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Measurement of Semileptonic B Decays into Orbitally-Excited Charmed Mesons

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We present a study of B decays into the semileptonic final states containing charged and neutral charmed states of the $j = s_q + L = 3/2$ doublet, $D_1(2420)$ and $D_2^*(2460)$, which decay via D wave transitions. The analysis is based on a data sample of $208\,\mathrm{fb}^{-1}$ collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC. With a simultaneous fit to four different decay chains, the semileptonic branching fractions are extracted from the measurements of the mass difference $\Delta m = m(D^{**}) - m(D)$ distributions. Product branching fractions are determined to be $\mathcal{B}(B^+ \to D_1^0 \ell^+ \nu_\ell) \times \mathcal{B}(D_1^0 \to D^{*+}\pi^-) = (2.97 \pm 0.17 \pm 0.18) \times 10^{-3}$, $\mathcal{B}(B^+ \to D_2^{*0} \ell^+ \nu_\ell) \times \mathcal{B}(D_2^{*0} \to D^{(*)+}\pi^-) = (2.29 \pm 0.23 \pm 0.20) \times 10^{-3}$, $\mathcal{B}(B^0 \to D_1^- \ell^+ \nu_\ell) \times \mathcal{B}(D_1^- \to D^{*0}\pi^-) = (2.78 \pm 0.24 \pm 0.26) \times 10^{-3}$ and $\mathcal{B}(B^0 \to D_2^{*-} \ell^+ \nu_\ell) \times \mathcal{B}(D_2^{*-} \to D^{(*)0}\pi^-) = (1.77 \pm 0.26 \pm 0.11) \times 10^{-3}$. In addition we measure the branching ratio $\Gamma(D_2^* \to D\pi^-)/\Gamma(D_2^* \to D^{(*)}\pi^-) = 0.62 \pm 0.03 \pm 0.06$.

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Higher excitations than the D^* play an important role in the understanding of semileptonic B decays. Precise knowledge of their properties is important to reduce the uncertainties on measurements of other semileptonic decays, and thus the determination of the CKM elements $|V_{cb}|$ and $|V_{ub}|$. One fraction of the excited charmed states is given by the orbitally-excited D^{**} states. In the framework of Heavy Quark Symmetry, they form two doublets with $j_q^P = 1/2^-$ and $j_q^P = 3/2^-$ where j_q^P denotes the spin-parity of the light quark coupled to the orbital angular momentum. The doublet with $j_q^P = 3/2^-$, namely the D_1 and D_2^*, have to decay via D-wave to conserve parity and angular momentum and therefore are narrow [1]. In this paper we describe a simultaneous measurement of all B semileptonic decays to the two narrow orbitally-excited charmed states without explicit reconstruction of the rest of the event.

The CLEO collaboration has reported a measurement for the neutral D_1 and an upper limit for the D_2^{*0} [2]. More recently Belle and *BABAR* have reported preliminary results using a technique in which one of the B in the process $\Upsilon(4S) \to B\overline{B}$ is fully reconstructed [3].

The data used in this analysis were collected with the *BABAR* detector at the PEP-II storage ring. A total integrated luminosity of $208\,\mathrm{fb}^{-1}$ has been recorded at a center of mass energy of the $\Upsilon(4S)$.

The *BABAR* detector and event reconstruction is described in detail elsewhere [4]. A Monte Carlo (MC) simulation based on GEANT4 [5] is used to estimate signal efficiencies and to understand the background. The sample of simulated $B\overline{B}$ events is equivalent to approximately three times the data sample. In addition a dedicated simulation of signal events has been produced with samples of roughly five times the expected signal events contained in the data based on the ISGW2 model [6].

D^{**} decays are reconstructed in the decay chains $D^{**}\to D^*\pi^-$ [7], and $D^{**}\to D\pi^-$. The former is accessible to both narrow D^{**} states while the latter has no contribution from the D_1. Intermediate D^* states are reconstructed in $D^*\to D^0\pi$ and the D mesons are reconstructed exclusively in $D^0\to K^-\pi^+$ and $D^+\to K^-\pi^+\pi^+$. Finally D^{**} candidates are paired with reconstructed leptons and required to be consistent with the semileptonic decays $B \to D^{**}\ell\nu$, as described in the following.

The signal event reconstruction proceeds as follows. First, events are selected which are likely to contain a semileptonic B decay. We require that there is a reconstructed D candidate and at least one lepton in the event with a momentum greater than $800\,\mathrm{MeV}/c$ in the center-of-mass (CM) frame [8]. Neutral D meson candidates are formed by $K^-\pi^+$ combinations requiring the invariant mass to be consistent with the D^0 mass within three sigma: $1.846 < m(K\pi) < 1.877\,\mathrm{GeV}/c^2$. This asymmetric mass window is choosen to take into account resolution effects of the detector.

D^0 candidates are combined with charged and neutral pions to form D^* candidates. For charged D^* the mass difference between the D^* and the D^0 is required to be $144 < m(D^0\pi^+) - m(D^0) < 148\,\mathrm{MeV}/c^2$. For neutral D^* the π^0 is reconstructed from a photon pair with an invariant mass of $115 < m_{\gamma\gamma} < 150\,\mathrm{MeV}/c^2$. Those photon pairs are re-fitted in a mass constrained fit to match the nominal mass of the π^0. The mass difference between the D^{*0} and the D^0 is required to be $140 < m(D^0\pi^0) - m(D^0) < 144\,\mathrm{MeV}/c^2$.

D^+ candidates are formed from $K^-\pi^+\pi^+$ combinations with an invariant mass of $1.854 < m(K\pi\pi) < 1.884\,\mathrm{GeV}/c^2$. The probability that the three tracks originate from a common vertex, P_{Vtx}, is required to be $P_{\mathrm{Vtx}}(K\pi\pi) > 0.01$.

Candidates for D and D^* are combined with charged pions to form D^{**} candidates. These are combined with muons or electrons. The charge of the lepton is required to match the charge of the kaon from the D decay. Assuming that the reconstructed visible part of the decay ($Y = D^{**}\ell$) is produced in a semileptonic B decay with a massless neutrino being the only missing particle, the decay kinematic is determined up to one angular quantity. The energy of the initial B is determined from the incident beam energies, hence conservation of four-momentum leads to the relation

$$\cos_{BY} = -\frac{2E_B E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$$

where E, $|\vec{p}|$ and m are the energies, momenta and masses of the B and the Y respectively measured in the CM-frame. If the assumption is correct, cos_{BY} is the cosine of the angle between the directions of flight of the B and the Y. If the assumption made is not correct, this quantity does not represent a physical angle and therefore can take any value. Thus only events with values of $|cos_{BY}| \leq 1$ are selected.

In case a D^* is reconstructed in the decay chain a veto is applied against decays $B \to D^*\ell\nu$ by calculating the variable $cos_{BY'}$ which is defined as above but the Y system is redefined to contain only the D^* and the lepton: $Y' = D^*\ell$. In this variable, signal events of the type $B \to D^{**}\ell\nu$ tend to have values less than -1. Background events, especially events with a true $B \to D^*\ell\nu$ decay, are rejected by the requirement $cos_{BY'} < -1$.

For the decay modes $D^{**}{\to}D\pi$ this veto cannot be applied. Instead, events reconstructed in this channel are rejected if the D^0 can be paired with any charged pion to form a D^{*+} candidate as described above. In addition, if multiple $D^{**}\ell$ candidates are present in the event, we retain the candidate with $\tilde{m}_\nu^2$ closest to zero, where $\tilde{m}_\nu^2$ is the neutrino mass squared, calculated under the approximation that the B momentum vanishes in the CM frame. The neutrino mass squared is given by $\tilde{m}_\nu^2 = m_B^2 + |\vec{p}^*_{D^{**}\ell}|^2 - 2E_B^* E^*_{D^{**}\ell}$, where $\vec{p}^*$ and E^* denote the momentum and energy of a particle in the CM frame.

Furthermore, $D^{**}\ell$ candidates are selected only if the angle between the direction of flight for the D^{**} and the lepton exceeds 90 degrees in the CM frame. This criterion rejects combinations where the lepton comes from the decay of the other B. Finally, an event is also rejected if the pion emitted by the D^{**} and the lepton have a probability to originate from a common vertex of less than 0.001. In about 2% of the events more than one $D^{**}\ell$ candidate is selected and if so all of them enter the analysis.

Remaining background events are dominantly decays $B \to D^{(*)}\ell\nu$. Backgrounds from the process $e^+e^- \to q\overline{q}$ with $q = u, d, s, c$ are small compared to the $B\overline{B}$ background sources.

We perform a binned χ^2 fit to the distributions of the mass difference $\Delta m = m(D^{**}) - m(D)$ to extract the yield of events in the four different final states, specifically $B^{+/0} \to D^{*+/0}\pi^-\ell\nu$ with contributions from both D_1 and D_2^*, and $B^{+/0} \to D^{+/0}\pi^-\ell\nu$ for D_2^* only. To disentangle the D_1 and D_2^* contributions, we subdivide the $D^*\pi^-\ell\nu$ data into subsamples, based on the helicity-angle ϑ_h of the D^*. This quantity is defined as the angle between the two pions emitted by the D^{**} and the D^* in the rest frame of the D^*. For a D^* produced by a D_2^* this angle must follow a distribution proportional to $\sin^2\vartheta_h$. For D_1 decays, the helicity-angle is distributed like $1 + A_{D_1}\cos^2\vartheta_h$, where A_{D_1} is a parameter which depends on the initial polarization of the D_1 and a possible contribution of the S-wave to the D_1 decay. For unpolarized D_1 decaying purely via D-wave, A_{D_1} is predicted to be $A_{D_1} = 3$. To make use of this, the spectra of the two decay chains including a D^* are split into four bins each of equal size in $|\cos\vartheta_h|$. This gives a total of ten mass-difference spectra which are fitted simultaneously.

The fit contains twelve parameters to describe the signals and 22 parameters for the backgrounds. Signal distributions in the mass-difference spectra are described by Breit-Wigner functions. For the signal the branching fractions of the D^{**} production for the charged and neutral narrow states give four free parameters. The masses of the states are also fitted, but are constrained to be equal for charged and neutral states, giving two parameters. Four additional parameters arise from the effective widths of the D^{**} states, which represent a convolution of the intrinsic widths and detector resolution effects. The detector resolution contributes approximately $2-3\,\mathrm{MeV}/c^2$ depending on the mode. For the decay of the D_2^*, namely the ratio $\mathcal{B}_{D/D^*} = \Gamma(D_2^* \to D\pi^-)/\Gamma(D_2^* \to D^{(*)}\pi^-)$, measurements and calculations point to a ratio near two, but with uncertainties of about 30% [9]. We therefore allow this ratio to vary freely in the fit and furthermore the mixing parameter A_{D_1} describing the distribution of the helicity-angle is a free parameter as well.

Backgrounds are modeled by polynomial functions of third order in the mass difference. For the modes $D^{**}{\to}D^*\pi^-$ the shape of the background events in Δm has been found to be independent of the helicity binning. Therefore only the normalisation of the background function is allowed to vary for the different spectra of a given reconstruction channel.

The selection efficiency is deduced from a fit to the simulation. This fit uses the same parameterization as the fit determining the branching fractions from data and is applied to the sum of the full background simulation and the simulation of only one signal, the D_1 or the D_2^*. In the D^* modes the efficiencies have been found to be equal for D_1 and D_2^*. For all four channels the efficiencies are: $\epsilon(D^{*+}\pi^-) = (6.89 \pm 0.12)\%$, $\epsilon(D^{*0}\pi^-) = (5.34 \pm 0.12)\%$, $\epsilon(D^+\pi^-) = (12.88 \pm 0.96)\%$ and $\epsilon(D^0\pi^-) = (17.56 \pm 0.70)\%$, where the quoted uncertainties are the statistical uncertainties from the fit. For the decays including a D^* the efficiency is multiplied by the probability for a D^{**} to decay with a value of $|\cos\vartheta_h|$ falling into a given bin. This factor includes the theoretical distribution discussed above as well as corrections for the different detector acceptances in the four helicity bins of up to 10%. The total number of B mesons in the full data sample is derived as described in [10]. For the charged and neutral B mesons we assume $\Gamma(\Upsilon(4S) \to B^+B^-)/\Gamma(\Upsilon(4S) \to B^0\overline{B}^0) = 1.065 \pm 0.026$ [11].

In order to validate the fit procedure several cross-checks have been made. The analysis procedure is tested on statistically independent MC simulated data samples and was found to successfully reproduce the simulated signal parameters with a $\chi^2/n = 12.66/12$, where n is the number of signal parameters. Consistent fit results were also obtained when the data sample was separated into subsamples representing specific data taking periods, or separated by electron on muon modes. Furthermore the fit is tested on data by restricting it to certain decay modes, using charged or neutral D^{**} only, or combining the helicity-bins.

The results of the fit are shown in figure 1. As expected the contribution of the D_2^* vanishes for large values of

TABLE I: Extracted yields for the four signal modes in the five relevant Δm-spectra.

mode	$\|\cos\vartheta_h\|$	D_1^0	D_2^{*0}	D_1^+	D_2^{*+}
$D^*\pi^+$	[0 |0.25]	344	273	212	152
$D^*\pi^+$	[0.25| 0.5]	470	238	286	123
$D^*\pi^+$	[0.5 |0.75]	699	170	439	83
$D^*\pi^+$	[0.75| 1]	1027	67	668	31
$D\pi^+$		–	8414	–	3361

$|\cos\vartheta_h|$ while the contribution of the D_1 is suppressed for $\cos\vartheta_h$ close to zero. The extracted yields are given in table I

All systematic uncertainties have been propagated through the fit procedure taking the correlations between the results into account. Efficiencies for reconstructing and selecting the particles of the final state are derived from Monte Carlo simulation. The simulation of the tracking and the π^0-reconstruction has been studied by comparing τ decays to one and three charged tracks and with or without a neutral pion. Uncertainties introduced by the particle identification for kaons and leptons are studied using control samples with high purities for the particles in question. The impact of the finite statistics of the simulated signal events is deduced from the fit-error of the efficiency-determination.

The branching fractions of the decays of the D^* and the D are taken from [9]. The uncertainty of the number of B mesons in the data set is determined as in [10]. In addition the uncertainty in the ratio of charged and neutral B mesons produced is taken into account.

Uncertainties introduced by the physics model which was used to simulate the MC have been addressed by re-doing the fit after fixing the functions describing the backgrounds to the shapes derived from the simulation. The deviations in the results are taken as a conservative estimate of the uncertainty. A possible influence of the background description has been tested by varying the parameterizations. The backgrounds are alternatively described by a square-root function multiplied by either polynomials or exponentials in Δm. Aa an additional crosscheck the fit was performed with one background-parameterization while using an aletrnative parameterization for the determination of the efficiencies.

Table II gives a summary on the various sources of systematic uncertainties and their impact on the results. Added in quadrature the total systematic uncertainties on the semileptonic branching fractions are 5-10% depending on the D^{**} type.

In summary, we have measured the four branching fractions of B mesons decaying semileptonically into narrow D^{**}. Taking into account the unknown decay rates

TABLE II: Summary of systematic uncertainties of the determination of the semileptonic branching fractions.

Source	$\Delta\mathcal{B}(B\to D^{**}\ell\nu)/\mathcal{B}(B\to D^{**}\ell\nu)[\%]$			
	D_1^0	D_2^{*0}	D_1^+	D_2^{*+}
tracking	1.76	1.39	1.03	1.14
π^0-efficiency	0.06	0.29	3.25	0.60
particle identification	2.61	2.75	3.11	1.60
MC statistics	1.80	5.61	2.50	3.32
helicity correction	0.65	0.14	0.17	0.31
number of B mesons	2.68	2.68	2.68	2.68
$\mathcal{B}(D^{*+}\to D^0\pi^+)$	0.76	0.19	0.04	0.10
$\mathcal{B}(D^{*0}\to D^0\pi^0)$	0.11	0.45	5.07	0.93
$\mathcal{B}(D^0\to K^-\pi^+)$	1.89	0.42	1.78	2.03
$\mathcal{B}(D^+\to K^-\pi^+\pi^+)$	0.07	2.67	0.24	0.54
bkg. parameterization	1.93	1.68	3.20	2.71
modeling	3.24	4.05	3.96	1.52
total systematic	6.23	8.68	9.45	6.06

of the D^{**} we find the product branching fractions

$$\begin{aligned}
\mathcal{B}(B^+ &\to D_1^0\ell^+\nu_\ell)\times\mathcal{B}(D_1^0\to D^{*+}\pi^-)\\
&= (2.97\pm 0.17_{stat}\pm 0.18_{syst})\times 10^{-3},\\
\mathcal{B}(B^+ &\to D_2^{*0}\ell^+\nu_\ell)\times\mathcal{B}(D_2^{*0}\to D^{(*)+}\pi^-)\\
&= (2.29\pm 0.23_{stat}\pm 0.20_{syst})\times 10^{-3},\\
\mathcal{B}(B^0 &\to D_1^-\ell^+\nu_\ell)\times\mathcal{B}(D_1^-\to D^{*0}\pi^-)\\
&= (2.78\pm 0.24_{stat}\pm 0.26_{syst})\times 10^{-3},\\
\mathcal{B}(B^0 &\to D_2^{*-}\ell^+\nu_\ell)\times\mathcal{B}(D_2^{*-}\to D^{(*)0}\pi^-)\\
&= (1.77\pm 0.26_{stat}\pm 0.11_{syst})\times 10^{-3}
\end{aligned}$$

and $\Gamma(D_2^*\to D\pi^-)/\Gamma(D_2^*\to D^{(*)}\pi^-) = 0.62\pm 0.03_{stat}\pm 0.06_{syst}$. We observe all modes with significances greater than 5σ and achieve for the modes already observed a better precision than previous measurements [2, 3, 12].

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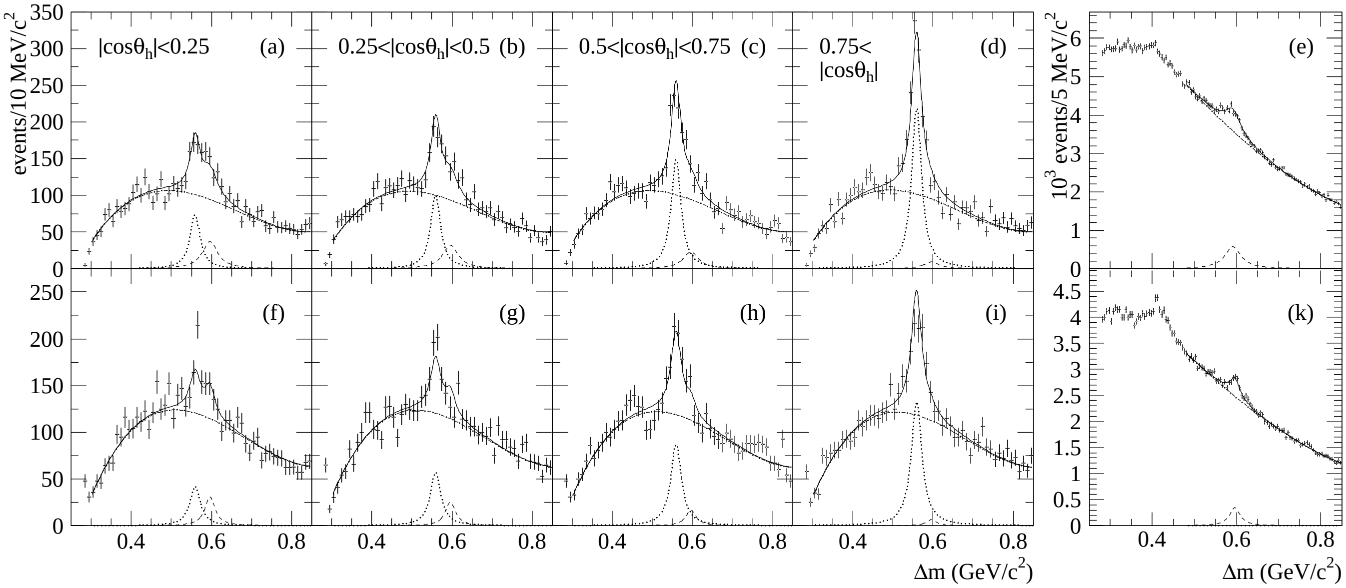

FIG. 1: Δm-spectra for the selected data and the results of the fitted functions. The solid line represents the complete fit function, dotted (D_1) and dashed (D_2^*) lines the signal parts and dash-dotted the background. (a) to (d) show the mode $D^{**0}\to D^{*+}\pi^-$ with increasing values for $|\cos\vartheta_h|$, (e) the mode $D^{**0}\to D^+\pi^-$. (f) to (i) show the corresponding bins in $|\cos\vartheta_h|$ for the mode $D^{**+}\to D^{*0}\pi^+$ and (k) the mode $D^{**+}\to D^0\pi^+$.

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