Direct CP Violation and Rare Decays at Belle

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The highlights of direct CP violation (DCPV) and hadronic rare decays by the Belle experiment are presented.

1. MACHINE, DETECTOR, BASIC METHOD

The Belle experiment operates at the asymmetric energy e^+e^- collider, KEK-B, on the $\Upsilon(4S)$ resonance, with $\beta\gamma = 0.425$. KEK-B has achieved a peak luminosity of $15.81 \text{ nb}^{-1}\text{s}^{-1}$, with $> 1 \text{ fb}^{-1}$ per day, and, as of summer 2005, Belle has accumulated a total of 469.8 fb^{-1} of data.

Besides tracking (SVD and CDC), EM calorimeter and also K_L/μ detection, one major element for the DCPV/Rare program is the Aerogel Cherenkov Counter, ACC, a threshold Cherenkov device with several n values. Together with dE/dx from CDC and TOF information, for $p_K > 500 \text{ MeV}$, one has kaon efficiency of order 80%, with pion fake rate of order 10% or less.

With precise knowledge of E_{beam} in c.m.s., together with predominance of $\Upsilon(4S) \rightarrow B\bar{B}$ decay, B signal reconstruction utilizes the M_{bc} and ΔE projections. A set of modified Fox-Wolfram moments is used to reject the continuum $q\bar{q}$ background via an $\mathcal{LR}$ likelihood ratio cut.

2. OBSERVATION OF DCPV IN $K\pi$

DCPV in B decays, defined as

$$\mathcal{A}_{CP} = \frac{\Gamma(\bar{B} \rightarrow \bar{f}) - \Gamma(B \rightarrow f)}{\Gamma(\bar{B} \rightarrow \bar{f}) + \Gamma(B \rightarrow f)}, \quad (1)$$

was first attempted by CLEO in 1999. In 2004, Belle and BaBar both measured DCPV in $B^0 \rightarrow K^+\pi^-$, with combined significance $> 5\sigma$. With 386M $B\bar{B}$ pairs, Belle [1] now finds 3026 ± 63 signal events, giving $\mathcal{A}_{CP}(K^+\pi^-) = -0.113 \pm 0.022 \text{ (stat.)} \pm 0.008 \text{ (syst.)}$ with $\sim 5\sigma$ significance (see Fig. 1). The current world average

is -0.115 ± 0.018 [2], and DCPV in the B system is firmly established. Together with evidence for DCPV in $\pi^+\pi^-$, i.e. $\mathcal{A}_{CP}(\pi^+\pi^-) \equiv \mathcal{A}_{\pi\pi} \equiv -\mathcal{C}_{\pi\pi} = 0.37 \pm 0.10$ [2] (caution: Belle and BaBar differ by 2.3σ), there is sizable strong phase between tree (T) and penguin (P) amplitudes.

For $B^+ \rightarrow K^+\pi^0$ decay, the 386M update finds 1084 ± 45 signal events, giving [1] $\mathcal{A}_{CP}(K^+\pi^0) = 0.04 \pm 0.04 \pm 0.02$. This implies [2] $\mathcal{A}_{CP}(K^+\pi^0) - \mathcal{A}_{CP}(K^+\pi^-) \neq 0$ at $> 3.8\sigma$ significance, and hints at a larger than expected color-suppressed C , or a large electroweak penguin P_{EW} .

3. OBSERVATION OF $\pi^0\pi^0$

A sizable C is indicated by a larger than expected $B^0 \rightarrow \pi^0\pi^0$ rate. The $B^0 \rightarrow \pi^0\pi^0$ mode

Figure 1. M_{bc} and ΔE projections for $K^-\pi^+$ vs. $K^+\pi^-$ events with 386M $B\bar{B}$.

Figure 2. Definition of transversity basis.

has been observed by Belle with 275M $B\bar{B}$, giving $\mathcal{B}(B^0 \rightarrow \pi^0 \pi^0) = (2.3_{-0.5}^{+0.4+0.2}) \times 10^{-6}$ with 5.8σ significance. This confirms the 2003 evidence from BaBar and Belle, and the current combined result is $(1.45 \pm 0.29) \times 10^{-6}$ [2]. The value is not fully understood, but clearly suggest that C is not as suppressed as anticipated.

A first attempt was made on DCPV, using same flavor-tagging techniques as the time-dependent CPV program. The result is [3] $\mathcal{A}_{CP}(\pi^0 \pi^0) = 0.44_{-0.52}^{+0.53} \pm 0.17$, and the combined world average is $0.28_{-0.39}^{+0.40}$ [2]. While not yet significant, this is now the main limiting factor for ϕ_2 extraction from the $\pi\pi$ program.

4. POLARIZATION IN ϕK^* , $\rho^+ K^{*0}$

For charmless $B \rightarrow VV$ decays, longitudinal polarization is expected to be dominant, with $1 - f_L$ suppressed by $\mathcal{O}(m_V^2/m_B^2)$. This is true for most T dominated decays measured to date, such as in $\rho\rho$ and $\rho\omega$ modes. However, for $B \rightarrow \phi K^*$, which is a pure penguin $b \rightarrow s\bar{s}s$ transition, it was found [4,5] that $f_L(\phi K^*) \sim 0.5$ only. Theoretical suggestions to account for this range from annihilation, rescattering or transversity of emitted gluon, to new physics.

The first full helicity amplitude analysis was conducted by Belle [4], based on 85.5M $B\bar{B}$. In part motivated by search for new physics, Belle has updated [6] with 275M $B\bar{B}$ (with comparable results for ϕK^{*0} by BaBar [7], based on 227M $B\bar{B}$). Signal yields are extracted by fits to ΔE , M_{bc} and M_{KK} , with $f_0(980)K^*$ and $K\bar{K}$ (non- ϕ) K^* components taken into account when making the fit. 173 ± 16 and 85_{-11}^{+12} signal events were

Table 1

Fitted amplitudes for $B \rightarrow \phi K^*$.

	ϕK^{*0}	ϕK^{*+}
$ A_0 ^2$	$0.45 \pm 0.05 \pm 0.02$	$0.52 \pm 0.08 \pm 0.03$
$ A_\perp ^2$	$0.30 \pm 0.06 \pm 0.02$	$0.19 \pm 0.08 \pm 0.02$
$\arg A_\parallel$	$2.39 \pm 0.24 \pm 0.04$	$2.10 \pm 0.28 \pm 0.04$
$\arg A_\perp$	$2.51 \pm 0.23 \pm 0.04$	$2.31 \pm 0.30 \pm 0.07$

extracted for neutral and charged B , respectively. No indication for DCPV was found.

To study ϕK^* polarization, the transversity basis (see Fig. 2) is used. The z direction is out of K^* decay plane, the ϕ direction defines the x axis, with y axis on same side of kaon from K^* decay. Then θ_{K^*} is the angle between the K^* direction and its daughter kaon direction in the K^* rest frame, and θ_{tr} , ϕ_{tr} are the polar and azimuthal angles, in ϕ rest frame, of K^+ from ϕ decay.

Denoting the longitudinal amplitude as A_0 , $A_\perp$ and $A_\parallel$ are the transverse polarized components along z and y axis. Normalizing to $|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2 = 1$ and taking A_0 as real, we make an unbinned maximum likelihood fit to ϕK^* candidates in the signal region. The fitted parameters $|A_0|^2$, $|A_\perp|^2$ and $|A_\parallel|^2$ are shown in Table 1. The results for ϕK^{*0} and ϕK^{*+} are consistent with each other, and $f_L = |A_0|^2 \simeq 0.5$ is confirmed. From $\arg A_\perp$, $\arg A_\parallel$, we see 4.3σ evidence for final state interactions (FSI, or strong phase), i.e. away from π .

The T -odd quantities

$$A_T^0 = \text{Im}(A_\perp A_0^*), \quad A_T^\parallel = \text{Im}(A_\perp A_\parallel^*), \quad (2)$$

measure triple products of momentum and polarization vectors, and probe T -odd CP -violation. We find $A_T^0 = 0.13_{-0.14}^{+0.11} \pm 0.04$ vs. $\bar{A}_T^0 = 0.28 \pm 0.08 \pm 0.01$, and likewise $A_T^\parallel = 0.03 \pm 0.08 \pm 0.01$ vs. $\bar{A}_T^\parallel = 0.03 \pm 0.06 \pm 0.01$, showing no significant difference between B and $\bar{B}$ decays.

A more sophisticated angular analysis has been performed on B^0 vs. $\bar{B}^0$ decays. It confirms the longitudinal fraction f_L and CP -odd fraction $f_\perp$, as well as the nonzero effect that arises from FSI. But variables that should vanish in absence of new physics are all consistent with zero.

Belle has studied [8] polarization in another

Figure 3. Fit to ρ^+K^{*0} helicity distributions. The dot-dash, dash and dotted histograms are the A_0 , $A_{\pm}$ and non-resonant $\rho K\pi$, respectively.

pure penguin VV decay, $B^+ \rightarrow \rho^+K^{*0}$, which is $b \rightarrow sdd$. Out of 275M $B\bar{B}$ pairs, 135 ± 17 $K^+\pi^+\pi^-\pi^0$ events are found, which includes non-resonant backgrounds. Selecting the nominal K^{*0} region, the $\pi^+\pi^0$ is predominantly ρ , hence there is little $K^{*0}\pi^+\pi^0$ background. However, selecting the nominal ρ region, besides a dominant K^{*0} component, one finds a significant non-resonant $\rho^+K^+\pi^-$ component in $M(K^+\pi^-)$ plot. This is taken into account in the angular analysis.

We perform a binned simultaneous χ^2 fit to the ρ and K^* helicity-angle distributions. An S -wave $K\pi$ system is assumed in the modelling of non-resonant $\rho^+K^+\pi^-$ component. The fit result is shown in Fig. 3 for the helicity angle $\cos\theta_{K^*}$. The fitted longitudinal fraction is $f_L(\rho^+K^{*0}) = 0.43 \pm 0.11^{+0.05}_{-0.02}$, which is consistent with ϕK^* case, and far below the expected $f_L \sim 1$. The branching fraction is found to be $\mathcal{B}(\rho^+K^{*0}) = (8.9 \pm 1.7 \pm 1.2) \times 10^{-6}$. Note, however, that some discrepancy exists with the BaBar result [9] based on 89M $B\bar{B}$, which finds $f_L = 0.79 \pm 0.08 \pm 0.04 \pm 0.02$ and $\mathcal{B} = (17.0 \pm 2.9 \pm 2.0^{+0.0}_{-1.9}) \times 10^{-6}$, where the last error is from non-resonant background.

5. Khh DALITZ ANALYSIS

Belle pioneered the Dalitz analysis of three-body $K^+h^+h^-$ decays, where $h = \pi, K$. A recent update [10] with 152M $B\bar{B}$ yields 1533 ± 69 $K^+\pi^+\pi^-$ events and 1089 ± 41 $K^+K^+K^-$ events. A first amplitude analysis gives clear signals in $K^{*0}\pi^+$, $f_0(980)K^+$, ϕK^+ , and $\chi_{c0}K^+$, includ-

Figure 4. $M(\pi^+\pi^-)$ spectra for (a) $K^-\pi^-\pi^+$ and (b) $K^+\pi^+\pi^-$, without helicity cut.

ing the first observation of $\rho^0 K^+$. $K_0^*(1430)^0\pi^+$ is observed, but rate determination suffers large model error. Broad structures are also seen in $M(\pi^+\pi^-)$ ($M(K^+K^-)$) at 1300 (1500) GeV/c^2 . Non-resonant $K^+\pi^+\pi^-$ and $K^+K^+K^-$ decays comprise a significant fraction of the total three-body signal, which presaged the $\rho^+K^+\pi^-$ case.

Belle has recently updated [11] with 386M for $K^\pm\pi^\pm\pi^\mp$, with an aim towards search for DCPV. Simultaneous fit to B^- and B^+ yields 2248 ± 79 $K^-\pi^-\pi^+$ signal events vs. 2038 ± 76 for $K^+\pi^+\pi^-$. The resulting asymmetry is $\mathcal{A}_{CP}(K^+\pi^+\pi^-) = 0.049 \pm 0.026 \pm 0.030$, which is consistent with zero. However, amplitude analysis allows DCPV in various quasi-two-body channels to be studied. The only channel where the statistical significance of the CP asymmetry exceeds the 3σ level is $\rho^0 K^+$.

We find $\mathcal{A}_{CP}(\rho^0 K^+) = 0.30 \pm 0.11 \pm 0.03^{+0.11}_{-0.04}$, which has 3.9σ statistical significance. This asymmetry is illustrated in Fig. 4 without any helicity cut. A helicity cut of $\cos\theta_{\pi\pi}^{\text{hel}} < 0$ would make the asymmetry even more apparent. The measured $\mathcal{A}_{CP}$ is consistent with the earlier result based on 275M [12], and consistent with the BaBar result [13] of $0.34 \pm 0.13 \pm 0.06^{+0.15}_{-0.20}$ based on 232M $B\bar{B}$ pairs. Modelling error is still large, but if confirmed with a larger data sample, this would be the first observation of CP violation in the decay of a charged meson.

6. BARYONIC MODES

In the $K^+h^+h^-$ study, taking $h = \pi, K$ was following CLEO convention. Another possibility is $h = p$. Belle observed $p\bar{p}K^+$ in 2002 [14], the first charmless baryonic decay mode of B mesons to be observed. Subsequently, a host of charmless bary-

Figure 5. Baryon pair mass spectra for (a) $p\bar{p}K^+$, (b) $p\bar{p}K_S$, (c) $p\bar{\Lambda}\pi^-$ and (d) $\Lambda\bar{\Lambda}K^+$.

onic modes have emerged: $p\bar{\Lambda}\pi^+$, $p\bar{p}\pi^+$, $p\bar{p}K^0$, $p\bar{p}K^{*+}$, $\Lambda\bar{\Lambda}K^+$, and also $p\bar{\Lambda}\gamma$. However, the corresponding two-body $p\bar{p}$, $\bar{\Lambda}p$, $\Lambda\bar{\Lambda}$ modes have not been seen [15], with 90% confidence level limits below 10^{-6} , which is in contrast to the mesonic case. Another type of rare three-body baryonic decay, $J/\psi\bar{\Lambda}p$, has been observed by Belle [16] at the 10^{-5} level.

One common feature of the observed three-body charmless baryonic modes is “threshold peaking” in the low baryon-pair mass spectrum. A recent study with 152M gives [17] $\mathcal{B}(B^+ \rightarrow p\bar{p}K^+) = (5.30^{+0.45}_{-0.39} \pm 0.58) \times 10^{-6}$, $\mathcal{B}(B^0 \rightarrow p\bar{p}K_S) = (1.20^{+0.32}_{-0.22} \pm 0.14) \times 10^{-6}$, $\mathcal{B}(B^0 \rightarrow p\bar{\Lambda}\pi^-) = (3.27^{+0.62}_{-0.51} \pm 0.39) \times 10^{-6}$, confirming earlier results, and [18] the first observation of $\mathcal{B}(B^+ \rightarrow \Lambda\bar{\Lambda}K^+) = (2.91^{+0.90}_{-0.70} \pm 0.38) \times 10^{-6}$. The corresponding baryon pair mass spectra are given in Fig. 5. Although the shape varies, all exhibit peaking behavior towards threshold, compared to phase space which is shaded. A similar study [19] with 152M finds $\mathcal{B}(B^+ \rightarrow p\bar{\Lambda}\gamma) = (2.16^{+0.58}_{-0.53} \pm 0.20) \times 10^{-6}$, and also exhibiting threshold peaking towards low $M(p\bar{\Lambda})$. This behavior is understood as resonant string fragmentation, while the three-body hadronic modes are not fully understood.

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