**B**⁰ → **K**⁰**K**₀ and Other Hadronic *b* → *d* Decays

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The *b* → *d* penguin-dominated modes *B* → *K*⁻⁻ have been observed at the *B* factories. In addition, the BABAR collaboration has reported the first time-dependent *CP*-violation measurement in *B*⁰ → *K*⁰*K*₀.

I. INTRODUCTION

These proceedings summarize measurements of *B* decays to two kaons at the *B* factories [1, 2]. Observations of the *B*⁰ → *K*⁰*K*₀ and *B*⁺ → *K*⁺⁻⁻ decays have been reported by the BABAR experiment at SLAC and the Belle experiment at KEK. The BABAR collaboration has also performed the first time-dependent *CP*-violation measurement in *B*⁰ → *K*⁰*K*₀. The *B*⁺ → *K*⁺⁻⁻ decay has not been observed by either experiment and the upper limits on its branching fraction were improved.

*B* → *K*⁻⁻ decays are expected to be dominated by the *b* → *d*śś amplitude involving a virtual loop with the emission of a gluon (Fig. 1). These decays are suppressed in the Standard Model (SM), with branching fractions at the 10⁻⁶ level. Assuming top-quark dominance in the virtual loop [3], the direct and mixing-induced *CP* asymmetries are expected to vanish in these modes. However, contributions from up and charm quarks as well as from non-SM particles could induce sizeable *CP* asymmetries [4]. These modes are thus analogous to the *b* → *ssśś* decays in the measurement of virtual effects of contributions from non-SM phenomena [5, 6]. Additional amplitudes could affect *b* → *d* penguin decays differently from *b* → *s* penguin decays. In addition, various relations between branching fractions and *CP* asymmetries in these modes provide a test of SM predictions [7]. Finally, the *B*⁺ → *K*⁺⁻⁻ decay has an annihilation contribution in the SM (Fig. 1). Thus, the difference in decay rate between branching modes and the neutral mode can be used to constrain the effect of this amplitude in *B* decays.

Here the *CP*-violation measurement in the center-of-mass (CM) frame and the beam energy; and a beam-energy substituted mass, *m*ES ≡ √[(s/2 + p_B·p_B)/E_e² − p_B²], where the *B*-candidate momentum *p*ₐ and the four-momentum of the initial *e*⁺⁻⁻ state (*Eᵣ, *pᵣ*) are calculated in the laboratory frame. Event-shape variables are used to suppress the dominant “continuum” *e*⁺⁻⁻ → *q́q́* (*q* = *u, d, s, c) background further, exploiting angular differences between the jet-like topology of continuum decays and the isotropically distributed decays of *B*⁻⁻ events. Particle-identification information is used to separate charged pion from charged kaon candidates in the *B*⁺ → *K*⁺⁻⁻ and *B*⁺ → *K*⁺⁻⁻ decays.

II. EXPERIMENTAL METHODS

A. Signal Extraction

Signal decays are separated from background decays using unbinned extended maximum likelihood fitting to distributions of kinematic and event-shape variables. The primary kinematic variables used to identify a reconstructed signal *B* candidate are the difference between its reconstructed energy in the center-of-mass (CM) frame and the beam energy; and a beam-energy substituted mass, *m*ES ≡ √[(s/2 + *p*ₐ·*p*ₐ)/E_e² − *p*ₐ²], where the *B*-candidate momentum *p*ₐ and the four-momentum of the initial *e*⁺⁻⁻ state (*Eᵣ, *pᵣ*) are calculated in the laboratory frame. Event-shape variables are used to suppress the dominant “continuum” *e*⁺⁻⁻ → *q́q́* (*q* = *u, d, s, c) background further, exploiting angular differences between the jet-like topology of continuum decays and the isotropically distributed decays of *B*⁻⁻ events. Particle-identification information is used to separate charged pion from charged kaon candidates in the *B*⁺ → *K*⁺⁻⁻ and *B*⁺ → *K*⁺⁻⁻ decays.

B. Time-Dependent *CP* Asymmetries

*CP* asymmetries in *B*⁰ → *K*⁰*K*₀ are determined from the difference in the time-dependent decay rates *f*⁺ and *f*⁻ for *B*⁺ and *B*⁰ signal decays, respectively, where

\[
f_±(Δt) = \frac{e^{-|Δt|/τ}}{4τ}[1 ± S \sin(Δm_dΔt) ± C \cos(Δm_dΔt)].
\]

Here *Δt* is the time difference between the decays of the signal *B* and the other *B* in the event, *τ* is the average *B*⁰ lifetime, and *Δm_d* is the *B*⁰⁻⁻ mixing frequency. The amplitude *S* describes *CP* violation in the interference between mixed and unmixed decays into the same final state, while *C* describes direct *CP* violation in decay. The time-dependent distribution is corrected for detector resolution effects and for mistag rates in the flavor identification of the other *B* in the event.

*B*⁰ → *K*⁰*K*₀ decays are reconstructed in the *K*⁰*K*₀ → *K*⁺⁻⁻ and *K*⁺⁻⁻ → *π*⁺⁻⁻ sub-decay modes. As the *K*⁺⁻⁻ meson has a relatively long lifetime of 90 ps, its decay vertex is separated from the *B* decay vertex by a
few centimeters, which complicates the measurement of the $z$ position of the signal $B$ in the absence of prompt charged tracks originating from its decay vertex. To perform the measurement, $\bar{B}$A\$ used a method previously employed in other $K_S$ analyses without prompt charged tracks, wherein the $B$ meson is constrained in the vertex fit to decay within the beamspot in the plane transverse to the beam direction $^{[10]}$. This method exploits the threshold nature of the $\Upsilon(4S) \rightarrow B\bar{B}$ decay, where the $B$ mesons are almost at rest in the CMS frame ($p_B^* \approx 300$ MeV/c) and therefore have negligible displacement in the lab frame in the non-boosted transverse direction. The resulting resolution of the $z$ position of the signal $B$ vertex is still better than the resolution on the vertex position of the other $B$ in the event, yielding a $\Delta t$ precision (approximately 0.9 ps) comparable to that in modes where the signal $B$ has prompt charged tracks in the final state. Only $K_S$ mesons that decay within the Silicon Vertex Tracker can be used with this technique. However, as there are two $K_S$ mesons in the final state, while only one is needed to employ this method, the fraction of signal decay tracks suitable for the time-dependent measurement at $\bar{B}$A\$ is approximately 82% in this mode.

If no time-dependent measurement is performed, an integrated flavor or charge asymmetry can be measured:

$$A_{CP} = \frac{N_{B^0,B^+} - N_{B^0,B^-}}{N_{B^0,B^+} + N_{B^0,B^-}}$$

A non-zero value of this asymmetry signifies the presence of direct $CP$ violation. In the $B^+$ modes, this is the only possible $CP$ measurement.

### III. EXPERIMENTAL RESULTS

#### A. $B^0 \rightarrow K^0\bar{K}^0$

Both $B$ factories observe clear signals in this decay mode, with a branching fraction at the $10^{-6}$ level, in agreement with each other and Standard-Model expectations. $\bar{B}$A\$ observes the signal at the $7.3\sigma$ level of significance, including systematic uncertainties, while Belle’s observation is at the $5.3\sigma$ level. The branching fraction results are summarized in Table I while projections of the fitted data in the $m_{ES}$ and $\Delta E$ variables with the results of the fit overlaid are shown in Figs. 2 and 3. The $B^+ \rightarrow K^0\pi^+$ mode has the same topology as the $B^+ \rightarrow K^0K^+$ mode, and its branching fraction is determined from the same fit, separating the two modes with particle ID. The results are in Table II. Neither experiment observes a significant direct $CP$ asymmetry in either mode.

#### B. $B^+ \rightarrow K^0K^+$ and $B^+ \rightarrow K^0\pi^+$

Both $B$ factories observe clear signals in this decay mode, with a branching fraction at the $10^{-6}$ level and a significance of $5.3\sigma$ in each experiment. The branching fractions are slightly higher than the corresponding values for the neutral mode in each experiment. Although the errors are too large at this point to make a substantive comparison, if this discrepancy holds up it would indicate a significant effect from the annihilation amplitude in the charged mode. The results are summarized in Table III while projections of the fitted data in the $m_{ES}$ and $\Delta E$ variables with the results of the fit overlaid are shown in Figs. 2 and 3. The $B^+ \rightarrow K^0\pi^+$ mode has the same topology as the $B^+ \rightarrow K^0K^+$ mode, and its branching fraction is determined from the same fit, separating the two modes with particle ID. The results are in Table III. Neither experiment observes a significant direct $CP$ asymmetry in either mode.

#### C. $B^0 \rightarrow K^+K^-$

This mode is dominated by a $W$-exchange amplitude and is not expected to be seen at the $B$ factories, although long-distance rescattering and effects from beyond-SM physics could affect this conclusion. The expected SM branching fractions are expected at the $10^{-8}$ to $10^{-7}$ level. Neither experiment sees any evidence for this mode, and upper limits are set as summarized in Table IV.

\[^1\] $A_{CP} = -C$

| Experiment | Observable | $N_{B^0} \times 10^5$ |
|------------|------------|-----------------------|
| $\bar{B}$A\$ | $B = (1.08 \pm 0.28 \pm 0.11) \times 10^{-6}$ | 347 |
| | $S = -1.26^{+0.80}_{-0.73} \pm 0.10$ | |
| | $C = -0.40 \pm 0.41 \pm 0.06$ | |
| Belle | $B = (0.87^{+0.20}_{-0.26} \pm 0.09) \times 10^{-6}$ | 449 |
| | $A_{CP} = -0.58^{+0.72}_{-0.66} \pm 0.04$ | |

| Experiment | Observable | $N_{B^0} \times 10^5$ |
|------------|------------|-----------------------|
| $\bar{B}$A\$ | $B = (1.61 \pm 0.44 \pm 0.09) \times 10^{-6}$ | 347 |
| | $A_{CP} = 0.10 \pm 0.26 \pm 0.03$ | |
| Belle | $B = (1.22_{-0.28}^{+0.42} \pm 0.16) \times 10^{-6}$ | 449 |
| | $A_{CP} = 0.13_{-0.24}^{+0.43} \pm 0.02$ | |

\[A_{CP} = -0.58^{+0.73}_{-0.66} \pm 0.01.\]
FIG. 2: Distributions of $m_{ES}$ (left) and $\Delta E$ (right) in data (solid histogram) from the Belle experiment with the results of the fit overlaid for signal (dot-dashed), continuum (dashed), charmless $B$ decays (hatched), feed-across background from misidentification (dotted), and the sum of all components (solid).

FIG. 3: Distributions of $m_{ES}$ (left) and $\Delta E$ (right) in data (points with error bars) from the BABAR experiment for signal (main plots) and background (insets) for $K_0\pi^+$ (a,b), $K^+K^+$ (c,d), and $K^0\bar{K}^0$ (e,f) candidates, with the results of the fit overlaid (solid lines). The distributions are obtained with the sPlot technique [11].
TABLE III: Experimental results on $B^+ \rightarrow K^0\pi^+$ decays, with the number of $B\bar{B}$ pairs listed in the last column.

| Experiment | Observable | $N_{BB} \times 10^6$ |
|------------|------------|------------------|
| BABAR      | $B = (23.9 \pm 1.1 \pm 1.0) \times 10^{-6}$ | 347             |
|            | $\mathcal{A}_{CP} = 0.029 \pm 0.039 \pm 0.010$ |                |
| Belle      | $B = (22.8 \pm 0.7 \pm 1.3) \times 10^{-6}$ | 449             |
|            | $\mathcal{A}_{CP} = 0.03 \pm 0.03 \pm 0.01$ |                |

IV. FUTURE OUTLOOK

Each of the $B$ factories is expected to accumulate 1 ab$^{-1}$ by the end of operations in 2008. With these datasets, the error on the branching fractions of $B^0 \rightarrow K^0\bar{K}^0$ and $B^0 \rightarrow \bar{K}^0K^+$ should decrease to the 15% level for each experiment. Also, each collaboration should achieve an error of $\sim 0.4$ on $S$ and $\sim 0.25$ on $C$ in $B^0 \rightarrow K^0\bar{K}^0$. These results will provide meaningful comparisons with theoretical predictions and constrain contributions from beyond-SM physics in $b \rightarrow d$ FCNC decays. The effect of the annihilation contribution in $B^0 \rightarrow \bar{K}^0K^+$ will be constrained as well.

V. SUMMARY

The $B$ factories have observed the $b \rightarrow d$ penguin dominated modes $B^0 \rightarrow K^0\bar{K}^0$ and $B^0 \rightarrow \bar{K}^0K^+$. The measured branching fractions are consistent with Standard Model predictions, although experimental errors are still too large for precision comparisons. BABAR has also performed the first time-dependent $CP$ violation measurement in $B^0 \rightarrow K^0\bar{K}^0$, excluding a part of the physically allowed region at greater than $3\sigma$ significance. This is the first step in the investigation of $CP$ violation in $b \rightarrow d$ flavor-changing neutral-current decays.

[1] BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 97, 171805 (2006).
[2] Belle Collaboration, hep-ex/0608049.
[3] BABAR Collaboration, B. Aubert et al., Nucl. Instrum. Meth. A 479, 1 (2002).
[4] Belle Collaboration, A. Abashian et al., Nucl. Instrum. Meth. A 479, 117 (2002).
[5] R. Fleischer, Phys. Lett. B 341, 205 (1994).
[6] A. K. Giri and R. Mohanta, J. of High Energy Phys. 11, 084 (2004).
[7] D. London and R. D. Peccei, Phys. Lett. B 223, 257 (1989); H. R. Quinn, Nucl. Phys. B, Proc. Suppl. 37A, 21 (1994).
[8] BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 71, 091102 (2003); Belle Collaboration, K. Abe et al., Phys. Rev. Lett. 91, 261602 (2003).
[9] R. Fleischer and S. Recksiegel, Eur. Phys. J. C 38, 251 (2004).
[10] BABAR Collaboration, B. Aubert et al., Phys. Rev. D 71, 111102 (2005).
[11] M. Pivk and F. R. Le Diberder, Nucl. Instrum. Meth. A 555, 356 (2005).
[12] BABAR Collaboration, B. Aubert et al., Phys. Rev. D 75, 012008 (2007).