Results on $\beta$ from BABAR

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1 Introduction

The CKM paradigm for quark mixing in the standard model accounts for the observed $CP$-symmetry violation in the quark sector. The CKM mechanism describes all transitions between quarks in terms of only four parameters: three rotation angles and one irreducible phase. Consequently, the flavor sector of the standard model is highly predictive.

One particularly interesting prediction is that the direct and mixing-induced $CP$ asymmetries, denoted $\mathcal{C}$ and $\mathcal{S}$, respectively, are approximately the same in decays governed by $b \rightarrow q\bar{q}s$ ($q = u, d, s$) transitions and those found in $b \rightarrow c\bar{c}s$ transitions. The level of approximation was estimated as $\sim 1\%$ [1]. The dominant contributions to $b \rightarrow c\bar{c}s$ transitions (typically using $B^0 \rightarrow J/\psi K^0_S$) are from tree-level diagrams. On the other hand, since flavor changing neutral currents are forbidden at tree level in the standard model, the $b \rightarrow q\bar{q}s$ transition proceeds almost uniquely via loop diagrams (penguins). In these channels, the weak phases in the respective dominant contributions are the same as in the standard model, which explains the prediction concerning the approximate equality between the $CP$-violation parameters.

The CKM angle $\beta$ is related to the mixing-induced $CP$ asymmetry by $\mathcal{S} = \sin(2\beta)$. Yet, other amplitudes than penguin may contribute, to some extent, to $b \rightarrow q\bar{q}s$ transitions (e.g., “tree pollution”). The angle extracted from the corresponding $\mathcal{S}$ parameter is therefore denoted $\beta_{\text{eff}}$ rather than $\beta$. Penguin diagrams are affected by new particles in many extensions of the standard model. As there may be $CP$-violating sources beyond the standard model, these penguin-dominated charmless hadronic $B$ decays, are of great interest because they are sensitive to new physics effects at large energy scales.

Various $b \rightarrow s$ dominated charmless hadronic $B$ decays have been studied in order to probe this prediction. By comparing the mixing-induced $CP$ asymmetry measured for each mode to that measured in $b \rightarrow c\bar{c}s$ transitions.
Here we present recent time-dependent analyses of $B^0$ meson decays to $K^0_S K^0_S K^0_S$ and $K^+ K^- K^0$ from the BABAR collaboration. The former is a $CP$ eigenstate, while in the latter the $CP$ content is determined by means of an amplitude analysis. They are described in detail in Refs. [2] and [3]. They both benefit from small theoretical uncertainties [4], which make the comparison with $\to c\bar{s}$ transitions more meaningful.

Measurement of $b \to c\bar{d}$ transitions such as $B^0 \to D^{(*)}+\bar{D}^{(*)}-$ should also yield the same value of $\sin(2\beta)$ as in $b \to c\bar{s}$ transitions, to the extent that the contributions from penguin processes may be neglected. The leading and sub-leading order processes contributing to $B^0 \to D^{(*)}+\bar{D}^{(*)}-$ decays are described by a tree diagram and a penguin diagram, respectively. The effect of neglecting the penguin amplitude has been estimated in models based on factorization and heavy quark symmetry, and the corrections are found to be a few percent [5, 6]. Loops involving non-SM particles (for example, charged Higgs or SUSY particles) could increase the contribution from penguin diagrams and introduce additional phases. A large deviation of the measured $CP$ asymmetry $S$ from the value of $\sin 2\beta$ measured in $b \to c\bar{s}$ transitions or a non-zero value of direct $CP$ violation would be strong evidence of new physics. Here we present the latest measurement of time-dependent $CP$ asymmetry of partially reconstructed $B^0 \to D^{(*)}+\bar{D}^{(*)}-$ decays from the BABAR collaboration [7].

The three analyses below use the final BABAR $\Upsilon(4S)$ dataset that consists of $468 \times 10^6 B\bar{B}$ decays.

2 Time-dependent $CP$ asymmetry of $B^0 \to K^0_S K^0_S K^0_S$ decays

The time-dependent $CP$-violation parameters $S$ and $C$ are extracted by modeling the proper-time distribution of $B^0 \to K^0_S K^0_S K^0_S$ decays with $K^0_S \to \pi^+\pi^-$, and events where one of the $K^0_S$ mesons decays to $\pi^0\pi^0$. The result is

$$S = -0.94^{+0.24}_{-0.21} \pm 0.06,$$

$$C = -0.17 \pm 0.18 \pm 0.04,$$

where the first quoted uncertainty is statistical and the second is systematic. The correlation between $S$ and $C$ is $-0.16$.

A two-dimensional statistical likelihood scan in $S$ and $C$, which is then convolved by the systematic uncertainties on the two parameters, is shown in Fig. 1. We find that $CP$ conservation is excluded at 3.8 standard deviations, and thus, for the first time, we measure an evidence of $CP$ violation in $B^0 \to K^0_S K^0_S K^0_S$ decays. The difference between our result and that from $B^0 \to c\bar{s}K^{(*)}$ is less than 2 standard deviations. The scan also shows that the result is close to the physical boundary, given by the constraint $S^2 + C^2 \leq 1$. 
Figure 1: Two-dimensional likelihood scan of $-2\Delta \ln L$ as a function of $S$ and $C$, including systematic uncertainty, in $B^0 \rightarrow K_S^0 K_S^0 K_S^0$. The gray scale is given in units of $\sqrt{-2\Delta \ln L}$. The result of the $\text{Babar}$ analyses of $B^0 \rightarrow c\pi K^{(*)}$ decays [8] is indicated as a white ellipse and the physical boundary ($S^2 + C^2 \leq 1$) is marked as a gray line. The scan appears to be trimmed on the lower left since the PDF becomes negative outside the physical region (i.e., the white region does not indicate that the scan flattens out at $5\sigma$).

3 Dalitz-plot analysis of $B^0 \rightarrow K^+ K^- K_S^0$ decays

Unlike $K_S^0 K_S^0 K_S^0$, $K^+ K^- K_S^0$ is not a $CP$ eigenstate, and therefore a Dalitz-plot analysis is necessary in order to disentangle $CP$-even from $CP$-odd states and measure $\beta_{\text{eff}}$. Because of the importance of understanding the Dalitz-plot structure in $B^0 \rightarrow K^+ K^- K_S^0$, we study the related modes $B^+ \rightarrow K^+ K^- K^+$ and $B^+ \rightarrow K_S^0 K_S^0 K^+$ along with $B^0 \rightarrow K^+ K^- K_S^0$. The mode $B^+ \rightarrow K^+ K^- K^+$ is valuable because it has the most signal events by far of any $B \rightarrow \pi\pi\pi$ mode. Far fewer events are observed in $B^+ \rightarrow K_S^0 K_S^0 K^+$, but its Dalitz-plot has a simplified spin-structure due to the fact that the two $K_S^0$ mesons in the final state are forbidden (by Bose-Einstein statistics) to be in an odd angular momentum configuration. A further benefit of a Dalitz-plot analysis is that it allows both $\sin 2\beta_{\text{eff}}$ and $\cos 2\beta_{\text{eff}}$ to be determined, through the interference of odd and even partial waves, which eliminates a trigonometric ambiguity between $\beta_{\text{eff}}$ and $90^\circ - \beta_{\text{eff}}$.

We describe the distribution of signal events in the Dalitz plot using an isobar approximation, which models the total amplitude as a coherent sum of amplitudes from individual decay channels (“isobars”). $K_S^0$ mesons are reconstructed both in $K_S^0 \rightarrow \pi^+ \pi^-$ and $K_S^0 \rightarrow \pi^0 \pi^0$.

We vary three sets of $\beta_{\text{eff}}$ and the $CP$ asymmetry, $A_{CP}$, values in the fit: one for the $\phi(1020)$, another for the $f_0(980)$, and a third that is shared by all the other charmless isobars in order to reduce the number of fit parameters. Note that this last set of
isobars contains both even-spin and odd-spin (P-wave) non-resonant terms. Figure 2 shows the time-dependent asymmetry for signal-weighted events, both for the \( \phi(1020) \) region \((1.01 < m_{K^+K^-} < 1.03 \text{ GeV}/c^2)\) and the \( \phi(1020) \)-excluded region. We find five solutions that are essentially degenerate in \( \beta_{\text{eff}} \), and determine \( \beta_{\text{eff}}(\phi K^0_S) = (21 \pm 6 \pm 2)^\circ \) from a likelihood scan. This is the most accurate result for \( \beta_{\text{eff}}(\phi K^0_S) \) at present.

Excluding the \( \phi(1020)K^0_S \) and \( f_0(980)K^0_S \) contributions, we measure \( \beta_{\text{eff}} = (20.3 \pm 4.3 \pm 1.2)^\circ \) for the remaining \( B^0 \rightarrow K^+K^-K^0_S \) decays, and exclude the trigonometric reflection \( 90^\circ - \beta_{\text{eff}} \) at 4.8\( \sigma \), including systematic uncertainties. All the results are in a good agreement with \( \beta \), measured in \( b \rightarrow c\bar{c}s \) decays.

![Figure 2: The asymmetry \((N_{B^0} - N_{B^0})/(N_{B^0} + N_{B^0})\) in \( B^0 \rightarrow K^+K^-K^0_S \) as a function of \( \Delta t \), in the \( \phi(1020) \) region (left) and \( \phi(1020) \)-excluded region (right). The points represent signal-weighted data, and the line is the fit model.](image)

4 **Time-dependent \( CP \) asymmetry of partially reconstructed \( B^0 \rightarrow D^{*+}D^{*-} \) decays**

Since \( B^0 \rightarrow D^{*+}D^{*-} \) is the decay of a scalar to two vector mesons, the final state is a mixture of \( CP \) eigenstates. The \( CP \)-odd and \( CP \)-even fractions, as well as the corresponding \( CP \) asymmetries have been previously measured from the angular analysis of completely reconstructed \( B^0 \rightarrow D^{*+}D^{*-} \) decays both by \( \text{BaBar} \) [9] and \( \text{Belle} \) [10]. Here, we report a recent measurement from \( \text{BaBar} \) based on the technique of partial reconstruction, which allows one to gain a factor of \( \approx 5 \) in the number of selected signal events with respect to the most recent \( \text{BaBar} \) full reconstruction analysis in [9]. This result is complementary to the latter measurement, because the statistics used are largely independent of each other.

In the partial reconstruction of a \( B^0 \rightarrow D^{*+}D^{*-} \) candidate, we fully reconstruct only one of the two \( D^{*\pm} \) mesons in the decay chain \( D^* \rightarrow D^0 \pi \), by identifying \( D^0 \)...
candidates in one of four final states: $K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$, $K^0\pi\pi$. Since the kinetic energy available in the decay $D^* \to D^0 \pi$ is small, we combine one reconstructed $D^{*\pm}$ with an oppositely charged low-momentum pion, assumed to originate from the decay of the unreconstructed $D^{*\mp}$, and evaluate the mass $m_{\text{rec}}$ of the recoiling $D^0$ meson and its direction by using the momenta of the two particles. For signal events $m_{\text{rec}}$ peaks at the nominal $D^0$ mass, while for background events no such peak is visible. The direction of the recoiling $D^0$ meson helps to reduce the additional dilution in $B$ flavor tagging due to tagging tracks from the unreconstructed $D^0$.

The analysis proceeds with a series of unbinned maximum-likelihood fits, performed simultaneously on the on- and off-resonance data samples. The procedure can be logically divided in the following three steps: determination of the signal fraction and several PDF-shape parameters, determination of the tagging dilution due to wrong tag assignments, and finally the time-dependent fit to the data, fixing all parameter values obtained in the previous steps.

The final results for $C$ and $S$, with their correlation coefficient $\rho$ are:

$$C = +0.15 \pm 0.09 \pm 0.04$$
$$S = -0.34 \pm 0.12 \pm 0.05 \quad \rho = 0.0649.$$

The measured values of $S$ and $C$ that we obtain from data only represent a weighted average of the $CP$-even and $CP$-odd wave function components. If penguin amplitudes can be neglected then $S_+ = -S_-, C_+ = -C_-$ and the value of the $CP$-even components $S_+$ and $C_+$, which we are interested in, can be obtained using the relations:

$$C = C_+$$
$$S = S_+ (1 - 2R_\perp),$$

where the factor $(1 - 2R_\perp)$ represents the dilution introduced by the $CP$-odd component $R_\perp$ in the signal. To compute $S_+$ we use the value measured by BABAR of $(R_\perp = 0.158 \pm 0.029)$ [9], where the uncertainty is the combined statistical and systematic. To evaluate the related systematic uncertainty, we vary this value by $\pm 1\sigma$. We obtain

$$C_+ = +0.15 \pm 0.09 \pm 0.04$$
$$S_+ = -0.49 \pm 0.18 \pm 0.07 \pm 0.04,$$

where the uncertainties shown are statistical and systematic; the third uncertainty is the contribution from the error on $R_\perp$ described above. This result is compatible with previous measurements from BABAR [9] and Belle [10] using fully reconstructed decays. It is approximately 20% more accurate than the previous BABAR measurement. This result well agrees with the standard model expectation of negligible contributions to the decay amplitude from penguin diagrams and thence with $S_+ = - \sin 2\beta$. 


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