OBSERVATION OF A NEW CHARMED-STRANGE MESON

ARGUS Collaboration

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Using the ARGUS detector at the DORIS II e^+e^- storage ring at DESY, we have obtained evidence for a new charmed–strange meson which decays into $D^{*+}K^0$ Its mass is observed to be 2535 9±0 6±2 0 MeV/c^2 and its width to be less than 4 6 MeV/c^2 at the 90% confidence level No structure is observed at this mass in the D^+K^0 invariant mass spectrum, which suggests that an unnatural spin–parity is preferred

Over the past four years, two new charmed mesons, ascribed to P-wave bound states of a charmed quark and either a $\bar{u}$ or a $\bar{d}$ quark, have been observed [1–5] A variety of models have been proposed which predict the masses and widths of the corresponding charmed–strange states [6–8] A feature common to many of these models is that the mass difference between a given $c\bar{d}$ state, and the $c\bar{s}$ state of the same spin–parity (J^P) is approximately independent of which J^P is under consideration. The various models predict this mass difference to be between 80 and 130 MeV/c^2 The mass difference between the S-wave charmed and charmed–strange mesons is about 100 MeV/c^2 In this letter we report evidence for a charmed–strange meson, which decays into $D^{*+}K^0$, at a mass about 115 MeV/c^2 above that of the $D_1(2414)^0$ [#1,2]

The data presented here were collected at a mean center-of-mass energy of 10.30 GeV with the ARGUS detector at the DORIS II e^+e^- storage ring at DESY The data sample consists of 311±9 pb^{-1}, collected on the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(4S)$ resonances, and in the nearby continuum A complete description of the detector, trigger conditions, multihadron selection criteria, luminosity determination and particle identification strategy can be found in ref. [9].

The search for excited charmed–strange states has been made using the decay chain

$$D_{sJ}^+ \to D^{*+}K^0 ,$$

where the D^{*+} decays to $D^0\pi^+$ and the D^0 is reconstructed in the modes

$$D^0 \to K^-\pi^+ , \quad (1)$$

$$\to K^-\pi^+\pi^+\pi^- , \quad (2)$$

$$\to K^-\pi^+\pi^0 \quad (3)$$

This includes 57% of all D^{*+} decays [10] and 24% of all D^0 decays [11].

Charged particles from the main vertex were required to have a momentum transverse to the beam direction greater than 60 MeV/c and to have a polar angle, θ, in the range $|\cos\theta| \leq 0.92$. These particles, identified on the basis of specific ionization, time of flight, energy deposition in the shower counters and penetration to the muon chambers were treated as $\pi^\pm$ or $K^\pm$ if the likelihood ratio [9] for the hypothesis under consideration exceeded 0 01. A K^0_S candidate was defined as a $\pi^+\pi^-$ pair coming from a secondary vertex [9] In addition it was required that $\cos\alpha \geq 0$ 95, where α is the angle between the K^0_S mo-

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[#1] References in this paper to a specific charged state are to be interpreted as implying the charge-conjugate state also
[#2] A recent analysis [5] separates the $J^P=1^+$ and 2^+ contributions to the $D_1(2420)^0$ [1–3] and presents the mass quoted above for the 1^+ state

Table 1
The mass intervals used to select the intermediate states for this analysis Except for the sideband selection, the invariant mass of each candidate was also required to be within four standard deviations of the known mass of the state The last column refers to the D^0 channels for which the cut is applicable The symbols D^{*+}_{side} and $\Delta(D^{*+})$ are defined in the text

Decay mode	Mass interval (MeV)	D^0 channel
$K^0_S \to \pi^+\pi^-$	$482\ 7 \leqslant m(\pi^+\pi^-) \leqslant 512\ 7$	
$D^0 \to K^-\pi^+$	$1800 \leqslant m(K^-\pi^+) \leqslant 1930$	
$\to K^-\pi^+\pi^+\pi^-$	$1820 \leqslant m(K^-\pi^+\pi^+\pi^-) \leqslant 1910$	
$\to K^-\pi^+\pi^0$	$1800 \leqslant m(K^-\pi^+\pi^0) \leqslant 1930$	
$D^{*+} \to D^0\pi^+$	$143\ 5 \leqslant \Delta(D^{*+}) \leqslant 147\ 5$	1,2
	$142\ 0 \leqslant \Delta(D^{*+}) \leqslant 148\ 0$	3
$D^{*+}_{side} \to D^0\pi^+$	$160 \leqslant \Delta(D^{*+}_{side}) \leqslant 220$	1
	$160 \leqslant \Delta(D^{*+}_{side}) \leqslant 180$	2,3
$D^+ \to K^-\pi^+\pi^+$	$1810 \leqslant m(K^-\pi^+\pi^+) \leqslant 1930$	

mentum and the vector which points from the main vertex to the decay vertex A photon was defined as a cluster of energy, greater then 50 MeV and not associated with any charged track, deposited in the shower counters A $\gamma\gamma$ pair was accepted as a π^0 candidate if its invariant mass lay within two standard deviations of the π^0 mass The criteria which defined candidates for the other intermediate states are summarized in table 1 Each π^0, D^0, D^{*+} and K^0_S candidate was kinematically fitted to its accepted mass [11]

It is expected that the momentum spectrum of a meson containing a leading charmed quark will be hard, whereas that of the combinatorial background will be softer Each $D^{*+}K^0_S$ combination was required, therefore, to have $x_p > 0\ 6$, where $x_p = p/p_{max}$ and $p^2_{max} = E^2(\text{beam}) - m^2(D^{*+}K^0_S)$

In approximately 25% of the $D^{*+}K^0_S$ combinations, the D^{*+} candidate shares at least one of its constituent particles with another D^{*+} candidate This is particularly a problem in channel 3 In order to reduce the combinatorial background, only one D^{*+} candidate was accepted per event, the one with the largest probability of the total χ^2 The total χ^2 is the sum of those from the intermediate mass fits and those from the particle identification degrees of freedom

The resulting $D^{*+}K^0_S$ mass spectra are shown in fig 1a, for channels 1 and 2, and in fig 1b for channel 3 A prominent, narrow structure, at 2536 MeV/c^2, is observed in both spectra Using a Monte Carlo simulation [12], the mass resolution of the detector was determined to be $\sigma = 1\ 7 \pm 0\ 2$ MeV/c^2 for the first two channels and $\sigma = 3\ 3 \pm 0\ 5$ MeV/c^2 for the third As a measure of the accuracy with which the simulation procedure predicts the mass resolution, the Monte Carlo resolution for a structure of similar width, namely the $D^{*+} - D^0$ mass difference, was compared with the measured resolution No discrep-

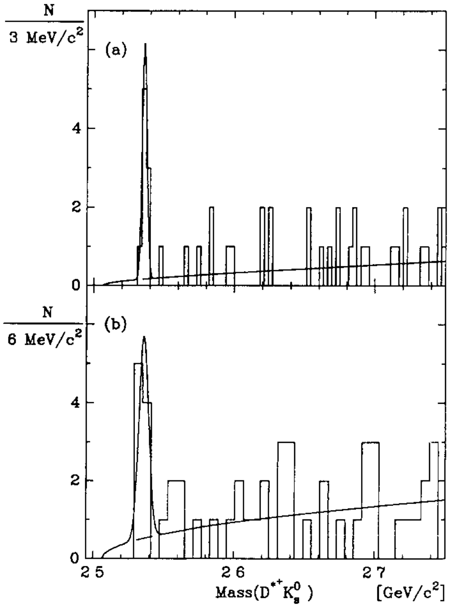

Fig 1 $D^{*+}K^0_S$ invariant mass spectra for the D^0 decay modes (a) $K^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$ and (b) $K^-\pi^+\pi^0$ The curves correspond to the fit described in the text

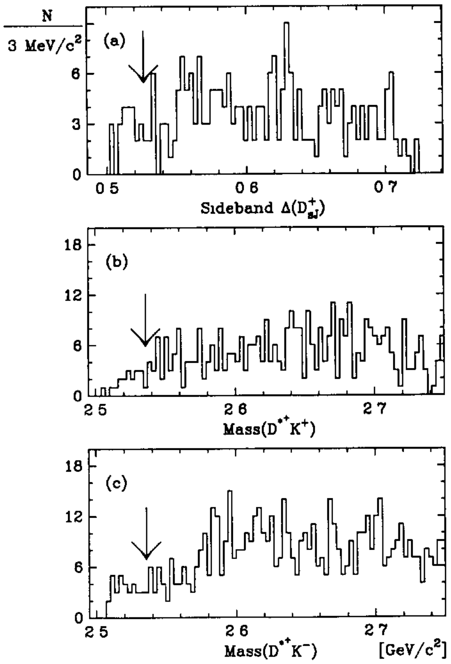

Fig 2 Background spectra The arrows indicate the mass, or the corresponding mass difference, at which the signal is observed in fig 1 (a) $m(D^{*+}_{side}K^0_S)-m(D^{*+}_{side})$ mass difference spectrum, where D^{*+}_{side} are $D^0\pi^+$ combinations from the upper sideband of the D^{*+} (b) $D^{*+}K^+$ invariant mass spectrum (c) $D^{*+}K^-$ invariant mass spectrum

ancy between the measured and predicted widths was observed.

In order to extract the parameters of the signal, each spectrum was fitted with the sum of a gaussian, to parameterize the signal, and a first order polynomial multiplied by a square root threshold factor, to parameterize the background The two spectra were fitted simultaneously, keeping the central values of the two gaussians equal The other parameters were allowed to vary separately for each spectrum This procedure yields a mass of 2535 9±0 6 MeV/c^2 and amplitudes of 8 5±3 events, for the signal in channels 1 and 2 combined, and 7 5±3 events for the signal in channel 3 Both fitted widths are consistent with the detector resolution In the signal region, defined to be from 2529 to 2541 MeV/c^2, there are 18 events in the two histograms The number of background events beneath the signal, estimated by integrating the background function over the signal region, is 0 6 ±0 3 for fig 1a and 1 1±0 3 for fig 1b, making a total of 1 7±0 4 events The observed 18 events correspond to a 6.7 standard deviation excess above this background If a more conservative, constant background parameterization is assumed, the significance is still 5 0 standard deviations. In order to estimate the systematic errors, the selection criteria, the mass resolution and the parameterization of the background were varied. The systematic error on the mass, including the uncertainty on the D^{*+} mass [11], is ±2 MeV/c^2 In the following, we shall refer to this state as the $D_{sJ}(2536)^+$

To obtain an upper limit for the natural width, Γ, of the $D_{sJ}(2536)^+$, the signal shape was parameterized by a Breit–Wigner line width convoluted with a gaussian resolution The widths of the two gaussians were fixed to their expected values and the mass was fixed at 2535 9 MeV/c^2 This yields an upper limit of $\Gamma<4$ 6 MeV/c^2, at the 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 sideband study, D^0 candidates were selected as above, combined with π^+ candidates and the mass difference

$$\Delta(D^{*+})=m(D^0\pi^+)-m(D^0)$$

was calculated The sideband D^{*+} candidates, D^{*+}_{side}, were selected according to the criteria in table 1 In order to have sufficient statistics for the sideband investigation, it was necessary to make the $\Delta(D^{*+})$ interval much larger than for the real D^{*+} selection. Consequently, the mass resolution for $D^{*+}_{side}K^0_S$ combinations is much poorer than for $D^{*+}K^0_S$ combinations This difficulty can be overcome by comparing, instead, a quantity with the same resolution for both the signal and the sideband combinations, namely the mass difference

$$\Delta(D^+_{sJ})=m(D^{*+}K^0_S)-m(D^{*+})$$

The $\Delta(D^+_{sJ})$ spectrum for real $D^{*+}K^0_S$ combinations is not shown because it is identical to fig. 1, except for the change in the horizontal scale The $\Delta(D^+_{sJ})$ spectrum for the sideband, with all three D^0 channels combined, is shown in fig 2a No significant signal is observed

The wrong charge mass spectra, $D^{*+}K^+$ and $D^{*+}K^-$, are shown in figs 2b and 2c, respectively Using a Monte Carlo simulation, the mass resolution for these channels was determined to be 2 1±0 1

MeV/c^2 for channels 1 and 2, and 3 6±0 5 for channel 3 The acceptance was determined to be more than three times larger than that of the $D^{*+}K_S^0$ combinations No significant signal is observed in either spectrum The absence of a signal in these spectra argues against exotic interpretations for the $D^{*+}K_S^0$ signal Because of strangeness mixing in the K_S^0 system, it is not certain that the signal arises from a $c\bar{s}$ system It might, for example, be produced by a $cs\bar{d}\bar{d}$ system Such a hypothesis, however, would require that signals also be present in the wrong charge spectra

A Monte Carlo simulation was performed to determine the acceptance of the detector as a function of x_p In each channel the acceptance was found to vary only slowly with x_p The fraction of the signal in each of the three channels is consistent with that expected from the acceptances and the known branching ratios [11]

The fragmentation function of the $D_{sJ}(2536)^+$ was extracted by fitting a weighted histogram of $x_p(D^{*+}K_S^0)$ For this study, the x_p cut described above was reduced to $x_p>0$ 5 Each $D^{*+}K_S^0$ combination in the signal region was assigned a weight of $(\eta\ \mathrm{BR})^{-1}$, where η is the efficiency and BR is the appropriate D^0 branching ratio The resulting x_p spectrum is shown in fig 3 The overlayed curve is the result of fitting the fragmentation model of Peterson et al [13],

$$\frac{d\sigma}{dx_p} \propto \left[x_p\left(1-\frac{1}{x_p}-\frac{\epsilon}{(1-x_p)}\right)^2\right]^{-1},$$

to the data The Peterson parameter, ϵ, was measured to be $0\,06^{+0\,02}_{-0\,01}\pm0\,02$, where the systematic error was determined by varying the cuts No correction was made for initial state photon or gluon radiation For comparison, the values of ϵ for the $D_1(2414)^0$, $D_2^*(2460)^0$ and $D_2^*(2113)^+$ are $0\,07\pm0\,04$ [14], $0\,06\pm0\,03$ [4], and $0\,04^{+0\,03}_{-0\,01}$ [15] respectively

In the above procedure events belonging to the background beneath the signal have been included This background was subtracted using the average weight The acceptance corrected number of events was determined by extrapolating the fragmentation function, using the Peterson model, to $x_p=0$ This result was then divided by the luminosity, and by the D^{*+}, K^0 and K_S^0 branching ratios [10,11] to obtain

$$\sigma(e^+e^-\to D_{sJ}(2536)^+X)\,BR(D_{sJ}(2536)^+\to D^{*+}K^0) = 16\pm5\pm3\ \mathrm{pb}\,,$$

at $E_{CM}=10\,30$ GeV If isospin invariance is assumed, one obtains

$$\sigma(e^+e^-\to D_{sJ}(2536)^+X)\ BR(D_{sJ}(2536)^+\to D^*K) = 32\pm9\pm6\ \mathrm{pb}$$

The systematic errors include the errors on the relevant branching ratios and the errors on the acceptances

A search was also performed to determine whether the same state decays to $D^+K_S^0$ The selection criteria for K^-, π^+ and K_S^0 were the same as above A D^+ candidate was defined as a $K^-\pi^+\pi^+$ combination which passed the criteria in table 1 Each D^+ and each K_S^0 candidate was kinematically fitted to its accepted mass [11] In order to reduce the combinatorial background, it was required that $x_p(D^+K_S^0)>0$ 6 and that the probability of the total χ^2, defined above, be greater than 0 01 The resulting $D^+K_S^0$ invariant mass spectrum is shown in fig 4 No signal is observed near 2536 MeV/c^2 To extract an upper limit on the presence of a signal, the spectrum was fitted with the sum

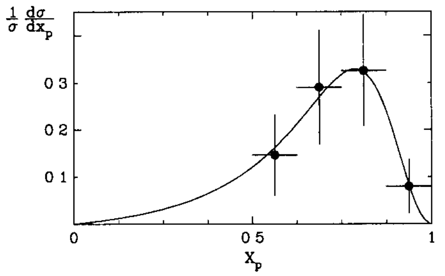

Fig 3 $D_{sJ}(2536)^+$ fragmentation function The curve corresponds to the fit described in the text

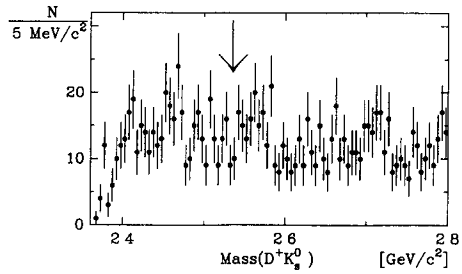

Fig 4 $D^+K_S^0$ invariant mass spectrum The arrow indicates the mass at which the signal is observed in fig 1 of gaussian, to parameterize any signal, and a third order polynomial, to parameterize the background. The central value of the gaussian was fixed to 2535 9 MeV/c^2, as determined above, and its width was fixed to 4 3 MeV/c^2, as determined by a Monte Carlo simulation This yields a 90% confidence level upper limit of 8 4 entries, which implies

$$\sigma(e^+e^- \to D_{sJ}(2536)^+X)\ BR(D_{sJ}(2536)^+ \to D^+K^0) \leqslant 7\ 3\ \text{pb}\ (90\%\ \text{CL})$$

This corresponds to

$$\frac{BR(D_{sJ}(2536)^+ \to D^+K^0)}{BR(D_{sJ}(2536)^+ \to D^{*+}K^0)} \leqslant 0\ 43\ (90\%\ \text{CL})$$

Phase space considerations require that, for a state so close to the D*K threshold, DK decays will, unless forbidden by some selection rule, dominate over D*K decays The suppression of the DK channel is, therefore, most easily understood if the state belongs to the unnatural spin–parity sequence The lowest mass, excited, unnatural J^P, c$\bar{s}$ states, are predicted to be the two 1^+ members of the P-wave multiplet [6]

Although the $D_{sJ}(2536)^+$ is, at first sight, surprisingly narrow, a natural explanation is available Unlike quarkonia and isovector mesons, the c$\bar{s}$ system has no conservation law which prevents the mixing of the $^3P_1$ and $^1P_1$ states It can be demonstrated [7] that, under fairly general assumptions, triplet–singlet mixing will cause one of the observable states to broaden and the other to become narrow One explicit calculation of the widths of P-wave c$\bar{s}$ mesons, including mixing of the $J^P = 1^+$ states, has been performed [8] In that model the narrow $J^P = 1^+$ state is predicted to lie below the D*K threshold When the observed masses of the D_{sJ}^+, D^{*+} and K_S^0 are used, however, the width is calculated to be about 3 MeV/c^2 [16]

Another group has reported, as yet unconfirmed, evidence for two states which they interpret to be P-wave c$\bar{s}$ mesons [17] One state, at a mass of 2537±28 MeV/c^2, is reported to decay to $D_s^{*+}\gamma$ but not to D*K Another, 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 one discussed in this paper

In summary, we observed a signal of more than five standard deviations in the $D^{*+}K_S^0$ mass spectrum, at a mass of 2535 9±0.9±2.0 MeV/c^2, which has a natural width less than 4 6 MeV/c^2 at the 90% confidence level The fragmentation function is consistent with production from a leading charmed quark. The mass and the absence of a signal in the $D^0K_S^0$ mode suggest that the state is one of the $J^P = 1^+$ members of the lowest lying, P-wave, c$\bar{s}$ multiplet

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