$B^-\to\omega K^-/\pi^-$ and Time-dependent CPV in $B^0\to\eta' K_S$ at Belle

Kai-Feng Chen
Department of Physics
National Taiwan University
Taipei 106, Taiwan, R.O.C.

1 Introduction

Charmless hadronic B decays are interesting for testing our understanding of heavy quark physics and search for CP violation. We report the measurements of charmless $B^-\to\omega\pi^-$ and $B^-\to\omega K^-$ decays. The $B^-\to\omega K^-$ mode was first reported by CLEO collaboration in 1998 [1], but superseded by nonobseravtion with a larger data set [2]. This result is supported by BaBar in 2001 [3]. The $B^-\to\omega\pi^-$ channel has also been reported by CLEO and BaBar collaborations. However, we find a significant signal in the $B^-\to\omega K^-$ mode. The data used in this analysis were based on an integrated luminosity of 29.4 fb^{-1} data sample on the $\Upsilon(4S)$ resonance taking by the Belle detector at the KEK B-factory.

Kobayashi and Maskawa (KM) showed CP violation could be accommodated in the Standard Model [4] (SM) in 1973. In the model, the CP violation arises from a complex phase in the weak interaction quark mixing matrix [5]. Belle and BaBar collaborations have measured the CP-violating parameter $\sin2\phi_1$ from $B^0\to c\bar{c}K^0$ decays. The $B^0\to\eta' K_S$ decay is also sensitive to the parameter $\sin2\phi_1$ and provides important tests of the KM model. Within the framework of SM, the charmless decay $B^0\to\eta' K_S$ are dominated by $b\to s$ penguin diagrams and a small color-suppressed $b\to u$ tree contribution. However, since the branching fractions of $B\to\eta' K$ decays are larger than current theoretical prediction, there might be an additional new phase beyond SM.

The time-dependent CP asymmetry is given by

$$
\begin{aligned}
A_{CP}(\Delta t) &= \frac{\Gamma(\overline{B^0}\to\eta' K_S) - \Gamma(B^0\to\eta' K_S)}{\Gamma(\overline{B^0}\to\eta' K_S) + \Gamma(B^0\to\eta' K_S)} \\
&= A_{\eta' K_S}\cos(\Delta m\Delta t) + S_{\eta' K_S}\sin(\Delta m\Delta t),
\end{aligned}
$$

where the CP-violating parameters $A_{\eta' K_S}$ and $S_{\eta' K_S}$ are expressed as

$$A_{\eta' K_S} = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}, \quad S_{\eta' K_S} = \frac{2\mathrm{Im}\lambda}{|\lambda|^2 + 1}, \tag{1}$$

where λ is a complex parameter that depends on both $B^0 - \overline{B^0}$ mixing and on the decay amplitude for $B^0(\overline{B^0}) \to \eta' K_S$. $|\lambda|$ is close to 1 in the SM with a good approximation. The measurement of CP-violating parameters in the decay $B \to \eta' K$ is based on a 41.8 fb^{-1} data sample.

The KEKB asymmetric e^+e^- (3.5 GeV e^+ and 8 GeV e^-) collider operates on the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ along the beam direction (z).

The Belle detector [6] is a general-purpose detector operating under 1.5 T magnetic field. It consists of a three layer silicon vertex detector (SVD), a central drift chamber (CDC) with 50 layers. Charged hadrons are distinguished by combining the information from an array of aerogel threshold Cerenkov counters (ACC), a time-of-flight scintillation counters (TOF), and the dE/dx measurements from CDC. Photons are detected in an array of 8736 CsI(Tl) crystals (ECL) located inside the magnet.The flux-return outside of the coil is instrumented for detection of muon and K_L (KLM).

2 Observation of $B^\pm \to \omega K^\pm$ Decay

Charged tracks are required to be inconsistent with electrons or muons, and are identified as kaons or pions according to a K/π likelihood ratio (KID), $\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$, where the $\mathcal{L}_{K(\pi)}$ is given by

$$\mathcal{L}_{K(\pi)} = \mathcal{L}^{\mathrm{ACC}}_{K(\pi)} \times \mathcal{L}^{\mathrm{TOF}}_{K(\pi)} \times \mathcal{L}^{dE/dx}_{K(\pi)}, \tag{2}$$

where $\mathcal{L}^{\mathrm{ACC}}_{K(\pi)}$, $\mathcal{L}^{\mathrm{TOF}}_{K(\pi)}$, and $\mathcal{L}^{dE/dx}_{K(\pi)}$ are the likelihood for ACC, TOF, and dE/dx from CDC measurement respectively. Neutral pions are reconstructed from pairs of photons, each consisting of energy greater than 50 MeV, with the $m_{\gamma\gamma}$ within a $\pm 3\sigma$ (σ = 5.4 MeV/c^2) mass window around the π^0 mass. A mass constrained fit is applied on the π^0 candidates. ω meson candidates are obtained by combining $\pi^+\pi^-\pi^0$ with invariant mass within ± 30 MeV/c^2 of the nominal ω mass. The momentum of candidate π^0's under ω is required to be greater than 350 MeV/c. This cut gives 84% efficiency, but removes 60% combinatorial background.

A charged kaon or a pion track is selected to combine with an ω candidate to form a $B^\pm$ candidate. B mesons are identified by two kinematic variables, the beam-constrained mass $M_{bc} = \sqrt{(E^{\mathrm{CM}}_{\mathrm{beam}})^2 - (p^{\mathrm{CM}}_B)^2}$ and the energy difference $\Delta E = E^{\mathrm{CM}}_B - E^{\mathrm{CM}}_{\mathrm{beam}}$, where the $E^{\mathrm{CM}}_{\mathrm{beam}} = \sqrt{s}/2 = 5.29$ GeV is the CM beam energy. The resolutions are 3 MeV/c^2 for M_{bc} and 23 MeV for ΔE from Monte Carlo simulations.

Continuum $e^+e^- \to q\overline{q}$ process is the dominant background in this analysis. The $q\overline{q}$ consists of light quark (u, d, s, or c) pairs. The continuum events which are jet-like have to be suppressed compared to the spherical $B\overline{B}$ events. A Fisher discriminant [7] is defined containing modified Fox-Wolfram moments [8]. We use a likelihood ratio method combining the Fisher discriminant, B-meson direction, and the helicity angle which is defined as the angle between the B flight direction and the vector perpendicular to the ω decay plane in the ω rest frame. The probability density functions (PDFs) are determined by Monte Carlo simulation. A signal (background) likelihood $\mathcal{L}_s$ ($\mathcal{L}_b$) is calculated by the PDFs for each event. The likelihood ratio is formed by $LR = \mathcal{L}_s/(\mathcal{L}_s + \mathcal{L}_b)$, and a cut $LR > 0.85$ is made to reject 95% continuum background but keeping 50% signal events.

Background from charmed and charmless B decays such as $B \to \omega K^*$, $B \to \omega\rho$, and non-resonant $B^- \to K^-\pi^+\pi^-\pi^0$ are studied by Monte Carlo simulation up to 20 times larger than current data amount. These backgrounds are negligible in the M_{bc}-ΔE signal region ($M_{bc} > 5.27$ GeV/c^2 and $|\Delta E| < 0.1$ GeV).

The signal yields are extracted by an unbinned maximum likelihood fit on M_{bc} and ΔE together. The signal PDF for M_{bc} is a Gaussian, and for ΔE [9], parameters are determined by MC simulation and calibrated by the $B^- \to D^0\pi^-$ decay, where D^0 decays to $K^-\pi^+\pi^0$. Background PDFs are threshold functions [10] determined from MC simulation. The yields are summarized in Table 1. The M_{bc} and ΔE projections of candidate events are shown in Figure 1.

The systematic uncertainties associated with the fit are determined by varying the parameters in the fitting functions by $\pm 1\sigma$ of their nominal values. The systematic error of ω detection efficiency is determined from detailed studies of charged particle tracking, π^0 detection, and particle identification. A 5% systematic error is assigned to the continuum suppression cut from $B^- \to D^{*0}\pi^-$ data and MC study. The combined uncertainty of the efficiency is 10.1%.

We make the consistency check of our analysis without KID requirement. Figure 2 shows the ΔE distribution and scatter plot of KID versus ΔE. The ωK^- signals are peaking at -51 MeV, where the $\omega\pi^-$ signals are placed at zero. The ΔE distributions confirm the ωK^- signals are larger than $\omega\pi^-$. We also examine the ω properties to confirm the ωK^- signal candidates. The ω invariant mass spectrum and the cosine of the helicity angle of the B candidate events are also shown in Figure 2.

We also measure the asymmetry in $B^\pm \to \omega K^\pm$ decays to search for direct CP violation. The asymmetry is defined as

$$A_{CP} = \frac{N(\omega K^-) - N(\omega K^+)}{N(\omega K^-) + N(\omega K^+)}. \tag{3}$$

The asymmetry is measured to be $-0.21 \pm 0.28 \pm 0.03$. The 90% confidence level interval is given by $-0.70 < A_{CP} < 0.28$.

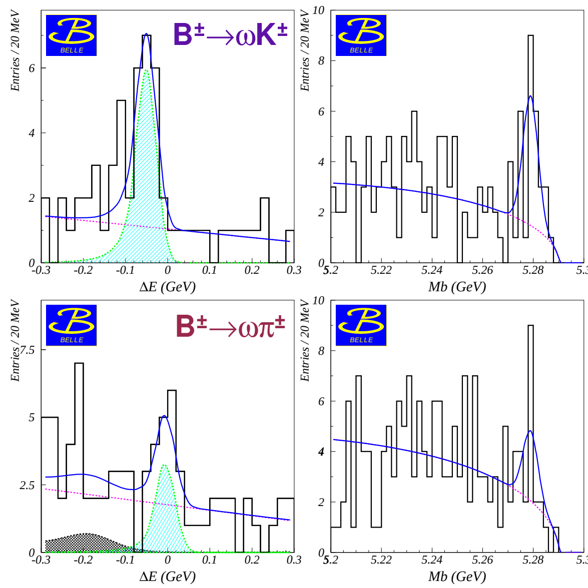

Figure 1: The M_{bc} and ΔE projection plots of $B^{-}\to\omega K^{-}$ and $B^{-}\to\omega\pi^{-}$ modes.

3 Search of Time-dependent CP Asymmetry in $B\to\eta' K$ Decay

The $B\to\eta' K$ event selection is described in the previous published branching ratio measurement [11]. The CP fit analysis is done nearly the same as the $B\to\pi^{+}\pi^{-}$ case.

The $K_S\to\pi^{+}\pi^{-}$ candidates are reconstructed with a pair of charged tracks with pion mass assumption. A ± 16 MeV$/c^2$ to the nominal K_S mass window cut is applied. Two decay channels are used for η' reconstruction: $\eta'\to\eta\pi^{+}\pi^{-}$ with the η decays to two photons and $\eta'\to\rho^0\gamma$. Candidate photons from η (η') are required to have a energy greater than 50 MeV (100 MeV). The B meson candidates are formed by combining η' and a K_S ($K^{\pm}$). The kinematic variables, ΔE and M_{bc} are used to identify B signal candidates.

The dominant background to $B\to\eta' K$ modes are $e^{+}e^{-}\to q\bar{q}$ continuum events, just like the $B\to\omega h$ modes. A loose cut of $|\cos\theta_T| < 0.9$ [11] is used rejecting 50% of the

	Signal Yield	Σ	$\epsilon(\%)$	BF $(\times 10^{-6})$	UL $(\times 10^{-6})$
ωK^{-}	$19.7^{+5.8+0.7}_{-4.7-0.5}$	6.4σ	6.3	$9.9^{+2.7}_{-2.4} \pm 1.0$	-
$\omega\pi^{-}$	$10.6^{+4.3+0.4}_{-4.5-0.6}$	3.3σ	7.7	$4.3^{+2.0}_{-1.8} \pm 0.5$	< 8.2

Table 1: The results of $B^{-}\to\omega K^{-}$ and $B^{-}\to\omega\pi^{-}$ decays.

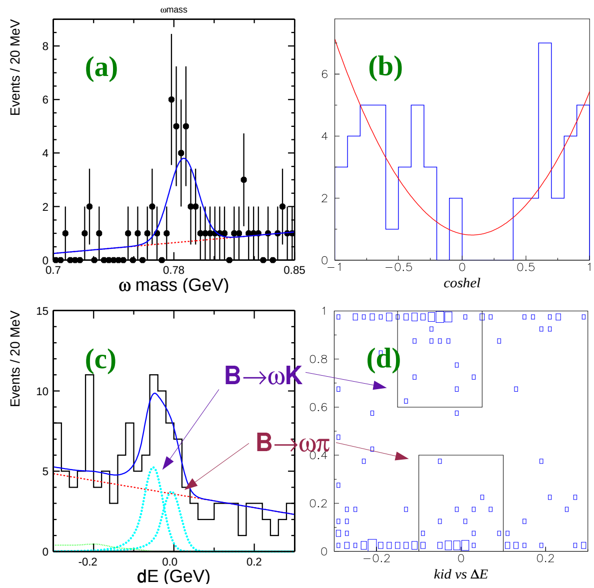

Figure 2: (a) The $\pi^+\pi^-\pi^0$ invariant mass spectrum. (b) The cosine of the helicity angle of $B\to\omega h$ modes. (c) The ΔE distribution without KID information. (d) The Belle KID versus ΔE spectrum.

background but retaining 90% of signal events.

The $\eta'\to\eta\pi^+\pi^-$ mode is clean enough after the $\cos\theta_T$ selection, but the $\eta'\to\rho^0\gamma$ is not as clean. We introduce a likelihood ratio method which is very close to the $B\to\omega h$ analysis. The only difference is the helicity angle of $\eta'\to\rho^0\gamma$ mode is defined with ρ^0 in η' rest frame. Finally, a $LR > 0.5$ is applied to reject 81% of the background and keep 80% of the signal. Other generic $B\overline{B}$ backgrounds mainly come from the decay of B to charm. They contribute 8.1% for the $\eta'(\to\rho^0\gamma)K_S$ mode but negligible in the $\eta'\to\eta\pi^+\pi^-$ modes. The projection plots for ΔE and M_{bc} of $\eta' K^\pm$ and $\eta' K_S$ decays are shown in Figure 3.

Leptons, charged pions, Λ's and kaons are not associated with the reconstructed $B^0\to\eta' K_S$ decay are used to identify the flavor of the accompanying B meson. The algorithm is the same as the $\sin 2\phi_1$ measurement. The vertex positions for $\eta' K_S$ and $B_{\rm tag}$ decays are reconstructed using tracks with at least two SVD hits in z axis and tracks from K_S candidates are removed.

The proper-time interval resolution for the signal, $R_{\rm sig}(\Delta t)$, is obtained by convolving a sum of two Gaussians. A main component due to the SVD vertex resolution and charmed meson lifetimes, with a tail component caused by poorly reconstructed tracks. The mean and width of the Gaussians are calculated event-by-event from the vertex fit error and the χ^2 values. The background resolutions, $R_{q\overline{q}}(\Delta t)$ and $R_{B\overline{B}}(\Delta t)$, have the same form but the parameters are determined from sideband events and generic B Monte Carlo. We obtain the lifetimes of charged and neutral B mesons with the same procedure, and the results agree with the world average values.

The CP violation parameters, $A_{\eta' K_S}$ and $S_{\eta' K_S}$, are determined by performing an unbinned maximum-likelihood fit to the measured Δt distributions. The expected PDF for signal,

$$P_{\rm sig}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 + q \cdot (1 - 2w_l) \cdot A_{CP}(\Delta t)\}, \tag{4}$$

is used in the fit. The τ_{B^0} and Δm_d are fixed to their world average values [12]. The PDF used for the background distribution is

$$P_{\rm bkg}(\Delta t) = \{f_\tau \cdot \frac{e^{-|\Delta t|/\tau_{\rm bkg}}}{2\tau_{\rm bkg}} + (1 - f_\tau) \cdot \delta(\Delta t)\}/2, \tag{5}$$

where f_τ is the background fraction with an effective lifetime $\tau_{\rm bkg}$. Parameters for continuum background are determined from sideband data. The PDF shape for $B\overline{B}$ background is from Monate Carlo simulation.

The likelihood value for each event are defined as:

$$P_i = \int f^l_{\rm sig} P_{\rm sig}(\Delta t') R_{\rm sig}(\Delta t_i - \Delta t') + f^l_{q\overline{q}} P_{q\overline{q}}(\Delta t') R_{q\overline{q}}(\Delta t_i - \Delta t')$$

$$+ f^l_{B\overline{B}} P_{B\overline{B}}(\Delta t') R_{B\overline{B}}(\Delta t_i - \Delta t') d\Delta t', \tag{6}$$

where the f^l_k(subscript k = sig, $q\overline{q}$, or $B\overline{B}$, and $l = 6$) are the weighted probability functions determined on an event-by-event basis as a function of ΔE and M_{bc}.

In the fit, $A_{\eta' K_S}$ and $S_{\eta' K_S}$ are free parameters that are determined by maximizing the likelihood function $\mathcal{L} = \Pi P_i$ over all $B^0 \to \eta' K_S$ candidates. The CP asymmetry parameters obtained from a total 73 $\eta' K_S$ signal events after subtracting the background are

$$\begin{aligned} S_{\eta' K_S} &= 0.28 \pm 0.55\ ({\rm stat})^{+0.07}_{-0.08}\ ({\rm syst}), \\ A_{\eta' K_S} &= 0.13 \pm 0.32\ ({\rm stat})^{+0.09}_{-0.06}\ ({\rm syst}). \end{aligned}$$

Figure 4 shows the Δt distributions for B^0 ($\overline{B^0}$) tagged events, and raw asymmetry of the $\eta' K_S$ sample.

We determine the systematic error due to fitting parameters (physics parameters, wrong tag fractions, signal and background PDFs) by repeating the fit after varying the parameters by $\pm 1\sigma$ determined from the data or MC.

A number of checks are also performed. The $\eta' K^\pm$ sample is analyzed in the same way as $\eta' K_S$. A fit to 230 candidate events give $S = 0.11 \pm 0.29$ and $A = -0.27 \pm 0.17$ consistent with no asymmetry. The other check by floating the $B^\pm$ (B^0) lifetime in the $B^{\pm}$ (B^0) sample is performed. The $B^{\pm}$ (B^0) lifetime determined with $\eta' K^{\pm}$ ($\eta' K_S$) samples is $1.54^{+0.14}_{-0.13}$ ($1.58^{+0.31}_{-0.26}$) ps, consistent with world average value [12].

In summary, we measure the time-dependent CP asymmetry parameters in $B^0(\overline{B^0}) \to \eta' K_S$ decay based on 41.8 fb^{-1} data sample collected with the Belle detector. The results, $S_{\eta' K_S} = 0.28 \pm 0.55$ (stat)$^{+0.07}_{-0.08}$ (syst) and $A_{\eta' K_S} = 0.13 \pm 0.32$ (stat)$^{+0.09}_{-0.06}$ (syst), are the first measurements of CP asymmetry parameters related to ϕ_1 with a charmless B^0 decay. With more data, the uncertainty in $S_{\eta' K_S}$ can be reduced and impose tighter constraints on the phases from physics beyond the Standard Model.

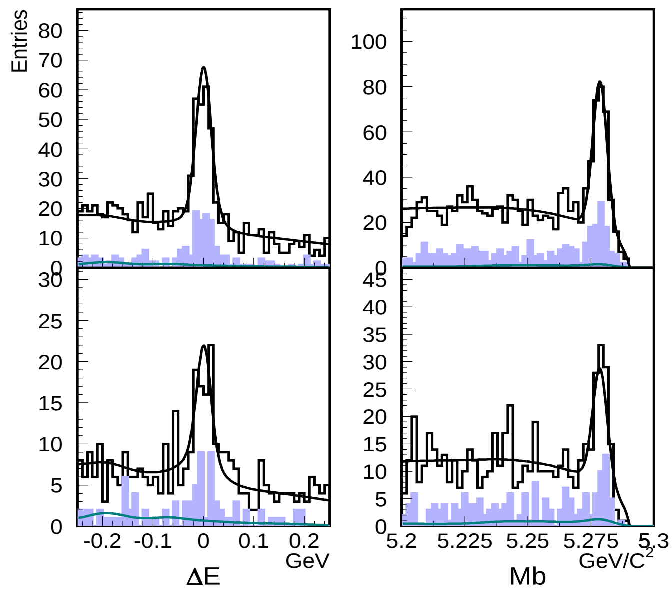

Figure 3: The M_{bc} and ΔE projection plots of $B^{\pm} \to \eta' K^{\pm}$ and $B^0 \to \eta' K_S$ modes.

References

[1] CLEO Collaboration, T. Bergfeld *et al.*, Phys. Rev. Lett. **81**, 272 (1998).

[2] CLEO Collaboration, C.P. Jessop *et al.*, Phys. Rev. Lett. **85**, 2881 (2000).

[3] BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **87**, 221802 (2001).

[4] D. London and A. Soni, Phys. Lett. **B 407** (1997) 61.

[5] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49** (1973) 652.

[6] Belle Collaboration, A. Abashian *et al.*, Nucl. Inst. Meth. **A 479** (2002) 117.

[7] R. A. Fisher, Annals of Eugenics, **7**, 179 (1936).

[8] Belle Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **87**, 101801 (2001).

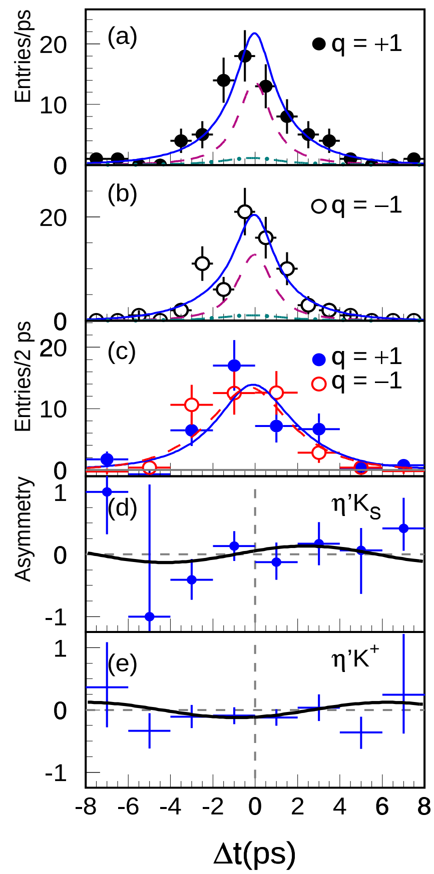

Figure 4: (a) The Δt distribution for B^0 tagged events. (b) The Δt distribution for $\overline{B^0}$ tagged events. (c) B^0 and $\overline{B^0}$ tagged events overlaid after background subtraction. (d) The asymmetries versus Δt plot. The solid curve is obtained from CP fit. (e) The asymmetries versus Δt plot for $\eta' K^{\pm}$.

[9] J. E. Gaiser *et al.*, Phys. Lett. **D 34** , 711 (1986).

[10] H. Albrecht *et al.*, Phys. Lett. **B 241** , 278 (1990).

[11] Belle Collaboration, K. Abe *et al.*, Phys. Lett. **B 517** (2001) 309.

[12] Particle Data Group, D. E. Groom *et al.*, Eur. Phys. J. **C 15** (2000) 1.