Rare hadronic $B$ decays.

Adrian Bevan
Department of Physics
Queen Mary, University of London, Mile End Road, E1 2NS, UK.
e-mail: bevan@slac.stanford.edu
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Rare hadronic $B$-meson decays allow us to study $CP$ violation. The class of $B$-decays final states containing two vector mesons provides a rich set of angular correlation observables to study. This article reviews some of the recent experimental results from the $BABAR$ and Belle collaborations.

1 Introduction

The study of rare hadronic $B$-meson decays with branching fractions $O(10^{-6})$ enable us to probe a wide range of phenomena. Such decays can be used to probe our understanding of the CKM [1] description of quark mixing and $CP$ violation ($CPV$) in the Standard Model of Particle Physics (SM) by measuring all three of the Unitarity Triangle angles $\alpha$, $\beta$ and $\gamma$, as well as charge asymmetries in direct $CPV$ $\Delta b = 1$ transitions. $CPV$ was first seen in the decay of neutral kaons [2]. The first observation of $CPV$ in $B$-meson decay was the measurement of a non-zero value of $\sin 2\beta$ by the $B$-factories [3]. The measurements of the Unitarity Triangle angles and time-dependent $CP$ observables ($S$ and $C$) in hadronic $B$-meson decays are discussed elsewhere [4].

The phenomenon of direct $CPV$ was experimentally established in the study of neutral kaon decay to two pion final states, through the measurement of a non zero value of the ratio $\epsilon'/\epsilon = (1.67 \pm 0.26) \times 10^{-3}$ [5, 6]. In contrast to the kaon system, where the direct $CPV$ parameter $\epsilon'$ is $O(\text{few} \times 10^{-6})$, one can accommodate large direct $CPV$ in $B$-meson decay. For a $B$-meson decays to a final state $f$, the direct $CP$ asymmetry is defined as

$$ A_{CP} = (N - \bar{N})/(N + \bar{N}), $$

where $N$ ($\bar{N}$) is the number of $B$ ($\bar{B}$) decays to $f$ ($\bar{f}$). In order for a decay to be direct $CP$ violating ($A_{CP} \neq 0$), one requires that there are at least two interfering amplitudes $A_i$ with both non-zero weak ($\phi$) and strong phase ($\delta$) differences where

$$ A_{CP} \propto \sum_{i,j;i\neq j} A_i A_j \sin(\phi_i - \phi_j) \sin(\delta_i - \delta_j). $$

The values of the strong phases of amplitudes are $a priori$ unknown. As a result, there is a limited amount of information that one can extract from a measured $CP$ asymmetry in a single decay channel.

There are still questions remaining on the subject of the hierarchy and values of the branching fractions of a number of rare hadronic $B$-meson decays. The $B$-factories, the $BABAR$ experiment at SLAC [7] and the Belle experiment at KEK [8], continue to improve measurements of such decays with the aim of providing theorists with more accurate data to test calculations. There has recently been significant progress on the experimental study of $B \to hh$ ($h = \pi, K$) final states, where the $BABAR$ experiment has accounted for the effects of final state radiation in $B$ meson decays to $\pi^+\pi^-$, $K^+\pi^-$, and $K^+K^-$ [9, 10]. The recent observation of $B^0 \to a_1^+\pi^-$ might lead to additional constraints on the value of the Unitarity Triangle angle $\alpha$ [11].

$B$-meson decays to two vector particles ($V$) are particularly interesting. In addition to the $CP$ violating observables, $S$, $C$, and $A_{CP}$, one has a number of angular correlation observables to measure and compare with predictions. Any deviations from theoretical expectations indicate either a deficiency in our current
understanding of these decays, or a tantalizing hint of possible new physics effects. There has been considerable 
activity in the study these $B \rightarrow VV$ decays recently.

The remaining sections of these proceedings discuss experimental techniques, results on searches for direct
$CP$ violation, branching ratios for the $B$-meson decays to $h^+h^-$ and $a_1^+\pi^-$, and studies of $B \rightarrow VV$ decays. 
There is a summary of results at the end of the article. Charge conjugation is implied throughout these
proceedings.

2 Experimental techniques

Signal candidates are identified using two kinematic variables $m_{ES}$ and $\Delta E$. The energy difference $\Delta E$ is defined
as the difference between the energy of the $B$ candidate and the beam energy, $\sqrt{s}/2$, in the center of mass (CM) frame. The beam-energy substituted mass, $m_{ES}$, is defined as

$$m_{ES} = \sqrt{(s/2 + p_i \cdot p_B)^2 / E_i^2 - p_i^2},$$

where $\sqrt{s}$ is the total energy of both beams (10.58 GeV), the $B$ momentum $p_B$ and four-momentum of the
initial state $(E_i, p_i)$ are defined in the laboratory frame.

Continuum $e^+e^- \rightarrow q\overline{q}$ ($q = u, d, s, c$) events are the dominant background to rare hadronic $B$-decays. To
discriminate signal from the continuum background one uses the fact that final state particles in $B$ events tend to
be spherically distributed, whereas continuum events are more jet-like. Event shape variables are combined
into a single variable with the purpose of discriminating between signal and continuum background events (For
example, see Refs. [12] and [13].). All of the results discussed here are obtained using an extended unbinned
maximum-likelihood fit to the data.

3 Results

3.1 Direct $CP$ violation searches

$B^0$-meson decays to the $K^+\pi^-$ and $K^-\pi^+$ final states are self tagging in that the charge of the kaon in the
final state determines the flavor of the decaying $B$-meson: $B^0 \rightarrow K^-\pi^+$, and $B^0 \rightarrow K^+\pi^-$. The $B$-factories
have measured a significantly non-zero $A_{CP}$ in these decays. The results reported are

$$A_{CP} \ K^+\pi^- = -0.113 \pm 0.022\text{(stat)} \pm 0.08\text{(syst)}, \text{(Belle)}$$

$$A_{CP} \ K^-\pi^+ = -0.133 \pm 0.030\text{(stat)} \pm 0.09\text{(syst)}, \text{(BABAR)}$$

using $386 \times 10^6$, and $227 \times 10^6$ $B\overline{B}$ pairs, respectively [14] [15]. On averaging the results one obtains $A_{CP} = -0.115 \pm 0.018$ [16]. This average includes results from the CDF and CLEO experiments, however the BABAR and Belle results dominate the average. This constitutes an observation of direct $CPV$ in $B$-meson decay, which is the second type of $CPV$ observed in $B$ decays. Figure 1 shows the $m_{ES}$ distributions of $B^0 \rightarrow K^-\pi^+$, and $B^0 \rightarrow K^+\pi^-$ from the BABAR data.

There is considerable activity in searching for other possible indications of direct $CPV$ at the $B$-factories. So far, there has been no additional observations of this effect to date. The best evidence obtained for direct $CPV$ in other $B$ decays is in the channel $B^0 \rightarrow \pi^+\pi^-$. More statistics are required to establish $CPV$ in this
decay. The Belle data give a 4.0$\sigma$ evidence for direct $CPV$ [12]. The BABAR data do not yet show any evidence for
direct $CPV$ [13]. The measurements are

$$C_{\pi\pi} = -0.56 \pm 0.12\text{(stat)} \pm 0.06\text{(syst)}, \text{(Belle)}$$

$$C_{\pi\pi} = -0.09 \pm 0.15\text{(stat)} \pm 0.04\text{(syst)}, \text{(BABAR)}$$

using $275 \times 10^6$, and $232 \times 10^6$ $B\overline{B}$ pairs, respectively.

Another promising decay channel that provides evidence for direct $CPV$ is $B^+ \rightarrow \rho^0K^+$. The Belle data
are consistent with a 3.9$\sigma$ evidence for direct $CPV$, whereas currently the BABAR data shows no indication of
an asymmetry [17]. The measured asymmetries are

\[ A_{CP}^{\rho K^+} = 0.30 \pm 0.11 \text{(stat)} \pm 0.02 \text{(syst)} \pm 1.1 \text{(model)}, \text{(Belle)} \]

\[ A_{CP}^{\rho K^+} = 0.32 \pm 0.13 \text{(stat)} \pm 0.06 \text{(syst)} \pm 8 \text{(model)}, \text{(BABAR)} \]

using \(3.86 \times 10^6\), and \(2.26 \times 10^6\) \(B\bar{B}\) pairs, respectively. Again, more data are required in order to establish direct \(CPV\) in this mode.

3.2 Branching fractions of \(B \to hh\) decays

The decay of \(B\) mesons to \(\pi\pi\), and \(K\pi\) final states are of general interest to the field of \(B\) physics. The \(B^0 \to \pi^+\pi^-\) branching fraction is an input to the \(\pi\pi\) isospin analysis, and measurement of \(\alpha\) [18], and measurements of the decays to \(K\pi\) are inputs to help elucidate the so-called \(K\pi\) puzzle [19].

The \(\text{BABAR}\) collaboration have recently updated these measurements with \(2.32 \times 10^6\) \(B\bar{B}\) pairs [9]. In this analysis, \(\text{BABAR}\) take into account the possible effects of final state radiation (FSR) [10]. Taking FSR into account has ramifications on the extraction of the signal yield, as well as the quoted signal efficiency that is used in calculating branching fractions. The results obtained are:

\[ B(B^0 \to K^+\pi^-) = (19.2 \pm 0.6 \text{(stat)} \pm 0.6 \text{(syst)}) \times 10^{-6}, \]

\[ B(B^0 \to \pi^+\pi^-) = (5.5 \pm 0.4 \text{(stat)} \pm 0.3 \text{(syst)}) \times 10^{-6}, \]

\[ B(B^0 \to K^+K^-) < 0.4 \times 10^{-6} \text{(90\% C.L.)}. \]

The \(K\pi\) \((\pi\pi)\) branching fractions reported are 7\% (17\%) higher than previous measurements from the \(B\)-factories [20]. This highlights the significance of further understanding and treatment of FSR in rare hadronic \(B\)-decays.

3.3 Observation of the decay \(B^0 \to a_1^\pm\pi^\mp\)

Some time ago it was suggested that one could measure the Unitarity Triangle angle \(\alpha\) using the non-\(CP\) eigenstate decay \(B^0 \to a_1^\pm\pi^\mp\) [21]. \(\text{BABAR}\) has recently observed the decay \(B^0 \to a_1^\pm\pi^\mp\), and Belle have

\[ \begin{array}{c}
\hline
\text{Asymmetry} \\
5.2 & 5.22 & 5.24 & 5.26 & 5.28 & 5.3 \\
Events / 2.5 MeV/c^2 \\
\hline
\end{array} \]
confirmed this observation [22]. The measured branching fraction for this decay is
\[
B(B^0 \rightarrow a_1^+ \pi^-) = \left(33.2 \pm 3.8\,(\text{stat}) \pm 3.0\,(\text{syst})\right) \times 10^{-6}, \quad (\text{BABAR})
\]
\[
B(B^0 \rightarrow a_1^+ \pi^-) = \left(48.6 \pm 4.1\,(\text{stat}) \pm 3.9\,(\text{syst})\right) \times 10^{-6}, \quad (\text{Belle})
\]

using $218 \times 10^6$ and $275 \times 10^6 \, B\overline{B}$ pairs, respectively. One can expect the $B$-factories to investigate the prospects of such a time-dependent $CP$ analysis in the coming years. An isospin analysis of $B \rightarrow a_1 \pi$ decays would be experimentally challenging. The use of $SU(3)$ to measure $a$ with $B \rightarrow a_1 \pi$ decays has recently been proposed [14] as an alternative. This approach requires experimental knowledge of the decays $B \rightarrow a_1 K$, $B \rightarrow K_1(1270)\pi$ and $B \rightarrow K_1(1400)\pi$. BABAR recently performed a search for the related decay $B^0 \rightarrow a_1^+ \rho^-$ [23] using $110 \times 10^6 \, B\overline{B}$ pairs. The result of this search was an upper limit of $< 61 \times 10^{-6} \,(90\%\,\text{C.L.}).$

### 3.4 Dynamics of $B$-meson decays to two vector particles

The $B$-factories have performed studies of the angular correlations of several types of $B \rightarrow VV$ decay: $B \rightarrow \rho\rho$, $B \rightarrow K^*\rho$, $B \rightarrow K^*\omega$, and $B \rightarrow K^*\phi$ [24, 25]. Figure 2 shows a schematic of the topology of a $B \rightarrow VV$ decay, where each vector particle decays to a two body final state, where $\theta_i \,(i=1,2)$ is the helicity angle of the vector particle defined as the angle between the daughter momentum in the vector particle rest frame and the flight direction of the $B^0$ in this frame. The angle $\phi$ is the angle between the decay planes of the vector mesons. Most of the decays studied have limited statistics and focus on extracting the fraction of longitudinally polarized events ($f_L$) from the data after integrating over $\phi$. The angular distribution used for these decays is
\[
\frac{d^2\Gamma}{d\cos\theta_1 d\cos\theta_2} = \frac{9}{4} \left( f_L \cos^2\theta_1 \cos^2\theta_2 + \frac{1}{4} (1 - f_L) \sin^2\theta_1 \sin^2\theta_2 \right), \quad (4)
\]

A full angular analysis is performed for $B$-meson decays to $\phi K^*$ [24, 25]. Early calculations of $f_L$ predicted the longitudinal polarization would dominate in $B \rightarrow VV$ decays [24]. Figure 3 shows the measured values of $f_L$ obtained from experiment. There is a pattern to the underlying physics processes which needs to be understood in the measured values of $f_L$. The tree dominated decays of $B$ mesons to $\rho\rho$, $K^*\omega$ and $K^*\rho$ are consistent with the naive expectation that: $f_L \sim O(1 - m^2_\rho/m^2_\pi)$. However the loop dominated modes ($K^*\phi$ and $K^{*+}\rho^-$) have lower values of $f_L$ than expected. It is possible that improvements in calculations of $f_L$ for the loop dominated modes could resolve this issue. Possible new physics contributions modifying these observables have also been discussed [25]. There remains work to be done in this area, both on the experimental and theoretical side. The $B$-factories need to perform as many different measurements in as many different $B \rightarrow VV$ decay modes as possible. One can also measure $CP$-violating, $T$-odd triple product asymmetries in $B \rightarrow VV$ decays [29].
4 Summary

The $B$-factories have established direct $CP$ violation in $B^0 \rightarrow K^{\pm}\pi^{\mp}$ decays in recent years. Tantalizing hints of direct $CPV$ are starting to emerge in other modes. As the $B$-factories continue to accumulate data we should see direct $CPV$ being established in more decay modes.

In summary, the study of rare hadronic $B$-meson decays has provided a rich harvest of information since the $B$-factories started taking data. There is still a wide range of physics that we can learn from using these decays. The recent observation of $B^0 \rightarrow a_1^{\pm\mp}\pi^{\mp}$ raises the possibility that the $B$-factories might be able to add another mode to the list of those providing measurements of the Unitarity Triangle angle $\alpha$. Experimental and theoretical work is required to understand the pattern of measured $f_L$ in $B \rightarrow VV$ decays.

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