CLEO CONF 97-21
EPS97 341

Investigation of Semileptonic B Meson Decay to P-Wave Charm Mesons

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(July 26, 1997)

Abstract

We have studied semileptonic B meson decays with a P-wave charm meson in the final state using 3.29×10^6 $B\bar{B}$ events collected by the CLEO II detector at the Cornell Electron-positron Storage Ring. We find a value for the exclusive semileptonic product branching fraction: $\mathcal{B}(B^- \to D_1^0 \ell^- \bar{\nu}_\ell)\, \mathcal{B}(D_1^0 \to D^{*+}\pi^-) = (0.373 \pm 0.085 \pm 0.052 \pm 0.024)\%$ and an upper limit for $\mathcal{B}(B^- \to D_2^{*0} \ell^- \bar{\nu}_\ell)\, \mathcal{B}(D_2^{*0} \to D^{*+}\pi^-) < 0.16\%$ (90% C.L.). These results indicate that at least 20% of the total B^- semileptonic rate is unaccounted for by the observed exclusive decays, $B^- \to D^0 \ell^- \bar{\nu}$, $B^- \to D^{*0} \ell^- \bar{\nu}$, $B^- \to D_1^0 \ell^- \bar{\nu}$, and $B^- \to D_2^{*0} \ell^- \bar{\nu}$.

(Submitted to Physical Review Letters)

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There is general agreement among a number of measurements of the exclusive semileptonic $\bar{B}$ meson decays, $\bar{B} \to D\ell\bar{\nu}_\ell$ and $\bar{B} \to D^*\ell\bar{\nu}_\ell$ [1]. Together they account for approximately 60 – 70% of the inclusive $\bar{B} \to X\ell\bar{\nu}_\ell$ branching fraction [2]. Since the branching fraction for $b \to u\ell\bar{\nu}$ is known to be small, the missing exclusive decays must be sought among $b \to c\ell\bar{\nu}$ decays to higher mass D_J states or nonresonant hadronic states with a D or D^* and other hadrons. Measurements of $B^- \to D_1^0\ell^-\bar{\nu}_\ell$ and $B^- \to D_2^{*0}\ell^-\bar{\nu}_\ell$ have been reported previously [3,4]. In this paper we report new measurements of these two decay modes.

The D_J mesons contain one charm quark and one light quark with relative angular momentum $L = 1$. The quark spins can sum to $S = 0$ or $S = 1$, so there are four spin-parity states given by $J^P = 1^+$ or 0^+, 1^+, and 2^+. Parity and angular momentum conservation restrict the decays available to the four states. According to Heavy Quark Effective Theory (HQET), there exists an approximate spin-flavor symmetry for hadrons consisting of one heavy and one light quark [5]. In the limit of infinite heavy quark mass, such mesons are described by the total angular momentum of the light constituents $j = S_q + L$. In HQET, the D_J mesons make up two doublets, $j = 1/2$ and $j = 3/2$. The members of the $j = 3/2$ doublet are predicted to decay only in a D-wave and to be relatively narrow. The $j = 1/2$ mesons are predicted to decay only in an S-wave and to be relatively broad. In this analysis we study the semileptonic decays of the B meson to final states containing the narrow (j=3/2) excited charm mesons: the ${}^jL_J = {}^{3/2}P_2$ and ${}^{3/2}P_1$, called D_2^* and D_1, respectively [6].

The data used in this analysis were collected by the CLEO II detector at the Cornell Electron-positron Storage Ring (CESR). The CLEO II detector [7] is a multipurpose high energy physics detector incorporating excellent charged and neutral particle detection and measurement. The data sample consists of an integrated luminosity of 3.11 fb^{-1} on the $\Upsilon(4S)$ resonance (ON Resonance), corresponding to 3.29×10^6 $B\bar{B}$ events, and 1.61 fb^{-1} at a center-of-mass energy $\sim$ 55 MeV below the $\Upsilon(4S)$ resonance (OFF Resonance).

The exclusive $B^- \to D_J^0\ell^-\bar{\nu}_\ell$ decay is studied by reconstructing the decay channel $D_J^0 \to D^{*+}\pi^-$ using the decay chain $D^{*+} \to D^0\pi^+$, and $D^0 \to K^-\pi^+$ or $D^0 \to K^-\pi^+\pi^0$ [8]. Hadronic events are required to have at least one track identified as a lepton with momentum between 0.8 GeV/c and 2.0 GeV/c for electrons and between 1.0 GeV/c and 2.0 GeV/c for muons. Electrons are identified by matching energy deposited in the CsI calorimeter and momentum measured in the drift chamber, their energy loss in the drift chamber gas and their time of flight in the detector. The muon identification relies upon penetration through layers of iron absorber to muon chambers. To reduce the background from continuum events, the events are required to satisfy the ratio of Fox-Wolfram [9] moments $R_2 < 0.4$. All charged tracks must originate from the vicinity of the e^+e^- interaction point. Charged kaon and pion candidates, with the exception of the slow pion from the decay of the D^{*+}, have measured ionization losses in the drift chamber within 3.0 and 2.5 standard deviations, respectively, of those expected for the hypothesis under consideration. The invariant mass of the two photons from $\pi^0 \to \gamma\gamma$ must be within 2.0 standard deviations ($\sigma = 5$ to 8 MeV/c^2) of the nominal π^0 mass.

The $K^-\pi^+$ and $K^-\pi^+\pi^0$ combinations are required to have an invariant mass within 16 and 25 MeV/c^2 ($\sim 2\sigma$) of the nominal D^0 mass, respectively. In addition, we select regions of the $D^0 \to K^-\pi^+\pi^0$ Dalitz plot to take advantage of the known resonant substructure [10], and we enforce a minimal energy for the π^0. In the $D^0 \to K^-\pi^+\pi^0$ mode we require $|\mathbf{p}_D| > 0.8$ GeV/c in order to further reject fake D^0 background. We then combine D^0 candidates with π^+ candidates to form D^{*+} candidates. The slow pion used to form the D^{*+} must have a momentum of at least 65

MeV/c. The reconstructed mass difference $\delta m = M(D^0\pi^+) - M(D^0)$ [11] is required to be within 2 MeV/c^2 of the known $D^{*+} - D^0$ mass difference [6]. The D^{*+} candidate is then combined with an additional π^- in the event to form a D_J^0 candidate. The D_J^0 candidates must have a scaled momentum $x_{D_J} = p_{D_J} / \left[E_{\text{beam}}^2 - M^2(D_J)\right]^{\frac{1}{2}} < 0.5$, the kinematic limit from B decays.

These D_J^0 candidates are then paired with leptons selected as described above to form candidates for $B^- \to D_J^0 \ell^- \bar{\nu}_\ell$ decays. To suppress background from $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$, we select $D_J^0\ \ell^-$ candidates that are consistent with $B^- \to D_J^0 \ell^- \bar{\nu}_\ell$ decays, and reject $D_J^0\ \ell^-$ candidates that are consistent with $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$. Thus, we require $D_J^0\ \ell^-$ candidates to have $|\cos\theta_{B-D_J\ell}| \leq 1$ and $\cos\theta_{B-D^*\ell} < -1$, where

$$\cos\theta_{B-D_J\ell} = \frac{|\mathbf{p}_{D_J\ell}|^2 + |\mathbf{p}_B|^2 - |\mathbf{p}_\nu|^2}{2|\mathbf{p}_B||\mathbf{p}_{D_J\ell}|} \tag{1}$$

and

$$\cos\theta_{B-D^*\ell} = \frac{|\mathbf{p}_{D^*\ell}|^2 + |\mathbf{p}_B|^2 - |\mathbf{p}_\nu|^2}{2|\mathbf{p}_B||\mathbf{p}_{D^*\ell}|}. \tag{2}$$

Here, $\theta_{B-D_J\ell}$ ($\theta_{B-D^*\ell}$) is the angle between $\mathbf{p}_B$ and $\mathbf{p}_{D_J\ell}$ ($\mathbf{p}_{D^*\ell}$), where $|\mathbf{p}_B|$ is the known magnitude of the B momentum, and $\mathbf{p}_{D_J\ell}$ ($\mathbf{p}_{D^*\ell}$) is the momentum of the $D_J^0\ \ell^-$ ($D^{*+}\ \ell^-$) candidate. The magnitude of the neutrino momentum $|\mathbf{p}_\nu|$ is inferred from energy conservation, using the beam energy for the B meson energy E_B. To reject uncorrelated background (background from events in which the D_J^0 comes from the $\bar{B}$ and the lepton from the B) we require the D_J^0 and the lepton to be in opposite hemispheres: $\cos\theta_{D_J\ell} < 0$, where $\theta_{D_J\ell}$ is the angle between the D_J^0 and the lepton. The remaining uncorrelated background is negligible.

The $B^- \to D_J^0 \ell^- \bar{\nu}_\ell$ signal is identified using the mass difference $\delta M_J = M(D^{*+}\pi^-) - M(D^{*+})$. To avoid multiple $D_J^0\ \ell^-$ combinations per event, we select the best combination in the event using M(π^0), M(D^0), δm, and $M^2(\nu_\ell) \simeq M_B^2 + M^2(D_J\ell) - 2E_B E(D_J\ell)$, where $E(D_J\ell)$ is the energy of the $D_J^0\ \ell^-$ candidate, and $\mathbf{p}_B$ is taken to be zero.

The δM_J distribution obtained by combining the two decay modes of the D^0 meson is shown in Fig. 1. An unbinned likelihood fit is performed on the δM_J distribution. The fitted function is the sum of a threshold background function [12] plus Breit-Wigner resonance functions with the masses and widths of the two narrow D_J^0 resonances fixed [6]. Each Breit-Wigner function is convoluted with a Gaussian that describes the detector resolution. The width of the Gaussian is estimated by Monte Carlo simulation to be $\sigma = 2.8$ MeV/c^2. The D_1^0 and D_2^{*0} yields obtained from the fit are summarized in Table I.

To check that the data are consistent with the presence of a signal, we fitted the δM_J distribution with only the smooth background function. The difference between the logarithm of the likelihood of the fit with the signal plus the background functions and the logarithm of the likelihood with only the background function is 18.7. Assuming Gaussian statistics, this corresponds to a 6.1σ statistical significance of the signal over the background. If the mass and the width of the D_1^0 resonance are allowed to float, the fitted mass and width obtained are 2420 ± 4 MeV/c^2 and 23 ± 9 MeV/c^2; which is in agreement with the PDG averages [6]. The D_1^0 and D_2^{*0} yields from this fit are 62.5 ± 16.7 and 10.5 ± 9.8, respectively.

The background from non-$B\bar{B}$ events is obtained by measuring the signal yields using OFF Resonance data. The results are scaled by the ratio of the luminosities and the square of the beam energies. Fake lepton background (the contribution in which a D_J^0 is paired with a hadron misidentified as a lepton) is estimated by performing the same analysis using tracks that are not leptons. The fake lepton yields are scaled by the appropriate misidentification hadron probabilities and abundances. The sums of these two types of backgrounds are subtracted from the ON Resonance Yields as indicated in Table I.

Semileptonic $\bar{B}$ decays to more highly excited charmed mesons which then decay to D_J^0 mesons are predicted to be small [13]. The smooth background function includes both combinatoric background and background from broad and non-resonant $D^{*+}\pi^- X$ states.

TABLE I. Yields and product branching fractions. The first error on the product branching fractions is statistical, the second is experimental systematic and the third is theoretical.

	D_1^0	D_2^{*0}
ON Resonance Yield	56.6 ± 11.9	10.3 ± 9.4
Background Yield	3.1 ± 2.8	1.5 ± 2.8
Net Yield	53.5 ± 12.2	8.8 ± 9.8
$\mathcal{P}(D_J^0)$	$(0.373 \pm 0.085 \pm 0.052 \pm 0.024)$ %	$(0.059 \pm 0.066 \pm 0.010 \pm 0.004)$ %

The product branching fractions $\mathcal{P}(D_1^0) = \mathcal{B}(B^- \to D_1^0\ell^-\bar{\nu}_\ell)\,\mathcal{B}(D_1^0 \to D^{*+}\pi^-)$ and $\mathcal{P}(D_2^{*0}) = \mathcal{B}(B^- \to D_2^{*0}\ell^-\bar{\nu}_\ell)\,\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-)$ are obtained by dividing the yields by the total numbers of B^- events in our data sample and the sum of the products of the efficiencies times the D^{*+} and D^0 branching fractions for the modes used. The reconstruction efficiencies (ε), summed over e and μ, are $\varepsilon_{D_1}^{K\pi} = (8.74{\pm}0.19)\%$, $\varepsilon_{D_1}^{K\pi\pi^0} = (2.18{\pm}0.05)\%$, $\varepsilon_{D_2^*}^{K\pi} = (9.21{\pm}0.19)\%$, and $\varepsilon_{D_2^*}^{K\pi\pi^0} = (2.21{\pm}0.05)\%$. Our event selection efficiencies were obtained using Monte Carlo data generated according to the ISGW2 model [13]. We assume that the branching fractions of $\Upsilon(4S)$ to charged and neutral $B\bar{B}$ pairs are each 50%. The values of the D^{*+} and D^0 branching fractions are taken from Ref. [6]. The contributions of the systematic uncertainties are listed in Table II. The theoretical uncertainties associated with the model dependence of the efficiency is obtained by varying the parameters and the form factors used in the ISGW2 model. We choose to quote the product of branching fractions because the branching fractions for $D_J^0 \to D^{*+}\pi^-$ have not been measured. We find:

$$\mathcal{P}(D_1^0) = (0.373 \pm 0.085 \pm 0.052 \pm 0.024)\ \% \tag{3}$$

$$\mathcal{P}(D_2^{*0}) = (0.059 \pm 0.066 \pm 0.010 \pm 0.004)\ \% < 0.16\ \%\ (90\%\ \text{C.L.}). \tag{4}$$

The first error on $\mathcal{P}(D_J^0)$ is statistical, the second is experimental systematic and the third is theoretical. For the quoted upper limit, we add the experimental systematic and the theoretical uncertainties in quadrature, and add the result to the upper limit computed with the statistical error only.

In order to estimate the contribution of these decays to the total semileptonic B meson branching fraction, we need to make some assumptions about the branching fractions of the D_J^0 mesons. Isospin conservation and CLEO measurements [14] of the decays of the D_J^0 mesons suggest that $\mathcal{B}(D_1^0 \to D^{*+}\pi^-) = 67\%$ and $\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-) = 20\%$. Using these estimates we find

$$\mathcal{B}(B^- \to D_1^0\ell^-\bar{\nu}_\ell) = (0.56 \pm 0.13 \pm 0.08 \pm 0.04)\ \% \tag{5}$$

$$\mathcal{B}(B^- \to D_2^{*0}\ell^-\bar{\nu}_\ell) < 0.8\ \%\quad (90\%\ \text{C.L.}), \tag{6}$$

where no attempt has been made to estimate the systematic uncertainties due to the $D_J^0 \to D^{*+}\pi^-$ branching fractions.

A clear picture of the exclusive modes which make up the 30 – 40% of the B semileptonic decays that are not $D\ell\nu$ and $D^*\ell\nu$ has not yet emerged. However, it appears that no more than half of the excess can be due to exclusive semileptonic decays to $D_1^0(2420)$ and $D_2^{*0}(2460)$.

In summary, we have studied exclusive semileptonic decays of the B mesons to P-wave charm mesons. We measured a branching fraction for $\mathcal{B}(B^- \to D_1^0\ell^-\bar{\nu}_\ell)\,\mathcal{B}(D_1^0 \to D^{*+}\pi^-)$ and an upper limit for $\mathcal{B}(B^- \to D_2^{*0}\ell^-\bar{\nu}_\ell)\,\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-)$. These results indicate that a substantial fraction ($\gtrsim$20%) of the inclusive B semileptonic rate is from modes other than $D\ell\nu$, $D^*\ell\nu$, $D_1\ell\nu$ and $D_2^*\ell\nu$.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the National Science Foundation, the U.S. Department of Energy, the Heisenberg Foundation, the Alexander von Humboldt Stiftung, the Natural Sciences and Engineering Research Council of Canada, le Fonds Québécois pour la Formation de Chercheurs et l'Aide à la Recherche, and the A.P. Sloan Foundation.

TABLE II. Systematic errors on the product branching fractions. Tracking uncertainties are for all charged particles other than the slow π.

Source of Systematic Error	$\mathcal{P}(D_1^0)$	$\mathcal{P}(D_2^{*0})$
M_{D_J}	1.0%	1.1%
Γ_{D_J}	10.0%	14.0%
Background Function	4.0%	5.0%
Uncorrelated Background	0.5%	0.4%
Lepton Fake	1.0%	1.0%
Lepton ID	1.3%	1.3%
MC Statistics	1.5%	1.5%
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	2.0%	2.0%
$\mathcal{B}(D^0 \to K^-\pi^+(\pi^0))$	3.5%	3.5%
Slow π Efficiency	5.0%	5.0%
Tracking Efficiency	4.0%	4.0%
π^0 Reconstruction	2.4%	2.4%
Dalitz Weight	1.9%	1.9%
Multiple Counting	1.4%	1.4%
Particle Identification	1.0%	1.0%
Luminosity	2.0%	2.0%
Total	14.0%	17.3%

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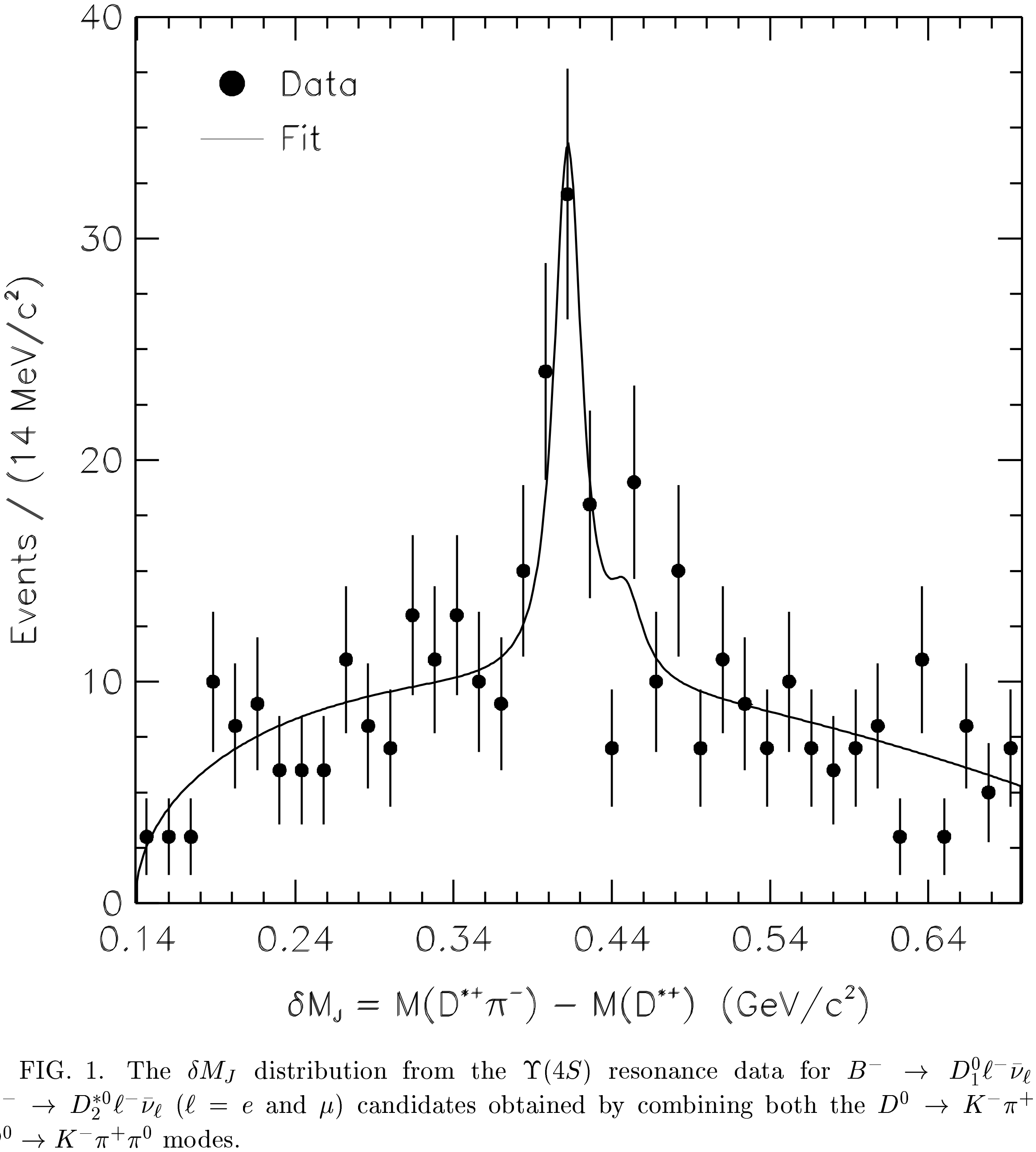

FIG. 1. The δM_J distribution from the $\Upsilon(4S)$ resonance data for $B^- \to D_1^0 \ell^- \bar{\nu}_\ell$ and $B^- \to D_2^{*0} \ell^- \bar{\nu}_\ell$ ($\ell = e$ and μ) candidates obtained by combining both the $D^0 \to K^- \pi^+$ and $D^0 \to K^- \pi^+ \pi^0$ modes.