Observation of $B^{\pm} \rightarrow \omega K^{\pm}$ Decay

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We report the first observation of the charmless two-body mode $B^\pm \to \omega K^\pm$ decay, and a new measurement of the branching fraction for the $B^\pm \to \omega\pi^\pm$ decay. The measured branching fractions are $\mathcal{B}(B^\pm \to \omega K^\pm) = (9.2^{+2.6}_{-2.3} \pm 1.0) \times 10^{-6}$ and $\mathcal{B}(B^\pm \to \omega\pi^\pm) = (4.2^{+2.0}_{-1.8} \pm 0.5) \times 10^{-6}$. We also measure the partial rate asymmetry of $B^\pm \to \omega K^\pm$ decays and obtain $\mathcal{A}_{CP} = -0.21 \pm 0.28 \pm 0.03$. The results are based on a data sample of 29.4 fb^{-1} collected on the $\Upsilon(4S)$ resonance by the Belle detector at the KEKB e^+e^- collider.

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Charmless hadronic B decays are of interest not only for testing our current understanding of heavy quark physics, but also as modes to search for direct CP violation. The $B^- \to \omega\pi^-$ and ωK^- decays [1] are dominated by tree-level and gluonic penguin diagrams [2], respectively, illustrated in Fig. 1. Thus, their branching fractions can give us further insight into gluonic penguin diagrams, while interference between tree and penguin diagrams can lead to a measurable direct CP asymmetry.

In factorization models with $N_c \simeq 2$–3, where N_c is the effective number of colors, the $\omega\pi$ mode is larger than the ωK mode by a factor of 2 or more [2]. This result is borne out by further studies in the QCD factorization [3] and perturbative QCD (pQCD) [4] frameworks. In this Letter, we report measurements of $B^- \to \omega K^-$ and $\omega\pi^-$ decays that indicate that the former is more prominent, which may suggest the influence of nonfactorized effects.

The $B^- \to \omega K^-$ mode has an interesting history. It was first reported by CLEO in 1998 [5] with 3.9σ significance, but subsequently superseded by nonobservation with a larger data set [6], a result that is supported by BABAR [7]. However, we report here a significant signal in this mode. The $B^- \to \omega\pi^-$ mode has been reported previously by the CLEO [6] and BABAR [7] collaborations at levels that are somewhat higher than our findings. The data used in this analysis were collected with the Belle detector [8] at KEKB [9], a double storage ring that collides 8 GeV electrons and 3.5 GeV positrons with a

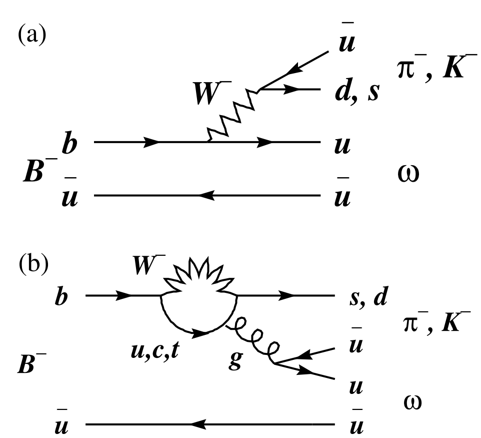

FIG. 1. Tree (left) and penguin (right) diagrams for $B^- \to \omega K^-$ and $B^- \to \omega\pi^-$ decays.

22 mrad crossing angle. The data sample corresponds to an integrated luminosity of 29.4 fb^{-1} on the $\Upsilon(4S)$ resonance, containing 31.9×10^6 $B\overline{B}$ pairs, and 2.3 fb^{-1} taken 60 MeV below the resonance.

Belle is a general-purpose detector with a 1.5 T superconducting solenoid magnet. Charged particle tracking, covering 86% of the total center-of-mass (c.m.) solid angle, is provided by a 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/π 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 a flux return that consists of 4.7 cm thick steel plates interspersed with resistive plate chambers to detect muons and K_L mesons (KLM). The Belle detector is described in detail elsewhere [8].

Well reconstructed tracks that are inconsistent with being electrons or muons are identified as kaon or pions according to a K/π likelihood ratio (KID), $\mathcal{L}_K/(\mathcal{L}_\pi + \mathcal{L}_K)$, where the $\mathcal{L}_{K(\pi)}$ are likelihoods derived from the responses of the dE/dx, ACC, and TOF systems. Candidate π^0 mesons are reconstructed from pairs of photons, each consisting of energy clusters greater than 50 MeV in the ECL, with $m_{\gamma\gamma}$ inside a $\pm 3\sigma$ ($\sigma = 5.4$ MeV/c^2) mass window around the π^0 mass [10]. A mass-constrained fit is then performed to improve the π^0 momentum resolution. Candidate ω mesons are formed from $\pi^+\pi^-\pi^0$ combinations with an invariant mass that is within ± 30 MeV/c^2 of the nominal ω mass [10]. (The natural width of the ω meson is 8.9 MeV.) To further reduce the large combinatorial background from low energy photons and π^0, an ω candidate is discarded if the daughter π^0 c.m. momenta is below 350 MeV/c. This selection on π^0 c.m. momentum loses 16% of the signal, but removes 60% of the combinatorial background.

We combine an ω candidate with either a K^- or a π^- track to form a B^- candidate. As part of this procedure, the momenta of the three charged tracks are recalculated subject to the constraint that they originate from the interaction point. Using the c.m. beam energy $E_{\rm beam}^{\rm CM} = \sqrt{s}/2 = 5.29$ GeV and the measured c.m. energy EBCM and momentum $p_B^{\rm CM}$ of the B candidate, we form two kinematic variables to select the signal events: The beam-constrained mass $M_{\rm bc} = \sqrt{(E_{\rm beam}^{\rm CM})^2 - (p_B^{\rm CM})^2}$ and the energy difference $\Delta E = E_B^{\rm CM} - E_{\rm beam}^{\rm CM}$.

The major background for this analysis is from continuum $e^+e^- \to q\overline{q}$ production, where q is a light quark (u, d, s, or c). The jetlike continuum events are suppressed relative to the more spherical $B\overline{B}$ events by characterization of the event shape, which is implemented with a Fisher discriminant [11] containing six modified Fox-Wolfram moments [12,13]. There are two types of combinatorial backgrounds from continuum events: fake ω mesons and fake B mesons. The former is suppressed using the cross product $|\vec{P}_+ \times \vec{P}_-|$ of the momenta of the charged pion daughters in the ω meson rest frame. The latter is suppressed using the B candidate flight direction relative to the positron beam axis, and the helicity angle of the candidate ω meson relative to the B meson. The helicity angle, $\theta_{\rm hel}$, is defined as the angle between the B flight direction and the vector perpendicular to the ω decay plane in the ω rest frame. We use a likelihood ratio technique that combines the Fisher discriminant, the cross product of the momenta of the charged pions from the ω, the B flight direction, and the cosine of the helicity angle, $\cos\theta_{\rm hel}$, to suppress the continuum background relative to the $B \to \omega h$ ($h = \pi$ or K) signal. The probability density functions (PDFs) for signal and background are constructed using Monte Carlo (MC) events. The background PDFs are in good agreement with those determined from on-resonant sideband data ($M_{\rm bc} < 5.26$ GeV/c^2 and $|\Delta E| < 0.3$ GeV). With these PDFs, we determine signal ($\mathcal{L}_{\rm S}$) and background ($\mathcal{L}_{\rm BG}$) likelihoods for each event that are used to form the normalized likelihood ratio $\mathcal{R} = \mathcal{L}_{\rm S}/(\mathcal{L}_{\rm S} + \mathcal{L}_{\rm BG})$; we discard events with $\mathcal{R} < 0.85$. This selection retains 50% of the signal while rejecting 95% of the continuum background.

To study background from B decays through the $b \to c$ transition and charmless B decays such as $B \to \omega K^*$ and $B \to \omega\rho$, and nonresonant $B \to K^-\pi^+\pi^-\pi^0$ decays, we used MC samples up to 20 times larger than our data sample, assuming the best known branching fraction for each decay [14]. We find negligible backgrounds from these decays in the $M_{\rm bc}$–ΔE signal region ($M_{\rm bc} > 5.27$ GeV/c^2 and $|\Delta E| < 0.1$ GeV).

The signal is extracted using $M_{\rm bc}$ and ΔE as independent variables in an unbinned maximum likelihood fit for events with $|\Delta E| < 0.3$ GeV and $M_{\rm bc} > 5.2$ GeV/c^2. The signal PDF for $M_{\rm bc}$ is a Gaussian and that for ΔE is the parametrization of Ref. [15]. The parameters are determined from MC simulation and calibrated by the decay chain $B^- \to D^0\pi^-$, $D^0 \to K^-\pi^+\pi^0$. The resolutions determined from MC are 3 MeV/c^2 for $M_{\rm bc}$ and 24 MeV for ΔE. The PDF of continuum background for $M_{\rm bc}$ is an empirically determined threshold function [16] that is obtained from the sideband data ($\Delta E > 0.1$ GeV), while the PDF for ΔE is a linear polynomial obtained from the data ($M_{\rm bc} > 5.27$ GeV/c^2) before the $\mathcal{R}$ cut. PDFs for other background sources are included: charmless B decays that survive the selection criteria and signal events with charged kaons misidentified as pions or vice versa. (In the last case, the PDFs have the same shape as the

TABLE I. The signal yields, statistical significances (Σ), efficiencies (ϵ), branching fractions ($\mathcal{B}$), and the 90% confidence level upper limit (UL) of the branching fraction for the $\omega\pi^-$ mode are listed. The efficiencies include the ω decay branching fraction.

	Signal yield	Σ	ϵ (%)	$\mathcal{B}$ ($\times 10^{-6}$)	UL ($\times 10^{-6}$)
ωK^-	$18.9^{+5.4}_{-4.7} \pm 0.6$	$6.0\,\sigma$	6.0	$9.2^{+2.6}_{-2.3} \pm 1.0$	$\cdots$
$\omega\pi^-$	$10.4^{+4.7+0.4}_{-4.3-0.6}$	$3.3\,\sigma$	7.7	$4.2^{+2.0}_{-1.8} \pm 0.5$	8.1

signal except that the central value of ΔE is shifted by 45 MeV.)

The signal yields from the maximum likelihood fit are summarized in Table I. The M_{bc} and ΔE distributions of candidate events and the best fit curves are shown in Fig. 2. The signal yields are $18.9^{+5.4}_{-4.7}$ and $10.4^{+4.7}_{-4.3}$ events for the ωK^- and $\omega\pi^-$ modes, respectively. The expected reflection due to π-K misidentification is 0.7 ± 0.3 (2.0 ± 0.6) events for the ωK^- ($\omega\pi^-$) mode; the fit gives 0.0 ± 2.4 (0.0 ± 3.9) events.

The statistical significance quoted in Table I is defined as $\sqrt{-2\ln[\mathcal{L}(0)/\mathcal{L}_{max}]}$, where $\mathcal{L}_{\rm max}$ is the maximized likelihood at the nominal signal yield and $\mathcal{L}(0)$ is the likelihood with the signal yield fixed at zero. We observe 18.9 signal events for $B^- \to \omega K^-$ with $6.0\,\sigma$ significance and find $10.4\omega\pi^-$ events with $3.3\,\sigma$ significance. Since the latter has less than $4\,\sigma$ significance, we use the 90% confidence level upper limit ($N_S^{\rm UL}$) of 17.3 events on $B^- \to \omega\pi^-$ yield, determined by integrating the likelihood as a function of the number of signal events to 90% of its total area.

We study the systematic error associated with the fit by varying the parameters in the fitting functions by 1σ from their nominal values. The change in the signal yield from each variation is added in quadrature to obtain an overall systematic error associated with the fit. The systematic errors in the detection efficiencies of the ω meson and the high-momentum K^- and π^- mesons are 8.5% and 2.2%, respectively, which are determined from detailed studies of charged particle tracking, π^0 detection, and particle identification. A 5% systematic uncertainty is assigned to the continuum suppression cut, which is obtained by applying a similar procedure to data and MC samples of $B^- \to D^{*0}\pi^-$ events. The combined uncertainty of the efficiency is 10.1%.

The branching fractions in Table I are calculated assuming equal numbers of B^+B^- and $B^0\overline{B}^0$ pairs in our data sample. The uncertainty in the number of $B\overline{B}$ events, 1%, is taken into account and included in the systematic error for the branching fraction. The upper limit of the branching fraction of $\omega\pi^-$ decay is calculated after increasing $N_S^{\rm UL}$ and reducing the efficiency by their respective systematic error.

Our branching fraction result for $B^- \to \omega K^-$ is larger than that for $B^- \to \omega\pi^-$. As a consistency check, we also performed the analysis without KID information. Figure 3 shows the ΔE distribution and a scatter plot of the KID likelihood ratio versus ΔE for the ωh^- candidates. In these plots, we use the π^- mass for the high-momentum hadron track. This causes a -45 MeV difference between the peak positions of ωK^- and $\omega\pi^-$ signals. The ΔE distribution is fitted with ωK^- and $\omega\pi^-$ signals, continuum background, and charmless background components. The signal yields are 17.1 ± 7.7 and 12.1 ± 7.0 events for ωK^- and $\omega\pi^-$, respectively, and are consistent with the

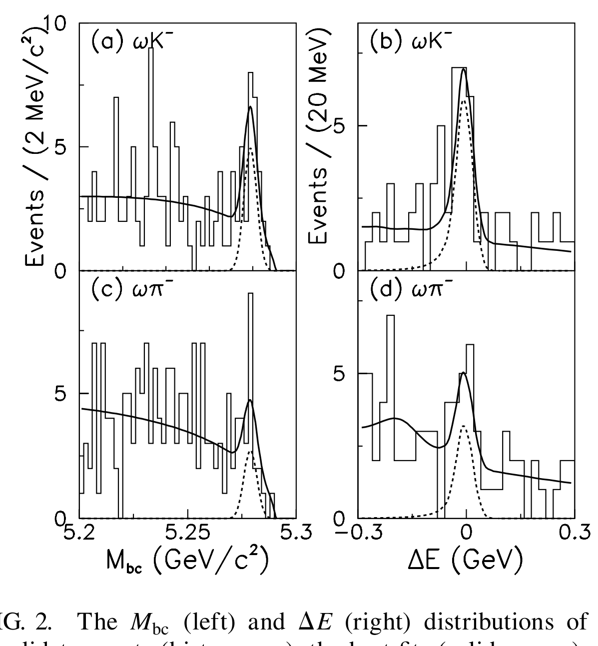

FIG. 2. The M_{bc} (left) and ΔE (right) distributions of the candidate events (histograms), the best fits (solid curves), and signal components (dashed curves).

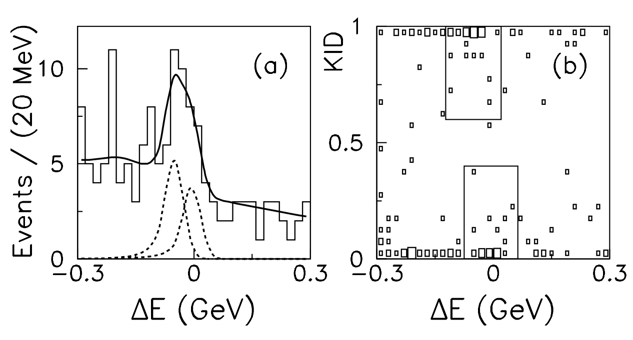

FIG. 3. The (a) ΔE distribution and (b) scatter plot of KID likelihood ratio versus ΔE for the ωh^- mode. The solid curve shows the fit result with the signal components shown by dashed curves.

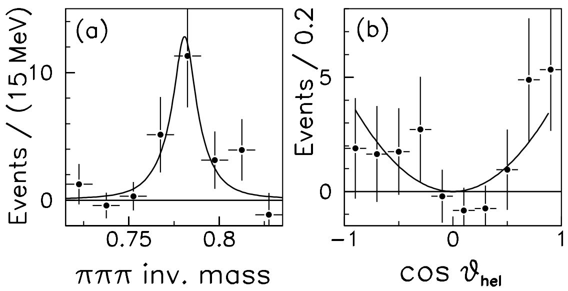

FIG. 4. The $B^- \to \omega K^-$ signal yield in bins of (a) $\pi^+\pi^-\pi^0$ invariant mass and (b) cosine of the ω helicity angle. The solid curve shows the fit result.

results using the KID for K/π separation. The scatter plot in Fig. 3(b) shows the distribution of events in KID versus ΔE. The large rectangles, which cover the $\pm 3\sigma$ signal regions in ΔE and high or low kaon probability, contain enhancements at the appropriate places for both modes.

We also examine the properties of the ω candidates to confirm the $B^- \to \omega K^-$ signal. The $B^- \to \omega K^-$ signal yield in $\pi^+\pi^-\pi^0$ invariant mass bins is shown in Fig. 4(a). A clear signal at the ω mass is seen. The fitted number of ω mesons is 18.0 ± 5.0 which is consistent with the ωK^- signal yield. Figure 4(b) shows the $B^- \to \omega K^-$ signal yield in $\cos\theta_{\rm hel}$ bins. The requirement on the likelihood ratio has been applied without including the helicity angle variable. The distribution is consistent with the expected $\cos^2\theta_{\rm hel}$ distribution.

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

$$\mathcal{A}_{CP} = \frac{N(\omega K^-) - N(\omega K^+)}{N(\omega K^-) + N(\omega K^+)}.$$

An application of the same event extraction and fitting procedure to the B^- and B^+ candidates separately yields 7.3 ± 3.5 and 11.2 ± 3.7 events for ωK^- and ωK^+, respectively, and an asymmetry value $\mathcal{A}_{CP} = -0.21 \pm 0.28 \pm 0.03$. The systematic error includes the uncertainty associated with the fit procedure as well as a contribution of 1% due to detector bias in reconstruction of positive and negative high-momentum kaon tracks. The 90% confidence level interval $-0.70 < \mathcal{A}_{CP} < 0.28$ is obtained by assuming a Gaussian statistical error convolved with the systematic error.

Our combined branching fraction of $(13.4^{+3.3}_{-2.9} \pm 1.1) \times 10^{-6}$ for $B^- \to \omega h^-$ ($h = \pi$ or K) agrees with CLEO's number, $(14.3^{+3.6}_{-3.2} \pm 2.0) \times 10^{-6}$ [6], although the individual branching fractions are not totally consistent. Our large $B^- \to \omega K^-$ branching fraction also disagrees with the upper limit of 4×10^{-6} reported by the BABAR collaboration [7], although our $B^- \to \omega\pi^-$ result is not in conflict. We note that BABAR's combined branching fraction for $B^- \to \omega h^-$ ($h = \pi$ or K) is low compared to CLEO and our result.

The large $B^- \to \omega K^-$ branching fraction and relatively low $B^- \to \omega\pi^-$ rate cannot be easily accounted for either by generalized factorization [2] with $N_c \simeq 2$–3 or by calculations based on pQCD [3,4]. To accommodate the large $B^- \to \omega K^-$ branching fraction that we observe, it appears that N_c has to deviate significantly from 3 [17], indicating the presence of large nonfactorizable effects.

In summary, using 31.9×10^6 $B\overline{B}$ pairs collected with the Belle detector, we report the first observation of the $B^- \to \omega K^-$ decay with branching fraction $\mathcal{B}(B^- \to \omega K^-) = (90.2^{+2.6}_{-2.3} \pm 1.0) \times 10^{-6}$; the statistical significance of the above signal is 6.0σ. We also measure $\mathcal{B}(B^- \to \omega\pi^-) = (4.2^{+2.0}_{-1.8} \pm 0.5) \times 10^{-6}$, with a statistical significance of 3.3σ. The partial rate asymmetry for $B^\pm \to \omega K^\pm$ decays is found to be $\mathcal{A}_{CP} = -0.21 \pm 0.28 \pm 0.03$, corresponding to a 90% confidence level interval of $-0.70 < \mathcal{A}_{CP} < 0.28$.

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