Observation of $\overline{B}^0 \to D^0\overline{K}^0$ and $\overline{B}^0 \to D^0\overline{K}^{*0}$ Decays

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We report on a search for $\bar{B}^0 \to D^{(*)0}\bar{K}^{(*)0}$ decays based on 85×10^6 $B\bar{B}$ events collected with the Belle detector at KEKB. The $\bar{B}^0 \to D^0\bar{K}^0$ and $\bar{B}^0 \to D^0\bar{K}^{*0}$ decays have been observed for the first time with the branching fractions $\mathcal{B}(\bar{B}^0 \to D^0\bar{K}^0) = (5.0^{+1.3}_{-1.2} \pm 0.6) \times 10^{-5}$ and $\mathcal{B}(\bar{B}^0 \to D^0\bar{K}^{*0}) = (4.8^{+1.1}_{-1.0} \pm 0.5) \times 10^{-5}$. No significant signal has been found for the $\bar{B}^0 \to D^{*0}\bar{K}^{(*)0}$ and $\bar{B}^0 \to \bar{D}^{(*)0}\bar{K}^{*0}$ decay modes, and upper limits at 90% C.L. are presented.

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Since the recent discovery of *CP* violation in the *B* meson system, through the measurement of nonzero values for $\sin 2\phi_1$ [1], attention has turned towards the measurement of the other unitary triangle angles. Such measurements will allow tests of the Kobayashi-Maskawa ansatz and of the standard model. Precise measurements of the branching fraction for $\bar{B}^0 \to D^0\bar{K}^{*0}$, $\bar{B}^0 \to \bar{D}^0\bar{K}^{*0}$, and $\bar{B}^0 \to D^0_{CP}\bar{K}^{*0}$ decays, where D^0_{CP} denotes D^0 or $\bar{D}^0$ decay to a *CP* eigenstate, will allow a measurement of the angle ϕ_3 [2]. The decay $\bar{B}^0 \to D^0\bar{K}^0$ can also be used to measure time-dependent *CP* asymmetry in *B* decays [3]. So far no experimental information is available for any of these decays.

In this Letter, we report on a search for the $\bar{B}^0 \to D^{(*)0}\bar{K}^0$, $\bar{B}^0 \to D^{(*)0}\bar{K}^{*0}$, and $\bar{B}^0 \to \bar{D}^{(*)0}\bar{K}^{*0}$ [4] decays with the Belle detector [5] at the KEKB asymmetric energy e^+e^- collider [6]. The results are based on a $78\ \mathrm{fb}^{-1}$ data sample collected at the center-of-mass (CM) energy of the $\Upsilon(4S)$ resonance, which contains 85×10^6 produced $B\bar{B}$ pairs.

The Belle detector has been described elsewhere [5]. Charged tracks are selected with a set of requirements based on the average hit residual and impact parameter relative to the interaction point (IP). We also require that the transverse momentum of the tracks be greater than $0.1\ \mathrm{GeV}/c$ in order to reduce the low momentum combinatorial background.

For charged particle identification (PID), the combined information from specific ionization in the central drift chamber (dE/dx), time-of-flight scintillation counters, and aerogel Čerenkov counters (ACC) is used. At large momenta ($> 2.5\ \mathrm{GeV}/c$) only the ACC and dE/dx are used. Charged kaons are selected with PID criteria that have an efficiency of 88%, a pion misidentification probability of 8%, and negligible contamination from protons. All charged tracks having PID consistent with the pion hypothesis that are not identified as electrons are considered as pion candidates.

Neutral kaons are reconstructed via the decay $K^0_S \to \pi^+\pi^-$ with no PID requirements for these pions. The two-pion invariant mass is required to be within $6\ \mathrm{MeV}/c^2$ ($\sim 2.5\sigma$) of the nominal K^0 mass and the displacement of the $\pi^+\pi^-$ vertex from the IP in the transverse (r-ϕ) plane is required to be between 0.2 and 20 cm. The direction from the IP to the $\pi^+\pi^-$ vertex is required to agree within 0.2 rad in the r-ϕ plane with the combined momentum of the two pions. A pair of calorimeter showers not associated with charged tracks, with an invariant mass within 15 MeV$/c^2$ ($\sim 3\sigma$) of the nominal π^0 mass is considered as a π^0 candidate. An energy deposition of at least 30 MeV and a photonlike shape are required for each shower. $\bar{K}^{*0}$ candidates are reconstructed from $K^-\pi^+$ pairs with an invariant mass within 50 MeV$/c^2$ (1Γ) of the nominal $\bar{K}^{*0}$ mass. We reconstruct D^0 mesons in the decay channels: $K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, and $K^-\pi^+\pi^0$, using a requirement that the invariant mass be within 20 MeV$/c^2$, 15 MeV$/c^2$, and 25 MeV$/c^2$ ($\sim 3\sigma$) of the nominal D^0 mass, respectively. In each channel we further define a D^0 mass sideband region, with a width twice that of the signal region and location within 0.1 GeV$/c^2$ from the nominal D^0 mass. For the π^0 from the $D^0 \to K^-\pi^+\pi^0$ decay, we require that its momentum in the CM frame be greater than 0.4 GeV$/c$ in order to reduce combinatorial background. D^{*0} mesons are reconstructed in the $D^{*0} \to D^0\pi^0$ decay mode. The mass difference between D^{*0} and D^0 candidates is required to be within 4 MeV$/c^2$ of the expected value ($\sim 4\sigma$).

We combine $D^{(*)0}$ candidates with K_S^0 or $\bar{K}^{*0}$ to form B mesons. Candidate events are identified by their CM energy difference, $\Delta E = (\sum_i E_i) - E_{\rm b}$, and the beam constrained mass, $M_{\rm bc} = \sqrt{E_{\rm b}^2 - (\sum_i \vec{p}_i)^2}$, where $E_{\rm b}$ is the beam energy and $\vec{p}_i$ and E_i are the momenta and energies of the B meson decay products in the CM frame. We select events with $M_{\rm bc} > 5.2$ GeV$/c^2$ and $|\Delta E| < 0.2$ GeV, and define a B signal region of $5.272 \text{ GeV}/c^2 < M_{\rm bc} < 5.288 \text{ GeV}/c^2$ and $|\Delta E| < 0.03$ GeV. In the rare cases where there is more than one candidate in an event, the candidate with the $D^{(*)0}$ and $\bar{K}^{(*)0}$ masses closest to their nominal values is chosen. We use Monte Carlo (MC) simulation to model the response of the detector and determine the efficiency [7].

To suppress the large combinatorial background dominated by the two-jet-like $e^+e^- \to q\bar{q}$ continuum process, variables that characterize the event topology are used. We require $|\cos\theta_{\rm thr}| < 0.80$, where $\theta_{\rm thr}$ is the angle between the thrust axis of the B candidate and that of the rest of the event. This requirement eliminates 77% of the continuum background and retains 78% of the signal events. We also construct a Fisher discriminant, $\mathcal{F}$, which is based on the production angle of the B candidate, the angle of the B candidate thrust axis with respect to the beam axis, and nine parameters that characterize the momentum flow in the event relative to the B candidate thrust axis in the CM frame [8]. We impose a requirement on $\mathcal{F}$ that rejects 67% of the remaining continuum background and retains 83% of the signal.

Among other B decays, the most serious background comes from $B^0 \to D^-\pi^+$, $D^- \to \bar{K}^{(*)0}K^-$, $\bar{K}^{(*)0}K^-\pi^0$, $\bar{K}^{(*)0}K^-\pi^-\pi^+$, and $B^0 \to D^-K^+$, $D^- \to \bar{K}^{(*)0}\pi^-$, $\bar{K}^{(*)0}\pi^-\pi^0$, $\bar{K}^{(*)0}\pi^-\pi^-\pi^+$. These decays produce the same final state as the $\bar{B}^0 \to D^{(*)0}\bar{K}^{(*)0}$ signal, and their product branching fractions are up to 10 times higher than those expected for the signal. To suppress this type of background, we exclude candidates if the invariant mass of the combinations listed above is consistent with the D^- hypothesis within 25 MeV$/c^2$ ($\sim 3\sigma$). The $\bar{B}^0 \to D^{*+}K^-$, $D^{*+} \to D^0\pi^+$ decay can also produce the same final state as the $\bar{B}^0 \to D^0\bar{K}^{*0}$ decay. But this decay is kinematically separated from the signal; the invariant mass selection criteria for $\bar{K}^{*0}$ candidates completely eliminates this background. Another potential $B\bar{B}$ background comes from the $\bar{B}^0 \to D^{(*)0}\rho^0$ decay channel [9] with one pion from ρ^0 decay misidentified as a kaon. The reconstructed $K^-\pi^+$ invariant mass spectra for these events overlap with the signal $\bar{K}^{*0}$ mass region, while their ΔE distribution is shifted by about 70 MeV$/c^2$. We study this background using MC simulation. The contribution to the $\bar{B}^0 \to D^{(*)0}\bar{K}^{*0}$ signal region is found to be less than 0.2 events. We examined the possibility that other B meson decay modes might produce backgrounds that peak in the signal region by studying a MC sample of generic $B\bar{B}$ events that corresponds to about 1.5 times the data statistics. No other peaking backgrounds were found.

The ΔE and $M_{\rm bc}$ distributions for $\bar{B}^0 \to D^0\bar{K}^{(*)0}$ candidates are presented in Fig. 1, where all three D^0 decay modes are combined. Each distribution is made for events from the signal region of the other parameter. Also shown in Fig. 1 by hatched histograms are the distributions for events in D^0 mass sideband. The sideband shape replicates the background shape well, confirming that the background is mainly combinatorial in nature. Clear signals are observed for the $D^0\bar{K}^0$ and $D^0\bar{K}^{*0}$ final states. As an additional cross check, we also study the K_S^0 candidates' invariant mass and flight distance distributions and $\bar{K}^{*0}$ candidates' invariant mass and helicity distributions for these decays. The helicity angle θ_{K^*} is defined as the angle between the $\bar{K}^{*0}$ momentum in the B meson rest frame and the K^- momentum in the $\bar{K}^{*0}$ rest frame. The distributions mentioned above are shown in Fig. 2, where points with error bars are the results of fits to the ΔE spectra for experimental events in the corresponding bin, and histograms are signal MC. All distributions are consistent with the MC expectation.

For each D^0 decay mode, the ΔE distribution is fitted with a Gaussian for signal and a linear function for background. The Gaussian mean value and width are fixed to the values from MC simulation of the signal events. The region $\Delta E < -0.1$ GeV is excluded from the fit to avoid contributions from other B decays, such as $B \to D^{(*)0}\bar{K}^{(*)0}(\pi)$ where (π) denotes a possible additional pion. For the $M_{\rm bc}$ distribution fit we use the sum of a signal Gaussian and an empirical background function with a kinematic threshold [10], with a parameter fixed from the analysis of the off-resonance data. For the calculation of branching fractions, we use the signal yields determined from the fit to the ΔE distribution.

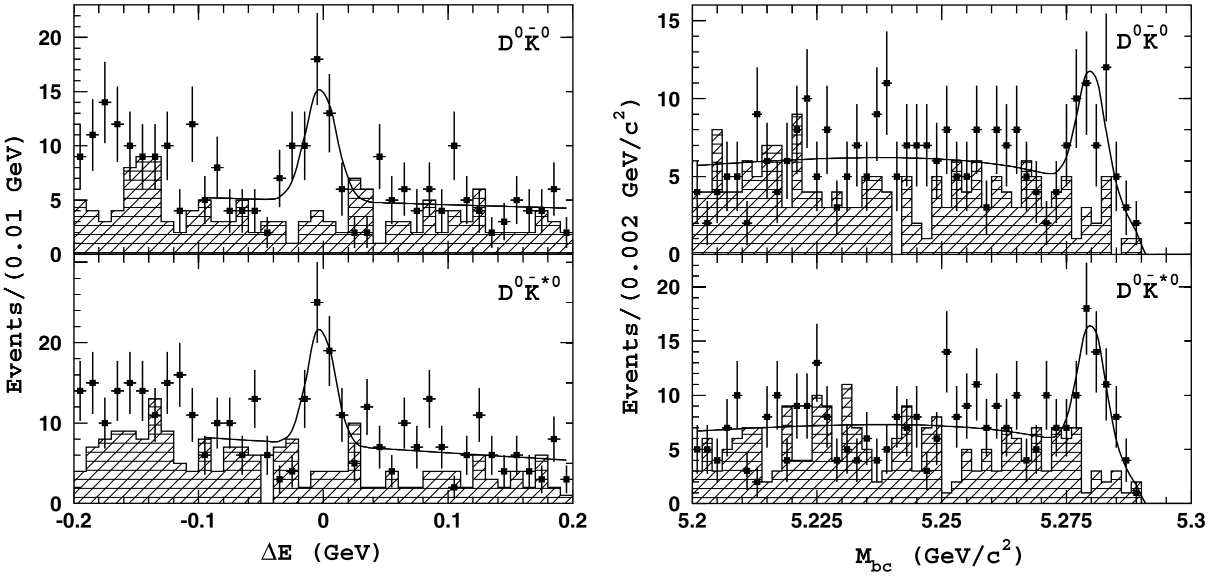

FIG. 1. ΔE (left) and $M_{\rm bc}$ (right) distributions for the $\bar{B}^0 \to D^0 \bar{K}^{(*)0}$ candidates. Points with errors represent the experimental data, hatched histograms show the D^0 mass sidebands and curves are the results of the fits.

This minimizes a possible bias from other B meson decays, which tend to peak in $M_{\rm bc}$ but not in ΔE. The fit results are presented in Table I, where the listed efficiencies include intermediate branching fractions. The statistical significance of the signal quoted in Table I is defined as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})}$, where $\mathcal{L}_{\max}$ and $\mathcal{L}_0$ denote the maximum likelihood with the nominal signal yield and the signal yield fixed at zero, respectively.

For the final result we use a simultaneous fit to the ΔE distributions for the three D^0 decay channels taking into

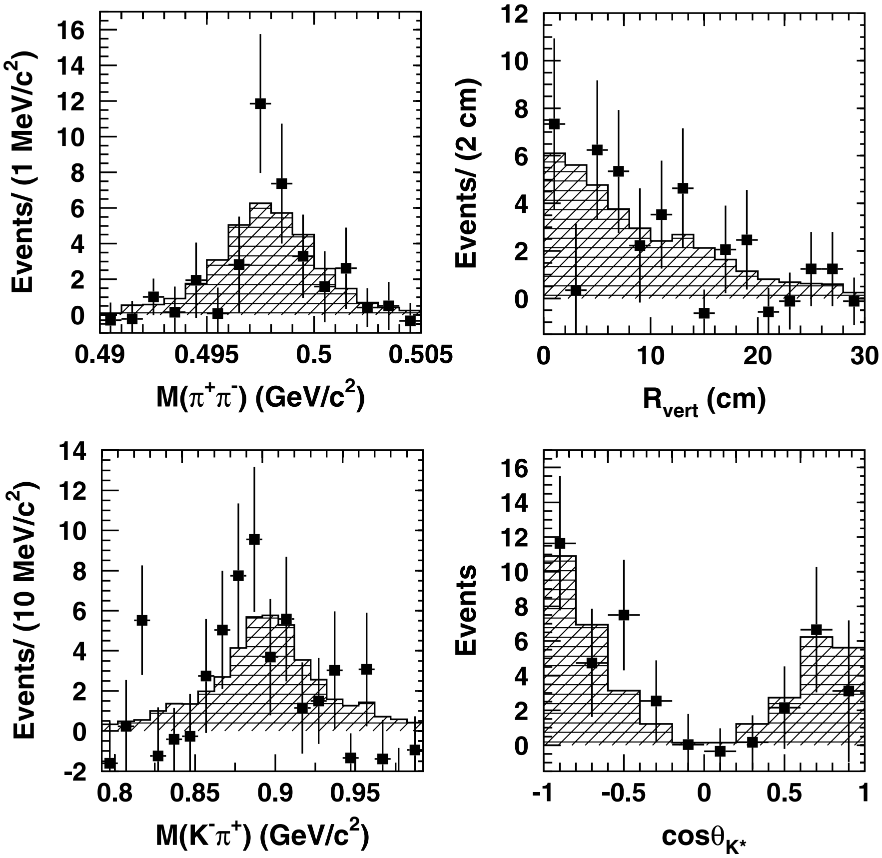

FIG. 2. From left to right: K_S^0 candidates' invariant mass and flight distance for the $\bar{B}^0 \to D^0 \bar{K}^0$ channel, $\bar{K}^{*0}$ candidates' invariant mass and helicity distributions for the $\bar{B}^0 \to D^0 \bar{K}^{*0}$ channel.

TABLE I. Fit results, efficiencies, branching fractions, and statistical significances for $\bar{B}^0 \to D^{(*)0}\bar{K}^{(*)0}$ decays.

Mode	ΔE yield	$M_{\rm bc}$ yield	Efficiency (10^{-3})	$\mathcal{B}$ (10^{-5})	Significance
$\bar{B}^0 \to D^0\bar{K}^0$, $D^0 \to K^-\pi^+$	$9.3^{+4.2}_{-3.6}$	$7.1^{+4.0}_{-3.4}$	2.50	$4.4^{+2.0}_{-1.7} \pm 0.5$	3.1σ
$\bar{B}^0 \to D^0\bar{K}^0$, $D^0 \to K^-\pi^+\pi^-\pi^+$	$14.9^{+5.5}_{-4.9}$	$13.1^{+5.2}_{-4.6}$	2.36	$7.4^{+2.7}_{-2.4} \pm 0.8$	3.6σ
$\bar{B}^0 \to D^0\bar{K}^0$, $D^0 \to K^-\pi^+\pi^0$	$8.7^{+5.3}_{-4.8}$	$7.0^{+4.2}_{-3.5}$	2.52	$4.0^{+2.5}_{-2.2} \pm 0.4$	1.9σ
$\bar{B}^0 \to D^0\bar{K}^0$, simultaneous fit	$31.5^{+8.2}_{-7.6}$	$27.0^{+7.6}_{-6.9}$	7.38	$5.0^{+1.3}_{-1.2} \pm 0.6$	5.1σ
$\bar{B}^0 \to D^0\bar{K}^{*0}$, $D^0 \to K^-\pi^+$	$14.8^{+4.8}_{-4.1}$	$11.7^{+4.6}_{-3.9}$	3.47	$5.0^{+1.6}_{-1.4} \pm 0.6$	4.3σ
$\bar{B}^0 \to D^0\bar{K}^{*0}$, $D^0 \to K^-\pi^+\pi^-\pi^+$	$15.1^{+5.6}_{-5.0}$	$13.4^{+5.4}_{-4.8}$	3.34	$5.3^{+2.0}_{-1.8} \pm 0.6$	3.6σ
$\bar{B}^0 \to D^0\bar{K}^{*0}$, $D^0 \to K^-\pi^+\pi^0$	$9.9^{+6.4}_{-5.9}$	$16.7^{+5.5}_{-4.9}$	3.34	$3.5^{+2.3}_{-2.1} \pm 0.4$	1.7σ
$\bar{B}^0 \to D^0\bar{K}^{*0}$, simultaneous fit	$41.2^{+9.0}_{-8.5}$	$41.0^{+8.7}_{-8.1}$	10.15	$4.8^{+1.1}_{-1.0} \pm 0.5$	5.6σ
$\bar{B}^0 \to D^{*0}\bar{K}^0$, simultaneous fit	$4.2^{+3.7}_{-3.0}$	$2.7^{+3.0}_{-2.4}$	1.98	<6.6 90% C.L.	1.4σ
$\bar{B}^0 \to D^{*0}\bar{K}^{*0}$, simultaneous fit	$6.1^{+5.2}_{-4.5}$	$8.6^{+4.2}_{-3.6}$	2.68	<6.9 90% C.L.	1.4σ
$\bar{B}^0 \to \bar{D}^0\bar{K}^{*0}$, simultaneous fit	$1.4^{+8.2}_{-7.6}$	$9.2^{+7.7}_{-7.2}$	10.15	<1.8 90% C.L.	···
$\bar{B}^0 \to \bar{D}^{*0}\bar{K}^{*0}$, simultaneous fit	$1.2^{+4.1}_{-3.6}$	$0.0^{+3.9}_{-3.2}$	2.68	<4.0 90% C.L.	···

account the corresponding detection efficiencies. The normalization of the background in each D^0 submode is allowed to float while the signal yields are required to satisfy the constraint $N_i = N_{B\bar{B}} \cdot \mathcal{B}[\bar{B}^0 \to D^{(*)0}\bar{K}^{(*)0}] \cdot \varepsilon_i$, where the branching fraction $\mathcal{B}[\bar{B}^0 \to D^{(*)0}\bar{K}^{(*)0}]$ is a fit parameter; $N_{B\bar{B}}$ is the number of $B\bar{B}$ pairs, and ε_i is the efficiency, which includes all intermediate branching fractions.

The statistical significances for the $\bar{B}^0 \to D^0\bar{K}^0$ and $\bar{B}^0 \to D^0\bar{K}^{*0}$ signals are higher than 5σ. The signals in the $\bar{B}^0 \to D^{*0}\bar{K}^{(*)0}$ channels are not significant and we set 90% confidence level (C.L.) upper limits for these final states. We do not observe a significant signal for the $\bar{B}^0 \to \bar{D}^{(*)0}\bar{K}^{*0}$ decays and also present upper limits for them. Figure 3 shows the ΔE distributions for $\bar{B}^0 \to D^{*0}\bar{K}^{(*)0}$ and $\bar{B}^0 \to \bar{D}^{(*)0}\bar{K}^{*0}$ candidates. The upper limit N is calculated from the relation $\int_0^N \mathcal{L}(n)dn = 0.9\int_0^\infty \mathcal{L}(n)dn$, where $\mathcal{L}(n)$ is the maximum likelihood with the signal yield equal to n. We take into account the systematic uncertainties in these calculations by reducing the detection efficiency by 1 standard deviation.

As a check, we apply a similar procedure to the decay chains with the same final states: $\bar{B}^0 \to D^+[K_S^0K^+]\pi^-$ and $\bar{B}^0 \to D^{*+}[D^0\pi^+]K^-$. The estimated branching fractions of $\mathcal{B}(\bar{B}^0 \to D^+\pi^-) = (2.5 \pm 0.3) \times 10^{-3}$ and $\mathcal{B}(\bar{B}^0 \to D^{*+}K^-) = (1.7 \pm 0.2) \times 10^{-4}$(statistical errors only), are consistent with the world average values [11], confirming our analysis.

The following sources of systematic errors are found to be significant: tracking efficiency (2% per track), kaon identification efficiency (2%), π^0 efficiency (6%), K_S^0 reconstruction efficiency (6%), efficiency for slow pions from $D^{*0} \to D^0\pi^0$ decays (8%), $D^{(*)0}$ branching fraction uncertainties (2%–6%), signal and background shape parametrization (4%) and MC statistics (2%–3%). The tracking efficiency error is estimated using η decays to $\gamma\gamma$ and $\pi^+\pi^-\pi^0$. The kaon identification uncertainty is determined from $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ decays. The π^0 reconstruction uncertainty is obtained using D^0 decays to $K^-\pi^+$ and $K^-\pi^+\pi^0$. We assume equal production rates for B^+B^- and $B^0\bar{B}^0$ pairs and do not include the uncertainty related to this assumption in the total systematic error. The overall systematic uncertainty is found to be 11% for $\bar{B}^0 \to D^0\bar{K}^{(*)0}$ and 14% for $\bar{B}^0 \to D^{*0}\bar{K}^{(*)0}$.

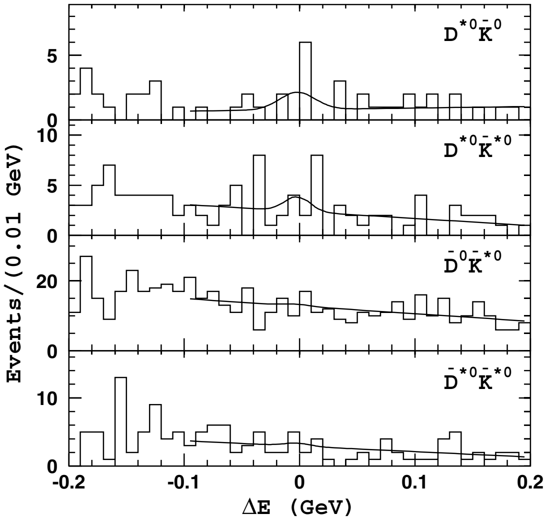

FIG. 3. ΔE distributions for the $\bar{B}^0 \to D^{*0}\bar{K}^{(*)0}$ and $\bar{B}^0 \to \bar{D}^{(*)0}\bar{K}^{*0}$ candidates. Open histograms represent the experimental data and curves show the results of the fits.

In summary, we report the first observation of $\bar{B}^0 \to D^0\bar{K}^{(*)0}$ decays. The branching fractions $\mathcal{B}(\bar{B}^0 \to D^0\bar{K}^0) = (5.0^{+1.3}_{-1.2} \pm 0.6) \times 10^{-5}$ and $\mathcal{B}(\bar{B}^0 \to D^0\bar{K}^{*0}) = (4.8^{+1.1}_{-1.0} \pm 0.5) \times 10^{-5}$ are measured with 5.1σ and 5.6σ statistical significance, respectively. Note that we ignore the possible contribution of $\bar{B}^0 \to D^0K^0$ to the former result, since we do not distinguish between $\bar{K}^0$ and K^0. No significant signal is observed in the $\bar{B}^0 \to D^{*0}\bar{K}^{(*)0}$ final states. The corresponding upper limits at the 90% C.L. are $\mathcal{B}(\bar{B}^0 \to D^{*0}\bar{K}^0) < 6.6 \times 10^{-5}$ and $\mathcal{B}(\bar{B}^0 \to D^{*0}\bar{K}^{*0}) < 6.9 \times 10^{-5}$. We also set the 90% C.L. upper limits for the V_{ub} suppressed $\bar{B}^0 \to \bar{D}^{(*)0}\bar{K}^{*0}$ decays: $\mathcal{B}(\bar{B}^0 \to \bar{D}^0\bar{K}^{*0}) < 1.8 \times 10^{-5}$ and $\mathcal{B}(\bar{B}^0 \to \bar{D}^{*0}\bar{K}^{*0}) < 4.0 \times 10^{-5}$.

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