of the KEK–B factory can be competitive with high energy colliders for probing such models.

Keywords : Rare $B$ decays

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1 Introduction

High luminosity upgrades of the KEK–B collider (hereafter to be called Super KEK–B) along with corresponding upgrades of the BELLE detector are being actively discussed [1]. Similar plans are also envisaged for BABAR [2]. Luminosities of $10^{35}\text{cm}^{-2}\text{s}^{-1}$ (or greater) are deemed attainable by the year 2006/2007, which would enable data samples of a few $10^{9}$ $B$ mesons per year of operation. Convincing theoretical motivation and proven complementarity to hadronic $B$ factories are crucial in order to justify such an upgrade. In this talk we focus on the purely leptonic decays of $B$ mesons, $B_{u,c}^{\pm}\rightarrow l^{\pm}\nu$ and $B_{d,s}^{0}\rightarrow l^{+}l^{-}$, which remain elusive to date, and discuss their role in motivating such a high luminosity option. We stress the theoretical interest in searching for these 18 decay modes. $B_{d,s}^{0}$ and $B_{c}^{\pm}$ mesons are too heavy to be produced at the $\Upsilon(4S)$ but their decays can be probed at hadronic $B$ factory experiments like LHC–B and B–TeV. These experiments will be operating at the time of the proposed Super KEK–B. Super KEK–B would be an ideal environment to search for $B_{u,c}^{\pm}\rightarrow l^{\pm}\nu$ and $B_{d}^{0}\rightarrow l^{+}l^{-}$ and has powerful advantages over the hadronic $B$ factories in several channels. Together these two distinct $B$ factories can provide much improved coverage of these 18 decays, which would offer measurements of the decay constants and/or probe models beyond the SM, especially $R$ parity violating extensions of the MSSM.

2 Leptonic $B$ meson decays.

Purely leptonic $B$ decays form a particularly appealing group of rare decays. For $B_{u,c}^{\pm}$ they proceed via annihilation to a $W^{\pm}$ in the SM (see Fig. [1]), and due to helicity suppression, the rate is proportional to $m_{t}^{2}$. Observation of such decays would allow a direct measurement of the $B^{\pm}$ meson decay constants. The tree–level partial width is given by (where $q = u$ or $c$):

$$\Gamma(B_{q}^{\pm}\rightarrow l^{\pm}\nu_{l}) = \frac{G_{F}m_{B_{q}}m_{l}^{2}f_{B_{q}}^{2}}{8\pi}|V_{qb}|^{2}\left(1 - \frac{m_{t}^{2}}{m_{B_{q}}^{2}}\right)^{2}$$

(1)

The decay constants are accurately known for $\pi^{\pm}$ and $K^{\pm}$, while those for $D^{\pm}$ mesons will be measured well at CLEO–c and (with probably less precision) at current runs of the $B$ factories. For $B_{u}^{\pm}\rightarrow l^{\pm}\nu$ the severe suppression factor of $|V_{ub}|^{2}$ renders the rates smaller than the analogous decays of the lighter mesons. The branching ratios (BRs) for $B_{c}^{\pm}\rightarrow l^{\pm}\nu$ are larger by a factor $|V_{cb}/V_{ub}|^{2}$ but this is compensated by the suppression in the production cross-section relative to that of $B_{u}^{\pm}$. The BRs for $B_{u,c}^{\pm}\rightarrow l^{\pm}\nu$ in the SM and the current experimental limits are given in Table 1. Note that the LEP search for $B_{u}^{\pm}\rightarrow \tau^{\pm}\nu_{\tau}$ is also sensitive to $B_{c}^{\pm}\rightarrow \tau^{\pm}\nu_{\tau}$, which has the same experimental signature. Thus the displayed limit constrains the BR of an
| Decay            | SM Prediction | CLEO  | Belle  | LEP / Tevatron |
|------------------|---------------|-------|--------|---------------|
| $B^+_u \to e^+\nu_e$ | $9.2 \times 10^{-12}$ | $\leq 1.5 \times 10^{-5}$ [3] | $\leq 5.4 \times 10^{-6}$ [4] | $\otimes$ |
| $B^+_u \to \mu^+\nu_\mu$ | $3.9 \times 10^{-11}$ | $\leq 2.1 \times 10^{-5}$ [3] | $\leq 6.8 \times 10^{-6}$ [4] | $\otimes$ |
| $B^+_d \to \tau^+\nu_\tau$ | $8.7 \times 10^{-5}$ | $\leq 8.4 \times 10^{-4}$ [3] | $\otimes$ | $\leq 5.7 \times 10^{-4}$ [3] / $\otimes$ |
| $B^+_c \to e^+\nu_e$ | $2.5 \times 10^{-9}$ | $\times$ | $\times$ | $\otimes$ |
| $B^+_c \to \mu^+\nu_\mu$ | $1.1 \times 10^{-4}$ | $\times$ | $\times$ | $\otimes$ |
| $B^+_c \to \tau^+\nu_\tau$ | $2.6 \times 10^{-2}$ | $\times$ | $\times$ | (see text) / $\otimes$ |

Table 1: SM predictions and current experimental limits from various machines.

Admixture of $B^+_u$ and $B^+_c$. BABAR studies have shown that 17 (8) events could be expected for $B^+_u \to \tau^+\nu$ ($B^+_c \to \mu^+\nu$) with 500 fb$^{-1}$ [2]. This is clearly insufficient to make a serious measurement of the decay constant $f_{B_u}$. Data samples an order of magnitude larger, which are feasible at Super KEK–B, would enable the first direct measurements of $f_{B_u}$.

The decays $B^0_{d,s} \to l^+ l^-$, for $i = j$ proceed via higher order diagrams in the SM and are very suppressed. For $i \neq j$ they are forbidden in the minimal SM. Thus measurements of the decay constants $f_{B_i}$ and $f_{B_s}$ are not feasible using these channels. However, the leptonic $B^0$ decays can play an additional role of probing models beyond the SM. Due to their very small rates in the SM, observation of these decays would be unequivocal evidence of new physics. Although the BRs for $B^\pm \to l^\pm\nu$ are larger, these decays can also probe physics beyond the SM. The MSSM with $R$ parity conservation can sizeably enhance at most a select few of these decays, i.e. i) $B^+_u \to \tau^+\nu$ via tree level exchange of $H^\pm$ to current experimental limits [4], ii) $B^+_u \to \mu^+\nu$ to the sensitivity of the larger data samples at the B factories [7], iii) $B^0_s \to \mu^+\mu^-$ can also be enhanced by neutral Higgs penguin diagrams [8], and could be in range at the Tevatron Run II. All other decays are too suppressed to be in reach in this model at current and planned experiments.

In contrast, such decays are very sensitive to $R$ parity violating interactions of the scalar sparticles. [3, 4, 5, 6, 7, 8]. In such models squarks and sleptons may mediate all 18 decays at tree-level, and thus these decays may play a crucial role in constraining or confirming $R$ parity violating extensions of the MSSM.

## 3 $R$ parity violation

The main motivation for $R$ parity violating SUSY [14, 15] is to account for the observed neutrino oscillations without increasing the particle content of the MSSM [16]. Although there are other mechanisms which can provide neutrino mass (see [17] for a recent review) $R$ parity violation should be taken as a reasonable candidate. At upcoming high energy colliders it is important to find distinctive signatures of models which can generate neutrino mass. The large number of couplings in the most general $R$ parity violating models, which is sometimes seen as a deficiency of the model, does bestow it a rich phenomenology. Thus if $R$ parity violation is the mechanism of neutrino mass generation, one would expect it to provide many other phenomenological signatures. This is in contrast to other mechanisms of neutrino mass generation which sometimes offer relatively few low energy signatures.
The superpotential is given by:

\[ W_R = \frac{1}{2} \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2} \lambda''_{ijk} U^c_i D^c_j D^c_k \]  

(2)

Bilinear terms \( \mu_i L_i H_2 \) are also possible, but have negligible impact on the annihilation decays we consider. Since the \( \lambda''_{ijk} U^c_i D^c_j D^c_k \) term can mediate proton decay it is customary to assume that the \( \lambda'' \) couplings vanish due to some discrete symmetry (e.g. baryon parity).

The simplest approach to \( R \) parity violating phenomenology is to assume that a single \( R \) parity violating coupling in the weak basis (\( \lambda'_{ijk} \)) is dominant with all others negligibly small. It was shown that such an approach leads to several non-zero \( R \) parity violating couplings in the mass basis (\( \lambda'_{mn} \)) due to quark mixing [18]:

\[ \lambda'_{mn} = \lambda'_{ijk} V^KM_{jm} \delta_{kn} \]  

(3)

Here we have assumed that all quark mixing lies in the up–type sector, so that the mixing matrix is the usual Kobayashi–Maskawa matrix \( V^KM \). This simplification avoids the appearance of the right–handed quark mixing matrix and gives the most conservative limits on the \( R \) parity violating couplings, which would otherwise be constrained more severely from the decay \( K^{\pm} \to \pi^{\pm} \nu \bar{\nu} \). A realistic \( R \) parity violating model would have many non–zero couplings in the weak basis and so in general would have a very rich phenomenology provided the couplings are not too small.

\( R \) parity violating trilinear couplings generate a neutrino mass at the 1–loop level. To fit the observed neutrino oscillations, values of \( 10^{-3} \to 10^{-4} \) are required, although there is an additional dependence on the L–R mixing in the squark/slepton sector which complicates the exact bounds which can be derived. The recently calculated two loop contributions can also be important [19]. In purely bilinear models the sneutrino vacuum expectation values provide a mass at tree–level to one neutrino, while all three neutrinos receive a 1–loop mass from the effective \( \lambda'_{33} \) couplings. The currently favoured large mixing angle solution can be accommodated with just trilinear couplings, or in purely bilinear models if the universality condition is relaxed [20, 21, 22]. Purely bilinear models, while having the advantage of possessing fewer free parameters, are not expected to give rise to enhanced leptonic decays due to the strong constraints on \( \mu_i \) from neutrino oscillations.

4 Distinctive signatures of \( R \) parity violation

We first briefly list some distinctive signatures of \( R \) parity violation.

4.1 Single production of sparticles

Single production of sparticles [23] can be observable at future high–energy colliders if the relevant \( R \) parity violating coupling is \( \mathcal{O}(0.1) \). Several \( \lambda, \lambda' \) couplings are relatively weakly constrained and may be of this order. Examples of single production at hadron colliders include slepton strahlung [24] and slepton production as a resonance in the \( s \)–channel [25].

4.2 Decaying neutral or charged LSP

Perhaps the most robust test of \( R \) parity violation. While the stable (necessarily neutral) LSP in \( R \) parity conserving models provides a missing energy signature at colliders, in \( R \) parity violating
models it decays, usually into visible particles \[26\]. The decays of a LSP neutralino \[21, 22, 27\] and sneutrino \[28\] have been investigated. Since the LSP is unstable it may be charged, and the case of a LSP \(\tilde{\tau}^{\pm}\) has been considered in \[29\]. If \(\lambda, \lambda' > \mathcal{O}(10^{-5})\), then the LSP decays in the detector.

4.3 Low energy probes

Many low energy processes are sensitive to \(R\) parity violating couplings and an extensive literature exists on the various constraints which can be derived e.g. see \[30\]. Recent single bounds on all the \(R\) parity violating couplings are listed in \[15\], assuming that one coupling is dominant. Bounds on products of couplings which mediate a given process are sometimes stronger than the product of the bounds on the individual couplings.

5 \(B\) decays as probes of \(R\) parity violation

5.1 The decays \(B_{\pm} \rightarrow l^{\pm} \nu\) and \(B^{0} \rightarrow l^{+}l^{-}\)

The purely leptonic decays \(B_{u,c}^{\pm} \rightarrow l^{\pm} \nu\) \[10,11,12\] are sensitive at tree level to \(R\) parity violating trilinear interactions, and thus these decays constitute excellent probes of the model. The relevant Feynman diagrams are depicted in Fig. 2 and consist of \(s\)– and \(t\)–channel exchange of sparticles. These additional channels modify the SM rate (Eq.1) by

\[
m_{l} \rightarrow (1 + \mathcal{A}_{ln}^{q}) m_{l} - (R_{l} + \mathcal{B}_{ln}^{q}) M_{D_{q}},
\]

(4)

Here \(R_{l} = m_{l} M_{D_{q}} \tan^{2} \beta/M_{H^{\pm}}^{2}\) stems from \(R\) parity conserving SUSY charged Higgs exchange which we will not consider further. This contribution is most important for the \(B_{u,c}^{\pm} \rightarrow \tau^{\pm} \nu_{\tau}\). The \(\mathcal{A}(\mathcal{B})\) coupling corresponds to squark (slepton) exchange.

\[
\mathcal{A}_{ln}^{q} = \frac{\sqrt{2}}{4 G_{F} V_{qb}} \sum_{i,j=1}^{3} \frac{1}{2 m_{q_{i}}^{2}} V_{q_{j} q_{l}}^{*} \lambda_{n_{3i}}^{l*} \lambda_{ij}^{*},
\]

(5)

\[
\mathcal{B}_{ln}^{q} = \frac{\sqrt{2}}{4 G_{F} V_{qb}} \sum_{i,j=1}^{3} \frac{2}{m_{l_{i}}^{2}} V_{q_{j} l_{l}}^{*} \lambda_{n_{3i}}^{l*} \lambda_{ij}^{*},
\]

(6)

\(q = u, c\). These formulae were derived in \[10\]. The analogous expressions for \(B_{d,s}^{0} \rightarrow l^{+}l^{-}\) can be found in \[13\]. The dominant \(\mathcal{B}_{ln}^{q}\) term (which is not helicity suppressed) requires one

![Figure 2: Leptonic \(B^{\pm}\) decay in \(R\) parity violating models: sparticle exchange](image-url)
non–zero $\lambda$ and one non–zero $\lambda'$. For a given decay $B^{\pm} \rightarrow l^{\pm} \nu$ (i.e. fixing $l$ and $n$) there are nine different combinations $(i, j = 1, 2, 3)$ of $\lambda \lambda'$ which contribute. For a given $B^0_{d,s} \rightarrow l^+_i l^-_j$ there are 6 combinations. Note that in practice the flavour of the neutrino ($n$) cannot be identified and so one must also sum over $n$.

Therefore it is clear that these leptonic decays are sensitive to many combinations of the $R$ parity violating couplings. All 18 decays can be enhanced by the $\mathcal{B}$ coupling alone up to current experimental sensitivity. Thus they might be observed any time in the current runs of the $B$ factories, and every new search improves limits on the relevant $\mathcal{B}$ coupling, which can be transformed into limits on particular combinations of $\lambda \lambda'$. Note that in a general $R$ parity violating model one would expect many non–zero $\lambda \lambda'$ combinations which would cause constructive and/or destructive interference in the $\mathcal{B}$ coupling. If one or more of these decays were observed in current runs then there would be strong motivation for Super KEK–B to measure more precisely the BRs and to search for other purely leptonic decays which might be similarly enhanced. Super KEK–B would be ideal for these measurements.

If no purely leptonic decays are observed in the current runs, except for a few events for $B^+_u \rightarrow \tau^+ \nu_\tau$ and $B^+_u \rightarrow \mu^+ \nu_\mu$ consistent with the SM prediction (see section 2), then the limits on the $\mathcal{B}$ coupling would be $\mathcal{O}(10^{-5})$. This would improve to $\mathcal{O}(10^{-6})$ at Super KEK–B.

5.2 Comparison with Hadronic machines

At the proposed time of operation of Super KEK–B (circa 2006/2007) the hadronic experiments LHC–B and B–TeV are expected to be running. These latter experiments aim to accumulate $\mathcal{O}(10^{11–12})$ $B$ mesons, which is more than what is anticipated at Super KEK–B $\mathcal{O}(10^{9–10})$. In Table 2 we list the 18 decays and compare the potential of the hadronic machines and Super KEK–B to carry out searches.

| Hadronic $B$ factory | KEK–B |
|----------------------|-------|
| $B^+_u \rightarrow e^+ \nu, \mu^+ \nu, \tau^+ \nu$ | maybe | no |
| $B^+_u \rightarrow e^+ \nu, \mu^+ \nu, \tau^+ \nu$ | maybe | yes |
| $B^0_{d,s} \rightarrow e^+ e^-, e^+ \mu^-, \mu^+ \mu^-$ | yes | no |
| $B^0_{d,s} \rightarrow e^+ \tau^-, \mu^+ \tau^-, \tau^+ \tau^-$ | maybe | no |
| $B^0_{d,s} \rightarrow e^+ e^-, e^+ \mu^-, \mu^+ \mu^-$ | yes | yes |
| $B^0_{d,s} \rightarrow e^+ \tau^-, \mu^+ \tau^-, \tau^+ \tau^-$ | maybe | yes |

One can see that Super KEK–B is superior at searching for decays with missing energy or at least one $\tau^\pm$. These channels are much more problematic for hadronic colliders, which up to now (e.g. the Tevatron) have only concentrated on searching for bi–lepton events. The capability of a hadronic machine to search for these missing energy and/or $\tau^\pm$ channels merits further consideration in our opinion. Hence Super KEK–B extends the coverage from 6 channels to 12, and in addition would offer complementary measurements of $B^0_{d,s} \rightarrow e^+ e^-, e^+ \mu^-, \mu^+ \mu^-$. 

Note that only the hadronic machines could search for $B^+_c \rightarrow e^+ \nu, \mu^+ \nu$, for which no experimental limits exist. We showed in [12] that these BRs can be greatly enhanced to $\mathcal{O}(10^{-2})$. The ratio $BR(B^+_u \rightarrow l^\pm \nu)/BR(B^+_c \rightarrow l^\pm \nu)$ is of theoretical interest since these two BRs would be correlated in the simplest $R$ parity violating models with a single dominant $\lambda \lambda'$ combination. This correlation would be relaxed if more combinations also contribute non–negligibly to $\mathcal{B}$. In fact, with only one non–zero $\lambda$ and two non–zero $\lambda'$ couplings there can be destructive interference that suppresses $BR(B^+_u \rightarrow l^\pm \nu)$ safely below experimental limits while allowing for
Figure 3: Destructive interference in the $R$ parity violating contributions to $B_u^\pm \rightarrow l^\pm \nu$ allowing large BRs for $B_c^\pm \rightarrow l^\pm \nu$ while respecting experimental bounds on $B_u^\pm \rightarrow l^\pm \nu$.

$O(10^{-2})$ for $\text{BR}(B_c^\pm \rightarrow l^\pm \nu)$. A diagram illustrating the destructive interference is shown in Fig. 3 taken from [12] where the difference between our conservative (“con”) and optimistic (“opt”) estimates is explained. BRs for $B_c^\pm \rightarrow l^\pm \nu$ of $O(10^{-2})$ are attainable in both cases.

For the reasons shown above, the measurement of the ratio $BR(B_u^\pm \rightarrow l^\pm \nu)/BR(B_c^\pm \rightarrow l^\pm \nu)$ is an example of how hadronic $B$ factories and Super KEK-B together could shed much light on the underlying structure of $R$ parity violating models and other models of physics beyond the SM. Studying correlations among rare $B$ decays in $R$ parity violating models has also been emphasized in [31].

6 Conclusions

We have discussed the role of the purely leptonic decays of the $B$ mesons in motivating a High Luminosity upgrade of the KEK–B collider. We showed that such decays are very sensitive to $R$ parity violating extensions of the MSSM and offer alternative ways of constraining/confirming $R$ violating theories which are competitive with other high energy colliders.

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