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Beautiful CP Violation

Isard Dunietz

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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Beautiful CP Violation

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Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510

Abstract. CP violation is observed to date only in K^0 decays and is parameterizable by a single quantity ϵ. Because it is one of the least understood phenomena in the Standard Model and holds a clue to baryogenesis, it must be investigated further. Highly specialized searches in K^0 decays are possible. Effects in B decays are much larger. In addition to the traditional $B_d \to J/\psi K_S, \pi^+\pi^-$ asymmetries, CP violation could be searched for in already existing inclusive B data samples. The rapid $B_s - \overline{B}_s$ oscillations cancel in untagged B_s data samples, which therefore allow feasibility studies for the observation of CP violation and the extraction of CKM elements with present vertex detectors. The favored method for the extraction of the CKM angle γ is shown to be unfeasible and a solution is presented involving striking direct CP violation in charged B decays. Novel methods for determining the B_s mixing parameter Δm are described without the traditional requirement of flavor-specific final states.

I INTRODUCTION

More than thirty years after its discovery, CP violation remains a mystery. Our entire knowledge about it can be summarized by the single parameter ϵ [1]. CP violation is not just a quaint tiny effect observed in K^0 decays, but is one of the necessary ingredients for baryogenesis [2]. Within the CKM model, it is connected also to the quark-mixing and hierarchy of quark masses. A successful theory of CP violation will have far-reaching ramifications in cosmology and high energy physics.

At present, we are not able to answer even the question raised by Wolfenstein more than 30 years ago: Is CP violation due to a new superweak interaction, which would show up essentially only in mixing-induced phenomena? Or are there direct CP violating effects? There exists a multitude of scenarios for CP violation, all consistent with ϵ. What is needed is the observation of many independent CP violating effects. This would be invaluable in directing us toward a more fundamental understanding of CP violation, in analogy to the history of parity violation. There a variety of measurements guided us to the successful $V-A$ theory [3].

Searches for (direct) CP violation in K and hyperon decays are important [1,4]. Because the expected effects are either tiny for processes with sizable BR's or could be large but then involve tiny BR's $\mathcal{O}(10^{-11})$, ingenious experimental techniques are being developed to overcome those handicaps.

A whole class of additional independent CP measurements can be obtained from studies of b-hadron decays. Although CP violation may not be (entirely) due to the CKM model, that model serves here as a guide. Decays of b-hadrons can access large CKM phases and thus large CP violation, because the b-quark is a member of the third generation. There are many proposed methods that involve large CP violating effects [5]. This talk focuses on recently discussed phenomena, some of which can be studied with presently existing data samples.

First, (semi-)inclusive B decays are expected to exhibit CP violation and CKM parameters can be extracted [6–8]. Even the B_s mixing-parameter Δm could be determined from such flavor-nonspecific final states, in addition to the conventional methods [9,10]. Second, untagged B_s data samples are predicted to exhibit CP violation and permit the extraction of CKM parameters, as long as the B_s width difference is significant [11]. The far-reaching physics potential of the $B_s \to J/\psi\phi$ process is touched upon. The third topic explains why the favorite method for determining the CKM angle γ, pioneered by Gronau-London-Wyler (GLW) [12], is unfeasible. The CKM parameter can be cleanly extracted [13], however, when one incorporates the striking, direct CP violating effects in $B \to D^0/\overline{D}^0$ transitions [14], which were not considered by GLW.

II EXCLUSIVE AND INCLUSIVE B DECAYS

Traditional methods involve exclusive modes such as $J/\psi K_S$ [15], $\pi^+\pi^-$ [16–18], and study the rate-asymmetry between

$$B_d(t) \to J/\psi K_S,\ \pi^+\pi^- \neq \overline{B}_d(t) \to J/\psi K_S,\ \pi^+\pi^- \ . \tag{1}$$

The effective BR is tiny $\sim 10^{-5}$, but the asymmetries are large $\mathcal{O}(1)$. How does this large asymmetry come about? The unmixed B_d could decay into $J/\psi K_S$ directly, $B_d \to J/\psi K_S$. The CP conjugated process is the direct decay, $\overline{B}_d \to J/\psi K_S$. To excellent accuracy, those two direct decay rates are equal. The B_d could mix first into a $\overline{B}_d$ and then decay to $J/\psi K_S, B_d(t) \to \overline{B}_d \to J/\psi K_S$. The CP conjugated process is the mixing-induced $\overline{B}_d(t) \to B_d \to J/\psi K_S$ transition. Again, to excellent accuracy, the magnitudes of the two mixing-induced amplitudes are the same. The large CP violation predicted in the CKM model occurs because of the interference of the direct and mixing-induced amplitudes. To form the asymmetry, it is not sufficient to reconstruct the final state $J/\psi K_S$. One must be able to distinguish those reconstructed events as originating from an initial B_d versus $\overline{B}_d$ (referred to as tagging).

Initially (at $t = 0$) the neutral B meson has no time to mix. At $t = 0$ there is no mixing-induced amplitude and thus no CP violation. There is almost no loss in measuring the asymmetry by not considering $J/\psi K_S$ events within the first B_d lifetime or so. While the rate is largest during that time-interval, the asymmetry is tiny and needs large proper times to build itself up [18,19]. Triggering on detached vertices is thus more efficient for such CP violation studies than one might think naively.

Inclusive B samples are many orders of magnitude larger than the exclusive ones and can be accessed by vertexing. The time-dependent, totally inclusive asymmetry,

$$I(t) \equiv \frac{\Gamma(B^0(t) \to \mathrm{a}ll) - \Gamma(\overline{B}^0(t) \to \mathrm{a}ll)}{\Gamma(B^0(t) \to \mathrm{a}ll) + \Gamma(\overline{B}^0(t) \to \mathrm{a}ll)} , \tag{2}$$

is CP violating [7,8]. That appears to be rather puzzling, especially because the CPT theorem guarantees that the totally inclusive width is the same for particle and antiparticle. That CPT stranglehold is removed, because $B^0 - \overline{B}^0$ mixing provides an additional amplitude and thus novel interference effects. The totally inclusive CP asymmetry $I(t)$ is related to the wrong-sign asymmetry [20,21]

$$\frac{\Gamma(B^0(t) \to W) - \Gamma(\overline{B}^0(t) \to \overline{W})}{\Gamma(B^0(t) \to W) + \Gamma(\overline{B}^0(t) \to \overline{W})} = -a = -Im \frac{\Gamma_{12}}{M_{12}} , \tag{3}$$

where W denotes "wrong-sign" flavor-specific modes that come only from $\overline{B}^0 \to W$ and never from $B^0 \to W$, such as $W = \ell^- X$ and $W = D_s^+ \left\{\pi^-, \rho^-, a_1^-\right\}$ for B_s decays [$W = D^{(*)} D_s^{(*)-}, D\overline{D}\ \overline{K}X, J/\psi \overline{K}^*$ for B_d decays].

The data samples for the $I(t)$ asymmetries exist already. For instance, the SLD collaboration determined the lifetime ratio of neutral to charged b-hadrons by an inclusive topological vertex analysis [22]. The polarization of Z^0 provides a large forward-backward asymmetry of b production and thus an effective initial flavor-tag [23] and it is clear that SLD can study inclusive asymmetries. Similarly, the LEP experiments are able to study $I(t)$ by using their b-enriched samples and optimal flavor-tagging algorithms. CDF has several million high P_T-leptons, which are highly enriched in b content. The data sample of detached vertices on the other hemisphere allows CDF to study $I(t)$. The newly installed vertex detector at CLEO permits meaningful studies, because the $I(t)$ asymmetry becomes significant only after a few B_d lifetimes, see Eq. (4) below.

For $\Delta\Gamma = 0$, the explicit time dependence is [7]

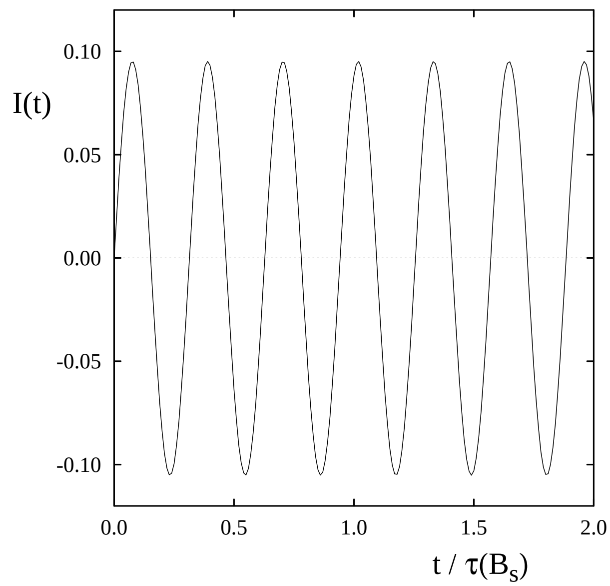

FIGURE 1. The totally inclusive CP asymmetry of $B_s(t) \to$ all, with $a = 0.01, \Delta, = 0$ and $x = 20$ (see Eqs. (2),(4)).

$$I(t) = a \left[\frac{x}{2} \sin \Delta m t - \sin^2 \frac{\Delta m t}{2} \right] , \qquad (4)$$

where $x \equiv \Delta m / ,$. The observable a can thus be extracted from a study of $I(t)$.

For B_s mesons, that extraction offers a significant statistical gain over the conventional method [Eq. (3)]. The factor of $x/2$ enhances $I(t)$ over a by an order of magnitude, which corresponds to a statistical gain of $\mathcal{O}(10^2)$. There is another gain, because all B_s decays are used rather than flavor-specific B_s modes that must be efficiently distinguished from B_d modes. The distinction involves stringent selection criteria. The reason is that the wrong-sign asymmetry [Eq. (3)] is time-independent, and the wrong-sign B_d asymmetry is an order of magnitude larger than the B_s one, within the CKM model. Thus, for instance, the high-p (-P_T) leptons must originate from B_s decays and not from B_d decays. This can be achieved by either studying wrong-sign B_s modes at very short proper times [24], or by inferring the existence of a D_s, or by observing such primary kaons that significantly enrich the B_s content, or by a combination of the above. In contrast, the unique time-dependence of $I(t)$ provides automatic discrimination. For the B_s meson at least, the time-dependent inclusive asymmetry may be more effective in extracting the CP violating observable a than the conventional wrong-sign asymmetry.

Figure 1 shows what to expect for the choice $x = 20$ and where New Physics is allowed to enhance $a = |,_{12}/M_{12}| \sim 0.01$. The observation of a non-vanishing $I(t)$ proves CP violation and in addition allows a determination of the $B_s - \overline{B}_s$ mixing parameter Δm from flavor-nonspecific final states. The traditional methods for extracting Δm require flavor-specific final states and tagging [9,10]. We will mention later on additional ways to extract Δm with flavor-nonspecific final states.

Within the CKM model, the totally inclusive asymmetries are tiny $\mathcal{O}(10^{-3})$ for B_d and $\mathcal{O}(10^{-4})$ for B_s [25,26]. The ability to select specific quark transitions enhances the asymmetries by orders of magnitude, at times to the $\sim (10-20)\%$ level [7]. Such selections permit extractions of CKM phases and to conduct the study in either a time-integrated or time-dependent fashion.[1] Those analyses should be pursued whenever feasible. There exist unitarity constraints, which allow systematic cross-checks. Future B detectors will be able to more fully explore the potential with such semi-inclusive data samples.

III PHYSICS WITH (UNTAGGED) B_S MESONS

One conventional way to determine the CKM angle γ is the time-dependent study of tagged $\overset{(-)}{B}_s(t) \to D_s^{\pm} K^{\mp}$ processes [27], and in the neglect of penguin amplitudes $\overset{(-)}{B}_s(t) \to \rho^0 K_S, \omega K_S$ transitions [17,18,28]. It requires flavor-tagging and the ability to trace the rapid $\Delta m t$-oscillations. The requirements are problematic:

(a) Flavor-tagging is at present only a few percent efficient at hadron accelerators [29].[2]

(b) Resolution of $\Delta m t$-oscillations is feasible for $x \lesssim 20$ with present vertex technology [9], but LEP experiments reported [10],

$$x \gtrsim 15 \ . \tag{5}$$

Though $\Delta m t$-oscillations may be too rapid to be resolved at present, such large Δm may imply a sizable width difference $\Delta,$ [31]. Non-perturbative effects may further enhance $\Delta,$ considerably [32]. Perhaps $\Delta,$ will be the first observable $B_s - \overline{B}_s$ mixing effect [11], which would circumvent problems (a) and (b). The $\Delta m t$-terms cancel in the time-evolution of untagged B_s [11],

$$f(t) \equiv \, , (B_s(t) \to f) + \, , (\overline{B}_s(t) \to f) = a e^{-\Gamma_L t} + b e^{-\Gamma_H t} \ , \tag{6}$$

which is governed by the two exponentials $e^{-\Gamma_L t}$ and $e^{-\Gamma_H t}$ alone. That fact permits many non-orthodox CP violating studies and extractions of CKM parameters [11]:

(1) Consider final states with definite CP parity, f_{CP}, such as $\rho^0 K_S, \omega K_S, \ldots$. If the untagged time-evolution $f_{CP}(t)$ is governed by both exponentials $e^{-\Gamma_L t}$ and $e^{-\Gamma_H t}$, then CP violation has occured [11]. The measurement of $f_{CP}(t)$

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1) For B_s mesons, Δm could be extracted from such more refined studies.
2) Though, in principle almost all B-decays could be flavor-tagged [30].

allows even the extraction of CKM parameters [11,33]. The physics of the $J/\psi\phi$ final state is very instructive. The time-evolution of untagged $J/\psi\phi$ could show CP violating effects [33]. The $\overset{(-)}{B}_s \to J/\psi\phi$ has CP-even and CP-odd amplitudes, $\overset{(-)}{A}_+$ and $\overset{(-)}{A}_-$ respectively. Angular correlations [34] allow to measure the interference terms between CP-even and CP-odd amplitudes, which for untagged data samples is proportional to [33],

$$\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\theta^2 2\eta\ , \quad \text{where} \quad \theta \approx 0.22. \tag{7}$$

The observation of such a non-vanishing term would prove CP violation and would permit the extraction of the CKM parameter η. Note that the observable depends optimally on the width difference.

Those interference terms once tagged allow the measurement of Δm, even though $J/\psi\phi$ is a flavor-nonspecific final state [34]. To demonstrate the point most sharply, neglect CP violation and set $\Delta\Gamma = 0$. Then $A_+(t) \sim e^{-im_L t}$ and $A_-(t) \sim e^{-im_H t}$. The observable $A_+(t)A_-^*(t) \sim e^{i\Delta m t}$ depends on $\Delta m \equiv m_H - m_L$. Ref. [35] describes yet another method for measuring Δm without flavor-specific final states.

(2) After several B_s lifetimes, the long-lived $B_s^H \sim B_s - \overline{B}_s$ will be significantly enriched over the short-lived B_s^L. Consider then final states f that can be fed from both B_s and $\overline{B}_s$, and that are non-CP-eigenstates. CP violation is proven if the time evolution of untagged $f(t)$ differs from untagged $\overline{f}(t)$,

$$f(t) \neq \overline{f}(t) \Rightarrow CP\ violation\ . \tag{8}$$

Furthermore, the CKM angle γ can be extracted from time-dependent studies of $D_s^{\pm}K^{\mp}(t)$, $\overset{(-)}{D^0}\ \phi(t)$ [11].[3] CP violating effects and CKM extractions can be enhanced by studying $D_s^{(*,**)\pm}K^{*\mp}(t)$ [36]. In summary, neither flavor-tagging nor exquisite tracing of Δmt-oscillations are necessary, only a large $\Delta\Gamma$.

IV DIRECT CP VIOLATION AND EXTRACTING CKM ANGLES

The favorite method (particularly at $\Upsilon(4S)$ factories) for determining γ has been developed by Gronau, London and Wyler (GLW) [12] and requires the measurements of the six rates $B^{\pm} \to D^0 K^{\pm}, \overline{D}^0 K^{\pm}$ and $D^0_{CP}K^{\pm}$. Here D^0_{CP} denotes that the D^0 is seen in CP eigenstates with either CP-even

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[3] The determination of γ from $\overset{(-)}{D^0}\ \phi(t)$ and $D^0_{CP}\phi(t)$ as presented in Ref. [11] must include the effect of doubly-Cabibbo suppressed $\overset{(-)}{D^0}$ decay-amplitudes [14,13].

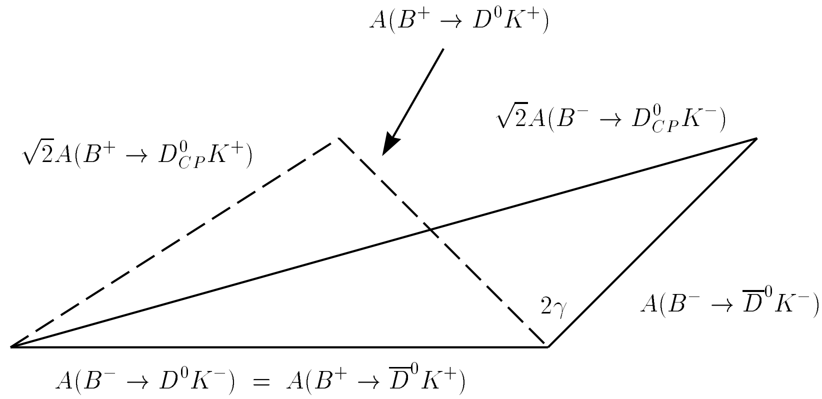

FIGURE 2. The traditional GLW method for extracting the CKM angle γ.

$(K^+K^-, \pi^+\pi^-, ...)$ or CP-odd $(K_S\phi, K_S\pi^0, ...)$ parity. The GLW method focuses on the CP violating rate difference of $B^+ \to D^0_{CP} K^+$ versus $B^- \to D^0_{CP} K^-$ [37], which can reach at best the 10% level and is probably significantly smaller.

In principle, the GLW method is a great idea. However, new CLEO data indicate that the method is unfeasible, and that the largest CP violating effect has been overlooked [14,13]. Once the effect has been incorporated, the CKM angles can be cleanly extracted [13].

Let us review the original GLW method, point out the problem, and show how it can be overcome. Consider CP even D^0_{CP}, for which

$$D^0_{CP} = \frac{1}{\sqrt{2}}(D^0 + \overline{D}^0) \ . \tag{9}$$

Then

$$\sqrt{2}A(B^- \to D^0_{CP} K^-) = A(B^- \to D^0 K^-) + A(B^- \to \overline{D}^0 K^-) \ , \tag{10}$$

and that amplitude triangle is shown in Figure 2. The weak phase difference of the two interfering amplitudes is γ. GLW argued that the magnitudes of each of the sides of the triangle can be measured (being proportional to the square roots of the respective rates), and thus claimed that the amplitude triangle can be fully reconstructed.

Figure 2 has not been drawn to scale. The $B^- \to \overline{D}^0 K^-$ amplitude is an order of magnitude smaller than the $B^- \to D^0 K^-$ one, which can be seen as follows [13]. The CKM factors suppress the amplitude ratio by about

1/3. The $\overline{D}^0 K^-$ is color-suppressed while $D^0 K^-$ is also color-allowed, yielding another suppression factor of about 1/4.

Nothing changes when the CP conjugated final states are considered, except that the CKM elements have to be complex conjugated. Apparently, the CP-conjugated triangle can also be determined, see Figure 2. The $A(B^+ \to D^0 K^+)$ is rotated by 2γ with respect to $A(B^- \to \overline{D}^0 K^-)$, and apparently the angle γ can be extracted. Note that the only CP violation in all these processes occurs in

$$\Gamma(B^+ \to D^0_{CP} K^+) \neq \Gamma(B^- \to D^0_{CP} K^-) \tag{11}$$

while there is no CP violation in

$$\Gamma(B^+ \to \overline{D}^0 K^+) = \Gamma(B^- \to D^0 K^-) \, , \; and \tag{12}$$

$$\Gamma(B^+ \to D^0 K^+) = \Gamma(B^- \to \overline{D}^0 K^-) \, . \tag{13}$$

In principle this argument is correct, but in practice the largest <u>direct</u> CP violating effects (residing in those processes) will be seen in [14,13]

$$B^+ \to D^0 K^+ \neq B^- \to \overline{D}^0 K^- \, . \tag{14}$$

The $\overline{D}^0$ produced in the $B^- \to \overline{D}^0 K^-$ process is seen in its non-leptonic, Cabibbo-allowed modes f, such as $K^+\pi^-, K\pi\pi$. It was assumed that the kaon flavor unambiguously informs on the initial charm flavor. This assumption overlooked the doubly-Cabibbo-suppressed $D^0 \to f$ process which leads to the same final state $B^- \to D^0[\to f]K^-$. Further, CLEO has measured [38]

$$\left| \frac{A(D^0 \to f)}{A(\overline{D}^0 \to f)} \right| \sim 0.1 \, , \tag{15}$$

which maximizes the interference,

$$\left| \frac{A(B^- \to K^- D^0[\to f])}{A(B^- \to K^- \overline{D}^0[\to f])} \right| \sim 1 \, , \tag{16}$$

$$A(B^- \to K^-[f]) = A(B^- \to K^- D^0[\to f]) + A(B^- \to K^- \overline{D}^0[\to f]) \, . \tag{17}$$

The conditions are ideal for striking direct CP violating effects. They require that the interfering amplitudes be comparable in size (Eq. (16)), that the weak phase difference be large (γ in our case), and that the relative final-state-phase difference be significant. It is an experimental fact that large final state phases occur in many D decays [39]. This enables us to engineer large

CP violating effects by optimally weighting relevant sections of generalized Dalitz plots.

The traditional focus on CP eigenmodes of D^0_{CP} automatically excludes this so potent source of final-state interaction phases. The orthodox method [37,12] accesses only the final-state phase difference residing in $B^- \to D^0 K^-$ versus $B^- \to \overline{D}^0 K^-$, which is expected to be significantly more feeble [40]. The CKM angle γ can be cleanly extracted once one incorporates the findings of this section [13], because penguin amplitudes are absent. The extraction of γ and the observation of CP violation is optimized by combining detailed (experimental) investigations of D^0 decays with $B^\pm$ decays to $\overset{(-)}{D^0}$ [13]. This provides yet another reason for accurate measurements of D^0 decays. Note also that observation of direct CP violation (as advocated in this section) would rule out superweak scenarios as the only source for CP violation.

V CONCLUSION

CP violation has been observed only in K^0 decays and is parameterizable by a single quantity ϵ. It is one of the necessary ingredients for baryogenesis [2], and within the CKM model is related to the quark-mixing and hierarchy of quark masses. It is one of the least understood phenomena in high energy physics and a very important one. Just as the successful $V-A$ theory of parity violation [3] emerged from a synthesis of many independent parity violating measurements, so a more fundamental understanding of CP violation will profit from many independent observations of CP violation.

This talk thus emphasized that CP violation should not only be searched in traditional exclusive $B_d \to J/\psi K_S, \pi^+\pi^-$ rate asymmetries. Observable CP violating effects could be present in (semi-)inclusive B decays, and could be searched for with existing data samples. The time-evolutions of untagged B_s data samples have no rapid Δmt-oscillations. Still CP violation could be observed and CKM parameters extracted as long as $\Delta\Gamma$ is sizable. Many striking direct CP violating effects in B decays are possible. The observation of CP violation and CKM extraction are optimized by detailed studies of D decays.

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