Search for $B^+ \rightarrow D^{**}\pi^0$ decay

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We report on a search for the doubly Cabibbo suppressed decay $B^+ \rightarrow D^{*+}\pi^0$, based on a data sample of $657 \times 10^6 \overline{B}B$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. We find no significant signal and set an upper limit of $\mathcal{B}(B^+ \rightarrow D^{*+}\pi^0) < 3.6 \times 10^{-6}$ at the 90% confidence level. This limit can be used to constrain the ratio between suppressed and favored $B \rightarrow D^*\pi$ decay amplitudes, $r < 0.051$, at the 90% confidence level.

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In the Standard Model, $CP$ violation arises from a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix $^{[1, 2]}$. Precise measurements of CKM matrix parameters are therefore of fundamental importance for the description of the weak interaction of quarks and the investigation for the new sources of $CP$ violation. Measurements of the time-dependent decay rates of $B^0(\overline{B}^0) \rightarrow D^{*+}\pi^\pm$ provide a theoretically clean method for extracting $\sin(2\phi_3) \, ^3$, where $\phi_1$ and $\phi_3$ are the interior angles of the CKM triangle $^3$. The $CP$ violation parameters $S^\pm$ are given by $^3$

$$S^\pm = \frac{2(1)^L r \sin(2\phi_1 + \phi_3 \pm \delta)}{1 + r^2}, \quad (1)$$

where $r$ is the ratio of the amplitudes of the doubly Cabibbo suppressed decay (DCSD), $B^0 \rightarrow D^{*+}\pi^-$ to the Cabibbo favored decay (CFD), $B^0 \rightarrow D^{*-}\pi^+$ (Fig. 1), $L$ denotes the angular momentum of the final state, and $\delta$ is the strong phase difference between DCSD and CFD. It is difficult to determine $r$ from $B^0$ decays because the DCSD amplitude is small compared to the contribution from mixing followed by CFD, $B^0 \rightarrow \overline{B}^0 \rightarrow D^{*+}\pi^-$. Using available branching fraction measurements, $r$ can be expressed as

$$r = \tan \theta_c \frac{f_{D^*}}{f_{D^+}} \frac{|\mathcal{B}(B^0 \rightarrow D^{*+}\pi^-)|}{|\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+)|}, \quad (2)$$

where $\theta_c$ is the Cabibbo angle, and the decay constants $f_{D^*}$ and $f_{D^+}$ are available from lattice QCD calculations. However, the assumption of SU(3) symmetry and additional $W$-exchange contributions result in an uncertainty of about 30% on $r$. In order to avoid this uncertainty, one can instead use the isospin relation,

$$r = \sqrt{\frac{\tau_{B^0}}{\tau_{B^+}} \frac{2|\mathcal{B}(B^+ \rightarrow D^{*+}\pi^0)|}{|\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+)|}}, \quad (3)$$

where $\tau_{B^+}/\tau_{B^0} = 1.071 \pm 0.009$ and $\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+) = (2.76 \pm 0.21) \times 10^{-3} \, ^3$. We naively estimate $\mathcal{B}(B^+ \rightarrow D^{*+}\pi^0) = 5.9 \times 10^{-7}$, taking into account the $r$ factor of 0.02 calculated from Eq. (2) $^3$. The previous search gives an upper limit of $\mathcal{B}(B^+ \rightarrow D^{*+}\pi^0) < 1.7 \times 10^{-4}$ at the 90% confidence level $^8$.

![Feynman Tree Diagrams](image)

**FIG. 1**: Feynman tree diagrams for (a) CFD $B^0 \rightarrow D^{*-}\pi^+$ with the CKM coupling $V_{ud}V_{ub}$, and (b) DCSD $B^{*+}(0) \rightarrow D^{*+}\pi^0(-)$ with the coupling $V_{cb}V_{ub}$.

In this paper, we report on a search for $B^+ \rightarrow D^{*+}\pi^0$ based on a data sample of 605 fb$^{-1}$ corresponding to $(657 \pm 9) \times 10^6 \overline{B}B$ events, collected with the Belle detector $^3$ at the KEKB asymmetric-energy $e^+e^-$ collider $^{10}$ operating at the T$(4S)$ resonance. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a magnetic field of 1.5 T. An iron flux-return located outside of the coil is instrumented to detect $K_S^0$ mesons and to identify muons.

To search for $B^+ \rightarrow D^{*+}\pi^0$, we reconstruct $D^{*+}$ candidates by pairing a low momentum charged pion ($\pi^\pm_{\text{slow}}$) and a $D^0$, which is reconstructed through its decays to $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, and $K_S^0\pi^+\pi^-$. Inclusion of charge conjugate modes is implied throughout this paper.
For charged kaon and pion candidates except pions from $K^0_S$'s, we require tracks to have a distance of closest approach to the interaction point within 5 cm along the z-axis (anti-parallel to the positron beam direction) and within 2 cm in a plane perpendicular to the z-axis. Particle identification (PID) is based on the likelihoods $R(K/\pi) = \mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$, where $\mathcal{L}_K$ ($\mathcal{L}_\pi$) is the likelihood of kaons (pions) derived from the TOF, ACC, and $dE/dx$ measurements in the CDC. The PID selections, which are $R(K/\pi) > 0.3$ ($< 0.3$) for kaons (pions) are applied to all charged particles except pions from $K^0_S$'s. The PID efficiencies are 94% (91%) for kaons (pions), while the probability of misidentifying a pion as a kaon (a kaon as a pion) is 12% (6%).

Neutral pions are formed from photon pairs with an invariant mass between 0.118 GeV/c$^2$ and 0.150 GeV/c$^2$, corresponding to $\pm 3$ standard deviations ($\sigma$). The photon momenta are then recalculated with a $\pi^0$ mass constraint. We require the $\pi^0$ momentum to be greater than 0.2 GeV/c in the center-of-mass system (c.m.s.), and the photon energy to be greater than 0.1 GeV in the laboratory frame.

$K^0_S$ candidates are reconstructed from pion pairs of oppositely-charged tracks with an invariant mass between 0.485 GeV/c$^2$ and 0.510 GeV/c$^2$, corresponding to $\pm 3\sigma$. Each candidate must have a displaced vertex with a flight direction consistent with that of a $K^0_S$ meson originating from the interaction point. Mass- and vertex-constrained fits are applied to obtain the 4-momenta of $K^0_S$ candidates.

For $D^0$ selection, the invariant mass of the daughter particles is required to be within $3\sigma$ from the nominal $D^0$ mass, where $\sigma$ ($\sim 5$ MeV/c$^2$) depends on the decay mode. $D^{*+}$ candidates are required to have a mass difference $\Delta M = M_{D^0} - M_D$ within $3\sigma$ from the nominal mass difference, where $\sigma$ ($\sim 0.5$ MeV/c$^2$) depends on the decay mode. Mass- and vertex-constrained fits are applied to obtain the 4-momenta and $D^{*0}$ candidates.

We reconstruct a $B^0$ candidate from a $D^{*+}$ and a $D^{*0}$ candidate. We identify $B$ decays based on requirements on the energy difference $\Delta E \equiv \sum_i E_i - E_{\text{beam}}$ and the beam-energy constrained mass $M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - \sum_i p_i^2}$, where $E_{\text{beam}}$ is the beam energy, and $E_i$ and $p_i$ are the momenta and energies of the daughters of the reconstructed $B$ meson candidate, all in the c.m.s. We select candidates in a fit region defined as $|\Delta E| < 0.25$ GeV and 5.20 GeV/c$^2 < M_{bc} < 5.29$ GeV/c$^2$. The signal region is defined as $|\Delta E| < 0.1$ GeV and 5.27 GeV/c$^2 < M_{bc} < 5.29$ GeV/c$^2$.

To suppress the background from continuum ($e^+e^- \rightarrow q\bar{q}$, $q = u, d, s, c$) events, we calculate modified Fox-Wolfram moments [11] and combine them into a Fisher discriminant. We calculate a probability density function (PDF) for this discriminant and multiply it by PDFs for $\cos \theta_B$, $\Delta z$, and $\cos \theta_h$, where $\theta_B$ is the polar angle between the $B$ direction and the beam direction in the c.m.s., $\Delta z$ is the displacement along the beam axis between the signal $B$ vertex and that of the other $B$, and $\theta_h$ is the angle between the $\pi^0_{low}$ direction and the opposite of the $B$ momentum in the $D^{*+}$ frame. The PDFs for signal, generic $B$ events and continuum are obtained from GEANT3-based Monte Carlo (MC) simulation. These PDFs are combined into a signal (background) likelihood variable $\mathcal{L}_{\text{sig(bkg)}}$, we then impose requirements on the likelihood ratio $R \equiv \mathcal{L}_{\text{sig}}/(\mathcal{L}_{\text{sig}} + \mathcal{L}_{\text{bkg}})$. Additional background suppression is achieved through the use of a $B$-flavor tagging algorithm [12], which provides a discrete variable indicating the flavor of the tagging $B$ meson and a quality parameter $r_{\text{tag}}$, with continuous values ranging from 0 for no flavor information to unity for unambiguous flavor assignment. The backgrounds from continuum and generic $B$ events are reduced by applying a selection requirement on $R$ for events in each $r_{\text{tag}}$ region that maximizes the value of $N_{\text{sig}}/\sqrt{N_{\text{sig}} + N_{\text{bkg}}}$, where $N_{\text{sig}}$ and $N_{\text{bkg}}$ denote the expected signal and background yields in the signal region, based on MC simulation. This requirement eliminates 99% (94%) of the background from continuum ($B$ decays) in the signal region, while retaining 35% of the signal.

The fraction of events with more than one candidate is 3%. We select the best $D^{*+}\pi^0$ candidate based on the value of $\chi^2_{\text{tot}} = \chi^2_{M(D^0)} + \chi^2_{M(\pi^0)}$, where each $\chi^2$ is defined as the squared ratio of the measured parameter from the expected signal value and the corresponding resolution. The reconstruction efficiency is determined to be 0.56%, using the fitting procedure described below for the signal MC samples. The branching fractions of $D^{*+}$ and $D^0$ are included in the efficiency [3].

After the selection criteria are applied, the dominant background sources in the fit region are the continuum events and $B^0 \rightarrow D^{*+}\rho^-$, while other $B$ decays such as $B^- \rightarrow D^0\rho^-$ and $B^0 \rightarrow D^{**}\pi^0$ have smaller contributions. To obtain the signal yield, we perform an unbinned two-dimensional (2D) extended-maximum-likelihood fit to the $\Delta E-M_{bc}$ distributions in the fit region. The likelihood function consists of the following components: signal, continuum background ($q\bar{q}$), $B^0 \rightarrow D^{*+}\rho^-$, and other $B$ decays.

The likelihood function for the signal is defined separately for each of the four $D^0$ decay modes and unified using the available branching fractions of the $D^0$ subdecays [4], while those for $q\bar{q}$ and backgrounds from $B$ decays are defined as the sum of four $D^0$ decay modes. Each $\Delta E$ and $M_{bc}$ shape for the signal is modeled by the sum of a Gaussian and a bifurcated Gaussian with means and widths fixed to the values obtained from MC simulation. The $\Delta E$ and $M_{bc}$ PDFs for $q\bar{q}$ are modeled by a linear function and an ARGUS function [14], respectively. The backgrounds from $B^0 \rightarrow D^{*+}\rho^-$ and other $B$ decays are modeled by the superposition of Gaussian distributions constructed from unbinned MC events, where the width of each Gaussian represents the smoothing param-
The systematic error components proportional to the signal yield are determined as follows. We estimate the systematic error from the $\mathcal{R}$ requirement by applying the $\mathcal{R}$ requirement to data and MC events using a $B^- \to D^0 \rho^-$ control sample. The systematic error on the $\Delta M$ requirement is estimated by applying the $\Delta M$ requirement to $\bar{B}^0 \to D^{\ast +} \pi^-$ data and $B^+ \to D^{\ast +} \pi^0$ MC samples. The systematic error on the secondary branching fraction is calculated from errors given in Ref. [8]. The systematic error due to the charged-track reconstruction efficiency is estimated to be 1.0% (1.6%) per charged kaon (pion) using partially reconstructed $D^{\ast +}$ events. The systematic error due to $R(K/\pi)$ selection has a relative uncertainty of 0.8% (1.4%) per charged kaon (pion), determined from $D^{\ast +} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ decays. The $\pi^0$ reconstruction is verified by comparing the ratio of $D^0 \to K^- \pi^+$ and $D^0 \to K^- \pi^+ \pi^0$ yields with the MC expectation; an uncertainty of 3.0% per particle is assigned. The $K^0_S$ reconstruction is verified by comparing the ratio of $D^+ \to K^0_S \pi^+$ and $D^+ \to K^- \pi^+ \pi^0$ yields with the MC expectation; an uncertainty of 4.9% is assigned. The systematic error due to the signal MC statistics is 0.5% and the error due to the uncertainty in the total number of $B\bar{B}$ pairs is 1.4%. The systematic error components proportional to the signal yield are summarized in Table I.

The systematic errors on the yield extraction are estimated as follows. We estimate the uncertainty of $|H_0|$ of $B^+ \to D^{\ast +} \rho^-$ by varying $|H_0|$ by $\pm 1\sigma$, where the error of $|H_0|$ is taken from Ref. [10]. Possible $\Delta E$ shifts between data and MC simulation for the $B^0 \to D^{\ast +} \rho^-$ background are evaluated by measuring the $\Delta E$ shift of the $B^- \to D^{\ast 0} \rho^-$ background component using a $B^0 \to D^{\ast 0} \pi^0$ control sample. To obtain the systematic error on the background fraction of other $B$ decays, we vary the normalizations of the individual sources by $\pm 1\sigma$, where the values are taken from Ref. [8]. The normalization of other background components are varied by $\pm 50\%$. The systematic error due to the uncertainty in the shape of the $B$ background PDF is determined by varying the Gaussian smoothing width by factors of two and one half from its nominal value. Uncertainties from the two-dimensional correlation in the signal and the $q\bar{q}$ components are estimated by applying 2D background PDFs to the signal and the $q\bar{q}$ shapes. The effect of a possible bias in the fitting procedure is estimated by a toy MC study. The systematic errors on the yield extraction in the signal region are summarized in Table I.

![Figure 2](image)

**Figure 2:** Projections of the unbinned two-dimensional likelihood fit to data in the region $|\Delta E| < 0.25$ GeV and $5.20$ GeV/$c^2 < M_{bc} < 5.29$ GeV/$c^2$. (a) $\Delta E$ distribution for $5.27$ GeV/$c^2 < M_{bc} < 5.29$ GeV/$c^2$ with a magnified view of $|\Delta E| < 0.07$ GeV in the inset. (b) $M_{bc}$ distribution for $|\Delta E| < 0.1$ GeV. The points with error bars represent the data, while the curves represent the various components from the fit: signal (thick solid line), continuum (dash-dotted line), $B^0 \to D^{\ast +} \rho^-$ decay (dotted line), other $B$ decays (dashed line), and the sum of all components (thin solid line).

### Table I: Systematic errors for $\mathcal{B}(B^+ \to D^{\ast +} \pi^0)$, proportional to the signal yield.

| Source                  | Systematic error (%) |
|-------------------------|-----------------------|
| $\mathcal{R}$ requirement | 3.0                   |
| $\Delta M$ requirement   | 3.3                   |
| Secondary branching fractions | 3.3                  |
| Track finding efficiency | 5.1                   |
| Particle identification  | 4.4                   |
| $\pi^0$ reconstruction   | 4.1                   |
| $K^0_S$ reconstruction   | 0.3                   |
| MC statistics            | 0.5                   |
| Number of $B\bar{B}$ pairs | 1.4               |
| Quadratic sum            | 9.8                   |

We then obtain the branching fraction of $B^+ \to D^{\ast +} \pi^0$ to be $\mathcal{B}(B^+ \to D^{\ast +} \pi^0) = [1.2^{+1.1}_{-0.9}(\text{stat})^{+0.3}_{-0.9}(\text{syst})] \times 10^{-6}$. 

The following parameters are allowed to vary: $q\bar{q}$ PDF parameters and yields of signal, $q\bar{q}$ and $B^0 \to D^{\ast +} \rho^-$ components. The yield of other $B$ decays is fixed to the branching fractions in Ref. [6].

Figure 3 shows the results of the fit to the data in the fit region. The projections of the fitted $B$ signal in $\Delta E (M_{bc})$ in the $M_{bc}$ ($|\Delta E|$) signal region are shown. We obtain $4.5^{+3.4}_{-2.8}$ $B^+ \to D^{\ast +} \pi^0$ signal candidates in the signal region (statistical error only). The significance is $1.4\sigma$, defined by $\sqrt{-2 \text{ln}(L_0/L_{\text{max}})}$ where $L_{\text{max}}$ ($L_0$) is the likelihood value at the maximum (with the signal fixed to zero). The likelihood function is convolved with an asymmetric Gaussian distribution that represents the systematic error.

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The likelihood distribution ($\mathcal{L}$), which is convolved with the systematic error, is used to obtain the upper limit on the branching fraction. We calculate the 90% confidence level (C.L.) upper limit (UL) using the relation $\int_0^{UL} \mathcal{L}dB/\int_0^\infty \mathcal{L}dB = 0.9$ to be

$$B(B^+ \to D^{*+} \pi^0) < 3.6 \times 10^{-6}.$$ (4)

The obtained upper limit is consistent with the naive estimate, $5.9 \times 10^{-7}$ discussed above. This result can be used to obtain an upper limit on the ratio of magnitudes of DCSD and CFD in $D^*\pi$ decay,

$$r < 0.051 \quad (90\% \text{ C.L.}).$$ (5)

To summarize, a search for the doubly Cabibbo suppressed decay $B^+ \to D^{*+} \pi^0$ in a data sample of 605 fb$^{-1}$ yields an upper limit of $B(B^+ \to D^{*+} \pi^0) < 3.6 \times 10^{-6}$ at the 90% confidence level. This limit can be used to constrain the ratio between suppressed and favored $B \to D^*\pi$ decay amplitudes, $r < 0.051$, at the 90% confidence level.

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