MEASUREMENT OF D^{*+} POLARIZATION IN THE DECAY $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$

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Using the ARGUS detector at the e^+e^- storage ring DORIS II, we have measured the average polarization of D^{*+} mesons originating from exclusive decays $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$. By comparing the D^{*+} decay angular distribution to a functional form $1+\alpha\cos^2\theta$, we determine α to be $\alpha=0.7\pm0.9$. This value of α leads to a ratio of longitudinal to transverse decay width $\Gamma_L/\Gamma_T=0.85\pm0.45$, which allows the determination, $|V_{cb}|=0.052\pm0.011$. The importance of the transverse helicity component is manifested in the q^2 and lepton spectra, which are also presented.

The recently measured decay $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}(\ell^- = e^-, \mu^-)$ [#1] has been found to have a large branching ratio, $BR(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}) = (7.0\pm1.2\pm1.9)\%$ [1]. Assuming the validity of the spectator model in B decays, this decay represents about 70% of the inclusive semileptonic rate [2]. It therefore dominates the lepton spectra in B decays. In view of the theoretical uncertainties in modeling semileptonic B decays [3–8], which are especially important for the extraction of $|V_{ub}|/|V_{cb}|$, it is highly desirable to have additional detailed information on the decay $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$. In particular, the degree of polarization of the daughter D^{*+} strongly influences the momentum spectrum of the decay particles as well as the $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ decay rate [7], which in turn is a measure of the Kobayashi–Maskawa element $|V_{cb}|$ [6]. The determination of this polarization in exclusively reconstructed decays, $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$, is the subject of this paper.

The data used were taken on the $\Upsilon(4S)$ resonance using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The event sample consists of 96 000 B meson pairs, corresponding to an integrated luminosity of 103 pb^{-1}. Leptons are identified in the ARGUS detector [9] by using information from all detector components and combining them into an overall likelihood. The information consists of dE/dx and time-of-flight measurements, the magnitude and topology of energy deposition in the shower counters. Additionally, for muons at least one hit in the outer muon chamber is required and the distance between the actual hit and the expected impact point is included in the likelihood. The e^- (μ^-) candidate is accepted if the corresponding likelihood ratio exceeds 70% and if the momentum is larger than 0.4 GeV/c (1.0 GeV/c). The fake rates due to lepton–hadron misidentification are less than 0.6% for electrons and 1.5% for muons.

D^{*+} mesons are reconstructed in the decay chain $D^{*+} \to \pi^+ D^0$, followed by $D^0 \to K^-\pi^+$ or $D^0 \to K^-\pi^+\pi^+\pi^-$, where both the D^0 and D^{*+} final states are kinematically constrained to the corresponding masses [10]. To reduce the combinatorial background from multiple counting, only one D^{*+} candidate per event for each D^0 final state is selected. The chosen candidate is required to maximise the χ^2 probability derived from kinematical fitting and particle identification contributions. In addition the χ^2 probability must exceed 5% for the $D^0 \to K^-\pi^+$ channel and 10% for the $D^0 \to K^-\pi^+\pi^+\pi^-$ final state. To suppress the continuum contribution the D^{*+} candidates are required to have $x_p<0.5$, where $x_p = p/\sqrt{E^2_{\rm Beam} - M^2_{D^{*+}}}$.

Due to the high efficiencies for electrons and muons as well as for the reconstruction of D^{*+} mesons, the decay $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ has been reconstructed with a sizeable rate on a small background. The neutrino in the decay is inferred from its effective mass:

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[#1] References to a specific particle state should be interpreted as implying the charge-conjugate state also.

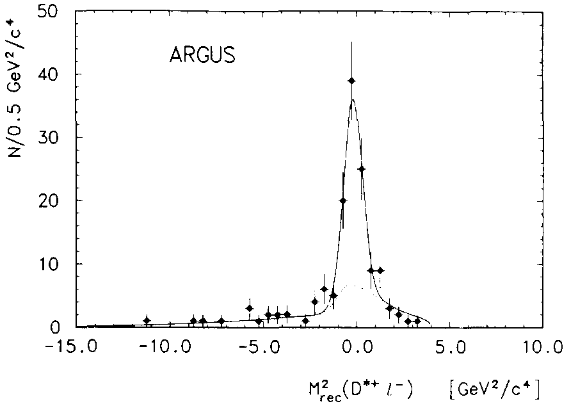

Fig. 1. M^2_{rec} distribution for $D^{*+}\ell^-$ combinations with $p_\ell > 1$ GeV/c and $x_p(D^{*+}) < 0.5$. The full line is a fit with a gaussian for the signal and a parametrisation of the background contributions, shown as a dotted line.

$$M^2_\nu = [E_B - (E_{D^{*+}} + E_{\ell^-})]^2 - (\boldsymbol{p}_B - \boldsymbol{p}_{D^{*+}} - \boldsymbol{p}_{\ell^-})^2 = 0 .$$

As the B^0 mesons are massive decay products of a $\Upsilon(4S)$ decaying at rest, $E_B = E_{Beam}$ and $\boldsymbol{p}_B \approx 0$. The decay $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ is therefore seen as a peak in the spectrum of the recoil mass squared, M^2_{rec}, at $M^2_{rec} \approx 0$ with

$$M^2_{rec} = [E_{Beam} - (E_{D^{*+}} + E_{\ell^-})]^2 - (\boldsymbol{p}_{D^{*+}} + \boldsymbol{p}_{\ell^-})^2 .$$

The M^2_{rec} spectrum is shown in fig. 1 for $D^{*+}\ell^-$ combinations with $p_\ell > 1$ GeV/c. The signal for the decay $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ amounts to 73 ± 11 events on a total background of 25 ± 5 events (dashed curve in fig. 1). The various background contributions are listed in table 1 and were derived from the data or from known branching ratios. Their shapes in M^2_{rec} were also studied with data and are reproduced by Monte Carlo simulations.

Possible contaminations from the decay sequence $\bar{B} \to D^*(2420)\ell^-\bar{\nu}$ with $D^*(2420) \to \pi D^{*+}$ were studied by searching for a $D^{*0}(2420)$ signal in the $\pi^- D^{*+}$ mass distribution, where $M^2_{rec}(\pi^- D^{*+}\ell^-)$ was restricted to $|M^2_{rec}(\pi^- D^{*+}\ell^-)| < 1$ GeV$^2/c^4$. No indication of a signal was found. The mass distribution was fitted with a smooth function for the background and a Breit–Wigner with the measured width and position of the $D^{*0}(2420)$ [11,12]. Using the branching ratios for the D^{*+} decay sequence [10,13] and the reconstruction efficiency, the following upper limit on the product of branching ratios is derived:

$$BR(B^- \to D^{*0}(2420)\ell^-\bar{\nu})\, BR(D^{*0}(2420) \to \pi^- D^{*+}) < 0.012 \quad \text{at 90\% CL} .$$

These conditions allow a detailed investigation of the decay $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$, where the polarization of the D^{*+} mesons is of special interest. The D^{*+} meson in this decay can be formed in two helicity states, either with $m=0$ (longitudinally polarized) or with $m = \pm 1$ (transversely polarized). The width for the decay

Table 1
Number of background $D^{*+}\ell^-$ combinations with $p_\ell > 1$ GeV/c. The rate for (4) is calculated using branching ratios given in refs. [10,13,14]. The rate for (5) is estimated using $BR(\bar{B}^0 \to D^{*+}X) = 0.65 \pm 0.15$, $BR(B^0 \to \ell^- X) = BR(B \to \ell^- X)$ and the mixing parameter r as measured by ARGUS [15]. The shape for uncorrelated $D^{*+}\ell^-$ combinations (4) and (5) can be obtained from $D^{*+}\ell^+$ combinations and compares well with Monte Carlo calculations. The upper limit for (6) has been derived from the data.

	Background source	Total event sample	$\lvert M^2_{rec}\rvert < 1$ GeV$^2/c^4$
1	continuum events	9 ± 7	3.5 ± 2.5
2	fake leptons	5 ± 1.5	2 ± 0.6
3	background under D^{*+} signal	35 ± 9	15 ± 4
4	$B \to \bar{D}^0(D^-)X$, $\bar{B} \to D^{*+}X$, with $\bar{D}^0(D^-) \to \ell^- X$	6 ± 2	1.5 ± 0.5
5	$B^0 \to \bar{B}^0 \to \ell^- X$, $\bar{B}^0 \to D^{*+}X$	15 ± 7	3 ± 1.5
6	$B^- \to D^{*0}(2420)\ell^-\bar{\nu}$, with $D^{*0}(2420) \to \pi^- D^{*+}$	< 4 at 90% CL	
	$\Sigma(1\text{–}5)$	70 ± 14	25 ± 5

$\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$ is therefore given by three contributions corresponding to the three helicity states:

$$\Gamma(\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}) = \Gamma_L + \Gamma_{T_-} + \Gamma_{T_+} ,$$

which can be rewritten as

$$\Gamma(\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}) = |V_{cb}|^2 \hat{\Gamma}_T (1 + \Gamma_L / \Gamma_T) ,$$

with $\Gamma_T = \Gamma_{T_-} + \Gamma_{T_+}$. The quantity $\hat{\Gamma}_T$ is predicted by different authors to be in the range $\hat{\Gamma}_T = (1.0\text{–}1.4) \times 10^{13} s^{-1}$ [3,6–18]. A measurement of the D^{*+} polarization yields the ratio Γ_L/Γ_T and therefore, in combination with the known branching ratio for the decay $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$ and the B lifetime, allows the determination of the KM matrix element $|V_{cb}|$. Moreover, the magnitude of this ratio fixes the lepton spectrum as well as the q^2 dependence.

The polarization of D^{*+} mesons can be measured by using the strong decay $D^{*+} \to \pi^+ D^0$ as an analyser. The distribution of $\cos \theta^*_{\pi^+}$, where $\theta^*_{\pi^+}$ is the decay angle of the π^+ in the D^{*+} rest frame with respect to the D^{*+} direction, is given by

$$dN / d \cos \theta^*_{\pi^+} \propto 1 + \alpha \cos^2 \theta^*_{\pi^+} ,$$

where α measures the ratio of longitudinal to transverse polarization:

$$\alpha = 2 \Gamma_L / \Gamma_T - 1 .$$

The $\cos \theta^*_{\pi^+}$ distribution is extracted from the events in the signal region ($|M^2_{rec}| < 1$ GeV$^2/c^4$) by subtracting the background contributions in this M^2_{rec} range. For the background sources (1)–(3) (see table 1) the shape in $\cos \theta^*_{\pi^-}$ is obtained from the data. The background sources (4), (5) are assumed to have a flat distribution in $\cos \theta^*_{\pi^+}$. An alternate method to obtain the distribution, in which the M^2_{rec} signal was fit in bins of $\cos \theta^*_{\pi^+}$ was also used. Both methods gave consistent results.

The kinematics of the process $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$ as well as the acceptance in $\cos \theta^*_{\pi^+}$ have been studied with a Monte Carlo simulation, which reproduces the measured lepton spectra as well as the q^2 dependence (fig. 3 and fig. 4). The smearing of the $\cos \theta^*_{\pi^+}$ distribution due to the B meson motion is found to be negligible. The acceptance in $\cos \theta^*_{\pi^+}$ depends mainly on the acceptance of the slow pion, which has momenta less than 250 MeV/c^2, in the decay $D^{*+} \to \pi^+ D^0$.

The acceptance corrected and normalized $\cos \theta^*_{\pi^+}$ distribution in the decay $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$ is shown in fig. 2. This distribution is fit to a form of $(1 + \alpha \cos^2 \theta^*_{\pi^+})$ resulting in a value of $\alpha = 0.7 \pm 0.8$. The result of the fit is shown as the solid line.

Systematic uncertainties in the determination of α are investigated by varying the shape of the $\cos \theta^*_{\pi^+}$ background distributions, as well as the acceptance function. The resulting systematic error on α amounts to $\sigma_\alpha = \pm 0.4$, which is small compared to the statistical error. The value of α has to be corrected for the limited phase space due to the cut on the lepton momentum and the vanishing acceptance for D^{*+} mesons with $x_p < 0.2$. The two corrections are individually 25%, but they cancel each other. This leads to

$$\alpha = 0.7 \pm 0.9 ,$$

where the statistical and systematic errors have been added in quadrature. From this value of α we deduce the ratio of the longitudinal and transverse component Γ_L/Γ_T:

$$\Gamma_L / \Gamma_T = 0.85 \pm 0.45 .$$

Using $\hat{\Gamma}_T = 1.2 \times 10^{13} s^{-1}$, $BR(\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}) = (7.0 \pm 1.2 \pm 1.9)\%$ and $\tau_B = (1.15 \pm 0.14) \times 10^{-12}$s [2] one obtains

$$|V_{cb}| = 0.052 \pm 0.011 .$$

This value for $|V_{cb}|$ compares well with the one ob-

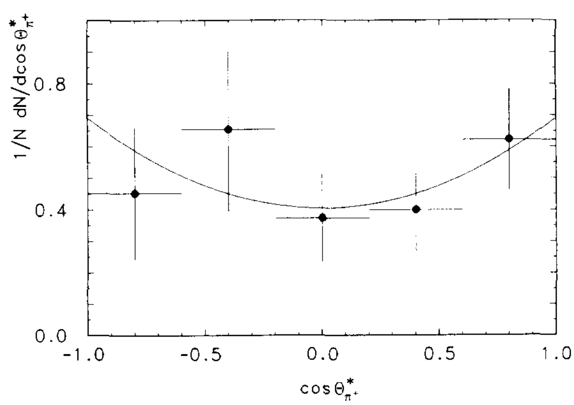

Fig. 2. $\cos \theta^*_{\pi^+}$ distribution from D^{*+} mesons with $|M^2_{rec}| < 1$ GeV$^2/c^4$ and $p_\ell > 1$ GeV/c. The distribution is background subtracted, acceptance corrected and normalized. The solid line is the result of the fit with the function described in the text.

tained from the investigation of the inclusive lepton spectra [2], which, however, suffers from the assumptions on the b quark mass and the magnitude of $|V_{ub}|$.

The measured value of Γ_L/Γ_T is in good agreement with the predicted ratio in refs. [3,6–8], whereas the models [4,5], giving values of $\Gamma_L/\Gamma_T>2$, can be ruled out with more than two standard deviations. The measured polarization of the D^{*+} mesons in the $\bar{B}^0\to D^{*+}\ell^-\bar{\nu}$ decay should also be reflected in the shapes of the lepton spectrum and the q^2 distribution. The endpoint region of the lepton spectrum in the decay $\bar{B}^0\to D^{*+}\ell^-\bar{\nu}$ is dominated by the T_- component [7]. This leads to a harder lepton spectrum for the decay $\bar{B}^0\to D^{*+}\ell^-\bar{\nu}$ than for the decay $\bar{B}\to D\ell^-\bar{\nu}$. The observed lepton momentum spectrum from the decay $\bar{B}^0\to D^{*+}\ell^-\bar{\nu}$ is shown in fig. 3. It is well described by the models of refs. [3,7,8] (full curve), which all predict both $\alpha\approx 1$ and the same shape for the lepton spectrum.

The q^2 spectrum was obtained by reconstruction of the decay $\bar{B}^0\to D^{*+}e^-\bar{\nu}$, with a cut on the electron momentum of $p_e>0.4$ GeV/c. The q^2 distribution can be inferred from the energy spectrum of the D^{*+} mesons by using

$$\begin{aligned} q^2 &= (p_B - p_{D^{*+}})^2 \\ &= (E_B - E_{D^{*+}})^2 - (\boldsymbol{p}_B - \boldsymbol{p}_{D^{*+}})^2 \\ &\approx (E_B - E_{D^{*+}})^2 - \boldsymbol{p}^2_{D^{*+}} . \end{aligned}$$

The effect of neglecting $\boldsymbol{p}_B$ in the above approximation was corrected for by means of Monte Carlo studies. The acceptance-corrected and background-subtracted q^2 spectrum is displayed in fig. 4. The presence of a strong transverse helicity component at large q^2 is clearly demonstrated by the data, which is fit well by the theoretical models of refs. [3,7] (solid curve in fig. 4).

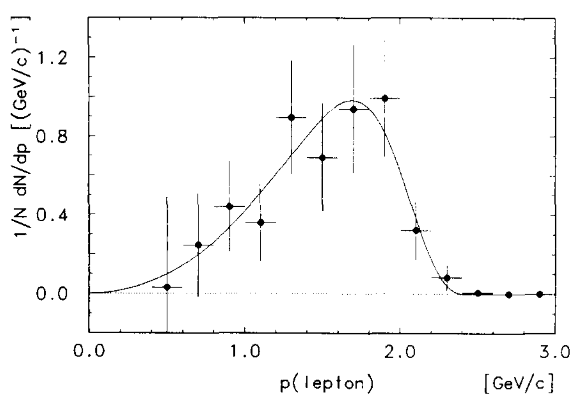

Fig. 3. Momentum spectrum of leptons from the decay $\bar{B}^0\to D^{*+}\ell^-\bar{\nu}$. The curve represents the prediction from ref. [7].

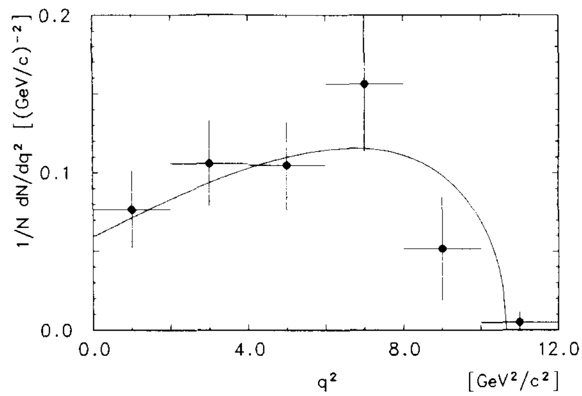

Fig. 4. q^2 spectrum for the decay $\bar{B}^0\to D^{*+}\ell^-\bar{\nu}$ compared to the model prediction of ref. [7] (full line).

In summary, we have investigated in detail the decay $\bar{B}^0\to D^{*+}\ell^-\bar{\nu}$ and determined the polarization of the D^{*+} mesons. The measured average polarization, $\alpha=0.7\pm0.9$, of the D^{*+} mesons leads to the conclusion that the transverse and longitudinal helicity components in the decay $\bar{B}^0\to D^{*+}\ell^-\bar{\nu}$ are about equal. The measurement of α further allows a determination of the KM matrix element, $|V_{cb}|=0.052\pm0.011$. The obtained lepton and q^2 spectra are in very good agreement with those predicted for the measured value of α.

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