OBSERVATION OF THE $D^{*0}(2459)$ IN e^+e^- ANNIHILATION

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Using the ARGUS detector at the DORIS II storage ring at DESY, we have observed a charmed meson of mass $(2455\pm3\pm5)$ MeV$/c^2$, decaying to $D^+\pi^-$ The natural width of this state is determined to be $(15^{+13}_{-10}{}^{+5}_{-10})$ MeV$/c^2$ The fragmentation function is hard, as expected for a leading charmed particle from nonresonant e^+e^+ annihilation Analysis of the decay angular distribution supports the hypothesis that the observed state is an $L=1$ excited charmed meson with spin–parity 2^+

The spectroscopy of excited charmed mesons provides an important means of exploring the spin-structure of the quark–antiquark potential at relatively large distances; predictions of the mass spectra and decay properties of these states have been made with several different models [1].

In 1985, the ARGUS collaboration reported the first observation [2,3] of a charmed meson of mass 2420 MeV$/c^2$ decaying to $D^{*+}(2010)\pi^-$ [#1]. The existence of the $D^*(2420)$, the first candidate for an $L=1$ excited charmed meson, has been confirmed recently by two other experiments [4,5]. Four such $L=1$ states should exist, with spin-parities of 0^+, 1^+, 1^+, and 2^+. The 2^+ state can decay to both $D\pi$ and $D^*(2010)\pi$ while, owing to parity conservation in strong decays, the 0^+ state can decay only to $D\pi$ and the 1^+ states only to $D^*(2010)\pi$.

The $D^*(2010)\pi$ final state is complicated experimentally by the fact that the 2^+–1^+ mass splittings are, in some models, predicted to be less than the natural widths, leading to overlapping signals. Furthermore, theoretical predictions for the 1^+ states are complicated since the two 1^+ states can, and most probably do, mix with each other.

The $D\pi$ final state provides the advantage that the 2^+ and 0^+ states should be well separated, since all models predict a 2^+–0^+ mass splitting in excess of 100 MeV$/c^2$. The E691 Collaboration recently reported [5] the observation of a state of mass $(2459\pm3\pm2)$ MeV$/c^2$ decaying to $D^+\pi^-$, which they refer to as the $D^{*0}(2459)$. Here we report on the first observation of this state in e^+e^- annihilation.

The analysis presented here is based on data collected at center-of-mass energies around 10 GeV with the ARGUS detector at the DORIS II e^+e^- storage ring at DESY. The data sample consists of 243 pb^{-1} collected on the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(4S)$ resonances, and in the nearby continuum. The ARGUS detector is a 4π spectrometer described in detail elsewhere [6]. Charged tracks are required to have momentum transverse to the beam direction greater than 60 MeV$/c$. Particle identification is made on the basis of specific ionization (dE/dx) and time-of-flight (TOF) measurements, with the information being combined into a likelihood ratio for each of the particle hypotheses, e, μ, π, K, and p. All particle hypotheses with a likelihood ratio in excess of 5% were accepted.

From our sample of multi-hadron events, we have searched for excited charmed mesons in the decay channel

$$D^{*0}\to D^+\pi^- ,$$

where the D^+ is observed in the decay mode

$$D^+\to K^-\pi^+\pi^+ .$$

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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

$K\pi\pi$ combinations which have an invariant mass within 40 MeV/c^2 of the D^+ mass [7], and which agree with the D^+ mass hypothesis with a χ^2 of less than 5, were accepted as D^+ candidates. These were then combined with all remaining π^- candidates from the same event

Two further requirements were made of the $D\pi$ combinations:

(1) $x_p(D\pi) > 0.55$, where the scaled momentum of the $D\pi$ combination, $x_p(D\pi)$, is defined by $x_p(D\pi) = p(D\pi)/p_{max}$ where $p_{max} = (E^2_{beam} - m^2(D\pi))^{1/2}$, and

(2) $\cos\theta^*_\pi > -0.9$, where θ^*_π is defined as the angle between the pion flight direction and the $D\pi$ boost direction, as measured in the $D\pi$ rest frame.

The first cut is motivated by the expectation that the x_p spectrum of particles containing a leading primary charm quark will be hard, while that of the combinatorial background will be peaked at low values of x_p. The second cut was used to specifically remove the large background arising from random combinations with the many slow pions, which will be peaked near $\cos\theta^*_\pi = -1$.

The mass difference spectrum, $m(D^+\pi^-) - m(D^+)$, for all $D\pi$ combinations surviving the cuts outlined above is shown in fig. 1. A clear peak at a mass difference of about 585 MeV/c^2 is observed.

In order to check that the structure observed is not a reflection or a kinematic effect of the cuts, two tests were performed. First, all "D^+"π^- combinations were examined, where the "D^+" was formed from $K\pi\pi$ combinations from the 40 MeV/c^2 wide sidebands immediately above and below the accepted D^+ signal region. The resulting mass difference spectrum, shown in fig. 2a, exhibits no peak. Second, all so-called "wrong-sign" combinations, $D^+\pi^+$, were examined. Again, the corresponding mass difference spectrum, shown in fig. 2b, shows no peak.

In order to extract the relevant parameters of the signal observed in fig. 1, we fit the mass difference spectrum with a simple non-relativistic Breit–Wigner convoluted with a gaussian to describe the signal, plus a third order polynomial to describe the background. The mass resolution was fixed to a value of 7.8 MeV/c^2, as determined from Monte Carlo studies. The fitted mass difference is (585.4 ± 2.7) MeV/c^2, corresponding to a mass of (2455 ± 3) MeV/c^2, in good agreement with the result of E691. For the natural width we obtain (15^{+13}_{-10}) MeV/c^2, based on a fitted number of events of 337 ± 100. The result of the fit is shown in fig. 1 By varying the cuts, the background parametrization, the form of Breit–Wigner used to describe the signal, and the Monte Carlo mass resolution, we estimate the systematic

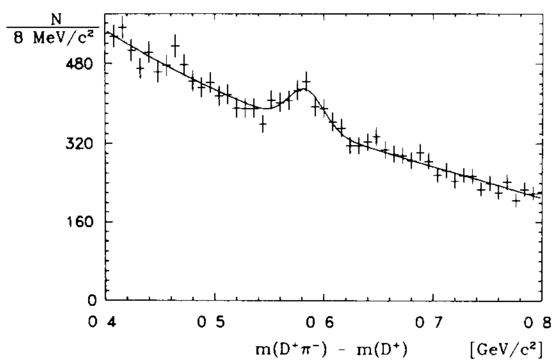

Fig. 1 $m(D^+\pi^-) - m(D^+)$ mass difference spectrum for all accepted $D^+\pi^-$ combinations The curve corresponds to the fit described in the text

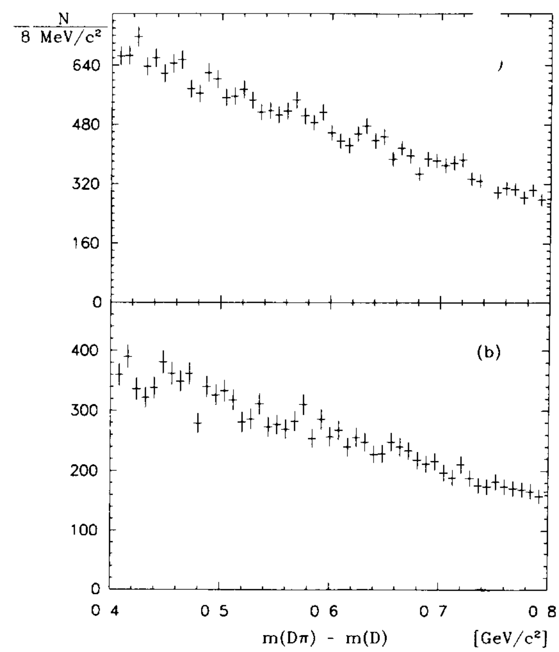

Fig. 2 (a) $m(\text{"}D^+\text{"}\pi^-) - m(\text{"}D^+\text{"})$ mass difference spectrum for all accepted "D^+"π^- combinations where the "D^+" is taken from the sidebands above and below the D^+ signal region (b) $m(D^+\pi^+) - m(D^+)$ mass difference spectrum for all accepted "wrong-sign" $D^+\pi^+$ combinations uncertainty in the mass difference to be ± 5 MeV$/c^2$ and in the natural width to be $^{+5}_{-10}$MeV$/c^2$.

The efficiency was carefully studied with a full detector Monte Carlo simulation, and determined to vary only slowly as a function of x_p and of $\cos\theta^*_\pi$.

The fragmentation function of the D*(2459) was obtained by releasing the x_p cut mentioned previously and then fitting the observed mass difference spectrum in five x_p bins, fixing the mass and width to the values listed above for the over-all fit, and the mass resolution to the value determined by Monte Carlo for each bin. For values of x_p less than 0.5, data collected on the $\Upsilon(4S)$ resonance were not used, in order to exclude a possible contribution due to D*(2459) mesons produced in decays of B mesons. The resulting acceptance-corrected x_p spectrum is shown in fig. 3, along with a fit to the fragmentation function of Peterson, et al. [8], in which

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

The spectrum is quite hard, as expected, and we obtain a value of the fragmentation variable $\epsilon=0.06\pm0.03$. For comparison, the ARGUS result for the D*(2420) spectrum is $\epsilon=0.07\pm0.04$ [3]. In neither case are corrections made for initial state photon and gluon radiation. In sharp contrast to the hard x_p spectrum of the signal, that of the combinatorial background underneath the peak within ± 30 MeV$/c^2$ of the fitted mass is sharply peaked at x_p values of around 0.25, and has a mean x_p of approximately 0.3.

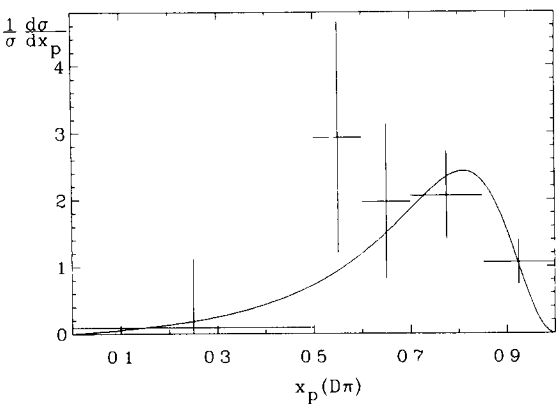

Fig 3 Acceptance-corrected x_p spectrum with a fit to the fragmentation function of Peterson et al

Using the Peterson et al. fragmentation function to extrapolate to zero momentum, and assuming a symmetric distribution in $\cos\theta^*_\pi$ in order to correct for the effect of the $\cos\theta^*_\pi$ cut applied, we calculate, for $\sigma(D^{*0}(2459))\times Br(D^{*0}(2459)\to D^+\pi^-)\times Br(D^+\to K^-\pi^+\pi^+)$, a value of $(5.3\pm1\,6\pm2.2)$ pb. The dominant contributions to the systematic error arise from the uncertainty in the extrapolation and in the natural width of the $D^{*0}(2459)$. Comparing with the D^+ production cross section at these energies [9], we obtain the result

$$\frac{\sigma(D^{*0}(2459))\times Br(D^{*0}(2459)\to D^+\pi^-)}{\sigma(D^+)}$$
$$=0.11\pm0.04\pm0.05\,.$$

As a check of the spin–parity assignment of the state observed, we have also examined the signal in bins of $\cos\theta^*_\pi$. For a spin–parity assignment of 0^+, the observed distribution should be flat, while a non-flat distribution would be possible for a 2^+ decay if the state were not produced with equal populations in all five possible helicity states. The observed acceptance-corrected angular distribution is shown in fig. 4, and shows a marked deviation from isotropy, although, as expected, it is symmetric about zero. This is in contrast to the angular distribution of the combinational background underneath the signal, shown as the histogram in fig. 4, which is markedly asymmetric about zero, being peaked near $\cos\theta^*_\pi=-1$ due

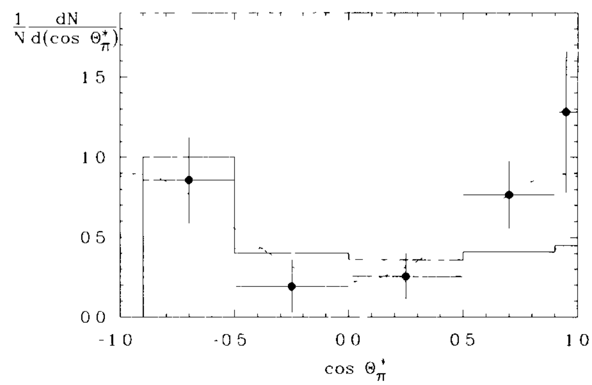

Fig 4 Acceptance-corrected $\cos\theta^*_\pi$ spectrum for the signal (data points with error bars) and background (histogram), where θ^*_π is as defined in the text The dotted line is the result of a fit of the signal points to an isotropic distribution, while the dashed line is the result of the fit described in the text

to the large background arising from the many low-momentum pion candidates. A fit of the signal distribution to an isotropic distribution yields a χ^2 of 11.4 for four degrees of freedom. If we assume that summing over all configurations of the remaining particles in the inclusive process $e^+e^- \to D^*(2459)$ X leads to an incoherent superposition of the initial helicity states, we can parameterize the distribution by three variables corresponding to the populations of the 0, the ± 1, and the ± 2 initial helicity states. A free fit yields populations for the ± 2 helicity states which are consistent with zero. Setting these identically to zero and assuming equal populations of the helicity $+1$ and helicity -1 states, the resulting fit yields approximately equal populations of initial helicity 0, -1, and $+1$, with a χ^2 of 1.4 for three degrees of freedom. The result of the fit is shown in fig. 4 as the dashed line. The evidence for an anisotropic distribution provides support for the 2^+ spin–parity assignment. This assignment is also favoured theoretically by the heavy mass and narrow width, since almost all models agree that the 2^+ state should be the heaviest and narrowest of the four $L=1$ charmed mesons [1].

In summary, we have observed the decay of a charmed meson of mass $(2455\pm3\pm5)$ MeV/c^2 to $D^+\pi^-$. We measure the natural width to be $(15^{+13}_{-10}{}^{+5}_{-10})$ MeV/c^2. The fragmentation function is hard, as expected for a particle containing a leading primary charm quark. An angular analysis provides strong support for the hypothesis that the observed state is the expected $L=1$ excited charmed meson with spin–parity 2^+.

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References

[1] A De Rújula, H. Georgi and S L Glashow, Phys Rev Lett 37 (1976) 785,
R Barbieri et al , Nucl Phys B 105 (1976) 125 ,
D Pignon and C A Piketty, Phys Lett B 81 (1979) 334,
E Eichten et al , Phys Rev D 21 (1980) 203,
S Godfrey and N Isgur, Phys. Rev. D 32 (1985) 189,
J L Rosner, Comm. Nucl Part Phys 16 (1986) 109

[2] ARGUS Collab , H Albrecht et al , Paper submitted to 1985 Intern. Symp on Lepton and photon interactions at high energies (Kyoto, 1985),
ARGUS Collab , H Albrecht et al , Phys Rev Lett 56 (1986) 549

[3] J C. Yun, Ph D thesis, Carleton University, Ottawa, Canada (1987), unpublished

[4] CLEO Collab , C Bebek et al , Paper submitted to 1987 Intern Symp on Lepton and photon interactions at high energies (Hamburg, 1987)

[5] Tagged Photon Collab , J C Anjos et al , Paper submitted to XXIV Intern Conf on High energy physics (Munich, 1988), and Fermilab preprint PUB88/155-E

[6] ARGUS Collab , H Albrecht et al , DESY report 88–080 (1988) Nucl Instrum Methods A, to be published

[7] Particle Data Group, M Aguilar- Benitez et al , Review of particle physics, Phys Lett B 170 (1986) 1

[8] C Peterson et al , Phys Rev D 27 (1983) 105

[9] P C H Kim, Ph D thesis, University of Toronto, Toronto , Canada (1987), unpublished