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A study of $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ and $B^0\overline{B}^0$ mixing using partial D^{*+} reconstruction

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Abstract

Using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY, we have studied the decay $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ by exploiting a partial D^{*+} reconstruction technique. The branching ratio for this mode was thereby determined to be $(4.5 \pm 0.3 \pm 0.4)\%$. Using the corresponding sample of tagged B^0 mesons, we measured the $B^0\overline{B}^0$ mixing parameter to be $r_d = 0.194 \pm 0.062 \pm 0.054$, a result only weakly dependent upon the ratio of semileptonic widths for and production rates of B^0 and B^+ mesons. We have also determined the branching ratio $\mathrm{Br}(\overline{B}^0 \to X\,\ell^-\overline{\nu})$ to be $(9.3 \pm 1.1 \pm 1.5)\%$. By comparing the results for full and partial D^{*+} reconstruction we found the absolute branching ratios for $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^+\pi^-$ to be $(4.5 \pm 0.6 \pm 0.4)\%$ and $(7.9 \pm 1.5 \pm 0.9)\%$, respectively.

In this paper, we report on an ARGUS measurement of the decay $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ using a partial D^{*+} reconstruction technique. This mode can be used efficiently for tagging B^0 mesons. With the tagged sample we are able to measure the B^0 semileptonic branching ratio. A comparison with the average semileptonic B meson branching ratio provides an estimate of the contribution of non-spectator effects to B decays. The sample is large enough to allow us to extract the absolute branching ratios for the D^0 decay channels $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^+\pi^-$ by comparing the results of $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ for the cases of full versus partial reconstruction of the D^{*+}.

The data used for this analysis were taken on the $\Upsilon(4S)$ resonance and in the nearby continuum using the ARGUS detector at the e^+e^- storage ring DORIS II. The integrated luminosity used in this analysis is 246 pb^{-1}, corresponding to 209000 ± 9500 $B\overline{B}$ pairs. The ARGUS detector, its trigger requirements and identification capabilities are described in detail elsewhere [1].

Particle identification is based on a likelihood ratio calculated from measurements of specific ionization and time-of-flight for the allowed mass hypotheses $(e, \mu, \pi, K$ and $p)$. Each particle is used as a pion or kaon if the corresponding likelihood ratio exceeds 1%.

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 associated hits 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, at least one hit in an outer layer of muon chambers is required. An electron or muon hypothesis was accepted if the appropriate likelihood ratio exceeded 70% and the lepton polar angle satisfied the requirement $|\cos\theta_\ell| < 0.9$. Converted photons were rejected by excluding all e^+e^- pairs with mass less than 100 MeV/c^2, as well as e^+e^- pairs from secondary verticies. We also re-

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quired the total multiplicity $N_{total} = N_{charged} + N_\gamma/2$ to be greater or equal to 5 to suppress leptons from QED processes and the second Fox-Wolfram moment to be less than 0.5 to suppress continuum events.

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

$$M^2_{recoil} = (E_{beam} - E_{D^*} - E_\ell)^2 - (p_{D^*} + p_\ell)^2.$$

This technique was introduced by ARGUS in 1987 [2] for measurements of exclusive semileptonic B mesons decays. It also works well when the D^0 from the decay $D^{*+} \to D^0\pi^+$ remains undetected. The energy release in this decay is only about 6 MeV, so the direction of the pion is close to that of the D^{*+} meson and their momenta are strongly correlated. From a Monte Carlo simulation it was found that the relation between the momenta of the D^{*+} meson and the pion can be approximated by

$$p_{D^*} = \alpha p_\pi + \beta \tag{1}$$

with $\alpha = 8.23$ and $\beta = 0.41$ GeV/c. Thus, in order to reconstruct D^{*+} mesons, we
- used every π^+ with momentum less than 200 MeV/c as a candidate for D^{*+}, incorporating 96% of D^{*+} decays;
- assumed that the D^{*+} direction coincides with the π^+ direction;
- calculated the D^{*+} momentum using (1).

We required the lepton momentum to be greater than 1.4 GeV/c to suppress leptons from semileptonic charm decays as well as decays through excited charm states, and less than 2.5 GeV/c, which is approximately the kinematic limit for B meson decays.

The result of a Monte Carlo simulation of the decay $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ based on the IGSW [3] model is shown in Fig. 1. The signal can be distinguished from feeddown from the cascade decay

$$\overline{B} \longrightarrow D^*_{(J)}\, \ell^-\, \overline{\nu}, \quad D^*_{(J)} \longrightarrow \pi\, D^{*+},$$

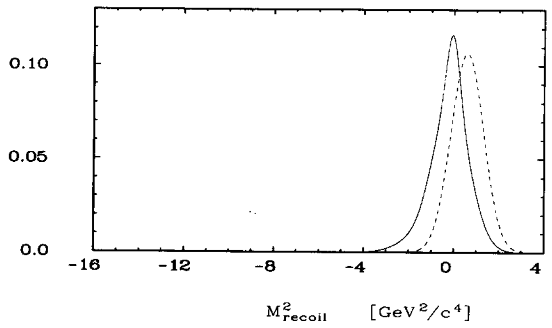

Fig. 1. M^2_{recoil} spectra for $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ (full line) and $B \to D^*_{(J)}\ell\nu$ (dashed line) obtained from Monte Carlo simulation.

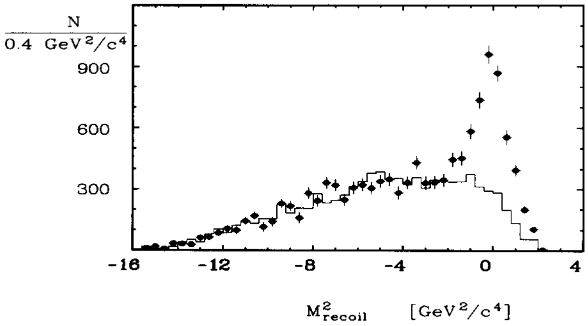

Fig. 2. Continuum and fake lepton subtracted M^2_{recoil} spectrum for $l^+\pi^-$ (points with errors) and $l^+\pi^+$ (histogram) combinations.

by a positive shift of about 1.0 GeV^2/c^4 in the recoil mass spectrum. The shape of the contribution from this process is also shown in Fig. 1.

The contribution from continuum events was determined using data collected at energies below the $\Upsilon(4S)$ resonance, taking into account the difference in cross sections and collected luminosities. The fraction of hadrons misidentified as leptons was determined using measured fake rates. After subtraction of these background sources we obtained the M^2_{recoil} spectra shown in Fig. 2. for right-sign ($\ell^+\pi^-$) and wrong-sign ($\ell^+\pi^+$) combinations. The prominent peak at $M^2_{recoil} \sim 0$ is attributed to $B \to D^*\,(\pi)\,\ell\,\nu$ decays. No signal can be seen in the wrong-sign spectrum.

The shapes of the spectra for right- and wrong-sign $\ell\pi$ combinations are well reproduced by a Monte Carlo simulation of $\Upsilon(4S) \to B\overline{B}$ events. Moreover, the shape of the background for the right-sign combinations is the same as that for the wrong-sign, with a well-reproduced relative normalization. This means

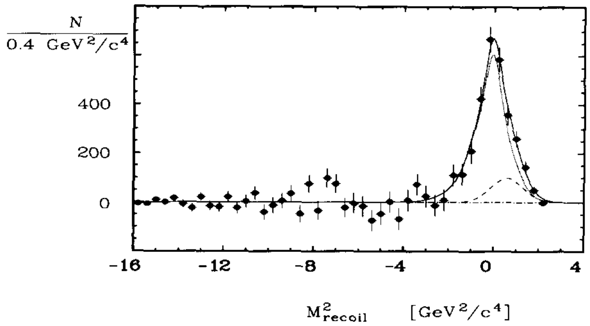

Fig. 3. Background subtracted M^2_{recoil} spectrum. The curves show the result of the fit described in text.

that the pion is generally soft enough so as not to have a strong correlation with the lepton and that this correlation is charge independent. The influence of the correlations on the wrong-sign distribution can be estimated by taking particles from different events, i.e. replacing all correlated pairs by uncorrelated ones. No significant difference was seen between the M^2_{recoil} spectra from mixed and real events.

Subtracting the background using the wrong-sign M^2_{recoil} spectrum we obtained the distribution shown in Fig. 3. The resulting spectrum was fit using contributions from both the D^{*+} and $D^*_{(J)}$ channels. The expected shapes of these contributions for the M^2_{recoil} distribution were derived from a Monte Carlo simulation based on the IGSW model. Possible backgrounds from

$$\overline{B} \longrightarrow \tau^- \; \overline{\nu_\tau} \; X$$
$$\quad \lfloor\!\longrightarrow \ell^- \; \nu_\tau \; \overline{\nu}$$
$$\overline{B} \longrightarrow D_s^- \; X$$
$$\quad \lfloor\!\longrightarrow \ell^- \; \overline{\nu} \; Y$$

were estimated using a Monte Carlo simulation and found to be negligible.

From the fit we find

$$\begin{aligned} N_{D^*} &= 2693 \pm 183 \pm 105 \\ N_{D^*_{(J)}} &= 423 \pm 138 \pm 35. \end{aligned} \tag{2}$$

The systematic error was estimated by:
- varying the value of the D^{*+} polarization within measurement errors;
- using the BSW [4] and KS [5] models for the simulation of the decay $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$;
- varying the relative branching ratios for semileptonic B-decays into different excited D-meson states. Fitting the recoil mass distribution in bins of lepton momentum allows one to extract the lepton momentum spectrum. The resulting distribution is consistent with expectations.

The acceptance was obtained from a Monte Carlo simulation using the IGSW model. The overall efficiency was determined to be 0.210 ± 0.015. Using the CLEO measurement [6] of $\text{Br}[D^{*+} \to D^0\pi^+] = (68.1 \pm 1.0 \pm 1.3)\%$ we obtain

$$\text{Br}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}) = (4.5 \pm 0.3 \pm 0.4)\%.$$

The systematic error reflects uncertainties in the fit procedure, the acceptance determination, the number of B^0 mesons, and the D^{*+} branching ratio. Our result is in good agreement with previous measurements by ARGUS [2,7] and CLEO [8].

An additional check was made to ensure that correlations between ℓ and π are really charge independent. Since the strength of these correlations is expected to increase with pion momentum, the cut on the pion momentum was varied from 150 to 300 MeV/c. The branching ratio remained stable under this change, confirming our assumption.

The sample of partially reconstructed $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ decays can also be used to measure D^0 branching ratios. For this purpose we used the numbers obtained in [7] for the fully reconstructed decays $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ with $D^{*+} \to D^0\pi^+$ and $D^0 \to K^-\pi^+$ or $D^0 \to K^-\pi^+\pi^+\pi^-$. The D^0 branching ratio is given by

$$\text{Br}(D^0 \to X) = \frac{N(B^0 \to D^{*-}\ell\nu, D^{*-} \to \pi^-\overline{D}^0, \overline{D}^0 \to X)}{N(B^0 \to D^{*-}\ell\nu, D^{*-} \to \pi^-\overline{D}^0)} \cdot \frac{\epsilon_p}{\epsilon_f}$$

where ϵ_f and ϵ_p are the acceptances for the full and partial reconstruction techniques. This method yields:

$$\text{Br}(D^0 \to K^-\pi^+) = (4.5 \pm 0.6 \pm 0.4)\%$$
$$\text{Br}(D^0 \to K^-\pi^+\pi^+\pi^-) = (7.9 \pm 1.5 \pm 0.9)\%$$

where the systematic error includes uncertainties in efficiency determination and background rates. Our

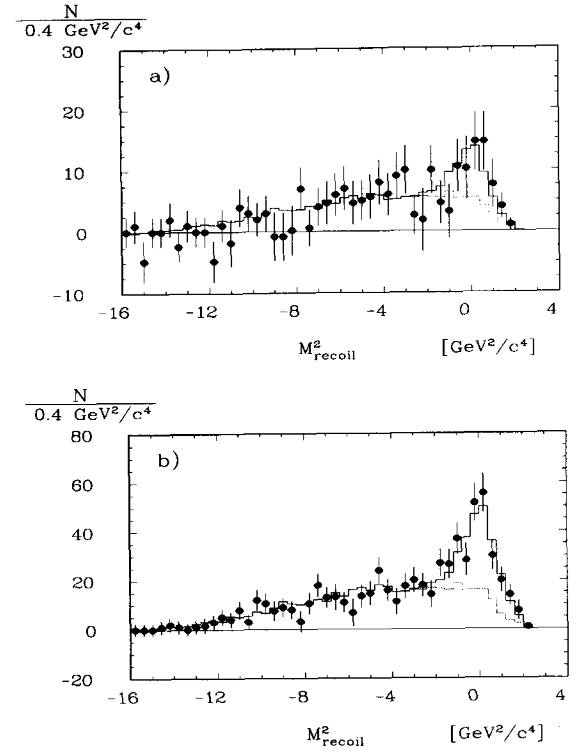

Fig. 4. M^2_{recoil} spectra for $l^+\pi^-$ (points with errors) for events with an additional lepton with momentum $1.4 < p_l < 2.5$: background (dotted histogram) and the result of the fit (full histogram) a) for like-sign leptons; b) for unlike-sign leptons.

result is in agreement with the world average [9].

Using the sample of B^0 mesons tagged in the $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ mode we can make a measurement of the $B^0\overline{B}^0$ mixing rate which is independent of $\lambda = b_+^2 f_+/b_0^2 f_0$, as well as determine the inclusive semileptonic branching ratio for neutral B mesons. Here, f^+ (f^0) is the branching ratio of the decay $\Upsilon(4S)$ into charged (neutral) B mesons and b_+ (b_0) the semileptonic branching ratio of charged (neutral) B mesons.

To extract the mixing parameter we studied the M^2_{recoil} distribution for events containing an additional lepton with momentum $1.4 < p_l < 2.5\,\text{GeV}/c$. The cut on the second Fox-Wolfram moment was relaxed. Leptons from J/ψ decays were eliminated by rejection of all e^+e^- and $\mu^+\mu^-$ pairs with invariant mass consistent with the J/ψ mass. The resulting distributions for like- and unlike-sign dileptons after continuum subtraction are shown in Fig. 4.

Table 1
Observed numbers of events and corrections.

	$N(l^\pm l^\pm)$	$N(l^+l^-)$
$\Upsilon(4S)$ – Continuum(scaled)	42.4 ± 10.6	171.6 ± 17.8
Fakes	7.0 ± 0.9	6.7 ± 0.9
fraction of primary leptons	0.794	0.955
fraction of ll from neutral B decays	0.941	0.824
Direct leptons from neutral B decays	26.5 ± 8.0	129.8 ± 14.0

We fit these distributions using the shape of the background from the previous analysis. The relative contributions of D^{**} and D^{*+} to the spectra were fixed from the one lepton case, and the fits were performed taking into consideration

$$2 \cdot \text{Br}(\overline{B}^0 \to D^{**+}\ell^-\overline{\nu}) \cdot \text{Br}(D^{**+} \to D^{*+}\pi^0)$$
$$= \text{Br}(B^- \to D^{**0}\ell^-\overline{\nu}) \cdot \text{Br}(D^{**0} \to D^{*+}\pi^-)$$

according to isospin invariance. Note that the charged B mesons contribute only to the unlike-sign dilepton sample. The fit yielded 42.4 ± 10.6 and 171.6 ± 17.8 events for like- and unlike-sign dileptons respectively. The number of fake leptons was determined from the data by folding the momentum spectrum of the additional lepton with the hadron fake probability. The contribution from primary leptons, as well as a correction factor for the anti-J/ψ cut efficiency were estimated using Monte Carlo simulation. The results are summarized in Table 1.

The mixing parameter r_d is

$$r_d = \frac{N(l^\pm l^\pm)}{N(l^+l^-)} \cdot \eta_{J/\psi} \tag{3}$$

where $\eta_{J/\psi} = 0.95$ is the correction factor for the anti-J/ψ cut. Using (3) we calculate

$$r_d = 0.194 \pm 0.062 \pm 0.054.$$

The systematic error includes uncertainties in the influence of the momentum cut for the additional lepton, the fraction of primary leptons, the correction factor for the anti-J/ψ cut efficiency, as well as the ratio of D^{**} to D^{*+} contributions. Our result is in good agreement with previous ARGUS [10,11], CLEO [13,12] and LEP [14] measurements.

The semileptonic branching ratio of the neutral B meson is given by

$$\mathrm{Br}(\overline{B}^0 \to X\, \ell^- \overline{\nu}) = \frac{N_{\ell\ell}^{\mathrm{corr}}}{N_{D^{*+}}} \cdot \frac{\epsilon_{\mathrm{mult}}^{\ell}}{\epsilon_{\mathrm{mult}}^{\ell\ell}}, \qquad (4)$$

where $N_{\ell\ell}^{\mathrm{corr}}$ is the acceptance corrected number of dileptons and $\epsilon_{\mathrm{mult}}^{\ell,\ell\ell}$ are the efficiencies of the multiplicity cut for the single lepton and dilepton samples respectively. From a Monte Carlo simulation it was found that

$$\frac{\epsilon_{\mathrm{mult}}^{\ell}}{\epsilon_{\mathrm{mult}}^{\ell\ell}} = 1.046 \pm 0.023.$$

To extract the inclusive semileptonic branching ratio of neutral B mesons we had to use a model to extrapolate the measured number of dileptons to low values of lepton momenta. The IGSW model was employed for this purpose. We find

$$\mathrm{Br}(\overline{B}^0 \to X\, \ell^- \overline{\nu}) = (9.3 \pm 1.1 \pm 1.5)\%,$$

which is in good agreement with the previous CLEO [16] measurement. The value is also consistent with the mean semileptonic branching ratio obtained by taking a weighted average of ARGUS [15] and CLEO [16] results, $\mathrm{Br}(\overline{B} \to X\, \ell^- \overline{\nu}) = 9.85 \pm 0.5\%$. Assuming the branching ratios of the $\Upsilon(4S)$ to charged and neutral B mesons are $f_- = f_0 = 0.5$, we can further estimate the ratio of the lifetimes of charged and neutral B mesons. We obtain

$$\frac{\mathrm{Br}(\overline{B} \to X\, \ell^- \overline{\nu})}{\mathrm{Br}(\overline{B}^0 \to X\, \ell^- \overline{\nu})} = 1.06 \pm 0.14 \pm 0.17$$

which implies

$$\tau(B^+)/\tau(B^0) = 1.12 \pm 0.27 \pm 0.34.$$

This value is in good agreement with the expectation that non-spectator effects in B meson decays are small.

In summary, applying a partial D^* reconstruction technique we have measured the branching ratio for the decay $\overline{B}^0 \to D^{*+} \ell^- \overline{\nu}$ to be $(4.5 \pm 0.3 \pm 0.4)\%$. Using the sample of tagged B^0 mesons obtained we find $\mathrm{Br}(D^0 \to K^- \pi^+) = (4.5 \pm 0.6 \pm 0.4)\%$ and $\mathrm{Br}(D^0 \to K^- \pi^+ \pi^+ \pi^-) = (7.9 \pm 1.5 \pm 0.9)\%$. In addition, we obtained a direct determination of the semileptonic branching ratio for neutral B mesons, $\mathrm{Br}(\overline{B}^0 \to X\, \ell^- \overline{\nu}) = (9.3 \pm 1.1 \pm 1.5)\%$. We also measured the $B^0\overline{B}^0$ mixing rate to be $r_d = 0.194 \pm 0.062 \pm 0.054$, a result almost free of uncertainties due to potential differences in the semileptonic branching ratios and the production fractions of B^0 and B^+ mesons.

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