CHARMLESS HADRONIC $B$ DECAYS AT BELLE and $\bar{B}\Lambda\bar{B}\Lambda R$

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I report on recent measurements from the Belle and $\bar{B}\Lambda\bar{B}\Lambda R$ collaborations on the decay of the $B$ meson to hadronic final states without a charm quark.

1 Introduction.

The study of the branching fractions and angular distributions of $B$ meson decays to hadronic final states without a charm quark probes the dynamics of both the weak and strong interactions, and plays an important role in understanding $CP$ Violation (CPV) in the quark sector. CP Violation at the $B$ factories is described graphically by a triangle with sides formed from the CKM matrix elements $V_{qd}V_{qb}^\ast (q = u, c, t)$ and internal angles $\alpha, \beta, \gamma$ (or $\phi_2, \phi_1, \phi_3$). Discrepancies in the measured values of the sides and angles could be an indication of New Physics beyond the Standard Model (SM) due to enhanced branching fractions or modified $CP$ asymmetries. The experimental measurements of branching fractions, $CP$ asymmetries, polarization and phases (both weak and strong) can be compared to theoretical models based on, for example, QCD factorization, SU(3) symmetry and Lattice QCD.

The results presented below assume charge-conjugate states and all branching fraction upper limits (UL) are at the 90% confidence level (C.L.). The time-integrated $CP$ asymmetry is defined as $A_{CP} = (N_b - N_{\bar{b}})/(N_b + N_{\bar{b}})$ where $N_b$ ($N_{\bar{b}}$) is the number of $B$ mesons containing a $b(\bar{b})$ quark. The latest results are based on a total dataset of $467 \times 10^6 B\bar{B}$ pairs for $\bar{B}\Lambda\bar{B}\Lambda R$ and $657 \times 10^6 B\bar{B}$ pairs for Belle, unless indicated.

2 Decays involving two-body final states.

The last few years have seen considerable advancement in the prediction of the branching fractions and polarizations of $B$ meson decays to Vector-Vector ($VV$), Vector-Scalar ($VS$) and Vector-Tensor ($VT$) final states. In general, there has been good agreement between theory and experiment on branching fractions (with some notable exceptions) but the polarization measurements have presented a challenge. The $VV$ states are expected to be almost fully longitudinally polarized ($f_L \sim 1$) and this should remain true in the presence of penguin loop decays. However, penguin-dominated decays seem to have a smaller $f_L$ (e.g. $f_L \sim 0.5$ for $B \rightarrow \phi K^\ast$).

Belle has recently measured the decay $B^- \rightarrow K^{*0}K^-$ which is dominated by $b \rightarrow ds\bar{s}$ gluonic penguin diagrams. They measure a yield of $47.7 \pm 11.1$ events, corresponding to a branching fraction $B(B^- \rightarrow K^{*0}K^-) = (0.68 \pm 0.16 \pm 0.10) \times 10^{-6}$ with a $4.4\sigma$ significance. The event yield for $B^- \rightarrow K_{2}^{*0}(1430)K^-$ is measured to be $23.4 \pm 12.1$ with an upper limit on the branching fraction of $B(B^- \rightarrow K_{2}^{*0}(1430)K^-) < 1.1 \times 10^{-6}$. A similar analysis has
been done for $B^0$ decays to the $VV$ final states $\rho^0 K^{*0}$ and $f_0 K^{*0}$. Unlike an earlier $B\bar{B}$ analysis, $B$ Belle sees no evidence for $\rho^0 K^{*0}$ and $f_0 K^{*0}$ (and, consequently, do not measure $f_L$) but observes $B^0 \rightarrow \rho^0 K^+\pi^-$ and sees first evidence for $B^0 \rightarrow f_0 K^+\pi^-$ and $B^0 \rightarrow \pi^+\pi^- K^{*0}$, with branching fractions (significance) of $(2.8 \pm 0.5 \pm 0.5) \times 10^{-6}$ ($5.0\sigma$), $(1.4 \pm 0.4^{+0.3}_{-0.4}) \times 10^{-6}$ ($3.5\sigma$), and $(4.5^{+1.1+0.9}_{-1.0-1.6}) \times 10^{-6}$ ($4.5\sigma$), respectively. $B\bar{B}$ has measured $B$ meson decay to an $\omega$ accompanied by a $K^*$, $\rho$ or $f_0$. Five measurements have a significance above 5$\sigma$, with another two above 3$\sigma$. This has allowed $B\bar{B}$ to measure both $f_L$ and $A_{CP}$. The $VV$ branching fractions agree with theory predictions and the asymmetries are consistent with zero, as expected, while $f_L \sim 0.5$ except for $\omega \rho^+ \sim 0.9$. The results are summarized in Table 1.

| Mode | Decay | $S(\sigma)$ | $\mathcal{B}$ | UL | $f_L$ | $A_{CP}$ |
|------|-------|-------------|--------------|----|-------|----------|
| $VV$ | $\omega K^{*0}$ | 4.1 | $2.2 \pm 0.6 \pm 0.2$ | - | $0.72 \pm 0.14 \pm 0.02$ | $+0.45 \pm 0.25 \pm 0.02$ |
| $VV$ | $\omega K^{*+}$ | 2.5 | $2.4 \pm 1.0 \pm 0.2$ | 7.4 | $0.41 \pm 0.18 \pm 0.05$ | $+0.29 \pm 0.35 \pm 0.02$ |
| $VS$ | $\omega(K\pi)_0^{*0}$ | 9.8 | $18.4 \pm 1.8 \pm 1.7$ | - | - | $-0.07 \pm 0.09 \pm 0.02$ |
| $VS$ | $\omega(K\pi)_0^{*+}$ | 9.2 | $27.5 \pm 3.0 \pm 2.6$ | - | - | $-0.10 \pm 0.09 \pm 0.02$ |
| $VT$ | $\omega K^0_2(1430)^0$ | 5.0 | $10.1 \pm 2.0 \pm 1.1$ | - | $0.45 \pm 0.12 \pm 0.02$ | $-0.37 \pm 0.17 \pm 0.02$ |
| $VT$ | $\omega K^0_2(1430)^+$ | 6.1 | $21.5 \pm 3.6 \pm 2.4$ | - | $0.56 \pm 0.10 \pm 0.04$ | $+0.14 \pm 0.15 \pm 0.02$ |
| $VV$ | $\omega \rho^0$ | 1.9 | $0.8 \pm 0.5 \pm 0.2$ | 1.6 | - | - |
| $VV$ | $\omega f_0$ | 4.5 | $1.0 \pm 0.3 \pm 0.1$ | 1.5 | - | - |
| $VV$ | $\omega \rho^+$ | 9.8 | $15.9 \pm 1.6 \pm 1.4$ | - | $0.90 \pm 0.05 \pm 0.03$ | $-0.20 \pm 0.09 \pm 0.02$ |

### Table 1: Branching fraction central value ($\mathcal{B}$) and upper limit (UL) in units of $10^{-6}$, significance $S$ in standard deviations, longitudinal polarization ($f_L$) and CP asymmetry $A_{CP}$ for the Vector-Vector ($VV$), Vector-Scalar ($VS$) and Vector-Tensor ($VT$) decays of $B \rightarrow \omega K^*$, $\omega f_0$ and $\omega \rho$.

### 3 Decays involving three-body final states.

An interesting use of the decay to final states with three particles is the search by Belle for the exotic state $X(1812)$ in the decay $B^+ \rightarrow K^+ X(1812), X(1812) \rightarrow \omega \phi$. This is similar to the observation by Belle of the $Y(3940)$ resonance in $B^+ \rightarrow K^+ \omega \phi$. Belle observes $N_{K^+\omega\phi} = 22.1^{+8.3}_{-7.2}$ events leading to a branching fraction for the Dalitz plot of $\mathcal{B}(B^+ \rightarrow K^+ \omega \phi) = (1.15^{+0.43}_{-0.38} \pm 0.13) \times 10^{-6}$ ($2.8\sigma$) and an upper limit $< 1.9 \times 10^{-6}$. Assuming the $X(1812)$ masses and width from BES$^7$, Belle searches for a near-threshold enhancement in the $M_{\pi^+\pi^-\pi^0 K^+K^-}$ mass spectrum. No significant yield is seen and an upper limit of $3.2 \times 10^{-7}$ is placed on the product branching fraction $\mathcal{B}(B^+ \rightarrow K^+ X(1812), X(1812) \rightarrow \omega \phi)$.

$B\bar{B}$ has also looked at rare processes in Dalitz plots. Previous measurements have shown that almost 50% of the events in $B^0 \rightarrow K^+K^-\pi^+$ can be assigned to an ill-defined resonance, called $f_X(1500)$ by $B\bar{B}$. If this is an even-spin resonance, the rate for $f_X(1500) \rightarrow K^0_S K^0_S$ would be expected to be half the rate for $f_X(1500) \rightarrow K^+K^-$. They see 15 $\pm$ 15 events in the whole Dalitz plot placing an upper limit on the total branching fraction of $\mathcal{B}(B^+ \rightarrow K^0_S K^0_S < 5.1 \times 10^{-7}$. This makes the even-spin hypothesis unlikely but interpretation is difficult as the exact quantum numbers of the $f_X(1500)$ are unknown.

Some MSSM models could enhance the branching fractions of SM-suppressed decays from the SM values of $\sim 10^{-16}$ to $\sim 10^{-6}$. $B\bar{B}$ has searched for $B^- \rightarrow K^+\pi^-\pi^-$ and $B^- \rightarrow K^-\pi^+\pi^+$ and placed upper limits of $9.5 \times 10^{-7}$ and $1.6 \times 10^{-7}$, respectively, on the branching fractions.

The decay $B^+ \rightarrow \pi^+\pi^-\pi^-$ can in principle be used to extract the CKM angle $\gamma$ by measuring the interference between $\pi^+\pi^-$ resonances and the $\chi_{c0}$ resonance which has no $CP$ violating phase. It can also be helpful in understanding broad resonances and nonresonant backgrounds.
that are present in $B^0 \to \pi^+\pi^-\pi^0$ and so improve our measurement of the CKM angle $\alpha$. $B\bar{B}$Ar's results for $B^+ \to \pi^+\pi^+\pi^-$ are summarized in Table 2. No significant direct CP asymmetry is measured and, although some resonances are significant, no evidence is found for $\chi_0$ and $\chi_2$, leading to branching fraction upper limits for $B^+ \to \chi_0\pi^+ < 1.5 \times 10^{-5}$ and $B^+ \to \chi_2\pi^+ < 2.0 \times 10^{-5}$, making the measurement of $\gamma$ in this mode unlikely at Belle or $B\bar{B}$Ar.

Table 2: Branching fraction ($B$), CP asymmetry $A_{CP}$, and Fit Fraction for the decay $B^+ \to \pi^+\pi^+\pi^-$ with the resonance decaying to $\pi^+\pi^-$. The errors are statistical, systematic and model-dependent, respectively.

| Decay                  | Fit Fraction (%) | $B \times 10^{-6}$ | $A_{CP}$ (%) |
|------------------------|------------------|--------------------|--------------|
| $\pi^+\pi^+\pi^-$ Total | -                | 15.2 ± 0.6 ± 1.2 $^{+0.4}_{-0.3}$ | 3.2 ± 4.4 $^{+2.5}_{-2.0}$ |
| $\pi^+\pi^+\pi^-$ nonresonant | 34.9 ± 4.2 ± 2.9 $^{+7.5}_{-3.4}$ | 5.3 ± 0.7 ± 0.6 $^{+1.1}_{-0.5}$ | $-14 \pm 14 \pm 7^{+17}_{-3}$ |
| $\rho^0(770)\pi^+\rho^0 \to \pi^+\pi^-$ | 53.2 ± 3.7 ± 2.5 $^{+1.3}_{-1.1}$ | 8.1 ± 0.7 ± 1.2 $^{+0.4}_{-1.1}$ | $18 \pm 7 \pm 5^{+2}_{-3}$ |
| $\rho^0(1540)\pi^+\rho^0 \to \pi^+\pi^-$ | 9.1 ± 2.3 ± 2.4 $^{+1.9}_{-1.5}$ | 1.4 ± 0.4 ± 0.4 $^{+0.8}_{-0.7}$ | $-6 \pm 28 \pm 20^{+12}_{-35}$ |
| $f_2(1270)\pi^+\pi^-f_2 \to \pi^+\pi^-$ | 5.9 ± 1.6 ± 0.4 $^{+2.0}_{-0.7}$ | 0.9 ± 0.2 ± 0.1 ± 0.3 | $41 \pm 25 \pm 13^{+12}_{-8}$ |
| $f_0(1370)\pi^+\pi^-f_0 \to \pi^+\pi^-$ | 18.0 ± 3.3 ± 2.6 $^{+4.3}_{-3.5}$ | 2.9 ± 0.5 ± 0.5 $^{+0.7}_{-0.5}$ ($<4.0$) | $72 \pm 15 \pm 14^{+6}_{-8}$ |
| $\chi_0\pi^+\pi^+\chi_0 \to \pi^+\pi^-$ | -                | < 1.5 | - |
| $\chi_2\pi^+\pi^+\chi_2 \to \pi^+\pi^-$ | -                | < 0.1 | - |

4 CP Violation and the CKM angle $\alpha(\phi_2)$.

The precision of the measurement of the CKM angle $\alpha(\phi_2)$ continues to improve. In the absence of penguin loops in the decays, the angle $\alpha$ can be measured in the time-dependent decay of $B^0 \to \rho\rho$ and $B^0 \to \pi\pi$. However the penguin contribution, particularly in $\pi^0\pi^0$, is not small and so the measured $\alpha_{eff}$ differs from the true $\alpha$ by $\Delta \alpha = \alpha - \alpha_{eff}$. $\Delta \alpha$ can be constrained by performing an Isospin analysis on the decays $B^0 \to \rho\rho$, $B^+ \to \rho^+\rho^0$ and $B^0 \to \rho^+\rho^-$. Table 3 summarizes the measurements from $B\bar{B}$Ar, where the CP parameters are quoted for the longitudinally polarized (CP-even) component of the VV decays. When combined, $\Delta \alpha$ is constrained to be between $-1.8^o$ and $6.7^o$ (68% C.L.). The angle $\alpha$ is measured to be $(92.4^{+6.6}_{-6.5})^\circ$ and can be compared to the recent result from Belle $^{13}$ of $\alpha = (91.7^{+14.9}_{-14.9})^\circ$. A similar analysis using $B \to \pi\pi$ decays produces a looser constraint $|\Delta \alpha| < 43^\circ$, which results in an exclusion range for $\alpha$ between $23^\circ$ and $43^\circ$ at the 90% C.L. The result of combining these measurements using the CKMfitter programme $^{14}$ with earlier measurements of $B \to \pi\rho$ are shown in Fig. 11.

Table 3: Branching fraction ($B$), longitudinal polarization ($f_L$), direct CP asymmetry ($C_L$), CP asymmetry in the interference between mixing and decay ($S_L$) and CP asymmetry $A_{CP}$ for the decays $B^0 \to \rho^+\rho^-$, $B^0 \to \rho^0\rho^0$ and $B^+ \to \rho^+\rho^0$ measured by $B\bar{B}$Ar.

| $B^0 \to \rho^+\rho^-$ | $B^0 \to \rho^0\rho^0$ | $B^+ \to \rho^+\rho^0$ |
|------------------------|------------------------|------------------------|
| $B(\times 10^{-6})$     | $B(\times 10^{-6})$     | $B(\times 10^{-6})$     |
| $B^0 \to \rho^+\rho^-$ | 25.5 ± 2.1 $^{+3.6}_{-3.9}$ | 0.92 ± 0.32 ± 0.14 | 23.7 ± 1.4 ± 1.4 |
| $f_L$                  | 0.992 ± 0.024 $^{+0.026}_{-0.013}$ | 0.75 ± 0.14 ± 0.04 | 0.950 ± 0.015 ± 0.006 |
| $C_L$                  | 0.01 ± 0.15 ± 0.06       | 0.2 ± 0.8 ± 0.3     | -                      |
| $S_L$                  | -10.17 ± 0.20 $^{+0.05}_{-0.06}$ | 0.3 ± 0.7 ± 0.2     | -                      |
| $A_{CP}$               | -                      | -                      | -10.054 ± 0.055 ± 0.01 |
Belle has seen direct $CP$ in $B^0 \rightarrow \pi^+\pi^-$ but $\overline{\text{B}}A\overline{\text{B}}\text{A}R$ does not, reporting only that $C_{\pi^+\pi^-} = -0.25 \pm 0.08 \pm 0.02$ with a significance of just 2.2$\sigma$. However, both experiments see significant direct $CP$ in $B^0 \rightarrow K^+\pi^-$ with $\overline{\text{B}}A\overline{\text{B}}\text{A}R$ reporting $A_{CP} = -0.107 \pm 0.016_{-0.006}^{+0.006}$ with 6.1$\sigma$ significance, to be compared to $-0.094 \pm 0.018 \pm 0.008$ from Belle. Both experiments also measure $A_{CP}$ for $B^\pm \rightarrow K^\pm \pi^0$ to be slightly positive but consistent with zero. $A_{CP}$ should be similar for both $K\pi$ modes but Belle reports a 4.4$\sigma$ difference and $\overline{\text{B}}A\overline{\text{B}}\text{A}R$ sees a similar discrepancy.\cite{15}

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