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Measurement of the branching fraction for the decay $B^0 \to D^{*+}D^{*-}$

The *BABAR* Collaboration

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Abstract

Decays of the type $B \to D^{(*)}\overline{D}^{(*)}$ can be used to provide a measurement of the parameter $\sin 2\beta$ of the Unitarity Triangle that is complementary to the measurement derived from the mode $B^0 \to J/\psi K^0_S$. In this document we report a measurement of the branching fraction for the decay $B^0 \to D^{*+}D^{*-}$ with the *BABAR* detector. With data corresponding to an integrated luminosity of $20.7\,\text{fb}^{-1}$ collected at the $\Upsilon(4S)$ resonance during 1999-2000, we have reconstructed 38 candidate signal events in the mode $B^0 \to D^{*+}D^{*-}$ with an estimated background of 6.2 ± 0.5 events. From these events, we determine the branching fraction to be $\mathcal{B}(B^0 \to D^{*+}D^{*-}) = (8.0 \pm 1.6(stat) \pm 1.2(syst)) \times 10^{-4}$(preliminary).

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1 Introduction

One of the most important goals of the *BABAR* experiment is to precisely measure the angles of the Unitarity Triangle. While the decay $B^0 \to J/\psi K^0_S$ can be used to measure $\sin 2\beta$, the Standard Model predicts that the time-dependent *CP* violating asymmetries in the decays [1] $B^0 \to D^{(*)+}D^{(*)-}$ can also be used to measure the same quantity. An independent measurement of $\sin 2\beta$ in these modes would therefore provide a consistency test of *CP*-violation in the Standard Model.

The vector-vector decay $B^0 \to D^{*+}D^{*-}$ is not, however, a pure *CP* eigenstate. A sizeable dilution of the measured asymmetry may be produced by a non-negligible *P*-wave *CP*-odd component. The dilution can, in principle, be completely removed by a time-dependent angular analysis of the decay products [2].

The rate for the Cabibbo-suppressed decays $B \to D^{(*)}\overline{D}^{(*)}$ can be estimated from the measured rate of the Cabibbo-favored decays $B \to D_S^{(*)}\overline{D}^{(*)}$:

$$\mathcal{B}(B \to D^{(*)}\overline{D}^{(*)}) \approx \left(\frac{f_{D^{(*)}}}{f_{D_S^{(*)}}}\right) \tan^2\theta_C \cdot \mathcal{B}(B \to D_S^{(*)}\overline{D}^{(*)}), \tag{1}$$

where θ_C is the Cabibbo angle, and $f_{D^{(*)}}$ and $f_{D_S^{(*)}}$ are decay constants. From this it follows that the $B \to D^{(*)}\overline{D}^{(*)}$ branching fractions are of the order of 0.1%. Previous measurements of branching fractions and upper limits for these modes are summarized in Table 1.

Table 1: Summary of branching fraction and upper limit measurements performed by the CLEO experiment [3]. Upper limits are quoted at the 90% confidence level.

Decay	Branching Fraction ($\times 10^{-4}$)
$B^0 \to D^{*+}D^{*-}$	$9.9^{+4.2}_{-3.3}(stat) \pm 1.2(syst)$
$B^0 \to D^{*+}D^-$	< 6.3
$B^0 \to D^+D^-$	< 9.4

2 The *BABAR* detector and dataset

The data used in this analysis were collected with the *BABAR* detector [4] at the PEP-II storage ring [5] located at the Stanford Linear Accelerator Center. The results presented in this paper are based on data taken during the 1999-2000 run. This data sample represents an integrated luminosity of $23.3\,\mathrm{fb}^{-1}$, with $20.7\,\mathrm{fb}^{-1}$ collected on the $\Upsilon(4S)$ resonance. The total number of $B\overline{B}$ pairs produced in this sample was $N_{B\overline{B}} = 22.7 \times 10^6$.

Charged particles are detected and their momenta measured with the combination of a 40-layer drift chamber (DCH) and a five-layer silicon vertex tracker (SVT) embedded in a 1.5 T solenoidal magnetic field. Photons are detected by a CsI electromagnetic calorimeter (EMC) that provides excellent angular and energy resolutions with a high efficiency for energies above 20 MeV. Charged particle identification is provided by the specific ionization loss ($\mathrm{d}E/\mathrm{d}x$) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the barrel region of the detector.

Table 2: D^0 and D^+ decay modes and branching fractions [7]. The branching fraction for $K^0_S \to \pi^+\pi^-$ is included for modes containing a K^0_S.

Decay Mode	Branching Fraction (%)
$D^0 \to K^-\pi^+$	3.83 ± 0.09
$D^0 \to K^-\pi^+\pi^0$	13.9 ± 0.9
$D^0 \to K^-\pi^+\pi^+\pi^-$	7.49 ± 0.31
$D^0 \to K^0_S\pi^+\pi^-$	1.85 ± 0.14
Total D^0 Branching Fraction	27.1
Decay Mode	Branching Fraction (%)
$D^+ \to K^-\pi^+\pi^+$	9.0 ± 0.6
$D^+ \to K^0_S\pi^+$	0.99 ± 0.09
$D^+ \to K^-K^+\pi^+$	0.87 ± 0.07
Total D^+ Branching Fraction	10.9

3 Determination of $\mathcal{B}(B^0 \to D^{*+}D^{*-})$

B^0 mesons are exclusively reconstructed by combining two charged D^* candidates reconstructed in a number of D^* and D decay modes. Events are pre-selected by requiring that there be three or more charged tracks and that the normalized second Fox-Wolfram moment [6] of the event be less than 0.6. We also require that the cosine of the angle between the reconstructed B direction and the thrust axis of the rest of the event be less than 0.9.

Charged kaon candidates are required to be inconsistent with the pion hypothesis, as inferred from the Cherenkov ring measured by the DIRC and the $\mathrm{d}E/\mathrm{d}x$ as measured by the SVT and DCH. There are two exceptions to this: tighter kaon identification is applied to one of the charged kaons in decay $D^+ \to K^-K^+\pi^+$, and no particle identification requirements are made for the kaon from the decay $D^0 \to K^-\pi^+$.

$K^0_S \to \pi^+\pi^-$ candidates are required to have an invariant mass within $25\,\mathrm{MeV}/c^2$ of the nominal K^0_S mass. The opening angle between the flight direction and the momentum vector of the K^0_S candidate is required to be less than 200 mrad, and the transverse flight distance from the primary event vertex must be greater than 2 mm.

Neutral pion candidates are formed from pairs of photons in the EMC with energy above 30 MeV, an invariant mass within $20\,\mathrm{MeV}/c^2$ of the nominal π^0 mass, and a summed energy greater than 200 MeV. A mass-constraint fit is then applied to these π^0 candidates. The π^0 from $D^{*+} \to D^+\pi^0$ decays ("soft" π^0), however, is required to have an invariant mass within $35\,\mathrm{MeV}/c^2$ of the nominal π^0 mass and momentum in the $\Upsilon(4S)$ frame of $70 < p^* < 450\,\mathrm{MeV}/c$, with no requirement on the summed photon energy.

The decay modes of the D^0 and D^+ used in this analysis were selected by an optimization of $S^2/(S+B)$ based on Monte Carlo simulations, where S is the expected number of signal events and B is the expected number of background events. The D^0 and D^+ modes used and their branching fractions are summarized in Table 2. D^0 (D^+) meson candidates are required to have an invariant mass within $20\,\mathrm{MeV}/c^2$ of the nominal D^0 (D^+) mass.

Table 3: D^* decay modes and branching fractions [7].

Particle	Decay Mode	Branching Fraction (%)
D^{*+}	$D^{*+} \to D^0\pi^+$	67.7 ± 0.5
	$D^{*+} \to D^+\pi^0$	30.7 ± 0.5
Total Visible D^{*+} Branching Fraction		98.4

The D^{*+} mesons are reconstructed in their decays $D^{*+} \to D^0\pi^+$ and $D^{*+} \to D^+\pi^0$. We include for this analysis the decay combinations D^{*+} D^{*-} decaying to (D^0 π^+, $\overline{D}^0$ π^-) or (D^0 π^+, D^- π^0), but not (D^+ π^0, D^- π^0) due to the smaller branching fraction and larger expected backgrounds. The branching fractions for these modes are summarized in Table 3. D^0 and D^+ candidates are subjected to a mass-constraint fit and then combined with soft pion candidates. A vertex fit is performed that includes the position of the beam spot to improve the angular resolution of the soft pion.

To select B^0 candidates with well reconstructed D^* and D mesons, we construct a χ^2 that includes all measured D^* and D masses:

$$\begin{aligned}\chi^2_{Mass} = \quad & \left(\frac{m_D - m_{D_{PDG}}}{\sigma_{m_D}}\right)^2 + \left(\frac{m_{\overline{D}} - m_{\overline{D}_{PDG}}}{\sigma_{m_{\overline{D}}}}\right)^2 \\ & + \left(\frac{\Delta m_{D^*} - \Delta m_{D^*_{PDG}}}{\sigma_{\Delta m}}\right)^2 + \left(\frac{\Delta m_{\overline{D}^*} - \Delta m_{D^*_{PDG}}}{\sigma_{\Delta m}}\right)^2\end{aligned}$$

where the subscript PDG refers to the nominal value, and Δm is the $D^* - D$ mass difference. For σ_{m_D} we use values computed for each D candidate, while for $\sigma_{\Delta m}$ we use fixed values of $0.83\,\mathrm{MeV}/c^2$ for $D^{*+} \to D^0\pi^+$ and $1.18\,\mathrm{MeV}/c^2$ for $D^{*+} \to D^+\pi^0$. A requirement that $\chi^2_{Mass} < 20$ is applied to all B^0 candidates. In events with more than one B^0 candidate, we chose the candidate with the lowest value of χ^2_{Mass}.

A B meson candidate is characterized by two kinematic variables. We use the energy-substituted mass, m_{ES}, defined as

$$m_{\mathrm{ES}} \equiv \sqrt{E^{*2}_{Beam} - {p^*_B}^2}$$

and the difference of the B candidate's energy from the beam energy, ΔE ,

$$\Delta E \equiv E^*_B - E^*_{Beam}$$

where E^*_B (p^*_B) are the energy (momentum) of the B candidate in the center-of-mass frame and E^*_{Beam} is one-half of the center-of-mass energy. The signal region in the ΔE *vs.* m_{ES} plane is defined to be $|\Delta E| < 25\,\mathrm{MeV}$ and $5.273 < m_{\mathrm{ES}} < 5.285\,\mathrm{GeV}/c^2$. The width of this region corresponds to approximately $\pm 2.5\sigma$ in both ΔE and m_{ES}.

To estimate the contribution from background in the signal region, we define a sideband in the ΔE *vs.* m_{ES} plane as

$$|\Delta E| < 200\,\mathrm{MeV}$$

$$5.20 < m_{\mathrm{ES}} < 5.26\,\mathrm{GeV}/c^2$$

and

$$50 < |\Delta E| < 200\,\mathrm{MeV}$$

$$5.26 < m_{\mathrm{ES}} < 5.29\,\mathrm{GeV}/c^2$$

We parameterize the shape of the background in the ΔE *vs.* m_{ES} plane as the product of an ARGUS function [8] in m_{ES} and a first-order polynomial in ΔE . Based on this parameterization we estimate that the ratio of the number of background events in the signal region to the number in the sideband region is $(1.72 \pm 0.10) \times 10^{-2}$. The uncertainty is derived from the observed variation of this ratio under alternative assumptions for the background shape in m_{ES} and ΔE .

Figure 1 shows the events in the ΔE *vs.* m_{ES} plane after all selection criteria have been applied. The small box in the figure indicates the signal region defined above, and the sideband is the entire plane excluding the region bounded by the larger box outside the signal region. There are a total of 38 events located in the signal region, with 363 events in the sideband region. The latter, together with the effective ratio of areas of the signal region to the sideband region, implies an expected number of background events in the signal region of $6.24 \pm 0.33(stat) \pm 0.36(syst)$. The quoted systematic uncertainty comes from the background shape variation discussed previously. Figure 2 shows a projection of the data on to the m_{ES} axis after requiring $|\Delta E| < 25\,\mathrm{MeV}$.

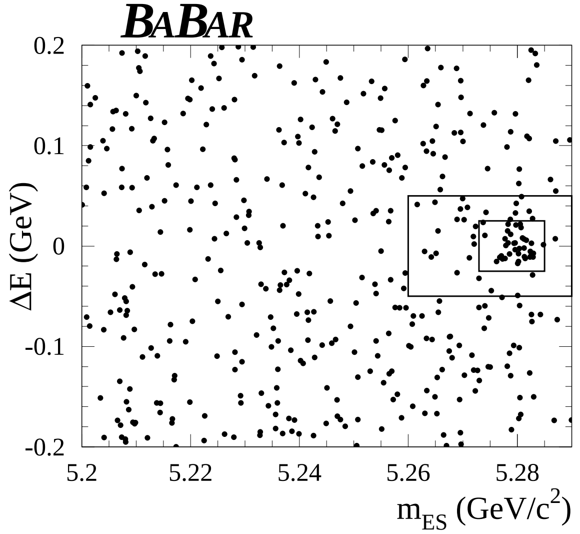

Figure 1: Distribution of events in the ΔE *vs.* m_{ES} plane. The small box indicates the signal region, while the sideband region is everything outside the larger box.

We use a detailed Monte Carlo simulation of the *BABAR* detector to determine the efficiency for reconstructing the signal. This, together with the total number of $B\overline{B}$ pairs produced during data collection, allows us to determine a preliminary branching fraction for $B^0 \to D^{*+}D^{*-}$ to be

$$\mathcal{B}(B^0 \to D^{*+}D^{*-}) = (8.0 \pm 1.6(stat) \pm 1.2(syst)) \times 10^{-4}$$

The dominant systematic uncertainty in this measurement comes from our level of understanding of the charged particle tracking efficiency (9.4%). The high charged particle multiplicity in this decay mode makes this measurement particularly sensitive to tracking efficiency. Uncertainties were assigned on a per track basis for π, K and slow π, and were added linearly due to large

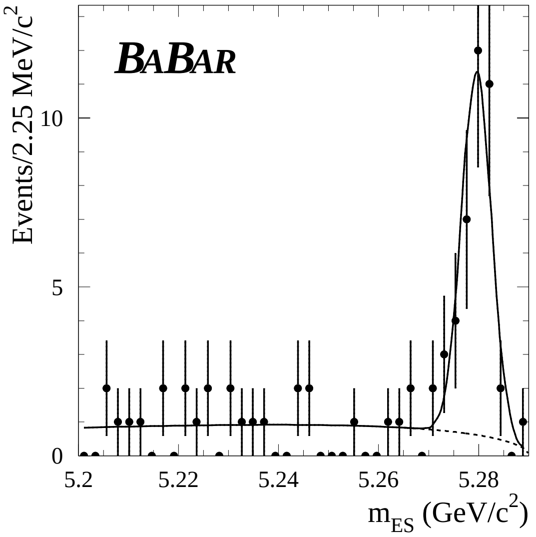

Figure 2: Distribution of events in $m_{\rm ES}$ plane with a cut of $|\Delta E| < 25$ MeV applied. The curve represents a fit to the distribution of the sum of a Gaussian to model the signal and an ARGUS function [8] to model the background shape.

correlations. The imprecisely known partial-wave content of the $B^0 \to D^{*+}D^{*-}$ final state is another source of systematic uncertainty (6.6%). This was estimated by calculating the change in the reconstruction efficiency for different final angular states in Monte Carlo. Other significant systematic uncertainties arise due to the uncertainties on the D^{*+}, D^0 and D^+ branching fractions (5.6%) and the differences in mass resolutions between Monte Carlo and data (4.1%). The total systematic uncertainty from all sources is 14.5%.

4 Summary

Using data collected by the *BABAR* experiment during 1999-2000, we have observed a signal of $31.8\pm6.2(stat)\pm0.4(syst)$ events in the decay $B^0 \to D^{*+}D^{*-}$. We measure a preliminary branching ratio to be

$$\mathcal{B}(B^0 \to D^{*+}D^{*-}) = (8.0 \pm 1.6(stat) \pm 1.2(syst)) \times 10^{-4}$$

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[1] Charge-conjugate states are implied throughout this paper and the symbol $D^{(*)}$ refers to either D or D^*.

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