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# Rare hadronic B decays from *BaBar*

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**Abstract.** A selection of rare decay results from *BaBar* are presented, from a data sample of $82fb^{-1}$ of data taken at the $\Upsilon(4S)$ resonance (corresponding to $88 \times 10^6$ $B\overline{B}$ pairs).

**PACS.** 13.25.Hw Decays of bottom mesons

## 1 Introduction

PEP II has produced a vast quantity of $B\overline{B}$ meson pairs, allowing *BaBar* to study "rare" decay modes of the $B$ previously considered beyond reach. Here, rare will be taken to mean $B$ decays with branching fracions of the order of $10^{-5}$ or $10^{-6}$, and only charmless hadronic decays will be considered. The decays discussed here break into two rough categories: those which are rare because the leading diagram contains a small CKM matrix element, and those for which there is no leading tree diagram, and penguin diagrams play the dominant role. Examples of the former are $B^0 \to \pi^+\pi^-$, $B^0 \to \pi^0\pi^0$, $B^+ \to K^+\pi^-\pi^+$, $B^+ \to \pi^+\pi^-\pi^+$ and $B^+ \to \rho^0\rho^+$. The later includes $B \to \phi K$, $B \to \eta K$ and $B \to \eta' K$.

These decays have several interesting features. Many of them enable the measurement of CKM angles (although this will not be covered in detail here). They also provide an excellent testing ground for QCD models. Perhaps the most interesting insight that these modes can offer is into new physics - some of these modes offer the potential for clear and unambiguous signals of new physics (generally through new particles entering into loop diagrams).

## 2 The dataset

The data used were collected with the *BaBar* detector [1]. Almost all analysis described here use $82fb^{-1}$ of data taken at the $\Upsilon(4S)$ resonance, corresponding to $88 \times 10^6$ $B\overline{B}$ pairs. The $B^+ \to K^+\pi^-\pi^+$ analysis uses $56.4fb^{-1}$.

### 2.1 Common analysis techniques

All of the analyses described here face the problem of small signals and relatively large backgrounds, and they use similar techniques to discriminate between the two. All use the kinematic variables $\Delta E$ and $M_{ES}$. $\Delta E$ is the difference between the measured energy of $B$ and its predicted energy, given that it came from an $\Upsilon(4S)$ decay. $M_{ES}$ is the mass of the $B$ calculated by substituting in this predicted energy of the $B$. Specifically, they are defined as $\Delta E = E^*_B - E^*_{beam}$ and $m_{ES} = \sqrt{(E^{*2}_B - p^{*2}_B)}$ where all quantities are calculated in the center of mass. For genuine $B$s, they peak at 0 and the mass of $B$ respectively. Continuum events follow phase space distributions.

All analyses also make use of event shape to discriminate between genuine $B$ decays and continuum background. $B$s decays isotropically, whereas continuum decays are jet like, and by combining event shape variables significant discrimination can be achieved.

## 3 $B \to hh$ decays ($h = \pi^{\pm}\, \pi^0, K^{\pm}$)

Two body charmless $B$ decays are of particular interest [2]. The decay $B^0 \to \pi^+\pi^-$ would provide a direct measurement of $\sin 2\alpha$, an important $CP$ parameter, if it decayed only by means of its leading tree diagram. Unfortunately, there is good cause to believe that the decay is "polluted" by a significant Penguin contribution. Hence an isospin analysis, requiring $B^- \to \pi^0\pi^-$ and $B^0 \to \pi^0\pi^0$ is needed to make this measurement. Table 1 lists *BaBar*'s results for these modes. The mode $B^0 \to \pi^0\pi^0$ could not be observed with this dataset, and hence an upper limit is calculated. As well as branching fractions, measurements of $A_{CP}$ (direct $CP$ asymmetry, defined as the normalised decay rate asymmetry between $B^0, \overline{B}^0$ or $B^+, B^-$) are shown for $B^+ \to \pi^+\pi^0$. No significant asymmetry is observed.

A related set of modes, $B \to K\pi$, are similar to the $B \to \pi\pi$ decays. They differ in that they are dominated by penguin diagrams, except in the case of $B^0 \to K^0\pi^0$ where the leading diagram is a colour suppressed tree. Results from *BaBar* are shown in Table 2. No significant direct $CP$ asymmetry is observed.

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**Table 1.** $B \to \pi\pi$ Decays

| Mode | $BR(10^{-6})$ | $A_{CP}$ |
|---|---|---|
| $B^0 \to \pi^+\pi^-$ | $4.7 \pm 0.6 \pm 0.2$ | |
| $B^+ \to \pi^+\pi^0$ | $5.5^{+1.0}_{-0.9} \pm 0.6$ | $-0.03^{+0.18}_{-0.17} \pm 0.02$ |
| $B^0 \to \pi^0\pi^0$ | $< 3.6$(90%CL) | |

**Table 2.** $B \to K\pi$ Decays

| Mode | $BR(10^{-6})$ | $A_{CP}$ |
|---|---|---|
| $B^0 \to K^+\pi^-$ | $17.9 \pm 0.9 \pm 0.6$ | $-0.102 \pm 0.050 \pm 0.016$ |
| $B^+ \to K^+\pi^0$ | $12.8^{+1.2}_{-1.0} \pm 1.0$ | $-0.09 \pm 0.09 \pm 0.01$ |
| $B^0 \to K^0\pi^0$ | $10.4 \pm 1.5 \pm 0.8$ | $0.03 \pm 0.35 \pm 0.09$ |
| $B^0 \to K^0\pi^+$ | $17.5 \pm 1.8 \pm 1.3$ | $-0.17 \pm 0.10 \pm 0.02$ |

**Table 3.** $B \to KK$ Decays

| Mode | $BR(10^{-6})$ |
|---|---|
| $B^0 \to K^+K^-$ | $< 0.6$ (90%CL) |
| $B^+ \to K^+K^0$ | $< 1.3$ (90%CL) |
| $B^0 \to K^0K^0$ | $< 1.6$ (90%CL) |

$B \to KK$ decays complete the set of two body measurements. These modes are expected to be suppressed relative to $B \to \pi\pi$ decays, and as expected no significant signal is observed in the given dataset. Upper limits are quoted in Table 3.

## 4 $B \to \eta h$ decays ($h = \pi^{\pm}\,\pi^0, K^{\pm}$)

There are a series of firm predictions for the relative branching fractions of decays of the form $B \to \eta(')h$ (where $h = \pi^{\pm}\,\pi^0, K^{\pm}$) [3]. $BR(B \to \eta K)$ is predicted to be $<< BR(B \to \eta' K)$ (and this relationship should be inverted for $\eta K^*$. As can be seen from Table 4, data from *BaBar* [4] support this prediction. In fact, the $(B \to \eta' K)$ BRs are rather too high - invoking $SU(3)$ symmetry, it is possible to form a triangular relationship between the amplitudes of $B \to \eta K$, $B \to \eta' K$ and $B \to \pi^0 K^0$, and given the measured branching ratios this is clearly not possible. Even taking $SU(3)$ breaking effects into account a discrepancy still exists. Although it is tempting to attribute this to New Physics, other effects (such as intrinsic charm or gluon fusion) need to be ruled out before such a claim could be made.

## 5 $B \to PseudoscalarVector$ decays

*BaBar* has observed and measured a great many $B \to PseudoscalarVector$ decays, many are listed in Table 5.

**Table 4.** $B \to \eta h$ Decays

| Mode | $BR(10^{-6})$ | |
|---|---|---|
| $B^+ \to \eta K^+$ | $2.8^{+0.8}_{-0.7} \pm 0.2$ | $0.32^{+0.20}_{-0.18} \pm 0.01$ |
| $B^0 \to \eta K^0$ | $< 4.6(90\%CL)$ | |
| $B^+ \to \eta\pi^+$ | $4.2^{+1.0}_{-0.9} \pm 0.3$ | $0.51^{+0.20}_{-0.18} \pm 0.01$ |
| $B^+ \to \eta' K^+$ | $76.9 \pm 3.5 \pm 4.4$ | $0.037 \pm 0.045 \pm 0.011$ |
| $B^0 \to \eta' K^0$ | $55.4 \pm 5.2 \pm 4.0$ | |

**Table 5.** $B \to PseudoscalarVector$ Decays

| Mode | $BR(10^{-6})$ | |
|---|---|---|
| $B^0 \to \rho^+\pi^-$ | $22.6 \pm 1.8 \pm 2.2$ | $-0.18 \pm 0.08 \pm 0.03$ |
| $B^0 \to \rho^+K^-$ | $7.3^{+1.3}_{-1.2} \pm 1.3$ | $0.28 \pm 0.17 \pm 0.08$ |
| $B^0 \to \omega K^0$ | $5.3^{+1.4}_{-1.2} \pm 0.5$ | |
| $B^+ \to \omega K^+$ | $5.0 \pm 1.0 \pm 0.4$ | $-0.05 \pm 0.16 \pm 0.01$ |
| $B^+ \to \omega\pi^+$ | $5.4 \pm 1.0 \pm 0.5$ | $0.04 \pm 0.17 \pm 0.01$ |
| $B^0 \to \phi K^0$ | $7.6^{+1.3}_{-1.2} \pm 0.5$ | |
| $B^+ \to \phi K^+$ | $10.0^{+0.9}_{-0.8} \pm 0.5$ | $-0.039 \pm 0.086 \pm 0.011$ |
| $B^+ \to \phi\pi^+$ | $< 0.41$ (90%CL) | |

Of particular interest are $B^0 \to \phi K^0$ decays, as this mode is regarded as extremely promising for the observation of new physics due to its pure gluonic penguin nature. Any deviation from the $CP$ violation predicted by the Standard Model (identical to that of $B \to J/\psi K^0$) would be an unambiguous sign of new physics. The only other potential cause would be from rescattering, and this effect can be constrained using measurements of $B^+ \to \phi\pi^+$. This mode is identical to $B \to \phi K$ except that it lacks the leading penguin amplitude, and is dominated instead by colour suppressed penguin and rescattering effects. Hence the upper limit on $BR(B^+ \to \phi\pi^+)$ provides a tight limit on the size of rescattering effects in $B \to \phi K$

## 6 $B \to hhh$ decays ($h = k^{\pm}\pi^{\pm}$)

*BaBar* has produced many results from three body decays [6]. Inclusively, $B^+ \to \pi^+\pi^-\pi^+$, $B^+ \to K^+\pi^-\pi^+$ and $B^+ \to K^+K^-K^+$ have been observed in this data set, and upper limits have been placed on $B^+ \to K^+K^-\pi^+$, $B^+ \to K^-\pi^+\pi^+$ and $B^+ \to K^+K^+\pi^-$ (see Table 6).

Three body modes such as these offer a rich resonance structure. Many exclusive decay modes are themselves of great interest, and regions of interference can provide important insights. Table 6 lists branching fractions and upper limits for decay modes covered by $B^+ \to K^+\pi^-\pi^+$ from a data set of 56.4 $fb^-1$. Fig. 1 shows the dalitz plot for identified $B^+ \to K^+\pi^-\pi^+$ events, with a cut on the likelihood ratio to enhance signal over background. Regions dominated by charmonium decays ($B^+ \to J/\psi K^+$, etc) have been excluded.

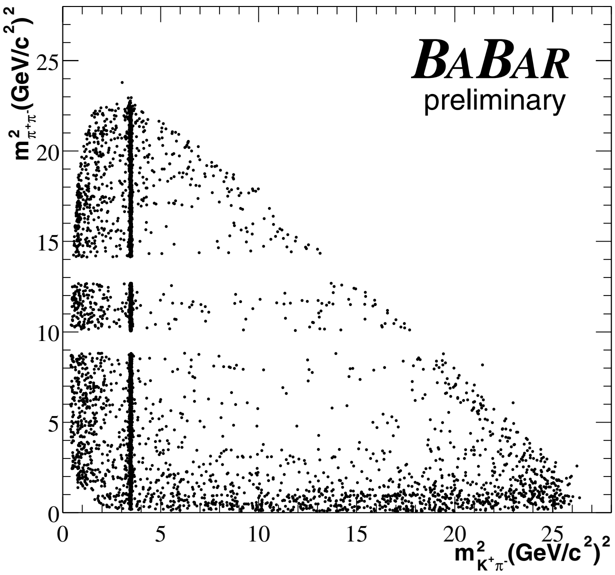

**Fig. 1.** Dalitz plot for $B^+ \to K^+\pi^-\pi^+$ with cut likelihood ratio to enhance signal over background

**Table 6.** $B \to hhh$ Decays

| Mode | $BR(10^{-6})$ | $A_{CP}$ |
|---|---|---|
| $B^+ \to \pi^+\pi^-\pi^+$ | $10.9 \pm 3.3 \pm 1.6$ | $-0.39 \pm 0.33 \pm 0.12$ |
| $B^+ \to K^+\pi^-\pi^+$ | $59.1 \pm 3.8 \pm 3.2$ | $0.01 \pm 0.07 \pm 0.03$ |
| $B^+ \to K^+K^-K^+$ | $29.6 \pm 2.1 \pm 1.6$ | $0.02 \pm 0.07 \pm 0.03$ |
| $B^+ \to K^+K^-\pi^+$ | $< 6.3$ (90%CL) | |
| $B^+ \to K^-\pi^+\pi^+$ | $< 1.8$ (90%CL) | |
| $B^+ \to K^+K^+\pi^-$ | $< 1.3$ (90%CL) | |

**Table 7.** $B^+ \to K^+\pi^-\pi^+$ Decays

| Mode | $BR(10^{-6})$ |
|---|---|
| $B^+ \to K^{*0}\pi^+$,$K^{*0} \to K^+\pi^-$ | $10.3 \pm 1.2^{1.0}_{-2.7}$ |
| $B^+ \to f^0(980)K^+$,$f^0 \to \pi^+\pi^-$ | $9.2 \pm 1.2^{2.1}_{-2.6}$ |
| $B^+ \to \chi^{c0}K^+$,$\chi^{c0} \to \pi^+\pi^-$ | $1.46 \pm 0.35 \pm 0.12$ |
| $B^+ \to D^0\pi^+$,$D^0 \to K^+\pi^-$ | $184.6 \pm 3.2 \pm 9.7$ |
| $B^+ \to$ higher $K^{*0}\pi^+$,$K^{*0} \to K^+\pi^-$ | $25.1 \pm 2.0^{11.0}_{-5.7}$ |
| $B^+ \to \rho^0(770)K^+$,$\rho^0 \to \pi^+\pi^-$ | $< 6.2$ (90%CL) |
| $B^+ \to K^+\pi^-\pi^+$ (non resonant) | $< 17$ (90%CL) |
| $B^+ \to$ higher $fK^+$,$f \to \pi^+\pi^-$ | $< 12$ (90%CL) |

**Table 8.** $B \to VectorVector$ Decays branching ratio and polarization

| # | Mode | $BR(10^{-6})$ | Polarization |
|---|---|---|---|
| 1 | $B^+ \to \rho^+\rho^0$ | $22.5^{5.7}_{5.4} \pm 5.8$ | $0.97^{+0.08}_{-0.07} \pm 0.04$ |
| 2 | $B^0 \to \rho^0\rho^0$ | $< 2.1$(90%CL) | |
| 3 | $B^+ \to \rho^0K^{*+}$ | $10.2^{2.9}_{2.5} \pm 2.3$ | $0.96^{+0.04}_{-0.15} \pm 0.04$ |
| 4 | $B^0 \to \phi K^{*0}$ | $11.1^{1.3}_{1.2} \pm 0.8$ | $0.65 \pm 0.07 \pm 0.02$ |
| 5 | $B^+ \to \phi^0K^{*+}$ | $12.1^{2.1}_{1.9} \pm 1.1$ | $0.46 \pm 0.12 \pm 0.03$ |

**Table 9.** $B \to vectorvector$ Decays asymmetries (modes numbered in Table 7

| # | $A_{CP}$ | $A_{TP}$ | $A_{SP}$ |
|---|---|---|---|
| 1 | $.04 \pm .12 \pm .02$ | $.09 \pm .24 \pm .04$ | $-.23 \pm .24 \pm .04$ |
| 3 | $.20^{+.04}_{-.15} \pm .04$ | $.03 \pm .29 \pm .03$ | $-.23^{+.24}_{-.33} \pm .04$ |
| 4 | $.04 \pm .12 \pm .02$ | $-.02 \pm .18 \pm .03$ | $-.04 \pm .18 \pm .03$ |
| 5 | $.16 \pm .17 \pm .03$ | $.06 \pm .12 \pm .02$ | $.07 \pm .12 \pm .02$ |

## 7 $B \to VectorVector$ decays

$B \to VectorVector$ decays offer a wide range of observables. On top of the branching fraction and $A_{CP}$ (direct $CP$) measurements which can be made for all modes it is possible to measure the polarization of the decay. In addition , two new asymmetries are observable: $A_{TP}$ and $A_{SP}$ [5]. Both of these quantities make use of the sign of the triple product formed from the decay products - essentially, the "handedness" of the decay. $A_{SP}$ is the normalised asymmetry between events with positive triple products and those with negative, and is sensitive to strong interaction phases. $A_{SP}$ is the normalised asymmetry between $\overline{B}$ decays with positive triple products or $B$ decays with negative triple products and decays in which the opposite combinations occur. This quantity is sensitive to $CP$ violation.

Table 7 lists the $B \to vectorvector$ modes that have been studied at *BaBar* with this dataset. It is worth noting that $B^+ \to \rho^+\rho^0$ and $B^+ \to \rho^0K^{*+}$ decays are observed to be almost entirely longitudinally polarised, whereas the $B \to \phi K^*$ decays are not. No significant asymmetry is seen in any of these modes.

## 8 Conclusion

*BaBar* has made many measurements probing the nature of rare hadronic $B$ decays. Many modes have been observed, and their direct $CP$ asymmetries measured (no significant effect has yet been seen). The wealth of data provides stringent tests for models of $B$ decay and the potential for the observation of New Physics.

## References

1. By BABAR Collaboration (B. Aubert et al.): Nucl. Instrum. Meth A **479**, 1–116 (2002)
2. By BABAR Collaboration (B. Aubert et al.): Phys. Rev. Lett **89**, 281802 (2002); Phys. Rev. Lett **91**, 021801 (2003)
3. H. Lipkin: Phys. Lett. B **515**, 81–88 (2001)
4. By BABAR Collaboration (B. Aubert et al.): Phys. Rev. Lett **91**, 161801 (2003)
5. G. Kramer and W.F. Palmer: Phys. Rev. D **45**, 193 (1992); C.H. Chen, Y.Y. Keum, and H.N. Li: Phys. Rev. D **66**, 054013 (2002)
6. By BABAR Collaboration (B. Aubert et al.): Phys. Rev. Lett **91**, 051801 (2003)