Charmless $B$ decays at $\text{BABAR}$

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Abstract. Recent results from the $\text{BABAR}$ experiment in charmless $B$ decays are presented, in particular the results of a search for the decays $B^0 \to \omega\omega$ and $B^0 \to \omega\phi$ and preliminary results of a Dalitz-plot analysis of $B^+ \to K^0\pi^+\pi^0$. The latter includes first evidence for $CP$ violation in the intermediate decay $B^+ \to K^*(892)^+\pi^0$.

1. Introduction
Charmless hadronic decays of $B$ mesons can typically proceed via two topologies: $b \to u$ tree and $b \to d,s$ loop (or “penguin”) diagrams. The amplitudes for these two processes, which have a relative weak phase (equal to the CKM angle $\gamma$ in the Standard Model (SM)) and may have a similar magnitude, can interfere with one another, potentially giving rise to large $CP$ violation effects. Recent analyses from LHCb of $B^+ \to h^+h^-h^-$ decays\(^1\) have observed unexpectedly large $CP$ asymmetries in regions of the Dalitz plots [1, 2, 3]. In addition, the observed $CP$ asymmetries in $B \to K\pi$ decays do not follow the expected behaviour, which is that $\Delta A_{CP}(K\pi) \equiv A_{CP}(K^+\pi^0) - A_{CP}(K^+\pi^-) = 0$. The current world average experimental results are $A_{CP}(K^+\pi^0) = 0.040 \pm 0.021$ and $A_{CP}(K^+\pi^-) = -0.082 \pm 0.006$ [4], leading to a value $\Delta A_{CP}(K\pi) = 0.122 \pm 0.022$, which is significantly different from zero. It has been pointed out (e.g. in Ref. [5]) that additional information can be obtained from $B \to K^*\pi$ and $B \to \rho K$ decays, giving incentive to improve the experimental precision on the asymmetry measurements in these modes. In the $K^*\pi$ system, the least well measured decay is $B^+ \to K^*(892)^+\pi^0$, where the only existing measurement comes from a $\text{BABAR}$ analysis of $B^+ \to K^+\pi^0\pi^0$ [6]: $A_{CP}(K^*(892)^+\pi^0) = -0.06 \pm 0.24$.

Another puzzle from charmless $B$ decays is the lower than expected longitudinal polarisation fraction in $B \to \phi K^*$ decays [7, 8, 9]. It is not clear if the large transverse component arises from SM contributions or beyond-SM effects. The study of other vector-vector decay modes is therefore strongly motivated. In particular, constraints on the SM contributions can be made using information on the branching fractions of $B^0 \to \omega\omega$ and $B^0 \to \omega\phi$ [10].

Both analyses described here use the full $\text{BABAR}$ dataset collected at the $\Upsilon(4S)$ resonance. It corresponds to an integrated luminosity of 429 fb\(^{-1}\) and contains 470.9 ± 2.8 million $B\bar{B}$ events.

2. First evidence for $B^0 \to \omega\omega$ and search for $B^0 \to \omega\phi$

The SM expectations for the branching fractions of the decays $B^0 \to \omega\omega$ and $B^0 \to \omega\phi$ are of order $10^{-6}$ and $10^{-7}$, respectively. The existing experimental limits come from a previous

\(^1\) The inclusion of charge conjugate processes is implied throughout, except in definitions of $CP$ asymmetries.
**BABAR** analysis [11] that used approximately half the data sample used here. Measurements of the mixing-induced $CP$ asymmetry and the longitudinal polarisation fraction made in these loop-dominated decays will be sensitive to possible new physics contributions. The $\omega$ ($\phi$) candidates are reconstructed in their decay to $\pi^+\pi^-\pi^0$ ($K^+K^-$), with their invariant masses required to be in the range $740 < m_{\pi^+\pi^-\pi^0} < 820$ MeV/$c^2$ ($1009 < m_{K^+K^-} < 1029$ MeV/$c^2$). Backgrounds are considered from both continuum light-quark production and from $B$ decays.

A maximum likelihood fit is used to separate signal from background and to obtain the signal yields. The likelihood fit is performed to following variables: the beam energy substituted mass of the $B$ candidate ($m_{ES}$), the difference between the beam energy and that of the reconstructed $B$ candidate ($\Delta E$), a Fisher discriminant of topological variables, the invariant mass and helicity angle of each $\omega$ and $\phi$ resonance, and the “internal” helicity angle of the $\omega$ resonance (defined as the polar angle of the $\pi^0$ with respect to the $\omega$ flight direction in the $\pi^+\pi^-$ rest frame). More details of the analysis can be found in Ref. [12]. The results of the fit can be seen in Figure 1 and the fitted yields of the two decays are found to be $69^{+16}_{-15}$ for $B^0 \rightarrow \omega\omega$ and $-2.9^{+5.7}_{-4.0}$ for $B^0 \rightarrow \omega\phi$, where the quoted uncertainties are statistical only. The significance of the $B^0 \rightarrow \omega\omega$ signal is determined to be $4.4\sigma$ (including systematic uncertainties) and the branching fraction is calculated to be $(1.2 \pm 0.3 \text{[stat]} \pm 0.3 \text{[syst]}) \times 10^{-6}$. The upper limit on the $B^0 \rightarrow \omega\phi$ branching fraction is determined to be $0.7 \times 10^{-6}$ at 90% confidence level. The largest sources of systematic uncertainty arise form the uncertainty on the longitudinal polarisation fraction (which is assumed to be 0.88 in the nominal fit and then varied between 0.58 and 1.0 to determine the systematic uncertainty) and from possible fit bias.

**Figure 1.** Projections of the fit results on the (left) $m_{ES}$ and (right) $\Delta E$ variables, for (top) $B^0 \rightarrow \omega\omega$ and (bottom) $B^0 \rightarrow \omega\phi$ decays. The points are the data, the solid curve is the total fit, the dashed curve is the signal, and the dot-dashed curve is the background.
3. Amplitude analysis of $B^{+} \rightarrow K_s^0 \pi^+ \pi^0$

The only previous measurement of the inclusive branching fraction of $B^{+} \rightarrow K_s^0 \pi^+ \pi^0$ is an upper limit from CLEO: $\text{BF}(B^{+} \rightarrow K_s^0 \pi^+ \pi^0) < 66 \times 10^{-6}$ [13]. However, the intermediate decay mode $B^{+} \rightarrow \rho(770)^+ K_s^0$ has been observed by the BABAR collaboration and its branching fraction measured to be $\text{BF}(B^{+} \rightarrow \rho(770)^+ K_s^0) = (8.0_{-1.3}^{+1.4} \pm 0.6) \times 10^{-6}$ [14]. The other expected intermediate decays $B^{+} \rightarrow K^*(892)^+ \pi^0$ and $B^{+} \rightarrow K^*(892)^0 \pi^+$ have both been observed, although not in their decays to this final state. In addition to providing measurements of the branching fractions and $CP$ asymmetries of the $K^{*+} \pi^0$, $K^{*0} \pi^+$ and $\rho^+ K_s^0$ intermediate states, a Dalitz-plot analysis of $B^{+} \rightarrow K_s^0 \pi^+ \pi^0$ will measure the relative phases of the various components. Of particular interest are the relative phases of the two $K^* \pi$ components, which can be used to determine the CKM angle $\gamma$ [15, 16].

The $K_s^0$ candidates are reconstructed in their decay to $\pi^+ \pi^-$ and are required to have an invariant mass within $15 \text{MeV}/c^2$ of the known $K_s^0$ mass. The $\pi^0$ candidates are are required to be in the invariant mass range $110 < m_{\gamma\gamma} < 160 \text{MeV}/c^2$. The largest backgrounds from $B$ decays contain $D^0$ mesons that subsequently decay to $K_s^0 \pi^0$. These are removed with a veto on the $K_s^0 \pi^0$ invariant mass: $1804 < m_{K_s^0 \pi^0} < 1924 \text{MeV}/c^2$. Approximately 32,000 candidates remain after all selection criteria are applied.

A maximum likelihood fit is performed to the variables $m_{E_S}, \Delta E$, the output of a Boosted Decision Tree (BDT) of topological variables and the Dalitz plot (DP). Since the kinematic variables, $m_{E_S}$ and $\Delta E$, are strongly correlated with the Dalitz-plot position for signal events, the signal probability density functions are parametrised as a function of the DP position. The fitted signal yield is 1014 ± 63, where the uncertainty is statistical only.

The signal Dalitz-plot model follows the isobar model formalism, where the total amplitude is formed from the sum of the amplitudes for the various intermediate states

$$\mathcal{A} = \sum_i \mathcal{A}_i = \sum_i |c_i|^2 F_i(m_{K_s^0 \pi^+}^2, m_{\pi^+ \pi^0}^2),$$

where the $F_i$ describe the dependence of the amplitude on the Dalitz-plot position (e.g., a Breit–Wigner function) and the $c_i$ are the complex coefficients that are determined from the fit. However, since only relative amplitudes can be determined, one component ($K^*(892)^0 \pi^+$ in the nominal fit) is fixed to be real and to have unit magnitude. Quantities such as the branching fractions, $CP$ asymmetries and relative phases are derived from these fitted coefficients. The signal model includes contributions from both the charged and neutral $K^*(892)$ resonances plus the corresponding $K \pi$ S-wave as well as the $\rho(770)^+$ resonance. The $K \pi$ S-wave is modelled using the LASS parametrisation [17], which consists of the sum of the $K_s^0(1430)$ resonance and an effective-range nonresonant term. No other nonresonant contributions were found to be needed to give a satisfactory fit to the data.

The preliminary results for the branching fractions, $CP$ asymmetries and relative phases are given in Table 1. The $CP$ asymmetry of $B^{+} \rightarrow K^*(892)^+ \pi^0$ has a very large, negative central value ($-52\%$) and is found to have a significance of 3.4$\sigma$, corresponding to first evidence of $CP$ violation in this decay. The projection of the fit onto the $K_s^0 \pi^+$ invariant mass can be seen in Figure 2, separated by the charge of the $B$ candidate, where the asymmetry in the $K^*(892)^+$ region can be clearly seen. The uncertainty on this quantity is much improved but is still large with respect to $K^{*+} \pi^-$ and as such still dominates the uncertainty on the updated value of $\Delta A_{CP}(K^* \pi) = -0.16 \pm 0.14$. An analysis of this decay mode by the Belle experiment would help to further improve this uncertainty. A journal paper describing the BABAR analysis and its results in detail is in preparation.

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Figure 2. Data distributions of $m_{K^0_{S}π^+}$ and the corresponding fit projections for (a) $B^+$, and (b) $B^-$ candidates. Points with error bars are the data, the solid (blue) lines are the total fit result, the dashed (green) lines are the total background contribution, and the dotted (red) lines are the $q\bar{q}$ component. The dash-dotted lines represent the signal contribution. The signal to background ratio has been increased by applying a tighter selection on $m_{ES}$, $ΔE$, and BDT.

Table 1. Measured $CP$-averaged branching fractions (BF), $CP$ asymmetries ($A_{CP}$), and $CP$-averaged phases measured relative to the $K^*(892)^{0}π^+$ reference amplitude. The first uncertainty is statistical, the second is systematic, and the third is due to the signal Dalitz-plot model.

| Isobar                  | BF ($×10^{-6}$) | $A_{CP}$ | $ϕ$ (°) |
|------------------------|-----------------|----------|---------|
| $K^0_{S}π^+π^0$        | 45.9 ± 2.6 ± 3.0 ± 8.6 | 0.07 ± 0.05 ± 0.03 ± 0.04 | –       |
| $K^*(892)^0π^+$        | 14.6 ± 2.4 ± 1.3 ± 0.5 | −0.12 ± 0.21 ± 0.08 ± 0.11 | –       |
| $K^*(892)^+π^0$        | 9.2 ± 1.3 ± 0.6 ± 0.5 | −0.52 ± 0.14 ± 0.04 ± 0.04 | −95 ± 43$^{+48}_{−36}$ ± 70 |
| $K_0^+(1430)^0π^+$    | 50.0 ± 4.8 ± 6.0 ± 4.0 | 0.14 ± 0.10 ± 0.04 ± 0.14 | 174 ± 11 ± 11 ± 6 |
| $K_0^+(1430)^+π^0$    | 17.2 ± 2.4 ± 1.5 ± 1.8 | 0.26 ± 0.12 ± 0.08 ± 0.12 | −89 ± 43$^{−53}_{+40}$ ± 18 |
| $ρ(770)^+K^0$         | 9.4 ± 1.6 ± 1.0 ± 2.6 | 0.21 ± 0.19 ± 0.07 ± 0.30 | −122 ± 43$^{−55}_{+47}$ ± 68 |

References

[1] Aaij R et al. (LHCb collaboration) 2013 Phys.Rev.Lett. 111 101801 (Preprint 1306.1246)
[2] Aaij R et al. (LHCb collaboration) 2014 Phys.Rev.Lett. 112 011801 (Preprint 1310.4740)
[3] Aaij R et al. (LHCb collaboration) 2014 (Preprint 1408.5373)
[4] Amhis Y et al. (Heavy Flavor Averaging Group) 2012 (Preprint 1207.1158)
[5] Gronau M, Pirjol D and Zupan J 2010 Phys.Rev. D81 094011 (Preprint 1001.0702)
[6] Lee S et al. (BABAR Collaboration) 2011 Phys.Rev. D84 092007 (Preprint 1109.0143)
[7] Aubert B et al. (BABAR Collaboration) 2007 Phys.Rev.Lett. 98 051801 (Preprint hep-ex/0610073)
[8] Aubert B et al. (BABAR Collaboration) 2007 Phys.Rev.Lett. 99 201802 (Preprint 0705.1798)
[9] Prim M et al. (Belle Collaboration) 2013 Phys.Rev. D88 072004 (Preprint 1308.1830)
[10] Oh S 1999 Phys.Rev. D60 034006 (Preprint hep-ph/9812530)
[11] Aubert B et al. (BABAR Collaboration) 2006 Phys.Rev. D74 051102 (Preprint hep-ex/0605017)
[12] Lee S et al. (BABAR Collaboration) 2014 Phys.Rev. D89 051101 (Preprint 1312.0058)
[13] Eckhart E et al. (CLEO Collaboration) 2002 Phys.Rev.Lett. 89 251801 (Preprint hep-ex/0206024)
[14] Aubert B et al. (BABAR Collaboration) 2007 Phys.Rev. D76 011103 (Preprint hep-ex/0702043)
[15] Ciuchini M, Pierini M and Silvestrini L 2006 Phys.Rev. D74 051301 (Preprint hep-ph/0601233)
[16] Gronau M, Pirjol D, Soni A and Zupan J 2007 Phys.Rev. D75 014002 (Preprint hep-ph/0608243)
[17] Aston D, Awaji N, Bienz T, Bird F, D’Amore J et al. 1988 Nucl.Phys. B296 493