Proceedings of the VIIIth International Workshop on Heavy Quarks and Leptons HQL06

October 2006

Deutsches Museum, Munich

Editors
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Organized by the Physics Department of the Technical University of Munich
and the Max-Planck Institute for Physics, Munich

Charmless B Decays

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1 Introduction

Rare charmless hadronic B decays are a good testing ground for the standard model. The dominant amplitudes contributing to this class of B decays are CKM suppressed tree diagrams and $b \to s$ or $b \to d$ loop diagrams ('penguins'). These decays can be used to study interfering standard model (SM) amplitudes and CP violation. They are sensitive to the presence of new particles in the loops, and they provide valuable information to constrain theoretical models of B decays.

The B factories BABAR at SLAC and Belle at KEK produce B mesons in the reaction $e^+e^- \to \Upsilon(4S) \to B\overline{B}$. So far they have collected integrated luminosities of about $406\,\mathrm{fb}^{-1}$ and $600\,\mathrm{fb}^{-1}$, respectively. The results presented here are based on subsets of about 200–500 fb^{-1} and are preliminary unless a journal reference is given.

2 ΔS from rare decays

The time-dependent CP asymmetry in B decays is observed as an asymmetry between B^0 and $\overline{B}^0$ decay rates into CP eigenstates f

$$\mathcal{A}_{cp}(\Delta t) = \frac{\Gamma(\overline{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\overline{B}^0 \to f) + \Gamma(B^0 \to f)} = S_f \sin \Delta m_d \Delta t - C_f \cos \Delta m_d \Delta t,$$

where $\Delta m_d = 0.502 \pm 0.007\ \mathrm{ps}^{-1}$ and Δt is the time difference between the decays of the two neutral B mesons in the event. The coefficients S_f and C_f depend on the final state f; for the 'golden' decay $B^0 \to J/\psi K^0_S$, for example, which proceeds via a $b \to c\bar{c}s$ transition, only one weak phase enters, and $S_{J/\psi K^0_S} = \sin 2\beta$, $C_{J/\psi K^0_S} = 0$. Here, $\beta \equiv \phi_1$ is one of the angles of the unitarity triangle of the CKM matrix.

In general, the presence of more than one contributing amplitude for the decay can introduce additional phases, so that S_f measured in such a decay deviates from the simple $\sin 2\beta$. Apart from standard-model amplitudes, particles beyond the standard model may contribute in loop diagrams. There are intriguing hints in experimental data that S_f is smaller than $\sin 2\beta$ in B decays involving the transition $b \to q\bar{q}s$, like $B^0 \to \phi K^0$, $B^0 \to \eta' K^0$, or $B^0 \to \pi^0 K^0$ (see Fig. 1). However, for each of these final states the SM contribution to $\Delta S_f \equiv S_f - \sin 2\beta$ from sub-dominant amplitudes needs to be determined in order to draw a conclusion about the presence of any new physics. Typically, models prefer $\Delta S_f > 0$ [1, 2], while for the final state $\eta' K^0_S$, a small, negative ΔS_f is expected [3]. Measuring B decays which are related to the ones above by approximate SU(3) flavour or isospin symmetries helps to constrain the standard-model expectation for ΔS_f.

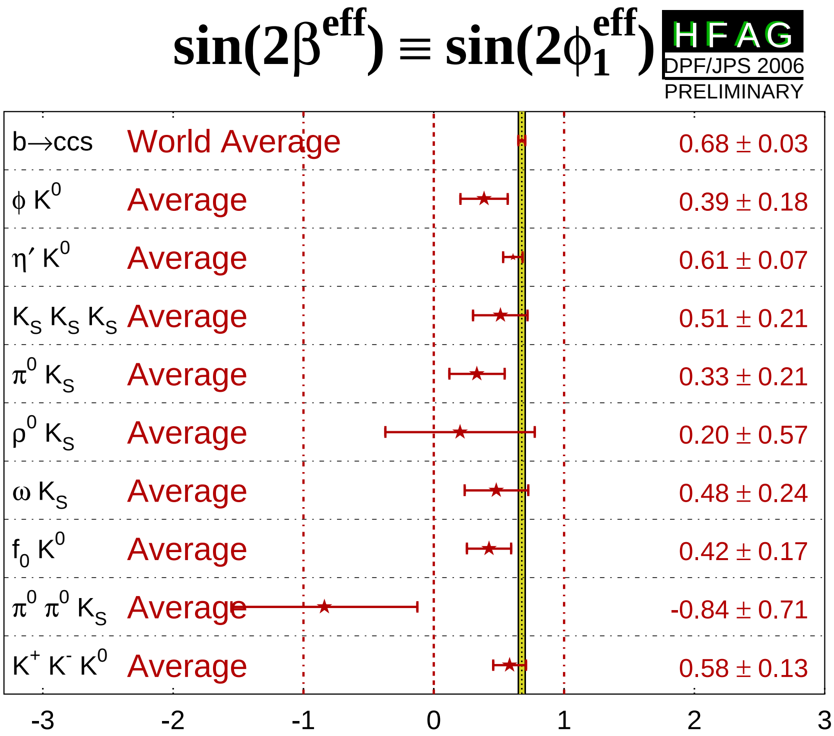

Figure 1: Average of S_f in the different $b \to q\bar{q}s$ decays [4].

2.1 $B^0 \to \phi K^0$

The sub-dominant amplitudes contributing to $B^0 \to \phi K^0$ can be constrained using SU(3) flavor relations [5]. This requires branching fraction measurements for eleven decay channels ($K^{*0}\overline{K}^0, \overline{K}^{*0}K^0$, and hh' with $h = \rho^0, \omega, \phi$ and $h' = \pi^0, \eta, \eta'$). BABAR has measured an upper limit for the sum $\mathcal{B}(K^{*0}\overline{K}^0) + \mathcal{B}(\overline{K}^{*0}K^0) < 1.9 \times 10^{-6}$ [6] and an updated upper limit for $\phi\pi^0$ of $\mathcal{B}(\phi\pi^0) < 2.8 \times 10^{-7}$ [7]. Together with the already known upper limits or branching fractions for the other decays in this list, this allows one to place a bound on $|\Delta S_{\phi K^0}| < 0.43$ [6].

2.2 $B^0 \to \eta' K^0$

The decays $B^0 \to \eta^{(\prime)}\pi^0, \eta'\eta$ can be used to constrain the SM pollution in $B^0 \to \eta' K^0$, The expected branching fractions are between 0.2 and 1×10^{-6} for $\eta^{(\prime)}\pi^0$ and 0.3 - 2×10^{-6} for $\eta'\eta$. Using $211\,\mathrm{fb}^{-1}$ of data, BABAR sets the following upper limits [8] at 90% confidence level (C.L.) in units of 10^{-6}: $\mathcal{B}(B^0 \to \eta\pi^0) < 1.3$, $\mathcal{B}(B^0 \to \eta'\eta) < 1.7$, $\mathcal{B}(B^0 \to \eta'\pi^0) < 2.1$, while Belle [9] measures $\mathcal{B}(B^0 \to \eta'\pi^0) = (2.79^{+1.02+0.25}_{-0.96-0.34}) \times 10^{-6}$ with 386×10^6 analysed $B\overline{B}$ pairs. With these new upper limits, the standard model expectation for $\Delta S_{\eta' K^0_S}$ is $-0.046 < \Delta S_{\eta' K^0_S} < 0.094$ [10]. A similar improvement for the measurement of $\sin 2\alpha$ in $B^0 \to \pi^+\pi^-$ is expected. Belle also measure $\mathcal{B}(B^+ \to \eta'\pi^+) = (1.76^{+0.67+0.15}_{-0.62-0.14}) \times 10^{-6}$ and a charge asymmetry in this channel of $\mathcal{A}_{ch} = 0.20^{+0.37}_{-0.36} \pm 0.04$.

2.3 Pure penguin decays

There is special interest in decays which only proceed via the $b \to s\bar{s}s$ penguin transitions. The $b \to u$ amplitudes can only contribute through rescattering. This drastically reduces the standard model 'pollution' in these decays, making them a very clean probe for the presence of new particles in the loop. An example for this class of decays is $B^0 \to K^0_S K^0_S K^0_S$, in which the CP violating parameters S and C have been measured by both BABAR [11] and Belle [12], with an average of $S = 0.51 \pm 0.21$, $C = -0.23 \pm 0.15$. BABAR has also searched for the related decay $B^0 \to K^0_S K^0_S K^0_L$. The non-resonant contribution (besides $B^0 \to \phi(K^0_S K^0_L)K^0_S$) to this final state has not been studied before and might be large [13]. Assuming a uniform Dalitz distribution and analysing $211\,\mathrm{fb}^{-1}$, BABAR [14] sets a 90% CL upper limit of $\mathcal{B}(B^0 \to K^0_S K^0_S K^0_L) < 7.4 \times 10^{-6}$. Due to a low product of efficiency and daughter branching fraction, this decay is therefore of limited use for the understanding of CP violation in $b \to q\bar{q}s$ decays.

3 Measurements related to α

Decays containing a $b \to u$ transition can be used to measure the angle $\alpha \equiv \phi_2$ in the unitarity triangle. In general several amplitudes with different weak phases contribute to these decays, only allowing the direct measurement of an effective parameter α_{eff}.

There are several methods to extract the true angle α in presence of this 'pollution.' Updated results for the decays $B \to \rho\rho$, have been presented by Christos Touramanis at this conference.

Another new decay studied by *BABAR* and Belle is $B^0 \to a_1^\pm \pi^\mp$, from which α can be extracted up to a four-fold ambiguity. Exploiting isospin or approximate SU(3) flavor symmetries this ambiguity can be overcome [15]. This needs also the measurement of related axial–vector decays, from which a model-dependent measurement of α can be derived. *BABAR* searches for $B^0 \to a_1^\pm \pi^\mp$ in $211\,\mathrm{fb}^{-1}$ and measures [16] a branching fraction of $\mathcal{B}(B^0 \to a_1^\pm \pi^\mp) = (33.2 \pm 3.8 \pm 3.0) \times 10^{-6}$, assuming $\mathcal{B}(a_1^+ \to (3\pi)^+) = 1$. With about the same luminosity, Belle measures a slightly larger branching fraction of $(48.6 \pm 4.1 \pm 3.9) \times 10^{-6}$ [17]. The next step is to extend this analysis to measure time-dependent CP violation in this decay.

BABAR also searched for the related decay $B^0 \to a_1^+ \rho^-$, which also could be used to measure α. In addition, B decays to 5π are an important background for the $B \to \rho\rho$ analyses. In $100\,\mathrm{fb}^{-1}$ no significant signal was seen; assuming a fully longitudinal polarisation, the analysis sets a 90% C.L. upper limit of $\mathcal{B}(B^0 \to a_1^+ \rho^-)\mathcal{B}(a_1^+ \to (3\pi)^+) < 61 \times 10^{-6}$ [18].

4 Charmless vector-vector decays

For tree-dominated B decays into two vector mesons, helicity conservation arguments together with factorisation suggest that the longitudinal polarisation fraction f_L is $f_L \sim 1 - m_V^2/m_B^2$, close to unity. Experimentally, this is seen in decays such as $B \to \rho\rho$, where $f_L \approx 0.95$ is observed. However, there seems to be a pattern emerging where f_L is smaller than the expectation in decays dominated by loop diagrams. This was first seen in the decays $B \to \phi K^*$, where f_L is near 0.5 with an uncertainty of about 0.04 [19, 20].

In the following sections, we describe a number of recent *BABAR* measurements for several of these vector-vector decays.

4.1 Decays involving an ω meson

To establish whether tree-induced decays generally have a large f_L, *BABAR* has searched for the related decays $B \to \omega V$ [21], where $V = \rho, K^*, \omega, \phi$. The results are summarised in Table 1. The only decay with a significant observed yield is $B^+ \to \omega\rho^+$ with $\mathcal{B}(B^+ \to \omega\rho^+) = (10.6 \pm 2.1^{+1.6}_{-1.0}) \times 10^{-6}$. The polarisation f_L is floated in the fit and a large value of $f_L = 0.82 \pm 0.11 \pm 0.02$ is found, as expected for a tree-dominated decay.

4.2 $B \to \rho K^*$

Conversely, the decays $B \to \rho K^*$ are penguin-dominated; some are known to have significant branching fractions and f_L can be measured. *BABAR* has published updated measurements of branching fractions, charge asymmetries and polarisation fractions [22].

$B^+ \to \rho^+ K^{*0}$

The decay $B^+ \to \rho^+ K^{*0}$ is particularly interesting because no tree diagram is thought to contribute to this decay. *BABAR* has a new measurement of the branching fraction, CP asymmetry and polarisation for this decay. The measured branching fraction is $\mathcal{B}(\rho^+ K^{*0}) = (9.6 \pm 1.7\,\mathrm{m}1.5) \times 10^{-6}$, $\mathcal{A}_{ch}(\rho^+ K^{*0}) = -0.01 \pm 0.16 \pm 0.02$. The observed polarisation is $f_L = 0.52 \pm 0.10 \pm 0.04$, as expected for a pure penguin decay and in good agreement with ϕK^*.

$B^+ \to \rho^0 K^{*+}$ and $B^0 \to \rho^0 K^{*0}$

The decays $B^+ \to \rho^0 K^{*+}$ and $B^0 \to \rho^0 K^{*0}$ are theoretically less clean because there is a Cabibbo-suppressed tree diagram contributing in addition to the penguin present for all $B \to \rho K^*$ decays. In addition, $B^+ \to \rho^0 K^{*+}$ is experimentally more challenging because of the smaller branching fraction.

For $B^+ \to \rho^0 K^{*+}$, *BABAR* measures a branching fraction of $(3.6^{+1.7}_{-1.6} \pm 0.8) \times 10^{-6}$, with a significance of only 2.6σ. The value of f_L determined by the fit is $f_L = 0.9 \pm 0.2$ although this is not considered a measurement for this decay, as the signal itself is not significant.

$B^0 \to \rho^0 K^{*0}$ is observed with a significance of 5.3σ; the branching fraction is $(5.6 \pm 0.9 \pm 1.3) \times 10^{-6}$ and $f_L = 0.57 \pm 0.09 \pm 0.08$.

	$\mathcal{B}(10^{-6})$	$S(\sigma)$	$\mathcal{B}$ U.L $\times 10^{-6}$	f_L	$\mathcal{A}_{ch}$
ωK^{*0}	$2.4 \pm 1.1 \pm 0.7$	2.4	4.2	$0.71^{+0.27}_{-0.24}$	–
ωK^{*+}	$0.6^{+1.4+1.1}_{-1.2-0.9}$	0.4	3.4	0.7 fixed	–
$\omega\rho^0$	$-0.6 \pm 0.7^{+0.8}_{-0.3}$	0.6	1.5	0.9 fixed	–
$\omega f_0(980)$	$0.9 \pm 0.4^{+0.2}_{-0.1}$	2.8	1.5	–	–
$\omega\rho^+$	$10.6 \pm 2.1^{+1.6}_{-1.0}$	5.7	–	$0.82 \pm 0.11 \pm 0.02$	$0.04 \pm 0.13 \pm 0.02$
$\omega\omega$	$1.8^{+1.3}_{-0.9} \pm 0.4$	2.1	4.0	0.79 ± 0.34	–
$\omega\phi$	$0.1 \pm 0.5 \pm 0.1$	0.3	1.2	0.88 fixed	–

Table 1: Results of the *BABAR* ωX analysis: measured branching fraction $\mathcal{B}$, significance including systematic uncertainties S, 90% C.L. upper limit, measured or assumed longitudinal polarisation f_L, charge asymmetry $\mathcal{A}_{ch}$.

	$\mathcal{B}(10^{-6})$	
	BABAR	BELLE
$B^0 \to \eta K^{*0}$	$16.5 \pm 1.1 \pm 0.8$	$15.9 \pm 1.2 \pm 0.9$
$B^+ \to \eta K^{*+}$	$18.9 \pm 1.8 \pm 1.3$	$19.7^{+2.0}_{-1.9} \pm 1.4$
$B^+ \to \eta \rho^+$	–	$4.1^{+1.4}_{-1.3} \pm 0.34$
$B^0 \to \eta \rho^0$	–	< 1.9
$B^0 \to \eta (K\pi)^{*0}_0$	$11.0 \pm 1.6 \pm 1.5$	–
$B^+ \to \eta (K\pi)^{*+}_0$	$18.2 \pm 2.6 \pm 2.6$	–
$B^0 \to \eta K^{*0}_2$	$9.6 \pm 1.8 \pm 1.1$	–
$B^+ \to \eta K^{*+}_2$	$9.1 \pm 2.7 \pm 1.4$	–

Table 2: Branching fractions for the decays $B \to \eta K^*$, $\eta\rho$, and $\eta(K\pi)$.

5 $B \to \eta^{(\prime)} K^{(*)}$

In B decays to final states comprising $\eta^{(\prime)} K^{(*)}$, the effect of the η–η' mixing angle combines with differing interference in the penguin diagrams to suppress the final states ηK and $\eta' K^*$, and enhance the final states $\eta' K$ and ηK^*. This pattern has now been experimentally established with rather precise measurements of the branching fractions for $\eta' K$ and ηK^* and the observation of the decays $\eta' K^*$. These decays are also important in light of measuring S in $B^0 \to \eta' K^0$.

5.1 $B \to \eta' K$

Belle's measurements for the branching fractions of $B \to \eta' \pi$ [9] were already mentioned above. The same analysis also obtains updated branching fraction measurements for the decays $B \to \eta' K$, with the results $\mathcal{B}(B^0 \to \eta' K^0) = (58.9^{+3.6}_{-3.5} \pm 4.3) \times 10^{-6}$, $\mathcal{B}(B^+ \to \eta' K^+) = (69.2 \pm 2.2 \pm 3.7) \times 10^{-6}$, $\mathcal{A}_{ch}(B^+ \to \eta' K^+) = 0.028 \pm 0.028 \pm 0.021$.

5.2 $B \to \eta K^*$ and $B \to \eta\rho$

BABAR [23] and Belle [24] have published updated results for the decays $B \to \eta K^*(892)$. Belle also observes the decay $B^+ \to \eta \rho^+$ and obtains an upper limit for $B^0 \to eta\rho^0$. These results confirm earlier measurements of $B \to \eta K^*$ and $\eta\rho$. *BABAR* also analyses the mass region $1035 < m_{K\pi} < 1535$ MeV of the $K\pi$ system and obtains branching fractions for the spin-0 ($\eta(K\pi)^*_0$) and spin-2 (ηK^*_2) contributions. For these two final states no predictions exist so far. The branching fraction results are summarised in Table 2.

	BABAR $\mathcal{B}(10^{-6})$	BELLE $\mathcal{B}(10^{-6})$
$\pi^+\ \pi^-$	$5.4 \pm 0.4 \pm 0.3$	$5.1 \pm 0.2 \pm 0.2$
$K^+\ \pi^-$	$18.6 \pm 0.6 \pm 0.6$	$20.0 \pm 0.4^{+0.9}_{-0.8}$
$K^+\ K^-$	< 0.40	—
$B^0 \to \pi^0\pi^0$	$1.48 \pm 0.26 \pm 0.12$	$2.3^{+0.4+0.2}_{-0.5-0.3}$
$B^+ \to \pi^+\pi^0$	$5.12 \pm 0.47 \pm 0.29$	$6.6 \pm 0.4^{+0.4}_{-0.5}$
$B^\pm \to K^\pm\pi^0$	$13.3 \pm 0.56 \pm 0.64$	$12.4 \pm 0.5^{+0.7}_{-0.6}$
$B^+ \to K^0\pi^+$	$23.9 \pm 1.1 \pm 1.0$	$22.9^{+0.8}_{-0.7} \pm 1.3$
$B^+ \to \overline{K}^0K^+$	$1.61 \pm 0.44 \pm 0.09$	$1.22^{+0.33+0.13}_{-0.28-0.16}$
$B^0 \to \overline{K}^0K^0$	$1.08 \pm 0.28 \pm 0.11$	$0.86^{+0.24}_{-0.21} \pm 0.09$
$B^0 \to K^0_S\pi^0$	$10.5 \pm 0.7 \pm 0.5$	$9.2^{+0.7+0.6}_{-0.6-0.7}$

Table 3: Branching fraction results for $B \to \pi\pi, \pi K, KK$

5.3 $B \to \eta' K^*$ and $B \to \eta' \rho$

BABAR [25] finds evidence for the decays $B \to \eta' K^*$ in $211\,\mathrm{fb}^{-1}$ and measures branching fractions of $\mathcal{B}(B^+ \to \eta' K^{*+}) = (4.9^{+1.9}_{-1.7} \pm 0.8) \times 10^{-6}$ and $\mathcal{B}(B^0 \to \eta' K^{*0}) = (3.8 \pm 1.1 \pm 0.5) \times 10^{-6}$. For the related decays into $\eta'\rho$, only $B^+ \to \eta'\rho^+$ is seen with $\mathcal{B}(B^+ \to \eta'\rho^+) = (8.7^{+3.1+2.3}_{-2.8-1.3}) \times 10^{-6}$, while $B^0 \to \eta'\rho^0$ is small with a 90% C.L. upper limit of $\mathcal{B}(B^0 \to \eta'\rho^0) < 3.7 \times 10^{-6}$. The direct CP asymmetries in the decays with a significant signal are compatible with zero. Theoretical predictions using SU(3) flavor symmetry [26], QCD factorisation [27], and perturbative QCD factorisation [28] agree within errors with the observed branching fractions. The observation of small branching fractions for $B \to \eta' K^*$ confirms the pattern of enhanced and suppressed decays to $\eta^{(\prime)} K^{(*)}$.

6 $B \to \pi\pi, \pi K, KK$

Updated branching fraction measurements for the two-body decays $B \to \pi\pi, \pi K$, and KK from BABAR [29–32] and Belle [33, 33–35] are summarised in Table 3. Both experiments observe the decays $B^+ \to \overline{K}^0 K^+$ and $B^0 \to \overline{K}^0 K^0$ with a statistical significance $> 5\sigma$; decays with $b \to d$ hadronic penguins have now been observed.

BABAR also studied time dependent CP violation in $B^0 \to \overline{K}^0 K^0$ [31] (reconstructed as $B^0 \to K^0_S K^0_S$) which is a pure $b \to d\bar{s}s$ penguin decay. Via flavour SU(3) symmetry, this decay also allows an estimate of the penguin contribution in $B^0 \to \pi^0\pi^0$. Direct CP asymmetry is expected to be zero. The result of the time-dependent fit is $S = -1.28^{+0.80+0.11}_{-0.73-0.16}$ and $C = -0.40 \pm 0.41 \pm 0.06$.

6.1 $B \to \eta'\eta' K$, $\phi\phi K$

Motivated by the large branching fraction for $B \to \eta' K$ and the observation that final states $P^0 P^0 X^0$ are CP eigenstates [36], *BABAR* searched for the decays $B \to \eta'\eta' K$. No significant signal was found in $211\,\mathrm{fb}^{-1}$, and the upper limits on the branching fractions of $\mathcal{B}(\eta'\eta' K^+) < 25 \times 10^{-6}$ and $\mathcal{B}(\eta'\eta' K^0) < 31 \times 10^{-6}$ are set [37].

BELLE searched for the decays $B \to \phi\phi K$. In these, direct CP violation could be enhanced in the interference between decays via the η_c and non-SM decays. In the analysis [38], charmless decays are selected by requiring that $m_{\phi\phi}$ is below the charm threshold. For these charmless decays, the observed branching fractions are $\mathcal{B}(\phi\phi K^+) = (3.2^{+0.6}_{-0.5} \pm 0.3) \times 10^{-6}$, $\mathcal{B}(\phi\phi K^0) = (2.3^{+1.0}_{-0.7} \pm 0.2) \times 10^{-6}$. The measured direct CP asymmetries are compatible with zero.

7 Summary

Charmless hadronic B decays provide a rich field for tests of QCD and the standard model of electroweak interactions. They allow to constrain the SM contribution to ΔS_f in loop-dominated B decays and precision tests of QCD models. The B factories have produced a large number of new and updated measurements. With the currently analysed statistics, decays with branching fractions of the order of 10^{-6} are within experimental reach.

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