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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 million $\Upsilon(4S) \to B\overline{B}$ 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. 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 $B \rightarrow D^{(*)}K^{(*)}$ 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 $B^- \rightarrow \overset{(-)}{D}{}^{*0}K^{*-}$ 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 $B^- \rightarrow D^{*0}K^{*-}$ is based on a sample of 15 events [6]. Here we report on an improved measurement of the branching fraction for $B^- \rightarrow D^{*0}K^{*-}$, and on the first measurement of the polarization in this decay.

Results are based on 86 million $\Upsilon(4S) \rightarrow B\overline{B}$ decays, corresponding to an integrated luminosity of 79 fb^{-1}, collected between 1999 and 2002 with the *BABAR* detector at the PEP-II B Factory at SLAC [7]. An additional 9.4 fb^{-1} sample of off-resonance data, recorded at e^+e^- center-of-mass (CM) energy 40 MeV below the $\Upsilon(4S)$ mass, is used to study "continuum" events, $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$, or c).

The *BABAR* detector is described elsewhere [8]. Only detector components relevant for this analysis are summarized here. Trajectories of charged particles are measured in a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) in a 1.5-T magnetic field. Charged particles are identified as pions or kaons using information from a detector of internally reflected Cherenkov light, as well as measurements of energy loss in the SVT and the DCH. Photons are detected in a CsI(Tl) calorimeter.

We reconstruct $B^- \rightarrow D^{*0}K^{*-}$ in the following modes: $D^{*0} \rightarrow D^0\pi^0$ and $D^0\gamma$; $D^0 \rightarrow K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^+\pi^-$; $K^{*-} \rightarrow K_S\pi^-$; $K_S \rightarrow \pi^+\pi^-$; $\pi^0 \rightarrow \gamma\gamma$ (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 $B^- \rightarrow D^{*0}\pi^-$ events to validate several aspects of the simulation and the analysis procedure.

We select K_S candidates from pairs of oppositely-charged tracks that form an invariant mass within 9 MeV (3σ) of the known [9] K_S mass. Each K_S candidate is combined with a negatively charged track, assumed to be a π^-, to form a K^{*-} 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 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.

We select D^0 candidates in the three decay modes listed above. To reduce backgrounds, tracks from $D^0 \rightarrow K^-\pi^+\pi^0$ and $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ must have momenta above 150 MeV. The kaon candidate track must satisfy a set of kaon identification criteria that provides a rejection factor of about 30 against pions. The kaon identification efficiency averaged over all kinematically allowed momentum and polar angle is 90%. For each $D^0 \rightarrow K^-\pi^+\pi^0$ candidate, we calculate the square of the decay amplitude ($|A|^2$) based on the kinematics of the decay products and the known properties of the Dalitz plot for this decay [10]. We retain candidates if $|A|^2$ is greater than 5.5% of its maximum possible value. The efficiency of this requirement is 76%. Finally, the measured 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 candidate must have momentum between 70 and 450 MeV in the CM frame. The photon candidate must have energy above 100 MeV in the laboratory frame. We reject photon candidates consistent with originating from π^0 decay when paired with another photon of energy above 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 $D^{*0} \rightarrow D^0\pi^0$ ($D^{*0} \rightarrow D^0\gamma$). The Δm resolution is 1.1 (6.4) MeV for the $D^0\pi^0$ ($D^0\gamma$) mode.

At each stage in the reconstruction chain, the measurement of the momentum vector of each intermediate particle is improved by refitting the momenta of its decay products with kinematic constraints. These constraints are based on the known mass of the intermediate particle and on the fact that its decay products originate from a common point in space.

Finally, we select B^- candidates by combining D^{*0} and K^{*-} candidates. A B^- candidate is characterized by the energy-substituted mass $m_{\rm ES} \equiv \sqrt{(\frac{1}{2}s + \vec{p}_0 \cdot \vec{p}_B)^2/E_0^2 - p_B^2}$ 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 CM frame, the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and B candidate, respectively, and s is the square of the CM energy. For signal events we expect $m_{\rm ES} = M_B$ within the experimental 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 all 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 make use of the ratio of the second to zeroth order Fox-Wolfram [11] moments ($R_2 < 0.4$), and the angle θ^*_T between the thrust axes of the B^- candidate and the remaining charged tracks and neutral 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 [12]. We require $\mathcal{F} < 0.40$ (0.28) for B^- candidates with a $D^{*0} \to D^0\pi^0$ ($D^0\gamma$). The energy flow, θ^*_T, and θ^*_B are all calculated in the CM 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 16% of the events there is more than one B^- candidate. In these events we retain the best candidate based on a χ^2 algorithm that uses the measured values, known values, and resolutions of the D^0 mass and the mass difference 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 [13]. The parameters of the Gaussian are determined from the m_{ES} distribution of the $B^- \to D^{*0}\pi^-$ sample. The total signal yield is 121 ± 15 events. The third column of Table I lists the yields for the individual D^{*0}/D^0 modes. Figure 1 shows the m_{ES} distribution of B^- candidates overlaid with the fit model.

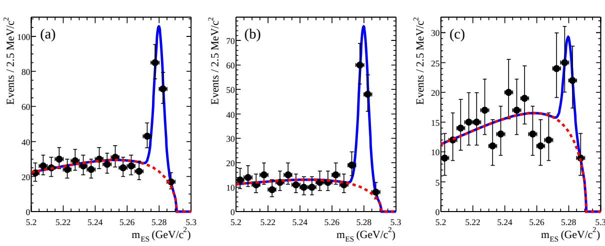

FIG. 1: Distributions of $m_{\rm ES}$ for $B^- \to D^{*0}K^{*-}$: (a) all modes; (b) $D^{*0} \to D^0\pi^0$ modes; (c) $D^{*0} \to D^0\gamma$ modes.

The yield from the m_{ES} fit includes contributions from "peaking backgrounds", which are backgrounds with m_{ES} near M_B. These backgrounds arise from B decay modes closely related to the signal mode; e.g., $\bar{B}^0 \to D^{*+}K^{*-}$. 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 branching fraction $\mathcal{B}(B^- \to D^{*0}K^{*-})$ is calculated from

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

where $N_{m_{ES}}$ is the event yield from the m_{ES} fit, N_{pk} is the peaking background, $N_{B\bar{B}} = (85.8 \pm 0.9) \times 10^6$ is the number of $B\bar{B}$ pairs in the data sample, $\mathcal{B}_{K^{*-}}$ and $\mathcal{B}_{K_S}$ are the branching fractions for $K^{*-} \to K_S\pi^-$ and $K_S \to \pi^+\pi^-$, i is an index that runs over the six D^{*0}/D^0 modes considered in this analysis, ϵ^i_{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 i-th 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 the branching fraction calculation are summarized in Table I. Combining the six D^{*0}/D^0 modes, we measure a branching fraction

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

The reconstruction efficiencies for photons and charged tracks are understood at the level of 2.5% per photon and 0.8% per track, based on studies of a variety of control samples. These are the dominant systematic uncertainties in the determination of $\mathcal{B}$. The efficiencies of many of the analysis requirements are measured in the large $B^- \to D^{*0}\pi^-$ control sample. The uncertainties on $\mathcal{B}$ are listed in Table II.

We also compute the branching fraction $\mathcal{B}(B^- \to D^{*0}K^{*-})$ using only events from the individual D^{*0}/D^0 modes (see Table I). The branching fractions measured in the $D^{*0} \to D^0\gamma$ modes are somewhat lower than those measured in the $D^{*0} \to D^0\pi^0$ modes. However, in the $B^- \to D^{*0}\pi^-$ sample, where the D^{*0} is reconstructed with identical techniques, we find agreement between data and expectations for the relative yields of events in all six modes. Thus, we ascribe the difference in the measured branching fractions between the modes listed in Table I to statistical fluctuations.

The angular distributions for the decay chains $B^- \to D^{*0}K^{*-}$ followed by $D^{*0} \to D^0\pi^0$ or $D^0\gamma$ are expressed in terms of three amplitudes H_0 (longitudinal), H_+, and H_-(transverse), and three angles, θ_D, θ_K and χ [14]. 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. The experimental acceptance is nearly independent of χ. Integrating over χ, the angular distributions reduce to

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

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

TABLE I: Summary of the elements of the branching fraction calculation. $N_{m_{ES}}$ is the yield from the m_{ES} fit; N_{pk} is the number of peaking background events; ϵ^i_{MC} is the event selection efficiency for the i-th 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 i-th mode.

D^{*0} mode	D^0 mode	$N_{m_{ES}}$	N_{pk}	$\sum(\epsilon^i_{MC}\times\mathcal{B}^i)(\times10^{-3})$		$\mathcal{B}(B^-\to D^{*0}K^{*-})(\times10^{-4})$
All	All	121 ± 15	6.8 ± 3.4	1.6 ± 0.2		$8.3\pm1.1\pm1.0$
$D^{*0}\to D^0\pi^0$	All	96 ± 12	4.8 ± 2.4	1.0 ± 0.1		$10.2\pm1.3\pm1.3$
$D^{*0}\to D^0\gamma$	All	24 ± 8	2.0 ± 1.0	0.6 ± 0.1		$4.4\pm1.7\pm0.8$
				ϵ^i_{MC}	$\mathcal{B}^i$	
$D^{*0}\to D^0\pi^0$	$D^0\to K^-\pi^+$	26 ± 5	1.7 ± 0.9	$(6.5\pm0.6)\%$	$(0.54\pm0.03)\%$	$8.0\pm1.8\pm0.9$
$D^{*0}\to D^0\pi^0$	$D^0\to K^-\pi^+\pi^0$	39 ± 8	1.7 ± 0.9	$(2.1\pm0.3)\%$	$(1.85\pm0.15)\%$	$10.9\pm2.4\pm1.7$
$D^{*0}\to D^0\pi^0$	$D^0\to K^-\pi^+\pi^+\pi^-$	31 ± 7	1.4 ± 0.7	$(2.9\pm0.4)\%$	$(1.06\pm0.07)\%$	$11.6\pm2.6\pm1.6$
$D^{*0}\to D^0\gamma$	$D^0\to K^-\pi^+$	11 ± 4	0.1 ± 0.1	$(5.7\pm0.5)\%$	$(0.33\pm0.03)\%$	$6.8\pm2.7\pm1.0$
$D^{*0}\to D^0\gamma$	$D^0\to K^-\pi^+\pi^0$	11 ± 5	1.7 ± 0.9	$(1.9\pm0.2)\%$	$(1.14\pm0.12)\%$	$5.3\pm2.9\pm1.0$
$D^{*0}\to D^0\gamma$	$D^0\to K^-\pi^+\pi^+\pi^-$	0 ± 5	0.2 ± 0.1	$(2.5\pm0.3)\%$	$(0.65\pm0.07)\%$	$-0.2\pm3.3\pm0.4$

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

Source	Uncertainty
Statistical	13.1%
π^0 and γ efficiency	6.0%
Tracking efficiency	4.5%
$m_{\rm ES}$ 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%

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 (θ_D,θ_K) distribution for events with $m_{ES} > 5.27$ GeV. The data distribution (D) is fit to the sum of distributions 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 combinatorial background determined from the m_{ES} yield fit, 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 of transverse and longitudinal decays, including detector acceptance effects. The distribution of C is estimated from data candidates in a sideband of $m_{\rm ES}$ ($5.20 < m_{\rm ES} < 5.27$ GeV). 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 $\Gamma_L/\Gamma = 0.87\pm0.07({\rm stat})\pm0.03({\rm syst})$ and $0.80\pm0.14({\rm stat})\pm0.04({\rm syst})$ 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 the results from the two D^{*0} modes, we find $\Gamma_L/\Gamma = 0.86\pm0.06({\rm stat})\pm0.03({\rm syst})$. The systematic uncertainty reflects the accuracy of the simulation ($\pm$ 0.017), the uncertainty on the fraction c ($\pm$ 0.017), the finite statistics of the simulation ($\pm$ 0.010), the uncertainties related to the fit assumptions ($\pm$ 0.010), and the uncertainty due to the assumption that the acceptance is independent of χ ($\pm$ 0.004). As a consistency check, we fit the θ_D distribution in the $B^-\to D^{*0}\pi^-$ sample. We find $\Gamma_L/\Gamma = 1.00\pm0.01$, in agreement with the expectation $\Gamma_L/\Gamma = 1$ from angular momentum conservation.

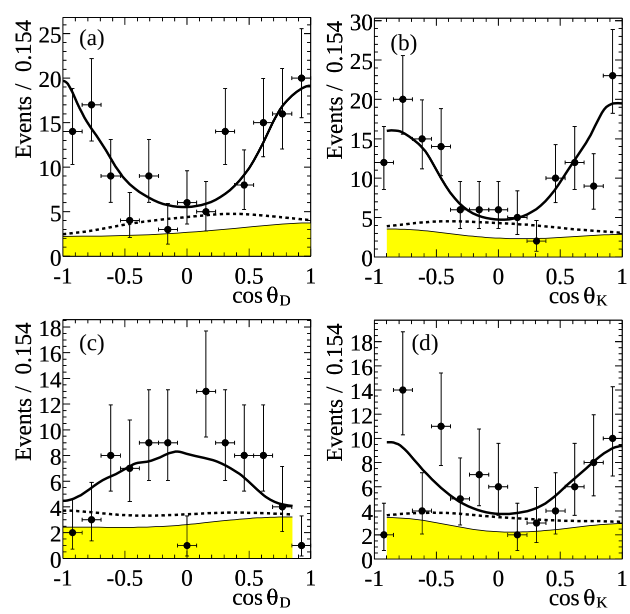

FIG. 2: Distributions of (a) $\cos\theta_D$ and (b) $\cos\theta_K$ for $D^{*0}\to D^0\pi^0$. Distributions of (c) $\cos\theta_D$ and (d) $\cos\theta_K$ for $D^{*0}\to D^0\gamma$. The solid line represents the full fit model, the dashed line represents the transverse component, and the shaded region represents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

In summary, we have measured the branching fraction for $B^- \to D^{*0}K^{*-}$ to be $\mathcal{B} = (8.3 \pm 1.1(\text{stat}) \pm 1.0(\text{syst})) \times 10^{-4}$. Our measurement is a factor of 2.5 more precise than the previous result. It is in agreement with predictions based on the measured $B^- \to D^{*0}\rho^-$ branching fraction [15], and the value of the Cabibbo angle. We have also measured the longitudinal polarization fraction in this decay to be $\Gamma_L/\Gamma = 0.86 \pm 0.06(\text{stat}) \pm 0.03(\text{syst})$. This last result is consistent with expectations [16] 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 $B^- \to D^{*0}K^{*-}$.

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