MEASUREMENT OF THE DECAY $B^0 \to D^- \ell^+ \nu$

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Using the ARGUS detector at the e^+e^- storage ring DORIS II, we have investigated the decay $B^0 \to D^- \ell^+ \nu$, where ℓ^+ is e^+ or μ^+. The B^0 mesons were produced in 150 000 $\Upsilon(4S)$ decays. Assuming electron-muon universality we obtain a branching ratio $BR(B^0 \to D^- e^+ \nu) = BR(B^0 \to D^- \mu^+ \nu) = (1.8 \pm 0.6 \pm 0.5)\%$.

The study of exclusive B meson semileptonic decays can provide important information on the Kobayashi–Maskawa (KM) matrix elements, the ratio of lifetimes for B^0 and B^- mesons, and the quark dynamics of the weak $b \to c$ transition. According to the theoretical predictions [1–8] the inclusive semileptonic width of the B^0 meson is nearly saturated by two exclusive channels [#1]:

$$B^0 \to D^- \ell^+ \nu\,, \qquad (1)$$

$$B^0 \to D^*(2010)^- \ell^+ \nu\,. \qquad (2)$$

Since the matrix element for reaction (1) contains only one substantial form factor, the measurement of $BR(B^0 \to D^- \ell^+ \nu)$ allows a nearly model independent determination of the KM matrix element $|V_{cb}|$.

D and D* (2010) mesons are the lowest-lying charmed hadronic states and thus the relative contributions of (1) and (2) determine the shape of the inclusive lepton spectrum from B meson decays near the endpoint. This region is important for the determination of the KM matrix element $|V_{ub}|$.

At present, theoretical models [1–8] predict various values for $\Gamma(B^0 \to D^- \ell^+ \nu)$, $\Gamma(B^0 \to D^*(2010)^- \ell^+ \nu)$ and for the ratio R,

$$R = \frac{BR(B^0 \to D^*(2010)^- \ell^+ \nu)}{BR(B^0 \to D^- \ell^+ \nu)}\,.$$

The decay mode (2) has already been measured by ARGUS [9,10]. Here we present the first measurement of the branching ratio for decay mode (1).

The data used for this analysis were taken on the $\Upsilon(4S)$ resonance. The total luminosity is 172 pb^{-1}, corresponding to about 150 000 B meson pairs. A description of the ARGUS detector and its trigger requirements as well as its particle identification capabilities can be found in ref. [11].

For lepton identification, information from all detector components is used coherently by combining the measurements into an overall likelihood ratio. The available information consists of dE/dx and time-of-flight measurements, and the magnitude and topology of energy deposition in the shower counters. In addition, for muons, a hit in an outer muon chamber is required and information on the distance between the hit and the expected impact point is included in the likelihood. The e^+ or μ^+ hypothesis is accepted if the appropriate likelihood ratio exceeds 70%.

The partial reconstruction of the decay $B^0 \to D^- \ell^+ \nu$ is possible because B^0 mesons from $\Upsilon(4S)$ decays are produced nearly at rest. The neutrino is unobserved, but can be inferred if the recoil mass squared against the $D^- \ell^+$ system, $M^2_{\rm recoil}$, is consistent with zero. $M^2_{\rm recoil}$ is defined by

$$M^2_{\rm recoil} = (E_{\rm beam} - E_{D^-} - E_{\ell^+})^2 - (\boldsymbol{p}_{D^-} + \boldsymbol{p}_{\ell^+})^2 \approx M^2_\nu.$$

In this expression the energy of the B meson is sub-

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[#1] References in this paper to a specific charged state are to be interpreted as implying the charged-conjugate state also.

stituted by the well measured beam energy and the unknown momentum of the B meson is neglected. D^- mesons are reconstructed in the decay channel $D^- \to K^+\pi^-\pi^-$.

For further analysis we selected events which contain $K^+\pi^-\pi^-\ell^+$ combinations and fulfill the following conditions:

(1) The number of reconstructed charged tracks from the main vertex is larger than 4.

(2) The momentum of the ℓ^+ and of the $K^+\pi^-\pi^-$ combinations is less than 2.5 GeV/c, the kinematical limit for particles produced in decay (1) at the Υ(4S) energy.

(3) The momentum of the lepton is larger than 1 GeV/c.

In addition the momentum of the $K^+\pi^-\pi^-$ combination was required to be greater than 1.5 GeV/c. This cut is very useful since only approximately 20% of D^- mesons from the decay (1) have momentum lower than 1.5 GeV/c, while the momentum spectrum of D^- mesons from the cascade decay

$$B^0 \to D(2010)^{*-}\ell^+\nu, \quad D(2010)^{*-} \to D^-(\pi^0 \text{ or } \gamma) \qquad (3)$$

is considerably softer [9]. Thus, the cut on the D^- momentum reduces the contribution from cascade decay (3), which is the main source of physical background. In addition this cut strongly reduces the combinatorial background.

Fig. 1 shows the $K^+\pi^-\pi^-$ invariant mass spectra for events which contain a positive lepton in different intervals of M^2_{recoil}. One observes a D^- peak at $M^2_{\text{recoil}} \approx 0$ and no signal in the M^2_{recoil} sidebands. The number of D^- mesons in each interval of M^2_{recoil} was obtained from fits to these spectra. The spectra were fitted with a function which is a sum of a gaussian to parametrize the signal and a background function. The background function is a sum of a gaussian, in order to describe a contribution from the decay $D^*(2010)^- \to \bar{D}^0\pi^-$ followed by $\bar{D}^0 \to K^+\pi^-$, plus a polynomial. The region of reflections from $\bar{D} \to K^+\pi^-\pi^-X$ decays was excluded from the fit. Other reflections were insignificant enough to be neglected. The results of this procedure are collected in table 1.

The remaining background sources in the observed $D^-\ell^+$ combinations are as follows:

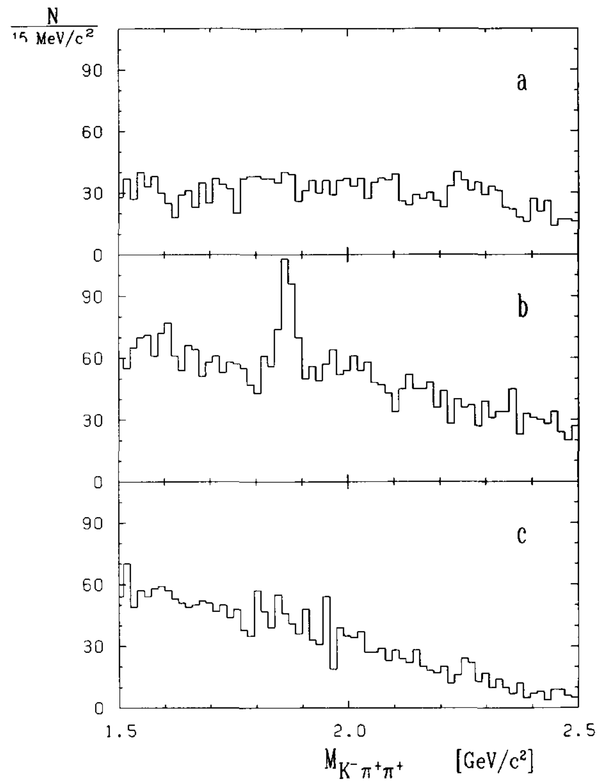

Fig. 1. Invariant mass spectrum of $K^+\pi^-\pi^-$ combinations in events which contain ℓ^+ for different intervals of M^2_{recoil}: (a) $-1.5 < M^2_{\text{recoil}} < -0.5$ GeV$^2/c^4$, (b) $-0.5 < M^2_{\text{recoil}} < 0.5$ GeV$^2/c^4$, (c) $0.5 < M^2_{\text{recoil}} < 1.5$ GeV$^2/c^4$.

(a) Continuum under the Υ(4S) resonance.

(b) Uncorrelated D^- and ℓ^+ from different B mesons.

(c) Fake leptons.

(d) Cascade decays (3).

The determination of backgrounds from (a), (b) and (c) is analogous to the technique used in ref. [10]. The background contributions from (a) and (b) have been determined from Monte Carlo studies. The background due to fake leptons has been measured directly from the data using the number of D^--hadron combinations and the misidentification probabilities. The background contributions from sources (a), (b) and (c) are presented in table 1. They are all relatively small.

Fig. 2 shows the M^2_{recoil} distribution for $D^+\ell^-$ combinations after subtraction of the backgrounds

Table 1
The observed number of $D^-\ell^+$ combinations and contributions from the background sources for different regions of M^2_{recoil}

	M^2_{recoil} [GeV $^2/c^4$] intervals		
	−1.5; −0.5	−0.5; 0.5	0.5; 1.5
number of $D^-\ell^+$ combinations	10±11	135±18	22±11
background sources:			
(a) continuum	6± 3	10± 4	6± 3
(b) uncorrelated D^- and ℓ^+	6± 3	6± 3	4± 2
(c) fake leptons	5± 3	6± 3	6± 3
signal for $B^0\to D^-\ell+\nu X$	− 7±12	113±19	6±12

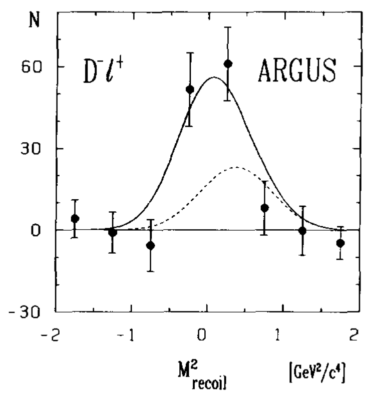

Fig. 2. Distribution of M^2_{recoil} against the $D^-\ell^+$ system. The dashed curve shows the contribution from the cascade decay $B^0\to D^*(2010)^-\ell^+\nu\to D^-(\pi^0,\gamma)\ell^+\nu$.

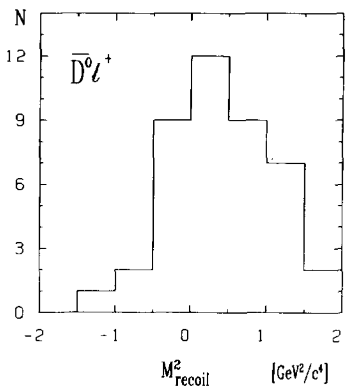

Fig. 3. Distribution of M^2_{recoil} against the $\bar{D}^0\ell^+$ system with $\bar{D}^0$ originating from cascade decays $B^0\to D^*(2010)^-\ell^+\nu$.

arising from (a), (b) and (c). The prominent peak at $M^2_{recoil}\approx 0$ includes the decay $B^0\to D^-\ell^+\nu$ as well as a contribution from cascade decay (3). The latter contribution has been determined from the data by studying the decay $B^0\to D^*(2010)^-\ell^+\nu$, followed by $D^*(2010)^-\to\bar{D}^0\pi^-$. This decay mode is completely analogous to decay mode (3). $\bar{D}^0$ mesons were reconstructed in the decay $\bar{D}^0\to K^+\pi^-$. For $\bar{D}^0\ell^+$ combinations we applied the same kinematical cuts as for D^- and ℓ^+. Fig. 3 shows the spectrum of the recoil mass squared against the $\bar{D}^0\ell^+$ system with $\bar{D}^0$ originating from D^{*-}. The spectrum is shifted from zero to positive values because in the this case M^2_{recoil} is determined by the invariant mass of the $\nu\pi^-$ system. The shape of the M^2_{recoil} distribution for this decay determined by Monte Carlo studies is in good agreement with the observed spectrum. Source of background for the $D^*(2010)^-\ell^+$ signal are described in detail in ref. [10]. In this analysis they are estimated to contribute 11±4 events. After background subtraction 30±7 $\bar{D}^0\ell^+$ candidates are retained. In order to determine the expected contribution from the cascade decay (3) to the M^2_{recoil} signal for $D^-\ell^+$ combinations (see fig. 2), one has to scale the obtained number of $\bar{D}^0\ell^+$ combinations by a factor

$$F=[1-BR(D^*(2010)^-\to\bar{D}^0\pi^-)]$$
$$\cdot BR(D^-\to K^+\pi^-\pi^-)\cdot\eta_{D^-}$$
$$\times[BR(D^*(2010)^-\to\bar{D}^0\pi^-)\cdot BR(\bar{D}^0\to K^+\pi^-)$$
$$\cdot\eta_{D^*(2010)^-}]^{-1},$$

where η_{D^-} ($\eta_{D^*(2010)^-}$) is the efficiency for reconstruction of D^- ($D^*(2010)^-$) folded with the spectrum of D^- ($D^*(2010)^-$) from the semileptonic decay (2). Using $BR(D^*(2010)^-\to\bar{D}^0\pi^-)=(57\pm4\pm)\%$ [12], $BR(D^-\to K^+\pi^-\pi^-)=(9.1\pm1.3$

$\pm 0.4)$%, BR($\bar{D}^0 \to K^+\pi^-$) = $(4.2 \pm 0.4 \pm 0.4)$% [13], $\eta_{D^-} = (42 \pm 2)$% and $\eta_{D^*(2010)^-} = (30 \pm 3)$%, we obtain $F = 2.3 \pm 0.5$.

A sum of two gaussians, representing the shapes of the direct (1) and cascade (3) decays was fitted to the $M^2_{\rm recoil}$ spectrum (fig. 2). The parameters of the gaussians were determined from Monte Carlo. The contribution from cascade decay (3) was constrained within the errors by the measured number of $\bar{D}^0\ell^-$ combinations multiplied by the factor F. By this procedure we obtain a signal of 82 ± 27 $B^0 \to D^-\ell^+\nu$ decays.

The dashed curve in fig. 2 shows the fit result for the contribution (55 ± 18 events) from cascade decays (3). The contribution from other possible cascade decays such as

$$B^0 \to \bar{D}_J(2420)^*\ell^+\nu, \quad \bar{D}_J \to D^- + X \qquad (4)$$

has been tested by including the reflection from (4) in the fit. The fit result for this contribution is consistent within errors with zero and does not change the number of $B^0 \to D^-\ell^+\nu$ decays.

The reconstruction efficiency for the decay $B^0 \to D^-\ell^+\nu$ has been determined from Monte Carlo studies to be 0.18 ± 0.02. The extrapolation to smaller ℓ^+ and D^- momenta was performed using the WBS model [1]. However, since the matrix element for $B^0 \to D^-\ell^+\nu$ decay contains only one substantial form factor, other theoretical models predict the same momentum spectra for ℓ^+ and D^-.

Assuming BR($\Upsilon(4S) \to B^0\bar{B}^0$) = 45% and electron–muon universality, we obtain

$$\mathrm{BR}(B^0 \to D^-e^+\nu) = \mathrm{BR}(B^0 \to D^-\mu^+\nu) = (1.8 \pm 0.6 \pm 0.5)\%,$$

where the first error is statistical and the second systematic. The statistical error includes the uncertainty of the scaling factor F. The systematic errors arise from the uncertainties in the number of $\Upsilon(4S)$ decays, BR($D^- \to K^+\pi^-\pi^-$), the reconstruction efficiency and the shapes of the recoil mass spectra for the direct (1) and cascade (3) decays.

Scaling the ARGUS branching ratio for $B^0 \to D^*(2010)^-\ell^+\nu$ [9] to the new value of BR($D^*(2010)^- \to \bar{D}^0\pi^-$) [12] used in this work, we obtain BR($B^0 \to D^*(2010)^-\ell^+\nu$) = $(6.0 \pm 1.0 \pm 1.4)$% and hence

$$R = \frac{\mathrm{BR}(B^0 \to D^*(2010)^-\ell^+\nu)}{\mathrm{BR}(B^0 \to D^-\ell^+\nu)} = 3.3^{+3.7}_{-1.1},$$

where statistical and systematic errors are added in quadrature.

The decay $B^0 \to D^-\ell^+\nu$ has been studied theoretically by several authors [1–8]. The theoretical predictions for the width and the parameter R are presented in table 2. Using the WBS model [1] and $\tau_B = (1.15 \pm 0.14) \times 10^{-12}$ s [14] we obtain

$$|V_{cb}| = 0.044 \pm 0.009.$$

The value for $|V_{cb}|$ obtained from other theoretical models are also shown in table 2. One observes that the model dependence of $|V_{cb}|$ is considerably smaller than the experimental errors.

In summary, we have observed the decay $B^0 \to D^-\ell^+\nu$ with a branching ratio $(1.8 \pm 0.6 \pm 0.5)$%.

Table 2
$\Gamma(B^0 \to D^-\ell^+\nu)$, ratio R and $|V_{cb}|$ as determined from this analysis using different models.

	R	$\Gamma(B^0 \to D^-\ell^+\nu)$ [10^{12} s^{-1}]	$\lvert V_{cb}\rvert$
this experiment	$3.3^{+3.7}_{-1.1}$	0.016 ± 0.007	
models			
WBS [1]	2.7	$8.1 \cdot \lvert V_{cb}\rvert^2$	0.044 ± 0.009
SP [2]	9.6	$7.2 \cdot \lvert V_{cb}\rvert^2$	0.047 ± 0.009
KS [4]	3.1	$8.3 \cdot \lvert V_{cb}\rvert^2$	0.044 ± 0.009
GISW [6]	2.2	$11.1 \cdot \lvert V_{cb}\rvert^2$	0.038 ± 0.009
CPK [7]	3.0	$9.0 \cdot \lvert V_{cb}\rvert^2$	0.042 ± 0.009
OS [8]	1.2	$9.4 \cdot \lvert V_{cb}\rvert^2$	0.041 ± 0.009

This measurement leads to an almost model independent value of $|V_{cb}| = 0.044 \pm 0.009$.

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