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Rare hadronic B decays.

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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 $\mathcal{O}(10^{-6})$ 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 α, β and γ, 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 ϵ' is $\mathcal{O}(\text{few} \times 10^{-6})$, 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

$$\mathcal{A}_{CP} = (\overline{N} - N)/(\overline{N} + N), \tag{1}$$

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

$$\mathcal{A}_{CP} \propto \sum_{i,j;i\neq j} A_i A_j \sin(\phi_i - \phi_j) \sin(\delta_i - \delta_j). \tag{2}$$

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 α [11].

B-meson decays to two vector particles (V) are particularly interesting. In addition to the CP violating observables, S, C, and $\mathcal{A}_{CP}$, 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

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understanding of these decays, or a tantalizing hint of possible new physics effects. There has been considerable activity in the study these $B \to VV$ decays recently.

The remaining sections of these proceedings discuss experimental techniques, results on searches for direct CP violation, branching fractions for the B-meson decays to h^+h^- and $a_1^+\pi^-$, and studies of $B \to VV$ 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 $m_{\rm ES}$ and ΔE. The energy difference ΔE 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, $m_{\rm ES}$, is defined as

$$m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}, \tag{3}$$

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

Continuum $e^+e^- \to q\overline{q}$ $(q = u, d, s, c)$ 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: $\overline{B}^0 \to K^-\pi^+$, and $B^0 \to K^+\pi^-$. The B-factories have measured a significantly non-zero $\mathcal{A}_{CP}$ in these decays. The results reported are

$$\begin{aligned} \mathcal{A}_{CP\;K\pi} &= -0.113 \pm 0.022(\text{stat}) \pm 0.08(\text{syst}), (\text{Belle}) \\ \mathcal{A}_{CP\;K\pi} &= -0.133 \pm 0.030(\text{stat}) \pm 0.09(\text{syst}), (\textit{BABAR}) \end{aligned}$$

using 386×10^6, and 227×10^6 $B\overline{B}$ pairs, respectively [14, 15]. On averaging the results one obtains $\mathcal{A}_{CP} = -0.115 \pm 0.018$ [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 $m_{\rm ES}$ distributions of $\overline{B}^0 \to K^-\pi^+$, and $B^0 \to K^+\pi^-$ 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 $B^0 \to \pi^+\pi^-$. More statistics are required to establish CPV in this decay. The Belle data give a 4.0σ evidence for direct CPV [12]. The *BABAR* data do not yet show any evidence for direct CPV [13]. The measurements are

$$\begin{aligned} C_{\pi\pi} &= -0.56 \pm 0.12(\text{stat}) \pm 0.06(\text{syst}), (\text{Belle}) \\ C_{\pi\pi} &= -0.09 \pm 0.15(\text{stat}) \pm 0.04(\text{syst}), (\textit{BABAR}) \end{aligned}$$

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

Another promising decay channel that provides evidence for direct CPV is $B^+ \to \rho^0K^+$. The Belle data are consistent with a 3.9σ evidence for direct CPV, whereas currently the *BABAR* data shows no indication of

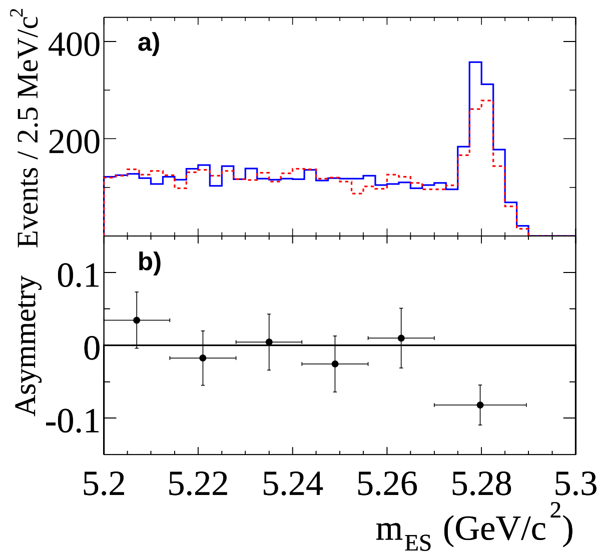

Figure 1: Distributions of (a) $m_{\rm ES}$ $\overline{B}^0 \to K^-\pi^+$, and $B^0 \to K^+\pi^-$ from the *BABAR* data, and (b) $\mathcal{A}_{CP}$ taken from Ref. [14]. The solid histogram is for $K^+\pi^-$ and the dashed histogram is for $K^-\pi^+$. The region below the B mass is dominated by continuum background. The Belle data exhibit similar properties [15].

an asymmetry [17]. The measured asymmetries are

$$\mathcal{A}_{CP\ \rho^0 K^+} = 0.30 \pm 0.11(\text{stat}) \pm 0.02(\text{syst})^{+11}_{-4}(\text{model}), (\text{Belle})$$
$$\mathcal{A}_{CP\ \rho^0 K^+} = 0.32 \pm 0.13(\text{stat}) \pm 0.06(\text{syst})^{+8}_{-5}(\text{model}), (\textit{BABAR})$$

using 386×10^6, and 226×10^6 $B\overline{B}$ 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 α [18], and measurements of the decays to $K\pi$ are inputs to help elucidate the so-called $K\pi$ puzzle [19].

The *BABAR* collaboration have recently updated these measurements with 232×10^{-6} B pairs [9]. In this analysis, *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:

$$\mathcal{B}(B^0 \to K^+\pi^-) = (19.2 \pm 0.6(\text{stat}) \pm 0.6(\text{syst})) \times 10^{-6},$$
$$\mathcal{B}(B^0 \to \pi^+\pi^-) = (5.5 \pm 0.4(\text{stat}) \pm 0.3(\text{syst})) \times 10^{-6},$$
$$\mathcal{B}(B^0 \to K^+K^-) < 0.4 \times 10^{-6}(90\%\, C.L.).$$

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 α using the non-*CP* eigenstate decay $B^0 \to a_1^\pm\pi^\mp$ [21]. *BABAR* has recently observed the decay $B^0 \to a_1^\pm\pi^\mp$, and Belle have confirmed this observation [22]. The measured branching fraction for this decay is

$$\begin{aligned}\mathcal{B}(B^0 \to a_1^{\pm}\pi^{\mp}) &= (33.2 \pm 3.8(\text{stat}) \pm 3.0(\text{syst})) \times 10^{-6}, (\textit{BABAR})\\ \mathcal{B}(B^0 \to a_1^{\pm}\pi^{\mp}) &= (48.6 \pm 4.1(\text{stat}) \pm 3.9(\text{syst})) \times 10^{-6}, (\text{Belle})\end{aligned}$$

using 218×10^6, and 275×10^6 $B\overline{B}$ 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 $B \to a_1\pi$ decays would be experimentally challenging. The use of $SU(3)$ to measure α with $B \to a_1\pi$ decays has recently been proposed [11] as an alternative. This approach requires experimental knowledge of the decays $B \to a_1K$, $B \to K_1(1270)\pi$ and $B \to K_1(1400)\pi$. *BABAR* recently performed a search for the related decay $B^0 \to a_1^{\pm}\rho^{\mp}$ [23] using 110×10^6 $B\overline{B}$ pairs. The result of this search was an upper limit of $< 61 \times 10^{-6}$ (90%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 $B \to VV$ decay: $B \to \rho\rho$, $B \to K^{\star}\rho$, $B \to K^{\star}\omega$, and $B \to K^{\star}\phi$ [24, 25]. Figure 2 shows a schematic of the topology of a $B \to VV$ decay, where each vector particle decays to a two body final state. where θ_i (i=1,2) is the helicity angle of the vector

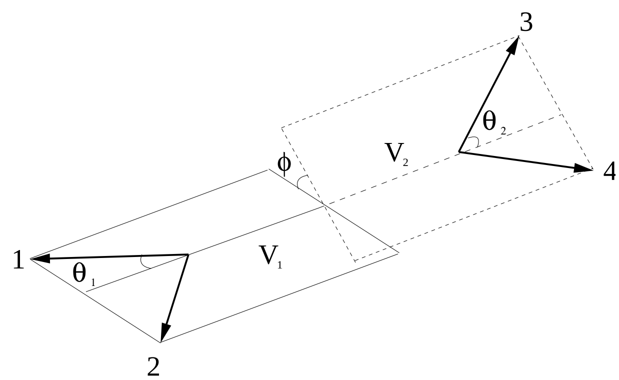

Figure 2: The decay of a B-meson to via two vector mesons, V_1 and V_2, to a four particle final state.

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 ϕ 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 ϕ. The angular distribution used for these decays is

$$\frac{d^2\Gamma}{\Gamma d\cos\theta_1 d\cos\theta_2} = \frac{9}{4}\left(f_L\cos^2\theta_1\cos^2\theta_2 + \frac{1}{4}(1-f_L)\sin^2\theta_1\sin^2\theta_2\right), \qquad (4)$$

A full angular analysis is performed for B-meson decays to ϕK^* [25, 26]. Early calculations of f_L predicted the longitudinal polarization would dominate in $B \to VV$ decays [27]. 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 $\rho\rho$, $K^{\star}\omega$ and $K^{\star}\rho$ are consistent with the naive expectation that: $f_L \sim \mathcal{O}(1 - m_V^2/m_b^2)$. However the loop dominated modes ($K^{\star}\phi$ and $K^{\star+}\rho^-$) 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 [28]. 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 $B \to VV$ decay modes as possible. One can also measure *CP*-violating, T-odd triple product asymmetries in $B \to VV$ decays [29].

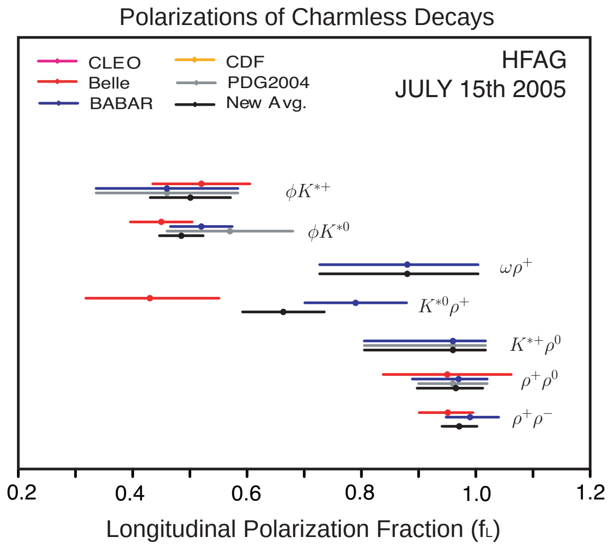

Figure 3: The measured values of f_L in $B \to VV$ decays [16].

4 Summary

The B-factories have established direct CP violation in $B^0 \to K^\pm\pi^\mp$ 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 $B^0 \to a_1^\pm\pi^\mp$ 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 α. Experimental and theoretical work is required to understand the pattern of measured f_L in $B \to VV$ decays.

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