Recent results of rare $B$ decay analyses based on 31.9 million $\bar{B}B$ collected with the Belle detector at the KEKB asymmetric $e^+e^-$ collider are presented. We have made the first observation of charmless baryonic decay $B^\pm \rightarrow p\bar{p}K^\pm$, the three-body $B^0 \rightarrow K^0\pi^+\pi^-$ and $B^0 \rightarrow K^0 K^+ K^-$. The measured branching fractions are $B(B^+ \rightarrow p\bar{p}K^+) = (4.3^{+1.1}_{-0.5} \pm 0.5) \times 10^{-6}$, $B(B^0 \rightarrow K^0\pi^+\pi^-) = (53.2 \pm 11.3 \pm 9.7) \times 10^{-6}$, and $B(B^0 \rightarrow K^0 K^+ K^-) = (34.8 \pm 6.7 \pm 6.5) \times 10^{-6}$. We also see strong evidence of $B^\pm \rightarrow \eta K^\pm$ and $B^\pm \rightarrow \eta\pi^\pm$, and observed the decay $B^\pm \rightarrow \omega K^\pm$ with $B(B^\pm \rightarrow \omega K^\pm) = (9.9^{+2.7}_{-2.4} \pm 1.0) \times 10^{-6}$. Preliminary results of improved measurements of the branching fractions for the decays $B \rightarrow K\pi$ and $\pi\pi$ are reported. No evidence for direct $CP$ violation is found in the decays $B^\pm \rightarrow K^\pm\pi^\mp$, $K^0\pi^\pm$, $\pi^+\pi^0$, and $\omega K^\pm$.

1 Introduction

One of the most important goals of experiments at B-factories is to precisely measure the sides and angles of the unitarity triangle in the Cabibbo-Kobayashi-Maskawa matrix (CKM) and check its consistency. Any inconsistency is a clear signal of new physics beyond the Standard Model (SM). Rare $B$ decays play an important role in working towards this goal.

Preliminary results of rare $B$ decay analyses based on a 31.9 million $\bar{B}B$ sample are presented here. The data were collected with the Belle detector at the KEKB asymmetric $e^+e^-$ collider.

Belle is a general-purpose detector with a 1.5 T superconducting solenoid magnet. Charged particle tracking, covering 92% of the total center-of-mass (CM) solid angle, is provided by the Silicon Vertex Detector (SVD) consisting of three concentric layers of double-sided silicon strip detectors and a 50-layer Central Drift Chamber (CDC). Charged hadrons are distinguished by combining the responses from an array of Silica Aerogel Čerenkov Counters (ACC), a Time of Flight Counter system (TOF), and $dE/dx$ measurements in the CDC. The combined response provides $K/\pi$ separation of at least $2.5\sigma$ for laboratory momenta up to 3.5 GeV/$c$. Photons and
electrons are detected in an array of 8736 CsI(Tl) crystals (ECL) located inside the magnetic field and covering the entire solid angle of the charged particle tracking system. The 1.5 T magnetic field is returned via an iron yoke, instrumented to detect muons and $K_L$ mesons (KLM). The KLM consists of alternating layers of resistive plate chambers and 4.7 cm thick steel plates.

In all the decay modes presented here, the continuum process ($e^+e^- \rightarrow q\bar{q}$) is the dominant background. Since $B\bar{B}$ events are spherical while the continuum events are jet-like, we apply cuts on various event shape variables (such as sphericity, thrust angle, Fox-Wolfram moments, and the production angle of $B$) to suppress the background.

$B$ candidates are identified using two kinematic variables: beam constrained mass: $M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$; and the energy difference: $\Delta E = E_B - E_{beam}$. Here $E_{beam}$ is the beam energy, $p_B$ and $E_B$ are the momentum and energy of a reconstructed $B$ candidate, respectively, where all variables are defined in the $\Upsilon(4S)$ rest frame.

$K/\pi$ separation is performed by applying a cut on the likelihood ratio, $L_K/(L_\pi + L_K)$, where $L_K$ ($L_\pi$) is a kaon (pion) likelihood computed from information from the particle identification devices: specific ionization loss in the central drift chamber, photo-electron yield in the aerogel Cherenkov counters, and time-of-flight.

### 2 Two-Body Charmless Hadronic $B$ Decays

These processes are manifestations of penguin or suppressed three amplitudes proportional to small couplings in hadronic flavor mixing (CKM matrix). Because of the absence of CKM favored $b \rightarrow c$ amplitudes, these decays are particularly sensitive to potentially new contributions from interference effects and virtual particles in loops.

#### 2.1 $B \rightarrow \pi\pi, K\pi, KK$

The charmless hadronic $B$ decays $B \rightarrow \pi\pi, K\pi,$ and $KK$ provide a rich sample to test the standard model and to probe new physics. Of particular interest are indirect and direct $CP$ violation
in the $\pi\pi$ and $K\pi$ modes, which are related to the angles $\phi_2$ and $\phi_3$ of the unitarity triangle, respectively. Measurements of branching fractions of these decay modes are an important step towards these $CP$ violation studies.

In this analysis, $B$ meson candidates are reconstructed in ten combinations: $h^+h'^-; h^+\pi^0; K^0_S h^+; K^0_S \pi^0; K^0_S K^0_S; \pi^0\pi^0$, where the symbols $h$ and $h'$ refer to $\pi$ or $K$. Candidate $\pi^0$ mesons are formed from pairs of photons and candidate $K^0_S$ mesons are reconstructed from pairs of oppositely charged tracks with a displaced vertex from the interaction point. Signal yields are extracted by fits to the $\Delta E$ distributions taking into account feed-across from other mis-identified $B \to hh' \pi$ decays and backgrounds from multi-body and radiative charmless $B$ decays. The fit results are given in Table 1 and the $\Delta E$ distributions are shown in Figure 1.

### 2.2 $B^\pm \to \eta h^\pm$

Previous measurements yielded large rates for $B \to \eta'K$ and $B \to \eta K^*$, motivating a number of new theoretical ideas. Measurement of related decays $B \to \eta K$ can help clarify these. Besides, it has been suggested that the decays of $B^+ \to \eta \pi^+$ is a good candidate for observing direct $CP$ violation.

In this analysis, we reconstruct $\eta$ mesons using the $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ decay channels. Candidate $\eta$ mesons are required to have invariant masses within $\pm 2.5\sigma$ of the $\eta$ peak, where $\sigma$ is 10.6 MeV/$c^2$ and 3.4 MeV/$c^2$ for the $\gamma\gamma$ and $\pi^+\pi^-\pi^0$ modes, respectively. For the $\pi^+\pi^-\pi^0$ mode, the $\pi^+\pi^-$ pair is constrained to a vertex. Both photons from the $\eta \to \gamma\gamma$ mode are required to have $E_\gamma > 100$ MeV and we remove $\eta$ candidates if either of the daughter photons can be combined with any other photon with $E_\gamma > 100$ MeV to form a $\pi^0$ candidate. The $\eta$ candidates are further constrained to the known $\eta$ mass.

Signal yields are obtained from extended unbinned maximum likelihood (ML) fits on the variables $M_{bc}$ and $\Delta E$. The signal probability density functions (PDF) are Gaussian for $M_{bc}$ and an empirically determined parameterization for $\Delta E$. The background PDF are taken to be an empirical function for $M_{bc}$ and a first-order polynomial for $\Delta E$. The statistical significance is defined as $\sqrt{-2\ln(L(0)/L_{max})}$, where $L_{max}$ is the likelihood at the nominal signal yield and the $M_{bc}$ and $\Delta E$ distributions for (left) $B^\pm \to \eta K^\pm$ and (right) $B^\pm \to \eta \pi^\pm$. Histograms represent data, with the $\eta_{\pi^+\pi^-\pi^0}$ subset shaded, the solid curves represent the fit functions.
We see strong evidence for the decays $B^\pm \to \omega h^\pm$ and $B^\pm \to \eta K^\pm$, respectively. Assuming the number of $B^0\overline{B}^0$ and $B^+B^-$ pairs to be equal, we find their branching fractions $B(B^\pm \to \omega K^\pm) = (5.3^{+1.8}_{-1.5} \pm 0.6) \times 10^{-6}$ and $B(B^\pm \to \eta\pi^\pm) = (5.4^{+2.0}_{-1.7} \pm 0.6) \times 10^{-6}$.

2.3 $B^\pm \to \omega h^\pm$

In this analysis, candidate $\omega$ mesons are reconstructed from $\pi^+\pi^-\pi^0$ combinations where the CM momentum of the $\pi^0$ is required to be greater than 350 MeV/c to reduce the large combinatorial background from low energy photons. The invariant mass of the $\pi^+\pi^-\pi^0$ combination is required to be within $\pm 30$ MeV/c$^2$ of the nominal $\omega$ mass (the natural width of the $\omega$ is 8.9 MeV/c$^2$).

Signal yields are extracted using unbinned ML fit simultaneously for $M_{bc}$ and $\Delta E$. The background functions include a combinatorial component and a component from other charmless $B$ decays. Due to the possible mis-identification between $K^-$ and $\pi^-$, we also include a component for feed-down from $\omega\pi^-$ to $\omega K^-$ fitting and vice versa. If a pion is mis-identified to a kaon, the wrong mass assignment shifts the $\omega\pi^-$ signal 44 MeV away from zero, and the feed-down component from $\omega\pi^-$ can be distinguished in the $\Delta E$ distribution. The results of the fit are summarized in the Table 1. The projections of the $M_{bc}$ and $\Delta E$ with the normalized signal and background PDFs are shown in Figure 3. We have observed the decay $B^\pm \to \omega K^\pm$ with $6.4\sigma$ significance. Our results on the $B^- \to \omega K^-$ and $\omega\pi^-$ branching fraction measurements disagree with the earlier ones from CLEO [4] and BABAR [5]. But the sum of the branching fractions of $B^- \to (\omega K^- + \omega\pi^-)$ is consistent with the CLEO’s result.

3 Three-Body Charmless Hadronic $B$ Decays

Belle has recently published results on tree body charmless hadronic decays $B^\pm \to K^\pm h^+h^-$ [6]. It is of interest to look for similar phenomena in the neutral channel, to further investigate the $b \to s$ penguin transitions which mediate these decays. In addition, these modes may in future be used to measure $CP$ violation.

3.1 $B^0 \to K^0 h^+h^-$

In this analysis, we reconstruct the decays $B^0 \to K^0 h^+h^-$ without any assumption on the intermediate hadronic resonance. Only $K^0 \to K_S^0 \to \pi^+\pi^-$ is considered here. As in other rare $B$ decay modes, continuum events are the dominant background source and are suppressed using various event shape and kinematic variables. In the $B^0 \to K^0\pi^+\pi^-$ mode, we also have large backgrounds from $B^0 \to D^- \pi^+, D^- \to K_S\pi^-$ and $B^0 \to J/\psi K_S, J/\psi \to \mu^+\mu^-$ where muons are
We also search for fractions upper limit is calculated to be included as a model-dependent error. The results are summarized in Table 2. The uncertainty due to possible interference between different intermediate states is to the $\Delta E$ respective. Assuming a set of two-body final states, we perform a simultaneous likelihood fit 

Figure 5 shows the $\Delta E$ (left) and $M_{bc}$ (right) distributions for three-body final states: $K_S\pi^+\pi^-$ (top), $K_SK^+K^-$ (middle) and $K_SK^+\pi^+$ (bottom).

misidentified as pions. These backgrounds are suppressed by requiring $|M(K_S\pi^-) - M_D^-| > 0.100 \text{ GeV}/c^2$, $|M(h^+h^-) - M_{J/\psi}| > 0.070 \text{ GeV}/c^2$, and $|M(h^+h^-) - M_{\phi(2S)}| > 0.050 \text{ GeV}/c^2$, where $h^+$ and $h^-$ are pion candidates. Signal yields are obtained from fits to the $\Delta E$ distributions. We find $60.3 \pm 11.0$ $B^0 \rightarrow K^0\pi^+\pi^-$ events and $57.9 \pm 10.0$ $B^0 \rightarrow K^0K^+K^-$ events, which corresponds to preliminary branching fractions:

$$B(B^0 \rightarrow K^0\pi^+\pi^-) = (53.2 \pm 11.3 \pm 9.7) \times 10^{-6}, \quad (6.6\sigma)$$

$$B(B^0 \rightarrow K^0K^+K^-) = (34.8 \pm 6.7 \pm 6.5) \times 10^{-6}, \quad (7.4\sigma)$$

Figure 4 shows the $\Delta E$ and $M_{bc}$ distributions for these decays after the background suppression. We also search for $B^0 \rightarrow K^0K^+\pi^+$ but do not observe significant signals. The 90% C.L. branching fraction upper limit is calculated to be $B(B^0 \rightarrow K^0K^+\pi^+) < 9.3 \times 10^{-6}$.

Further studies of intermediate resonant states of these decays are made with a Dalitz plot style analysis. Figure 5 shows the $\pi^+\pi^-$ and $K_S^0\pi^\pm$ invariant mass distributions for selected $B^0 \rightarrow K_S^0\pi^+\pi^-$ candidates in the $B$ signal region, and the $K^+K^-$ and $K_S^0K^+$ invariant mass for $B^0 \rightarrow K_S^0K^+K^-$. Clear contributions from $K^*(892)^\pm\pi^\mp$ and $\phi(1020)K^0$ are seen. We also find broad resonances in $K_S^0\pi^\pm$ and $K^+K^-$ mass around 1.4 GeV/$c^2$ and 1.5 GeV/$c^2$, respectively. Assuming a set of two-body final states, we perform a simultaneous likelihood fit to the $\Delta E$ distributions for various resonance regions and determine the exclusive branching fractions. The uncertainty due to possible interference between different intermediate states is included as a model-dependent error. The results are summarized in Table 3.

Figure 5: (a) $\pi^+\pi^-$ and (b) $\pi^+K_S^0$ invariant mass spectra for selected $B^0 \rightarrow K_S^0\pi^+\pi^-$. (c) $K^+K^-$ and (d) $K^+K_S^0$ for $B^0 \rightarrow K_S^0K^+K^-$, signal events (open histograms) and for background events in the $\Delta E$ sidebands (hatched).
4 Charmless Baryonic B Decays

In contrast to charm meson decay, final states with baryons are allowed in B meson decay. To date, a few low multiplicity B decay modes with baryons in the final state from $b \to c$ transitions have been observed. Rare B decays due to charmless $b \to s$ and $b \to u$ transitions should also lead to final states with baryons. A number of searches for such modes have been carried out by CLEO, ARGUS, and LEP, but only upper limits were obtained. Stringent upper limits for two-body modes such as $B \to p\bar{p}, \Lambda\bar{p}$, and $\Lambda\bar{\Lambda}$ have recently been reported by Belle.

4.1 $B^\pm \to p\bar{p}K^\pm$

We have searched for the decay modes $B^\pm \to p\bar{p}K^\pm$ and $B^0 \to p\bar{p}K_S^0$. These modes are expected to proceed mainly via $b \to s$ penguin diagrams. We also search for $B^+ \to p\bar{p}\pi^+$ which is expected to occur primarily via a $b \to u$ tree process. Once these are established, these baryonic modes may be used to either constrain or observe direct $CP$ violation in $B$ decay.

To reconstruct signal candidates in the $B^+ \to p\bar{p}K^+$ mode, we form combinations of a kaon, proton and anti-proton that are inconsistent with the following $b \to c\bar{c}s$ transitions: $B^+ \to J/\psi K^+$, $J/\psi \to p\bar{p}$; $B^+ \to \eta_c K^+$, $\eta_c \to p\bar{p}$; $B^+ \to \eta^' K^+$, $\eta^' \to p\bar{p}$ and $B^+ \to \chi_{c[0,1]} K^+$. This set of requirements is referred to as the charm veto. Similar charm vetoes are applied in the analysis of the other decay modes. In the case of $B^0 \to p\bar{p}K_S$, events with $pK_S$ or $\bar{p}K_S$ masses consistent with the $\Lambda_c$ are rejected.

In Figure 8, we show the $\Delta E$ distribution (with $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$) and $M_{bc}$ distribution (with $|\Delta E| < 50 \text{ MeV}$) for the signal candidates. We fit the $\Delta E$ distribution with a double Gaussian for signal and a linear background function with slope determined from the $M_{bc}$ sideband. The fit to the $\Delta E$ distribution gives a yield of $42.8_{-14.5}^{+10.8}$ with a significance of $5.6\sigma$. This is the first observation of a $b \to s$ transition with baryons in the final state.

We also examine the $M_{p\bar{p}}$ mass distributions for events in the $\Delta E$, $M_{bc}$ signal region. The signal yield as a function of $p\bar{p}$ mass is shown in Figure 8(c). These yields were determined by fits to the $\Delta E$ distribution in bins of $p\bar{p}$ invariant mass. The distribution from a three-body phase space MC normalized to the area of the signal is superimposed. It is clear that the observed mass distribution is not consistent with three-body phase space but instead is peaked at low $p\bar{p}$ mass. This feature is suggestive of quasi two-body decay. It is also possible that the decay is a genuine three-body process and that this feature of the $M_{p\bar{p}}$ spectrum is a baryon form factor effect.

To avoid model dependence in the determination of the branching fraction for $p\bar{p}K^+$, we fit the $\Delta E$ signal yield in bins of $M_{p\bar{p}}$ and correct for the detection efficiency in each bin using a
The partial rate asymmetry can be written as

\[ \text{asymmetry} = \frac{A_{\ell\ell}}{A_{\ell\ell} + A_{\ell\ell}} \]

where \( A_{\ell\ell} \) and \( A_{\ell\ell} \) are the amplitudes that have different final states. Direct \( CP \) violation in the \( B \) meson system will occur in a decay containing at least two amplitudes that have different \( CP \) conserving and \( CP \) violating relative phases between amplitudes \( A_1 \) and \( A_2 \); \( B \) represents either a \( B_0^q \) or \( B^+ \) meson, \( f \) represents a self tagging final state, and \( \bar{B} \) and \( \bar{f} \) are the conjugate states. In the Standard Model, DCPV occurs in charmless hadronic \( B \) decay modes that involve both penguin (P) amplitudes and weak \( b \rightarrow u \) tree (T) amplitudes containing the CP violating weak phase \( \phi_3 = \text{arg} (V_{ub}^*) \) (in a standard convention [3]).

To verify the analysis procedure and branching fraction determination, we remove the \( J/\psi \) veto and examine the decay chain \( B^+ \rightarrow J/\psi K^+ \), \( J/\psi \rightarrow p\bar{p} \). The \( p\bar{p} \) invariant mass spectrum for \( J/\psi K^+ \) signal candidates is shown as an inset in Figure 6(c). The obtained branching fraction is in good agreement with the PDG world average.

To obtain an upper limit at 90% C.L. of \( \mathcal{B}(B^0 \rightarrow p\bar{p}K^0) < 7.2 \times 10^{-6} \) and \( \mathcal{B}(B^+ \rightarrow p\bar{p}\pi^+) < 3.7 \times 10^{-6} \).

## 5 Search for Direct \( CP \) Violation

The most straightforward indication for \( CP \) violation in the \( B \) meson system would be a time-independent rate asymmetry between \( CP \) conjugate decays into flavor specific or self-tagging final states. Direct \( CP \) violation (DCPV) of this type will occur in a decay containing at least two amplitudes that have different \( CP \) conserving and \( CP \) violating phases. The charge asymmetry will be most evident in decays where the two amplitudes are of comparable strength.

The partial rate asymmetry can be written as

\[ \mathcal{A}_{CP} = \frac{N(\bar{B} \rightarrow \bar{f}) - N(B \rightarrow f)}{N(B \rightarrow f) + N(\bar{B} \rightarrow \bar{f})} = \frac{2|A_1||A_2| \sin \delta \sin \phi}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2| \cos \delta \cos \phi} \]

where \( \delta \) and \( \phi \) are the \( CP \) conserving and \( CP \) violating relative phases between amplitudes \( A_1 \) and \( A_2 \); \( B \) represents either a \( B_0^q \) or \( B^+ \) meson, \( f \) represents a self tagging final state, and \( \bar{B} \) and \( \bar{f} \) are the conjugate states. In the Standard Model, DCPV occurs in charmless hadronic \( B \) decay modes that involve both penguin (P) amplitudes and weak \( b \rightarrow u \) tree (T) amplitudes containing the \( CP \) violating weak phase \( \phi_3 = \text{arg} (V_{ub}^*) \) (in a standard convention [3]).

We search for direct \( CP \) violation in the \( B \rightarrow K^+\pi^- \), \( K^+\pi^0 \), \( K^0_S\pi^+ \), and \( \omega K^+ \) decay modes by measuring the difference between the yields of \( B \) and \( \bar{B} \) decays into the self tagging final states. The asymmetries obtained are summarized in Table 3. All the results are consistent with null asymmetry, hence we set 90% C.L. limits. Note that the systematic bias from charge asymmetry in the detectors is less than 1%, much smaller than the statistical errors at present.
Table 3: Results of searches for direct \( CP \) violation.

| mode            | \( N(B) \)   | \( \Delta N(B) \) | \( \Delta \epsilon \) | 90\% C.L. |
|-----------------|--------------|-------------------|-----------------------|-----------|
| \( K^+ \pi^- \) | 103 ± 12     | 115 ± 14          | -0.06 ± 0.08 ± 0.01   | -0.20:0.09|
| \( K^+ \pi^0 \) | 28 ± 8       | 30 ± 8            | -0.04 ± 0.19 ± 0.03   | -0.39:0.30|
| \( K_S^0 \pi^+ \) | 49 ± 8       | 18 ± 6            | 0.46 ± 0.15 ± 0.02    | 0.18:0.73 |
| \( \pi^+ \pi^0 \) | 24 ± 8       | 13 ± 7            | 0.31 ± 0.31 ± 0.05    | -0.25:0.89|
| \( \omega K^+ \) | 7.4 ± 3.5    | 11.6 ± 3.7        | -0.22 ± 0.27 ± 0.04   | -0.70:0.26|

6 Summary

We have made the first observation of charmless baryonic decay \( B^{\pm} \rightarrow p\overline{p}K^{\pm} \), the three-body \( B^0 \rightarrow K^0\pi^+\pi^- \) and \( B^0 \rightarrow K^0K^+K^- \), and see strong evidence of \( B^{\pm} \rightarrow \eta K^{\pm} \) and \( B^{\pm} \rightarrow \eta\pi^{\pm} \). We also observed the decay \( B^{\pm} \rightarrow \omega K^{\pm} \) and measured the branching fractions for the decays \( B \rightarrow K\pi \) and \( \pi\pi \). We find no evidence for direct \( CP \) violation in the observed decays. By summer 2002 it is anticipated that Belle will have collected 90 \( fb^{-1} \) of data providing a rich sample to continue the search for rare \( B \) decays and measure \( CP \) violating effects in a variety of \( B \) decay modes.

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