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CP Asymmetries and Charmless Branching Fractions with *BABAR*

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A summary of recent results of searches for direct CP Violation and measurements of charmless B-meson decay branching fractions with the *BABAR* detector is presented.

1. INTRODUCTION

Direct CP Violation (CPV) is manifest in processes where the amplitude for a B-meson to decay to a final state f, $|A_f|$, differs from that of its CP conjugate, $|\overline{A}_{\overline{f}}|$. In order for a process to be direct CP violating, one requires interference between decay amplitudes with different weak, ϕ_i, and strong, δ_i, phases (i.e. different CP-odd and CP-even phases) as can be seen in the following

$$|A_f| - |\overline{A}_{\overline{f}}| \propto \sum_{i,j} A_i A_j sin(\phi_i - \phi_j) sin(\delta_i - \delta_j) \quad (1)$$

Thus far direct CPV has only been observed in the neutral kaon system and is measured via the double ratio method. Recent experimental results of these measurements from the NA48 and KTeV collaborations show a non-zero ϵ' [1,2]. In contrast to the neutral kaon system, direct CPV in B-meson decays is expected to be large (few $\sim$ 80% depending on the mode).

In B-meson decays one can define a time integrated CP asymmetry, A_{CP} , as

$$A_{CP} = \frac{BR(\overline{B} \to \overline{f}) - BR(B \to f)}{BR(\overline{B} \to \overline{f}) + BR(B \to f)} \quad (2)$$

where $BR(B \to f)$ is the branching ratio of a B-meson decaying to a final state f, and $BR(\overline{B} \to \overline{f})$ is the branching ratio for the CP conjugate process. For neutral B-meson decays one either calculates A_{CP} and subsequently corrects for the effect of mixing when looking for direct CPV, or performs a time dependent analysis. Charged B-mesons do not mix and as such one can determine the B-flavour from decay products or tagging the other B-meson decay in the event. So one can use a time integrated asymmetry to look for direct CPV in charged B-meson decays.

Direct CPV is maximal when the interfering amplitudes are of comparable magnitude. As a result one is interested in rare or suppressed processes. Measurement of decays involving $b \to u$ suppressed tree and $b \to s, d$ penguin processes are be useful for direct CPV searches. The former can manifest large A_{CP} [3] whereas the latter penguin dominated modes are predicted to have small A_{CP}. Standard model behaviour such as A_{CP}'s and branching ratios can be modified in the presence of new physics effects via loops [4–6].

2. Extracting signals

PEP-II is an asymmetric e^+e^- collider located at the Stanford Linear Accelerator Center. The accelerator collides 9.0 GeV electrons with 3.1 GeV positrons at the $\Upsilon(4s)$ resonance to produce a $B\overline{B}$ pair nearly at rest in the center of mass. The *BABAR* detector is used to measure the decay products of these events. Both PEP-II and *BABAR* are described in detail elsewhere [7].

When measuring A_{CP}'s, one has to correct for flavour mixing of neutral B-mesons and detector effects such as charge asymmetries in triggering, reconstruction, event selection and final analysis. In addition to this, there is the formidable task of extracting a rare process from a large light quark continuum background coming from u, d, s, c quarks.

The main variables used to discriminate signal

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Mode	$BR(\times 10^{-6})$	A_{CP}
$B^0 \to K^+\pi^-$	$(17.9 \pm 0.9 \pm 0.7)$	$-0.102 \pm 0.050 \pm 0.016$
$B^+ \to K^+\pi^0$	$(12.8^{+1.2}_{-1.1} \pm 1.0)$	$-0.09 \pm 0.09 \pm 0.01$
$B^+ \to \pi^+\pi^0$	$(5.5^{+1.0}_{-0.9} \pm 0.6)$	$-0.03^{+0.18}_{-0.17} \pm 0.02$
$B^0 \to K^0\pi^0$	$(10.4 \pm 1.5 \pm 0.8)$	$0.03 \pm 0.36 \pm 0.09$
$B^0 \to \pi^+\pi^-$	$(4.7 \pm 0.6 \pm 0.2)$	$0.30 \pm 0.25 \pm 0.04$
‡ $B^+ \to K^0\pi^+$	$(17.5^{+1.8}_{-1.7} \pm 1.3)$	$-0.17 \pm 0.10 \pm 0.02$
$B^0 \to \pi^0\pi^0$	< 3.6 (90% C.L.)	-
$B^0 \to K^+K^-$	< 0.6 (90% C.L.)	-
‡ $B^+ \to K^+K^0$	< 1.3 (90% C.L.)	-

Table 1
Branching ratios, upper limits and A_{CP} measured for the decays $B \to hh$.

from continuum background in the analyses discussed here are M_{ES}, ΔE, cosines of the angle between the direction of the B-candidate and the thrust or sphericity axis of the rest of the event [3] and fisher discriminants based on energy flow of the events. The beam energy substituted mass, M_{ES} is defined as $M_{ES} = \sqrt{(E^{*2}_{BEAM} - P_B^2)}$, where E^*_{BEAM} is the center of mass energy of the beam and P_B is the reconstructed B-candidate momentum. The energy variable ΔE is given by $\Delta E = E_B - E^*_{BEAM}$, where E_B is the energy of the B-candidate. There are two main fisher discriminants used in the different analyses presented here which are described in [8] and [9].

3. RESULTS

3.1. Charmless two body decays

The decays $B \to hh$, where $h = \pi, K$, can be used in the determination of the weak phases α and γ and may also prove useful in searching for direct CPV [10]. Analysis of these decays is discussed in detail elsewhere [8]. The A_{CP}'s and branching ratios measured for these modes come from a data set comprising approximately 88×10^6 $B\overline{B}$ pairs as shown in Table 1 (entries denoted by ‡ use 56.2×10^6 $B\overline{B}$ pairs [11]). The A_{CP} measured in $B^0 \to K^+\pi^-$ is the most precise one from *BABAR* in a mode where there is a non-zero asymmetry expected. The total uncertainty on this asymmetry is 5.2%. Also the $B^0 \to \pi^+\pi^-$ asymmetry quoted explicitly assumes $q/p = 1$.

Mode	$BR(\times 10^{-6})$
$B^+ \to K^+\pi^-\pi^+$	$59.2 \pm 4.7 \pm 4.9$
$B^+ \to K^+K^-K^+$	$34.7 \pm 2.0 \pm 1.8$
$B^+ \to \pi^+\pi^-\pi^+$	< 15 (90% C.L.)
$B^+ \to K^+K^-\pi^+$	< 7 (90% C.L.)

Table 2
Branching ratios and upper limits of the decays $B^+ \to h^+h^-h^+$.

3.2. Charmless three body decays

The branching fractions of the decays $B^+ \to h^+h^-h^+$, where $h = \pi, K$, have been measured using a cut based analysis of the whole Dalitz plot [12]. The data sample analysed for these modes contain approximately 56.2×10^6 $B\overline{B}$ pairs. Once observed these decays are of interest as one can search for direct CPV and ultimately, with sufficient statistics, fit to the Dalitz plot in order to extract the weak angle γ [13].

Significant signals are observed for the decays $B^+ \to K^+K^-K^+$ and $B^+ \to K^+\pi^-\pi^+$, whereas we place an upper limit on $B^+ \to \pi^+\pi^-\pi^+$ and $B^+ \to K^+K^-\pi^+$ as given in Table 2. The Dalitz plots and M_{ES} distributions for the decays $B^+ \to K^+K^-K^+$ and $B^+ \to K^+\pi^-\pi^+$ are shown in Figure 1. One can see in the case of $B^+ \to K^+\pi^-\pi^+$ that there is a significant resonant contamination in the Dalitz plot. This comes from B-decays with charm in the final state, i.e. J/ψ, ψ_{2s} and D-mesons. To remove these, 3σ cuts are applied to the data around the nominal resonance masses. This leaves behind a small peaking background under the signal which can be seen in the M_{ES} distribution for $B^+ \to K^+\pi^-\pi^+$.

3.3. Charmless quasi-two-body decays

One can search for direct CPV in the suppressed tree and penguin dominated quasi-two-body decays $B \to \eta' K^{(*)}$ and $B \to \omega K$, $\omega\pi$ respectively. Decays with η' in the final state are of interest as, depending on the final state one may have a large A_{CP}. Also, by virtue of a $b \to u$ transition one can try to extract information about the weak angle γ from these decays. Experimentally one observes larger than expected branching

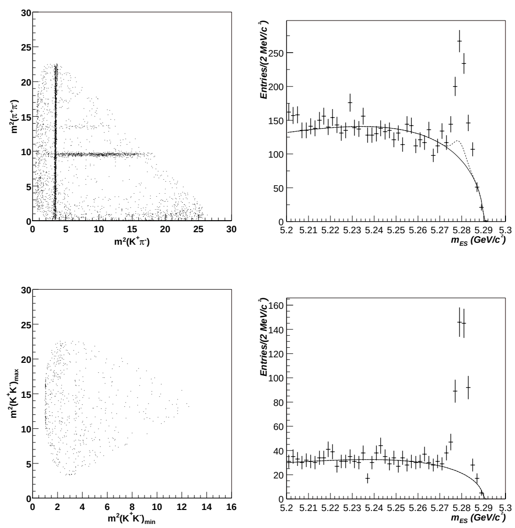

Figure 1. The (left) Dalitz plot and (right) M_{ES} distributions for (top) $B^+ \to K^+\pi^-\pi^+$and (bottom) $B^+ \to K^+K^-K^+$.

Mode	A_{CP}
$B^+ \to \eta' K^+$	$-0.11 \pm 0.11 \pm 0.02$
$B^+ \to \omega\pi^+$	$-0.01^{+0.29}_{-0.31} \pm 0.03$
$B^+ \to \phi K^+$	$-0.05 \pm 0.20 \pm 0.03$
$B^+ \to \phi K^{\star +}$	$-0.43^{+0.36}_{-0.30} \pm 0.06$
$B^0 \to \phi K^{\star 0}$	$0.00 \pm 0.27 \pm 0.03$

Table 3
Measured A_{CP} 's for quasi-two-body charmless decays using 22.7×10^6 $B\overline{B}$ pairs

ratios for these modes. As such it is important to measure as many of these as possible in the hope of understanding the mechanism involved.

Decays with ω in the final state have a theoretically small A_{CP} and give access to α and γ [14]. Table 3 lists the measured A_{CP} of these decays and the branching ratios can be found in Table 4. The decay $B^0 \to \omega K^0$ has been observed with a significance of 6.6σ.

The penguin decays $B \to \phi K^{(\star)}$, $\phi\pi$ are interesting as the standard model A_{CP} is a few percent, whereas new physics can alter this appreciably [5]. In addition, one can measure $sin2\beta$ which in the absence of new physics has the same value as that measured in charmonium modes. The measured A_{CP}'s and branching fractions for these decays are shown in Tables 3 and 4 respectively. Details of the quasi-two body analyses can be found in [15].

Mode	$N(B\overline{B}) \times 10^6$	$BR(\times 10^{-6})$
$B^+ \to \eta' K^+$	61.5	$67 \pm 5 \pm 5$
$B^+ \to \eta' K^0$	61.5	$46 \pm 6 \pm 4$
$B^+ \to \eta' K^{\star 0}$	61.5	< 13 (90% C.L.)
$B^+ \to \omega\pi^+$	22.7	$6.6^{+2.1}_{-1.8} \pm 0.7$
$B^0 \to \omega K^0$	61.5	$5.9^{+1.7}_{-1.5} \pm 0.9$
$B^+ \to \phi K^+$	61.5	$9.2 \pm 1.0 \pm 0.8$
$B^0 \to \phi K^0$	61.5	$8.7^{+1.7}_{-1.5} \pm 0.9$
$B^+ \to \phi K^{\star +}$	61.5	$9.7^{+4.2}_{-3.4} \pm 1.7$
$B^0 \to \phi K^{\star 0}$	61.5	$8.7^{+2.5}_{-2.1} \pm 1.1$
$B^+ \to \phi\pi^+$	61.5	< 0.56 (90% C.L.)

Table 4
Measured branching ratios for quasi-two-body charmless decays.

3.4. Other decays

One can search for direct CPV in decays other than the charmless ones described above, in particular we have looked for direct CPV in $B^0 \to K^\star\gamma$ and $B^- \to D^0_{(CP)}K^-$. The radiative penguin decay $B^0 \to K^\star\gamma$ provides a window to constrain new physics, as this can enhance the standard model A_{CP} from $< 1\%$ to large values [6]. Using 22.7×10^6 $B\overline{B}$ decays we measure $A_{CP} = -0.044 \pm 0.076 \pm 0.012$ [16].

Given sufficient statistics, one can access γ via the decay $B^- \to D^0_{(CP)}K^-$ [17]. Here the CP subscript refers to reconstruction of a D-meson decaying to a CP eigenstate. The measured A_{CP} for this mode is also consistent with zero within errors; $0.17 \pm 0.23^{+0.09}_{-0.07}$ [18].

4. CONCLUSIONS

There is no signal for direct CPV in the B system yet. The search for direct CPV in B_d decays is well underway at *BABAR* but more data are required over the next few years to further these efforts. The most precise measurement of a CP asymmetry, where a non-zero value of A_{CP} is predicted, has a total uncertainty of 5.2%. This uses $88\times10^6 B\overline{B}$ pairs which is almost our full data-set. In searching for direct CPV in radiative penguin decays *BABAR* has already started to constrain the parameter space of new physics models. As we increase our statistics over the next few years, the search for direct CPV will become more interesing as will measurements of the weak angles of the unitarity triangle and constraints on new physics models from these rare decays.

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