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Observation of the decay $D_{s1}(2536) \to D^{*0}K^+$

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Using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY, we have observed a new decay channel for the excited charm-strange meson $D_{s1}(2536)^+ \to D^{*0}K^+$. The production cross section for the $D_{s1}(2536)^+$ decaying via this channel is measured to be $\sigma(D_{s1}(2536)^+)\cdot BR(D_{s1}(2536)^+ \to D^{*0}K^+) = 18 \pm 4 \pm 3$ pb at $E_{CM} = 10.4$ GeV. The mass of the $D_{s1}(2536)^+$ is found to be $2535.2 \pm 0.5 \pm 1.5$ MeV/c^2 in agreement with the value obtained from an analysis of the $D_{s1}(2536)^+ \to D^{*+}K^0_S$ decay channel. The natural width is determined to be less than 3.9 MeV/c^2 at 90% CL.

The spectroscopy and decay of excited charmed mesons are an important means of obtaining information about the spin-structure of the quark–antiquark potential at relatively large distances. Many models have been put forward which predict the properties of these resonances [1–3]. ARGUS, CLEO and TPS observed several charmed states [4–9] which are assumed to be P-wave mesons.

In the case of the charmed–strange excited states the situation is not so well developed. ARGUS [9] and CLEO [10] have observed a signal in the $D^{*+}K^0_S$ mass spectrum [#1] at a mass of $2535.9 \pm 0.6 \pm 2.0$ MeV/c^2 and $2535.6 \pm 0.7 \pm 0.4$ MeV/c^2, and with a natural width less than 4.6 MeV/c^2 and 5.44 MeV/c^2 (90% confidence level) respectively. In the following we shall refer to this state as the $D_{s1}(2536)^+$. As in the case of excited charmed mesons (D_J), it is expected that there should be four $L=1$ D_{sJ} states having spin-parities (J^P) 0^+, 1^+, 1^+ and 2^+. The 2^+ state can decay to both D^*K and DK while, because of spin-parity constraints, the 1^+ states can only decay to D^*K and the 0^+ state to DK. The absence of the $D^+K^0_S$ decay mode for the $D_{s1}(2536)^+$ [9] provides evidence that this state has spin-parity 1^+. In the limit of the infinite charm-quark mass one of the 1^+ states should decay into D^*K in a pure S-wave while the other one decays in a pure D-wave. For finite mass, the two states generally mix, so that decays will occur in a combination of S- and D-wave.

Evidence for two other states which are interpreted as P-wave $c\bar{s}$ mesons has also been reported [11]. One, at a mass of 2537 ± 28 MeV/c^2, is seen to decay to $D_s^{*+}\gamma$ but not to D^*K. The other one, at a mass of 2564.3 ± 4.4 MeV/c^2, is claimed in the mode D^*K. It is difficult to identify either of these states with the $D_{s1}(2536)^+$. Evidence for a meson which was assumed to be a $c\bar{s}$ radially excited state was obtained in the hybrid E-564 experiment [12]. Using nuclear emulsion placed inside the 15 ft bubble chamber one candidate at a mass of 2794 ± 23 MeV/c^2 was found decaying to $D^{*0}K^+$.

In this paper, we report the first observation of the decay $D_{s1}(2536)^+ \to D^{*0}K^+$, confirming the existence of this charmed–strange excited state. The D^{*0} were reconstructed using both the $D^{*0} \to D^0\pi^0$ and $D^0\gamma$ modes. Isotopic spin invariance requires that the matrix element for this decay be the same as that for $D^{*+}K^0$. However, the small differences in the D^{*+}, D^{*0} and K^0, K^+ masses result in about a 10% variation in the momenta $Q_{D^{*0}K^+}$ and $Q_{D^{*+}K^0}$ of $D_{s1}(2536)^+$ decay products in the $D_{s1}(2536)^+$ rest frame. This can result in a difference in the ratio of branching ratios $BR(D_{s1}(2536)^+ \to D^{*0}K^+)/BR(D_{s1}(2536)^+ \to D^{*+}K^0_S)$ ranging from $Q_{D^{*0}K^+}/Q_{D^{*+}K^0} = 1.1$ for the S-wave to $(Q_{D^{*0}K^+}/Q_{D^{*+}K^0})^5 = 1.7$ for the D-wave decay.

The analysis presented here is based on a data sample of 455 pb^{-1} taken at an average center-of-mass energy of 10.4 GeV while running on the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(4S)$ resonances and in the nearby continuum using the ARGUS detector at the e^+e^- storage

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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.

ring DORIS II at DESY. The ARGUS detector is a 4π spectrometer described in detail elsewhere [13]. Charged particles from the main event vertex were required to have a polar angle, θ, in the range $|\cos\theta| < 0.92$. These particles were identified on the basis of specific ionization, time of flight, energy deposition in the shower counters and penetration to the muon chambers. In reconstructing the D^0 meson, particles were treated as $\pi^\pm$ or $K^\pm$ if the likelihood ratio for the appropriate mass hypothesis exceeded 1%. Kaons from $D_{s1}(2536)^+ \to D^{*0}K^+$ decays, which have a softer momentum spectrum, were required to have a likelihood ratio greater than 10%. This cut decreases the background from misidentified pions. It also removes a possible reflection near 2600 MeV/c^2 from the decay $D_J^*(2470)^+ \to D^{*0}\pi^+$. This mode has not been reconstructed before but is expected to exist if the $D_J^*(2470)^+$ observed in the $D^0\pi^+$ mode [7] is a 2^+ state.

K_S^0 candidates were defined as $\pi^+\pi^-$ pairs with an invariant mass within ± 30 MeV/c^2 of the K_S^0 mass originating from a secondary vertex [13]. In addition the angle α between the K_S^0 momentum and the vector which points from the main vertex to the decay vertex was required to satisfy $\cos\alpha > 0.9$. Photons were defined as clusters of energy deposited in the electromagnetic calorimeter, but with no associated charged track. Two photons were accepted as a π^0 candidate if their energies were greater than 50 MeV and their mass lay within two standard deviations of the π^0 mass. Photons from $D^{*0} \to D^0\gamma$ decays are more energetic than those from $D^{*0} \to D^0\pi^0$, followed by $\pi^0 \to \gamma\gamma$. Therefore their energies were required to be greater than 100 MeV in order to suppress background from soft photons.

D^{*0} mesons were reconstructed in the modes $D^{*0} \to D^0\pi^0$, $D^0\gamma$ followed by the decay of the D^0 meson into the $K^-\pi^+$, $K_S^0\pi^+\pi^-$, or $K_S^0K^+K^-$ final states. D^0 candidates were required to have an invariant mass within ± 40 MeV/c^2 or ± 30 MeV/c^2 of the nominal value for two-body and three-body modes, respectively. The mass of the $D^0\pi^0$ ($D^0\gamma$) pair was required to lie within ± 8 MeV/c^2 (± 40 MeV/c^2) of the D^{*0} mass. To improve momentum resolution a mass constraint fit was applied to all intermediate states (K_S^0, π^0, D^0, and D^{*0}).

In the $D^0 \to K^-\pi^+$ channel, a large background is produced by random combinations of kaons with slow pions. For this channel only, we required $\cos\theta_K^* < 0.9$, where θ_K^* is defined as the angle between the kaon momentum vector and the D^0 boost direction, as measured in the D^0 rest frame. The distribution of $\cos\theta_K^*$ for D^0 decays should be isotropic since the D^0 has spin zero, while the background is peaked towards $\cos\theta_K^* = +1.0$. Thus the efficiency of this cut is 95% for the signal, while the background for this mode is suppressed by a factor of 1.5.

In the $D^{*0} \to D^0\gamma$ mode a large combinatorial background arises from the many photons produced by π^0 decays. To reduce this background to a manageable level an anti-π^0 cut was applied: events were rejected where the photon from the D^{*0} decay combined with any other photon with energy greater than 80 MeV had an invariant mass lying within ± 50 MeV/c^2 of the π^0 mass. This interval corresponds approximately to two standard deviations in the reconstruction resolution for the π^0. The efficiency of this requirement has been estimated to be 63% for the signal, while the background is further suppressed by a factor of 3.

The momentum spectrum of a meson containing a leading charmed quark has been demonstrated to be hard, in contrast to the combinatorial background. Therefore all $D^{*0}K^+$ combinations were required to have $x_p > 0.6$, where $x_0 = p/p_{max}$ and $p_{max} = [E_{beam}^2 - m(D^{*0}K^+)^2]^{1/2}$.

The resulting $D^{*0}K^+$ mass spectra are shown in fig. 1a for D^{*0} mesons reconstructed via the $D^0\pi^0$ decay mode and in fig. 1b for $D^0\gamma$. A signal in the first figure and an enhancement in the second one are observed. These spectra were fitted with a second-order polynomial multiplied by a square-root threshold factor to describe the background, and two gaussian terms. The first gaussian served to parametrize the $D_{s1}(2536)^+$ signal itself. Its width was fixed to the Monte Carlo determined detector resolution of 1.6 MeV/c^2 which was found to be the same for both channels. The second gaussian was added in order to take into account possible cross talk between the π^0 and γ from the $D^{*0} \to D^0\pi^0$, $D^0\gamma$ decays, as well as feeddown arising when one photon (or even two) from the D^{*0} are lost and a photon (photons) from the rest of the event is taken to form D^{*0} candidate. These processes can produce an enhancement in the signal region, particularly in case of the $D^0\pi^0$ mode

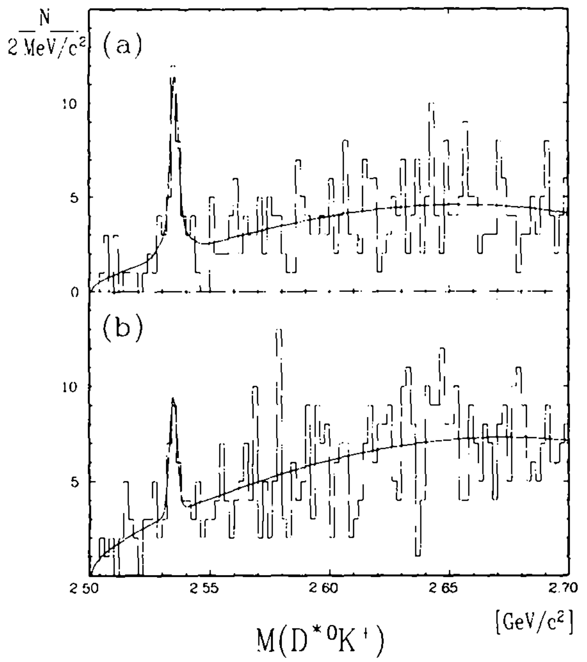

Fig. 1. Invariant mass distributions of all accepted $D^{*0}K^+$ combinations in the D^{*0} decay modes (a) $D^0\pi^0$ and (b) $D^0\gamma$. The curves correspond to the fit described in the text.

where the energy release in D^{*0} decay is very small, and the D^0 "remembers" the direction and momentum of the D^{*0} meson. The widths of the second gaussian were fixed to 5 MeV/c^2 and 8 MeV/c^2 for the $D^0\pi^0$ and $D^0\gamma$ modes respectively. These values are slightly larger than the widths of 3.2 MeV/c^2 and 7.3 MeV/c^2 for the signals in the D^0K^+ mass spectra produced by $D_{s1}(2536)^+\to D^{*0}K^+$, followed by $D^{*0}\to D^0\pi^0$ and $D^0\gamma$ respectively, where the neutrals are not reconstructed. The same central value is chosen for both gaussians. The amplitude for the $D^0\gamma$ mode, where the width of the peak ($\sigma=8$ MeV/c^2) is much larger than the detector resolution of 1.6 MeV/c^2, was left free. For the $D^0\pi^0$ mode the ratio of the number of events in the second gaussian was fixed to be 62% of the primary peak, as determined by Monte Carlo simulation.

The resulting numbers of events obtained in fitting to the spectra in figs. 1a and 1b are 15.8 ± 4.0 and 12.2 ± 5.6 respectively. A variation of the ratio of secondary to primary gaussians by 20% changes the signal in the $D^0\pi^0$ mode by only ±1.4 events and is included as a systematic error. The mass was determined to be 2535.4 ± 0.6 MeV/c^2 and 2534.8 ± 0.8 MeV/c^2 for the $D^0\pi^0$ and $D^0\gamma$ modes respectively. These numbers are in good agreement with the values obtained in the analysis of the $D_{s1}(2536)^+\to D^{*+}K^0_S$ decay channel: $2535.9\pm0.6\pm2.0$ MeV/c^2 [9] and $2535.6\pm0.7\pm0.4$ MeV/c^2 [10].

To obtain an upper limit for the natural width, Γ, of the $D_{s1}(2536)^+$, the signal shape for the $D^0\pi^0$ mode was parameterized by a non-relativistic Breit-Wigner convoluted with a gaussian resolution function.. The width of the gaussian was fixed to its expected value of 1.6 MeV/c^2. The fit yields an upper limit of $\Gamma<3.9$ MeV/c^2 at 90% confidence level.

In order to demonstrate that the signal is not an artifact of the selection criteria, a sideband study and a wrong-charge study were performed for the $D^0\pi^0$ mode. For the sideband study, $D^0\pi^0$ combinations were selected from the region $2020<m(D^0\pi^0)<2040$ MeV/c^2. Since the kinematic fit to the D^{*0} mass cannot be applied here we used a mass difference technique instead. The sideband candidates were combined with all K^+ mesons in the event and the mass difference

$$\Delta(D_{s1})=m(D^0\pi^0K^+)-m(D^0\pi^0)\ ,$$

calculated. No signal is observed in the corresponding spectrum shown in fig. 2a. Applying the mass difference technique to $D^{*0}K^+$ combinations yields approximately the same result as shown in fig. 1a, except for the change in the horizontal scale, with a signal of 14.9 ± 3.9 events. The observed mass difference is 527.5 ± 0.7 MeV/c^2 corresponding to the $D_{s1}(2536)^+$ mass of 2534.8 ± 0.7 MeV/c^2. The small deviation in comparison with the value of 2535.4 ± 0.6 MeV/c^2 quoted above was included into the systematic error on the mass. For the wrong-charge study, we used only the $D^0\to K^-\pi^+$ channel in order to distinguish between D^0 and $\overline{D}^0$. The corresponding mass spectra for $D^{*0}K^-$ and $D^{*0}K^+$ combinations are shown in figs. 2b and 2c, respectively. No signal is observed in the wrong-charge spectrum (-0.6 ± 0.8 events) while there are 8.3 ± 2.7 events in the right-charge distribution.

As a further check of these results, the invariant mass distributions of $D^0\pi^0$ pairs from the $D_{s1}(2536)^+$ region ($|\Delta(D_{s1})-527.5$ MeV/$c^2|<3$ MeV/c^2), and from $D_{s1}(2536)^+$ sidebands ($6<|\Delta(D_{s1})-527.5$

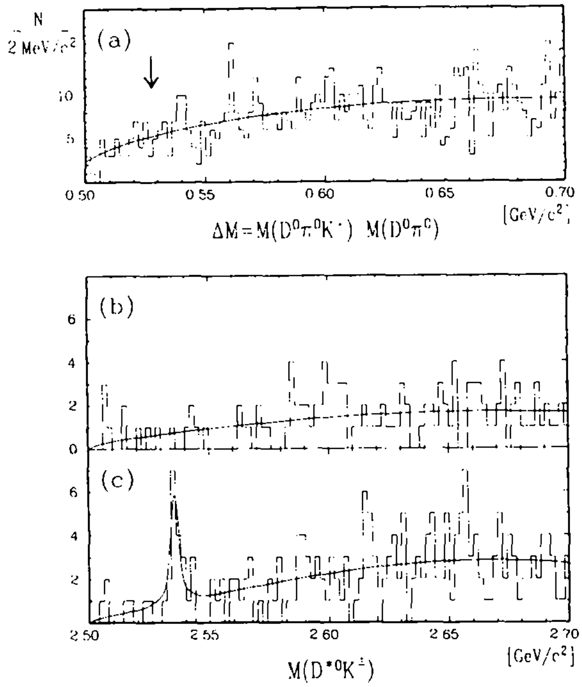

Fig. 2. (a) $M(D^0\pi^0K^+)-M(D^0\pi^0)$ mass difference spectrum for $D^0\pi^0$ combinations from D^{*0} sidebands ($2020<m(D^0\pi^0)<2040$ MeV/c^2). (b), (c) Invariant mass spectra of all accepted $D^{*0}K^-$ and $D^{*0}K^+$ combinations respectively, where the D^{*0} was reconstructed in the decay chain $D^{*0}\to D^0\pi^0$, $D^0\to K^-\pi^+$ to distinguish between a D^0 and $\bar{D}^0$. The curves correspond to the fit described in the text.

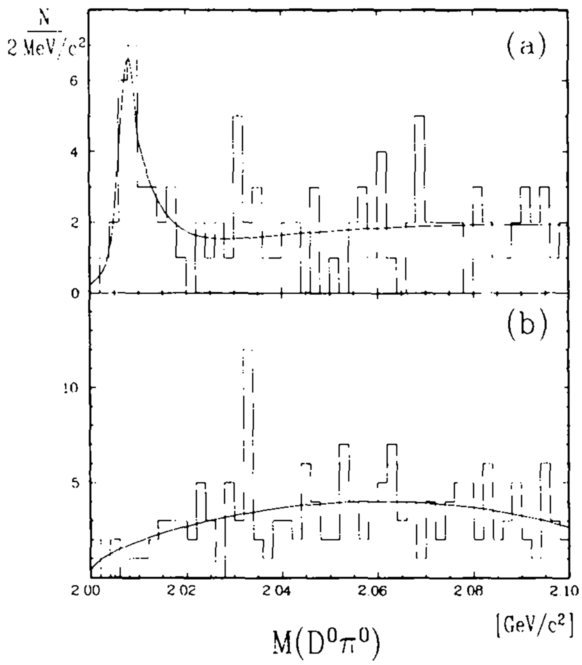

Fig. 3. $D^0\pi^0$ invariant mass distributions (a) from the $D_{s1}(2536)^+$ region ($|\Delta(D_{s1})-527.5$ MeV/$c^2|<3$ MeV/c^2), and (b) from $D_{s1}(2536)^+$ sidebands ($6<|\Delta(D_{s1})-527.5$ MeV/$c^2|<12$ MeV/c^2). The curves correspond to the fit described in the text.

MeV/$c^2|<12$ MeV/c^2), were studied. These spectra are shown in figs. 3a and 3b. According to the Monte Carlo simulation, the presence of a threshold near the D^{*0} mass modifies the simple gaussian shape for D^{*0} signal and produces the long tail to the high mass side of the distribution. To take this into account, the tail was parameterized by an exponential function with slope fixed by Monte Carlo, while for the main part of the D^{*0} signal a gaussian with a fixed width of 1.9 MeV/c^2 was used. The background was described by a second-order polynomial multiplied by a square-root threshold factor. The number of D^{*0} mesons from the $D_{s1}(2536)^+$ region was found to be 21 ± 6, in agreement with the expected value of 17 ± 4. No signal was seen in the $D_{s1}(2536)^+$ sidebands (-8 ± 3 events). The central value of the gaussian obtained from the fit to the D^{*0} signal in fig. 3a, 2008.1 ± 0.8 MeV/c^2, is in agreement with the expected position of 2007.1 MeV/c^2.

As a final confirmation of these results, the D^0K^+ mass spectrum was studied, since the $D_{s1}(2536)^+$ can produce an enhancement in the region near $M(D_{s1}(2536)^+)-M(D^{*0})+M(D^0)\simeq2400$ MeV/c^2 if the π^0 or γ from D^{*0} decay is not reconstructed. Although the signal for the $D^0\gamma$ mode becomes rather broad ($\sigma=7.3$ MeV/c^2) and difficult to observe according to the Monte Carlo simulation, the $D^0\pi^0$ decay channel, where the mass of D^{*0} is very close to threshold, has an expected signal width of only 3.2 MeV/c^2. There is no feeddown or cross talk between neutrals in this approach. In this analysis the x_p requirement was reduced to $x_p(D^0K^+)>0.5$ where $x_p(D^0K^+)$ was defined as $p(D^0K^+)/[E^2_{\rm beam}-m(D^0K^+)^2]^{1/2}$. Due to a higher level of background in comparison with the $D^{*0}K^+$ mass spectra, tighter cuts were applied against slow pions in the D^0 reconstruction, requiring that $\cos\theta^*_K<0.6$ for both $K^-\pi^+$ and $K^0_S\pi^+\pi^-$ decay channels. The resulting spectrum is shown in fig. 4. For comparison, the same spectrum for wrong-charge combinations D^0K^- is shown by the hatched histogram, where only the $D^0 \to K^-\pi^+$ mode was used to distinguish between a D^0 and $\bar{D}^0$. A peak is visible at the expected position of about 2400 MeV/c^2 in the right-charge distribution while the wrong-charge spectrum does not show any enhancement in this region. The spectra were fitted with two gaussians with the widths fixed at 3.2 and 7.3 MeV/v^2 and the same central values. The ratio of numbers of events in the two gaussians was chosen to be equal to $\mathrm{BR}(D^{*0}\to D^0\pi^0)/\mathrm{BR}(D^{*0}\to D^0\gamma) = 0.57:0.43$ [14] since the efficiencies for $D^0K^\pm$ reconstruction are the same for both the $D^{*0}\to D^0\pi^0$ and $D^0\gamma$ modes. The resulting number of events in both gaussians for the D^0K^+ mass spectrum is $71\pm17\pm10$ where the second error comes from the variation of the fit range. This value is in agreement with the expectation of 103 ± 23 obtained from the numbers of $D_{s1}(2536)^+$ events observed in the $D^{*0}K^+$ mass spectra (figs. 1a, 1b). The observed position of the peak, 2393.2 ± 1.2 MeV/c^2, is also in good agreement with the expected value of 2393.1 MeV/c^2 determined by the Monte Carlo simulation with the $D_{s1}(2536)^+$ mass fixed at 2535.2 MeV/c^2. The number of events in the wrong-charge spectrum, -11 ± 8, is consistent with zero.

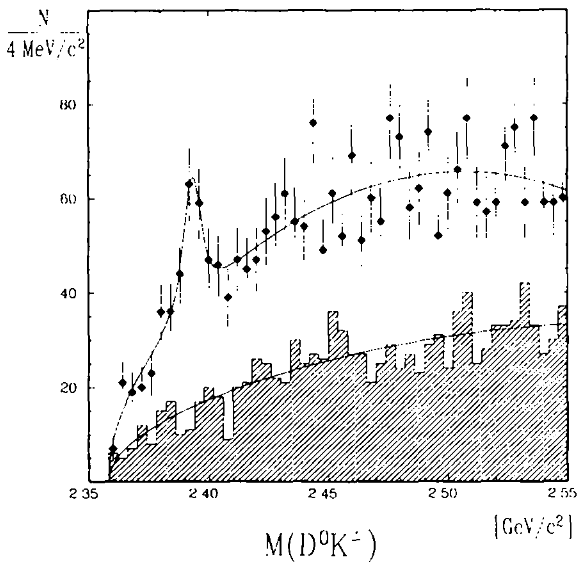

Fig. 4. $D^0K^\pm$ invariant mass spectra. Data points represent the D^0K^+ mass distribution while the hatched histogram corresponds to "wrong" charge D^0K^- pairs, where only the $D^0\to K^-\pi^+$ mode was used. The curves correspond to the fit described in the text.

In order to convert the fitted numbers of $D_{s1}(2536)^+$ events in the $D^{*0}K^+$ mass spectra (figs. 1a, 1b) to the $D_{s1}(2536)^+$ production rate in the continuum at $E_{CM}=10.4$ GeV for $x_p>0.6$, we used the known branching ratios for $\mathrm{BR}(D^{*0}\to D^0\pi^0) = (57.0\pm3.7\pm4.2)\%$, $\mathrm{BR}(D^{*0}\to D^0\gamma) = (43.0\pm3.7\pm4.2)\%$ [14] and D^0 and K^0_S [15]. This gives: $\sigma(D_{s1}(2536)^+, x_p>0.6)\cdot\mathrm{BR}(D_{s1}(2536)^+\to D^{*0}K^+) = 14\pm3\pm3$ pb for the $D^{*0}\to D^0\pi^0$ and $\sigma(D_{s1}(2536)^+, x_p>0.6)\cdot\mathrm{BR}(D_{s1}(2536)^+\to D^{*0}K^+) = 10\pm5\pm4$ pb for the $D^{*0}\to D^0\gamma$ mode. The quoted systematic errors include contributions from the variation of the cuts and the fit parameters, uncertainties in the Monte Carlo simulation and in the D^0 and D^{*0} branching ratios. Averaging over the two channels gives

$$\sigma(D_{s1}(2536)^+, x_p>0.6)\cdot\mathrm{BR}(D_{s1}(2536)^+\to D^{*0}K^+) = 12\pm3\pm2\ \mathrm{pb}\,.$$

Using the Peterson et al. fragmentation function with $\epsilon = 0.06^{+0.02}_{-0.01}\pm0.02$ [16] obtained in the analysis of the decay $D_{s1}(2536)^+\to D^{*+}K^0_S$ we can extrapolate to zero momentum:

$$\sigma(D_{s1}(2536)^+)\cdot\mathrm{BR}(D_{s1}(2536)^+\to D^{*0}K^+) = 18\pm4\pm3\ \mathrm{pb}\,.$$

This result can be compared with previous measurements of $\sigma(D_{s1}(2536)^+)\cdot\mathrm{BR}(D_{s1}(2536)^+\to D^{*+}K^0_S = 13\pm4\pm2$ pb [9] and $\sigma(D_{s1}(2536)^+)\cdot\mathrm{BR}(D_{s1}(2536)^+\to D^{*+}K^0_S) = 13\pm4$ pb [10]. The first of these was recalculated using the branching ratio $\mathrm{BR}(D^{*+}\to D^0\pi^+) = (66.1\pm1.8\pm2.2)\%$ from ref. [14]. The second was extracted from $\sigma(D_{s1}(2536)^+)\cdot\mathrm{BR}(D_{s1}(2536)^+\to D^{*0}K^+)\sigma(D^{*+}) = (2.6\pm0.7)\%$ as determined in ref. [10] for $x_p>0.6$ using the x_p distribution of D^{*+} mesons in continuum from refs. [17,18], and the same values noted above for ϵ and $\mathrm{BR}(D^{*+}\to D^0\pi^+)$.

The average mass of the $D_{s1}(2536)^+$ obtained from the fitting to the $D^{*0}K^+$ mass spectra is found to be

$$M(D_{s1}) = 2535.2\pm0.5\pm1.5\ \mathrm{MeV}/c^2\,,$$

where the systematic error includes contributions from the variation of the cuts and the fit parameters, the shift in the $M(D_{s1})$ value observed in using the mass difference technique, and the uncertainty on the D^{*0} mass [15].

In summary, we have observed the decay $D_{s1}(2536)^+ \to D^{*0}K^+$ and have determined the production rate for the $D_{s1}(2536)^+$ at $E_{CM} = 10.4$ GeV to be $\sigma(D_{s1}(2536)^+) \cdot BR(D_{s1}(2536)^+ \to D^{*0}K^+) = 18 \pm 4 \pm 3$ pb. The mass of the $D_{s1}(2536)^+$ was found to be $2535.2 \pm 0.5 \pm 1.5$ MeV/c^2 and the width to be smaller than 3.9 MeV/c^2 at 90% CL.

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