

Measurement of the Branching Fractions and CP Asymmetry of $B^- \rightarrow D_{(CP)}^0 K^-$ Decays with the $BABAR$ Detector

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We present a study of $B^- \rightarrow D_{CP}^0 K^-$ decays, where D_{CP}^0 is reconstructed in CP -even channels, based on a sample of $88.8 \times 10^6 Y(4S) \rightarrow B\bar{B}$ decays collected with the BABAR detector at the PEP-II e^+e^- storage ring. We measure the ratio of Cabibbo-suppressed to Cabibbo-favored branching fractions $\mathcal{B}(B^- \rightarrow D_{CP}^0 K^-)/\mathcal{B}(B^- \rightarrow D_{CP}^0 \pi^-) = [8.8 \pm 1.6(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-2}$ and the CP asymmetry

$A_{CP} = 0.07 \pm 0.17(\text{stat}) \pm 0.06(\text{syst})$. We also measure $\mathcal{B}(B^- \rightarrow D^0 K^-)/\mathcal{B}(B^- \rightarrow D^0 \pi^-) = [8.31 \pm 0.35(\text{stat}) \pm 0.20(\text{syst})] \times 10^{-2}$ using a sample of $61.0 \times 10^6 B\bar{B}$ pairs.

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The recent observation of CP violation in the B meson system [1] has provided a clean measurement of the angle β of the unitarity triangle. Although this measurement is in good agreement with the expectations of the standard model derived from other measurements of weak interactions, further measurements of CP violation in B decays are needed to overconstrain the unitarity triangle and confirm the Cabibbo-Kobayashi-Maskawa (CKM) mechanism or observe deviations from it. A theoretically clean measurement of the angle $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ can be obtained from the study of $B^- \rightarrow D^{(*)0}K^{(*)-}$ decays by exploiting the interference between the $b \rightarrow c\bar{u}s$ and $b \rightarrow u\bar{c}s$ decay amplitudes [2]; among the proposed methods, the one originally proposed by Gronau, Wyler, and London exploits the interference between $B^- \rightarrow D^0 K^-$ and $B^- \rightarrow \bar{D}^0 K^-$ when the D^0 and \bar{D}^0 decay to CP eigenstates.

We define the ratios of Cabibbo-suppressed to Cabibbo-favored branching fractions

$$R_{(CP\pm)} = \frac{\mathcal{B}(B^- \rightarrow D_{(CP\pm)}^0 K^-) + \mathcal{B}(B^+ \rightarrow \bar{D}_{(CP\pm)}^0 K^+)}{\mathcal{B}(B^- \rightarrow D_{(CP\pm)}^0 \pi^-) + \mathcal{B}(B^+ \rightarrow \bar{D}_{(CP\pm)}^0 \pi^+)} \quad (1)$$

with D^0 reconstructed in Cabibbo-allowed or CP -even/odd eigenstate ($D_{CP\pm}^0$) channels, and the direct CP asymmetry

$$A_{CP\pm} = \frac{\mathcal{B}(B^- \rightarrow D_{CP\pm}^0 K^-) - \mathcal{B}(B^+ \rightarrow D_{CP\pm}^0 K^+)}{\mathcal{B}(B^- \rightarrow D_{CP\pm}^0 K^-) + \mathcal{B}(B^+ \rightarrow D_{CP\pm}^0 K^+)} \quad (2)$$

Neglecting the $D^0 - \bar{D}^0$ mixing and the ratio r_π of the amplitudes of the $B^- \rightarrow \bar{D}^0 \pi^-$ and $B^- \rightarrow D^0 \pi^-$ processes ($|r_\pi| \lesssim 0.02$), $R_{CP\pm}/R = 1 + r^2 \pm 2r \cos\delta \cos\gamma$ and $A_{CP\pm} = \pm 2r \sin\delta \sin\gamma / (1 + r^2 \pm 2r \cos\delta \cos\gamma)$, where $r \approx 0.1-0.2$ is the magnitude of the ratio of the amplitudes for the processes $B^- \rightarrow \bar{D}^0 K^-$ and $B^- \rightarrow D^0 K^-$, and δ is the (unknown) relative strong phase between these two amplitudes [2]. The measurement of R , $R_{CP\pm}$, and $A_{CP\pm}$ allows us to constrain the three unknowns r , δ , and the CKM angle γ .

In this Letter we present the measurement of R , R_{CP+} , and A_{CP+} . The measurement of R uses a sample of $61.0 \times 10^6 Y(4S)$ decays in $B\bar{B}$ pairs collected with the $BABAR$ detector at the PEP-II asymmetric-energy B factory. The measurements of R_{CP+} and A_{CP+} use a sample of $88.8 \times 10^6 B\bar{B}$ pairs. Since the $BABAR$ detector is described in detail elsewhere [3], only the components that are crucial to this analysis are summarized here. Charged-particle tracking is provided by a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). For charged-

particle identification, ionization energy loss in the DCH and SVT, and Cherenkov radiation detected in a ring-imaging device (DIRC) are used. Photons are identified by the electromagnetic calorimeter (EMC), which comprises 6580 thallium-doped CsI crystals. These systems are mounted inside a 1.5-T solenoidal superconducting magnet. We use the GEANT [4] software to simulate interactions of particles traversing the detector, taking into account the varying accelerator and detector conditions.

We reconstruct $B^- \rightarrow D^0 h^-$ decays, where the prompt track h^- is a kaon or a pion (reference to the charge-conjugate state is implied here and throughout the text unless otherwise stated). Candidates for D^0 are reconstructed in the non- CP flavor eigenstates $K^- \pi^+$, $K^- \pi^+ \pi^+ \pi^-$, $K^- \pi^+ \pi^0$ (non- CP modes) and in the CP -even eigenstates $\pi^- \pi^+$ and $K^- K^+$ (CP modes).

To reduce the combinatorial background, only charged tracks with momenta greater than 150 MeV/ c are used to reconstruct $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ and $D^0 \rightarrow K^- \pi^+ \pi^0$; the prompt particle h is required to have momentum greater than 1.4 GeV/ c . Particle ID information from the drift chamber and, when available, from the DIRC must be consistent with the kaon hypothesis for the K meson candidate in all D^0 modes and with the pion hypothesis for the π^\pm meson candidates in the $D^0 \rightarrow \pi^- \pi^+$ mode. For the prompt track to be identified as a pion or a kaon, we require that its Cherenkov angle be reconstructed with at least five photons. We reject a candidate track if its Cherenkov angle is consistent with that of a proton or if it is identified as an electron by the DCH and by the EMC.

Photon candidates are required to have energies greater than 70 MeV. Photon pairs with invariant mass within the range 124–144 MeV/ c^2 and total energy greater than 200 MeV are considered π^0 candidates. To improve the momentum resolution, the π^0 candidates are kinematically fit with their mass constrained to the nominal π^0 mass [5].

The invariant mass of a D^0 candidate, $M(D^0)$, must be within 3σ of the mean fitted mass for the channels $K^- \pi^+$, $K^- \pi^+ \pi^+ \pi^-$, and $K^- K^+$, and within 2σ for the $K^- \pi^+ \pi^0$ channel. Candidates for $D^0 \rightarrow \pi^- \pi^+$ are selected in the range $1.80 < M(D^0) < 1.93$ GeV/ c^2 and the invariant mass of the $(h^- \pi^+)$ system, where π^+ is the pion from D^0 and h^- is the prompt track taken with the kaon mass hypothesis, must be greater than 1.9 GeV/ c^2 to reject the background from $B^- \rightarrow D^0[\rightarrow K^- \pi^+] \pi^-$ and $B^- \rightarrow K^*[\rightarrow K^- \pi^+] \pi^-$ decays. For all the D^0 decay channels except the $\pi^- \pi^+$ mode a kinematical fit to the nominal D^0 mass [5] is applied. The $D^0 \rightarrow \pi^- \pi^+$ selection differs because of its particular background, as described later.

We reconstruct B meson candidates by combining a D^0 candidate with a track h . For the non- CP modes, the charge of the track h must match that of the kaon from the D^0 meson decay. We select B meson candidates by using the beam-energy-substituted mass $m_{ES} = \sqrt{(E_i^{*2}/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - p_B^2}$ and the energy difference $\Delta E = E_B^* - E_i^*/2$, where the subscripts i and B refer to the initial e^+e^- system and the B candidate, respectively, and the asterisk denotes the center-of-mass (CM) frame. The m_{ES} distributions for $B^- \rightarrow D^0 h^-$ signals are Gaussian distributions centered at the B mass with a resolution of $2.6 \text{ MeV}/c^2$, which does not depend on the decay mode or on the nature of the prompt track. In contrast, the ΔE distributions depend on the mass assigned to the prompt track and on the D^0 momentum resolution. We evaluate ΔE with the kaon mass hypothesis so that the distributions are centered near zero for $B^- \rightarrow D^0 K^-$ events and shifted by approximately 50 MeV for $B^- \rightarrow D^0 \pi^-$ events. The ΔE resolution is about 20 MeV for the $D^0 \rightarrow \pi^- \pi^+$ mode, and typically 17 MeV for the other D^0 decay modes. We select B mesons in the range $5.2 < m_{ES} < 5.3 \text{ GeV}/c^2$ with the exception of the $D^0 \rightarrow \pi^- \pi^+$ mode, for which m_{ES} is required to be within 3σ of the mean value. All B candidates are selected in the range $-0.10 < \Delta E < 0.13 \text{ GeV}$. For events with multiple $B^- \rightarrow D^0 h^-$ candidates, the best candidate is chosen based on the values of $M(D^0)$ and m_{ES} ; this happens in fewer than 1% of the selected events for two-body D^0 decays and in $\approx 4\%$ of the events for the other D^0 decays.

To reduce backgrounds from continuum production of light quarks, we make use of two quantities that exploit the different topologies of $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) and $B\bar{B}$ events. The first quantity is the normalized second Fox-Wolfram moment [6], $R_2 \equiv H_2/H_0$, where H_l is the l -order Fox-Wolfram moment of all the charged tracks and neutral clusters in the event. Only events with $R_2 < 0.5$ are selected. The second quantity is the angle θ_T between the thrust axes of the B candidate and of the remaining charged tracks and neutral clusters, evaluated in the CM. We require $|\cos\theta_T| < 0.9$ for the $D^0 \rightarrow K^- \pi^+$ mode and $|\cos\theta_T| < 0.7$ for the $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ and $D^0 \rightarrow K^- \pi^+ \pi^0$ modes. For the $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ modes an additional quantity is used to suppress further the continuum background: the angle θ_{Dh} between the direction of one of the decay products of the D^0 and the direction of flight of the B , in the D^0 rest frame. The quantities $\cos\theta_T$ and $\cos\theta_{Dh}$ are uncorrelated for the signal but *not* for the continuum background. This correlation is exploited to make a more efficient cut in the $\cos\theta_T - \cos\theta_{Dh}$ plane.

The total reconstruction efficiencies, based on simulated signal events, are 42% ($K^- \pi^+$), 14% ($K^- \pi^+ \pi^+ \pi^-$), 8% ($K^- \pi^+ \pi^0$), 34% ($K^- K^+$), and 36% ($\pi^- \pi^+$).

The main contributions to the $B\bar{B}$ background for the non- CP modes come from the processes $B \rightarrow D^* h$ ($h =$

π, K), $B^- \rightarrow D^0 \rho^-$, and misreconstructed $B^- \rightarrow D^0 h^-$. For D_{CP}^0 decays, the backgrounds $B^- \rightarrow K^- K^+ K^-$ and $B^- \rightarrow K^- \pi^+ \pi^-$ [7] must also be considered, since they have the same ΔE and m_{ES} distribution as the $D^0 K^-$ signal. The resonant component of these decays is negligible after the selection requirements for the CP modes.

For each D^0 decay mode an extended unbinned maximum-likelihood fit to the selected data events determines the signal and background yields n_i ($i = 1$ to M , where M is the total number of signal and background channels). Two kinds of signal events, $B^- \rightarrow D^0 \pi^-$ and $B^- \rightarrow D^0 K^-$, are considered, while the number of background sources depends on the D^0 channel. For non- CP modes we consider four kinds of backgrounds: candidates selected either from continuum or from $B\bar{B}$ events, in which the prompt track is either a pion or a kaon. In the case of $D^0 \rightarrow K^- K^+$ we consider two kinds of background depending on the nature of the prompt track. Finally, in the case of $D^0 \rightarrow \pi^- \pi^+$ we consider four contributions: the $B^- \rightarrow K^- \pi^+ \pi^-$ and $B^- \rightarrow \pi^- \pi^+ \pi^-$ decays and two kinds of generic background depending on the nature of the prompt track.

The input variables to the fit for the non- CP and the $D^0 \rightarrow K^- K^+$ modes are m_{ES} , ΔE , and a particle identification probability for the prompt track based on the Cherenkov angle θ_C , the momentum p , and the polar angle θ of the track. For the $D^0 \rightarrow \pi^- \pi^+$ mode, m_{ES} is replaced by $M(D^0)$. This allows us to separate the $B^- \rightarrow D^0 K^-$ from the nonresonant $B^- \rightarrow K^- \pi^+ \pi^-$ contributions since the $(\pi^- \pi^+)$ -invariant-mass distribution peaks at the D^0 mass for signal while it is featureless for background. The extended likelihood function \mathcal{L} is defined as

$$\mathcal{L} = \exp\left(-\sum_{i=1}^M n_i\right) \prod_{j=1}^N \left[\sum_{i=1}^M n_i \mathcal{P}_i(\vec{x}_j; \vec{\alpha}_i) \right], \quad (3)$$

where N is the total number of observed events. The M functions $\mathcal{P}_i(\vec{x}_j; \vec{\alpha}_i)$ are the probability density functions (PDFs) for the variables \vec{x}_j , given the set of parameters $\vec{\alpha}_i$. They are evaluated as a product $\mathcal{P}_i = \mathcal{P}_i(\Delta E, x) \times \mathcal{P}_i(\theta_C)$, where $x = m_{ES}$ or $M(D^0)$ depending on the D^0 channel.

The Gaussian shape of the m_{ES} PDF for signal events is determined from a pure sample of $B^- \rightarrow D^0 \pi^-$, $D^0 \rightarrow K^- \pi^+$ decays selected from on-resonance data. The ΔE distribution for $B^- \rightarrow D^0 K^-$ signal events is parametrized with a Gaussian distribution whose parameters are determined from a pure sample of $B^- \rightarrow D^0 \pi^-$ events selected after the pion mass is assigned to the prompt track. The displaced ΔE distribution for $B^- \rightarrow D^0 \pi^-$ is parametrized with a sum of two Gaussian distributions. The shape of $M(D^0)$ is also described by a Gaussian distribution whose parameters are determined from data.

The parameters for the ΔE and m_{ES} distributions for the continuum background of the non- CP and $D^0 \rightarrow K^- K^+$ modes are determined from off-resonance data.

The background shape in ΔE is parametrized with a linear function, while that of the m_{ES} is parametrized with an ARGUS threshold function [8] $f(m_{\text{ES}}) \propto m_{\text{ES}} \sqrt{1-y^2} \exp[-\xi(1-y^2)]$, where $y = m_{\text{ES}}/m_0$ and m_0 is the mean CM energy of the beams. The correlation between m_{ES} and ΔE for the generic $B\bar{B}$ background is taken into account with a two-dimensional PDF determined from simulated events through a method based on the kernel estimation [9] technique. For the $D^0 \rightarrow K^- K^+$ mode the contribution from the nonresonant $B^- \rightarrow K^- K^- K^+$ decays is estimated [7] and added to the continuum and the generic $B\bar{B}$ background.

The ΔE and $M(D^0)$ distributions for the continuum and generic $B\bar{B}$ background of the $D^0 \rightarrow \pi^- \pi^+$ mode are determined from off-resonance data and simulated events, respectively. The ΔE distribution is described by a linear function while $M(D^0)$ is parametrized with the sum of a linear function (combinatorial background) and a Gaussian distribution (real $D^0 \rightarrow \pi^- \pi^+$). The $M(D^0)$ PDFs of the nonresonant $B^- \rightarrow h^- \pi^- \pi^+$ decays are described by linear functions, while the ΔE distributions are parametrized with one or two Gaussian distributions, as for the $B^- \rightarrow D^0 h^-$ signals.

Finally, the parametrization of the particle identification PDF is performed by fitting with a Gaussian distribution the background-subtracted distribution of the difference between the reconstructed and expected Cherenkov angles of the kaons and pions from D^0 decays, in a pure $D^{*+} \rightarrow D^0 \pi^+$ ($D^0 \rightarrow K^- \pi^+$) control sample.

The results of the fit are summarized in Table I. Figure 1 shows the distributions of ΔE for the combined non- CP and CP modes after enhancing the $B \rightarrow D^0 K$ purity by requiring that the prompt track be consistent with the kaon hypothesis and that $|m_{\text{ES}} - \langle m_{\text{ES}} \rangle| < 3\sigma$ ($|M(\pi^- \pi^+) - \langle M(\pi^- \pi^+) \rangle| < 3\sigma$ for $D^0 \rightarrow \pi^- \pi^+$). The projection of a likelihood fit, modified to take into account the tighter selection criteria, is overlaid in Fig 1.

The ratios R and R_{CP+} are computed by scaling the ratios of the numbers of $B^- \rightarrow D^0 K^-$ and $B^- \rightarrow D^0 \pi^-$

TABLE I. Results from the maximum-likelihood fit. For the $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ modes we quote the results for the fits performed on the whole sample and on the B^+ and B^- subsamples.

D^0 mode	$N(B \rightarrow D^0 \pi)$	$N(B \rightarrow D^0 K)$	$N[\Upsilon(4S)]$
$K^- \pi^+$	4440 ± 69	360 ± 21	61.0×10^6
$K^- \pi^+ \pi^+ \pi^-$	2914 ± 56	242 ± 18	61.0×10^6
$K^- \pi^+ \pi^0$	2650 ± 56	208 ± 18	61.0×10^6
$K^- K^+$	565 ± 25	44.3 ± 9.0	88.8×10^6
$K^- K^+ [B^+]$	286 ± 18	16.7 ± 5.8	88.8×10^6
$K^- K^+ [B^-]$	280 ± 18	27.8 ± 6.8	88.8×10^6
$\pi^- \pi^+$	195 ± 17	24.2 ± 7.2	88.8×10^6
$\pi^- \pi^+ [B^+]$	99 ± 12	$16.8^{+5.6}_{-4.9}$	88.8×10^6
$\pi^- \pi^+ [B^-]$	96 ± 12	$6.5^{+5.1}_{-4.3}$	88.8×10^6

mesons by correction factors that account for small differences in the efficiency between $B^- \rightarrow D^0 K^-$ and $B^- \rightarrow D^0 \pi^-$ selection, estimated with simulated signal samples. The results are listed in Table II.

The direct CP asymmetry A_{CP+} for the $B^\pm \rightarrow D_{CP}^0 K^\pm$ decays is calculated from the measured yields of positive and negative charged meson decays reported in Table I. We measure $A_{CP+} = 0.07 \pm 0.17(\text{stat}) \pm 0.06(\text{syst})$.

Systematic uncertainties in the ratios R , R_{CP+} and in the CP asymmetry A_{CP+} arise primarily from uncertainties in signal yields due to imperfect knowledge of the PDF shapes. The parameters of the analytical PDFs are varied by $\pm 1\sigma$ and the difference in the signal yields is taken as a systematic uncertainty. When a $B\bar{B}$ PDF is parametrized through the kernel estimation, we repeat the fit using several statistically independent simulated $B\bar{B}$ samples to define the PDF. The width of the distribution of the difference between the new yields and the original yield is taken as the systematic uncertainty.

The uncertainties in the branching fractions of the channels contributing to the $B\bar{B}$ background have been taken into account. The correlations between the different

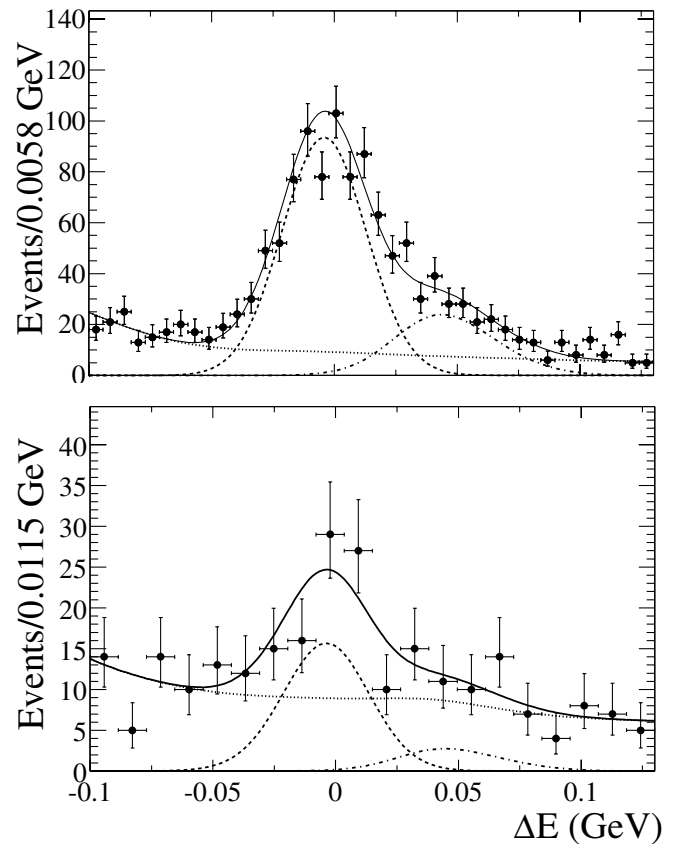


FIG. 1. Distributions of ΔE for events enhanced in $B \rightarrow D^0 K$ signal. Top: $D^0 \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^+ \pi^-$, $K^- \pi^+ \pi^0$; bottom: $D^0 \rightarrow K^- K^+$, $\pi^- \pi^+$. Solid curves represent projections of the maximum likelihood fit; dashed, dashed-dotted, and dotted curves represent, respectively, the $B \rightarrow D^0 K$, $B \rightarrow D^0 \pi$, and background contributions.

TABLE II. Measured ratios R and R_{CP+} for different D^0 decay modes. The first error is statistical, the second is systematic.

$B^- \rightarrow D^0 h^-$ decay mode	$\mathcal{B}(B \rightarrow DK)/\mathcal{B}(B \rightarrow D\pi)$ (%)
$D^0 \rightarrow K^- \pi^+$	$8.4 \pm 0.5 \pm 0.2$
$D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$	$8.7 \pm 0.7 \pm 0.2$
$D^0 \rightarrow K^- \pi^+ \pi^0$	$7.7 \pm 0.7 \pm 0.3$
Weighted mean	$8.31 \pm 0.35 \pm 0.20$
<hr/>	
$D^0 \rightarrow K^- K^+$	$8.0 \pm 1.7 \pm 0.6$
$D^0 \rightarrow \pi^- \pi^+$	$12.9 \pm 4.0^{+1.1}_{-1.5}$
Weighted mean	$8.8 \pm 1.6 \pm 0.5$

sources of systematic errors, when non-negligible, are considered. An upper limit on intrinsic detector charge bias due to acceptance, tracking, and particle identification efficiency has been obtained from the measured asymmetries in the processes $B^- \rightarrow D^0[\rightarrow K^- \pi^+]h^-$ and $B^- \rightarrow D_{CP}^0 \pi^-$, where CP violation is expected to be negligible. This limit (0.04) has been added in quadrature to the total systematic uncertainty on the CP asymmetry.

In conclusion, we have reconstructed $B^- \rightarrow D^0 K^-$ decays with D^0 mesons decaying to non- CP and CP -even eigenstates. The measured ratio R is consistent with standard model expectation ($\approx 7.5\%$) assuming factorization [10] and is equal to R_{CP+} within errors. A_{CP+} is consistent with zero. These results, together with the ones obtained by CLEO and Belle [11], represent the first step towards the measurement of the angle γ and of direct CP violation in the B system using the $B^- \rightarrow D^0 K^-$ decays.

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