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Measurement of the decay $B^- \to D^{*0} \ell^- \bar{\nu}$

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Using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY, we have studied the decay $B^- \to D^{*0}\ell^-\bar{\nu}$, where $\ell^- = e^-$ or μ^-, using the $D^0\gamma$ and $D^0\pi^0$ decay modes of the D^{*0} meson. B mesons were produced in 209 000 decays of $\Upsilon(4S)$. Assuming electron–muon universality, we obtain a value for the branching ratio of $BR(B^- \to D^{*0}\ell^-\bar{\nu}) = (5.8 \pm 1.4 \pm 1.3)\%$.

The observation and detailed study of the decays [#1] $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ and $B^0 \to D^-\ell^+\nu$ [1–4] have allowed the extraction of a value for the Cabibbo–Kobayashi–Maskawa matrix element $|V_{cb}|$ and the investigation of quark dynamics in the $b \to c$ transition. The study of the decay $B^- \to D^{*0}\ell^-\bar{\nu}$ can provide additional information on these important questions. Furthermore, a comparison of branching ratios for semileptonic decays of charged and neutral B mesons into D^{*0} and D^{*+} gives an additional method to measure the lifetime ratio $\tau(B^+)/\tau(B^0)$.

In previous papers the decay $B^- \to D^{*0}\ell^-\bar{\nu}$ has been studied without reconstruction of the D^{*0} meson. The CLEO Collaboration has used the spectrum of recoil mass squared against the $D^0\ell^-$ system in $\Upsilon(4S)$ decays to obtain a value for the branching ratio of $BR(B^- \to D^{*0}\ell^-\bar{\nu}) = (4.6 \pm 0.9 \pm 0.9)\%$ [5] [#2]. The Crystal Ball Collaboration has performed a more indirect analysis [7]. From a study of the angular correlations between π^0's from D^{*0} (D^{*+}) decays and electrons with momentum near the endpoint of the lepton spectrum in semileptonic decays of B mesons into $D^*\ell^-\nu$, they found $BR(B^- \to D^{*0}\ell^-\bar{\nu}) = (8.0 \pm 3.4)\%$. Information on the lifetime ratio $\tau(B^+)/\tau(B^0)$ has been previously obtained by ARGUS [8,9], and by CLEO [5]. The lifetime ratios were found to be consistent with unity. These results are in good agreement with the theoretical expectation of approximately equal lifetimes [10,11].

In this paper, we report the first direct study of the decay $B^- \to D^{*0}\ell^-\bar{\nu}$ where the D^{*0} meson is fully reconstructed. B mesons are reconstructed from an observed D^{*0} meson and a lepton with the appropriate charge. The neutrino is unobserved, but can be inferred if the recoil mass squared against the $D^{*0}\ell^-$ system,

$$M^2_{\text{recoil}} = (E_{B^-} - E_{D^{*0}} - E_{\ell^-})^2 - (\boldsymbol{P}_{D^{*0}} + \boldsymbol{P}_{\ell^-})^2 ,$$

is consistent with zero. In decays of the $\Upsilon(4S)$, the energy of the B mesons is known to be the beam energy and its small momentum can be neglected.

The data used for this analysis were taken on the $\Upsilon(4S)$ resonance using the ARGUS detector at the e^+e^- storage ring DORIS II. The integrated luminosity of the sample is 246 pb^{-1}, corresponding to $209\,000 \pm 10\,000$ $\Upsilon(4S)$ decays. The ARGUS detector, its trigger requirements and particle identification capabilities have been described in detail elsewhere [12].

Charged particles are required to originate from the main vertex with a polar angle, θ, in the range $|\cos(\theta)| < 0.92$. Particle identification is based on a likelihood ratio calculated from measurements of specific ionization and time-of-flight for the allowed mass hypotheses (e, μ, π, K and p). Each particle is used as a pion or kaon if the corresponding likelihood ratio exceeds 1%. A K^0_S candidate is defined as a $\pi^+\pi^-$ pair forming a secondary vertex and having an invariant mass within ± 30 MeV/c^2 of the K^0_S

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[#1] References in this paper to a specific charged state are to be interpreted as also implying the charged-conjugate state.
[#2] Branching ratios have been adjusted to reflect current best values for D^0 decays [6].

mass. Photons are identified as clusters in the electromagnetic calorimeter which are not associated with a charged track and have energy larger than 80 MeV/c.

For lepton identification, the size and lateral spread of the associated energy deposition in the calorimeter, or the quality of the match between the projected particle track and the associated hit in the muon chambers, located outside the magnet return yoke, are included in the calculation of the electron and muon likelihood ratios respectively. In particular, for muons, a hit in an outer layer of muon chambers is required. A lepton hypothesis is accepted if the appropriate likelihood ratio exceeds 70%. Contamination from photon conversion is suppressed by eliminating electron candidates which have an invariant mass of less than 100 MeV/c^2 when combined with any oppositely charged particle in the event consistent with an electron hypothesis. With these requirements leptons are identified with high efficiency and a small misidentification rate ((0.5 ± 0.1)% for electrons and (2.0 ± 0.5)% for muons). Finally, lepton momenta are restricted to be greater than 1 GeV/c, to suppress cascade decay sources, and less than 2.3 GeV/c, which is close to the kinematic limit for the decay under consideration.

D^{*0} mesons are reconstructed in the decay chain $D^{*0} \to D^0\gamma$ followed by the decay of the D^0 meson into the $K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$ or $K^0_S\pi^+\pi^-$ final state. The $K^-\pi^+$, $K^0_S\pi^+\pi^-$ ($K^-\pi^+\pi^+\pi^-$) combinations with mass lying within ± 30 (20) MeV/c^2 of the D^0 mass are kinematically constrained to the nominal D^0 mass. Only those $(K^-\pi^+)\gamma$, $(K^-\pi^+\pi^+\pi^-)\gamma$, $(K^0_S\pi^+\pi^-)\gamma$ combinations with momentum less than 2.3 GeV/c are studied.

The main difficulty for D^{*0} reconstruction arises from the large combinatorial background created by the many soft photons from π^0 decays. In order to reduce this background to a manageable level, thereby increasing the sensitivity of the D^{*0} reconstruction, the following additional requirements were applied:

(1) No more than 5 photons were allowed in the event. This requirement has an efficiency for the signal of 60% while suppressing the background under the signal by a factor of 3.

(2) Photons from π^0 decays can be efficiently removed by eliminating those photon pairs whose invariant mass lies within ± 50 MeV/c^2 of the nominal π^0 mass. The efficiency of this requirement has been estimated to be 60% for the signal, while the background is further suppressed by a factor of 4.

After application of these cuts the $D^0\gamma$ system shows a prominent excess near the mass of the D^{*0} meson for $|M^2_{recoil}| < 1$ GeV^2/c^4 (fig. 1a), while there is no signal in the recoil-mass sidebands defined by $|M^2_{recoil}| > 2$ GeV^2/c^4 (fig. 1b). The histograms in these figures are obtained by taking photon combinations with candidates in the sidebands of the D^0 mass distribution, normalized to the amount of back-

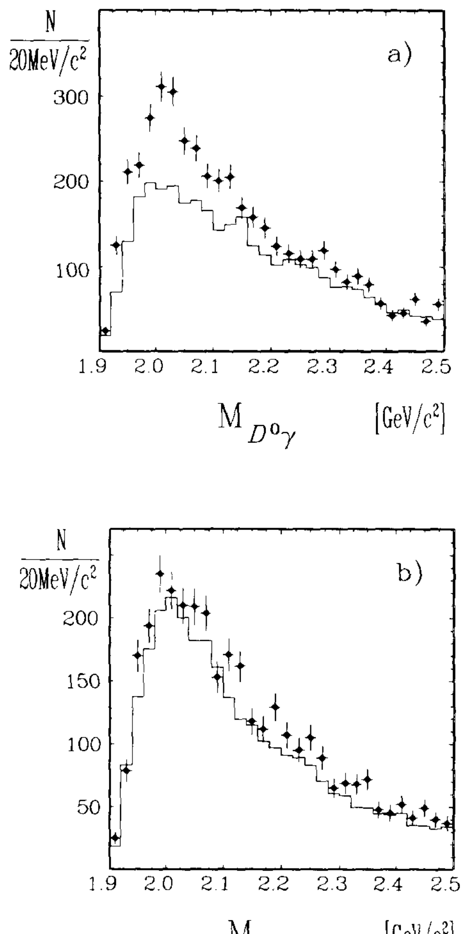

Fig. 1 $D^0\gamma$ invariant mass distribution for (a) $|M^2_{recoil}| < 1$ GeV^2/c^4 and (b) $|M^2_{recoil}| > 2$ GeV^2/c^4. Points with errors show the distribution for the D^0 mass region, while histograms are for the D^0 meson sidebands, normalized to the number of random $K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$, and $K^0_S\pi^+\pi^-$ combinations under the D^0 signal.

ground under the D^0 signal estimated from the fit of the $K^-\pi^+$, $K^0_S\pi^+\pi^-$ and $K^-\pi^+\pi^+\pi^-$ mass distributions. Clearly, a major fraction of the background in the recoil mass distributions can be attributed to background under the D^0 meson peak combined with photons, constituting about 75% and 90% of the entries for $|M^2_{\rm recoil}| < 1$ GeV$^2/c^4$ and $|M^2_{\rm recoil}| > 2$ GeV$^2/c^4$ respectively. The small fraction of the events containing combinations of D^0 and D^{*0} mesons with a negative hadron misidentified as a lepton can also be reliably estimated directly from the data using known misidentification rates. By this means, misidentification is found to contribute less than 3%.

The distribution of $D^0\gamma$ invariant mass after subtraction of the contributions from these two background sources is shown in fig. 2. The shoulder on the low-mass side of the peak is a contribution from the decay $D^{*0}\to D^0\pi^0$, followed by $\pi^0\to\gamma\gamma$. If one of the two photons is used to make an entry in the $D^0\gamma$ mass distribution, the corresponding D^{*0} signal is shifted to lower masses. Typically π^0 mesons produced in the decay $D^{*0}\to D^0\pi^0$ have very small momenta. Therefore, decays in this channel predominantly (about 80%) result in at least one photon with an energy below 80 MeV, thus failing the anti-π^0 cut.

The remaining background under the D^{*0} signal is due to random combinations of D^0 mesons and photons in the events with a lepton. D^0 mesons in the events with a right-sign lepton can originate from the following sources:

(1) $D^0\ell^-$ combinations produced in the continuum under the $\Upsilon(4S)$ resonance.

(2) An uncorrelated D^0 meson and ℓ^- originated from the different B mesons. This background arises as a result of either (a) $B^0\to\bar{B}^0$ oscillations or (b) incorrect interpretation of a D^0 as a $\bar{D}^0$. The latter can occur because of double misidentification of $K^-\pi^+$ combinations in $K^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$ final states, or in the flavour-blind $K^0_S\pi^+\pi^-$ final state.

(3) An uncorrelated D^0 meson and a secondary ℓ^- produced in the decay of a charmed meson.

(4) A D^0 and ℓ^0 produced in the decay of a single B meson. This source of the background is associated with different types of semileptonic decays, such as $B^-\to D^{*0}\ell^-\bar{\nu}$, $\bar{B}^0\to D^{*+}\ell^-\bar{\nu}$, $B^-\to D^0\ell^-\bar{\nu}$ and $B\to D^{**}\ell^-\bar{\nu}$.

The main part of the background arises from the correlated production of ℓ^- and D^0 mesons in semileptonic B decays (4). In order to model the shape of this background, various semileptonic B decays resulting in D^0 mesons are simulated using the GISW model [13]. The relative fractions of B decays into D^0, D^* and D^{**} mesons are fixed according to the prediction of the model. Since the shape of $D^0\gamma$ invariant mass distribution depends only slightly on the D^0 momentum spectrum, the uncertainty due to the unknown fractions is small, but is included in the systematic error.

The shapes and relative fractions of backgrounds (1)–(3) are studied with a Monte Carlo simulation using the Lund generator for continuum $e^+e^-\to c\bar{c}$ events and a $B\bar{B}$ generator for backgrounds (2), (3). The semileptonic decays of charmed mesons are simulated using the BSW model [14]. The contribution from processes (1)–(3) comprises a small share (about 10%) of the overall contribution from processes (1)–(4). The dotted line in the fig. 2 represents the summarized background from (1)–(4) sources normalized to the number of D^0 mesons observed in events with leptons of a proper sign.

After subtraction of this background, a function describing the D^{*0} signal is fitted to the $D^0\gamma$ invariant mass distribution. The shape of the function has been shown by Monte Carlo simulation to be well described by the sum of two gaussians corresponding to

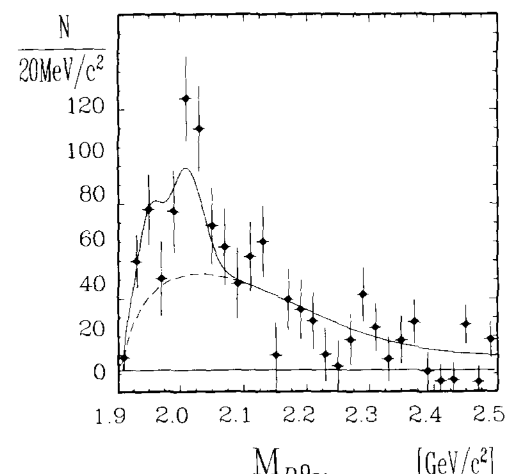

Fig. 2. $D^0\gamma$ invariant mass distribution for $|M^2_{\rm recoil}(D^0\gamma\ell^-)| < 1$ GeV$^2/c^4$ after D^0 sideband and fake lepton subtraction. The calculated background is shown by the dashed line. The solid line represents the fit result for the D^{*0} signal.

contributions from the $D^0\gamma$ and $D^0\pi^0$ decay modes. The solid curve in fig. 2 shows the result of the fit which finds 244 ± 46 events for the D^{*0} signal.

Part of this D^{*0} signal originates from background sources analogous to processes (1)–(3) discussed above for uncorrelated $D^0\gamma$ combinations. The corresponding fractions are listed in table 1. The contributions of uncorrelated $D^{*0}\ell^-$ production in $\Upsilon(4S)$ decays (backgrounds 2 and 3) have been obtained by Monte Carlo simulation in the same way as for $D^0\ell^-$ combinations. For this purpose, the yield of D^{*0} mesons in B decays is assumed to be equal to that measured for D^{*+} mesons. From the naive spectator model it is natural to assume that D^{*0} mesons are mainly produced in B^- decays. Therefore we ignore the background 2a, i.e. D^{*0} production in B^0 decays accompanied by B^0–$\bar{B}^0$ mixing. In any case the possible contribution of this background is very small. The continuum production of D^{*0} mesons is estimated using data taken at a center-of-mass energy just below the open beauty threshold. In order to diminish the error due to continuum subtraction, the number of continuum events contributing to the D^{*0} signal is evaluated from well reconstructed D^{*+} mesons assuming isospin invariance in quark hadronization.

After subtracting backgrounds (1)–(3) the observed peak in fig. 2 includes D^{*0} mesons from the decay $B^- \to D^{*0}\ell^-\bar{\nu}$, as well as a possible contribution from the cascade decay $B \to D^{**}\ell^-\bar{\nu}$ followed by $D^{**} \to D^{*0}\pi$. Since the latter is not measured, its contribution is evaluated from the data by examining the distribution of the signal in recoil mass squared. Shown in fig. 3 is the result obtained by fitting the observed $D^0\gamma$ invariant mass spectrum and subtracting all backgrounds, in separate bins of M^2_{recoil}. The

Table 1
Event and background summary for the D^{*0} signal in the interval $|M^2_{\text{recoil}}| < 1\ \text{GeV}^2/c^4$.

total number of events		244 ±46
backgrounds:	(1) continuum events	8.8± 7.9
	(2a) $B^0 \to \bar{B}^0 \to \ell^- X$, $\bar{B}^0 \to D^{*0}X$	$0^{+2.4}_{-0.0}$
	(2b) wrong interpretation: $\bar{D}^{*0}$ as D^{*0}	5.5± 3.7
	(3) D^{*0} + secondary leptons	5.3± 4.5
$B \to D^{*0}\ell^- X\bar{\nu}$		224 ±47

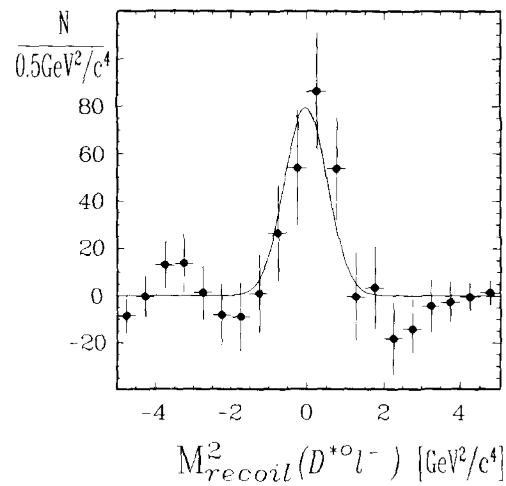

Fig. 3. $M^2_{\text{recoil}}(D^{*0}\ell^-)$ distribution after subtraction of all backgrounds. The line represents the fit result for the decay $B^- \to D^{*0}\ell^-\bar{\nu}$.

solid line is the result of a fit to the recoil mass distribution using the sum of two gaussians, corresponding to the contributions from the signal channel and the cascade decays. The masses, widths and ratio of the contributions of $D^0\gamma$ and $D^0\pi^0$ decay modes are fixed from Monte Carlo simulation. The signal for $B^- \to D^{*0}\ell^-\bar{\nu}$ is determined to be 224 ± 54 events, while an upper limit of 100 events (90% CL) is found for the contribution from the decay $B \to D^{**}\ell^-\bar{\nu}$ followed by $D^{**} \to D^{*0}X$ over the whole recoil mass interval.

The efficiency for all selection criteria and the geometric acceptance of the detector are obtained by a Monte Carlo simulation which has been verified using the data. In particular, the momentum spectra of photons, D^0 mesons and leptons, as well as the photon multiplicity in $\Upsilon(4S)$ decays, are well reproduced by the Monte Carlo. Including the relevant branching ratios, $BR(D^{*0} \to D^0\gamma) = (45 \pm 5)\%$ and $BR(D^0 \to K^-\pi^+) = (3.71 \pm 0.25)\%$, $BR(D^0 \to K^-\pi^+\pi^+\pi^-) = (7.8 \pm 0.6)\%$, $BR(D^0 \to K^0\pi^+\pi^-) = (5.3 \pm 0.5)\%$ [6], a reconstruction and event selection efficiency for D^{*0} mesons of $\eta(D^{*0} \to D^0\gamma) + \eta(D^{*0} \to D^0\pi^0) = 0.017 \pm 0.002$ is obtained. The systematic error is mainly due to the uncertainties in the branching ratios for D^0 meson decays and in the neutral multiplicity of charged B meson decays. The efficiency for detection and identification of a lepton with momentum $p>1$ GeV/c is determined to be $\eta(e^-)=0.75\pm0.05$ and $\eta(\mu^-)=0.69\pm0.07$. The momentum requirement itself reduces the acceptance for primary leptons in B decays by a factor of 0.75 ± 0.08, as determined by Monte Carlo simulation.

Assuming the fraction of the charged B mesons in $\Upsilon(4S)$ decays is 50%, and using e–μ universality, we obtain

$$BR(B^-\to D^{*0}e^-\bar{\nu})=BR(B^-\to D^{*0}\mu^-\bar{\nu})$$
$$=(5.8\pm1.4\pm1.3)\%\,,$$

where the first error is statistical and the second is systematic. The systematic error includes the uncertainties in the efficiency of the D^{*0} meson and lepton detection, and the errors due to uncertainties in the shape of the $D^0\gamma$ invariant mass distribution for background and signal events.

The lifetime ratio, $\tau(B^+)/\tau(B^0)$, can be obtained from the ratio of the branching ratios for $B^-\to D^{*0}\ell^-\bar{\nu}$ and $\bar{B}^0\to D^{*+}\ell^-\bar{\nu}$, assuming that $\Gamma(\bar{B}^0\to D^{*+}\ell^-\bar{\nu})=\Gamma(B^-\to D^{*0}\ell^-\bar{\nu})$:

$$\frac{\tau(B^+)}{\tau(B^0)}=\frac{f_0\,BR(B^-\to D^{*0}\ell^-\bar{\nu})}{f_+\,BR(\bar{B}^0\to D^{*+}\ell^-\bar{\nu})}\,.$$

The ratio $f_0/f_+=BR(\Upsilon(4S)\to B^0\bar{B}^0)/BR(\Upsilon(4S)\to B^+B^-)$ is assumed to be equal to unity as suggested by the almost equal masses of the B^+ and B^0 mesons [15]. The branching ratio for the decay $\bar{B}^0\to D^{*+}\ell^-\bar{\nu}$ was taken from ref. [1], rescaled to $f_0/f_+=1$, and adjusted for the D^0 and D^{*+} branching ratios used in this analysis [6]. Thereby, we obtain

$$\tau(B^+)/\tau(B^0)=0.91\pm0.27\pm0.21\,.$$

Theoretical models explaining the lifetime difference of charged and neutral D mesons predict a much smaller difference in the case of B mesons [10,11]. Our result agrees with these predictions and with previous experimental results [5,8,9].

For the determination of $|V_{cb}|$, the momentum distribution of D^{*0} mesons in the decay $B^-\to D^{*0}\ell^-\bar{\nu}$ is used. This channel is particularly suitable since the reconstruction efficiency for the D^{*0} is practically independent of momentum in contrast to the case for the D^{*+} in the decay $\bar{B}^0\to D^{*+}\ell^-\bar{\nu}$. As has been shown by Voloshin and Shifman [16] the decay rate for $B^-\to D^{*0}\ell^-\bar{\nu}$ when the momentum of the D^{*0} is small can be found, in the infinite quark mass limit, in a model independent way. Corrections to this prediction are of the order of $\mu^2/m_c^2\sim5\%$, where μ is a characteristic momentum of quarks in the meson. Heavy quark effective theory is a recent generalization of this result, described in more detail in refs. [16,17]. In this approach, the decay width over the full Dalitz plot depends only on the $|V_{cb}|$ matrix element and a single universal form factor, the Isgur–Wise function $\xi(v\cdot v')$, where $v\cdot v'$ is a product of the four-velocities of the B and D^* mesons. Following Neubert [18], $|V_{cb}|\xi(1)$ is determined by extrapolation from the full momentum interval. Fig. 4 shows $|V_{cb}|\xi(y)$ extracted from the data using the following formula [18]:

$$|V_{cb}|^2\xi(y)^2=\frac{1}{\sqrt{y^2-1}}\frac{d\Gamma}{dy}\cdot48\pi^3$$
$$\times\{G_F^2\,m_{D^*}^3(m_B-m_{D^*})^2\,[1+\beta_{A_1}\alpha_s(m)/\pi]^2$$
$$\times[F_{B\to D_T^*}(y)+F_{B\to D_L^*}(y)]\}^{-1}\,,$$

where the definitions of $F_{B\to D_T^*}(y)$, $F_{B\to D_L^*}(y)$, and β_{A_1} can be found in ref. [18] and $y=v\cdot v'$. In our case y is equal with sufficient accuracy to

$$y=E_{D^*}/m_{D^*}\,.$$

The shape of the Isgur–Wise function is not fixed

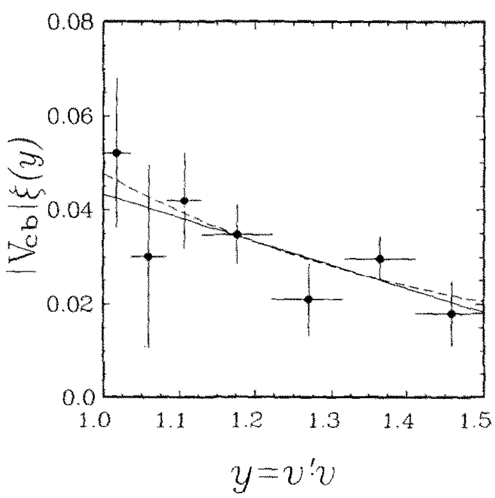

Fig. 4. Distribution of $|V_{cb}|\xi(y)$. The solid line shows the fit result with linear parametrization of the Isgur–Wise function, the dotted line shows the fit result with single-pole parametrization of the Isgur–Wise function.

by theory; however, it is equal to unity when $y=1$ [16]. We use a linear parametrization for the Isgur–Wise function: $\xi(y)=1-\rho^2(y-1)$. The fit finds $\rho=1.07\pm0.17$ and $|V_{cb}|=0.044\pm0.007$ using $\tau_B=(1.27\pm0.07)\times10^{-12}$ s [19]. Similar results are obtained for $|V_{cb}|$ under different parametrizations for the Isgur–Wise function, such as a single-pole model ($\rho=1.30\pm0.28$ and $|V_{cb}|=0.047\pm0.009$) or an exponential dependence for $\xi(y)$ ($\rho=1.38\pm0.29$ and $|V_{cb}|=0.048\pm0.010$) [17]. The systematic errors are dominated by the same sources as for the branching ratio determination. Adding the statistical and systematic errors in quadrature we obtain

$$|V_{cb}|=0.044\pm0.009\ .$$

We obtain the $|V_{cb}|$ matrix element and ρ-parameter which are in good agreement with the values obtained from the analysis of $\bar{B}^0\to D^{*+}\ell^-\bar{\nu}$ decays [18].

In summary, we have observed the decay $B^-\to D^{*0}\ell^-\bar{\nu}$. The extracted value for the branching ratio, together with the previously measured $BR(\bar{B}^0\to D^{*+}\ell^-\bar{\nu})$, allow an estimate of the ratio of the lifetimes of charged and neutral B mesons. The CKM matrix element $|V_{cb}|$ is obtained from an investigation of the momentum spectrum of the D^{*0} meson.

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