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Angles of the unitarity triangle: measurements and perspectives

M. Beneke[a], M.Ciuchini[b], R. Faccini[c], S. Gardner[d], D. London [e], Y. Sakai[f], A. Soni[g]

[a]Institut für Theoretische Physik E, RWTH Aachen, Sommerfeldstr. 28, D - 52074 Aachen

[b]INFN, Sezione di Roma III and Dip. di Fisica, Univ. di Roma Tre, Via della Vasca Navale 84, I-00146 Rome, Italy.

[c]Dipartimento di Fisica, Università degli Studi "La Sapienza" and I.N.F.N. Rome, P[le]A.Moro2, I-00186, Italy.

[d]Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055, USA

[e]Laboratoire René J.-A. Lévesque, Université de Montréal, C.P. 6128, succ. centre-ville, Montréal, QC, Canada H3C3J7

[f] High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, 305-0801, Japan

[g]High Energy Theory, Brookhaven National Lab,Upton, NY 11973, USA

Understanding the CP violation mechanism in the Standard Model (SM) via the measurement of the elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix, is one of the highlights of the current program in particle physics. We present a summary of the current measurements of the angles of the Unitarity Triangle and the future perspectives. We consider separately the measurement of β and the measurements of CP-violation in $B \to D$ decays, charmless multi-pion decays and all other charmless decays.

1 Measurements of β

Four years after the start of the asymmetric B-factories a precise measurement of $\sin 2\beta$ in B decays is available [1]: $\sin 2\beta = 0.734 \pm 0.055$.

Once the CP-violation in B decays is established and the result is in agreement with the predictions from indirect measurements, the interest shifts to other two aspects: the search for deviations from the SM due to new physics and the resolution of the ambiguities in the solutions of β.

1.1 Search for new physics in measurements of β

Two ways to probe new physics are discussed here: the comparison between the CP violation measured in several modes and the angular analysis of B decays into two vectors ($B \to V_1 V_2$).

It is expected that the values of β extracted from CP asymmetries in $J/\psi K_S$, $\eta' K_S$, ϕK_S and $K^+K^-K_S$ should all be nearly the same. Deviations from this equality would therefore signal new physics. The theoretical error in the prediction that one can obtain $\sin 2\beta$ from $J/\psi K_S$ is small, at most 1%. To the extent that the final state $\eta' K_S$ is dominated by a $b \to s$ penguin with an internal t quark, this decay also measures $\sin 2\beta$. However, this decay also receives a contribution from the tree-level $b \to u\bar{u}s$ decay. Since this contribution is suppressed by $O(\lambda^2)$ compared to the penguin amplitude, we expect that the theoretical error on

the equality between the CP violation in these modes in the SM is about 5%. This also applies to the final states ϕK_S and $K^+K^-K_S$ (assuming that the CP of this latter state is known), although the tree pollution is more likely to be small.

In $B \to V_1 V_2$ decays, one can define the triple product $\vec{p}_{final} \cdot (\vec{\varepsilon}_1 \times \vec{\varepsilon}_2)$ [2]. Triple products (TP) are T-violating quantities that, using CPT, may also signal CP violation. In order to have a nonzero TP, one needs two interfering amplitudes with a relative weak phase. Thus, no TP's are expected in decays which in the SM have only a single decay amplitude. Measuring sizeable triple products for instance in $B \to D_s^* D^*$, $B \to J/\psi K^*$, or $B \to \phi K^*$ would therefore signal new physics. It should be noted that new physics is found even in the case where the strong phase is small and the direct CP would not be observable. The sensitivity to the relative magnitude of concurrent amplitudes of the angular analysis of $B \to V_1 V_2$ decays allows also to quantify the impact of penguin contributions [3]. This is for instance the case for $B \to D^* D^*$ decays where the full angular analysis could allow to set limits on the difference between the the CP-asymmetry measured in this mode and $\sin 2\beta$. Finally, also semileptonic decays can exhibit TP thatwould be pure signals of new physics. They could be studied in $B \to D\tau\nu_\tau$ decays [4].

1.2 Resolution of the sign ambiguities

Measuring $\sin 2\beta$ leaves four possible solutions for β. Two of these can be eliminated by measuring the sign of $\cos 2\beta$. The angular analysis of $J/\psi K^*$ allows one to obtain $\cos 2\beta \cos\delta$, where δ is a strong phase. However, since the sign of $\cos\delta$ is not known, the sign of $\cos 2\beta$ cannot be measured and the ambiguity persists. It has been suggested though, that factorization could calculate the sign of $\cos 2\beta$ even if the precision on the the amplitude of the strong phase would be large. This has been proven wrong by comparing the factorization predictions of the Branching Fraction $B \to \chi_c^0 K^+$ and the experimental data [5]. Within factorization, the decay $B \to \chi_c^0 K^+$ is not allowed in the SM. Nevertheless, this decay has been observed with a sizeable branching ratio ($\sim 10^{-4}$). Clearly nonfactorizable effects are important here and it has been estimated that the rescattering effects could justify the observed rates. This implies that the strong phases are completely dominated by these effects and that the sign of $\cos\delta$ cannot be computed in factorization.

The literature present several other methods to measure the sign of $\cos 2\beta$: the study of $B_d^0 \to J/\Psi K \to J/\Psi(\pi^-\ell^+\nu)$, known as "cascade mixing" [6] involving both B^0–$\bar{B}^0$ mixing and K^0–$\bar{K}^0$ mixing, the time-dependent measurement of $B_d(t) \to D^{*+}D^{*-}K_S$ [7], and the Dalitz-plot analysis of $B_d(t) \to D^+D^-K_S$ [8]. However, the first method is experimentally too challenging while there is considerable model dependence in the last two methods. Still, since all one wants is the sign of $\cos 2\beta$, it might be possible to crosscheck these model calculations by measuring the sign of $\cos 2\beta$ in several modes.

2 CP violation in $B \to D$ decays

B decays to final states containing charm meson are a very powerful way to extract the angles of the unitarity triangle. There are 4 key points to be emphasized:

- the method is very clean and can lead to large asymmetries in many cases.
- there is a large number of available modes
- direct CP leading to partial rate asymmtries gives γ and time dependent CP asymmetry gives $\delta \equiv \beta - \alpha + \pi \equiv 2\beta + \gamma$ as well as β.
- Most of the proposed techniques make use of decays of the D mesons to final states accessible both to D^0 and $\bar{D}^0$ mesons. Charm factories can therefore give significant help in the use of these methods.

The experimetal issues are discussed in Ref. [9].

With the perspective of $\sin 2\beta$ determination by the B-factories which is in very good agreement of the theoretical expectation based on the SM, clean and precise extraction of all the three angles has become extremely important. It is clear now that the CKM-phase is the dominant player in $B \to J/\psi K_s$ asymmetry and may well be so in general in B-decays. Thus even if a new CP-odd phase due to physics beyond the SM exists and is $O(1)$ its effects in B-physics may be very small[10]. After all the CKM-phase (which we now know is O(1)) causes only very small asymmetries ($\approx 10^{-3}$) in K-decays. Searches for the effects of the BSM-phase in B-physics may well therefore require lots and lots of B-data samples as well as very clean methods of analysis. If the deviations are as small as those in K-decays ($\approx 10^{-3}$) then even the use of isospin symmetry may be a bad approximation.

In the early papers D-decays to CP-eigenstates (CPES, such as $K_s^0[\pi^0, \eta, \eta', \omega, \rho], K^+K^-, \pi^+\pi^-$) were discussed[11]. However this has the difficulty that the flavor tagging of D^0 versus $\bar{D}^0$ appears very difficult[12]. Also the CP asymmetries tend to be small. Both of these difficulties are overcome when one focuses on $D^0, \bar{D}^0$ decays to CP-non-eigenstates (CPNES, such as K^+ $(K^{*+})[\pi^-, \rho^-, a_1^-]$) that are doubly Cabibbo suppressed. Of course this comes at a prize that the effective branching ratio become very small ($10^{-7} - 10^{-6}$) range. Actually, there are also CPNES that are singly Cabibbo suppressed[13], such as K^+K^{*-},$\pi^+\rho^-(a_1^-)$. So they tend to have larger BR but their CP asymmetries tend to be small.

For the case of direct CP involving a single common decay mode (say $K^+\pi^-$) of D^0 and $\bar{D}^0$ there are two observables (rates for B and that of $\bar{B}$) involving 3 unknown parameters: 1 strong phase, the (suppressed) BR ($B^- \to K^- + \bar{D}^0$) which is very difficult to measure experimentally and the CP-odd weak phase γ, that we are after. So there is not enough information to solve for γ. But if we consider 2 such final states that are common to D^0 and $\bar{D}^0$, for example, $K^+\pi^-$ and $K^{*+}\pi^-$, then we have 4 observables and 4 unknowns and the system becomes soluble and γ can be obtained without theory assumptions. In practice though, the solution can be hampered by discrete ambiguities. For that reason and others it is helpful to include more final states.

In addition to the several categories of common decay modes of D^0, $\bar{D}^0$, it is also possible to include several variants in the B decay; for example, $B^- \to K^-(K^{*-}, K^- + n\pi...)D^0(\bar{D}^0)$. All this redundacy should be very helpful in overcoming discrete ambiguities as well as achieving precision on γ.

The $B \to KD^0$ method of direct CP to γ is easily generalizable to time dependent CP asymmetry (TDCPA) in $B^0 \to K^0 + D^0$ leading to a clean extraction of $\delta \equiv \beta - \alpha + \pi \equiv 2\beta + \gamma$ as well as β[14]. The time dependent decay rate can be fitted to give 3 observables for particle and 3 for the conjugate reaction leading to a CP-NES decay mode of D^0 such as $K^+\pi^-$. These 6 observables involve 5 unknown parameters of which one is the weak phase δ that we are after. So, in principle, TDCPA measurements to the FS $K_s[K^+\pi^-]$ and $K_s[K^-\pi^+]$ can give δ; however, this is seriously handicapped by discrete ambiguities. Therefore in practice several modes need to be included and fortunately this should not be hard. In the case of $D^0, \bar{D}^0$ decay to a CPES, for example, $K_s\omega$, involves only 3 observables and 4 parameters which are just a subset of the 5 parameters needed to describe decay to CPNES. Thus adding a CPES mode to a CPNES mode leads to 9 observables and only 5 parameters; the resultant redundacy is very effective in dealing with discrete ambiguities. Of course, the process can be generalized. If one includes a second CPNES mode, say $D^0 \to K^{*+}\pi^-$, one will have altogether (6 + 3 + 6) 15 observables and (5 + 1) 6 parameters, etc.

Some other noteable points follow.

- TDCPA measurements for the $B^0 \to K^0D^0$ type of modes give not only δ but also they can give β allowing for another test of the SM as this value of β must agree with that from $B \to J/\psi K_s$.
- Many features of the decays of $D^0, \bar{D}^0$ are

common to direct CP studies involving $B^{\pm}$ decays and those for TDCP studies of $B^0, \bar{B}^0$; so information such as doubly cabibbo suppressed branching ratios or strong phases in D decays can be used in both types of measurements. Infact, a powerful way to handle the analysis may be to use inclusive D decays, i.e. identifying only the kaon coming from the D decay and using partial reconstruction techniques.

- K_L detection if feasible could aid the analysis even though this is not essential[14]. It is to be noted that contrarily to the case of the measurement of $\sin 2\beta$ the use of the modes with K_L mesons would not only cross check the results, but provide independent information and therefore reduce ambiguities.

At this workshop there will be 3 talks on the variant of this scheme.

- Petersen will talk on using color allowed modes such as $B^0 \to D^{+-} K_s^0 \pi^{-+}$[16].
- Zupan presents a possible use of D^0 decays to multi-body final states[17].
- Atwood will discuss the use of inclusive decays of D^0 and the possible use of charm factory data[18].

Listed below are also some issues that should be addressed in our working group.

- $D^{(*)}K^{(*)}$ modes: How to resolve ambiguites?
  How much luminosity is needed?
  What are the prospects for observation of large CP asymmetry even if there is not enough information yet to get γ?
- $D^{(*)}\pi$: How to get the ratio of amplitudes $\frac{A(B^0 \to D^+\pi^-)}{A(B^0 \to D^-\pi^+)}$.
- For vector vector states such as $D^*\rho(a_1)$, how much statistics is needed to do the full angular analysis and are there any theoretical traps.
- Are there any new modes worth pursuing?
- Can the semi-lepton flavor tag of $D^0, \bar{D}^0$ work?
- Can the K_L be detected in these decay modes?

3 CP violation in charmless multipion B decays

The analysis of B-meson decays to charmless, multi-pion states, under an assumption of isospin symmetry, permits the determination of the CKM angle $\alpha\,(\phi_2)$, or $\gamma\,(\phi_3)$ if $\beta\,(\phi_1)$ is known, as $\alpha = \pi - \beta - \gamma$. As reviewed by G. Raven in the plenary session [1], $\sin(2\beta)$ is now known to better than 10%, so that the isospin analyses in the charmless, multi-pion modes can also be regarded as determinations of γ. In another plenary talk, H. Sagawa reviewed the current data on $B \to \pi\pi$ and $B \to \rho\pi$ decays[19]. In $B \to \pi^+\pi^-$ decay, data on both the time-dependent asymmetry induced through the interference of $B - \bar{B}$ mixing and direct decay, $S_{\pi\pi}$, and the direct CP-violating term, $C_{\pi\pi}$, exist, though no empirical consensus on their values has yet emerged [19]. With the anticipation of improved measurements of these and other quantities, needed to bring the isospin analyses in $B \to \pi\pi$ and $B \to \rho\pi$ decays to fruition, the overarching goals of our subgroup are:

- Construct a systematic, exhaustive list of the errors associated with each method and estimate them.
- Determine what ancillary measurements, if any, can reduce these errors.

To begin, we recall the isospin analysis possible in $B \to \pi\pi$ decay [20]. Under the assumption of isospin symmetry, a $\pi\pi$ final state has an isospin of $I_f = 0$, or 2, whereas the B-meson has isospin $I_i = 1/2$. Thus, without further assumption, we can have $|\Delta I| = 1/2, 3/2$, or $5/2$ transitions, and the independent amplitudes are labeled by $A_{|\Delta I|, I_f}$, to yield three amplitudes in all, so that this procedure in itself

is without dynamical assumption. The operators of the $|\Delta B| = 1$ effective Hamiltonian are of $|\Delta I| = 1/2, 3/2$ character, however, so that the third amplitude, here of $|\Delta I| = 5/2$ character, is generated by isospin-violating effects [21,22]. Neglecting the third amplitude and assuming the penguin contributions to be purely of $|\Delta I| = 1/2$ character, as both follow from the neglect of the charge and mass differences of the u and d quarks, we recover the isospin analysis of Gronau and London [20]. The sensitivity of the results to these assumptions hinges on the value of the penguin-to-tree (P/T) ratio; the larger the value of P/T, the smaller the impact of isospin-violating effects on $\sin 2\alpha$ [21]. Unfortunately, though, $\mathrm{Br}(B \to \pi^0\pi^0)$ appears to be small, so that it may be difficult to determine P/T well. Given this, the following alternatives are available.

- One can compute P/T in a theoretical approach, such as QCD factorization [23], estimating the $\mathcal{O}(1/M_B)$ corrections, so that the isospin analysis is unneeded.
- One can use the relations of the underlying isospin analysis and the empirical branching ratios, including the limits on $Br(B \to \pi^0\pi^0)$, to realize bounds on the hadronic uncertainty in the extraction of $\sin(2\alpha)$ [24–27].

The contribution of L. Roos addresses these points, indicating, in particular, the expected, allowed regions for $\alpha - \alpha_{\rm eff}$ as a function of the integrated luminosity, as well as a comparison of $|P/T|$ determined from $S_{\pi\pi}$ and $C_{\pi\pi}$ and that computed in QCD factorization, for SM values of ρ, η [28]. The application of the bounds on $|\alpha - \alpha_{\rm eff}|$ appear to give rather weak constraints [28,19]. Certain bounds are more sensitive to isospin-violating effects and can underestimate the size of the hadronic uncertainty [21,22], but such considerations are unimportant given the weakness of the current constraints.

We now turn to the isospin analysis in $B \to \rho\pi$ decay [29–31]. Under the assumption of isospin symmetry, a $\rho\pi$ final state has an isospin of $I_f = 0, 1$, or 2. As in $B \to \pi\pi$ decay, we can have $|\Delta I| = 1/2, 3/2$, or $5/2$ transitions, so that there are five, independent $A_{|\Delta I|, I_f}$ amplitudes, though only three linearly independent combinations appear in neutral B-meson decays. The key assumptions in this analysis are that i) the amplitude for $B \to \pi^+\pi^-\pi^0$ decay, e.g., can be written as $A(B^0 \to \pi^+\pi^-\pi^0) = f_+\, a_{+-} + f_-\, a_{-+} + f_0\, a_{00}$, where f_i describes $\rho^i \to \pi\pi$ and a_{ij} describes $B \to \rho^i\pi^j$, and ii) that the penguin contributions are purely of $|\Delta I| = 1/2$ in character. Only the latter assumption emerges from the neglect of the charge and mass differences of the lightest quarks. The functions f_i can be determined elsewhere, so that only a_{ij} need be determined from the Dalitz plot. The rich structure of the Dalitz plot in $B \to 3\pi$ decay encodes sufficient information to determine the parameters in a_{ij}; in principle, the charged modes are not necessary to determine a_{ij} completely [31]. The $B \to \rho\pi$ analysis relies, in part, on hadronic input, so that a variety of questions arise, although most issues can be examined — and resolved — in an empirically driven way. That is,

i) How good is the assumption of "ρ dominance"? To what extent do other contributions populate the Dalitz plot in the ρ signal region?

ii) How significant are corrections to the Ansatz $A(B \to \rho^i\pi^j \to 3\pi) = a_{ij}\, f_i$? Does their size vary across the Dalitz plot? Can they be included in a systematic way?

iii) Are the f_i known well enough?

iv) How significant are isospin-violating effects?

v) How well can the parameters of the isospin analysis be determined?

Discussions of these questions dominated the $B \to \rho\pi$ sessions; we refer to the proceeding contributions of J. Stark, A. D. Polosa, and J. Oller [32–34] for specifics. Nevertheless, let us

add some observations to set these contributions in context.

Regarding i), it is worth noting the recent studies of $D^- \to \pi^-\pi^+\pi^-$ decay by the E791 collaboration: $D^- \to \pi^-\sigma(500) \to \pi^-\pi^+\pi^-$ accounts for roughly half of the total decay rate [35]. Deandrea and Polosa have argued, in analogy, that the $\sigma(500)$ plays a similar role in $B \to 3\pi$ decay [36]. In $B \to \rho\pi \to \pi^+\pi^-\pi^0$ decay, the $\sigma\pi$ intermediate state would contribute preferentially to the $\rho^0\pi^0$ channel and break the assumed relation between the penguin contributions — it would mimic isospin violation [22]. The analyses of Ref. [22] and Refs. [35,36] employ different scalar form factors; only the former is consistent with low-energy data. Nevertheless, Refs. [36,22] agree in that both calculations predict a significant role for the $\sigma(500)$ in $B^\pm \to \sigma(500)\pi^\pm \to \pi^+\pi^-\pi^\pm$ decay. The calculation of Ref. [22] predicts a small role for the $\sigma(500)$ in neutral B-meson decay. Note that the $B \to \sigma\pi$ channel has definite properties under CP, so that it could be included in the $\rho\pi$ analysis if necessary. Charged B modes have been included in the analysis reported by Stark [32], but they are not essential to resolving the penguin pollution expected in the time-dependent studies [31]. The earlier work of Ref. [37] also attributed a significant background to the B^* resonance, but their treatment of the $\pi B^* B$ vertex is inconsistent with recent empirical constraints on the $B^\pm \to \pi^+\pi^-\pi^\pm$ decay rate [38,39], as also discussed in related modes by Refs. [40,41].

As per ii), the most problematic corrections to the $A(B \to \rho^i\pi^j \to 3\pi) = a_{ij} f_i$ Ansatz occur at the corners of the Dalitz plot. One natural, non-$\rho\pi$ contribution to consider is one in which the three pions are coupled in relative s-waves; its presence can be constrained by its distinct angular-momentum character.

The f_i factors have been studied extensively to determine the hadronic vacuum polarization contribution to $g-2$ of the μ, note, e.g., Ref. [42]. The f_i are sufficiently well-known that isospin-violating effects are clearly observed in the comparison of $e^+e^- \to \pi^+\pi^-$ and hadronic τ data. Generally, isospin violation can not only distinguish the f_i, but can also generate a $|\Delta I| = 5/2$ amplitude, as well as penguin contributions of $|\Delta I| = 3/2$ character, which can be estimated. In contradistinction to $B \to \pi\pi$ decay, the presence of the $|\Delta I| = 5/2$ amplitude does not impact the analysis of $B \to \rho\pi \to \pi^+\pi^-\pi^0$ decay, to the extent that the $A_{3/2,2}$ and $A_{5/2,2}$ amplitudes, which appear as $A_{3/2,2} + A_{5/2,2}$, share the same weak phase. This follows if $A_{3/2,2}$ is much larger than $A_{1/2,0}$ [22].

Finally, Stark reported the expected constraints on α in extrapolations to larger, integrated luminosities, given different scenarios [32]. Interestingly, the quasi-two-body analysis yields a large value for the direct-CP-violating observable $A_{\rm CP}^{\rho\pi}$, which is tantamount to the population asymmetry observable discussed in Ref. [43].

The investigation of the issues raised in this subgroup is ongoing.

4 CP violation in other charmless B decays

More than thirty branching fractions of two- and three-body B decays with no open charm or charmonium in the final state have now been measured or bounded by CLEO and the two B factory experiments, accessing BRs as small as 10^{-6}. For many of them the direct CP asymmetry has also been measured with no conclusive evidence of direct CP violation up to now. Charmless decays may exhibit large interference of tree and penguin amplitudes with different weak phases allowing for the determination of the CKM angle γ in principle. The status and prospects for the corresponding measurements were reviewed in the plenary talk by J. Olsen [44].

Yet determining γ precisely is a daunting task, since it requires that one controls the hadronic matrix elements that describe the hadronisation of the quarks produced in the weak interaction into an exclusive final state. Over the past few years the theoretical toolkit has expanded considerably. The two basic strategies rely on exploiting

- isospin and SU(3) flavour symmetry
- the heavy quark expansion and/or perturbative QCD methods ("QCD factorisation", "PQCD")

Both approaches are based on expansions in small parameters. However, often it is very difficult to ascertain the size of subleading corrections, either in SU(3) symmetry breaking or in $\Lambda_{\rm QCD}/m_b$. Validation of a particular approach therefore requires a tight interplay of theoretical analysis and phenomenological input. The current influx of data opens the exciting perspective of simultaneously exploring weak phases and flavour-changing transitions as well as the limitations of theoretical approaches.

Accordingly, the subgroup on general charmless decays has focused on the following principal tasks:

- Assess the theoretical tools available for particular decay modes, specify the underlying assumptions and attempt to quantify theoretical errors.
- Assess the additional information on unitarity angles and theoretical methods from final states with vector mesons. Identify final states that are particularly worth pursuing (experimentally or theoretically).

The seven contributions to this subgroup of Working Group IV reflect these tasks in various ways. The presentations by N. de Groot [45] and V. Morenas [46] described a global fit of QCD factorisation to the available data on pseudoscalar-vector (Morenas) and on pseudoscalar-pseudoscalar and pseudoscalar-vector (de Groot) final states, comparing different approaches to the inclusion of subleading corrections. The contribution by A. Sanda [47] provides an overview of results obtained by the Perturbative QCD method. QCD sum rules may give valuable insights on corrections that cannot be computed in the factorisation or perturbative approaches. The sum rule method was used by B. Melic [48] to estimate power corrections from penguin-loops and by A. Khodjamirian [49] to estimate SU(3) flavour symmetry breaking effects. J. Matias [50] described the extraction of γ from the $\pi\pi$ and πK final states together with $B_s \to K^+K^-$ assuming SU(3) flavour symmetry. T.N. Pham [40] explored the possibility to determine γ from three-body decays.

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