CP Violation with Beautiful Baryons

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ABSTRACT

CP violation can be studied in modes of charmed or bottom baryons when a decay process is compared with its charge-conjugated partner. It can show up as a rate asymmetry and in a study of other decay parameters. Neither tagging nor time-dependences are required to observe CP violation with modes of baryons, in contrast to the conventional B^0 modes. Numerous modes of bottom baryons have the potential to show large CP-violating effects within the Standard Model. Those effects can be substantial for modes with a D^0 , which is seen in a final state that can also be fed from a $\bar{D}^0$. For instance, a comparison of the $\Lambda_b \rightarrow \Lambda D_{CP}^0$ with the $\bar{\Lambda}_b \rightarrow \bar{\Lambda} D_{CP}^0$ process can show sizeable CP violation. Here D_{CP}^0 denotes CP eigenstates of D^0 , which occur at a few percent. Six related processes, such as $\Lambda_b \rightarrow \Lambda D^0$, $\Lambda_b \rightarrow \Lambda \bar{D}^0$, $\Lambda_b \rightarrow \Lambda D_{CP}^0$, and their charge-conjugated counterparts, can extract ϕ , which is the most problematic angle of the unitarity triangle and which is conventionally probed with the $B_s \rightarrow \rho^0 K_S$ asymmetry. Here D^0 and $\bar{D}^0$ are identified by their charged kaon or lepton. We predict $B(\Lambda_b \rightarrow \Lambda D^0) \sim 10^{-5}$, thus $B(\Lambda_b \rightarrow \Lambda D_{CP}^0) \sim 10^{-7}$. Under favourable circumstances, CP violation can occur at the few tens of percent level. Thus 10^2 – 10^3 $\Lambda_b \rightarrow \Lambda D_{CP}^0$ decays start probing ϕ . Tables list many additional modes with typical branching ratios at the 10^{-5} – 10^{-6} level, with large detection efficiencies (in contrast to the D_{CP}^0), and with potentially large CP-violating effects, such as $\Xi_b^0 \rightarrow \Lambda \Psi$, $\Lambda \phi$, $\Lambda \rho^0$; $\Lambda_b \rightarrow \Lambda K_S$, ΛK^{*0} ; $\Xi_b^- \rightarrow \Lambda K^{(*)-}$, $\Xi^- K_S$, $\Xi^- K^{*0}$; $\Omega_b^- \rightarrow \Xi^- \phi$, $\Xi^- \rho^0$, $\Lambda K^{(*)-}$, $\Omega^- K_S$, $\Omega^- K^{*0}$.

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1. Introduction

CP violation remains a mystery almost thirty years after its discovery. The only evidence for it comes from K_L decays.¹ Many studies predict sizeable CP-non-invariance effects with B mesons and a few promising modes have been identified.² In contrast, not much effort has been channelled into studying CP violation with b-flavoured baryons.³ This work explores the possibility that large CP violation can occur with numerous modes of b-flavoured baryons. Baryon number conservation causes the baryons to have an advantage over several promising modes of B^0 mesons. Neither tagging -- that is, the distinction between a neutral B meson and its anti-particle -- nor time-dependences are required to observe CP violation effects with modes of baryons.

We start by reviewing how CP violation can be tested, regardless of a specific model. All the modes of this work could be subjected to those tests; CP violation would thus be probed in a model-independent manner. Not only the partial decay rates, but all other decay parameters, should be compared, since CP violation can show up anywhere.

For instance, the decay $1/2 \rightarrow 1/2 + 0$ involves, in addition to the partial decay rate Γ , the three decay parameters α, β, γ .^{4, 5, 6} (Other decay parameters are involved for different modes of baryons, such as $1/2 \rightarrow 1/2 + 1, 1/2 \rightarrow 3/2 + 0, 1/2 \rightarrow 3/2 + 1$.) CP invariance requires $\bar{\Gamma} = \Gamma, \bar{\alpha} = -\alpha, \bar{\beta} = -\beta, \bar{\gamma} = +\gamma$, where the barred quantities describe the charge-conjugated process.^{7, 8} CP violation occurs when one or more of the above conditions is violated. Subtle effects are involved, because naive T-odd operators can be constructed. Even when final-state phase differences vanish, CP violation could still be observed by comparing β with $\bar{\beta}$. In contrast, in order to observe

CP violation, a final-state phase difference is required in the B-meson decays, $B \rightarrow \pi K, \bar{K} K, \pi \rho$.^{9, 10, 11, 12}

While we encourage the search for CP violation in a model-independent manner, we are aware that proposals are currently evaluated on whether or not they can observe CP-violating effects predicted by the Standard Model. Within the Standard Model, CP non-invariance arises due to complex elements of the 3×3 CKM (Cabibbo-Kobayashi-Maskawa) matrix.¹³ The Standard Model, also referred to as the CKM model in this paper, does not explain, but merely accommodates CP violation. The latter part of this work shows that promising CP-violating effects within the CKM model can occur for many modes of b-flavoured baryons.

The unitarity triangle is the graphic representation in the complex plane of the unitarity relation between the first and third columns of the CKM matrix. Its angle ϕ (see Figure 1) is very difficult to measure. The conventional way to determine ϕ uses the processes $B_s \rightarrow \rho^0 K_S, \omega K_S$ with predicted tiny rates and inherent theoretical uncertainties.

This angle ϕ can alternatively be probed when modes of B-mesons with a D^0 are studied.^{14, 15, 16, 17} Here the D^0 must be seen in a final state that is common to a $\bar{D}^0$. This work generalizes the idea to modes of b-flavoured baryons. In principle, six related processes, such as $\Lambda_b \rightarrow \Lambda D^0, \Lambda_b \rightarrow \Lambda \bar{D}^0, \Lambda_b \rightarrow \Lambda D_{CP}^0$, and their three charge-conjugated partners, can extract the angle ϕ , regardless of whether a final-state phase difference exists. The D_{CP}^0 denotes all neutral D modes with a definite CP-parity.¹⁸ $D_{CP}^0 \equiv (D^0 + \bar{D}^0) / \sqrt{2}$, when CP-even modes are considered, such as $\pi^+ \pi^-$ and $K^+ K^-$. In contrast, $D_{CP}^0 \equiv (D^0 - \bar{D}^0) / \sqrt{2}$, for CP-odd ones, such as $K_S \pi^0, K_S \rho^0, K_S \omega$ and $K_S \phi$. CP eigenstates of a D^0 occur at the few percent level. Nonetheless this report rounds their observable branching ratio down to 1%, because many of those

modes are difficult to detect in hadronic collisions. The data sample could be increased by using D^0 modes which are admixtures of opposite CP-parities. The increase could be achieved by detailed angular correlation studies, which would separate the opposite CP-parities.¹⁹

Modes of baryons that involve $b \rightarrow d + \bar{s}s$, $b \rightarrow d + \bar{d}d$, $b \rightarrow d + \bar{u}u$, $b \rightarrow s + \bar{u}u$ or $b \rightarrow d + \bar{c}c$ transition could show large CP-violating effects. Modes governed by $b \rightarrow s + \bar{s}s$ and $b \rightarrow s + \bar{d}d$ quark-subprocesses may not show such large effects for bottom baryons that do not contain a valence up-quark. Photonic decays of baryons may show CP-violating effects of the order of 1-10% and 0.1-1% for $b \rightarrow d + \gamma$ and $b \rightarrow s + \gamma$, respectively.²⁰ So far we have discussed only baryonic decays.

It is worthwhile to review in more detail the extraction of ϕ from earlier methods, where only B mesons were considered. The angle ϕ can be extracted from specific B_s modes, in which case the modes require time-dependent studies in addition to tagging – that is, the distinction between a B_s and a $\bar{B}_s$. The conventional $B_s \rightarrow \rho^0 K_S$, ωK_S modes measure $\sin 2\phi$, but suffer from predicted tiny rates. Even if a $B_s \rightarrow \rho^0 K_S$, ωK_S rate difference could be established, it would not be clear that $\sin 2\phi$ had been measured, because amplitudes with other weak phases may contribute significantly. Time-dependent studies of the $B_s \rightarrow D^0 \phi$,¹⁴ and $B_s \rightarrow D_s^{(*)\pm} K^{(*)\mp}$ modes²¹ extract the weak phase ϕ because, in principle, final-state phases can be removed.²²

Another way to measure the angle ϕ requires neither time-dependence nor tagging. Large CP-violating effects can occur in B modes with a D^0 .²³ For two interfering amplitudes to exist with a weak phase difference ϕ , the D^0 must decay into modes that can also be fed from a $\bar{D}^0$. As there is no reason for the final-state phase difference to vanish, large CP non-invariance effects may occur. The weak phase ϕ can be determined if six related rates can be

measured – for instance, $B \rightarrow D^0 K^{(*)}$, $B \rightarrow \bar{D}^0 K^{(*)}$, $B \rightarrow D_{CP}^0 K^{(*)}$ and their three charge-conjugated counterparts.^{14–17} In principle, the determination can be made even when the final-state phase difference vanishes.

Section 2 reviews the observables which arise in a generic weak decay of a spin-1/2 baryon into a final spin-1/2 baryon and a spinless meson. They are the partial rate Γ and the α , β and γ parameters, which characterize the strengths of the s- and p-waves. Measuring the partial rate requires no polarization, while the measurements for α , β and γ do. If the final baryon subsequently decays, α can generally be determined from this decay distribution. The requirements for CP invariance are reviewed, CP violation occurring when one or more of them is not fulfilled. It is not necessary to have non-vanishing final-state phase differences to observe CP non-invariance. In principle, even when all final-state phase differences vanish, CP violation could still be observed by comparing β with $\bar{\beta}$. The observable decay parameters for other generic processes, such as $1/2 \rightarrow 3/2 + 0$, $1/2 \rightarrow 1/2 + 1$ and $1/2 \rightarrow 3/2 + 1$, could also show CP-violating effects. Although we do not derive them here, we wish to signal their existence.

Section 3 discusses the modes with a D^0 . The interfering amplitudes of the CP-violating processes in Section 3 are comparable in magnitude. They involve the weak phase difference ϕ within the CKM model. Thus, large CP violation could occur.

Section 4 discusses how to extract the weak phase ϕ by removing a final-state phase difference. The removal is accomplished by determining separately the modulus of each individual amplitude, of which there are six for each helicity configuration. In principle, ϕ can be determined even when no CP violation is seen.

Section 5 predicts the rate and other decay parameters for the $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$ processes. We estimate a rate of 10^{-5} for $\Lambda_b \rightarrow \Lambda D^0$. The

$\Lambda_b \rightarrow \Lambda D_{CP}^0$ process, where CP violation could occur, then has a rate at the 10^{-7} level, since the fraction of D^0 decaying into CP eigenstates is a few percent.¹⁸ Since CP-violating effects could be at the tens of percent level, obtaining 10^{10} Λ_b 's starts probing them.

Section 6 shows that modes with a D^0 in no way exhaust the possibilities for CP-violating effects of b-flavoured baryons. Examples are tabulated of many exclusive modes, for which large effects are possible. CP-violating effects at the few x 10% level are possible (under optimal conditions) for exclusive modes with 10^{-5} – 10^{-6} branching ratios; see Table 1 for examples. Some of those final states are especially attractive, because they have large detection efficiencies, in contrast to modes with a D^0 . In order to search for large CP-violating effects, the modes with a D^0 require the D^0 to be seen in a mode that can also be fed from a $\bar{D}^0$. The requirement costs us two orders of magnitude or more in statistics. Section 7 concludes and presents prospects for further work.

2. Review of α , β , γ Formalism and CP Violation

The observables that characterize the generic $1/2 \rightarrow 1/2 + 0$ decay are reviewed. They are the partial decay rate, Γ , and the α , β and γ decay parameters.^{4–6} The charge-conjugated process is then discussed. CP invariance relates any observable to its charge-conjugated counterpart.^{7, 8} A comparison of a process with its charge-conjugated partner probes CP invariance not only in their partial decay rates, but in all other decay parameters as well. Even when all final-state phase differences vanish, CP violation can still show up in naive T-odd operators. The β observable is a coefficient of such a T-odd observable.

The most general matrix element for a two-body decay of a spin-1/2 baryon H_i into a final spin-1/2 baryon H_f and a spinless meson $M(0)$,²⁴

$$H_i(1/2) \rightarrow H_f(1/2) + M(0), \quad (2.1)$$

is

$$T = \bar{u}_f (A - B \gamma_5) u_i. \quad (2.2)$$

u_i and u_f are the Dirac spinors of the initial and final baryons, and A and B are complex constants. Examples of eq. (2.1) are $\Lambda_b \rightarrow \Lambda D^0$ or the well-known process $\Lambda \rightarrow p\pi^-$. In two-component notation, the matrix element becomes

$$T = \chi_f^\dagger (S + P \vec{\sigma} \cdot \vec{k}) \chi_i, \quad (2.3)$$

where

$$S = A, \quad P = \frac{|\vec{k}|}{E + m} B. \quad (2.4)$$

Here χ_i and χ_f are the Pauli spinors. The 4-momentum of the final baryon in the rest frame of the initial one is $(E, \vec{k})$. The mass of the final baryon is m , and S and P are the s- and p-wave amplitudes, respectively.

Table 2 defines the observables for the decay-process given in eq. (2.1). Up to trivial kinematic factors, the partial decay-rate Γ measures $|S|^2 + |P|^2$. No polarization for either the initial or the final baryon is required. In contrast, learning about the s- and p-wave interferences requires information about polarization. Either initial or final polarization suffices to determine α , while both polarizations are required to extract β and γ .²⁵ We remind the reader that α , β and γ are not independent, because

$$\alpha^2 + \beta^2 + \gamma^2 = 1. \quad (2.5)$$

In summary, the observables of the two complex s- and p-wave amplitudes are their respective magnitudes and their relative phase. When

$$S = |S| e^{i\delta} \quad \text{and} \quad P = |P| e^{i\tau}, \quad (2.6)$$

the observables are

$$|S|, |P| \text{ and } \Delta = \tau - \delta. \quad (2.7)$$

In processes where the final baryon subsequently decays, such as

$$\Lambda_b \rightarrow \Lambda (\rightarrow p\pi^-) D^0, \quad (2.8)$$

α is obtained from the decay-distribution of the final baryon, $\Lambda \rightarrow p\pi^-$.²⁵ The observables β and γ also require an initial polarization.

It is conceivable in hadronic experiments that strongly produced Λ_b 's (and other b-flavoured baryons) will be polarized perpendicular to their production plane, in analogy to the large polarizations measured for the Λ 's.²⁶ In e^+e^- collisions at the Z^0 resonance, the Z^0 decays mainly into left-handed b-quarks. The hadronization into a Λ_b occurs when the b-quark combines with a diquark ($\equiv ud$), which is a spin and isospin singlet. Because the diquark is spinless, it is likely that the helicity of the Λ_b is mainly that of the b-quark. The Z^0 resonance can be an excellent source of polarized Λ_b 's. However, the number of Λ_b 's produced from the Z resonance is probably not enough to probe CP violation with the rare processes advocated here.

CP violation is tested by comparing the process of eq. (2.1) to its charge-conjugated one,

$$\bar{H}_b(1/2) \rightarrow \bar{H}_b(1/2) + \bar{M}(0). \quad (2.9)$$

The observables for the charge-conjugated process are $\bar{\Gamma}$, $\bar{\alpha}$, $\bar{\beta}$, $\bar{\gamma}$. CP invariance requires that^{7, 8}

$$\bar{\Gamma} = \Gamma, \quad (2.10 \text{ a})$$

$$\bar{\alpha} = -\alpha, \quad (2.10 \text{ b})$$

$$\bar{\beta} = -\beta, \quad (2.10 \text{ c})$$

$$\bar{\gamma} = +\gamma. \quad (2.10 \text{ d})$$

Many of the modes in this work may show sizeable rate asymmetries, $\bar{\Gamma} \neq \Gamma$. Even if $\bar{\Gamma} \approx \Gamma$, it may still happen that $\bar{\alpha} \neq -\alpha$, $\bar{\beta} \neq -\beta$ or $\bar{\gamma} \neq +\gamma$. That is, CP violation may be seen by studying the interferences between the s- and p-waves. The quantities α and $\bar{\alpha}$ are automatically measured from the decay-distributions of the final baryon, while a measurement of β and $\bar{\beta}$ (as well as γ and $\bar{\gamma}$) also requires an initial polarization.

In $p\bar{p}$ or e^+e^- colliders equal amounts of heavy baryons and antibaryons are created. Comparing the rates of an exclusive mode ($\bar{\Gamma} = \Gamma$) is straightforward. In contrast, in a pp or fixed target environment, unequal amounts of baryons and antibaryons could be produced. Because the typical branching ratio for the promising exclusive modes is 10^{-5} – 10^{-6} , the rates could still be compared by normalizing against modes with much larger data samples for which vanishing or negligible CP-violating effects are predicted.²⁷

Even when all final-state phase differences vanish, the baryonic decays under discussion can still show CP violation. When all final-state phase differences vanish,

$$\bar{\Gamma} = \Gamma, \quad (2.11 \text{ a})$$

$$\bar{\alpha} = -\alpha, \quad (2.11 \text{ b})$$

$$\bar{\beta} = +\beta, \quad (2.11 \text{ c})$$

$$\bar{\gamma} = \gamma. \quad (2.11 \text{ d})$$

Although no CP violation will be observed by comparing the partial rates [eq. (2.11 a)] or the α parameters [eq. (2.11 b)], a non-zero β shows CP violation [compare eq. (2.11 c) with eq. (2.10 c)]. For vanishing final-state phase differences, a non-zero β signals that two interfering amplitudes with different weak phases are involved.

It is a straightforward exercise to determine the observables for other generic decays, such as $1/2 \rightarrow 1/2 + 1$, $1/2 \rightarrow 3/2 + 0$ and $1/2 \rightarrow 3/2 + 1$.²⁸ CP violation ought to be probed not only in their partial decay rates, but in all other decay parameters. In a CP-invariant world, the relationship between the various decay parameters and their charge-conjugated counterparts has been known for more than twenty years. We advocate searching for CP-violating effects in all modes of heavy-flavoured baryons. That holds for beauty as well as charmed baryons. Although the CKM model does not predict large CP-violating effects with charmed baryons, they should be tested if data is available. We should probe for CP-violating effects with beauty baryons, where the CKM model predicts small ones or none at all. The most exciting fact is, however, that beauty baryons may show large CP-violating effects. By using the CKM model with its unique CP-violating phase as a guideline, many promising modes can be identified. Section 3 discusses the encouraging modes with a D^0 , while Section 6 lists other promising modes.

3. Modes with a D^0

This section presents two scenarios where large CP-violating effects can occur within the CKM model. The first scenario appears to be the more promising of the two. We include the second one for the sake of completeness. In the first, the $b \rightarrow s + D^0$ amplitude interferes with the $b \rightarrow s + \bar{D}^0$ one, when the $\bar{D}^0$ is seen in a CP eigenstate.²³ In the second scenario, the $b \rightarrow d + D^0$ amplitude interferes with the $b \rightarrow d + \bar{D}^0$ one.¹⁷ Although the $b \rightarrow d + D^0$ amplitude dominates the $b \rightarrow d + \bar{D}^0$ one by $\sim \theta^{-2}$ -- where $\theta = 0.22$ denotes the Cabibbo angle -- large CP violation can occur when the D^0 is seen in a doubly-Cabibbo-suppressed mode, $D^0 \rightarrow g$. The second scenario is technically more

demanding than the first, because it requires a reasonable signal-to-background ratio for the much suppressed modes of the D^0 . Thus superb K and π separation is mandatory, which may be achievable with dedicated detectors.²⁹

In addition to $b \rightarrow s(d) + \bar{D}^0$ (see Figures 2-3), other amplitudes contribute to processes where the b-flavoured baryon has a valence up-quark (see Figure 4). Because the CKM elements of the amplitudes seen in Figs. 3(a) and 4(a) are the same, as are those in Figs. 3(b) and 4(b), nothing changes in the following discussions. It is important to notice that unique CKM elements are involved, since penguin diagrams of the form $b \rightarrow s(d)$ cannot contribute to the processes.

a. The interference of $b \rightarrow s + D^0$ with $b \rightarrow s + \bar{D}^0$

CP violation may take place when the $b \rightarrow s + D^0$ amplitude interferes with the $b \rightarrow s + \bar{D}^0$ one. The former is governed by the $V_{cb}V_{us}^*$ CKM combination, and the latter by $V_{ub}V_{cs}^*$. Not only do they have comparable strengths but, more importantly, they have the angle ϕ as their relative weak phase difference,

$$\frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}} = \left| \frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}} \right| e^{i\phi} \sim \frac{1}{2} e^{i\phi}. \quad (3.1)$$

The interference is accomplished when the D^0 and $\bar{D}^0$ are seen in modes with definite CP-parity. To increase statistics, different D^0 modes with the same CP-parity are to be added. Adding modes with opposite CP-parities would dilute the CP-violating effects. A further increase in statistics could be achieved by disentangling the CP-even from the CP-odd contributions of D^0 modes, which are admixtures of both.¹⁹

Large CP violation effects may appear when the processes are compared with their charge-conjugated counterparts. Examples for the processes are

$$\begin{aligned}
 \Lambda_b (\equiv bud) &\rightarrow \Lambda D_{CP}^0 & [B(\Lambda \rightarrow p\pi^-) \approx 64\%], \\
 \Xi_b^- (\equiv bsd) &\rightarrow \Xi^- D_{CP}^0 & [B(\Xi^- \rightarrow \Lambda\pi^-) \approx 100\%], \\
 \Xi_b^0 (\equiv bsu) &\rightarrow \Xi^0 D_{CP}^0 & [B(\Xi^0 \rightarrow \Lambda\pi^0) \approx 100\%], \\
 \Omega_b^- (\equiv bss) &\rightarrow \Omega^- D_{CP}^0 & [B(\Omega^- \rightarrow \Lambda K^-) \approx 68\%].
 \end{aligned} \tag{3.2}$$

Those CP violation effects may occur because final-state phase differences could be sizeable and the relative weak phase is substantial.³⁰

$$0.1 \leq \sin(-\phi) \leq 1. \tag{3.3}$$

In fact, a maximum likelihood fit to current data suggests that $\sin(-\phi)$ is very large (to 1σ accuracy).³¹

$$0.3 \leq \sin(-\phi) \leq 0.8. \tag{3.4}$$

Large CP-violating effects can occur in additional modes, where the D_{CP}^0 is replaced by CP eigenstates of an excited D^0 , such as D^{*0} . Because the D^{*0} modes are either $D^{*0}\pi^0$ or $D^{*0}\gamma$, the whole D^{*0} mode is a CP eigenstate as long as the subsequent D^0 is seen in a CP eigenstate.¹⁸ The D^{*0} mode $D^{*0}\pi^0$ must be distinguished from $D^{*0}\gamma$ (when the subsequent D^0 is seen in a CP eigenstate), since their CP-parities differ by a sign.

b. The Interference of $b \rightarrow d + D^0$ with $b \rightarrow d + \bar{D}^0$

Whereas the $b \rightarrow d + D^0$ amplitude involves the $V_{cb}V_{ud}^*$ CKM combination, the $b \rightarrow d + \bar{D}^0$ involves the much suppressed $V_{ub}V_{cd}^*$ one. A comparable interference of the two amplitudes occurs when the D^0 is seen in a doubly-Cabibbo-suppressed mode, $D^0 \rightarrow g$, which has a very small branching ratio. This g is then a Cabibbo-favoured mode for $\bar{D}^0$. Examples for g are $K^+\pi^-$, $K^+\rho^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, etc. The two interfering amplitudes have comparable CKM elements and a weak phase difference ϕ . Large CP violation could occur if we compared the process with its charge-conjugated partner. Examples for such b-flavoured processes are

$$\begin{aligned}
 \Lambda_b &\rightarrow N \bar{D}^0 (\rightarrow g), \\
 \Xi_b^0 &\rightarrow \Lambda \bar{D}^0 (\rightarrow g), \quad \Sigma^0 \bar{D}^0 (\rightarrow g), \\
 \Xi_b^- &\rightarrow \Sigma^- \bar{D}^0 (\rightarrow g), \\
 \Omega_b^- &\rightarrow \Xi^- \bar{D}^0 (\rightarrow g).
 \end{aligned} \tag{3.5}$$

Here N denotes either a neutron or an excited baryon with odd quark content. Recall that g is a doubly-Cabibbo-suppressed mode of D^0 . Clearly, instead of the $\bar{D}^0$ we could use an excited neutral charmed meson, such as $\bar{D}^{*0}$. Once this excited neutral charmed particle decays down to $\bar{D}^0$, we require the latter to decay into the doubly-Cabibbo-suppressed mode of D^0 , g .

Both scenarios are sensitive to the weak phase ϕ , which is large [see eqs. (3.3)-(3.4)]. It is possible to obtain CP-violating effects of order unity -- that is, spectacular ones. Detailed studies of six related processes can extract the weak phase ϕ , as will be discussed in the next section.¹⁴⁻¹⁷ In principle, the extraction of ϕ can be accomplished irrespective of whether CP violation occurs.

4. Extraction of weak phase ϕ

This section extracts the weak phase ϕ from b-flavoured modes of the sort $1/2 \rightarrow 1/2 + 0$, such as $\Lambda_b \rightarrow \Lambda D^0$, $\Xi_b^- \rightarrow \Xi^- D^0$, $\Xi_b^0 \rightarrow \Xi^0 D^0$. Six related processes must be observed to make the extraction. We prefer to explain the method through an example, $\Lambda_b \rightarrow \Lambda D^0$, instead of keeping the discussion general and abstract. Once the example has been presented, it will be clear how to determine ϕ from the other modes, as well as from $\Omega_b^- \rightarrow \Omega^- D^0$, because Ω^- being spin-3/2 should not pose a problem. The weak angle ϕ could also be extracted from additional modes, obtained when the spinless D^0 is replaced by the spin-1 D^{*0} , or when the final baryon is replaced by one of its resonances, or both.

The six related processes of $\Lambda_b \rightarrow \Lambda D^0$ consist of three Λ_b processes and their charge-conjugated counterparts. The 3 Λ_b processes are

$$\begin{aligned}\Lambda_b &\rightarrow \Lambda D^0, \\ \Lambda_b &\rightarrow \Lambda \bar{D}^0, \\ \Lambda_b &\rightarrow \Lambda D_{CP}^0,\end{aligned}\tag{4.1}$$

with partial-decay rates Γ_D , $\Gamma_{\bar{D}}$, and Γ , respectively. The three corresponding charge-conjugated channels are

$$\begin{aligned}\bar{\Lambda}_b &\rightarrow \bar{\Lambda} \bar{D}^0, \\ \bar{\Lambda}_b &\rightarrow \bar{\Lambda} D^0, \\ \bar{\Lambda}_b &\rightarrow \bar{\Lambda} D_{CP}^0,\end{aligned}\tag{4.2}$$

with partial rates $\bar{\Gamma}_{\bar{D}} (= \Gamma_D)$, $\bar{\Gamma}_D (= \Gamma_{\bar{D}})$, and $\bar{\Gamma}$. In general, $\bar{\Gamma} \neq \Gamma$, which signals CP violation. The D^0 and $\bar{D}^0$ are identified by the charge of their decay

kaon or lepton, while the D_{CP}^0 is identified by the rarer CP eigenstates of the D^0 , which occur at the few percent level.

In principle, the extraction of ϕ can be accomplished under any circumstances. Whereas the general case must disentangle the various helicity amplitudes of the six processes in order to obtain ϕ , three specific cases can determine ϕ from the rates of the six processes alone. The three cases are when

- (a) the p-wave dominates,
- (b) the s-wave dominates, and
- (c) the p- to s-wave ratio is a constant.

The next section shows that case (c) occurs if factorization holds.

To determine experimentally whether one of the three simple cases is actually realized in nature, it is sufficient to measure Γ , α , β , and γ for the first two processes alone ($\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$), instead of for all six. Using only those two processes aids in the study of CP violation, because they are channels with higher statistics than the ones with a D_{CP}^0 . Furthermore, in a fixed target experiment or pp collider, the Λ_b may be polarized while the $\bar{\Lambda}_b$ are not. The β and γ parameters for the $\bar{\Lambda}_b$ decays could then not be measured, because the initial polarization vanishes. However, as long as an initial Λ_b polarization occurs and the four Γ , α , β , γ parameters of the two Λ_b processes are measured, the four parameters for the two charge-conjugated processes are automatically known. That knowledge, which holds true within the CKM model, follows from the fact that CP is not violated in relating each of the two processes to their charge-conjugated counterparts, because a unique weak phase is involved in each relation.³²

Thus, were the p-wave (s-wave) to dominate the $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$ decays, that would also be the case for their charge-conjugated

partners. Furthermore, the p-wave (s-wave) dominates the $\Lambda_b \rightarrow \Lambda D_{CP}^0$ as well as $\bar{\Lambda}_b \rightarrow \bar{\Lambda} D_{CP}^0$ decays, except for an unlikely scenario which has observable consequences and which can be ruled out experimentally.³³ Similar arguments hold for the third case up to a minus sign [see case (c) below].

We have seen that whether or not one of the three simple cases occurs in nature can be determined from a detailed study of just the two processes $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$. Once we establish that one of those three cases occurs, the phase ϕ can be extracted from the six rates. There is no need to disentangle the s- from the p-waves for the other four processes. We now demonstrate how to extract the weak phase ϕ when the p-wave dominates.

a. p-wave dominates

When the p-wave is much larger than the s-wave, the rate essentially probes $|P|^2$. Because for the $\Lambda_b \rightarrow \Lambda D^0$ process no weak phase is involved, its p-wave amplitude is

$$P_D = |P_D| e^{i\delta_1}, \quad (4.3)$$

where δ_1 is a possible final-state phase. The $\Lambda_b \rightarrow \Lambda \bar{D}^0$ process has, in addition to the weak phase ϕ , a possible final-state phase δ_2 ,

$$P_{\bar{D}} = |P_{\bar{D}}| e^{i(\phi + \delta_2)}. \quad (4.4)$$

Consider now the third Λ_b process, $\Lambda_b \rightarrow \Lambda D_{CP}^0$. Here D_{CP}^0 are the neutral D modes with definite CP-parity, η . For a CP-even (CP-odd) D^0 mode, η equals 1 (-1). The p-wave for the process is denoted by P ,

$$P = \frac{P_D + \eta P_{\bar{D}}}{\sqrt{2}}. \quad (4.5)$$

The $\Lambda_b \rightarrow \Lambda D_{CP}^0$ rate essentially measures the square of its p-wave amplitude. Explicitly, the p-wave is

$$\sqrt{2} P = e^{i\delta_1} \left\{ |P_D| + \eta |P_{\bar{D}}| e^{i(\phi + \delta)} \right\}, \quad (4.6)$$

where $\delta = \delta_2 - \delta_1$. The three observables $|P|$, $|P_D|$ and $|P_{\bar{D}}|$ determine $\cos(\phi + \delta)$.

The three charge-conjugated processes extract $\cos(-\phi + \delta)$. The p-waves for the charge-conjugated processes are obtained by complex-conjugating the weak phase, while leaving the final-state phases unchanged. Table 3 shows the p-waves for all six processes. The p-wave for the $\bar{\Lambda}_b \rightarrow \bar{\Lambda} D_{CP}^0$ process is

$$\bar{P} = \frac{\eta \bar{P}_D + \bar{P}_{\bar{D}}}{\sqrt{2}}, \quad (4.7)$$

that is, $\sqrt{2} \bar{P} = \eta e^{i\delta_1} \left\{ |P_D| + \eta |P_{\bar{D}}| e^{i(-\phi + \delta)} \right\}. \quad (4.8)$

The quantity $\cos(-\phi + \delta)$ is extracted from the three observables $|\bar{P}|$, $|P_D|$ and $|P_{\bar{D}}|$. CP violation happens when $|\bar{P}| \neq |P|$. That is seen by a rate difference between the process $\Lambda_b \rightarrow \Lambda D_{CP}^0$ and its charge-conjugated partner, $\bar{\Lambda}_b \rightarrow \bar{\Lambda} D_{CP}^0$.

When both $\cos(\phi + \delta)$ and $\cos(-\phi + \delta)$ have been determined, trigonometry derives $\sin^2 \phi$ up to a two-fold ambiguity. That translates into a two-fold ambiguity in $\sin \phi$, because $\sin \phi$ is always negative [see eqs. (3.3)-(3.4)]. While CP violation requires a non-vanishing final-state phase difference, $\delta \neq 0 \bmod \pi$, the weak phase ϕ can, in principle, be extracted for any value of δ .

Although implausible, it might happen that while the p-wave dominates the $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$ processes (and thus also their charge-conjugated partners), it might not dominate the $\Lambda_b \rightarrow \Lambda D_{CP}^0$ mode -- that is, $|P| \approx 0$. For $|P| \approx 0$ to happen, two conditions must simultaneously be satisfied:

$$|P_D| \approx |P_{\bar{D}}|, \quad (4.9)$$

as well as $\eta e^{i(\phi + \delta)} = -1$. (4.10)

In the unlikely event that eqs. (4.9)-(4.10) occur, CP violation would happen. The p-wave for the $\Lambda_b \rightarrow \Lambda D_{CP}^0$ process would be zero, $|P| \approx 0$. A non-vanishing rate would happen because of the much suppressed s-wave. In contrast, the rate for the charge-conjugated $\bar{\Lambda}_b \rightarrow \bar{\Lambda} D_{CP}^0$ process would be large, because its p-wave would be sizeable,

$$\bar{P} = \sqrt{2} \eta e^{i(-\phi + \delta_1)} |P_D| \sin \phi. \quad (4.11)$$

Since $\sin(-\phi)$ is sizeable [see eqs. (3.3)-(3.4)], the p-wave for $\bar{\Lambda}_b \rightarrow \bar{\Lambda} D_{CP}^0$ is guaranteed to be large. We remark that the suppression of the p-wave occurs for a definite CP-parity (η). The other CP-parity would yield +1 on the right-hand side of eq. (4.10), and no suppressed rate would occur. This concludes the unlikely scenario.

If the modes $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$ both have a small s-wave contamination, one should still be able to extract the unitarity angle ϕ from the six rates alone. That follows from the fact that $|p\text{-wave}|^2$ yields the rate up to a tiny correction, which depends quadratically on the small ratio $|s\text{-wave} / p\text{-wave}|$. The third and sixth processes $[\Lambda_b \rightarrow \Lambda D_{CP}^0$ and $\bar{\Lambda}_b \rightarrow \bar{\Lambda} D_{CP}^0]$ have suppressed s-waves, except for the unlikely scenario mentioned above, where the rate for either $\Lambda_b \rightarrow \Lambda D_{CP}^0$ or $\bar{\Lambda}_b \rightarrow \bar{\Lambda} D_{CP}^0$ is suppressed. The extraction of ϕ from the six rates alone involves negligible corrections that depend on $|s\text{-wave} / p\text{-wave}|^2$. As for the unlikely scenario, the suppressed rate would be negligible in comparison with $\Gamma_D \approx \Gamma_{\bar{D}}$. Whether the main contribution to that suppressed rate arises from the p- or s-wave would be irrelevant to a first approximation for the extraction of ϕ .

b. s-wave dominates

When the s-wave dominates the six processes [eqs. (4.1)-(4.2)], the rates essentially measure $|S|^2$. Arguments similar to those given for the previous case apply. CP violation will be seen as a rate asymmetry ($\bar{\Gamma} \neq \Gamma$) between the process $\Lambda_b \rightarrow \Lambda D_{CP}^0$ and its charge-conjugated partner, $\bar{\Lambda}_b \rightarrow \bar{\Lambda} D_{CP}^0$. It requires a non-vanishing, final-state phase difference. The weak phase ϕ can, in principle, be determined for any final-state phase difference, even when it is 0 mod π .

c. Constant p- to s-wave ratio

This case assumes that there exists one complex constant, $z \in \mathbb{C}$, which relates the s- and p-waves for the $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$ processes -- that is,

$$P_D = z S_D \quad \text{and} \quad P_{\bar{D}} = z S_{\bar{D}}. \quad (4.12)$$

If eq. (4.12) holds, then the third Λ_b process satisfies

$$P = z S, \quad (4.13)$$

while all three $\bar{\Lambda}_b$ processes satisfy

$$\begin{aligned} \bar{P}_D &= -z \bar{S}_{\bar{D}}, \\ \bar{P}_D &= -z \bar{S}_D, \\ \bar{P} &= -z \bar{S}. \end{aligned} \quad (4.14)$$

No CP violation occurs with the α , β and γ parameters, since they satisfy eqs. (2.10 b)-(2.10 d). In contrast, CP non-invariance may show up as a rate asymmetry, $\bar{\Gamma} \neq \Gamma$. Up to identical constants, Γ and $\bar{\Gamma}$ are proportional to their respective s-waves,

$$\Gamma \sim (1 + |z|^2) |S|^2, \quad (4.15)$$

whereas $\bar{\Gamma} \sim (1 + |z|^2) |\bar{S}|^2$. (4.16)

The phase ϕ can again be extracted from the six rates in analogy to cases (a) or (b). Note that case (c) reduces to cases (a) or (b) in the appropriate limit.

d. General case

For the general case, the s- and p-waves for the six processes are shown in Table 4. The process $\Lambda_b \rightarrow \Lambda D^0$ has no weak phase, but may have final-state phases δ_1 and $\delta_1 + \Delta_1$ for the p- and s-waves, respectively. The observables are $|S_D|$, $|P_D|$ and Δ_1 . The $\Lambda_b \rightarrow \Lambda \bar{D}^0$ process involves the overall weak phase ϕ , with final-state phases δ_2 and $\delta_2 + \Delta_2$ for the p- and s-waves. The neutral D meson of the $\Lambda_b \rightarrow \Lambda D_{CP}^0$ process is seen in a CP eigenstate with CP-parity η ($= 1$ or -1). The s- and p-wave amplitudes are

$$\sqrt{2} S = e^{i(\delta_1 + \Delta_1)} \left\{ |S_D| + \eta |S_{\bar{D}}| e^{i(\phi + \delta + \Delta)} \right\} \quad (4.17)$$

and $\sqrt{2} P = e^{i\delta_1} \left\{ |P_D| + \eta |P_{\bar{D}}| e^{i(\phi + \delta)} \right\}, \quad (4.18)$

where $\delta = \delta_2 - \delta_1$, $\Delta = \Delta_2 - \Delta_1$.

Three independent methods, each with a two-fold ambiguity, can determine the phase $\phi + \delta$. The ambiguity can in most cases be removed by using more than one method. The first method extracts $\cos(\phi + \delta)$ from the information in the p-wave column of Table 4 alone, as was done for case (a). The second method extracts $\cos(\phi + \delta + \Delta)$ from the s-wave column. Recall that Δ is an observable final-state phase difference. This additional information may eliminate the ambiguity in $\phi + \delta$. The third method obtains the phase $\phi + \delta$ within a two-fold ambiguity, because $e^{i(\phi + \delta)}$ satisfies a quadratic equation, the coefficients of

which depend upon the observables SP^* , Δ_1 , $|S_D|$, $|S_{\bar{D}}|$, Δ , $|P_D|$ and $|P_{\bar{D}}|$ [see eqs. (4.17)-(4.18)].

The charge-conjugation transformation complex-conjugates the weak phases and leaves the final-state phases unchanged. In addition, it introduces a relative sign between the s- and p-waves, which is incorporated into the s-waves.

No CP violation can occur when the process $\Lambda_b \rightarrow \Lambda D^0$ or $\Lambda_b \rightarrow \Lambda \bar{D}^0$ is compared to its respective charge-conjugated partner, because only one weak phase is involved.³² That allows for consistency checks and may help control systematics. Turning the argument around, the mode together with its charge-conjugated partner could be added to increase statistics by a factor of two.

The first two methods extract $\cos(-\phi + \delta)$ and $\cos(-\phi + \delta + \Delta)$ from the p- and s-wave columns, respectively. The last one obtains the phase $(-\phi + \delta)$ from $\bar{S} \bar{P}^*$ and other observables, within a two-fold ambiguity. The weak phase ϕ can be obtained within a discrete ambiguity, which in general can be eliminated.

Much more difficult would be the extraction of ϕ from six related modes driven by $b \rightarrow d + D^0$. The problems which need to be overcome for that extraction have been mentioned elsewhere in the context of B-meson modes.¹⁷ When modes of baryons are considered, the s- and p-waves must also be disentangled.

This section has shown that the extraction of ϕ is possible under any circumstance -- that is, whether or not CP-violating effects are seen. The next section attempts estimates of the observables for the $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$ examples.

5. Predictions

This section attempts to estimate the observables for the two $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$ examples in the previous section. Because we know of no satisfactory way to predict final-state phases, they will not be estimated here. Factorization predicts $\alpha \approx -1$ for the $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$ processes. Because no CP violation can occur in comparing those processes with their corresponding charge-conjugated partners (since unique CKM elements are involved in their respective decays), $\bar{\alpha} \approx 1$ for $\bar{\Lambda}_b \rightarrow \bar{\Lambda} \bar{D}^0$ and $\bar{\Lambda}_b \rightarrow \bar{\Lambda} D^0$.³² When $|\alpha| \approx 1$, β and γ would be small (recall the constraint $\alpha^2 + \beta^2 + \gamma^2 = 1$). No initial polarization is then required, because all the information about the relative s- and p-wave strengths would be obtained simply by analyzing the subsequent decay of the final baryon ($\Lambda \rightarrow p\pi^-$). Case (c) introduced in Section 4 would hold and ϕ could be extracted from the six rates alone.

With further assumptions about form factors, factorization estimates a branching rate at the 10^{-5} level for $\Lambda_b \rightarrow \Lambda D^0$. The $\Lambda_b \rightarrow \Lambda D_{CP}^0$ process, where CP violation could occur, then has a rate at the 10^{-7} level, since the fraction of D^0 decaying into CP eigenstates is a few percent.¹⁸

There are objections to the validity of the factorization assumption. In addition to the factorizable diagrams, non-factorizable ones exist for both $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$ decays (see Figures 3 and 4, respectively).³⁴ The factorizable diagrams show that the diquark of the b-baryon remains the diquark of the Λ . In contrast, the non-factorizable graph of Fig. 4(b) shows that the original diquark breaks up during the weak transition, where its up quark and the $\bar{c}$ together create the $\bar{D}^0$. The non-factorizable graph of Fig. 4(a) should also be taken into account. A related objection to the validity of factorization for the modes considered here arises from rescattering effects.

Factorization for two-body modes may be more justifiable for colour-allowed processes than for colour-suppressed ones (see Fig. 5).³⁵ The reason is simple. Within the factorization assumption, rates of colour-suppressed modes are tiny with respect to colour-allowed ones. The colour-allowed modes may rescatter via final-state interactions and yield a larger rate for the colour-suppressed processes, for instance $\Lambda_b \rightarrow \Lambda_c^+ K^{(*)-} \rightarrow \Lambda D^0$ or $\Lambda_b \rightarrow p D_s^{(*)-} \rightarrow \Lambda \bar{D}^0$.

Because the six related processes of the $\Lambda_b \rightarrow \Lambda D^0$ example are colour-suppressed, such rescatterings would render our predictions unreliable. However, far from being a bother, rescattering would be a blessing. The rates -- and thus, the observability of the processes -- would probably be larger than the estimates based upon colour-suppressed factorization alone. Because final-state interactions would be involved, it would be possible for final-state phases to occur. Those phases are important for creating sizeable CP-violating effects. Furthermore, the factorization prediction that $|\alpha| \approx 1$ need not hold. CP-violating effects might be seen in all the decay parameters: $\Gamma, \alpha, \beta, \gamma$. The unitarity angle ϕ could always be extracted (see Section 4), regardless of whether rescattering occurs or the factorization approximation holds.

A good mode for testing colour-suppressed factorization is $\Lambda_b \rightarrow \Lambda \Psi$. It has a very clean experimental signature and is CKM-favoured. Factorization predicts a branching ratio at the 10^{-3} level. The experimental situation is a bit confused. The CDF collaboration does not see any such signal and quotes a preliminary upper limit of $f_{\Lambda_b} \times B(\Lambda_b \rightarrow \Lambda \Psi) < 5.5 \times 10^{-4}$ (90% CL),³⁶ while the UA(1) collaboration claims to have found a positive signal.³⁷ $f_{\Lambda_b} \times B(\Lambda_b \rightarrow \Lambda \Psi) = (1.8 \pm 1.1) \times 10^{-3}$. Here f_{Λ_b} is the fraction of b-quarks that hadronize into a Λ_b , argued to be at the 10% level.³⁷

The rest of this section derives the predictions in a technical manner. Three approaches for estimating the observables are presented. They all use the factorization assumption, where the Hamiltonian factorizes into two currents. One current creates a $\bar{D}^0$ from the vacuum, while the other causes the $\Lambda_b \rightarrow \Lambda$ transition. Whereas the first approach treats only Λ_b as a heavy baryon and allows Λ to be considered light, the second assumes that both Λ_b and Λ are heavy. The third approach looks at the $\Lambda_b \rightarrow \Lambda$ as the quark transition $b \rightarrow s$ -- that is, the diquark is considered a spectator which does not appreciably interact during the transition.

Explicitly, factorization means that

$$\begin{aligned} \langle \Lambda \bar{D}^0 | H_{\text{eff}} | \Lambda_b \rangle &\sim a_2 \langle \bar{D}^0 | \bar{c} \gamma_\mu \gamma_5 u | 0 \rangle \langle \Lambda | \bar{s} \gamma^\mu (1 - \gamma_5) b | \Lambda_b \rangle = \\ &= a_2 \langle \bar{D}^0 | \bar{c} \gamma_\mu \gamma_5 u | 0 \rangle \langle \Lambda | \bar{s} \gamma^\mu (1 - \gamma_5) b | \Lambda_b \rangle. \end{aligned} \quad (5.1)$$

We use the colour-suppression parameter^{35, 38} $|a_2| = 0.2$, and the $\bar{D}^0$ decay constant^{39, 38} $f_D = 220$ MeV. The 4-momentum of the particle is denoted by the symbol of the particle -- D_μ for the $\bar{D}^0$ and below s_μ and Λ_μ for the s-quark and Λ .

All three approaches predict $\alpha \approx -1$ for the $\Lambda_b \rightarrow \Lambda \bar{D}^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$ processes. The numerical values for a_2 , f_D , and the relevant CKM elements are irrelevant for this prediction, because they all cancel. In contrast to the estimate for α , a rate estimate requires the value of the form factors at the momentum transfer scale, $q^2 = m_D^2$.

The decay parameter α is discussed first. The 4-momentum and mass of the Λ is (k, m) , while the 4-velocity and mass of the Λ_b is (v, M) . Thus, $q^2 = (k - M v)^2$. For a transition described by an arbitrary Dirac matrix R , the first approach involves two real form factors, $F_1(q^2)$ and $F_2(q^2)$,⁴⁰

$$\langle \Lambda | \bar{s} R b | \Lambda_b \rangle = \bar{u}_\Lambda(k) (F_1 + F_2 \not{v}) R u_{\Lambda_b}(v). \quad (5.2)$$

Because the b-quark can probably be considered heavy, the two form factors F_1 and F_2 describe the most general $\Lambda_b \rightarrow \Lambda$ transition. We do not know how to predict F_1 and F_2 . We do know, however, that in the heavy s-quark limit, F_2 / F_1 tends to zero. Since the s-quark has an intermediate mass, we expect the ratio $|F_2 / F_1|$ to be small. While no rate is estimated within this approach, Figure 6 plots α as a function of F_2 / F_1 . The parameter $\alpha \approx -1$, for it is likely that $|F_2 / F_1| \lesssim 1$ [see Fig. 6(a)].

The second approach treats the s-quark as heavy. The transition involves a unique form factor, $F(q^2)$,⁴¹

$$\langle \Lambda | \bar{s} R b | \Lambda_b \rangle = F(q^2) \bar{u}_\Lambda R u_{\Lambda_b}. \quad (5.3)$$

This approach predicts $\alpha \approx -1$ without arbitrariness, because the unique form factor cancels.

A branching ratio of 10^{-5} is obtained for the $\Lambda_b \rightarrow \Lambda \bar{D}^0$ decay when we use

$$|F(m_D^2)|^2 \approx 0.1. \quad (5.4)$$

Eq. (5.4) is obtained when the q^2 dependence is chosen as

$$F(q^2) \sim \frac{1}{1 - \left(\frac{q^2}{m_{bs}^2}\right)^2}, \quad \text{with } m_{bs} = 5.4 \text{ GeV}. \quad (5.5)$$

At maximum momentum transfer, that $F(q_{\text{max}}^2) = 1$ is assumed -- that is, the $\Lambda_b \rightarrow \Lambda$ wave-function overlap is taken as 1, which is an overestimate. In addition to the form factor, we use the known masses for $\bar{D}^0$ and Λ ,⁴² and 5.64 GeV for the Λ_b .^{43, 37} The branching ratio,

$$B(\Lambda_b \rightarrow \Lambda \bar{D}^0) = 1.36 \times 10^{-5} \left(\frac{|a_2|}{0.2}\right)^2 \left(\frac{f_D}{220 \text{ MeV}}\right)^2 \left(\frac{|F(m_D^2)|^2}{0.114}\right) \left(\frac{|V_{cb} V_{us}|^2}{0.046 \times 0.22}\right) \left(\frac{\tau}{1.2 \text{ psec}}\right), \quad (5.6)$$

follows from

$$\Gamma(\Lambda_b \rightarrow \Lambda D^0) = \frac{G_F^2 |V_{cb}|^2 |V_{us}|^2 f_D^2}{8 \pi M^2} \left[(M^2 - m^2)^2 - m_D^2 (M^2 + m^2) \right]. \quad (5.7)$$

Here $\vec{k}_D$ is the 3-momentum of the D^0 in the Λ_b rest frame, and recall that the masses of the Λ_b and Λ are M and m , respectively.

To obtain the above equation, the transition matrix element [eq. (5.1)] is simplified to

$$\langle \Lambda D^0 | H_{\text{eff}} | \Lambda_b \rangle \sim a_2 f_D \bar{u}_\Lambda [M(1 + \gamma_5) - m(1 - \gamma_5)] u_{\Lambda_b}. \quad (5.8)$$

This simplification can be obtained in several ways. One way is to introduce the Λ and Λ_b spinors by applying eq. (5.3) with $R = \gamma^\mu(1 - \gamma_5)$. Once the 4-momentum of D^0 is expressed in terms of that for Λ_b minus that for Λ and contracted with γ^μ , Dirac equations upon the spinors yield eq. (5.8).

Another way to prove eq. (5.8) is to use Dirac equations on the quark currents and the implicit assumption that both the heavy quark and its baryon have the same 4-velocity,

$$s_\mu / m_s = \Lambda_\mu / m. \quad (5.9)$$

Because m_s cancels, we obtain

$$D_\mu \bar{s} \gamma^\mu (1 - \gamma_5) b = \bar{s} \left[M(1 + \gamma_5) - \frac{m}{m_s} m_s (1 - \gamma_5) \right] b, \quad (5.10)$$

irrespective of whether constituent or current masses are used for the s-quark. Eq. (5.3) with $R = 1 \pm \gamma_5$ yields the simplification [eq. (5.8)].

The third approach considers the $\Lambda_b \rightarrow \Lambda D^0$ transition as $b \rightarrow s D^0$,

$$\langle \Lambda | \bar{s} \gamma^\mu (1 - \gamma_5) b | \Lambda_b \rangle \sim \bar{u}_s \gamma^\mu (1 - \gamma_5) u_b. \quad (5.11)$$

Once the quark masses $m_b = 5 \text{ GeV}$ and $m_s = 0.5 \text{ GeV}$ are used, the predictions $\alpha = -1$ and $B(b \rightarrow s D^0) \sim 10^{-4}$ follow. In summary, assuming factorization we

derived for the process $\Lambda_b \rightarrow \Lambda D^0$ that $\alpha \approx -1$ and that its branching ratio is at the 10^{-5} level.

Let us turn now to the $\Lambda_b \rightarrow \Lambda \bar{D}^0$ process. Within the factorization assumption, the $\Lambda_b \rightarrow \Lambda \bar{D}^0$ decay is analogous to the $\Lambda_b \rightarrow \Lambda D^0$ one, except for different CKM elements. Factorization predicts the same α parameters for both decays and

$$\frac{B(\Lambda_b \rightarrow \Lambda \bar{D}^0)}{B(\Lambda_b \rightarrow \Lambda D^0)} = \left| \frac{V_{ub} V_{cs}}{V_{cb} V_{us}} \right|^2 \approx \frac{1}{4}. \quad (5.12)$$

Case (c) of Section 4 applies when $\alpha = -1$ for both $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$. Then CP violation between $\Lambda_b \rightarrow \Lambda D_{CP}^0$ and $\bar{\Lambda}_b \rightarrow \bar{\Lambda} D_{CP}^0$ decays will not be seen in the α, β, γ decay parameters, while it may be seen as a rate asymmetry. For the rate asymmetry to happen, a non-vanishing final-state phase difference must exist between the $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$ amplitudes. In contrast to the CP-violating rate asymmetry, the weak phase ϕ could be extracted from the rates of the six processes alone, irrespective of whether or not the final-state phase difference vanishes (see Section 4).

Finally we wish to discuss the $\Lambda_b \rightarrow \Lambda \Psi$ process. Factorization estimates that

$$B(\Lambda_b \rightarrow \Lambda \Psi) = 1.36 \times 10^{-3} \left(\frac{|a_2|}{0.2} \right)^2 \left(\frac{f_\Psi}{384 \text{ MeV}} \right)^2 \left(\frac{|F(m_\Psi)|^2}{0.197} \right) \left(\frac{|V_{cb} V_{cs}|}{0.046 \times 0.98} \right)^2 \left(\frac{\tau}{1.2 \text{ psec}} \right) \quad (5.13)$$

The Ψ decay constant is obtained from its leptonic width,^{44, 42} $f_\Psi = 384 \text{ MeV}$, and our assumptions about the form factor yield $|F(m_\Psi)|^2 = 0.197$ [see the discussion after eq. (5.4)]. Finally, when the underlying $b \rightarrow s \Psi$ transition is studied, $B(b \rightarrow s \Psi) \approx 5 \times 10^{-3}$. That branching ratio is consistent with the experimental result from B mesons, $B(B \rightarrow \Psi X) \approx 10^{-2.45}$.

Colour-suppressed factorization predicts $B(\Lambda_b \rightarrow \Lambda D^0) = 10^{-5}$, $B(\Lambda_b \rightarrow \Lambda \bar{D}^0) / B(\Lambda_b \rightarrow \Lambda D^0) = (|V_{ub}V_{cs}| / |V_{cb}V_{us}|)^2$ and $\alpha \approx -1$ for the two processes $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$. Because only a few percent of the D^0 modes are CP eigenstates, the branching ratio for the CP-violating decay $\Lambda_b \rightarrow \Lambda D_{CP}^0$ is at the 10^{-7} level. Rescattering effects and non-factorizable diagrams (see Fig. 4) might invalidate the factorization assumption for those modes. If that turns out to be the case, larger branching ratios and decay parameters different than predicted are likely to happen. Final state interactions would probably be involved, and thus final-state phase differences could arise. Those phase differences are important for large CP-violating effects to occur.

6. Other modes

Previous sections focused on modes with a D^0 , where large CP-violating effects could occur. Those modes in no way exhaust the possibilities for observing sizeable effects. Many other modes could exhibit promising CP-violating effects in partial decay rates and in other decay parameters. Their branching ratios are at the 10^{-5} – 10^{-6} level, and a few have clean experimental signatures with large detection efficiencies. In contrast, the branching ratios for modes with a D^0 are tiny, partly because the D^0 must be seen in rare channels so as to allow for potentially large CP violation.

The modes of Table 5 involve amplitudes with different weak phases. See Figure 7 where the spectator, penguin and W-exchange diagrams are shown. The W-exchange diagram is a tree graph which only exists for decays of bottom baryons with a valence up quark (or a valence charm quark).

The estimates in Table 5 use the concept of c.s. (colour-suppressed) and c.a. (colour-allowed) modes^{35, 38} and the existing literature about the

magnitudes of spectator and penguin contributions.^{9–12} Refs. 9–12 estimate the final-state phase difference from the absorptive parts of penguin diagrams. Rescattering effects could introduce additional final-state phase differences for exclusive modes, which are uncalculable nowadays. To develop a feeling for the optimal possible CP-violating effects, the final-state phase difference is chosen to maximize the rate asymmetry, denoted by optimal asymmetry. This asymmetry also uses the fact that $\sin(-\phi)$ could be close to 1 [see eq. (3.4)]. For the Λ_b and Ξ_b^0 modes the additional W-exchange diagram is assumed to have strength comparable to that of a c.a. spectator amplitude that would be governed by identical CKM elements.

We have not taken into account any of the special dynamics involved for a given exclusive mode. Rescattering effects and the detailed dynamics for specific modes could invalidate the estimates for the branching ratio and optimal asymmetry. Thus, the branching ratios could be off by orders of magnitude and the optimal asymmetries of Column 4 might vary up to an order of magnitude or more, for different exclusive modes. The optimal asymmetry should be regarded as an indication of how large CP-violating effects could possibly be under optimal conditions. It would be surprising if real life would show effects as large. The promising exclusive modes of Table 1 require detailed theoretical investigations into their actual branching ratios and CP-violating effects, not only in partial decay rates but in other decay parameters as well.

Table 5 presents examples of exclusive modes (Column 2) governed by the quark-transition (Column 1), their typical branching ratios (Column 3), and their optimal asymmetry (Column 4). In Column 2, $\bar{D}^0$ stands for either K^0 , $K^{*+}\pi^-$, K^{*0} , or other resonances of a K^0 ; Z^+ stands for either K^+ , K^{*+} , or other resonances of a K^+ ; X^+ stands for either π^+ , ρ^+ , a_1^+ , or other resonances with a “u $\bar{d}$ ” quark-

content; X^0 stands for either π^0 , ρ^0 , ω , a_1^0 , or other such resonances; and N stands for either a neutron or one of its resonances. Whether some subset of exclusive modes could be summed over and still show potentially large CP-violating effects is an open question. The summation can not be too inclusive, however, because then no effects would be seen.⁴⁶

Because many sizeable CP-violating effects require large final-state phase differences, it is crucial to predict them more reliably. Sizeable final-state phases might not occur for the modes of Table 5. Then the optimal CP-violating effects (Column 4 of Table 5) are academic and cannot be reached. CP violation in naive T-odd operators [see, for instance, eq. (2.11 c)] might still be seen.

The list of exclusive modes of Table 5 is not exhaustive. It is a simple exercise to determine the underlying quark-subprocesses of additional promising modes. The typical branching ratios of these modes and their optimal CP-violating effects can then be constructed from Table 5.

For the $b \rightarrow d + \bar{s}s$ and $d + \bar{d}d$ ($b \rightarrow s + \bar{s}s$ and $s + \bar{d}d$) quark-subprocesses, the Ξ_b^- and Ω_b^- modes involve only the penguin diagram, while the Λ_b and Ξ_b^0 have the additional W-exchange contribution governed by $V_{ub}V_{ud}^*$ ($V_{ub}V_{us}^*$). For the $b \rightarrow d + \bar{u}u$ ($b \rightarrow s + \bar{u}u$) transition, the Ξ_b^- and Ω_b^- involve penguin and spectator graphs, but no W-exchange ones. The Λ_b and Ξ_b^0 modes involve all three diagrams, where the spectator and W-exchange graphs are governed by the same CKM combination $V_{ub}V_{ud}^*$ ($V_{ub}V_{us}^*$).

In contrast, the spectator and W-exchange graphs have different CKM combinations for Λ_b and Ξ_b^0 modes governed by $b \rightarrow d + \bar{c}c$. The spectator graph is governed by $V_{cb}V_{cd}^*$, and the W-exchange graph by $V_{ub}V_{ud}^*$. The CKM elements are comparable in magnitude and differ by the weak phase ϕ . The penguin graph also contributes. The W-exchange and penguin graphs are

suppressed in comparison with the spectator, because the $c\bar{c}$ pair is created from as many gluons as needed. Interesting CP-violating effects are possible under optimal circumstances. Table 5(e) shows that the $\Xi_b^0 \rightarrow \Lambda \psi$ branching ratio is at the 10^{-5} level. We selected this mode since the CDF collaboration and UA(1) can already observe it. The mass resolution of this mode must be good enough, however, to discriminate against the much larger background $\Lambda_b \rightarrow \Lambda \psi$. Good mass resolution and good particle identification are essential for many of the modes considered here.

Some modes of weakly decaying bottom baryons with a valence charm quark could have remarkable CP-violating effects. Those modes have two interfering tree graphs with CKM combinations that differ by the weak angle ϕ . The spectator amplitude, $b \rightarrow u + \bar{u}d$, is governed by $V_{ub}V_{ud}^*$, while the W-exchange one, $bc \rightarrow cd$, by $V_{cb}V_{cd}^*$. The two interfering amplitudes could be comparable and large CP-violating effects could occur. Penguin contributions also exist.

Even modes with a photon may show CP-violating effects, at the 0.1-1% level for $b \rightarrow s + \gamma$ processes and at the 1-10% level for $b \rightarrow d + \gamma$ ones.²⁰ Their inclusive branching ratios are estimated at a few 10^{-4} and a few 10^{-5} , respectively.^{47, 20} Examples for $b \rightarrow d + \gamma$ processes are

$$\Lambda_b \rightarrow N \gamma, \Xi_b^0 \rightarrow \Lambda^0 \gamma, \Xi_b^0 \rightarrow \Sigma^0 \gamma, \Xi_b^- \rightarrow \Sigma^- \gamma, \Omega_b^- \rightarrow \Xi^- \gamma, \quad (6.1)$$

while examples for $b \rightarrow s + \gamma$ processes are

$$\Lambda_b \rightarrow \Lambda \gamma, \Xi_b^0 \rightarrow \Xi^0 \gamma, \Xi_b^- \rightarrow \Xi^- \gamma, \Omega_b^- \rightarrow \Omega^- \gamma. \quad (6.2)$$

The single hard photon provides a clean experimental signature, which makes the modes in eqs. (6.1)-(6.2) attractive.

Finally, branching ratios and CP-violating effects with rare decays of b-flavoured baryons could also be investigated. Examples for the $b \rightarrow d + \ell^+ \ell^-$ transition are

$$\Lambda_b \rightarrow N \ell^+ \ell^+, \Xi_b^0 \rightarrow \Lambda^0 \ell^+ \ell^+, \Xi_b^0 \rightarrow \Sigma^0 \ell^+ \ell^+, \Xi_b^- \rightarrow \Sigma^- \ell^+ \ell^+, \Omega_b^- \rightarrow \Xi^- \ell^+ \ell^+, \quad (6.3)$$

while examples for $b \rightarrow s + \ell^+ \ell^-$ processes are

$$\Lambda_b \rightarrow \Lambda \ell^+ \ell^-, \Xi_b^0 \rightarrow \Xi^0 \ell^+ \ell^-, \Xi_b^- \rightarrow \Xi^- \ell^+ \ell^-, \Omega_b^- \rightarrow \Omega^- \ell^+ \ell^-. \quad (6.4)$$

This section lists many modes of b-flavoured baryons with typical branching ratios at the 10^{-5} – 10^{-6} level and with potentially large CP-violating effects. Progress on both the theoretical and experimental fronts is desirable. Quantitative estimates of final-state phase differences, of branching ratios, and of all the CP-violating effects for a few choice modes could guide experimentalists toward the optimal modes. On the other hand, experimentalists could search for CP-violating effects in the promising modes of Tables 1 or 5, regardless of whether theoretical progress is made in predicting observables and final-state phase differences. The cooperation between theorists and experimentalists will prove to be fruitful on both fronts. It will allow us to take full advantage of a program with modes of b-flavoured baryons. Finding the most promising modes will probably come about by such a cooperation between new experimental measurements and theoretical calculations.

7. Conclusions

Many exclusive modes of bottom baryons have the potential for large CP-violating effects. By comparing a mode with its charge-conjugate, those effects could be seen as a partial rate asymmetry or in other decay parameters as well. Not all CP-violating effects require non-vanishing final-state phase differences. For instance, coefficients of naive T-odd operators could show CP violation even in their absence [see, for instance, eq. (2.11 c)]. The detailed comparisons

between modes of charmed or beautiful baryons with their charge-conjugated partners test CP violation in a model-independent manner.

CP violation studies with modes of baryons have a two-fold advantage over the classic modes of neutral B-mesons, such as $B_d \rightarrow \bar{\psi} K_S$ or $B_s \rightarrow \rho^0 K_S$, ωK_S . Since baryon number is conserved, neither tagging nor time-dependences are required for modes of baryons, while they are required for modes of the neutral B-mesons. A disadvantage is that there is no guarantee that sizeable effects will occur with modes of baryons, though they might be large under optimal circumstances.

Polarization studies of heavy baryons are not only interesting in their own right, but may aid in probing CP violation, which remains one of the more fundamental questions in high energy physics. Even without information about the polarization of the heavy baryon, CP violation can be tested in the partial decay rates and the decay parameters that do not require an initial polarization. For instance, an analysis of the subsequent decay of the final baryon can obtain the α parameter without information about the initial polarization (see Section 2). Knowledge of the initial polarization, however, completes the picture and allows CP-violating tests in additional decay parameters.

Currently the CKM model accounts for the observed CP violation in K_L . It allows for potentially large effects for many modes of bottom baryons. Among the many attractive modes, a few involve a D^0 . In addition to having potentially sizeable CP-violating effects, the modes with a D^0 can determine the angle ϕ , which is the most problematic angle of the unitarity triangle (see Fig. 1). The conventional way to determine that angle is by a CP-violating study of the $B_s \rightarrow \rho^0 K_S$, ωK_S modes, with predicted tiny rates and inherent theoretical difficulties. Other existing suggestions to probe ϕ are modes of B-mesons with 14 – 17 a D^0 or time-dependent studies of $B_s \rightarrow D^{(*)-} K^{*+}$.²¹

the weak phase ϕ by removing a final-state phase difference. The removal is accomplished as follows. For a given helicity configuration, the magnitudes of all three amplitudes, the two interfering ones as well as the total amplitude, are observables. That is, all three sides of a helicity-amplitude triangle are measurable. Once the analogous measurements are made for the charge-conjugated processes, the final-state phases can be removed and the weak phase ϕ determined. In principle, the weak phase ϕ can always be extracted, regardless of the existence of a final-state phase difference.

Although Section 4 discussed this idea in the equivalent LS-scheme, we chose to summarize it via the helicity-formalism, because the helicity-formalism allows simple generalizations. In principle, enough decay parameters exist to extract the weak phase ϕ from six related processes of the sort $1/2 \rightarrow 3/2 + 0$, such as $\Omega_b^- \rightarrow \Omega^- D_{CP}^0$.

The study of CP violation with b-flavoured baryons warrants a dedicated program. In addition to the modes with a D^0 , numerous new modes could have promising, large CP-violating effects. Those large CP non-invariance effects could be seen in any of the decay parameters when a process is compared with its charge-conjugated partner. Examples for non-leptonic modes can be found in Table 5. Table 1 lists the more promising ones among them. Even modes with a single hard photon and other rare decays may show sizeable CP-violating effects, although their branching ratios are suppressed.

Quantitative calculations for the observables of many promising exclusive modes would be helpful, since our estimates could be off by orders of magnitude. Much progress would be made if the final-state phases could be more reliably calculated. Currently, only their short-distance origins have been addressed,⁹⁻¹² while rescattering effects await quantitative studies. Our hope is

Large CP violation can occur and the weak phase ϕ be extracted when a mode with a D^0 interferes with that with a $\bar{D}^0$. Two scenarios were considered:

- (a) either the $b \rightarrow s + D^0$ amplitude interferes with the $b \rightarrow s + \bar{D}^0$ one, or
- (b) the $b \rightarrow d + D^0$ amplitude interferes with the $b \rightarrow d + \bar{D}^0$ one.

The interference is accomplished in the former case when the D^0 is seen in a CP eigenstate, while in the latter the D^0 is seen in a doubly-Cabibbo-suppressed mode, g. The interfering amplitudes then have comparable magnitudes and differ by the weak phase ϕ . No contamination by other weak phases is possible, in contrast to the conventional $B_s \rightarrow \rho^0 K_S, \omega K_S$ modes. Large CP violation could occur when the processes are compared with their charge-conjugated counterparts. Examples can be found in eqs. (3.2) and (3.5). Not only is large CP violation in the rates $\bar{\Gamma} \neq \Gamma$ possible, but also in the other decay parameters, such as in α, β, γ for $1/2 \rightarrow 1/2 + 0$ processes. Sizeable effects could also occur when the D^0 is replaced by its resonances, such as D^{*0} .

Concerning feasibility, the decay parameters for the Λ_b example were estimated. While factorization predicts $\alpha \approx -1$ for the $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$ processes and for $B(\Lambda_b \rightarrow \Lambda D^0) \sim 10^{-5}$, rescattering effects could increase the rate and introduce final-state phases. Those final-state phases are important for large CP-violating effects. The fraction of CP eigenstates of the D^0 modes is at the few percent level. Thus, a rate of 10^{-5} for $\Lambda_b \rightarrow \Lambda D^0$ translates into 10^{-7} for $\Lambda_b \rightarrow \Lambda D_{CP}^0$. Although 10^{-7} is a small rate, CP-violating effects could be seen. The effects are potentially large and neither tagging nor time-dependences are required.

Section 4 showed how to extract the weak phase ϕ from modes of bottom baryons of the sort $1/2 \rightarrow 1/2 + 0$. Six related processes -- such as $\Lambda_b \rightarrow \Lambda D^0$, $\Lambda_b \rightarrow \Lambda \bar{D}^0$, $\Lambda_b \rightarrow \Lambda D_{CP}^0$, and their three charge-conjugated partners -- obtain

that future proposals which aim at observing CP violation with B mesons will also incorporate many promising modes of b-flavoured baryons.

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References

- 1 J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. **13**, 138 (1964).
- 2 I. I. Bigi, V. A. Khoze, N. G. Uraltsev and A. I. Sanda, in "CP Violation," ed. C. Jarlskog (World Scientific, Singapore, 1989), p. 175.
- 3 I. I. Bigi and B. Stech, in Proceedings of the Workshop on High Sensitivity Beauty Physics at Fermilab, Batavia, IL, November 11-14, 1987, edited by A. J. Slaughter, N. Lockyer, and M. Schmidt, p. 239.
- 4 T. D. Lee and C. N. Yang, Phys. Rev. **108**, 1645 (1957).
- 5 J. W. Cronin and O. E. Overseth, Phys. Rev. **129**, 1795 (1963).
- 6 W. Koch, in "Analysis of scattering and decay," ed. by M. Nikolic (Gordon and Breach, New York-London-Paris, 1968), p. 231.
- 7 T. D. Lee, in "Preludes in Theoretical Physics," edited by A. De-Shalit, H. Feshbach and L. Van Hove (North-Holland Publishing Company, Amsterdam, 1966), p. 5.
- 8 O. E. Overseth and S. Pakvasa, Phys. Rev. **184**, 1663 (1969).
- 9 M. Bander, D. Silverman, and A. Soni, Phys. Rev. Lett. **43**, 242 (1979).
- 10 H. Simma, G. Eilam and D. Wyler, Nucl. Phys. **B352**, 367 (1991).
- 11 J.-M. Gérard and W. S. Hou, Phys. Lett. **B253**, 478 (1991); and Phys. Rev. **D43**, 2909 (1991).
- 12 H. Simma and D. Wyler, Phys. Lett. **B272**, 395 (1991).
- 13 M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49** (1973) 652.
- 14 M. Gronau and D. London, Phys. Lett. **B253**, 483 (1991).
- 15 M. Gronau and D. Wyler, Phys. Lett. **B265**, 172 (1991).
- 16 I. Dunietz, Phys. Lett. **B270**, 75 (1991).

- 17 I. Dunietz, preprint, CERN-TH.6239/91 (1991), to be published in "B Decays," edited by S. Stone.
- 18 I. Dunietz and A. Snyder, Phys. Rev. **D43**, 1593 (1991); see especially the longer version, SLAC report, SLAC-PUB-5234, 1990 (unpublished).
- 19 I. Dunietz, H. Quinn, A. Snyder, W. Toki and H. J. Lipkin, Phys. Rev. **D43**, 2193 (1991).
- 20 J. M. Soares, Nucl. Phys. **B367**, 575 (1991).
- 21 R. Aleksan, I. Dunietz and B. Kayser, preprint, CERN-TH.6238/91 (1991), to be published in Z. Phys. C.
- 22 R. Aleksan, I. Dunietz, B. Kayser and F. Le Diberder, Nucl. Phys. **B361**, 141 (1991).
- 23 A. B. Carter and A. I. Sanda, Phys. Rev. Lett. **45**, 952 (1980); Phys. Rev. **D23**, 1567 (1981); L. Wolfenstein, Ann. Rev. Nucl. Part. Sci. **36**, 137 (1986); I. I. Bigi and A. I. Sanda, Phys. Lett. **B211**, 213 (1988).
- 24 E. D. Commins and P. H. Bucksbaum, "Weak Interactions of Leptons and Quarks," (Cambridge University Press, Cambridge, U. K., 1983); W. Koch, ref. 6; G. Källén, "Elementary Particle Physics," (Addison-Wesley Publishing Company, Reading, Mass., 1964).

25 The example of $\Lambda_b \rightarrow \Lambda D^0$ as a way to measure the decay parameters is reviewed here. The decay parameters α, β, γ for the $\Lambda_b \rightarrow \Lambda D^0$ process can be extracted from the angular distribution of the subsequent $\Lambda \rightarrow p \pi^-$ decay, as follows:

$$\begin{aligned}
 I(\theta_3) &= 1 + \alpha_\Lambda \cos \theta_3, \\
 I(\theta_2) &= 1 - \frac{\pi}{4} \alpha_\Lambda P_{\Lambda_b} \beta \cos \theta_2, \\
 I(\theta_1) &= 1 - \frac{\pi}{4} \alpha_\Lambda P_{\Lambda_b} \gamma \cos \theta_1.
 \end{aligned}$$

Here $\vec{P}_{\Lambda_b}$ and $\alpha_\Lambda \approx 0.64$ denote the Λ_b polarization and the known decay parameter for $\Lambda \rightarrow p \pi^-$, respectively. In the definition of the angles $\cos \theta_k \equiv \hat{p} \cdot \hat{e}_k$, $\hat{p}$ is the emission direction of p in the Λ rest frame, and the $\hat{e}_k$ are defined in the Λ_b rest frame as

$$\begin{aligned}
 \hat{e}_3 &\equiv \hat{\Lambda}, \\
 \hat{e}_2 &\equiv \vec{P}_{\Lambda_b} \times \hat{\Lambda} / |\vec{P}_{\Lambda_b} \times \hat{\Lambda}|, \\
 \hat{e}_1 &\equiv (\vec{P}_{\Lambda_b} \times \hat{\Lambda}) \times \hat{\Lambda} / |\vec{P}_{\Lambda_b} \times \hat{\Lambda}|.
 \end{aligned}$$

The emission direction of Λ in the Λ_b rest frame is denoted by $\hat{\Lambda}$. The azimuthal dependence has been integrated out in the intensities $I(\theta_k)$ [for $k = 1, 2, 3$].

From $I(\theta_3)$ and the known $\alpha_\Lambda \approx 0.64$, the decay parameter α can be extracted. The initial polarization can be measured from modes with much larger data samples than the very rare exclusive modes of interest in this work, which have potentially large CP-violating effects. Thus, β and γ can be obtained from the measured intensities $I(\theta_2)$ and $I(\theta_1)$. Although this footnote uses a non-relativistic framework, the relations remain true for particles in relativistic motion when an elaborate procedure of boosts is applied, see W. Koch, ref. 6.

- 26 For a review see J. Lach, Fermilab report, 1991, FERMILAB-Conf-91/200.
- 27 A. De Rujula et al., in Proc. of LHC Workshop (Aachen 1990), edited by G. Jarlskog and D. Rein, CERN 90-10, Vol. II, p. 201.
- 28 M. Jacob and G. C. Wick, Ann. Phys. (N. Y.) **7**, 404 (1959); W. Koch, ref. 6.
- 29 J. Seguinot and T. Ypsilantis, CERN report, 1991, CERN-LAA/PI/91-004.
- 30 C.O. Dib, I. Dunietz, F.J. Gilman and Y. Nir, Phys. Rev. **D41**, 1522 (1990).

- 31 J. L. Rosner, Enrico Fermi Institute report, 1991, EFL 91-49, to be published in "B Decays," edited by S. Stone; M. Schmidtler and K. R. Schubert, Z. Phys. C53, 347 (1992).
- 32 New physics could introduce CP-violating effects between $\Lambda_b \rightarrow \Lambda D^0$ and its charge-conjugated counterpart, and between $\Lambda_b \rightarrow \Lambda \bar{D}^0$ and its counterpart. We thank L. Lavoura for pointing this out to us.
- 33 The unlikely scenario requires equality between the $\Lambda_b \rightarrow \Lambda D^0$ and $\Lambda_b \rightarrow \Lambda \bar{D}^0$ rates. It would cause a much suppressed rate in either $\Lambda_b \rightarrow \Lambda D_{CP}^0$ or $\bar{\Lambda}_b \rightarrow \bar{\Lambda} D_{CP}^0$, which would show up as a large CP-violating rate asymmetry. Finally, no suppression in rate would occur when the D^0 is seen in modes with the opposite CP-parity.
- 34 This non-factorizable graph is absent in the 6 relevant processes of $\Xi_b^- \rightarrow \Xi^- D^0$ and $\Omega_b^- \rightarrow \Omega^- D^0$, because no valence u-quark exists in the initial b-flavoured baryon.
- 35 For a definition of colour-allowed and colour-suppressed processes see, for instance, M. Bauer, B. Stech and M. Wirbel, Z. Phys. C34, 103 (1987).
- 36 Avi Yagil, talk presented at La Thuile, March 1992.
- 37 C. Albajar et al., Phys. Lett. B273, 540 (1991).
- 38 M. Neubert et al., Heidelberg report, HD-THEP-91-28, 1991, to be published in "Heavy Flavours," edited by A. J. Buras and M. Lindner.
- 39 J. L. Rosner, Phys. Rev. D42 (1990) 3732; Enrico Fermi Institute report, EFL 90-80, 1990, presented at Snowmass 90.
- 40 T. Mannel, W. Roberts and Z. Ryzak, Nucl. Phys. B355, 38 (1991); Phys. Lett. B255, 593 (1991).
- 41 N. Isgur and M. B. Wise, Nucl. Phys. B348, 278 (1991); H. Georgi, Nucl. Phys. B348, 293 (1991).
- 42 Particle Data Group, J. J. Hernández et al., Phys. Lett. B239, 1 (1990).
- 43 D. Izatt et al., Nucl. Phys. B199, 269 (1982).
- 44 The leptonic width is given by $\Gamma_{ee} = \frac{4\pi}{3} \left(\frac{4}{9}\right) \frac{\alpha^2}{m_\nu} f_\psi^2$, where the electromagnetic fine structure constant is $\alpha \approx 1/137$.
- 45 M. Danilov, review talk of heavy flavour physics (non-LEP) given at the Joint International Lepton-Photon Symposium & Europhysics Conference on High Energy Physics, CERN, Geneva, Switzerland, 1991.
- 46 Lincoln Wollenstein, Phys. Rev. D43, 151 (1991).
- 47 M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Phys. Rev. D18, 2583 (1978); S. Bertolini, F. Borzumati and A. Masiero, Phys. Rev. Lett. 59, 180 (1987); N. G. Deshpande et al., Phys. Rev. Lett. 59, 183 (1987); B. Grinstein, R. Springer and M. B. Wise, Nucl. Phys. B339, 269 (1990); A. Ali and C. Greub, Phys. Lett. B259, 182 (1991); Z. Phys. C49, 431 (1991).

Table 1: A few examples of exclusive modes of bottom baryons with potentially large CP-violating effects. Column 1 shows the underlying quark-subprocess for the exclusive modes (Column 2).

Quark - subprocess	Examples for exclusive modes
$b \rightarrow d + \bar{c}c$	$\Xi_b^0 \rightarrow \Lambda \psi$
$b \rightarrow s + \bar{u}u$	$\Lambda_b \rightarrow p K^{(*)-}, \Lambda \pi^0, \Lambda \rho^0, \Lambda \omega,$ $\Xi_b^- \rightarrow \Lambda K^{(*)-}, \Xi^- \pi^0, \Xi^- \rho^0, \Xi^- \omega,$ $\Omega_b^- \rightarrow \Omega^- \pi^0, \Omega^- \rho^0, \Omega^- \omega$
$b \rightarrow d + \bar{u}u$	$\Lambda_b \rightarrow p \pi^-, p \rho^-, p a_1^-,$ $\Xi_b^0 \rightarrow \Lambda \pi^0, \Lambda \rho^0, \Lambda \omega, p K^{(*)-}$ $\Xi_b^- \rightarrow \Lambda \pi^-, \Lambda \rho^-, \Lambda a_1^-$ $\Omega_b^- \rightarrow \Xi^- \pi^0, \Xi^- \rho^0, \Xi^- \omega, \Lambda K^{(*)-}$
$b \rightarrow d + \bar{s}s$	$\Lambda_b \rightarrow \Lambda K_S, \Lambda K^{*0},$ $\Xi_b^0 \rightarrow \Lambda \phi, \Xi^- K^{*+},$ $\Xi_b^- \rightarrow \Xi^- K_S, \Xi^- K^{*0},$ $\Omega_b^- \rightarrow \Omega^- K_S, \Omega^- K^{*0}, \Xi^- \phi$
$b \rightarrow s + \bar{s}s$	$\Lambda_b \rightarrow \Lambda \phi, \Xi^- K^{*+},$ $\Xi_b^0 \rightarrow \Omega^- K^{*+}$
$b \rightarrow s + \bar{d}d$	$\Xi_b^0 \rightarrow \Lambda K_S, \Lambda \bar{K}^{*0}, \Xi^- \pi^+, \Xi^- \rho^+, \Xi^- a_1^+$
$b \rightarrow d + \gamma$	$\Xi_b^0 \rightarrow \Lambda \gamma,$ $\Omega_b^- \rightarrow \Xi^- \gamma$
$b \rightarrow d + \bar{l}l^+$	$\Xi_b^0 \rightarrow \Lambda l^- l^+,$ $\Omega_b^- \rightarrow \Xi^- l^- l^+$

Table 2: The four observables in the $1/2 \rightarrow 1/2 + 0$ decay. Whether or not the initial ($\vec{P}_i$) and final ($\vec{P}_f$) baryon polarizations are required to measure the various observables is indicated in Column 2.

Observable	Required Polarization Knowledge
$\Gamma \sim S ^2 + P ^2$	None
$\alpha \equiv \frac{2 \text{Re } SP^*}{ S ^2 + P ^2}$	$\vec{P}_i$ or $\vec{P}_f$
$\beta \equiv \frac{2 \text{Im } SP^*}{ S ^2 + P ^2}$	$\vec{P}_i$ and $\vec{P}_f$
$\gamma \equiv \frac{ S ^2 - P ^2}{ S ^2 + P ^2}$	$\vec{P}_i$ and $\vec{P}_f$

Table 3: P-wave dominates.

Process	P-wave
$\Lambda_b \rightarrow \Lambda D^0$	$P_D = P_D e^{i\delta_1}$
$\Lambda_b \rightarrow \Lambda \bar{D}^0$	$P_{\bar{D}} = P_{\bar{D}} e^{i(\phi+\delta_2)}$
$\Lambda_b \rightarrow \Lambda D_{CP}^0$	$P = \frac{P_D + \eta P_{\bar{D}}}{\sqrt{2}}$

Table 4: General case.

Process	S-wave	P-wave	Observables
$\Lambda_b \rightarrow \Lambda D^0$	$S_D = S_D e^{i(\delta_1+\Delta_1)}$	$P_D = P_D e^{i\delta_1}$	$ S_D , P_D , \Delta_1$
$\Lambda_b \rightarrow \Lambda \bar{D}^0$	$S_{\bar{D}} = S_{\bar{D}} e^{i(\phi+\delta_2+\Delta_2)}$	$P_{\bar{D}} = P_{\bar{D}} e^{i(\phi+\delta_2)}$	$ S_{\bar{D}} , P_{\bar{D}} , \Delta_2$
$\Lambda_b \rightarrow \Lambda D_{CP}^0$	$S = \frac{S_D + \eta S_{\bar{D}}}{\sqrt{2}}$	$P = \frac{P_D + \eta P_{\bar{D}}}{\sqrt{2}}$	$ S , P , \phi+\delta$

Process	P-wave
$\bar{\Lambda}_b \rightarrow \bar{\Lambda} D^0$	$\bar{P}_{\bar{D}} = P_D$
$\bar{\Lambda}_b \rightarrow \bar{\Lambda} \bar{D}^0$	$\bar{P}_D = P_{\bar{D}} e^{i(-\phi+\delta_2)}$
$\bar{\Lambda}_b \rightarrow \bar{\Lambda} D_{CP}^0$	$\bar{P} = \eta \frac{\bar{P}_D + \eta P_D}{\sqrt{2}}$

Process	S-wave	P-wave	Observables
$\bar{\Lambda}_b \rightarrow \bar{\Lambda} D^0$	$\bar{S}_{\bar{D}} = -S_D$	$\bar{P}_{\bar{D}} = P_D$	$ S_D , P_D , \Delta_1$
$\bar{\Lambda}_b \rightarrow \bar{\Lambda} \bar{D}^0$	$\bar{S}_D = - S_{\bar{D}} e^{i(-\phi+\delta_2+\Delta_2)}$	$\bar{P}_D = P_{\bar{D}} e^{i(-\phi+\delta_2)}$	$ S_{\bar{D}} , P_{\bar{D}} , \Delta_2$
$\bar{\Lambda}_b \rightarrow \bar{\Lambda} D_{CP}^0$	$\bar{S} = \eta \frac{\bar{S}_D + \eta S_D}{\sqrt{2}}$	$\bar{P} = \eta \frac{\bar{P}_D + \eta P_D}{\sqrt{2}}$	$ \bar{S} , \bar{P} , -\phi+\delta$

Table 5(a): The quark-subprocesses $b \rightarrow d + \bar{s}s$ and $b \rightarrow d + \bar{d}d$.

Quark - subprocess	Examples of exclusive modes	BR for exclusive mode	Optimal Asymmetry
$b \rightarrow d + \bar{s}s$	$\Lambda_b \rightarrow \Lambda \bar{Z}^0, \Sigma^0 \bar{Z}^0, N \phi, \Sigma^- Z^+,$ $\Xi_b^0 \rightarrow \Xi^0 \bar{Z}^0, \Lambda \phi, \Sigma^0 \phi, \Xi^- Z^+$	$8 \times 10^{-5} - 8 \times 10^{-6}$	0.25
	$\Xi_b^- \rightarrow \Xi^- \bar{Z}^0, \Sigma^- \phi,$ $\Omega_b^- \rightarrow \Omega^- \bar{Z}^0, \Xi^- \phi$	$3 \times 10^{-6} - 3 \times 10^{-7}$	0.75
$b \rightarrow d + \bar{d}d$	$\Lambda_b \rightarrow \Delta^- X^+,$ $\Xi_b^0 \rightarrow \Sigma^- X^+, N Z^0$	$8 \times 10^{-5} - 8 \times 10^{-6}$	0.25
	$\Xi_b^- \rightarrow \Delta^- Z^0,$ $\Omega_b^- \rightarrow \Sigma^- Z^0$	$3 \times 10^{-6} - 3 \times 10^{-7}$	0.75

Table 5: CP-violating effects under optimal circumstances in exclusive modes. Columns 1-4 list the quark-subprocess, examples of exclusive modes, typical branching ratio for an exclusive mode, and optimized asymmetry. In Column 2, $\bar{Z}^0$ stands for either $K^0, K^{*0}, K^{*0},$ or other resonances of a K^0 ; Z^+ stands for either $K^+, K^{*+},$ or other resonances of a K^+ ; X^+ stands for either $\pi^+, \rho^+, a_1^+,$ or other resonances with a "u $\bar{d}$ " quark-content; X^0 stands for either $\pi^0, \rho^0, \omega, a_1^0,$ or other such resonances; and N stands for either a neutron or one of its resonances.

Table 5(c): The quark-subprocess $b \rightarrow s + \bar{u}u$.

Quark - subprocess	Examples of exclusive modes	BR for exclusive mode	Optimal Asymmetry
$b \rightarrow s + \bar{u}u$	<u>colour-allowed modes:</u> $\Lambda_b \rightarrow p Z^-$, $\Xi_b^0 \rightarrow \Sigma^+ Z^-$, $\Xi_b^- \rightarrow \Lambda Z^-, \Sigma^0 Z^-$, $\Omega_b^- \rightarrow \Xi^0 Z^-$	$6 \times 10^{-5} - 6 \times 10^{-6}$	0.66
	<u>colour-suppressed modes:</u> $\Lambda_b \rightarrow \Lambda X^0, \Sigma^0 X^0, \Sigma^+ X^-$, $\Xi_b^0 \rightarrow \Xi^0 X^0$	$6 \times 10^{-5} - 6 \times 10^{-6}$	0.66
	$\Xi_b^- \rightarrow \Xi^- X^0, \Xi^0 X^-$, $\Omega_b^- \rightarrow \Omega^- X^0$	$6 \times 10^{-5} - 6 \times 10^{-6}$	0.14

Table 5(b): The quark-subprocess $b \rightarrow d + \bar{u}u$.

Quark - subprocess	Examples of exclusive modes	BR for exclusive mode	Optimal Asymmetry
$b \rightarrow d + \bar{u}u$	<u>colour-suppressed modes:</u> $\Lambda_b \rightarrow N X^0$, $\Xi_b^0 \rightarrow \Lambda X^0, \Sigma^0 X^0, p Z^-$, $\Xi_b^- \rightarrow \Sigma^- X^0, N Z^-$, $\Omega_b^- \rightarrow \Xi^- X^0, \Lambda Z^-, \Sigma^0 Z^-$	$8 \times 10^{-5} - 8 \times 10^{-6}$	0.25
	$\Xi_b^- \rightarrow \Sigma^- X^0, N Z^-$, $\Omega_b^- \rightarrow \Xi^- X^0, \Lambda Z^-, \Sigma^0 Z^-$	$3 \times 10^{-6} - 3 \times 10^{-7}$	0.94
	<u>colour-allowed modes:</u> $\Lambda_b \rightarrow p X^-$, $\Xi_b^0 \rightarrow \Sigma^+ X^-$, $\Xi_b^- \rightarrow \Lambda X^-, \Sigma^0 X^-$, $\Omega_b^- \rightarrow \Xi^0 X^-$	$8 \times 10^{-5} - 8 \times 10^{-6}$	0.25

Table 5(e): The quark-subprocess $b \rightarrow d + \bar{c}c$.

Quark - subprocess	Examples of exclusive modes	BR for exclusive mode	Optimal Asymmetry
$b \rightarrow d + \bar{c}c$	<u>colour-suppressed modes:</u> $\Lambda_b \rightarrow N \Psi$ $\Xi_b^0 \rightarrow \Lambda \Psi, \Sigma^0 \Psi$	$3 \times 10^{-5} - 3 \times 10^{-6}$	0.28
	$\Xi_b^- \rightarrow \Sigma^- \Psi$ $\Omega_b^- \rightarrow \Xi^- \Psi$	$3 \times 10^{-5} - 3 \times 10^{-6}$	5.9×10^{-2}
	$\Lambda_b \rightarrow \Sigma_c^0 \bar{D}^{(*)0},$ $\Xi_b^0 \rightarrow \Xi_c^0 \bar{D}^{(*)0}, \Lambda_c^+ D_s^{(*)-}, \Sigma_c^+ D_s^{(*)-}$	$3 \times 10^{-5} - 3 \times 10^{-6}$	0.97
	$\Xi_b^- \rightarrow \Sigma_c^0 D_s^{(*)-},$ $\Omega_b^- \rightarrow \Xi_c^0 D_s^{(*)-}$	$3 \times 10^{-5} - 3 \times 10^{-6}$	0.32

Table 5(d): The quark-subprocesses $b \rightarrow s + \bar{s}s$ and $b \rightarrow s + \bar{d}d$.

Quark - subprocess	Examples of exclusive modes	BR for exclusive mode	Optimal Asymmetry
$b \rightarrow s + \bar{s}s$	$\Lambda_b \rightarrow \Lambda \phi, \Sigma^0 \phi, \Xi^- Z^+, \Xi^0 \bar{Z}^0,$ $\Xi_b^0 \rightarrow \Xi^0 \phi, \Omega^- Z^+$	$3 \times 10^{-5} - 3 \times 10^{-6}$	0.66
	$\Xi_b^- \rightarrow \Xi^- \phi, \Omega^- \bar{Z}^0,$ $\Omega_b^- \rightarrow \Omega^- \phi$	$3 \times 10^{-5} - 3 \times 10^{-6}$	4.4×10^{-2}
$b \rightarrow s + \bar{d}d$	$\Lambda_b \rightarrow N Z^0, \Sigma^- X^+,$ $\Xi_b^0 \rightarrow \Lambda Z^0, \Sigma^0 Z^0, \Xi^- X^+$	$3 \times 10^{-5} - 3 \times 10^{-6}$	0.66
	$\Xi_b^- \rightarrow \Sigma^- Z^0,$ $\Omega_b^- \rightarrow \Xi^- Z^0$	$3 \times 10^{-5} - 3 \times 10^{-6}$	4.4×10^{-2}

Figure Captions

Figure 1: The unitarity triangle. It shows the unitarity relation between the first and third columns of the CKM matrix in the complex plane. The angle ϕ is defined.

Figure 2. Spectator amplitudes for

- (a) $b \rightarrow s (d) + D^0$
- (b) $b \rightarrow s (d) + \bar{D}^0$.

Figure 3. Factorizable amplitudes for

- (a) $\Lambda_b \rightarrow \Lambda D^0$
- (b) $\Lambda_b \rightarrow \Lambda \bar{D}^0$.

Figure 4. Non-factorizable amplitudes for

- (a) $\Lambda_b \rightarrow \Lambda D^0$
- (b) $\Lambda_b \rightarrow \Lambda \bar{D}^0$.

Figure 5. Examples for colour-allowed and colour-suppressed amplitudes.

- (a) A colour-allowed amplitude for $\Lambda_b \rightarrow \Lambda_c^+ K^{*-}$.
- (b) A colour-suppressed amplitude for $\Lambda_b \rightarrow \Lambda D^0$.

Figure 6. Decay parameter α for the $\Lambda_b \rightarrow \Lambda \bar{D}^0$ processes as a function of the form factor ratio F_2 / F_1 [defined in eq. (5.2)].

- (a) $-1 \leq F_2 / F_1 \leq 1$.
- (b) $-10 \leq F_2 / F_1 \leq 10$.

Table 5(e) continued:

Quark - subprocess	Examples of exclusive modes	BR for exclusive mode	Optimal Asymmetry
$b \rightarrow d + c\bar{c}$	<u>colour-allowed modes:</u>		
	$\Lambda_b \rightarrow \Lambda_c^+ D^{(*)-}, \Sigma_c^+ D^{(*)-},$ $\Xi_b^0 \rightarrow \Xi_c^+ D^{(*)-}$	$10^{-3} - 10^{-4}$	0.28
	$\Xi_b^- \rightarrow \Xi_c^0 D^{(*)-},$ $\Omega_b^- \rightarrow \Omega_c^0 D^{(*)-}$	$10^{-3} - 10^{-4}$	5.9×10^{-2}

Figure 7. Possible amplitudes for an exclusive mode.

- (a) Spectator amplitude.
- (b) Penguin amplitude.
- (c) W-exchange amplitude.

Fig. 1

Fig. 2

Fig. 3

Figure 5

Fig. 4

(a)

(b)

(a)

(b)

(c)

Fig. 6

Fig. 7