Study of *CP* Violating Effects in Time Dependent $B^0(\bar{B}^0) \to D^{(*)\mp}\pi^\pm$ Decays

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We report measurements of time dependent decay rates for $B^0(\bar{B}^0) \to D^{(*)\mp}\pi^\pm$ decays and extraction of CP violation parameters containing ϕ_3. Using fully reconstructed $D^{(*)}\pi$ events from a 140 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance, we obtain the CP violation parameters for $D^*\pi$ and $D\pi$ decays, $2R_{D^{(*)}\pi}\sin(2\phi_1 + \phi_3 \pm \delta_{D^{(*)}\pi})$, where $R_{D^{(*)}\pi}$ is the ratio of the magnitudes of the doubly Cabibbo-suppressed and Cabibbo-favored amplitudes, and $\delta_{D^{(*)}\pi}$ is the strong phase difference between them. Under the assumption of $\delta_{D^{(*)}\pi}$ being close to either 0° or 180°, we obtain $|2R_{D^*\pi}\sin(2\phi_1 + \phi_3)| = 0.060 \pm 0.040(\text{stat}) \pm 0.019(\text{syst})$ and $|2R_{D\pi}\sin(2\phi_1 + \phi_3)| = 0.061 \pm 0.037(\text{stat}) \pm 0.018(\text{syst})$.

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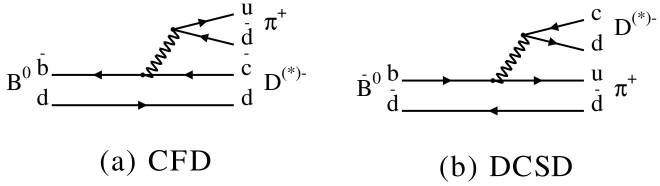
The good agreement between direct measurements of $\sin 2\phi_1$ [1,2] and the outcome of global fits to the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix elements [3] strongly supports the standard model explanation of CP violation. To determine whether it is the complete description or whether additional factors come into play, further measurements of other CKM parameters are required. Among these parameters, ϕ_3 is of particular importance. The measurements of time-dependent decay rates of $B^0(\bar{B}^0) \to D^{(*)\mp}\pi^\pm$ provide a theoretically clean method for extracting $\sin(2\phi_1 + \phi_3)$, since loop diagrams do not contribute to these decays [4,5].

There are two ways for a state that is initially B^0 to be found as $D^{(*)-}\pi^+$ at a later time t. It can occur either directly through a Cabibbo-favored decay (CFD) or through mixing followed by doubly Cabibbo-suppressed decay (DCSD), as shown in Fig. 1. Interference of the two processes introduces the term containing ϕ_3 to the time dependent decay rates, which are given by [6,7]

$$\begin{aligned}
P(B^0 \to D^{(*)+}\pi^-) &= c[1 - \cos(\Delta m t) - 2\,\mathrm{Im}(\bar{\lambda})\sin(\Delta m t)],\\
P(B^0 \to D^{(*)-}\pi^+) &= c[1 + \cos(\Delta m t) + 2\,\mathrm{Im}(\lambda)\sin(\Delta m t)],\\
P(\bar{B}^0 \to D^{(*)+}\pi^-) &= c[1 + \cos(\Delta m t) + 2\,\mathrm{Im}(\bar{\lambda})\sin(\Delta m t)],\\
P(\bar{B}^0 \to D^{(*)-}\pi^+) &= c[1 - \cos(\Delta m t) - 2\,\mathrm{Im}(\lambda)\sin(\Delta m t)],
\end{aligned} \tag{1}$$

where $c = (e^{-t/\tau_{B^0}})/2\tau_{B^0}$ with τ_{B^0} denoting the lifetime of the neutral B meson and Δm is the B^0-$\bar{B}^0$ mixing parameter. The λ and $\bar{\lambda}$ are defined as $\lambda = (q/p)(\mathcal{A}(\bar{B}^0 \to D^{(*)-}\pi^+)/\mathcal{A}(B^0 \to D^{(*)-}\pi^+))$ and $\bar{\lambda} = (p/q)(\mathcal{A}(B^0 \to D^{(*)+}\pi^-)/\mathcal{A}(\bar{B}^0 \to D^{(*)+}\pi^-))$, where p and q relate the mass eigenstates to the flavor eigenstates in the neutral B meson system [6]. Their imaginary parts lead to CP violating terms $\mathrm{Im}(\lambda) = -(-1)^L R\sin(2\phi_1 + \phi_3 - \delta)$ and $\mathrm{Im}(\bar{\lambda}) = (-1)^L R\sin(2\phi_1 + \phi_3 + \delta)$, where R and δ are the ratio of the magnitudes and the strong phase difference of the DCSD and CFD amplitudes, respectively (here the magnitudes of both the CFD and DCSD amplitudes are assumed to be the same for B^0 and $\bar{B}^0$ decays), and L is the angular momentum of the final state (1 for $D^*\pi$ and 0 for $D\pi$). R and δ are not necessarily the same for $D^*\pi$ and $D\pi$ final states, and are denoted with subscripts, $D^*\pi$ and $D\pi$, in what follows.

This study uses a 140 fb^{-1} data sample, which contains 152×10^6 $B\bar{B}$ events, collected with the Belle detector [8] at the KEKB collider [9]. The selection of hadronic events is described elsewhere [10].



(a) CFD (b) DCSD

FIG. 1. Contributions to $B^0 \to D^{(*)-}\pi^+$ can come either (a) from CFD or (b) from mixing followed by DCSD.

For the $\bar{B}^0 \to D^{*+}\pi^-$ event selection, we use the decay chain $D^{*+} \to D^0\pi^+$, and $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, or $K^-\pi^+\pi^+\pi^-$ (charge conjugate modes are implied throughout this Letter). For the $\bar{B}^0 \to D^+\pi^-$ event selection, we use $D^+ \to K^-\pi^+\pi^+$ decays. Charged tracks except the slow π^+ in the $D^{*+} \to D^0\pi^+$ decay are required to have a minimum of one hit (two hits) in the r-ϕ (z) plane of the vertex detector in order to allow precise production point determination. To separate kaons from pions, we form a likelihood for each track, $\mathcal{L}_{K(\pi)}$. The kaon likelihood ratio, $P(K/\pi) = \mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$, has values between 0 (likely to be a pion) and 1 (likely to be a kaon). We require charged kaons to satisfy $P(K/\pi) > 0.3$. No such requirement is imposed to select charged pions coming from D decays.

For D^0 selection, the invariant mass of the daughter particles is required to be within ± 16.5, ± 24.0, and ± 13.5 MeV$/c^2$ of the nominal D^0 mass, for $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^+\pi^-$ modes, respectively. These intervals correspond to $\pm 3\sigma$, where σ is the Monte Carlo determined invariant mass resolution. For the D^+, the invariant mass is required to be within ± 12.5 MeV$/c^2$ of the nominal D^+ mass. For the $D^0 \to K^-\pi^+\pi^0$ reconstruction, we further require the π^0 momentum to be greater than 200 MeV$/c$ in the $\Upsilon(4S)$ rest frame. We use a mass- and vertex-constrained fit for D^0 and a vertex-constrained fit for D^+.

The D^{*+} is reconstructed by combining D^0 candidates with a slow π^+. Here, slow pions are required to have momentum less than 300 MeV$/c$ in the $\Upsilon(4S)$ rest frame. The D^* candidates are required to have a mass difference $\Delta M \equiv M_{D^0\pi} - M_{D^0}$ within ± 7, ± 2, or ± 4 MeV$/c^2$ of the nominal value, for the $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^+\pi^-$ modes, respectively.

We reconstruct B candidates by combining the $D^{(*)+}$ candidate with a π^- candidate satisfying $P(K/\pi) < 0.8$. We identify B decays based on requirements on the energy difference $\Delta E \equiv \sum_i E_i - E_{\rm beam}$ and the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{E_{\rm beam}^2 - (\sum_i \vec{p}_i)^2}$, where $E_{\rm beam}$ is the beam energy, $\vec{p}_i$ and E_i are the momenta and energies of the daughters of the reconstructed B meson candidate, all in the $\Upsilon(4S)$ rest frame. If more than one B candidate is found in the same event, we select the one with the best D vertex quality. We define a signal region in the ΔE-$M_{\rm bc}$ plane of $5.27 < M_{\rm bc} < 5.29$ GeV$/c^2$ and $|\Delta E| < 0.045$ GeV, corresponding to about $\pm 3\sigma$ of both quantities. For the determination of background parameters, we use events in a sideband region defined by $M_{\rm bc} > 5.2$ GeV$/c^2$ and $-0.14 < \Delta E < 0.20$ GeV, excluding the signal region.

Charged leptons, pions, and kaons that are not associated with the reconstructed $D^{(*)}\pi$ decays are used to identify the flavor of the accompanying B meson. The algorithm [1] leads to two parameters, q and r, where $q = +1$ indicates $\bar{b}$ hence B^0 and $q = -1$ indicates b hence $\bar{B}^0$. The parameter r is an event-by-event dilution factor ranging from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. More than 99.5% of the events are assigned nonzero values of r.

The decay vertices of the $B \to D^{(*)}\pi$ are fitted using the momentum vectors of the D and π (except the slow π from D^* decay) and a requirement that they are consistent with the interaction region profile. For the decay vertices of the tagging B meson, the remaining well reconstructed tracks in the event are used. Tracks that are consistent with K_S^0 decay are rejected. The proper-time difference between the fully reconstructed and the associated B decays is calculated as $\Delta t = (z_{\rm rec} - z_{\rm tag})/c\beta\gamma$, where $z_{\rm rec}$ and $z_{\rm tag}$ are the z coordinates of the two B decay vertices and $\beta\gamma = 0.425$ is the Lorentz boost factor at KEKB. After application of the event selection criteria and the requirement that both B's have well defined vertices and $|\Delta t| < 70$ ps ($\sim 45\tau_{B^0}$), 7763 and 9351 events remain as the $D^*\pi$ and $D\pi$ candidates, respectively. The signal fractions of the samples, which vary for different r bins, are 96% for $D^*\pi$ and 91% for $D\pi$.

Unbinned maximum likelihood fits to the four time dependent decay rates are performed to extract Im(λ) and Im($\bar{\lambda}$). We minimize $-2\sum_i \ln L_i$ where the likelihood for the ith event is given by

$$L_i = (1 - f_{\rm ol})[f_{\rm sig}P_{\rm sig} \otimes R_{\rm sig} + (1 - f_{\rm sig})P_{\rm bkg} \otimes R_{\rm bkg}] + f_{\rm ol}P_{\rm ol}. \tag{2}$$

The signal fraction $f_{\rm sig}$ is determined from the (ΔE, $M_{\rm bc}$) value of each event. The signal distribution is the product of the sum of two Gaussians in ΔE and a Gaussian in $M_{\rm bc}$; that for the background is the product of a first order polynomial in ΔE and an ARGUS function [11] in $M_{\rm bc}$.

The Δt distribution is modeled by a core distribution convolved with resolutions. A small number of events have poorly reconstructed vertices resulting in a very broad Δt distribution. We account for the contributions from these "outliers" by adding a Gaussian component $P_{\rm ol}$ with a width and fraction determined from the B lifetime analysis [12]. The Δt resolution, denoted by $R_{\rm sig}$ and $R_{\rm bkg}$ for the signal and background, is determined on an event-by-event basis, using the estimated uncertainties on the z vertex positions [13].

The signal Δt distribution is given by

$$P_{\rm sig}(D^{(*)\pm}\pi^\mp) = (1 - w_-)P(B^0 \to D^{(*)\pm}\pi^\mp) + w_+P(\bar{B}^0 \to D^{(*)\pm}\pi^\mp) \tag{3}$$

for the $q = -1$ sample and

$$P_{\rm sig}(D^{(*)\pm}\pi^\mp) = (1 - w_+)P(\bar{B}^0 \to D^{(*)\pm}\pi^\mp) + w_-P(B^0 \to D^{(*)\pm}\pi^\mp) \tag{4}$$

for the $q = +1$ sample. Here w_- and w_+ are wrong tag fractions for the $q = -1$ and $q = +1$ samples, respectively. P's are given by Eq. (1) with t and c replaced by Δt and $(e^{-|\Delta t|/\tau_{B^0}})/4\tau_{B^0}$, respectively. The background Δt distribution is parametrized as a sum of a δ-function component and an exponential component with an experimentally determined lifetime.

While the tagging side should have no asymmetry if the flavor is tagged by primary leptons, it is possible to introduce a small asymmetry when daughter particles of hadronic decays such as $D^{(*)}\pi$ are used for the flavor tagging, due to the same CP violating effect, which is the subject of this Letter [14]. This effect is taken into account by replacing the coefficients of $\sin(\Delta m t)$ in Eqs. (1) by $\mathrm{Im}(\bar{\lambda}) - \mathrm{Im}(\bar{\lambda}')$, $\mathrm{Im}(\lambda) - \mathrm{Im}(\bar{\lambda}')$, $\mathrm{Im}(\bar{\lambda}) - \mathrm{Im}(\lambda')$, and $\mathrm{Im}(\lambda) - \mathrm{Im}(\lambda')$, respectively. Here the $\mathrm{Im}(\lambda')$ and $\mathrm{Im}(\bar{\lambda}')$ represent the CP violating effect due to the presence of $B^0 \to \bar{D}X$ and $B^0 \to DX$ amplitudes in the flavor tagging side. Note that unlike the $\mathrm{Im}(\lambda)$ and $\mathrm{Im}(\bar{\lambda})$, which are rigorously defined in terms of $B^0 \to D^{(*)\mp}\pi^{\pm}$ and $\bar{B}^0 \to D^{(*)\pm}\pi^{\mp}$ amplitudes, $\mathrm{Im}(\lambda')$ and $\mathrm{Im}(\bar{\lambda}')$ are effective quantities that include effects of the fraction of $B \to DX$ components in the tagging B decays and all experimental effects of subsequent behavior of D mesons. Therefore, these quantities must be determined experimentally.

The values of $\mathrm{Im}(\lambda')$ and $\mathrm{Im}(\bar{\lambda}')$ are determined in each of six r bins by fitting the Δt distributions of a $D^* l\nu$ control sample [15] using the signal distributions of Eqs. (3) and (4) and setting $\mathrm{Im}(\lambda)$ and $\mathrm{Im}(\bar{\lambda})$ to zero. Since the $D^* l\nu$ final states have specific flavor, any observable asymmetry must originate from the tagging side. The results for the combined r bins are $2\,\mathrm{Im}(\lambda') = 0.038 \pm 0.014(\mathrm{stat}) \pm 0.005(\mathrm{syst})$ and $2\,\mathrm{Im}(\bar{\lambda}') = 0.002 \pm 0.014(\mathrm{stat}) \pm 0.009(\mathrm{syst})$.

The procedures for Δt determination and flavor tagging are tested by extracting τ_{B^0} and Δm. When all four signal categories in Eq. (1) are combined, the signal Δt distribution reduces to an exponential lifetime distribution. We obtain $\tau_{B^0} = 1.583 \pm 0.029$ ps (1.575 ± 0.032 ps) for the $D^*\pi$ ($D\pi$) samples, in good agreement with the world average (1.542 ± 0.016 ps) [3]. Combining the two CFD-dominant modes and the two mixing-dominant modes and ignoring the CP violating terms, the asymmetry behaves as $\cos(\Delta m \Delta t)$. We obtain $\Delta m = 0.490 \pm 0.015\ \mathrm{ps}^{-1}$ ($0.483 \pm 0.014\ \mathrm{ps}^{-1}$) for the $D^*\pi$ ($D\pi$) samples, also in good agreement with the world average ($0.489 \pm 0.008\ \mathrm{ps}^{-1}$) [3]. The same fits also provide wrong tag fractions w_- and w_+ in each r bin for both $D^*\pi$ and $D\pi$ data samples. The errors of these results are statistical only.

We then perform fits to determine the $\mathrm{Im}(\lambda)$ and $\mathrm{Im}(\bar{\lambda})$ by fixing τ_{B^0} and Δm to the world average values and using w_-, w_+, $\mathrm{Im}(\lambda')$, and $\mathrm{Im}(\bar{\lambda}')$ for each r bin, as obtained from the above fits. The results are $2\,\mathrm{Im}(\lambda_{D^*\pi}) = 0.011 \pm 0.057$, $2\,\mathrm{Im}(\bar{\lambda}_{D^*\pi}) = -0.109 \pm 0.057$, $2\,\mathrm{Im}(\lambda_{D\pi}) = -0.037 \pm 0.052$, and $2\,\mathrm{Im}(\bar{\lambda}_{D\pi}) = 0.087 \pm 0.054$. The errors are statistical only. The Δt distributions for the subsamples having the best quality flavor tagging ($0.875 < r \leq 1.000$) are shown in Fig. 2 for the $D^*\pi$ and in Fig. 3 for the $D\pi$ samples, respectively.

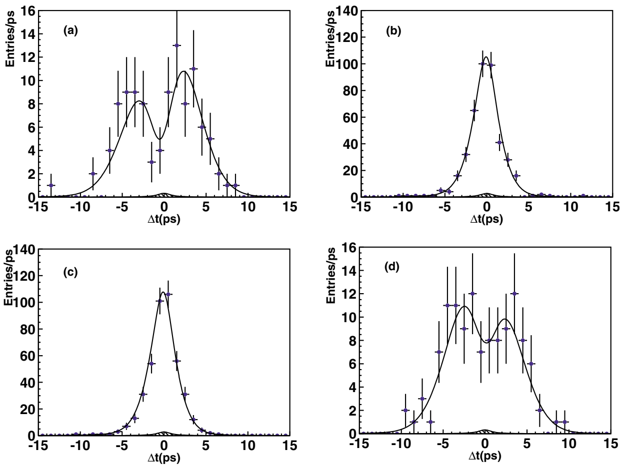


FIG. 2 (color online). Δt distributions for the $D^*\pi$ data in the $0.875 < r \leq 1.000$ flavor tagging quality bin. (a) $B^0 \to D^{*+}\pi^-$, (b) $B^0 \to D^{*-}\pi^+$, (c) $\bar{B}^0 \to D^{*+}\pi^-$, (d) $\bar{B}^0 \to D^{*-}\pi^+$. Curves show the fit results with the entire event sample, hatched regions indicate the backgrounds.

The systematic errors come from (i) the uncertainties of parameters that are constrained in the fit, including Δt resolution parameters, background parameters, wrong tag fractions, and physics parameters; (ii) uncertainties of the tagging side asymmetries; (iii) fit biases induced by the vertexing and other unknown factors. For item (i), we repeat the fits varying each parameter value by $\pm 1\sigma$. To estimate item (ii), we repeat the fits by varying $\mathrm{Im}(\lambda')$ and $\mathrm{Im}(\bar{\lambda}')$ by their errors. Errors are not explicitly assigned for item (iii), since they are included in the errors of $\mathrm{Im}(\lambda')$ and $\mathrm{Im}(\bar{\lambda}')$ from the $D^* l\nu$ control sample fit [item (ii)]. Table I summarizes the systematic errors.

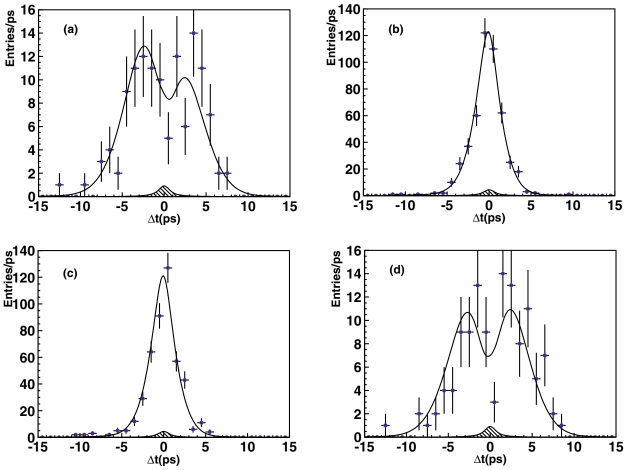


FIG. 3 (color online). Δt distributions for the $D\pi$ events in the $0.875 < r \leq 1.000$ flavor tagging quality bin. (a) $B^0 \to D^+\pi^-$, (b) $B^0 \to D^-\pi^+$, (c) $\bar{B}^0 \to D^+\pi^-$, (d) $\bar{B}^0 \to D^-\pi^+$. Curves show the fit results with the entire event sample; hatched regions indicate the backgrounds.

TABLE I. Systematic errors in the $2R\sin(2\phi_1 + \phi_3 \pm \delta)$ extractions.

Sources	$D^*\pi$	$D\pi$
Signal Δt resolution	0.014	0.013
Background Δt shape	0.001	0.003
Background fraction	0.002	0.001
Wrong tag fraction	0.006	0.006
Vertexing	0.005	0.005
Physics parameters (Δm, τ_{B^0})	0.001	0.002
Tagging side asymmetry	0.009	0.009
Combined	0.019	0.018

We obtain

$$\begin{aligned} 2R_{D^*\pi}\sin(2\phi_1 + \phi_3 + \delta_{D^*\pi}) &= 0.109 \pm 0.057 \pm 0.019, \\ 2R_{D^*\pi}\sin(2\phi_1 + \phi_3 - \delta_{D^*\pi}) &= 0.011 \pm 0.057 \pm 0.019, \\ 2R_{D\pi}\sin(2\phi_1 + \phi_3 + \delta_{D\pi}) &= 0.087 \pm 0.054 \pm 0.018, \\ 2R_{D\pi}\sin(2\phi_1 + \phi_3 - \delta_{D\pi}) &= 0.037 \pm 0.052 \pm 0.018. \end{aligned} \tag{5}$$

The first and second errors are statistical and systematic. At present, the statistical errors are too large to allow any meaningful conclusion to be drawn. However, it is interesting to consider how the four results can be combined using knowledge of R and δ to improve the precision of $\sin(2\phi_1 + \phi_3)$. Several methods have been proposed to measure R [4]. However, the present errors are too large to conclude that the two R values are equal [16]. On the other hand, there are solid theoretical grounds for assuming $\delta_{D^*\pi}$ and $\delta_{D\pi}$ to be very small and therefore equal [17]. However, some argue that there is an ambiguity of 180° between $\delta_{D^*\pi}$ and $\delta_{D\pi}$ [7]. Assuming $\delta_{D^{(*)}\pi}$ is close to either 0° or 180°, we obtain $|2R_{D^*\pi}\sin(2\phi_1 + \phi_3)| = 0.060 \pm 0.040(\mathrm{stat}) \pm 0.019(\mathrm{syst})$ and $|2R_{D\pi}\sin(2\phi_1 + \phi_3)| = 0.061 \pm 0.037(\mathrm{stat}) \pm 0.018(\mathrm{syst})$. Recently, the *BABAR* Collaboration presented a lower limit on $|\sin(2\phi_1 + \phi_3)|$ [5] from similar analyses and measurements related to $R_{D^{(*)}\pi}$. Since all these input measurements have large errors at present, we defer such analysis until more precise values of $R_{D^{(*)}\pi}$ are available, and the extraction of $\delta_{D^{(*)}\pi}$ is feasible from the data.

In summary, we measure the time dependent CP violation parameters $2R\sin(2\phi_1 + \phi_3 \pm \delta)$ for the $B^0(\bar{B}^0) \to D^{(*)\mp}\pi^\pm$ decays using 152×10^6 $B\bar{B}$ events. Under the assumption of $\delta_{D^{(*)}\pi}$ being close to either 0° or 180°, we obtain $|2R_{D^*\pi}\sin(2\phi_1 + \phi_3)| = 0.060 \pm 0.040(\mathrm{stat}) \pm 0.019(\mathrm{syst})$ and $|2R_{D\pi}\sin(2\phi_1 + \phi_3)| = 0.061 \pm 0.037(\mathrm{stat}) \pm 0.018(\mathrm{syst})$.

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