Revised Version

DESY-96-062
CERN-TH/96-100
EFI-96-11

hep-ph/9604319 16 Apr 1996

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EFI-96-11
hep-ph/9604319
April 1996

TWO TOPICS IN b PHYSICS[1]

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Abstract

(1) A simple transversity analysis permits one to separate the P-even and P-odd partial waves in such decays as $B_s \to J/\psi\phi$ and $B \to J/\psi K^*$. This method is relevant to the separation of contributions of CP-even and CP-odd final states in B_s decays, and hence to the measurement of a possible lifetime difference between mass eigenstates. (2) The enhancement $\Delta\Gamma(\Lambda_b)$ of the Λ_b decay rate due to four-fermion processes is calculated in terms of the $\Sigma_b^* - \Sigma_b$ hyperfine splitting, the $B^* - B$ hyperfine splitting, and the B meson decay constant f_B. Despite a relatively large hyperfine splitting observed by the DELPHI Collaboration, the mechanism falls far short of being able to explain the observed enhancement.

[1] Presented at 10th Rencontre de La Thuile, Val d'Aosta, Italy, March 4-9, 1996.
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1 Introduction

Recent experimental results on b physics include the first report of an angular distribution analysis for the decay $B_s \to J/\psi\phi \to e^+e^-K^+K^-$ [1], and a persistent difference between the Λ_b lifetime (around 1.2 ps) and those of the B mesons (at least 1.5 ps) [2].

In collaboration with A. Dighe, I. Dunietz, and H. Lipkin [3], we have used a transversity analysis [4] to separate out partial waves of even and odd parity in decays of pseudoscalar mesons to pairs of vector mesons. This analysis, described in Section 2, permits separation of CP-even and CP-odd mass eigenstates of the B_s meson in the decay $B_s \to J/\psi\phi$. By applying a similar analysis to obtain the relative contributions of $S+D$- vs. P-wave decays in $B \to J/\psi K^*$ (for which the present data sample is much more copious), and using flavor SU(3), one can obtain related information.

Some time ago it was suggested [5] that the enhanced decay rate of Λ_c was due to the weak scattering process $cd \to su$. We find [6] that the corresponding effect in the Λ_b falls short of explaining the observed rate enhancement. A similar conclusion has been reached by others [7]. As described in Sec. 3, we estimate the four-quark matrix element using the hyperfine splitting between the Σ_b^* and the Σ_b reported by the DELPHI Collaboration [8]. Although one thus obtains a value of the four-quark matrix element which is at least twice as large as a naïve estimate, it falls far short of what is needed.

We summarize in Section 4.

2 Angular distributions and lifetime differences

The strange B meson $B_s \equiv \bar{b}s$ and its charge-conjugate $\bar{B}_s \equiv b\bar{s}$ are expected to mix with one another with a large amplitude. The mass eigenstates B_s^H ("heavy") and B_s^L ("light") with masses m_H and m_L are expected to be split by $\Delta m \equiv m_H - m_L \approx 25\bar{\Gamma}$, give or take a factor of two [9], where $\bar{\Gamma} \equiv (\Gamma_H + \Gamma_L)/2 \approx \Gamma(B^0)$ ($B^0 \equiv \bar{b}d$). The measurement of such a large mass difference poses an experimental challenge.

Aside from small CP-violating effects, the mass eigenstates correspond to those $B_s^{(\pm)}$ of even and odd CP. The decay of a $\bar{B}_s$ meson via the quark subprocess $b(\bar{s}) \to c\bar{c}s(\bar{s})$ gives rise to predominantly CP-even final states [10]. Thus the CP-even eigenstate should have a greater decay rate. An explicit calculation [11] gives

$$\frac{\Gamma(B_s^{(+)}) - \Gamma(B_s^{(-)})}{\overline{\Gamma}} \simeq 0.18 \frac{f_{B_s}^2}{(200\ \mathrm{MeV})^2} \quad , \tag{1}$$

where $f_{B_s} \approx 200$ MeV is the B_s decay constant (in a normalization in which $f_\pi = 132$ MeV). The estimate of f_{B_s} [9, 12] is probably good to about 20%.

The ratio of the mass splitting to the width difference of strange B's is predicted to be large and independent of CKM matrix elements [13, 14]: $\Delta m/\Delta\Gamma \simeq \mathcal{O}(-[1/\pi][m_t^2/m_b^2]) \simeq -200$, where $\Delta\Gamma \equiv \Gamma_H - \Gamma_L$. In view of the sign in Eq. (1) and since $\Delta m > 0$ by definition, we then identify $B_s^L = B_s^{(+)}$ and $B_s^H = B_s^{(-)}$ [13]. If the mass difference Δm turns out to be too large to measure at present because of the rapid frequency of $B_s - \bar{B}_s$ oscillations it entails, the width difference $\Delta\Gamma$ may be large enough to detect [10, 11, 15].

One can measure $\bar{\Gamma}$ using semileptonic decays, while decays to CP eigenstates can be measured by studying the correlations between the polarization states of the vector mesons in $B_s^{(\pm)} \to J/\psi\phi$. In this section we describe a means by which the $J/\psi\phi$ final states of definite CP in B_s decays may be separated from one another using an angular distribution based on a *transversity* variable [4]. This variable allows one to directly separate the summed contribution of the even partial waves (S, D) from the odd one (P) by means of their opposite parities.

Consider the final state $J/\psi\phi \to \ell^+\ell^- K^+K^-$, where $\ell = e$ or μ. In the rest frame of the J/ψ let the direction of the ϕ define the x axis. Let the plane of the K^+K^- system define the y axis, with $p_y(K^+) > 0$, so the normal to that plane defines the z axis. (We assume a right-handed coordinate system.) We define the angle θ as the angle between the ℓ^+ and the z axis. Then the time-dependent rate for the $J/\psi\phi$ mode is given by

$$\frac{d^2\Gamma}{d\cos\theta\ dt} = \frac{3}{8}p(t)\left(1+\cos^2\theta\right) + \frac{3}{4}m(t)\sin^2\theta \quad , \tag{2}$$

where

$$p(t) = p(0)e^{-\Gamma_L t} \quad \text{(CP even)} \quad , \quad \mathrm{m(t) = m(0)e^{-\Gamma_H t}} \quad \text{(CP odd)} \quad , \tag{3}$$

so that the probability of having a CP-even [CP-odd] state at proper time t is given by $p(t)/(p(t)+m(t))$ $[m(t)/(p(t)+m(t))]$. The angular distribution is normalized in such a way that

$$\frac{d\Gamma}{dt} = \int_{-1}^{1} d(\cos\theta)\frac{d^2\Gamma}{d\cos\theta\ dt} = p(t) + m(t) \quad . \tag{4}$$

As t increases, one should see a growth of the $\sin^2\theta$ component.

The derivation of Eq. (2) is elementary. The ϕ is coupled to K^+K^- through an amplitude $\epsilon_\phi \cdot (p_{K^+} - p_{K^-})$, where the quantities denote 4-vectors. Thus the plane of (linear) ϕ polarization is related to that of the K^+K^- system in the J/ψ rest frame. By definition, we have taken the ϕ linear polarization vector to lie in the $x-y$ plane.

One can decompose the decay amplitude A into three independent components [16], corresponding to linear polarization states of the vector mesons which are either longitudinal (0), or transverse to their directions of motion and parallel ($\|$) or perpendicular ($\perp$) to one another. The states 0 and $\|$ are P-even, while the state $\perp$ is P-odd. Since J/ψ and ϕ are both C-odd eigenstates, the properties under P are the same as those under CP.

The case of transverse ($\|$ or $\perp$) polarization states is reminiscent of photon polarization correlations [17] in neutral pion decay. Thus, an amplitude $A_\|$ (related to an interaction Lagrangian proportional to $\mathbf{E}^2 - \mathbf{B}^2$) would have signified that the π^0 had even CP, whereas the observed decay, involving the amplitude $A_\perp$ and an interaction Lagrangian $\sim \mathbf{E} \cdot \mathbf{B}$, signifies odd CP. For the present case of massive vector mesons, there are also longitudinal polarization states, corresponding to another even-CP amplitude.

Consider the spatial components of the polarization three-vectors $\boldsymbol{\epsilon}_{J/\psi}$ and $\boldsymbol{\epsilon}_\phi$ in the J/ψ rest frame. They must be correlated since the decaying strange B is spinless. The J/ψ then has a single linear polarization state $\boldsymbol{\epsilon}$ for each amplitude. For longitudinally polarized ϕ and J/ψ, characterized by the CP-even amplitude A_0, we have $\boldsymbol{\epsilon}_{J/\psi} = \hat{x}$. For transversely polarized ϕ, with $\boldsymbol{\epsilon}_\phi = \hat{y}$, we have two possibilities: The CP-even amplitude $A_\|$ corresponds to $\boldsymbol{\epsilon}_{J/\psi} = \hat{y}$, while the CP-odd amplitude $A_\perp$ corresponds to $\boldsymbol{\epsilon}_{J/\psi} = \hat{z}$.

A unit vector n in the direction of the ℓ^+ in J/ψ decay may be defined to have components

$$(n_x, n_y, n_z) = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta) \tag{5}$$

where φ is the angle between the projection of the ℓ^+ on the K^+K^- plane in the J/ψ rest frame and the x axis. The sum over lepton polarizations then leads to a tensor in the J/ψ rest frame with spatial components (in the limit of zero lepton mass, assumed here)

$$\sum_{\ell^\pm pol} [\bar{u}\gamma_i v]^*[\bar{u}\gamma_j v] \sim L_{ij} \equiv \delta_{ij} - n_i n_j \quad . \tag{6}$$

Physically this tensor expresses the electromagnetic coupling of massless lepton pairs to transverse polarization states of the J/ψ.

When contracted with amplitudes corresponding to $|A_0|^2$, $|A_\||^2$, or $|A_\perp|^2$, the lepton tensor then yields terms $1-n_x^2$, $1-n_y^2$, or $1-n_z^2$, respectively. The first two, when averaged over φ, each give terms $(1+\cos^2\theta)/2$, while the last gives $\sin^2\theta$. We thus identify

$$p(t) = |A_0|^2 + |A_\||^2 \quad , \quad m(t) = |A_\perp|^2 \quad . \tag{7}$$

In the limit of flavor SU(3) symmetry, one expects the ratios of the relative components in $B^0 \to J/\psi K^{*0}$ to be the same as those *at proper time* $t = 0$ in the decays $B_s \to$

$J/\psi\phi$ [18]. Thus, an analysis of $B^0 \to J/\psi K^{*0}$ can provide an independent estimate of the relative contributions of CP-even and CP-odd final states at $t = 0$ to the decays $B_s \to J/\psi\phi$, enhancing the ability to determine Γ_H and Γ_L. The dominance of the $|A_0|^2$ contribution in $B^0 \to J/\psi K^{*0}$ decays [1, 19, 20] implies via flavor SU(3) that the $|A_0|^2$ contribution should also dominate $B_s \to J/\psi\phi$, and hence that $B_s^{(-)} \to J/\psi\phi$ is likely to be suppressed in comparison with $B_s^{(+)} \to J/\psi\phi$. Thus the initial angular distribution is very likely to be dominated by the $1 + \cos^2\theta$ component. As time increases, the fraction of the angular distribution proportional to this component will decrease while that proportional to $\sin^2\theta$ will increase. It should be possible to separate out the two components by a combined analysis in θ and proper decay time. If the $\sin^2\theta$ component does not show up even at large times, a single-exponential fit to the decay should provide a good estimate of the lifetime of the CP-even eigenstate.

The analysis performed by CDF [1] for $B_s \to J/\psi\phi$ separated out the transverse component from the longitudinal component. In the absence of vertex cuts these would be, respectively, $\Gamma_T \equiv \int_0^\infty dt(|A_\parallel|^2 + |A_\perp|^2)$ and $\Gamma_0 \equiv \int_0^\infty dt(|A_0|^2)$. With a minimum vertex cut of 50 μm, the result obtained was $\Gamma_0/(\Gamma_0 + \Gamma_T) = 0.56 \pm 0.21(\text{stat})\ ^{+0.02}_{-0.04}(\text{sys})$. The transverse component contains both CP-even and CP-odd contributions, while the longitudinal component is CP-even.

Corresponding determinations of $\Gamma_0/(\Gamma_0+\Gamma_T)$ for the decay $B^0 \to J/\psi K^{*0}$ are $0.65 \pm 0.10 \pm 0.04$ (CDF) [1], $0.97 \pm 0.16 \pm 0.15$ (ARGUS) [19], $0.80 \pm 0.08 \pm 0.05$ (CLEO) [20], and 0.74 ± 0.07 (world average) [1]. This last value is compatible with the corresponding one for $B_s \to J/\psi\phi$. A discrepancy would have indicated either a violation of SU(3) or the lifetime effect mentioned above.

3 Enhancement of the Λ_b decay rate

The differences among lifetimes of particles containing heavy quarks are expected to become smaller as the heavy quark mass increases and free-quark estimates become more reliable. Thus, mesons and baryons containing b quarks are expected to have lifetimes differing no more than a few percent [7, 21]. For example, the process, $bu \to cd$ in the Λ_b ("weak scattering"), when considered in conjunction with the partially offsetting process $bd \to c\bar{u}dd$ ("Pauli interference") should lead to a small enhancement in the Λ_b decay rate, so that $\tau(\Lambda_b) = (0.9 \text{ to } 0.95)\tau(\text{B}^0)$.

The observed Λ_b lifetime is $\tau(\Lambda_b) = 1.20 \pm 0.07$ ps, while the B^0 decays more slowly: $\tau(B^0) = (1.58 \pm 0.05)$ ps. Here we have averaged a compilation of world data [2] (for

which $\tau(\Lambda_b) = 1.18 \pm 0.07$ ps) with a new value [22] $\tau(\Lambda_b) = 1.33 \pm 0.16 \pm 0.07$ ps. The ratio of these two quantities is $\tau(\Lambda_b)/\tau(B^0) = 0.76 \pm 0.05$, indicating an enhancement of the Λ_b decay rate beyond the magnitude of usual estimates.

We find [6] that, in spite of a large wave function for the bu pair in the initial baryon, which we denote by $|\Psi(0)|^2_{bu}$, only $(13 \pm 7)\%$ of the needed enhancement of the Λ_b decay rate can be explained in terms of the effects of the four-fermion matrix element. If we assume wave functions are similar in all baryons with a single b quark and two nonstrange quarks, this quantity can be related to the hyperfine splitting $M(\Sigma_b^*) - M(\Sigma_b)$, for which the DELPHI Collaboration at LEP [8] has recently quoted a large value of 56 ± 16 MeV. We estimate the effect of gluon exchange by performing a similar calculation for B mesons, relating the $B^* - B$ splitting to the B meson decay constant and taking account of differing spin and hyperfine factors in the meson and baryon systems.

A relation for the enhancement of the Λ_c decay rate due to the weak scattering process $cd \to su$ was first pointed out in Ref. [5]. At the same order in heavy quark mass, one must also take account of Pauli interference (interference between identical quarks in the final state) [23]. Thus, for the Λ_b, one considers not only the process $bu \to cd$ (involving matrix elements between Λ_b states of $(\bar{b}b)(\bar{u}u)$ operators), but also those processes involving matrix elements of $(\bar{b}b)(\bar{d}d)$ operators) which contribute to interference. The net result of four-quark operators in the Λ_b is an enhancement of the decay rate by an amount (see, e.g., Ref. [23])

$$\Delta\Gamma(\Lambda_b) = (G_F^2/2\pi)|\Psi(0)|^2_{bu}|V_{ud}|^2|V_{cb}|^2 m_b^2(1-x)^2[c_-^2 - (1+x)c_+(c_- - c_+/2)] \quad . \tag{8}$$

We have neglected light-quark masses; $x \equiv m_c^2/m_b^2$, while c_- and $c_+ = (c_-)^{-1/2}$ are the short-distance QCD enhancement and suppression factors for quarks in a color antitriplet and sextet, respectively [24]: $c_- = [\alpha_s(m_c^2)/\alpha_s(M_W^2)]^\gamma$, where $\gamma \equiv 12/(33 - 2n_F)$, with $n_F = 5$ the number of active quark flavors between m_b and M_W. The c_-^2 term reflects the weak scattering process $bu \to cd \to bu$; the remaining terms arise from destructive interference between the two intermediate d quarks in the process $bd \to c\bar{u}dd \to bd$.

Taking [6] $\alpha_s(m_b^2) = 0.193$ and $\alpha_s(M_W^2) = 0.114$, we find $c_- = 1.32$, $c_+ = 0.87$. An estimate of $|\Psi(0)|^2_{bu}$ is then needed. We find it by comparing hyperfine splittings in mesons and baryons, under the assumption that the strength of the one-gluon exchange term is the same for the light quark – heavy quark pair in each system. Our result is that

$$|\Psi(0)|^2_{bu} = 2 \cdot \frac{2}{3} \cdot \frac{M(\Sigma_b^*) - M(\Sigma_b)}{M(B^*) - M(B)} \cdot \frac{M_B f_B^2}{12} \quad , \tag{9}$$

where the first factor relates to color, the second to spin, and the last term is the non-relativistic estimate of the $b\bar{u}$ wave function in the B meson [25]. (Here one may use

the spin-averaged value of vector and pseudoscalar masses for M_M.) With the DELPHI value of $M(\Sigma_b^*) - M(\Sigma_b)$, the $B^* - B$ splitting of 46 MeV [26], and the estimate [9, 12] $f_B = 190 \pm 40$ MeV, we obtain $|\Psi(0)|^2_{bu} = (2.6 \pm 1.3) \times 10^{-2}$ GeV^3. This is to be compared with $|\Psi(0)|^2_{b\bar{u}} = M_B f_B^2/12 = (1.6 \pm 0.7) \times 10^{-2}$ GeV^3 for the B meson.

In both Σ_b and Σ_b^*, the light quarks are coupled up to spin 1. The splitting then depends purely on the light quark – heavy quark interaction. The wave function between a light quark and a heavy one is assumed to be identical in the Λ_b and in the $\Sigma_b - \Sigma_b^*$ system. The value of $\langle \hat{s}_Q \cdot \hat{s}_{\bar{q}} \rangle$ is $(1/4, -3/4)$ for a $({}^3S_1,\ {}^1S_0)$ $Q\bar{q}$ meson, where Q and q are the heavy and light quark. For a baryon Qqq with $S_{qq} = 1$, one has $\langle \hat{s}_Q \cdot \hat{s}_q \rangle = (1/4,\ -1/2)$ for states with total spin $(3/2,\ 1/2)$. Thus the difference in $\hat{s}_i \cdot \hat{s}_j$ for the $\Sigma_b^* - \Sigma_b$ splitting (counting a factor of 2 for the two light quarks in the baryons) is 3/2 that for the $B^* - B$ splitting. The factor of 2/3 in Eq. (9) compensates for this ratio. The color factor takes account of the fact that in a meson, the quark and antiquark are a color **3** and **3*** coupled to a singlet, while in a baryon the two **3**'s are coupled to a **3***.

In the relation (8) we now neglect $\sin\theta_c$ (setting $V_{ud} = 1$), and choose $m_b = 5.1$ GeV, $m_c = 1.7$ GeV, and $|V_{cb}| = 0.040 \pm 0.003$. We then find

$$\Delta\Gamma(\Lambda_b) = 0.025 \pm 0.013\ ps^{-1} \quad . \tag{10}$$

The decay rates of the B^0 and Λ_b are $\Gamma(B^0) = 0.63 \pm 0.02$ ps^{-1} and $\Gamma(\Lambda_b) = 0.83 \pm 0.05$ ps^{-1}, differing by $\Delta\Gamma(\Lambda_b) = 0.20 \pm 0.05$ ps^{-1}. The four-quark processes noted above can explain only $(13 \pm 7)\%$ of this difference, leading to an enhancement of only $(4 \pm 2)\%$ of the total Λ_b decay rate in contrast with the needed enhancement of $(32 \pm 8)\%$.

The corresponding calculation for charmed particles makes use of the following inputs.

1. The D meson decay constant was taken [9] to be $f_D = 240 \pm 40$ MeV, leading to $|\Psi(0)|^2_{c\bar{d}} = (0.95 \pm 0.32) \times 10^{-2}$ GeV^3; *2. The $D^* - D$ splitting* is assumed to be 141 MeV (the average for charged and neutral states [26]); *3. Charmed baryon masses* are taken to be $M(\Sigma_c) = 2453$ MeV [26] and $M(\Sigma_c^*) = 2530 \pm 7$ MeV [27]; *4. The strong fine-structure-constant* at m_c^2 is taken to be $\alpha_s(m_c^2) = 0.289$, consistent with the QCD scale mentioned above, leading to $c_- = 1.60,\ c_+ = 0.79$; *5. The strange quark mass* is taken to have a typical constituent-quark value, $m_s = 0.5$ GeV. We continue to neglect u and d-quark masses for simplicity; *6. The CKM factors* in Eq. (8) undergo the replacements $|V_{ud}|^2|V_{cb}|^2 \to |V_{cs}|^2|V_{ud}|^2$, which we approximate by 1 (again neglecting $\sin\theta_c$).

Our results for systems with c and b quarks are summarized in Table 1. Remarks:

(a) The difference between the central values of $|\Psi(0)|^2_{Q\bar{q}}$ for charm and beauty reflects the likely importance of $1/m_Q$ corrections (see, e.g., Ref. [12]), or – in the language of the

Table 1: Comparison of predicted squares of wave functions and decay rate enhancements for Λ_c and Λ_b.

Quantity (units)	Charm	Beauty
f_M (MeV)	240 ± 40	190 ± 40
$\lvert\Psi(0)\rvert^2_{Q\bar{q}}$ (10^{-2} GeV^3)	0.95 ± 0.32	1.6 ± 0.7
$M(^3S_1) - M(^1S_0)$ (MeV)	141	46
$M(\Sigma^*) - M(\Sigma)$ (MeV)	77 ± 7	56 ± 16
$\lvert\Psi(0)\rvert^2_{Qq}$ (10^{-2} GeV^3)	0.69 ± 0.24	2.6 ± 1.3
c_-	1.60	1.32
c_+	0.79	0.87
$c_-^2 - (1+x)c_+(c_- - c_+^2/2)$	1.52	0.88
$\Delta\Gamma(\Lambda_Q)$ (ps^{-1})	0.8 ± 0.3	0.025 ± 0.013

quark model – of reduced mass effects.

(b) The $\Sigma_c^* - \Sigma_c$ hyperfine splitting used in this calculation is based on one claim for observation of the Σ_c^* [27], which requires confirmation.

(c) The value of $\lvert\Psi(0)\rvert^2_{bu}$ is large in comparison with the others for light-heavy systems. It would be helpful to verify the DELPHI $\Sigma_b^* - \Sigma_b$ hyperfine splitting [8]. The ratio of hyperfine splittings for charmed and beauty mesons is approximately 3:1, as expected if these splittings scale as $1/m_Q$. In contrast, the corresponding ratio for baryons is considerably smaller, indicating a violation of $1/m_Q$ scaling.

(d) The enhancement of the Λ_c decay rate is quite modest. With $\Gamma(\Lambda_c) \approx 5$ ps^{-1}, to be compared with $\Gamma(D^0) \approx 2.4$ ps^{-1} and $\Gamma(D^+) \approx 1$ ps^{-1}, one seeks an enhancement of at least $\Gamma(\Lambda_c) - \Gamma(D^0) \approx 2.6$ ps^{-1}. If the enhancements $\Delta\Gamma(\Lambda_Q)$ in Table 1 were about a factor of 4 larger, we could accommodate both the Λ_c and Λ_b decay rates, but this is not consistent with our estimates of the matrix elements and their effects on decay rates. In particular, the effect of Pauli interference is to cut the naïve estimate of the enhancement due to weak scattering alone [5] by roughly a factor of 2.

4 Summary

A combined analysis with respect to proper decay time and a single transversity angle in the decay $B_s \to J/\psi\phi$ can determine the lifetime of at least the CP-even and possibly the CP-odd mass eigenstates of the $B_s - \bar{B}_s$ system. Additional information about the properties of the $J/\psi\phi$ mode at proper time $t = 0$ can be obtained by a similar analysis of the decays $B^0 \to J/\psi K^{*0}$. Such analyses are in progress with the data samples [1, 20] now in hand.

The DELPHI value [8] of the $\Sigma_b^* - \Sigma_b$ hyperfine splitting permits an estimate of the overlap of quark wave functions between the b quark and the light quarks in the Λ_b, and hence of the effect of four-quark operators on its decay rate. Even though the matrix element deduced from the DELPHI result is quite large on the scale of those for heavy-light systems, one can only account for $(13 \pm 7)\%$ of the difference between the Λ_b and B^0 decay rates. A similar approach also falls short of accounting for the corresponding enhancement for the Λ_c decay rate.

Acknowledgments

I thank the Fermilab, CERN, and DESY Theory Groups and the Physics Department of The Technion for their hospitality during various parts of this work; the organizers of this workshop for partial support; Amol S. Dighe, Isard Dunietz, and Harry J. Lipkin for an enjoyable collaboration on angular distributions in decays; and B. Kayser, R. Kutschke, G. Martinelli, M. Neubert, K. Ohl, M. Paulini, E. A. Paschos, C. T. Sachrajda, M. P. Schmidt, M. Shifman, N. G. Uraltsev, and W. Wester for fruitful discussions. This work was supported in part by the United States Department of Energy under Contract No. DE FG02 90ER40560 and by the United States – Israel Binational Science Foundation under Research Grant Agreement 94-00253/1.

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