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Measurement of the Branching Fraction and Polarization for the Decay $B^- \to D^{*0}K^{*-}$

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We present a study of the decay $B^- \to D^{*0} K^{*-}$ based on a sample of 86×10^6 $\Upsilon(4S) \to B\overline{B}$ decays collected with the BABAR detector at the PEP-II asymmetric-energy B Factory at SLAC. We measure the branching fraction $\mathcal{B}(B^- \to D^{*0} K^{*-}) = (8.3 \pm 1.1(\mathrm{stat}) \pm 1.0(\mathrm{syst})) \times 10^{-4}$, and the fraction of longitudinal polarization in this decay to be $\Gamma_L/\Gamma = 0.86 \pm 0.06(\mathrm{stat}) \pm 0.03(\mathrm{syst})$.

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Following the discovery of CP violation in B-meson decays and the measurement of the angle β of the unitarity triangle [1], focus has turned towards the measurements of the angles α and γ. Measurement of all three angles overconstrains the triangle and constitutes a stringent test of the standard model. A precise determination of γ requires larger samples of B decays than are currently available, and is likely to be based on information from several decay modes. Decays of the type $B \to D^{(*)}K^{(*)}$ are expected to play a leading role in this program [2]; among these modes, those with a K^* have distinct advantages in some of the proposed methods [3]. Decay modes into two vector mesons present unique opportunities due to interference between helicity amplitudes. It has been suggested that angular analysis of $B^- \to \overset{(-)}{D}{}^{*0} K^{*-}$ can yield information on γ without external assumptions [4]. More generally, such a study would be sensitive to T-violating asymmetries that probe physics beyond the standard model [5].

The previously available information on $B^- \to D^{*0}K^{*-}$ is based on a sample of 15 events [6]. Here we present an improved measurement of the branching fraction and the first measurement of the polarization in this decay.

Results are based on $(85.8 \pm 0.8) \times 10^6$ $\Upsilon(4S) \to B\bar{B}$ decays ($N_{B\bar{B}}$), corresponding to an integrated luminosity of 79 fb^{-1}, collected between 1999 and 2002 with the BABAR detector [7] at SLAC. A 9.4 fb^{-1} sample of off-resonance data, recorded at e^+e^- center-of-mass (c.m.) energy 40 MeV below the $\Upsilon(4S)$mass, is used to study "continuum" events, $e^+e^- \to q\bar{q}$ ($q = u, d, s$, or c).

We reconstruct $B^- \to D^{*0}K^{*-}$ in the following modes: $D^{*0} \to D^0\pi^0$ and $D^0\gamma$; $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^+\pi^-$; $K^{*-} \to K_S\pi^-$; $K_S \to \pi^+\pi^-$; $\pi^0 \to \gamma\gamma$ (charged conjugate decay modes are implied throughout this Letter). The optimization of the event selection was based on studies of off-resonance data and simulated $B\bar{B}$ events. A key feature of the analysis is the use of a sample of 4500 $B^- \to D^{*0}\pi^-$ events to determine efficiencies and resolutions. The event yield in this mode is consistent with expectations based on its known branching fraction and our acceptance calculation.

We select K_S candidates from pairs of oppositely charged tracks with invariant mass within 9 MeV (3σ) of the known [8] K_S mass. Each K_S candidate is combined with a negatively charged track to form a $K^{*-} \to K_S\pi^-$ candidate. We retain K^{*-} candidates with mass within 75 MeV of the known K^{*-} mass. The K_S vertex must be displaced by at least 3 mm from the K^{*-} vertex. This last requirement rejects combinatorial background and is 96% efficient for real K_S decays.

Photon candidates are constructed from calorimeter clusters with lateral profiles consistent with photon showers. Neutral-pion candidates are formed from pairs of photon candidates with invariant mass between 115 and 150 MeV. The π^0 mass resolution is 6.5 MeV.

To reduce backgrounds, tracks from $D^0 \to K^-\pi^+\pi^0$ and $D^0 \to K^-\pi^+\pi^+\pi^-$ must have momenta above 150 MeV. The $K^\pm$ candidate track must satisfy particle identification criteria that provide a rejection factor of about 30 against pions. The efficiency of these criteria averaged over all kinematically allowed momenta and polar angles is 90%. For each $D^0 \to K^-\pi^+\pi^0$ candidate, we compute the square of the decay amplitude ($|A|^2$) from the kinematics of the decay products and the known properties of the Dalitz plot for this decay [9]. We retain candidates if $|A|^2$ is greater than 5.5% of its maximum possible value. This requirement selects mostly the $K\rho$ region of the Dalitz plot. It rejects 40% of the backgrounds, with an efficiency of $(76 \pm 1)\%$, as measured in the $D^{*0}\pi$ control sample. The invariant mass of D^0 candidates must be within 2.5σ of the D^0 mass.

We select D^{*0} candidates by combining D^0 candidates with a π^0 or photon candidate. The π^0 must have momentum between 70 and 450 MeV in the c.m. frame. The photon must have energy above 100 MeV in the laboratory frame. We reject photons consistent with originating from π^0 decay when paired with another photon of energy greater than 100 MeV. We require the mass difference $\Delta m \equiv m(D^{*0}) - m(D^0)$ to be between 138.7 and 145.7 (130.0 and 156.0) MeV for $D^{*0} \to D^0\pi^0$ ($D^{*0} \to D^0\gamma$). The Δm resolution is 1.1 (6.4) MeV for the $D^0\pi^0$ ($D^0\gamma$) mode.

Finally, we select B^- candidates by combining D^{*0} and K^{*-} candidates. A B^-candidate is characterized by the energy-substituted mass $m_{\text{ES}} \equiv \sqrt{(\frac{1}{2}s + \vec{p}_0 \cdot \vec{p}_B)^2/E_0^2 - p_B^2}$ and energy difference $\Delta E \equiv E_B^* - \frac{1}{2}\sqrt{s}$, where E and p are energy and momentum, the asterisk denotes the c.m. frame, the subscripts 0 and B refer to the $\Upsilon(4S)$ and B candidate, respectively, and s is the square of the c.m. energy. For signal events, $m_{\text{ES}} = M_B$ within the resolution of about 3 MeV, where M_B is the known B^- mass.

We require $|\Delta E| \leq 40$ MeV for B^- candidates with a $D^0 \to K^-\pi^+\pi^0$, and $|\Delta E| \leq 27.5$ MeV for the other modes. The ΔE resolution is approximately 19 MeV in the $K^-\pi^+\pi^0$ mode and 10 MeV in the other modes.

To reduce continuum backgrounds, we use the ratio of the second to zeroth order Fox-Wolfram [10] moments ($R_2 < 0.4$), and the angle θ_T^* between the thrust axes of the B^- candidate and the remaining tracks and clusters in the event ($|\cos\theta_T^*| < 0.85$). We also make requirements on the polar angle θ_B^* of the B^- candidate ($|\cos\theta_B^*| < 0.9$), and the energy flow in the rest of the event. We construct a Fisher discriminant $\mathcal{F}$ based on the energy flow in nine concentric cones around the direction of the B^- candidate [11]. We select candidates consistent with an isotropic event energy flow by requiring $\mathcal{F} < 0.40$ (0.28) for B^- candidates with a $D^{*0} \to D^0\pi^0$ ($D^0\gamma$). The energy

TABLE I. Summary of the elements of the branching fraction calculation. $N_{m_{\rm ES}}$ is the yield from the $m_{\rm ES}$ fit; $N_{\rm pk}$ is the number of peaking background events; $\epsilon^i_{\rm MC}$ is the event selection efficiency for the ith mode; $\mathcal{B}^i \equiv \mathcal{B}_{K^{*-}} \cdot \mathcal{B}_{K_S} \cdot \mathcal{B}^i_{D^{*0}} \cdot \mathcal{B}^i_{D^0}$ is the product of branching fractions for the K^*, K_S, D^*, and D decays in the ith mode.

D^{*0} mode	D^0 mode	$N_{m_{\rm ES}}$	$N_{\rm pk}$	$\sum(\epsilon^i_{\rm MC} \times \mathcal{B}^i)(\times 10^{-3})$		$\mathcal{B}(B^- \to D^{*0}K^{*-})(\times 10^{-4})$
All	All	121 ± 15	6.8 ± 3.4	1.6 ± 0.2		8.3 ± 1.1 ± 1.0
$D^{*0} \to D^0\pi^0$	All	96 ± 12	4.8 ± 2.4	1.0 ± 0.1		10.2 ± 1.3 ± 1.3
$D^{*0} \to D^0\gamma$	All	24 ± 8	2.0 ± 1.0	0.6 ± 0.1		4.4 ± 1.7 ± 0.8
				$\epsilon^i_{\rm MC}$	$\mathcal{B}^i$	
$D^{*0} \to D^0\pi^0$	$D^0 \to K^-\pi^+$	26 ± 5	1.7 ± 0.9	(6.5 ± 0.6)%	(0.54 ± 0.03)%	8.0 ± 1.8 ± 0.9
$D^{*0} \to D^0\pi^0$	$D^0 \to K^-\pi^+\pi^0$	39 ± 8	1.7 ± 0.9	(2.1 ± 0.3)%	(1.85 ± 0.15)%	10.9 ± 2.4 ± 1.7
$D^{*0} \to D^0\pi^0$	$D^0 \to K^-\pi^+\pi^+\pi^-$	31 ± 7	1.4 ± 0.7	(2.9 ± 0.4)%	(1.06 ± 0.07)%	11.6 ± 2.6 ± 1.6
$D^{*0} \to D^0\gamma$	$D^0 \to K^-\pi^+$	11 ± 4	0.1 ± 0.1	(5.7 ± 0.5)%	(0.33 ± 0.03)%	6.8 ± 2.7 ± 1.0
$D^{*0} \to D^0\gamma$	$D^0 \to K^-\pi^+\pi^0$	11 ± 5	1.7 ± 0.9	(1.9 ± 0.2)%	(1.14 ± 0.12)%	5.3 ± 2.9 ± 1.0
$D^{*0} \to D^0\gamma$	$D^0 \to K^-\pi^+\pi^+\pi^-$	0 ± 5	0.2 ± 0.1	(2.5 ± 0.3)%	(0.65 ± 0.07)%	−0.2 ± 3.3 ± 0.4

flow, θ^*_T, and θ^*_B are computed in the c.m. frame. These requirements remove about 80% of the continuum backgrounds and are 79% (74%) efficient for signal in the $D^0\pi^0$ ($D^0\gamma$) mode.

In the 16% of the events with multiple B^- candidates, we pick the best candidate based on a χ^2 algorithm that uses the measured values, known values, and resolutions of the D^0 mass and Δm.

We extract the yield of $B^- \to D^{*0}K^{*-}$ events from a binned maximum likelihood fit to the $m_{\rm ES}$ distribution of B^- candidates. The signal distribution is parametrized as a Gaussian and the combinatorial background as a threshold function, $f(m_{\rm ES}) \propto m_{\rm ES}\sqrt{1-x^2}\exp[-\zeta(1-x^2)]$, where ζ is a fit parameter, $x = 2m_{\rm ES}/\sqrt{s}$. The parameters of the Gaussian are determined from the $B^- \to D^{*0}\pi^-$ sample. The total signal yield is 121 ± 15 events. Fits to the ΔE distribution for events with $m_{\rm ES} > 5.27$ GeV give consistent results (140 ± 21). The third column of Table I lists the yields for the individual D^{*0}/D^0 modes. Figure 1 shows the $m_{\rm ES}$ distribution of B^- candidates overlaid with the fit model.

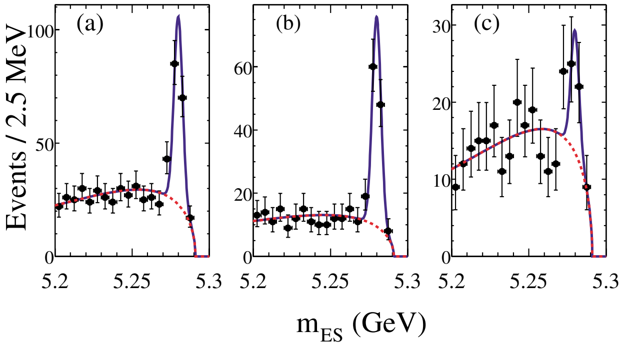

FIG. 1 (color online). Distributions of $m_{\rm ES}$ for $B^- \to D^{*0}K^{*-}$: (a) all modes; (b) $D^{*0} \to D^0\pi^0$ modes; (c) $D^{*0} \to D^0\gamma$ modes. The dashed lines represent the combinatorial background.

The yield from the $m_{\rm ES}$ fit includes contributions from "peaking" backgrounds (those with $m_{\rm ES}$ near M_B). The main modes contributing to these backgrounds are $B^- \to D^{*0}K_S\pi^-$, $\bar{B}^0 \to D^{*+}K^{*-}$, and $B^- \to D^0K^{*-}$. From a Monte Carlo simulation we estimate that they contribute 6.8 ± 3.4 events to the signal yield, where the uncertainty reflects the limited knowledge of the branching fractions for these modes. The predicted amount of $B^- \to D^{*0}K_S\pi^-$ background (2.7 ± 2.7 events) is consistent with the observed $m(K_S\pi^-)$ distribution.

The branching fraction $\mathcal{B}(B^- \to D^{*0}K^{*-})$ is calculated from

$$\mathcal{B} = \frac{N_{m_{\rm ES}} - N_{\rm pk}}{N_{B\bar{B}} \cdot \mathcal{B}_{K^{*-}} \cdot \mathcal{B}_{K_S} \cdot \sum_i(\epsilon^i_{MC} \cdot \mathcal{B}^i_{D^{*0}} \cdot \mathcal{B}^i_{D^0})},$$

where $N_{m_{\rm ES}}$ is the event yield from the $m_{\rm ES}$ fit, $N_{\rm pk}$ is the peaking background, $\mathcal{B}_{K^{*-}}$ and $\mathcal{B}_{K_S}$ are the branching fractions for $K^{*-} \to K_S\pi^-$ and $K_S \to \pi^+\pi^-$, the index i runs over the six D^{*0}/D^0 modes, $\epsilon^i_{\rm MC}$ is the event selection efficiency, and $\mathcal{B}^i_{D^{*0}}$ ($\mathcal{B}^i_{D^0}$) is the D^{*0} (D^0) branching fraction for the ith mode. This calculation assumes $\mathcal{B}(\Upsilon(4S) \to B^+B^-) = \mathcal{B}(\Upsilon(4S) \to B^0\bar{B}^0)$. The Monte Carlo efficiency determination uses the value of the polarization reported in this Letter.

The inputs to this calculation are shown in Table I. Combining the six D^{*0}/D^0 modes, we find

$$\mathcal{B}(B^- \to D^{*0}K^{*-}) = (8.3 \pm 1.1(\text{stat}) \pm 1.0(\text{syst})) \times 10^{-4}.$$

We list the uncertainties on $\mathcal{B}$ in Table II. The largest systematic errors, the uncertainty in the reconstruction efficiencies for photons (2.5% per photon) and charged tracks (0.8% per track), are determined from independent control samples. The efficiencies of most requirements are measured with the large $B^- \to D^{*0}\pi^-$ sample.

Table I also shows the branching fractions for the $D^{*0} \to D^0\gamma$ and $D^{*0} \to D^0\pi^0$ modes separately. Though the latter is somewhat larger than the former, we find agreement for the same quantities in the

$B^- \to D^{*0}\pi^-$ sample, where the D^{*0} is reconstructed with identical techniques. Thus, we ascribe the difference between the two modes to statistical fluctuations.

The angular distributions for the decays are expressed in terms of three amplitudes H_0 (longitudinal), H_+, and H_- (transverse), and three angles, θ_D, θ_K, and χ [12]. The angle θ_D (θ_K) is the angle of the D^0 (K_S) with respect to the B^- direction in the D^{*0} (K^{*-}) rest frame; χ is the angle between the decay planes of the D^{*0} and the K^{*-} in the B^- rest frame. Since the acceptance is nearly independent of χ, we integrate over χ, obtaining

$$\frac{d^2\Gamma}{d\cos\theta_D d\cos\theta_K} \propto 4|H_0|^2\cos^2\theta_D\cos^2\theta_K + (|H_+|^2 + |H_-|^2)\sin^2\theta_D\sin^2\theta_K,$$
$$\frac{d^2\Gamma}{d\cos\theta_D d\cos\theta_K} \propto 4|H_0|^2\sin^2\theta_D\cos^2\theta_K + (|H_+|^2 + |H_-|^2)(1 + \cos^2\theta_D)\sin^2\theta_K$$

for $D^{*0} \to D^0\pi^0$ and $D^{*0} \to D^0\gamma$, respectively.

The longitudinal polarization fraction Γ_L/Γ, given by

$$\frac{\Gamma_L}{\Gamma} = \frac{|H_0|^2}{|H_0|^2 + |H_+|^2 + |H_-|^2},$$

is extracted from an unbinned maximum likelihood fit to the data distribution $D(\theta_D, \theta_K)$ for events with $m_{\mathrm{ES}} > 5.27$ GeV. This distribution is fit to the sum of those for longitudinally (L) and transversely (T) polarized signal events, and combinatorial background events (C):

$$D(\theta_D, \theta_K) = a \cdot L(\theta_D, \theta_K) + b \cdot T(\theta_D, \theta_K) + c \cdot C(\theta_D, \theta_K).$$

Here c is the fraction of background, combinatorial and peaking, determined from the m_{ES} yield fit and simulation, respectively, and $b = 1 - a - c$. Thus, a is the only free parameter in the fit.

The distributions of L and T are obtained from simulations, including detector acceptance effects. The distribution of C is estimated from data candidates in a sideband of m_{ES} ($5.20 < m_{\mathrm{ES}} < 5.27$ GeV) and has been verified to describe the angular distributions of both combinatorial and peaking backgrounds. We exclude from the fit (θ_D, θ_K) regions where the efficiency changes rapidly: $\cos\theta_K < -0.9$ and, in the $D^0\gamma$ mode, $\cos\theta_D > 0.85$.

We find longitudinal polarization fractions $\Gamma_L/\Gamma = 0.87 \pm 0.07(\mathrm{stat}) \pm 0.03(\mathrm{syst})$ and $0.80 \pm 0.14(\mathrm{stat}) \pm 0.04(\mathrm{syst})$ from fits to the $D^{*0} \to D^0\pi^0$ and $D^{*0} \to D^0\gamma$ samples, respectively. Figure 2 shows projections of the (θ_D, θ_K) distributions for the event sample. Combining these two results, we find $\Gamma_L/\Gamma = 0.86 \pm 0.06(\mathrm{stat}) \pm 0.03(\mathrm{syst})$. The systematic uncertainty reflects the accuracy of the simulation (± 0.017), the uncertainty on c (±0.017), the finite statistics of the simulation and sideband data (± 0.010), the uncertainties related to the fit assumptions (± 0.010), and the assumption that the acceptance is independent of χ (± 0.004). As a consistency check, we fit the θ_D distribution in the $B^- \to D^{*0}\pi^-$ sample. We find $\Gamma_L/\Gamma = 1.00 \pm 0.01$, in agreement

TABLE II. Uncertainties for $\mathcal{B}(B^- \to D^{*0}K^{*-})$.

Source	Uncertainty
Statistical	13.1%
π^0 and γ efficiency	6.0%
Tracking efficiency	4.5%
m_{ES} fitting assumptions	3.8%
Event selection criteria	3.8%
D^{*0} and D^0 branching fractions	3.2%
Peaking background estimates	3.0%
Kaon identification efficiency	2.0%
K_S efficiency	1.9%
Polarization uncertainty	1.8%
Monte Carlo statistics	1.7%
$N_{B\bar{B}}$	1.1%
Total systematics	11.7%

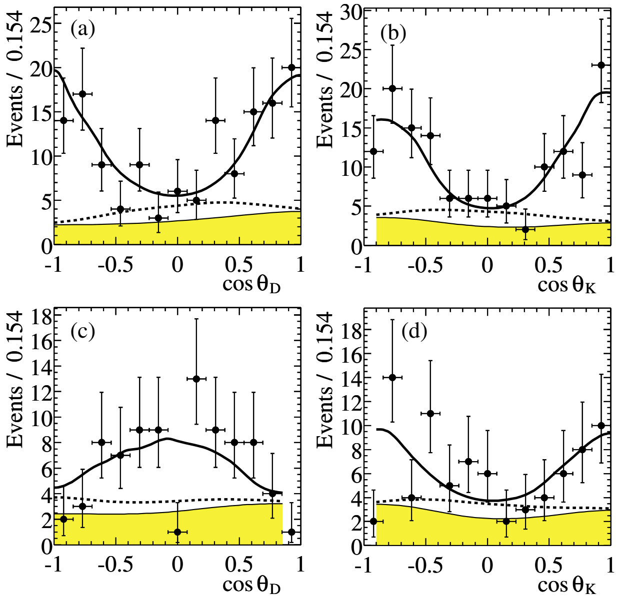

FIG. 2 (color online). Distributions of (a) $\cos\theta_D$ and (b) $\cos\theta_K$ for $D^{*0} \to D^0\pi^0$. Distributions of (c) $\cos\theta_D$ and (d) $\cos\theta_K$ for $D^{*0} \to D^0\gamma$. The solid line represents the full fit model, the dashed line represents the transverse component, and the shaded region represents the combinatorial background component.

with the expectation $\Gamma_L/\Gamma = 1$ from angular momentum conservation.

In summary, we have measured $\mathcal{B}(B^- \to D^{*0}K^{*-}) = (8.3 \pm 1.1(\mathrm{stat}) \pm 1.0(\mathrm{syst})) \times 10^{-4}$. Our measurement is 2.5 times more precise than the previous result. It is in agreement with predictions based on the measured $B^- \to D^{*0}\rho^-$ branching fraction [13], and the value of the Cabibbo angle. We have also measured the longitudinal polarization fraction in this decay to be $\Gamma_L/\Gamma = 0.86 \pm 0.06(\mathrm{stat}) \pm 0.03(\mathrm{syst})$. This last result is consistent with expectations [14] based on factorization, heavy quark effective theory, and the measurement of semileptonic B-decay form factors, assuming that the external spectator amplitude ($b \to cW^{*-}$; $W^{*-} \to K^{*-}$) dominates in $B^- \to D^{*0}K^{*-}$. This study represents a first step towards a measurement of γ from an analysis of $B^- \to D^{*0}_{(CP)}K^{*-}$ as described in [4].

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