Observation of the decays $D_s^- \to \phi e^- \bar{\nu}$ and $D^- \to K^{*0} e^- \bar{\nu}$

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Using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY, we have studied semileptonic charmed meson decays through ϕ– and K^{*0}–electron correlations in continuum production. Evidence for the decay $D_s^- \to \phi e^- \bar{\nu}$ has been observed, with a branching ratio relative to the channel $D_s^- \to \phi\pi^-$ determined to be $0.57 \pm 0.15 \pm 0.15$. The decay $D^- \to K^{*0} e^- \bar{\nu}$ was also seen, with a value of $0.55 \pm 0.08 \pm 0.10$ extracted for the branching ratio relative to the channel $D^- \to K^+\pi^-\pi^-$. The ratio of the two measurements, after application of SU(3) corrections, implies a branching ratio for $D_s^- \to \phi\pi^-$ of $(2.4 \pm 1.0)\%$.

Semileptonic decays of charmed mesons are well suited for testing theoretical predictions for heavy quark decays. Present models [1–3] successfully describe semileptonic charm decays to pseudoscalar mesons, e.g. $D^0 \to K^- e^+ \nu$ [#1], but have some difficulties with the decay $D^- \to K^{*0} e^- \bar{\nu}$. The E691 Collaboration has found the branching ratio for the latter to be one-half that predicted [4]. The difficulty is compounded by the observation that the K^{*0} is strongly polarized, in disagreement with the theoretical expectations. Hence, it is important to obtain an independent determination of the branching ratio.

For the analogous process $D_s^- \to \phi e^- \bar{\nu}$, one expects similar values for the partial width and polarization, based on SU(3) symmetry in the framework of the spectator model. A study of this decay channel, the first semileptonic decay of the D_s^- observed so far, is presented here. Assuming that the SU(3) corrections are small and reliably predicted, an absolute scale for the D_s^- branching ratios can be extracted using the ratio of observed semileptonic D_s^- and D^- decays.

The study presented here is based on continuum $c\bar{c}$ events collected with the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. A detailed description of the detector can be found in ref. [5]. Two data samples have been used: 104 pb^{-1} of continuum data taken at an average centre-of-mass energy of 10.35 GeV, and 229 pb^{-1} taken on the $\Upsilon(4S)$ resonance where the physics interest was, in this case, the non-resonant $c\bar{c}$ component. For the latter, a topological cut requiring the second Fox–Wolfram moment to be larger than 0.35 removes $(93 \pm 3)\%$ of the $\Upsilon(4S)$ resonance decays.

Identification of final state particles was made on the basis of specific ionization in the drift chamber, time-of-flight measurements, muon-chamber hits, and size and lateral distribution of energy depositions in the electromagnetic calorimeter. For all charged particles, this information was used coherently by calculating a normalized likelihood for each of the viable mass hypotheses e, μ, π, K, and p [6]. For an acceptable hadron hypothesis, the corresponding likelihood was required to be greater than 1%.

Electrons were accepted if their momenta exceeded 0.4 GeV/c, where reliable identification begins. The electron likelihood ratio was required to exceed 0.8, which is a compromise between demands for high acceptance (80%) and good particle separation. The rate for misidentification of hadrons as electrons with this requirement was determined using two different methods. First, particles recognized as electrons in $\Upsilon(1S)$ decays, where the fraction of leptons is negligible, were counted as fakes or as contamination from photon conversions. Second, the clean samples of pions, kaons, and protons provided in K_s^0, ϕ, and Λ decays, were scanned for tracks fulfilling the electron identification criterion. The two

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methods agree on both the absolute scale and the momentum dependence of the misidentification rate. The rate averaged over the hadron momentum spectrum is 0.006 fake electrons per hadron.

In the study of semileptonic decays, the neutrino of course escapes detection. Therefore a signature for the process must be obtained only from the observable decay products, i.e. the vector meson and the electron. In order to label charm decays we look for electrons in continuum events, where the only sources of direct leptons are semileptonic decays of charmed particles. In addition we exploit the hard momentum spectrum of D mesons in continuum $c\bar{c}$ events, which leads to small opening angles between the daughter particles. As a consequence, the approach used for our study was to search for events containing a vector meson and an electron, requiring an opening angle between the combination of less than 90°.

We first investigated the reaction $D^- \to K^{*0} e^- \bar{\nu}$ by studying K^{*0}–e^- correlations. Wrong-charge ($\bar{K}^{*0} e^-$) combinations cannot be attributed to charm decays and are therefore well suited for estimating the reliability of the background determination. The K^{*0} mesons were reconstructed in the decay channel $K^{*0} \to K^+ \pi^-$. The $K\pi$ invariant mass distribution of events containing an electron candidate is shown in fig. 1. A fit to the data using a P-wave Breit–Wigner plus a heuristic background function $f(m) = (m-a)^b \times (a e^{-\alpha m} + B e^{-\beta m})$, and a term describing the ρ_0 reflection, yields 1441 ± 96 K^{*0} mesons. The threshold region, which contains a reflection from the $K^+\pi^-$ combination in the decay chain $D^{*-} \to \bar{D}^0 \pi^-$ followed by $\bar{D}^0 \to K^+ \ell^- X$, has been excluded from the fit.

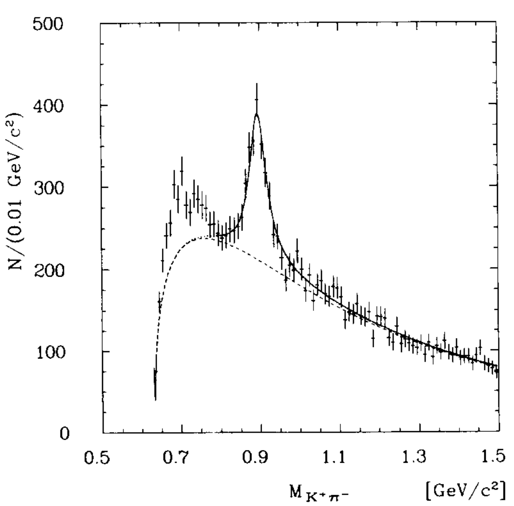

Fig. 1. Invariant $K^+\pi^-$ mass distribution for events containing an electron. The fitted curve is described in the text.

In addition to the signal from semileptonic D^- decays, this data sample includes contributions from the following background sources:

- A fake electron contribution of 256 ± 51 events, which has been determined from K^{*0}–hadron combinations by integrating the convolution of the hadron momentum spectrum with the misidentification rate described above.
- An estimated 185 ± 46 K^{*0} mesons originating from the fragmentation processes in coincidence with electrons from charm decays. This source was investigated using a Monte Carlo simulation of $c\bar{c}$ events.
- A total of 120 ± 52 combinations from $\Upsilon(4S)$ resonance decays. This source has been evaluated by comparing the number of K^{*0}–electron combinations in data samples taken at the $\Upsilon(4S)$ energy with and without application of the Fox–Wolfram cut $H_2 > 0.35$, i.e. depleting and enriching the direct $\Upsilon(4S)$ component.

Thus, the sum of all background sources is found to be 561 ± 86 events.

The background determination has been quantitatively checked by studying wrong-charge combinations. The observed number of 573 $\bar{K}^{*0} e^-$ fitted events is in good agreement with the detailed calculation (586 ± 88 events), which follows the same procedure as for the $K^{*0} e^-$ combinations. Further details are discussed in ref. [7].

Subtracting the background of 561 events, there remain 880 ± 129 right-charge $K^{*0} e^-$ combinations, which are attributed to D^- decays. The acceptance, as determined by a Monte Carlo simulation of $c\bar{c}$ production, has been found to be $(20 \pm 2)\%$ for continuum data. An efficiency of $(56 \pm 7)\%$ was estimated for the additional Fox–Wolfram cut applied to the $\Upsilon(4S)$ data, by studying the shape of events containing decays $D^- \to K^+ \pi^- \pi^-$ in the data. For the product of cross section times branching ratio we find $\sigma_{D^-} \mathrm{BR}(D^- \to K^{*0} e^- \bar{\nu}) = (2.8 \pm 0.4 \pm 0.4)$pb at a centre-of-mass energy of 10.55 GeV. The branching ratio for $D^- \to K^{*0} e^- \bar{\nu}$ can be obtained using the known cross section $\sigma_{D^-} = (0.66 \pm 0.07 \pm 0.09)$nb

[8,9] [#2], which in turn was deduced with $BR(D^- \to K^+\pi^-\pi^-) = (7.7 \pm 1.0)\%$ [10]. A value of $(4.2 \pm 0.6 \pm 1.0)\%$ is found for the branching ratio for $D^- \to K^{*0}e^-\bar{\nu}$. The systematic error receives contributions from the uncertainty of the parametrization of the $K\pi$ mass distribution, including the effects of the reflections from the ϕ, K^0_s and ρ, as well as the uncertainty in the D^- cross section and the acceptance calculation. The latter is insensitive to variation of the assumption concerning the polarization of the K^{*0}. The branching ratio obtained with different restrictions on the $K^{*0}e^-$ invariant mass is consistent within errors. Therefore, we conclude that there is no sizeable contribution from decays to final states with additional pions. The result agrees with the E691 measurement of $BR(D^- \to K^{*0}e^-\bar{\nu}) = (3.8 \pm 0.7)\%$ [4], where this number has been rescaled using the $BR(D^- \to K^+\pi^-\pi^-)$ given above.

The analogous technique of ϕ–e^- correlations has been employed for the study of the decay $D_s^- \to \phi e^-\bar{\nu}$. The K^+K^- decay channel was used to reconstruct ϕ mesons. Fig. 2 shows the K^+K^- invariant mass distribution for events containing an electron candidate. The ϕ signal was fitted with a P-wave Breit–Wigner folded with a gaussian, a background parametrized by a third-order polynomial times a square-root threshold factor, and a term describing the K^{*0} reflection. The number of events containing a ϕ–e^- candidate was found to be 200 ± 21.

[#2] The quoted cross section in ref. [9] is $\sigma_{D^+} = (0.65 \pm 0.09 \pm 0.09)$ nb at $E_{cms} = 10.6$ GeV.

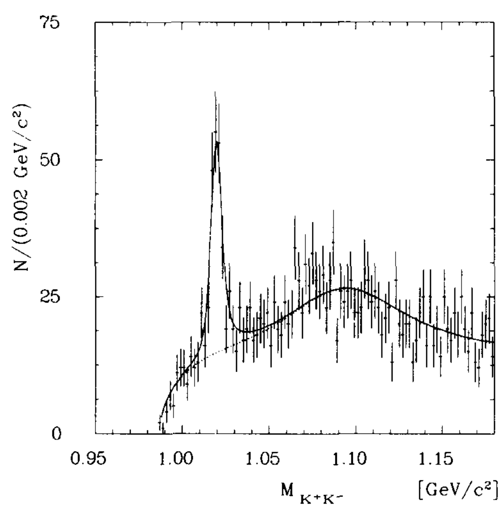

Fig. 2. Invariant K^+K^- mass distribution for events containing an electron. The fitted curve is described in the text.

All the backgrounds processes described above for the $D^- \to K^{*0}e^-\bar{\nu}$ channel lead to background events here as well. Using the same methods as employed for the K^{*0}–e^- study we find the following contributions:

- A fake contribution of 45 ± 9 events.
- An estimated 35 ± 11 events with ϕ mesons originating from fragmentation processes or D-meson decays respectively combined with electrons from charm decays.
- A total of 16 ± 7 combinations from $\Upsilon(4S)$ decays.

After subtraction, there remain 104 ± 26 ϕ–electron pairs which are attributed to the decay $D_s^- \to \phi e^-\bar{\nu}$. The background-subtracted ϕ–electron invariant mass distribution, shown in fig. 3, is in good agreement with the prediction of the model of Wirbel, Bauer, and Stech (WBS) [11,12]. In particular, the absence of an excess for ϕ–electron masses below 1.4 GeV/c^2 precludes a sizeable contribution from decays of the type $D \to \phi K e \nu$.

The acceptance for continuum data $(19.9 \pm 2)\%$ and the efficiency for the Fox–Wolfram cut $(65 \pm 10)\%$ have been determined as described above. For the latter, events containing decays $D_s^- \to \phi\pi^-$ were studied. The result for the product $\sigma_{D_s} BR(D_s^- \to \phi e^-\bar{\nu})$ was found to be $(4.1 \pm 1.0 \pm 0.8)$ pb, at a centre-of-mass energy of 10.55 GeV. For the ratio of branching ratios, we find

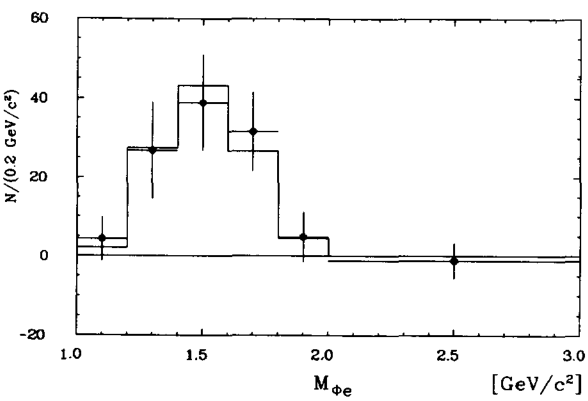

Fig. 3. Invariant $\phi e^\pm$ mass distribution in the decay $D_s^- \to \phi e^-\bar{\nu}$ (points with error bars). The histogram corresponds to the prediction of refs. [11,12].

$$\frac{BR(D_s^- \to \phi e^- \bar{\nu})}{BR(D_s^- \to \phi \pi^-)} = 0.57 \pm 0.15 \pm 0.15 ,$$

using $\sigma_{D_s} BR(D_s^- \to \phi \pi^-)$ from ref. [13]. The CLEO result of $(0.49 \pm 0.10^{+0.10}_{-0.14})$ [14] agrees well with this measurement, while the upper limit of 0.45 at the 90% confidence level [15] obtained by the E691 Collaboration is still consistent.

An example of the theoretical relationship between the semileptonic partial widths for decays $D^- \to K^{*0} e^- \bar{\nu}$ and $D_s^- \to \phi e^- \bar{\nu}$ is provided by the WBS model [11,12]. In an updated version of this model, Wirbel and Bauer treat the overlap integral which simultaneously controls the semileptonic decay rate and the polarization of the vector meson as a free parameter. If this parameter is adjusted to achieve agreement with the average of $(3.7 \pm 0.7) \times 10^{10} s^{-1}$ from the ARGUS and E691 measurements of $\Gamma(D^- \to K^{*0} e^- \bar{\nu})$, the surprisingly large polarization of the K^{*0} is also reproduced [4]. Keeping this parameter fixed, the model prediction for the decay $D_s^- \to \phi e^- \bar{\nu}$ is $\Gamma(D_s^- \to \phi e^- \bar{\nu}) = (3.1 \pm 0.6) \times 10^{10} s^{-1}$, corresponding to a branching ratio of $(1.4 \pm 0.3)\%$. Here the D-meson lifetimes are taken from ref. [10]. This prediction, in combination with our measurement of the product of cross section times branching ratio, allows us to derive a D_s production cross section of $\sigma_{D_s} = (0.30 \pm 0.11)$nb at $E_{cms} = 10.55$ GeV, leading to a branching ratio of $(2.4 \pm 1.0)\%$ for the decay $D_s^- \to \phi \pi^-$. Assuming a probability of 15% for $s\bar{s}$ pickup in the fragmentation process, the total charm cross section of $(2.4 \pm 0.04 \pm 0.25)$nb reported by CLEO [16] implies that $\sigma_{D_s} = (0.36 \pm 0.01 \pm 0.04)$nb. The difference between this value and that derived here might be explained by the production of excited D_s states, which decay into non-strange charmed mesons [17].

In conclusion, the semileptonic decays $D^- \to K^{*0} e^- \bar{\nu}$ and $D_s^- \to \phi e^- \bar{\nu}$ have been observed in continuum $e^+ e^-$ events. For the D^- decay the branching ratio is found to be $(4.2 \pm 0.6 \pm 1.0)\%$, in agreement with the result of E691 [4]. For the decay $D_s^- \to \phi e^- \bar{\nu}$ the product of cross section times branching ratio is determined to be $(4.1 \pm 1.0 \pm 0.8)$pb. Using the model of Wirbel, Bauer, and Stech we derive a D_s production cross section of (0.30 ± 0.11)nb. From the ratio of the two branching ratio measurements we find $BR(D_s^- \to \phi \pi^-) = (2.4 \pm 1.0)\%$.

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