

B meson decays to open charm and charmonium at BaBar

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Since it began recording data in 1999, the BaBar detector at the SLAC B Factory has collected nearly 90 million B meson pairs. Using this sample, we are able to make precise measurements of B decays to open charm and charmonium. In particular, we have measured the rates for $B \rightarrow D\bar{D}K$, for the color-suppressed modes $B^0 \rightarrow D^0\pi^0$, $B^0 \rightarrow D^0\eta$, and $B^0 \rightarrow D^0\omega$, for $B^+ \rightarrow \chi_c^0 K^+$, and for $B^0 \rightarrow D_s^{(*)+} D^{*-}$. We have also begun preparations for a measurement of the CKM angle γ by studying the modes $B^+ \rightarrow D^0 K^+$, $B^0 \rightarrow D_s^{(*)+} \pi^-$, and $B^0 \rightarrow D_s^{(*)+} K^-$.

1. Introduction

There are two primary motivations for studying B decays to open charm and charmonium. The first is to improve the understanding of hadronic B meson decay. In particular, we can test the decay rates to two-body modes predicted in some models.

The second motivation is to improve our understanding of CP violation in the B meson system. Decays to charmonium states have already been used to perform a precision measurement of $\sin 2\beta$ [1]. A program aimed at measuring the other sides and angles of the Unitarity Triangle may reveal CP violation that cannot be explained by the standard model. Some open charm decays offer the promise of measuring the angle γ , and the first steps in the program are presented here.

2. Detector and Dataset

The BaBar detector is described in detail in [2]. It consists of a five-layer double-sided silicon tracker followed by a 40-layer drift chamber and Cherenkov particle identification system. A CsI(Tl) electromagnetic calorimeter provides precision measurement of electron and photon energies. All of these detectors are contained within the bore of a 1.5T solenoid. The flux return is in-

strumented with resistive plate chambers to allow detection of muons and neutral hadrons.

BaBar began collecting data in 1999, and has recorded nearly 90 million B meson pair events; some analyses discussed here use only a subset of this sample.

3. B Meson Reconstruction

B mesons are reconstructed by combining tracks or photons to form candidates for the intermediate mesons in the decay, constraining these mesons to their known masses, and then combining them to form B candidates. Two kinematic variables distinguish signal from background. The first is $\Delta E \equiv E_B^* - E_{\text{beam}}^*$, where E_B is the B candidate energy and E_{beam} is the beam energy, and the asterisks denote that these quantities are calculated in the center-of-mass frame. The second variable is $m_{ES} \equiv \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}}$, where p_B is the B candidate's momentum. True B mesons will have ΔE near zero and m_{ES} near the known B mass.

Backgrounds from continuum quark pair production are reduced using variables that differentiate the two-jet structure typical of continuum events from the uniform energy distribution of $B\bar{B}$ events. Two of the most important variables

are the ratio of the second to zeroth Fox-Wolfram moments and the angle between the B candidate direction and the thrust axis of the particles not taken as originating from the B candidate.

4. Measurement of $\mathcal{B}(B \rightarrow D^{(*)}\overline{D}^{(*)}K)$

Measurements of the B meson's semileptonic branching fraction \mathcal{B}_{sl} are lower than one would expect from a naive parton model. In addition, the average number of charm quarks produced during a decay n_c is also lower than expected [3], and reconciling these two measurements is not straightforward.

Recently, more sophisticated models of B decay have predicted a \mathcal{B}_{sl} consistent with experiment [4]. Also, in the past n_c has been inferred under the assumption that the quark transition $b \rightarrow c\bar{c}s$ always produced either a D_s or charmonium meson, so there may be a neglected contribution arising from light quark pair production from the vacuum, resulting in $D^{(*)}\overline{D}^{(*)}K$ final states.

The primary challenge in measuring $\mathcal{B}(B \rightarrow D^{(*)}\overline{D}^{(*)}K)$ is that there are a total of 10 (12) such modes for neutral (charged) B mesons. The measurement presented here is the first in which all 22 B decay modes are considered. D^{*+} mesons are reconstructed via their decay to $D^0\pi^+$, and D^{*0} mesons are reconstructed via both $D^0\pi^0$ and $D^0\gamma$. D^0 candidates are formed from $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^-\pi^+$, and D^+ candidates are formed from $K^-\pi^+\pi^+$. After selecting candidates with ΔE less than 2.5σ from its central value, a fit to the m_{ES} distribution of all modes summed in a sample of 82 million $B\overline{B}$ pairs yields a signal of $823 \pm 57 B^0$ and $969 \pm 65 B^+$ events. To extract the branching fraction, a binned Poisson likelihood fit is performed for each submode. The fit accounts for the varying reconstruction efficiencies, background levels, and cross-feed among modes. Of the 22 B decay modes, 11 have signals with greater than 4σ significance. The branching fraction for $B^0 \rightarrow D^*\overline{D}^{(*)}K$ is found to be $(4.3 \pm 0.3(\text{stat.}) \pm 0.6(\text{syst.}))\%$, and that for $B^+ \rightarrow D^*\overline{D}^{(*)}K$ is $(3.5 \pm 0.3(\text{stat.}) \pm 0.5(\text{syst.}))\%$. These values confirm that $D^*\overline{D}^{(*)}K$ modes do

make a significant contribution to n_c . A more complete description of this analysis is available in [5].

5. Measurement of Color-suppressed Decay Rates

In the simplest versions of the factorization model, two-body B decays are classified according to whether the quarks from the virtual W boson decay hadronize as a single meson (color-allowed decay) or pair with the c and spectator quarks in forming mesons (color-suppressed decay) [6]. The non-perturbative components of the decay amplitude are assumed to be the same for all decays in each class, and are denoted a_1 and a_2 for color-allowed and color-suppressed decays respectively. Within this framework, the rates for the color-suppressed decays $B \rightarrow D^0\pi^0$, $B \rightarrow D^0\eta$, and $B \rightarrow D^0\rho$ are expected to be between 0.3 and 0.7×10^{-4} .

We reconstruct these decays by forming D^0 mesons from $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^-\pi^+$, π^0 and η mesons from photon pairs, and ω mesons from $\pi^+\pi^-\pi^0$. The $D^0\pi^0$ mode faces a substantial background from the color-allowed decay $B^+ \rightarrow D^0\rho^+$, which can mimic the signal if the π^+ originating from the ρ^+ is sufficiently soft. To reduce this background, any candidates to which a π^+ can be added to create a viable $D^0\rho^+$ candidates are excluded. In the $D^0\omega$ analysis, the vector nature of the ω results in its daughters having distinctive angular distributions, and this fact is exploited to reduce backgrounds.

The ΔE distributions for candidates in all three modes in a sample of 49 million B meson pairs are shown in Fig. 1. The signals are extracted using an unbinned maximum likelihood fit to the m_{ES} distributions, and corrected for the amount of peaking background predicted from Monte Carlo simulations. $291 \pm 31 D^0\pi^0$, $101 \pm 14 D^0\eta$, and $78 \pm 12 D^0\omega$ events are observed, which correspond to branching fractions of $(2.89 \pm 0.29(\text{stat.}) \pm 0.38(\text{syst.})) \times 10^{-4}$, $(2.41 \pm 0.39(\text{stat.}) \pm 0.32(\text{syst.})) \times 10^{-4}$, and $(2.48 \pm 0.40(\text{stat.}) \pm 0.32(\text{syst.})) \times 10^{-4}$ respectively. These values are significantly higher than the factorization model predicts, indicating that

the phenomenology of B decays requires a more detailed treatment. A more complete description of this analysis can be found in [7].

6. Measurement of $\mathcal{B}(B^+ \rightarrow \chi_{c0}K^+)$

Another prediction of factorization models is that decays such as $B^+ \rightarrow \chi_{c0}K^+$ are disallowed, since there is no color-singlet operator that can give rise to this final state [8]. However, if soft gluon interactions (i.e. color-octet operators) play a significant role, the decay can proceed [9]. By comparing the rate of $B^+ \rightarrow \chi_{c0}K^+$ to that for $B^+ \rightarrow \chi_{c1}K^+$ (which can proceed through both color-singlet and -octet operators) the importance of soft gluon interactions in these decays can be estimated.

We reconstruct χ_{c0} candidates via their decay to $\pi^+\pi^-$ and K^+K^- , with particle identification information used to assign the proper mass to the tracks. Rejection of continuum background is achieved by combining eleven variables into a Fisher discriminant. The most dangerous residual background is that arising from non-resonant $B^+ \rightarrow \pi^+\pi^-K^+$ or $K^+K^-K^+$, which have the same distribution in m_{ES} and ΔE as the signal. To mitigate their impact, any candidates with a $K\pi$ pair having invariant mass near the D^0 mass, or a KK pair near the ϕ mass, are excluded from the analysis. Monte Carlo simulation predicts that the remaining ‘‘exact match’’ backgrounds are negligible. This is confirmed by extracting the signal with two methods. In the first, candidates near the χ_{c0} mass are selected, and the signal taken from a fit to the m_{ES} distribution. In the second method, the χ_{c0} mass window is widened, and a two-dimensional fit to the m_{ES} and χ_{c0} mass distributions is used to extract the signal. The central value for the branching fraction is derived from the first method, and the difference between the two is taken as a systematic uncertainty.

The resulting preliminary branching fraction of $(2.4 \pm 0.7(\text{stat.} \oplus \text{syst.})) \times 10^{-4}$ is significantly non-zero, but smaller than that for $B^+ \rightarrow \chi_{c1}K^+$, implying that soft gluon exchange plays an important, but not dominant, role in B decay to charmonium final states. Further details are available

in [10].

7. Measurement of Rate and Polarization of $B^0 \rightarrow D_s^{(*)+}D^{*-}$

An additional constraint on models of B decay can be obtained from decays of the type $B^0 \rightarrow D_s^{(*)+}D^{*-}$. In this case, not only the decay rate but also the polarization of the vector-vector mode $B^0 \rightarrow D_s^{*+}D^{*-}$ can be compared to their predicted values. The factorization model predicts: $\mathcal{B}(B^0 \rightarrow D_s^+D^{*-}) = (0.58 - 0.70)\%$, $\mathcal{B}(B^0 \rightarrow D_s^{*+}D^{*-}) = (2.32 - 2.45)\%$, and $\Gamma_L/\Gamma_{\text{tot}} = 52\%$ [6].

For this analysis, a full reconstruction of the B meson is not done. Rather, only the $D_s^{(*)}$ and the soft pion from the D^* decay are found. Applying kinematic constraints from the B and D^* masses and the beam energy allows the B meson to be reconstructed up to an arbitrary angle about the slow pion direction. The variable used to distinguish signal from background is the missing mass, which peaks at the D mass for signal. This technique is much more efficiency than fully reconstructing the D^* meson, so only 23 million B meson pairs are required for this analysis.

The signal yields are determined by fitting a Gaussian signal and empirical background shape to the missing mass distribution, and the branching fractions are calculated using the signal efficiency and cross-feed determined by Monte Carlo simulation. The preliminary results are $\mathcal{B}(B^0 \rightarrow D_s^+D^{*-}) = (1.03 \pm 0.14(\text{stat.}) \pm 0.13(\text{syst}) \pm 0.26(\text{meson } \mathcal{B}))\%$ and $\mathcal{B}(B^0 \rightarrow D_s^{*+}D^{*-}) = (1.97 \pm 0.14(\text{stat.}) \pm 0.13(\text{syst}) \pm 0.26(\text{meson } \mathcal{B}))\%$. These values are consistent within 2σ with the values predicted by factorization.

The polarization of the $D_s^{*+}D^{*-}$ mode is determined from the helicity angles of the slow pion from the D^* decay and the photon from the D_s^{*+} decay. Here the missing mass is constrained to the D mass to fix the pion angle. The observed distributions are corrected for background and detector acceptance. To minimize the magnitude of these corrections, only the purest subsample, that in which the D_s^+ is reconstructed as $\phi\pi^+$, is used. The preliminary resulting polarization

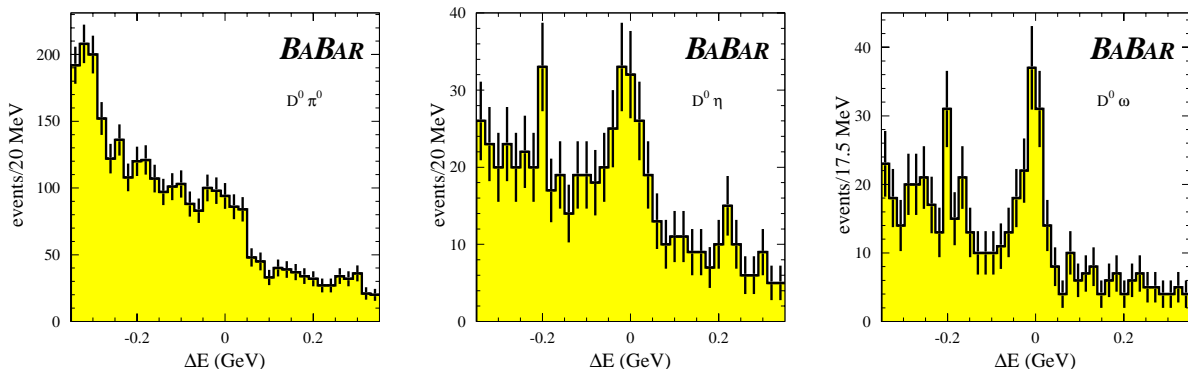


Figure 1. ΔE distributions for $B^0 \rightarrow D^0 \pi^0$ (left), $B^0 \rightarrow D^0 \eta$ (center), and $B^0 \rightarrow D^0 \omega$ (right) candidates.

is $\Gamma_L/\Gamma_{\text{tot}} = (51.9 \pm 5.0(\text{stat.}) \pm 2.8(\text{syst.}))\%$, in excellent agreement with the prediction from factorization. For further details on this analysis, see [11].

8. Measurement of Rate and CP Asymmetry for $B^+ \rightarrow D^0 K^+$

Measurement of the CKM angle γ in a manner analogous to that of the $\sin 2\beta$ measurement requires the study of B_s decay, and thus will not be possible at BaBar for the foreseeable future. However, other techniques have been proposed, some of which depend on measuring the rate and direct CP asymmetry in the decay $B^+ \rightarrow D^0 K^+$ [12].

For the rate analysis, D^0 mesons are reconstructed via their decays to $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^-\pi^+$. The primary challenge is that the $D^0 K^-$ signal has the same distribution in m_{ES} as the more common $D^0 \pi^-$ mode. To separate the signal from this and other backgrounds, a three-dimensional unbinned maximum likelihood fit to the m_{ES} , ΔE , and K identification probability distributions is used. To partially cancel systematics, the relative rate of $D^0 K^-$ to $D^0 \pi^-$ is measured, and the preliminary result (based on a total extracted signal of 810 ± 33 events from 58 million B meson pairs), is $(8.31 \pm 0.35(\text{stat.}) \pm 0.20(\text{syst.}))\%$.

For the CP asymmetry measurement, decays of the D to a CP eigenstate must be used, and we choose the mode $D^0 \rightarrow K^+ K^-$. Since the

uncertainty for this measurement is dominated by statistics, the sample size is increased to 81 million B pairs. Within this sample we observe $21.7 \pm 5.6 B^-$ and $15.3 \pm 5.6 B^+$ candidates, yielding a preliminary CP asymmetry of $0.17 \pm 0.23(\text{stat.})_{-0.08}^{+0.09}(\text{syst.})$, consistent with zero. Further information about these analyses can be found in [13].

9. Study of $B^0 \rightarrow D_s^{(*)+} \pi^-$ and $B^0 \rightarrow D_s^{(*)+} K^-$

Another way to obtain information about γ is to measure the time-dependent CP asymmetry in $B^0 \rightarrow D^{(*)+} \pi^-$, for which the amplitude $\propto \sin(2\beta + \gamma)$. However, the measurement is not as simple that for $\sin 2\beta$ since the interference that leads to the asymmetry is between the Cabibbo-allowed $\overline{B}^0 \rightarrow D^{(*)+} \pi^-$ and Cabibbo-suppressed $B^0 \rightarrow D^{(*)+} \pi^-$ decays. This means not only that the asymmetry is small ($\mathcal{O}(10^{-2})$) but also that one must know the ratio of the Cabibbo-suppressed to Cabibbo-allowed rates $\lambda_{D\pi}$ in order to extract $\sin(2\beta + \gamma)$.

A step in this direction may be taken by measuring the rate of $B^0 \rightarrow D_s^{*+} \pi^-$, which in the factorization approximation is related via SU(3) to $\lambda_{D\pi}$. This relation only holds, however, to the extent that the W -exchange contribution to $B^0 \rightarrow D^{(*)+} \pi^-$ is small. This can be determined by measuring the rate for $B^0 \rightarrow D_s^{*+} K^-$, which proceeds only via W exchange. The latter mea-

surement is also of interest as no pure W exchange B decays have been previously observed.

Using 84 million B pairs, evidence at the 3.3 and 3.5σ levels is seen for the decays $B^0 \rightarrow D_s^+ \pi^-$ and $B^0 \rightarrow D_s^+ K^-$ respectively, with branching fractions of $(3.2 \pm 0.9(\text{stat.}) \pm 1.0(\text{syst.})) \times 10^5$ and $(3.2 \pm 1.0(\text{stat.}) \pm 1.0(\text{syst.})) \times 10^5$. There is less evidence for $B^0 \rightarrow D_s^{*+} \pi^-$ and $B^0 \rightarrow D_s^{*+} K^-$, so we only quote upper limits on the branching fractions at 90% confidence level of 4.1×10^{-5} and 2.5×10^{-5} respectively. The m_{ES} distributions are shown in Fig. 2.

These results imply that the rate for W -exchange diagrams is less than 1% of that for the dominant W -emission diagram, and therefore that the correction to $\lambda_{D\pi}$ under the factorization assumption is negligible. In this model, then, $\lambda_{D\pi}$ is $0.020 \pm 0.005(\text{stat.} \oplus \text{syst.})$. The central question of whether factorization is a reasonable model for these decays will only be answered through an extensive program of measuring these and related decay rates. Further details of this analysis are available in [14].

10. Summary

B meson decays to open charm and charmonium provide excellent constraints on models of hadronic B decay, and also offer possibilities of providing additional information about CP violation in the B system. The results presented here show that the average charm multiplicity in B meson decay is consistent with expectations. It is also seen that the simplest factorization models cannot explain all hadronic B decays, such as those to color-suppressed modes. Finally, we have demonstrated the ability to complete the first steps of a program to measure the CKM angle γ .

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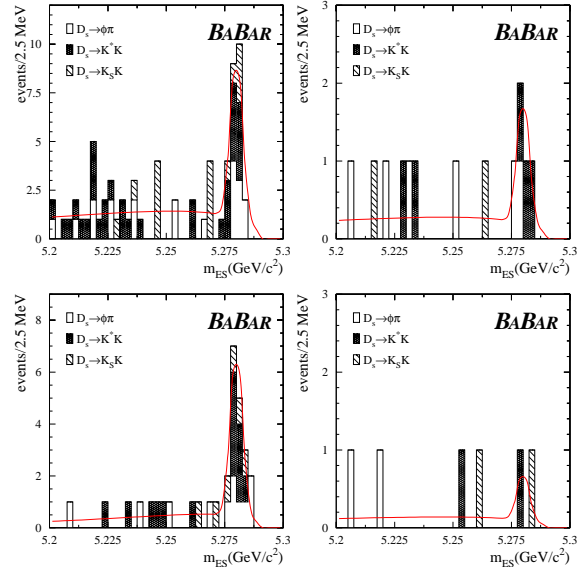


Figure 2. m_{ES} distributions of candidates for $B^0 \rightarrow D_s^+ \pi^-$ (upper left), $B^0 \rightarrow D_s^+ K^-$ (upper right), $B^0 \rightarrow D_s^{*+} \pi^-$ (lower left) and $B^0 \rightarrow D_s^{*+} K^-$ (lower right).

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