PHYSICAL REVIEW D **70,** 111103(R) (2004)

Observation of $B^0 \to D^{*-}(5\pi)^+$, $B^+ \to D^{*-}(4\pi)^{++}$ and $B^+ \to \overline{D}^{*0}(5\pi)^+$

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(Received 1 September 2004; published 22 December 2004)

We report the first observation of a number of decay modes of the B meson, namely $B^0 \to D^{*-}(5\pi)^+$, $B^+ \to D^{*-}(4\pi)^{++}$, and $B^+ \to \overline{D}^{*0}(5\pi)^+$, where $(n\pi)$ implies the combination of n charged pions. The analysis is based on a 140 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at KEKB. We measure $\mathcal{B}[B^0 \to D^{*-}(5\pi)^+] = (4.72 \pm 0.59 \pm 0.71) \times 10^{-3}$, $\mathcal{B}[B^+ \to D^{*-}(4\pi)^{++}] = (2.56 \pm 0.26 \pm 0.33) \times 10^{-3}$, and $\mathcal{B}[B^+ \to \overline{D}^{*0}(5\pi)^+] = (5.67 \pm 0.91 \pm 0.85) \times 10^{-3}$. We also provide improved measurements of the branching fractions for the decay modes $B^0 \to D^{*-}(3\pi)^+$, $B^+ \to \overline{D}^{*0}(3\pi)^+$, and $B^0 \to \overline{D}^{*0}(4\pi)^0$.

DOI: 10.1103/PhysRevD.70.111103 PACS numbers: 13.25.Hw

A large fraction ($\sim 35\%$) of B meson decays is due to decay modes which are still unknown. While a sizable fraction of B's decay into semileptonic final states ($\sim 24\%$) [1], decays into hadronic final states are dominant. At present, however, only half of these final states correspond to measured exclusive hadronic decays.

On average, B mesons decay into a large number of particles: the mean charged particle multiplicity in hadronic B decay is measured to be 5.8 ± 0.1 [2]. Decay products of D mesons make a significant contribution, but B decays to charmed states with a large number of accompanying pions, $B \to \overline{D}^{(*)}(n\pi)$, where the π are charged pions and $n = 3, 4$, have already been observed [3]. The invariant mass distribution of the multipion system, and the resonant decomposition for such decays, are important for the study of factorization [4].

In this paper, we present a study of inclusive $B \to \overline{D}^{*0(-)}(n\pi)$ final states, where $n = 3, 4$, and 5, and measure branching fractions for six decay modes. Inclusion of charge conjugate modes is implied throughout this paper.

The analysis is based on a 140 fb^{-1} data sample at the $\Upsilon(4S)$ resonance (10.58 GeV) and a 16 fb^{-1} data sample 60 MeV below the $\Upsilon(4S)$ peak (referred to as *off-resonance* data), collected by the Belle detector [5] at the asymmetric e^+e^- collider KEKB [6]. The data sample contains $152 \times 10^6 B\overline{B}$ events.

The Belle detector is a general purpose magnetic spectrometer with a 1.5 Tesla magnetic field provided by a superconducting solenoid. Charged particles are measured using a 50 layer Central drift chamber (CDC) and a three layer double sided silicon vertex detector (SVD). Photons are detected in an electromagnetic calorimeter (ECL) consisting of 8736 CsI(Tl) crystals. Exploiting the information acquired from an array of 128 time-of-flight counters (TOF), an array of 1188 silica aerogel Čerenkov threshold counters (ACC) and dE/dx-measurements in the CDC we derive particle identification likelihoods $\mathcal{L}_{\pi/K}$. A kaon candidate is identified by a requirement on the likelihood ratio $\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$ such that the average kaon identification efficiency is ~90% and the pion fake rate is ~9%. Similarly charged pions are selected with an efficiency of ~91% and the kaon fake rate is ~10%. We select charged pions and kaons that originate from the region $|\Delta r| < 0.2$ cm and $|\Delta z| < 4$cm with respect to the run dependent interaction point, where Δr, Δz are the distances of closest approach of π/K tracks to the interaction vertex in the plane perpendicular to the beam axis and along the beam axis, respectively. All tracks compatible with the electron hypothesis ($\sim 0.2\%$ fake rates from pion/kaon) are eliminated. No attempt is made to identify muons, which represent a background of about 2.7% to the pion tracks. Candidate π^0 mesons are identified as a pair of isolated ECL clusters with invariant mass in the window $118 \text{ MeV}/c^2 < M_{\gamma\gamma} < 150 \text{ MeV}/c^2$. The energy of each photon is required to be greater than 30 MeV in the barrel region, defined as $32° < \theta_\gamma < 128°$, and greater than 50 MeV in the endcap regions, defined as $17° < \theta_\gamma \leq 32°$ or $128° < \theta_\gamma \leq 150°$, where θ_γ denotes the polar angle of the photon with respect to the direction opposite to the e^+ beam. A mass constrained fit is applied to obtain the 4-momenta of π^0's.

Beam gas events are rejected using the requirements $|P_z| < 2$ GeV/c and $0.5 < E_{\text{vis}}/\sqrt{s} < 1.25$, in the $\Upsilon(4S)$ rest frame, where P_z and E_{vis} are the sum of the longitudinal momentum and the energy of all reconstructed particles, respectively, and $\sqrt{s}$ is the sum of the beam energies in the $\Upsilon(4S)$ rest frame.

The $\overline{D}^0$ meson is reconstructed through its decay to $K^+\pi^-$. A vertex constrained fit is performed and the invariant mass is required to be within 17 MeV/c^2 ($\sim 3.5\sigma$) of the nominal D mass. D^{*-}'s are then reconstructed by combining the $\overline{D}^0$ with a slow charged pion with $|\Delta r| < 2.0$ cm and $|\Delta z| < 10.0$ cm with respect to the D vertex (D

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vertex resolutions are $\sigma_r \sim 0.026$ cm and $\sigma_z \sim 0.016$ cm). The signals of $B \to \overline{D}^{*0}(n\pi)$ are reconstructed through the decay chain $\overline{D}^{*0} \to \overline{D}^0\pi^0$. Candidate D^{*-} ($\overline{D}^{*0}$) are selected when the reconstructed mass difference between $\overline{D}^*$ and $\overline{D}^0$ is within 2.0 (2.4) MeV/c^2 of the nominal mass difference ΔM, which corresponds to $\sim$3.5(3.0) σ resolution on ΔM. A kinematic fit with the nominal $\overline{D}^*$ mass is applied to obtain the 4-momenta of the $\overline{D}^*$ candidate.

The $\overline{D}^*$ candidate is then combined with n pions to reconstruct the B meson. All n pions in this combination are required to satisfy $|\Delta r| < 0.2$ cm and $|\Delta z| < 0.8$ cm with respect to the $\overline{D}$ vertex. Continuum ($e^+e^- \to q\bar{q}$, where $q = u, d, s, c$) events are suppressed with the criterion $|\cos\theta_{\rm thrust}| < 0.8$, where $\theta_{\rm thrust}$ is the angle between the thrust axis of the B candidate daughters and the thrust axis of the remaining tracks and isolated ECL clusters.

The signal can then be identified by two kinematic variables calculated in the $\Upsilon(4S)$ rest frame. The first is the energy difference, $\Delta E = E_{D^*} + \sum_{i=1}^{n} E_{\pi_i} - E_{\rm beam}$, where E_{D^*} is the energy of the $\overline{D}^*$ candidate, E_{π_i} is the energy of the ith pion in the $n\pi$ system and $E_{\rm beam} = \sqrt{s}/2$ (Fig. 1). The second variable is the beam-energy constrained mass, $M_{\rm bc} = \sqrt{E_{\rm beam}^2 - |\vec{P}_{D^*} + \sum_{i=1}^{n}\vec{P}_{\pi_i}|^2}$, where $\vec{P}_{D^*}$ and $\vec{P}_{\pi_i}$ are momentum vectors of the $\overline{D}^*$ candidate, and the ith pion in the $n\pi$ system. Typical resolutions for these variables are 8.5 MeV and 2.7 MeV/c^2, respectively. In the extraction of the signal yield, we require 5.273 GeV/c$^2 < M_{\rm bc} <$ 5.288 GeV/c^2 and $M_{\rm bc} >$ 5.27 GeV/c^2 for $D^{*-}(n\pi)$ and $\overline{D}^{*0}(n\pi)$, respectively, and we fit the ΔE distribution from -150 MeV to 150 MeV. In many B decay analyses, the ΔE distribution includes peaks or other structures due to related B decays with an additional particle, one particle less than in the mode under study or misidentification of a particle from a topologically similar decay mode. In this case, we do not observe such structures within our fitting range. We do not use the $M_{\rm bc}$ distribution to obtain signal yields, because peaking backgrounds in that distribution cannot be distinguished from signal. Selected events contain multiple B candidates with a multiplicity depending on the signal channels, which varies from 1.2 to 1.8. For each event we choose a unique B candidate, taking the combination resulting in the minimum value of $[(M_{\rm bc} - M_B)/\sigma_{M_{\rm bc}}]^2 + (\Delta M_D/\sigma_{M_D})^2 + (\Delta M_{D^*}/\sigma_{M_{D^*}})^2$, where $\Delta M_D(\Delta M_{D^*})$ is the difference of the reconstructed and nominal mass of $D(D^*)$, and $\sigma_{M_{\rm bc}}, \sigma_{M_D}$, and $\sigma_{M_{D^*}}$ are resolutions in $M_{\rm bc}, M_D$ and M_{D^*}, respectively.

We have studied continuum events and other B decays as possible sources of background. Background due to continuum events is studied by analysing the 16 fb^{-1} off-resonance data and there we do not find any peak near $\Delta E = 0$.

B decays (both signal and background due to other decay modes) are studied with Monte Carlo (MC) event

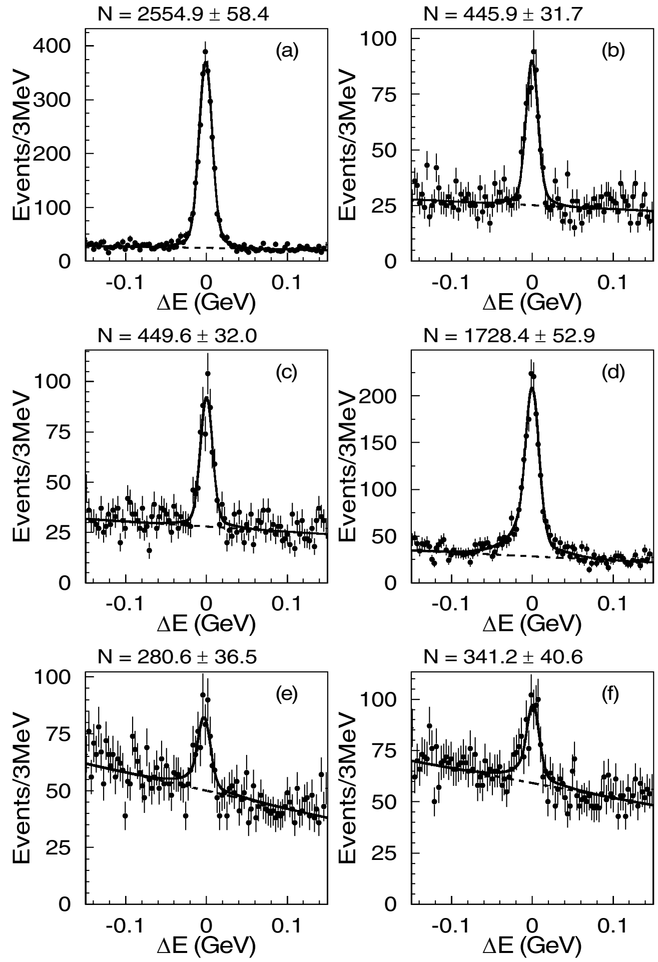

FIG. 1. ΔE distributions for six $\overline{D}^*(n\pi)$ combinations: (a) $B^0 \to D^{*-}(3\pi)^+$, (b) $B^+ \to D^{*-}(4\pi)^{++}$, (c) $B^0 \to D^{*-}(5\pi)^+$, (d) $B^+ \to \overline{D}^{*0}(3\pi)^+$, (e) $B^0 \to \overline{D}^{*0}(4\pi)^0$, and (f) $B^+ \to \overline{D}^{*0}(5\pi)^+$. Points with error bars are the observed events in data, solid lines are the results from the fit and dashed lines represent the background components.

samples. MC events are generated using the QQ event generator [7] with a phase space distribution for the $n\pi$ system, and the response of the Belle detector is simulated by a GEANT3-based program [8]. The simulated events are then reconstructed and analysed with the same procedure as is used for the real data.

We have investigated the possibility of reconstructing $B \to \overline{D}^{*-(0)}(n'\pi)(m\pi^0)$ channels as $D^{*-(0)}(n\pi)$ due to the loss and/or addition of pions, where $n = 3, 4$ or 5, $n' = n$, $n \pm 1$, and $m = 0$ or 1 and here we observe a linear background without any structure around $\Delta E = 0$. We have also studied $B \to \overline{D}^{*0}$ ($\to \overline{D}^0\gamma)(n\pi)$ MC events reconstructed as $B \to \overline{D}^{*0}$ ($\to \overline{D}^0\pi^0$) $(n\pi)$ and $D^{*-(0)}(n\pi)$ events reconstructed as $D^{*0(-)}(n\pi)$. In each case, we find a ΔE distribution peaked at zero, but with a larger width than the corresponding signal distribution. We also consider backgrounds due to $B \to \overline{D}^0(n\pi)$ and $B \to \overline{D}^0(n\pi)\pi^0$ with $n \geq 4$. Such decays are not yet observed.

Assuming branching fractions equal to those of the corresponding $B \to \overline{D}^{*0}(n\pi)$ and $B \to \overline{D}^{*0}[(n+1)\pi]$ modes, respectively, we find a small background to $D^{*-}(n\pi)$ for $n = 3, 4$, and a negligible contribution to the other final states. Finally, we fit MC signal distributions without and with contributions from the various feed-across backgrounds. The ratio of those two signal yields (F_r) depends on the signal channels and varies from 0.99 to 0.87. Observed signal yields are corrected with the corresponding F_r when extracting branching fractions.

The following six B decay modes are studied: $B^0 \to D^{*-}(3\pi)^+$, $B^+ \to \overline{D}^{*0}(3\pi)^+$, $B^+ \to D^{*-}(4\pi)^{++}$, $B^0 \to \overline{D}^{*0}(4\pi)^0$, $B^0 \to D^{*-}(5\pi)^+$, and $B^+ \to \overline{D}^{*0}(5\pi)^+$. Figure 1 shows the ΔE distributions for these decay modes. Statistically significant structures near $\Delta E = 0$ are observed. We have also checked the corresponding ΔE distributions for events in the M_{bc} sideband region ($5.23\ \mathrm{GeV/c^2} < M_{bc} < 5.26\ \mathrm{GeV/c^2}$): no structure is observed. For all the decay modes under study, backgrounds are fitted with a linear function. The signal shape is modeled with a sum of two Gaussian distributions for $B \to \overline{D}^{*-}(n\pi)$. The $\overline{D}^{*0}(n\pi)$ signal is parametrized as a sum of the crystal ball lineshape (CB) [9],

$$F(\Delta E) = A \cdot \exp\left[-0.5 \cdot \left(\frac{\Delta E}{\sigma_{\Delta E}}\right)^2\right]$$

for $\quad \Delta E \geq -\alpha\sigma_{\Delta E}$

$$= A \cdot \exp(-0.5 \cdot \alpha^2) \cdot \left[1 - \frac{\alpha}{n} \cdot \frac{\Delta E}{\sigma_{\Delta E}} - \frac{\alpha^2}{n}\right]^{-n}$$

for $\quad \Delta E < -\alpha\sigma_{\Delta E}$,

and a Gaussian. The n and α parameters of the CB and the fractional area of the second Gaussian are fixed from fits to the MC sample. Signal yields obtained from the fit are summarized in Table I.

The signal efficiency depends on the invariant mass ($M_{n\pi}$) of the $n\pi$ system. Signal efficiencies are calculated from MC event samples in 100 $\mathrm{MeV/c^2}$ bins of $M_{n\pi}$.

In order to obtain the signal yield in each $M_{n\pi}$ bin, we perform a fit to ΔE distributions in each bin to avoid the possible uncertainty due to different background shapes in signal and sideband regions of M_{bc}. Efficiency corrected $M_{n\pi}$ spectra are shown in Fig. 2. Invariant mass distributions of the 3π system ($M_{(3\pi)}$) in $B \to \overline{D}^*(3\pi)$ decays show clear evidence for the presence of a_1 [Fig. 2(a) and 2(d). The $M_{4\pi}$ distributions in Fig. 2(b) and 2(e) do not show any resonant structure. $M_{5\pi}$ distributions in Fig. 2(c) and 2(f)show a peak around 2 $\mathrm{GeV/c^2}$ which, however, does not correspond to any known resonance. We also search for narrow resonances in the $M_{5\pi}$ distributions, after the subtraction of ΔE sidebands. Apart from a peak due to the D_s^+, no narrow structure is observed.

Inclusive branching fractions obtained for the six modes are listed in Table I, where the first error is statistical and the second error is systematic. This is the first measurement of the branching fractions of $B^+ \to D^{*-}(4\pi)^{++}$, $B^0 \to D^{*-}(5\pi)^+$, and $B^+ \to \overline{D}^{*0}(5\pi)^+$. The branching fractions for the decay modes $B^0 \to D^{*-}(3\pi)^+$, $B^+ \to \overline{D}^{*0}(3\pi)^+$, and $B^0 \to \overline{D}^{*0}(4\pi)^0$ are measured with better precision than in previous studies [1]. We do not exclude contributions from exclusive channels $B \to \overline{D}^* D_s^+$, $B \to \overline{D}^* D^{*+}$, $B \to \overline{D}^* D^+$, $B \to \overline{D}^* D^{*+} K_S$ etc. The largest contributions of this type to inclusive $\overline{D}^*(3\pi)$ and $\overline{D}^*(5\pi)$ are expected to come from $\overline{D}^* D_s^+$, with $D_s^+ \to (3\pi)^+$ ($\mathcal{B} = 1.01 \pm 0.28\%$ [1]) and $D_s^+ \to (5\pi)^+$ ($\mathcal{B} = 0.65 \pm 0.18\%$ [1]), respectively. We conduct a search for these modes by fitting invariant mass distributions of $n\pi$, $M_{n\pi}$, for signal

TABLE I. Measured signal yields and branching fractions.

Channel	Signal yield	$\mathcal{B} \times 10^3$
$B^0 \to D^{*-}(3\pi)^+$	2554.9 ± 58.4	$6.81 \pm 0.23 \pm 0.72$
$B^+ \to D^{*-}(4\pi)^{++}$	445.9 ± 31.7	$2.56 \pm 0.26 \pm 0.33$
$B^0 \to D^{*-}(5\pi)^+$	449.6 ± 32.0	$4.72 \pm 0.59 \pm 0.71$
$B^+ \to \overline{D}^{*0}(3\pi)^+$	1728.4 ± 52.9	$10.55 \pm 0.47 \pm 1.29$
$B^0 \to \overline{D}^{*0}(4\pi)^0$	280.6 ± 36.5	$2.60 \pm 0.47 \pm 0.37$
$B^+ \to \overline{D}^{*0}(5\pi)^+$	341.2 ± 40.6	$5.67 \pm 0.91 \pm 0.85$

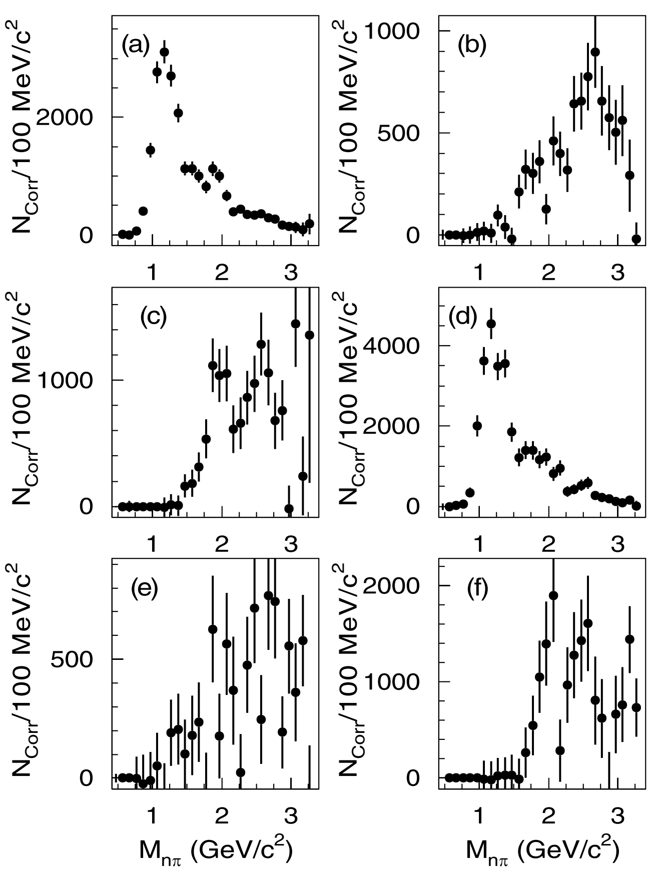

FIG. 2. Efficiency corrected $n\pi$ invariant mass spectra for (a) $B^0 \to D^{*-}(3\pi)^+$, (b) $B^+ \to D^{*-}(4\pi)^{++}$, (c) $B^0 \to D^{*-}(5\pi)^+$, (d) $B^+ \to \overline{D}^{*0}(3\pi)^+$, (e) $B^0 \to \overline{D}^{*0}(4\pi)^0$, and (f) $B^+ \to \overline{D}^{*0}(5\pi)^+$.

events ($|\Delta E| < 30$ MeV) and find yields of 27.8 ± 7.7, 15.6 ± 5.4, 8.4 ± 3.9, and 11.3 ± 5.4 in $B^0 \to D^{*-}(3\pi)^+$, $B^+ \to \overline{D}^{*0}(3\pi)^+$, $B^0 \to D^{*-}(5\pi)^+$, and $B^+ \to \overline{D}^{*0}(5\pi)^+$ channels, respectively. Within the statistical errors, these results are consistent with PDG expectations. The expected contribution from other modes are smaller than $B \to \overline{D}^* D_s^+$ by a factor $\sim$4.

The systematic uncertainty is obtained from a quadratic sum of nine terms, which are shown in Table II. The uncertainty in track finding efficiency ranges from 1% per track for high momentum tracks to 8% per track for 80 MeV/c pions, calculated from partially reconstructed $D^{*-} \to \overline{D}^0[\to K_S(\to \pi^+\pi^-)\pi^+\pi^-]\pi^-$ events and a track embedding study; the uncertainty in the π^0 finding efficiency is 7%. Kaon and pion selection efficiencies are determined using $D^{*-} \to \overline{D}^0(\to K^+\pi^-)\pi^-$ events. The uncertainties in the branching fractions of $D^{*-} \to \overline{D}^0\pi^-$, $\overline{D}^{*0} \to \overline{D}^0\pi^0$, and $\overline{D}^0 \to K^+\pi^-$ are also taken into account. Uncertainty in the feed-across from other decay modes is determined by changing the relative branching fractions of backgrounds and signal by 1 standard deviation in their errors, and repeating the fits to extract signal yields.

Uncertainty due to the fitting procedure is determined by fitting Delta E distributions with a single Gaussian (CB), modified Gaussian (CB) with the exponent changed from two to 1.4, asymmetric Gaussian, modified Gaussian (CB) plus an extra Gaussian term, and asymmetric Gaussian with an extra Gaussian term, and comparing the yields in each fit. (In each case, the term in parentheses applies for $\overline{D}^{*0}(n\pi)$.) The remaining three uncertainties are due to the selection criteria, calculated by varying those criteria by 1 standard deviation in their errors; limited MC statistics; and estimation of the total number of $B\overline{B}$ events, ($N_{B\overline{B}}$).

TABLE II. Contributions of systematic uncertainties (in %).

	D^{*-}			$\overline{D}^{*0}$		
2–7	3π	4π	5π	3π	4π	5π
Track finding	8.7	11.0	12.7	5.4	6.6	7.9
Slow π^0	–	–	–	7.0	7.0	7.0
K/pi selection	4.9	5.0	4.8	5.0	5.2	5.3
Branchings	2.5	2.5	2.5	5.3	5.3	5.3
Feed-across	0.8	1.0	2.0	0.9	1.4	2.2
Fitting	0.5	1.2	1.4	2.4	4.0	5.5
Selection	2.5	3.7	4.9	3.3	5.7	4.7
MC	0.8	0.8	2.2	1.2	1.1	1.7
$N_{B\overline{B}}$	0.5	0.5	0.5	0.5	0.5	0.5
Total	10.6	13.0	15.0	12.3	14.1	15.0

In summary, we observe for the first time the decay channels $B^0 \to D^{*-}(5\pi)^+$, $B^+ \to D^{*-}(4\pi)^{++}$, and $B^+ \to \overline{D}^{*0}(5\pi)^+$ using 152×10^6 $B\overline{B}$ events. We measure inclusive branching fractions for these three decay modes. The branching fractions for the decay channels $B^0 \to D^{*-}(3\pi)^+$, $B^+ \to \overline{D}^{*0}(3\pi)^+$, and $B^0 \to \overline{D}^{*0}(4\pi)^0$ are measured with better precision.

We thank the KEKB group for the excellent operation of the accelerator, the KEK Cryogenics group for the efficient operation of the solenoid, and the KEK computer group and the NII for valuable computing and Super-SINET network support. We acknowledge support from MEXT and JSPS (Japan), ARC and DEST (Australia), NSFC (Contract No. 10175071, China), DST (India), the BK21 program of MOEHRD and the CHEP SRC program of KOSEF (Korea), KBN (Contract No. 2P03B 01324, Poland), MIST (Russia), MESS (Slovenia), Swiss NSF, NSC and MOE (Taiwan), and DOE (USA).

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