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DIRECT CP VIOLATION - RECENT RESULTS FROM BABAR

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Measurements of the CKM parameter $\sin(2\beta)$ have established CP violation in the B^0 meson system arising from the interference between mixing and decay. However, direct CP violation, arising from the interference among different terms in the decay amplitude, had not been observed so far. We report a first observation of direct CP violation in $B^0 \to K^+\pi^-$ decays with the BaBar detector. Other selected results based on the search for direct CP violation in several other B decays are also presented.

1 Introduction

We use the term "direct CP Violation" for CP violation in meson decays, when the CP violation appears as a result of interference among various terms in decay amplitude and will not occur unless at least two terms have different weak phases and different strong phases. For a decay process, $B \to f$, and its charge conjugate $\bar{B} \to \bar{f}$, the direct CP asymmetry is defined by

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} \tag{1}$$

Here B refers to either a charged or a neutral B meson. With the decay amplitudes $A_f = |A_f| e^{i\phi_{weak}} e^{i\theta_{strong}}$ and $\bar{A}_{\bar{f}} = |A_{\bar{f}}| e^{-i\phi_{weak}} e^{i\theta_{strong}}$, and $R = |A_f|/|\bar{A}_{\bar{f}}|$, Eq. 1 becomes

$$A_{CP} = \left[\frac{2}{R + 1/R + \cos(\Delta\phi_{weak})\cos(\Delta\theta_{strong})}\right] \sin(\Delta\phi_{weak})\sin(\Delta\theta_{strong}) \tag{2}$$

Given a measurement of the CP asymmetry, the interpretation of the result depends on the relative strong phase (θ_{strong}) that arises from the final state interactions which are a not well understood. It is therefore important to have a large variety of experimental inputs to better understand the non-perturbative physics leading to the occurrence of strong phase and to further confirm or refute the Kobayashi-Maskawa picture of CP violation in Standard Model(SM) [1].

Depending on the model used, expected CP asymmetries in B meson decays vary widely. An asymmetry as small as $2 - 10\%$ is expected in a factorization model calculation [2], while new physics could introduce new large phases directly leading to an expected asymmetry of $40 - 60\%$ [3]. In some classes of B decays (such as radiative $B \to X_s\gamma$), the expected CP asymmetry is less than 1% [4]. A measurement of significant non-zero CP asymmetry will be an evidence for the contribution of new physics in such B decays. The dedicated physics program at the B factories will continue to do stringent tests of the various models and improve our understanding of the source of CP violation significantly. In this article, we will briefly review

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some of the ongoing search for direct CP violation in B decays with the BaBar detector [5] at the Stanford Linear Accelerator Center (SLAC) PEP-II e^+e^- asymmetric-energy storage ring.

2 General Analysis Procedure

For each event, charged tracks and neutral particles in the detector are identified using various quality requirements on reconstructed tracks and neutral showers. B candidates are selected using two kinematic variables $M_{ES} = \sqrt{E^2_{beam} - p^{*2}_B}$, the energy substituted mass and $\Delta E = E_{beam} - E^*_B$, where E^*_{beam} is the beam energy and $p^*_B(E^*_B)$ is the measured momentum (energy) of the B candidate in the $\Upsilon(4S)$ center-of-mass(CM) frame. While M_{ES} expresses the momentum conservation in the decay, ΔE expresses the energy conservation of the particles in the decay and is sensitive to the missing particles and K/π misidentification. In most of the cases considered here, the analyses are affected by the dominant source of background arising from $e^+e^- \rightarrow q\bar{q}(q = u, d, c, s)$ transitions. To reject this, we exploit the difference in topology between jetty hadronization of continuum events and spherical decays of B's on the $\Upsilon(4S)$ CM frame. The topology is described using the angle θ_T between the thrust axis of the B candidate and the thrust axis of the charged and neutral particles in the rest of the event (ROE) [5]. Sometimes the angle θ_S, defined in the CM frame, between sphericity axis [7] of the B candidate and the sphericity axis of the ROE is also used to discriminate signal from continuum background. For background events, $|\cos\theta_S|$ peaks sharply near unity, while it is nearly uniform for signal events. Other useful quantity that characterize the event topology are two sums over the ROE: $L_0 = \sum |\vec{p_i}^*|$ and $L_2 = \sum |\vec{p_i}^*| \cos^2\theta_i$, where θ_i is the angle between the momentum $\vec{p_i}^*$ and the thrust axis of the B candidate. Additional separation is achieved using the angle θ_B between the B momentum direction and the beam axis. To maximize the separation power, these four event shape variables are often combined into a Fisher discriminant $\mathcal{F}$ [6]. In some analyses, neural network algorithm is used to combine information from a set of event shape variables, including a set of energy flow cones. Finally, the Fisher/neural net variables are combined with kinematic variables in a maximum likelihood fit to determine simultaneously the signal yield and the charge asymmetry.

3 Measurement of the CP Asymmetry

In this section we review the results on a few selected measurements of CP asymmetries performed with the BaBar detector. Unless otherwise stated, all measurements presented here are preliminary.

3.1 First Observation of Direct CP Violation in B decays: $A_{K\pi}(B^0 \rightarrow K^+\pi^-)$ [8]

The decay $B^0 \rightarrow K^+\pi^-$ occurs through two different diagram types of diagram ("penguin" and "tree"), which carry different weak phases and, in general, different strong phases. The direct CP violating asymmetry for this mode is defined by

$$A_{K\pi} = \frac{n_{K^-\pi^+} - n_{K^+\pi^-}}{n_{K^-\pi^+} + n_{K^+\pi^-}} \tag{3}$$

where $n_{K^-\pi^+}$ and $n_{K^+\pi^-}$ are the measured yields for the two final states. We require that each track has an associated Cherenkov-angle (θ_c) measured with detector of internally reflected Cherenkov light (DIRC). This information is used to separate kaons and pions in a maximum-likelihood fit that determines signal and background yields corresponding to the four distinguishable final states ($\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$ and K^+K^-). The likelihood of any event is obtained by summing the product of the "event yield" ($n_{K^\pm\pi^\mp}$) and the probability density

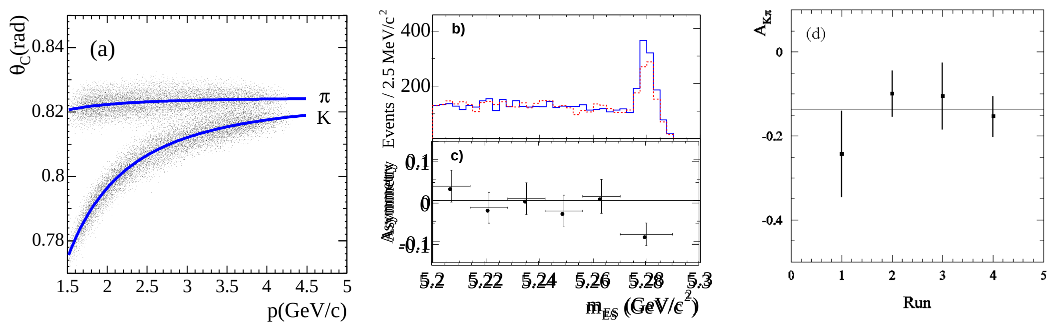

Figure 1: (a) The measured Cerenkov angle distribution for pions and kaons from $D^* \to D^0\pi$, and $D^0 \to K\pi$ decays from data. The lines show the expected angle θ_c as a function of laboratory momentum. (b) Distribution of M_{ES} enhanced in $K^+\pi^-$ (solid histogram) and $K^-\pi^+$ (dashed histogram). (c) CP asymmetry calculated for different ranges of M_{ES}. (d) Measured CP Asymmetry in different data samples.

function (PDF) which use observables m_{ES}, ΔE, $\mathcal{F}$, θ_c^+, θ_c^-. The $\theta_c^{\pm}$ PDFs are obtained from a sample of approximately 430000 $D^{*+} \to D^0\pi^+(D^0 \to K^-\pi^+)$ decays reconstructed in data as shown in Fig. 1(a). The $K^{\mp}\pi^{\pm}$ yields are parametrized as $n_{K^{\pm}\pi^{\mp}} = n_{k\pi}(1 \mp A_{K\pi})/2$, where $n_{k\pi}$ is the total yield. Based on a data sample of 253 fb^{-1}, a fit to the signal events measures $n_{K\pi} = 1606 \pm 51$, $A_{K\pi} = -0.133{\pm}0.030(\text{stat}){\pm}0.009(\text{syst})$ and the background asymmetry $A^b_{K\pi} = 0.001 \pm 0.008$. As shown in Fig. 1(b,c), a clear enhancement of $K^+\pi^-$ (solid histogram) is observed in the distribution with $M_{es} > 5.27$ GeV whereas the charge asymmetry is negligible for the background events with m_{ES} <5.27 GeV. As part of the consistency check, we divided the entire data sample into the approximate periods in which the data were recorded. We find $A_{K\pi} < 0$ (Fig.1(d)) and background asymmetries consistent with zero in each data set.

Five years after direct CP violation was observed in K-meson decays, this measurement establishes direct CP violation in B^0-meson system at the level of 4.2 standard deviations.The Belle collaboration has recently reported an updated measurement [9] of $A_{K\pi} = -0.101 \pm 0.025 \pm 0.005$ which confirms our observation. The results are consistent within the expected range of SM.

3.2 First Measurement of $A_{CP}(B^+ \to K^+K^0_SK^0_S)$ [10]

Since this process is expected to be dominated by $b \to s\bar{s}s$ loop transition, the SM prediction of A_{CP} is zero. Hence, this could be a place where one may observe a signal for new physics. The measurement of $A_{CP}(B^+ \to K^+K^0_SK^0_S)$ is based on 122 million $B\bar{B}$ pairs. An unbinned extended maximum likelihood fit was performed to the data sample where the event yields are split by the charge and extracted separately for signal, continuum and peaking B background. We have reconstructed a total of 6144 signal events in this mode and measured value of $A_{CP}(B^+ \to K^+K^0_SK^0_S) = -0.04{\pm}0.11{\pm}0.02$. The measured CP asymmetry is consistent with SM prediction.

3.3 Measurement of $A_{CP}(b \to s\gamma)$ [11]

In the SM the inclusive decay $b \to s\gamma$ is a flavor changing neutral current process described by a radiative loop diagram and the predicted direct CP asymmetry is close to zero [12]. Direct CP asymmetry is calculated from

$$A_{CP} = \frac{1}{\langle D\rangle}\left(\frac{(n-\bar{n})}{(n+\bar{n})} - \frac{\Delta D}{2}\right) - A^{det}_{CP} \quad (4)$$

where n and $\bar{n}$ are the numbers of observed $b \to s\gamma$ and $\bar{b} \to \bar{s}\gamma$ events after peaking background is subtracted, ΔD is the difference in the wrong flavor-fraction between b and $\bar{b}$ decays, and

$\langle D \rangle$ is the dilution factor from the average wrong flavor-fraction. The correction term A_{CP}^{det} is the flavor asymmetry in the detector and measured to be -0.014 ± 0.015. Signal events are reconstructed as the sum of eight exclusive final states: $B^- \to K^-\pi^0\gamma$, $K^-\pi^+\pi^-\gamma$, $K^-\pi^0\pi^0\gamma$, $K^-\pi^+\pi^-\pi^0\gamma$ and $B^- \to K_S^0\pi^-\gamma$, $K_S^0\pi^-\pi^0\gamma$, $K_S^0\pi^-\pi^0\pi^0\gamma$ and $K_S^0\pi^-\pi^+\pi^-\gamma$.

Based on a measurement with 89 million $B\bar{B}$ pairs, our recently published results are $A_{CP}(b \to s\gamma) = 0.025 \pm 0.050 \pm 0.015$ for the total sample and $A_{CP}(b \to s\gamma) = -0.04 \pm 0.10 \pm 0.02$ for the lepton-tagged sample. This value is consistent with SM prediction.

3.4 Measurement of $A_{CP}(B \to K^*\gamma)$ [13]

Unlike inclusive decays, exclusive $B \to K^*\gamma$ decay rates have large uncertainties due to non-perturbative hadronic effects, limiting their usefulness for probing new physics. However, the interest in measuring $A_{CP}(B \to K^*\gamma)$ clearly lies in making a stringent test of the SM which predicts this value to be less than 1%. We reconstruct $B^0 \to K^{*0}\gamma$ in the $K^{*0} \to K^+\pi^-$ mode and $B^+ \to K^{*+}\gamma$ in the $K^{*+} \to K^+\pi^0, K_S^0\pi^+$ modes. Using a sample of 88 million $B\bar{B}$ events, we measure a combined direct CP asymmetry of $-0.013 \pm 0.036 \pm 0.010$ which is, within experimental error, consistent with SM prediction.

4 Conclusion and Prospects

We reported the first observation of direct CP violation in the B meson decay in $B^0 \to K^-\pi^+$. We do not observe any significant CP asymmetry in other decay modes such as $B^+ \to K^+K_S^0K_S^0$, $b \to s\gamma$ and $B \to K^*\gamma$. Improved statistics will reveal new insights in the ongoing searches for direct CP violation. With the excellent running performances of the BaBar detector and lot more luminosity from PEP-II to come, we look forward to an exciting time that will confirm or refute the SM and its description of CP violation.

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