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B and collider physics: Working group report

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Abstract. This report summarises the work done during WHEPP-6 (Institute of Mathematical Sciences, Chennai, India, Jan 3–15, 2000) in Working group on 'B and collider physics'.

Keywords. Supersymmetry; anomaly mediation; R-parity; inverted hierarchy; B-decays; CP violation.

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As the name suggests, this working group focussed on physics issues concerning the present and upcoming colliders and B-factories. The scope of the investigations included the identification of viable signatures for physics going beyond the Standard Model (SM) as well as the precise determination of the SM contributions to such processes. The latter aspect is of particular importance in the study of CP violation and rare B-decays. While many different scenarios going beyond the SM were discussed, most of the activity concentrated on supersymmetric models.

This report summarises [1] the activities of the working group on 'B and collider physics'. Presented are the results of investigations relating to various scenarios of supersymmetry breaking and their collider signatures and the consequences of violation of R-parity for both collider signals as well as various B-meson decay modes. Also discussed are techniques for constraining new physics (NP) in a model independent way using B decays to two vector meson modes. Finally, the spectators quark effect in inclusive beauty decays are also reviewed.

1. Anomaly mediated SUSY breaking

The mechanism of supersymmetry breaking is shrouded in mystery. While most studies have assumed supergravity (SUGRA) to be the driving force, it has its share of problems (e.g. see §2). Consequently, alternate scenarios have been proposed and examined to some detail. One such is anomaly mediation, wherein there is no tree level coupling between the SUSY breaking sector and the visible sector. Rather, SUSY breaking is communicated at one-loop through the super-Weyl anomaly.

A striking feature of this scenario is the near-degeneracy of the triplet of Winos because of the mass ratios $M_3 : M_2 : M_1 \simeq 8.8 : 1 : 3.3$. Thus the lighter chargino can now go into a charged pion and a neutralino which is the lightest supersymmetric particle (LSP) over most of the parameter space. A possible problem is that the sleptons tend to become tachyonic, but this problem can be cured by invoking other mechanisms.

We propose a study of the sparticle spectrum of the above type by looking for signatures of selectrons in high energy e^+e^- colliders. Although the left selectron tends to be heavier than its right-handed partner, it actually has the higher rate of pair-production. This can be attributed to the contribution from the t-channel diagram with the Wino dominated LSP (this being absent for the $\tilde{e}_R$). The characteristic signal can be through the decay of one selectron into the lighter chargino and the other, to the lightest neutralino. Now using the decay

$$\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 \pi^{\pm}$$

final states of the type

$$\pi^{\pm} e^{\mp} + \not{E}$$

are predicted.

The less copiously produced $\tilde{e}_R$ on the other hand has its two body decay modes relatively less suppressed. Nevertheless, the small Bino-component of the lightest neutralino can allow the decay

$$\tilde{e}_R \to e\tilde{\chi}^0$$

with a suppression factor of $10^{-4} - 10^{-5}$ in the total width.

The other possible mechanism of a two body decay, namely, through $\tilde{e}_L - \tilde{e}_R$ mixing gets suppressed to the level of $\sim 10^{-4}$ in the amplitude itself. Thus, a scope of discovering the signature of $\tilde{e}_R$ is there only when it goes into three or four body final states ($\tilde{\chi}_1^0 \nu \pi^{\pm}$,

$el^+l^-\tilde{\chi}_1^0$) through the mediation of $\tilde{\chi}_1^+$ or of the higher mass neutralinos or the $\tilde{e}_L$. The Higgsino components of these neutralinos can be as high as 80% in $\tilde{\chi}_0^2$ in some cases can significantly boost the rates from taus in the final states. On the other hand, a light $\tilde{\tau}$ eigenstate driven by a large $\tan\beta$ can lead to the 3-body decay $\tilde{e}_R \rightarrow e\tau\tilde{\tau}$ which may make the consequent final states competitive with the two body decay channel.

A detailed scan of the spectrum and comparative estimates of the various particle decay modes are necessary before any final conclusion can be drawn on the viabilities of these signals.

2. Inverted mass hierarchy at the LHC

While the supersymmetric solution for the gauge hierarchy problem requires the superpartner masses to be $\mathcal{O}(\lesssim 1$ TeV)—the *naturalness criterion*—this is difficult to accommodate in an uncontrived manner in view of the many stringent laboratory constraints. The strongest of the latter, namely those from the smallness of the flavor changing neutral currents, the electric dipole moment (EDM) of electron and neutron, proton lifetime etc. are applicable mainly to the first two generations of scalars (squarks and sleptons) and suggest that their common mass at the GUT scale (m_0) to be rather large ($m_0 \gg 1$ TeV). On the other hand, within a SUGRA-GUT framework with a large enough m_0 ($m_{\rm high}$), large Yukawa couplings may eventually drive the third generation scalar masses to the infra-red fixed points of the governing renormalization group equations (RGEs). Since these fixed points lie in the sub-TeV region ($m_{\rm light}$), the *naturalness* criterion is thus satisfied.

Thus we see that, in such scenarios, the hierarchy between fermion and sfermion masses is reversed. This approach of radiatively generating an inverted mass hierarchy (IMH) making use of infra-red fixed point of the relevant RGEs was first investigated in ref. [2] and generalized in the case of unified theories in ref. [3].

In this project we undertake the study of typical signatures of such a scenario at LHC. The framework of our analysis is an SO(10) SUGRA GUT. It has already been shown in ref. [3] that along with gauge coupling unification, such a scenario can also provide large and universal Yukawa coupling for the third generation while a possible fixed point structure is facilitated by the existence of the naturally heavy right-handed neutrino required to implement the see-saw mechanism. Note that these two things are instrumental in triggering a plausible IMH.

We assume the simplified set of RGEs of ref. [3]. Neglecting the common gaugino mass and the trilinear A-terms ($m_{1/2}, A_{\rm GUT} \ll m_{\rm high}$), and assuming complete Yukawa unification within a generation at the grand unification scale ($M_{\rm GUT}$) as well as their identical pattern of RG-evolution [3] we are led to the following simple boundary condition at M_G for the Higgs and the third generation scalar masses:

$$m_Q^2 = m_U^2 = m_D^2 = m_L^2 = m_E^2 = m_N^2 = \frac{1}{2}m_{H_u}^2 = \frac{1}{2}m_{H_d}^2,$$

where m_N is the mass of the singlet neutrino and others are in usual notation. With the above assumptions the framework is completely specified by two parameters – h_G, the universal third generation Yukawa coupling, and m_N. We have successfully reproduced the results of [3] as a first step.

Note that in ref. [3], the authors neglected $m_{1/2}$ in comparison to m_0 and dropped it from the RGEs of scalar mass-squared evolution. However, since we are interested in the gluino signal, we can no longer do so. Rather, we consider a weak scale value of gluino mass, $m_{\tilde{g}} = 600$ GeV (which is beyond the Tevatron reach but well within LHC reach), apart from the parameters $M_G = 2 \times 10^{16}$ GeV, $m_0 \simeq m_{\rm high} = 4$ TeV, $h_G = 2$ and $m_N = 10^{13}$ GeV. The inclusion of gluino mass results in a contribution of roughly $\frac{8}{9} m_{\tilde{g}}^2$ to the squark masses at the weak scale through the RG evolution. Combining all the contributions, the soft masses of the third generation squarks are as follows :

$$m_Q = 807 \, \mathrm{GeV}, \; m_U = 709 \, \mathrm{GeV}, \; m_D = 895 \, \mathrm{GeV}.$$

While such a spectrum cannot be probed at Tevatron Run II, the LHC has a large enough cross-section for gluino pair production for our choice of $m_{\tilde{g}}$. As the production occurs primarily from the fusion of gluons, the large fluxes at the LHC are a great help.

As we have assumed all the Yukawa couplings to be unified within a particular (third) generation and in a SO(10) SUGRA GUT framework, we settle for a $\tan\beta$ value on the higher side ($\tan\beta = 40$, say). Along with two representative choices of μ, the higgsino mass parameter (in conformity with LEP constraints), viz., $\mu = 200, 600$, we shall be able to probe two characteristic regions of parameter space for the electroweak gauginos that appear in cascades of strongly interacting particles (here gluinos). The masses of the lighter chargino, the lightest neutralino and the second lightest neutralino for $\mu = 200(600)$ are 133(167), 79(85) and 136(167) GeV respectively while those of lighter stop and sbottom are approximately 461(461) GeV and 573(528) GeV respectively. As we are working with high $\tan\beta$ the variation of μ is more pronounced in the sbottom masses.

Having the masses in the above range, once gluinos are pair produced at LHC they will undergo only 3-body decays in the following channels with third generation squarks in the propagators :

$$\begin{aligned} \tilde{g} &\to t\bar{t}\tilde{\chi}_1^0, \\ &\to b\bar{b}\tilde{\chi}_1^0, \\ &\to b\bar{t}\tilde{\chi}_1^+ \; (t\bar{b}\tilde{\chi}_1^-), \\ &\to t\bar{t}\tilde{\chi}_2^0, \\ &\to b\bar{b}\tilde{\chi}_2^0. \end{aligned}$$

The novel feature common to all possible final states arising from the decay of a single gluino is that there are two b-jets and up to 4 leptons. Thus, with two decaying gluinos the final state will definitely be rich in b-jets and isolated leptons. We are using a parton level Monte Carlo simulation to look for final states with at least 3 b-jets in both leptonically quiet and multilepton environments. If a reasonable b-tagging efficiency at the LHC is assumed, this will definitely suggest typical signals characteristic of the inverted mass hierarchy.

3. Signatures of bilinear R-parity violation at the LHC

Supersymmetry and gauge invariance, together with the field content of the minimal supersymmetric standard model (MSSM), allow a family of terms in the superpotential that violate baryon (B) and lepton number (L) [4], and can lead to catastrophic proton decay.

In the MSSM, these terms are forbidden in an *ad hoc* manner by imposing a global Z_2 discrete symmetry [5] under which the quark and lepton superfields change by a sign, while the Higgs superfields remain invariant. This symmetry is often referred to as matter parity (R-parity at the level of component fields). At the level of the MSSM, such a discrete symmetry is not required for the internal consistency of the theory, and is imposed only for phenomenological reasons. Consequently, it is of interest to study the consequences of the absence of this symmetry (while keeping at least one of B and L intact), especially since this renders the LSP unstable. The R-parity violating terms in the superpotential can be parametrized as

$$W_{\not R} = \epsilon_{ab} \left[\epsilon_i L_i^a H_u^b + \lambda_{ijk} \, L_i^a \, L_j^b \, E_k^c + \lambda'_{ijk} \, L_i^a \, Q_j^b \, D_k^c + \lambda''_{ijk} \, U_i^c \, D_j^c \, D_k^c \right] ,$$

where L_i and Q_i are SU(2) doublet lepton and quark superfields respectively. E_i^c, U_i^c and D_i^c are SU(2) singlet charged lepton, up and down quark superfields. H_u is the higgs superfield responsible for the generation of the up-type quark masses. The presence of non-zero λ, λ' or the dimensionful ϵ_is lead to L violation while λ'' violates B. The λs are antisymmetric under the exchange of first two indices while λ''s are anti-symmetric under the exchange of last two.

One of the important consequences of the R-parity violating term $\epsilon_i L_i H_2$ in the superpotential is that it can trigger mixing between the charginos and charged leptons as well as between neutrinos and neutralinos. These mixings give rise to certain two-body decays of the LSP, namely, $\tilde{\chi}_1^0 \to \tau W$ and $\tilde{\chi}_1^0 \to \mu W$, if they are kinematically allowed. The enhancement in the neutralino mass matrix also leads to a tree level mass of one of the netrinos. If the requirement of large angle mixing between ν_μ and ν_τ is imposed then this may result in the production of comparable numbers of muons and tau's with real W-bosons at a very large rate at the LHC. In addition, a measurable decay length in decays of the lightest neutralino is a characteristic feature of this scenario. This displaced vertex makes this kind of signals free from Standard Model backgrounds and also distinguishes it clearly from the R-parity conserving case.

A recent study has discussed in detail the dimuons or ditau signals, together with a real W, in the context of the Fermilab Tevatron with upgraded energy and luminosity. In this case since the lightest neutralino must be heavier than at least the W, the gluinos must also be very heavy (well above 500 GeV), assuming a common gaugino mass at the GUT scale. Thus the gluino has a very small production cross-section at the Tevatron. On the other hand, at LHC one can also have pair-produced LSPs resulting from the cascade decays of the gluinos, in addition to those coming from squarks or other superparticles. This can make the characteristic signal of the bilinear R-parity violating scenario mentioned above considerably different from that at the Tevatron and this requires a detailed investigation.

4. Search for R-parity violating supersymmetry in B-decays

Among all the extensions beyond the Standard Model (BSM), R-parity violating (RPV) SUSY enjoys a special status as far as B-decays are concerned: the BSM physics affects the SM results in the tree-level, and thus both CP-conserving and CP-violating observables have the chance to deviate from the SM predictions. Furthermore, with the plethora of RPV couplings, all B-decay modes may be affected.

In this work, we concentrate upon some of the modes which are expected to be extremely tiny in the SM, and thus even a single event seen in the upcoming B-factories may signal BSM physics. In the quark level, some such processes are:

$$b\bar{d} \to s\bar{u}u\bar{s},\ s\bar{c}c\bar{s}, \quad b\bar{s} \to d\bar{u}u\bar{d},\ d\bar{c}c\bar{d}.$$

These processes are penguin-annihilation (PA) type and are thus extremely suppressed in the SM. The corresponding meson-level processes are:

$$B^0 \to K^+K^-,\ D_s^+D_s^-,\ J/\psi\phi; \quad B_s \to \pi^+\pi^-, D^+D^-.$$

This list also includes the higher resonances, e.g., K^{*+}, D_s^{*+} and ρ.

The SM topology for these processes, as we have already mentioned, is penguin, and another $q\bar{q}$ pair coming out from the vacuum. In RPV, the penguin is replaced by a tree-level process (slepton or squark mediated), and this is where it gains over the SM amplitude.

Ali *et al* [6] have pointed out that the $B \to P_1P_2$ (P is a pseudoscalar meson) annihilation form factors vanish if $m_{P_1} = m_{P_2}$. Thus, $B_s \to \pi^+\pi^-$ and D^+D^- modes are expected to have zero amplitudes in the SM. The same is true for RPV amplitudes too; so the best place is to look at the PV modes.

Among the various mesonic modes listed, K^+K^- suffers from the drawback that the dominant part of the amplitude can come from $K^0 - \bar{K^0}$ rescattering, which is a long-distance effect and is hardly computable. Other modes are free from such uncertainties.

The $B^0 \to J/\psi\phi$ mode is a VV type, and may be observed if the RPV couplings are sufficiently strong (at their experimental bounds).

We obtained a one to two orders of magnitude enhancement from the RPV couplings over the SM amplitude, which may make these modes observable at the factories. A detailed calculation is in progress.

4.1 *Looking for bilinear $\not{R}_p$ in B decays*

The simplest extension of the minimal supersymmmetric standard model (MSSM) that violates R-parity is the 'ϵ model', which includes only the bilinear terms with all the trilinear terms set to zero in the superpotential. The presence of such bilinear terms allows the sneutrino fields to acquire nonzero vacuum expectation values. Further consequences include new types of mixing, e.g. that of neutrinos with neutralinos, charged leptons with charginos and sleptons with Higgs etc., as well as the generation of a small neutrino mass without fine tuning.

We assume, for simplicity, that only $\epsilon_3 \neq 0$ (hence only tau number is nonconserved). Along with $\langle\tilde{\nu}_\tau\rangle$, this generates all the L_τ violating trilinear couplings as well as certain other terms that are absent in the trilinear part of $W_{\not{R}}$. The relative strengths of all these couplings being fixed by ϵ_3 and the mixing matrices, the supersymmetric contributions to the amplitudes for various B decay modes become correlated. A careful study of the same may thus allow us to distinguish bilinear R violation from the trilinear form. Such a study is currently under progress.

5. Constraining new physics in a model independent way using the $B \to J/\psi K^*$ mode

New physics (NP) can contribute to CP violation in B mesons either by directly affecting B decays or by contributing to $B^0 - \overline{B^0}$ mixing. Most studies probing NP contributions focus on NP contributions to $B^0 - \overline{B^0}$ mixing. There are, however, a class of models in which NP contributes mainly to the decays. This group discussed general techniques to study such effects in $B \to J/\psi K^*$ decays. The final state $J/\psi K^*$ has multiple partial waves [7] and hence is advantageous when constraining NP parameters in comparison to modes such as $B \to J/\psi K_S$. The top-quark two-Higgs doublet model (T2HDM) [8], which has been extensively studied [9] for possible signals in B decays was considered as an example.

In the presence of a NP contribution that has a well defined weak phase ϕ, the amplitude $\mathcal{A}$ for the decay $B \to J/\psi K_S$ may be written as

$$\mathcal{A} = a_{\rm SM} {\rm e}^{i\delta_{\rm SM}} + a_{\rm NP} {\rm e}^{i\phi} {\rm e}^{i\delta_{\rm NP}}, \tag{1}$$

where $a^{\rm SM}(\delta_{\rm SM})$ and $a^{\rm NP}(\delta_{\rm NP})$ are the magnitudes of the amplitudes (strong phases) for SM and new physics respectively. To a good approximation no weak phase is present at the amplitude level for this decay in the SM.

An analysis of $B^0(t) \to J/\psi K_S$ and $\overline{B^0}(t) \to J/\psi K_S$ can provide at best three observables – the two magnitudes of the amplitudes and their relative phase. Without time dependent measurement only two observables are possible – the magnitudes of the amplitudes. Theoretically in the presence of NP the amplitudes are described by at least five parameters. Excluding a time dependent analysis one is left with only four variables. Since the direct CP asymmetry is proportional to

$$\mathcal{A}_{\rm CP}^{\rm dir} \propto a_{\rm SM} a_{\rm NP} \sin\delta \sin\phi, \tag{2}$$

it is clear that a constraint on the NP phase ϕ will involve δ the strong phase difference between NP and SM amplitudes. However, the strong phase cannot be reliably estimated, implying that the constraints on the NP parameters are unreliable. If the constraints are considered as a function of δ, even large values of $a_{\rm NP}$ cannot be constrained for small δ by measuring direct CP asymmetry in $B \to J/\psi K_S$.

The situation can be resolved to a great extent if one considers the mode $B^0 \to J/\psi K^*$ instead. As will be discussed in detail the final state consists of three partial waves, with helicities $0, \|$ and $\perp$. Thus, one can in principle measure eleven observables if time dependence of the decays is studied. Without a time dependent study, however, one can not measure the relative phases between $\mathcal{A}_\lambda$ and $\bar{\mathcal{A}}_\lambda$, providing only ten observables. Theoretically one has thirteen (twelve) variables for the case with (without) a time dependent study. We thus have exactly two more variables than observables, just as in the case of $J/\psi K_S$ mode. However, the key difference is that now one can assume two of the SM helicity amplitudes, that can be reliably calculated by theory, rather than the strong phase. The strong phase differences can now in fact be solved for, in terms of the assumed amplitudes.

The top-quark two-Higgs doublet model (T2HDM) [8] contains flavour violation and new sources of CP violation. The unique predictions of the model for the CP asymmetries in both neutral and charged B decays has led to an extensive study [9] pointing out the many experimental tests at the B-factories. The model has new CP violating phases besides the CKM phase. The new phases come from the unitary diagonalization matrix acting on the right-handed up type quarks. Also, some charged Higgs Yukawa couplings are greatly enhanced for large $\tan\beta$, where $\tan\beta$ is the usual ratio of the two Higgs vacuum expectation values (VEV). Further details of the model can be found in [8,9]. It is known that in this model, $B^0 - \overline{B^0}$ mixing receives small contribution from charged Higgs exchange for moderate values of ξ, the $c_R - t_R$ mixing parameter, through which the new weak phases enters. The constraints on the model are therefore likely to come from the effect on the decay amplitudes.

The tree-level Hamiltonian for the transition $b \to c\bar{c}s$, has a rather simple form in the large $\tan\beta$ limit [9]

$$\mathcal{H}_{\rm eff} \approx 2\sqrt{2} G_F V_{cb} V_{cs}^* \left(\bar{c}_L \gamma_\mu \, b_L \, \bar{s}_L \gamma^\mu \, c_L + 2\zeta_H {\rm e}^{i\delta_H} \bar{c}_R \, b_L \, \bar{s}_L \gamma^\mu \, c_R \right), \qquad (3)$$

where

$$\zeta_H {\rm e}^{i\delta_H} = \frac{1}{2} \frac{V_{tb}}{V_{cb}} \left(\frac{m_c \tan\beta}{m_H} \right)^2 \xi^* .$$

By Fierz transformation we can show that the above effective Hamiltonian has the form

$$\mathcal{H}_{\rm eff} \approx 2\sqrt{2} G_F V_{cb} V_{cs}^* \left(\bar{c}_L \gamma_\mu \, c_L \, \bar{s}_L \gamma^\mu \, b_L - \zeta_H {\rm e}^{i\delta_H} \bar{c}_R \, \gamma_\mu \, c_R \, \bar{s}_L \gamma^\mu \, b_L \right) \qquad (4)$$

which consists of two different operators, $\bar{c}_L \gamma_\mu \, c_L \, \bar{s}_L \gamma^\mu \, b_L$ and $\bar{c}_R \, \gamma_\mu \, c_R \, \bar{s}_L \gamma^\mu \, b_L$. The effective amplitudes for the decay $B \to (J/\psi K^*)_\lambda$, where the helicity of the $(J/\psi K^*)$ state is λ, can now be written by generalizing eq. (1) as

$$A\Big(B \to (J/\psi K^*)_\lambda\Big) \equiv A_\lambda = a_\lambda^{\rm SM} {\rm e}^{i\delta_{\rm SM}^\lambda} + a_\lambda^{\rm NP} {\rm e}^{i\phi} {\rm e}^{i\delta_{\rm NP}^\lambda}, \qquad (5)$$

where $a_\lambda^{\rm SM}(\delta_{\rm SM}^\lambda)$ and $a_\lambda^{\rm NP}(\delta_{\rm NP}^\lambda)$ are the magnitudes of the amplitudes (strong phases) for SM and new physics respectively, and ϕ is the weak phase corresponding to the new physics contributions. To a good approximation no weak phase is present in the SM at the amplitude level for this decay. We now define

$$A_\lambda = a_\lambda^{\rm SM} {\rm e}^{i\delta_{\rm SM}^\lambda} (1 + r_\lambda {\rm e}^{i\phi} {\rm e}^{i\delta^\lambda}), \qquad (6)$$

where $r_\lambda = a_\lambda^{\rm NP} / a_\lambda^{\rm SM}$ and $\delta^\lambda = \delta_{\rm NP}^\lambda - \delta_{\rm SM}^\lambda$. Clearly, r_λ depends on $\zeta_H {\rm e}^{i\delta_H}$, which are parameters of the T2HDM. Explicit solutions for r_λ have been obtained in terms of observables, allowing us to constrain NP independent of the unknown strong phases.

6. Spectators effect in inclusive beauty decays

The role of the spectator quarks effect in the inclusive beauty decays were studied. The evaluation of the expectation values of four-quark operators between hadronic states and its consequences were discussed.

Inclusive decays of heavy hadrons are described by the heavy quark expansion (HQE), an expansion in the inverse powers of the heavy quark mass (m) based on the operator product expansion (OPE) in QCD and the heavy quark effective theory (HQET) assuming quark-hadron duality [10]. The leading order hadronic decay rate, proportional to m^5, is that of the free heavy quark. Corrections appear at $O(1/m^2)$ and beyond. They are due to the heavy quark motion inside the hadron and the chromomagnetic interaction at $O(1/m^2)$ and the spectator quarks processes at $O(1/m^3)$. The decay rate at order two in $1/m$ splits up into the mesonic one on the one hand and the baryonic on the other. This is because of the vanishing chromomagnetic interaction in the baryons with an exception of Ω_Q. Among the predictions of the HQE for the inclusive properties which are confronted by the experimental values like the lifetime of Λ_b, semileptonic branching ratio of B and the charm counting in the final state [11], we address the ratio $\tau(\Lambda_b)/\tau(B^0)$ which is 0.9 by theory but 0.79 from experiment), the specators effect in charmless semileptonic decay of Λ_b on $\mathrm{Br}(b \to X_u l \nu_l)$ and the validity of the assumption of quark-hadron duality.

In view of the discrepancy of the theoretical prediction with the experimental one for $\tau(\Lambda_b)$, it is necessary to accommodate the contribution coming from the third order term in the HQE:

$$C(\mu)\langle H|(\bar{b}\Gamma q)(\bar{q}\Gamma b)|H\rangle, \tag{7}$$

where the Wilson coefficient, $C(\mu)$, describes the spectator quarks processes: in the decay $Q(q) \to Q' q_1 q_2(q)$, if either q_1 or q_2 is the same as q, then both of them interfere destructively; if q_1 or q_2 is the antiquark of q, then they weakly annihilate; and the other one is the W-scattering: $Qq_{1(2)}W \to Q'q_{2(1)}$. These processes are found to enhance the decay rate of Λ_Q. On the other hand, the central issue in the systematic incorporation of the spectators effect is the evaluation of the expectation values of the four-quark operators (EV_{FQO}). Traditionally, for mesons, the EV_{FQO} is obtained, with the vacuum saturation approximation, in terms of the leptonic decay constant of the hadron, f_H; on the other hand, for baryons, the valence quark model is employed. This procedure and other methods [12–14] found that the FQO do not account for the discrepancy. However, we have shown in our recent works [15,16] that the FQO accounts for the difference in the lifetimes of Λ_b and B.

The EV_{FQO} between hadronic states is related to the form factor characterising the light quark scattering off the heavy quark inside the hadron [17]:

$$\frac{1}{2M_H}\langle H|(\bar{b}\Gamma q)(\bar{q}\Gamma b)|H\rangle = |\Psi(0)|^2 = \int \frac{d^3}{(2\pi)^3} F(q^2). \tag{8}$$

In [15], representing the form factor by $\mathrm{e}^{-q^2/4\beta^2}$, the wave function density is obtained as

$$|\Psi(0)|^2 = \frac{\beta^3}{4\pi^{3/2}}, \tag{9}$$

where β is determined by solving the Schrödinger equation in variational procedure for the wave function $\frac{\beta^{3/2}}{\pi^{3/4}}\mathrm{e}^{-\beta^2 r^2/2}$ with the potential $V(r)_{\mathrm{meson}} = a/r + br + c$ and $V(r)_{\mathrm{baryon}} = a/r + br + \beta r^2 + c$. In this description, the baryon is considered as a two body system of a heavy quark-diquark. The β's for the hadrons are: $\beta_{B^-} = 0.4, \beta_{B^s} = 0.44$ and β_{Λ_b} = 0.72, all in GeV units. Using these values for the wave function density, the ratio of lifetimes of Λ_b and B is found to be 0.79.

If one assumes that the HQE is an asymptotic expansion, then the expansion for the decay rate can safely be considered as converging at $O(1/m^3)$. Recently, Voloshin [19] has analysed the relations between the inclusive decay rates of the charmed and beauty baryons triplet (Λ_Q, Ξ_Q) [18]. The relations depend only on the HQE and on the flavour symmetry under SU(3)$_f$. In this procedure, the EV$_{\rm FQO}$ between baryon states is obtained using the differences in the total decay rates. In [16], strongly assuming that the HQE converges at $O(1/m^3)$, we extended the Voloshin analysis to SU(3)$_f$ triplet of the B mesons, B^-, B^0 and B_s^0. Their total decay rate splits up due to their light quark flavour dependence at the third order in the HQE. The differences in the decay rates of the triplet, are related to the third order terms in $1/m$ by

$$\mathrm{d}\Gamma_{B^0-B^-} = -\Gamma_0'(1-x)^2\left\{Z_1\frac{1}{3}(c_0+6)+(c_0+2)\right\}\langle O_6\rangle_{B^0-B^-}\,, \tag{10}$$

$$\mathrm{d}\Gamma_{B_s^0-B^-} = -\Gamma_0'(1-x)^2\left\{Z_2\frac{1}{3}(c_0+6)+(c_0+2)\right\}\langle O_6\rangle_{B_s^0-B^-}\,, \tag{11}$$

$$\mathrm{d}\Gamma_{B_s^0-B^0} = -\Gamma_0'(1-x)^2\left\{(Z_1-Z_2)\frac{1}{3}(c_0+6)\right\}\langle O_6\rangle_{B_s^0-B^0}\,. \tag{12}$$

On the other hand, for the triplet baryons, Λ_b, Ξ^- and Ξ^0, with $\tau(\Lambda_b) < \tau(\Xi^0) \approx \tau(\Xi^-)$, we have the relation between the difference in the total decay rates and the terms of $O(1/m^3)$ in the HQE, as

$$\mathrm{d}\Gamma_{\Lambda_b-\Xi^0} = \frac{3}{8}\Gamma_0'(c_0-2)\langle O_6\rangle_{\Lambda_b-\Xi^0}\,. \tag{13}$$

For the decay rates $\Gamma(B^-) = 0.617$ ps^{-1}, $\Gamma(B^0) = 0.637$ ps^{-1} and $\Gamma(B_s^0) = 0.645$ ps^{-1}, the EV$_{\rm FQO}$ are obtained for B meson, as an average, from eqs (4–6): $\langle O_6\rangle_B = 8.08\times 10^{-3}$ GeV^3. The EV$_{\rm FQO}$ for the baryon $\langle O_6\rangle_{\Lambda_b-\Xi^0} = 3.072\times 10^{-2}$ GeV^3, where we have used the decay rates corresponding to the lifetimes 1.24 ps and 1.39 ps of Λ_b and Ξ^0 respectively. The EV$_{\rm FQO}$ for baryon is about 3.8 times larger than that of B. For these values $\tau(\Lambda_b)/\tau(B) = 0.78$. Using the experimental value of $\tau(B^-) = 1.55$ ps alongwith the above theoretical value, the lifetime of Λ_b turns out to be $\tau(\Lambda_b) = 1.20$ ps.

We now turn up to the spectator quarks effect in $\Lambda_b \to \Lambda_u l\nu_l$ [20], in view of the ALEPH measurement [21] of Br$(b \to X_u l\nu_l)$. When b decays into $ul\nu_l$, the final state u quark constructively interferes with the u quark in the initial state. This effect increases the decay rate leading to the ratio, using the $EV_{\rm FQO}$ for baryons obtained above,

$$\frac{\Gamma(\Lambda_b \to X_u l\nu_l)}{\Gamma(b \to X_u l\nu_l)} = 1.34. \tag{14}$$

The b-baryon contributes about 10% to Br$(b \to X_u l\nu_l)$. The above estimate will have effect on the branching ratio considerably if there is no compensation from elsewhere. The estimate above will increase if the spectators effect from Ξ^0. It seems that any compensation is absent to offset the above estimate plus that one from Ξ^0. This will, though modestly, effect the value of the CKM matrix element $|V_{ub}|$.

Concerning quark-hadron duality in the heavy hadron decays, we make inference that follows the results obtained above. The agreement found between theory and experiment for $\tau(\Lambda_b)$, besides consistency in the B mesons case, clearly signals that quark-hadron duality holds good in the HQE. In the previous case, eqs (2–3), by the choice of the form factor representation, we obtained $\tau(\Lambda_b)/\tau(B)$, whereas in the latter it is the very assumption that the HQE converges at $O(1/m^3)$ which leads to the prediction for the ratio. The validity of the assumption that we made needs to be verified [22]. In the recent lattice study [23], the authors stated that the role of the FQO is significant to explain $\tau(\Lambda_b)$. We hope that their claim will throw light.

The evaluation of the $EV_{\rm FQO}$ is model dependent one in the first case [15] and is subject to the validity of the assumption on the convergence of the HQE in the latter one [16]. The intriguing point is that $|\Psi(0)|^2$ for meson is smaller than the estimate in terms of the leptonic decay constant. The ratio $|\Psi(0)|^2_{\Lambda_b}/|\Psi(0)|^2_B$ is larger than expected.

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