RESONANCE DECOMPOSITION OF THE D*(2420)^0 THROUGH A DECAY ANGULAR ANALYSIS

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Using data collected with the ARGUS detector, we have performed a decay angular analysis of the enhancement, previously known as the $D^*(2420)$, seen in the final state $D^*(2010)^+\pi^-$. We thereby exhibit that the observed broad structure is actually due to two relatively narrow resonances, one of which is identified as the $D^*(2459)^0$, while the mass of the other is measured to be $(2414\pm2\pm5)$ MeV/c^2. The results of the analysis are in good agreement with the interpretation of the two states as $L=1$ D mesons of spin–parities 2^+ and 1^+ respectively.

The spectroscopy of excited charmed mesons provides an important means of exploring the spin-structure of the quark–antiquark potential at relatively large distances. Here we are concerned in particular with the $L=1$ D mesons; there should be four such states with spin–parities (J^P) of 0^+, 1^+, 1^+, and 2^+. Predictions of the mass spectra and decay properties of these states have been made with several different models [1–3]. The predictions depend on J^P and, therefore, the extraction of useful information from experimental measurements requires an identification of the J^P of the state observed. Spin–parity conservation in strong decays implies that the 2^+ state can decay to both $D\pi$ and $D^*(2010)\pi$ while the 0^+ state can decay only to $D\pi$ and the 1^+ states only to $D^*(2010)\pi$.

Of the possible final states so far examined, the theoretical situation for $D\pi$ is particularly clear, since all models predict a 2^+–0^+ mass splitting in excess of 100 MeV/c^2. Furthermore, the natural width of the 0^+ is predicted to be much larger than for the 2^+ state. The Tagged Photon Collaboration has reported [4] the observation of a charmed meson of mass 2459 MeV/c^2, henceforth referred to as the $D^*(2459)^0$, decaying to $D^+\pi^+$. This state has subsequently been observed by ARGUS [5] and by CLEO [6]. ARGUS has also recently reported [7] evidence for a $D^0\pi^+$ resonance of mass 2469 MeV/c^2, henceforth referred to as the $D^*(2469)^+$, which is most likely the charged isospin partner of the $D^*(2459)^0$. The observed heavy masses and narrow widths favour the interpretation of the $D^*(2459)^0$ and the $D^*(2469)^+$ as the 2^+ states. This conclusion is further supported by a decay angular analysis performed by ARGUS [5] which suggests the $D^*(2459)^0$ is produced with non-zero spin alignment, impossible for the 0^+ state.

If indeed the $D^*(2459)^0$ is the 2^+ state, then it should also decay to $D^*(2010)^+\pi^-$. As noted above, this decay is forbidden for a 0^+ meson, while for the $2^+L=1$ state, theory [2,3] predicts $\Gamma[2^+\to D\pi]/\Gamma[2^+\to D^*(2010)\pi]$ in the approximate range from 1.5 to 3.5.

It has been known for some time that a relatively

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broad enhancement exists, at a mass close to 2420 MeV/c^2, in the invariant mass spectrum of $D^*(2010)^+\pi^-$ [#1] combinations. This enhancement, which has become known as the $D^*(2420)^0$, was discovered by ARGUS [8,9] in 1985, and has since been confirmed by two other experiments [10,4]. However, the physical interpretation of the $D^*(2420)^0$ is complicated due to 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 difficult since the two 1^+ states can mix with each other; the predicted natural widths, in particular, are extremely sensitive to the magnitude of the mixing angle [3]. Thus, the $D^*(2420)^0$ could be either of the 1^+ states, the 2^+ state, or any combination of more than one of these. The nearby proximity of the $D^*(2459)^0$ adds to the likelihood that the $D^*(2420)^0$ is indeed composed of more than one overlapping resonance. In the light of this hypothesis, we report here a more detailed investigation of the $D^*(2420)^0$ using a significantly enlarged data sample. In particular, a decay angular analysis has been used to demonstrate that the $D^*(2420)^0$ is, in fact, composed of two quite narrow resonances separated in mass by approximately 40 MeV/c^2.

The analysis presented here [11,12] 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 354 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 [13]. Charged particles are identified on the basis of specific ionization and time-of-flight measurements, with the information being combined into an overall likelihood ratio for each of the mass hypotheses, e, μ, π, K, and p. All particle hypotheses with a likelihood ratio is excess of 1% were accepted.

We have searched for excited charmed mesons in the decay channel

$$D_J^{(*)0} \longrightarrow D^*(2010)^+\pi^- \\ \quad \hookrightarrow D^0\pi^+ \\ \qquad \hookrightarrow K^-\pi^+\,,\ K_s^0\pi^+\pi^-\,,\ K^-\pi^+\pi^+\pi^- \,. \tag{1}$$

[#1] References in this paper to a specific charged state are to be interpreted as implying the charge-conjugate state also.

K_s^0 mesons were reconstructed from $\pi^+\pi^-$ pairs forming a secondary decay vertex [13].

All intermediate K_s^0, D^0, and $D^*(2010)^+$ mesons were required to have an invariant mass which agreed with the relevant mass hypothesis with a χ^2 of less than 9. In addition, the candidate mass was required to lie within a restricted interval around the nominal mass [14]. Specifically, the allowed ranges were ± 15 MeV/c^2 for K_s^0, ± 30 MeV/c^2 for D^0 (± 40 MeV/c^2 for the $K^-\pi^+$ decay mode), and ± 3 MeV/c^2 for $D^*(2010)^+$ mesons. A mass-constraint fit was then applied to all accepted candidates.

In the $K^-\pi^+\pi^+\pi^-$ channel, there is a larger background arising from random combinations of kaons with slow pions. For this channel only, we required $\cos\theta_K^* < 0.75$, 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 $\cos\theta_K^*$ distribution for D^0 decays should be isotropic since the D^0 has spin zero, while the background is peaked towards $\cos\theta_K^* = +1.0$. Similarly, for all channels, we accepted only those $D^*(2010)^+\pi^-$ combinations which satisfy $\cos\theta_{D^*}^* < 0.7$, where $\theta_{D^*}^*$ is defined as the angle between the $D^*(2010)$ momentum vector and the $D^*(2010)\pi$ boost direction, as measured in the $D^*(2010)\pi$ rest frame.

It is expected that the momentum spectrum of particles containing a primary charmed quark will be hard, while that of the combinatorial background will be soft. We therefore required $x_p[D^*(2010)\pi] > 0.55$. Here, $x_p[D^*(2010)\pi] = p[D^*(2010)\pi]/p_{max}$, and p_{max} is given by $p_{max} = \sqrt{E_{beam}^2 - m^2[D^*(2010)\pi]}$.

The mass spectrum for all $D^*(2010)^+\pi^-$ combinations surviving the cuts outlined above is shown in fig. 1. A broad enhancement is observed at a mass of approximately 2420 MeV/c^2.

In decay (1), the helicity distribution of the $D^*(2010)^+$ can be used to spin-analyze the parent $D_J^{(*)0}$. In the case of the decay of a 2^+ state, the $D^*(2010)^+$ and the π^- must, due to spin-parity conservation, be emitted in a relative D wave. This fact implies that the $D^*(2010)^+$ must have helicity ± 1, regardless of the initial polarization of the $D_J^{(*)0}$. On the other hand, the decay of a 1^+ resonance could proceed through either an S-wave or a D-wave decay, or some mixture of both. We denote by α the angle, as measured in the $D^*(2010)^+$ rest frame, between

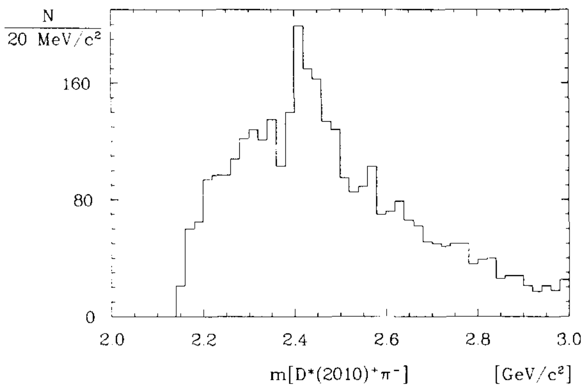

Fig. 1. Invariant mass spectrum of all accepted $D^*(2010)^+\pi^-$ combinations.

the π^- from the parent $D_J^{(*)0}$ decay and the π^+ from the $D^*(2010)^+$ decay. The predicted angular distributions, assuming unpolarized production of the initial $D_J^{(*)0}$, can then be written for the possible J^P assignments of the $D_J^{(*)0}$ as

$$\frac{dN}{d\cos\alpha} \propto \sin^2\alpha$$

for the decay of a 2^+ state ,

$$\propto (1+3\cos^2\alpha)$$

for a pure D-wave decay of a 1^+ state ,

$$\propto 1$$

for a pure S-wave decay of a 1^+ state .

Theoretically, the mixing of the 1^+ states is expected to result in two physical states which, in the limit of an infinite charmed quark mass, decay either via a pure D-wave or via a pure S-wave respectively [2,3].

Due to the uncertainty in the admixture of partial waves in the 1^+ decay, and also the uncertainty in the polarization of the initial $L=1$ D meson, the most general assumption is

$$\frac{dN}{d\cos\alpha} \propto \sin^2\alpha$$

for the decay of a 2^+ state ,

$$\propto (1+A\cos^2\alpha)$$

for the decay of a 1^+ state ,

where A lies is the range from -1 to 3 inclusively. The allowed range of A extending below zero results from possible polarized production of the initial $D_J^{(*)0}$. Note that a superposition of 2^+ and 1^+ states could lead to an isotropic distribution, such as reported by CLEO [10].

Assuming that the $D^*(2420)^0$ were a single resonance, fitting the signal in different bins of $\cos\alpha$ should always yield the same mass and width. On the other hand, if it were an overlap of two or more resonances, one might expect to see shifts in the fitted mass and width as a function of angle due to changes in the relative contributions of the underlying resonances. Shown in fig. 2 are the accepted $D^*(2010)^+\pi^-$ candidates in two different bins of $|\cos\alpha|$ chosen at opposite ends of the physical $|\cos\alpha|$ range. Superimposed are the results of fits of the mass spectra to a sum of a single Breit–Wigner and a third order polynomial multiplied by a threshold factor. The resulting masses and widths are summarized in table 1, and exhibit an obvious depen-

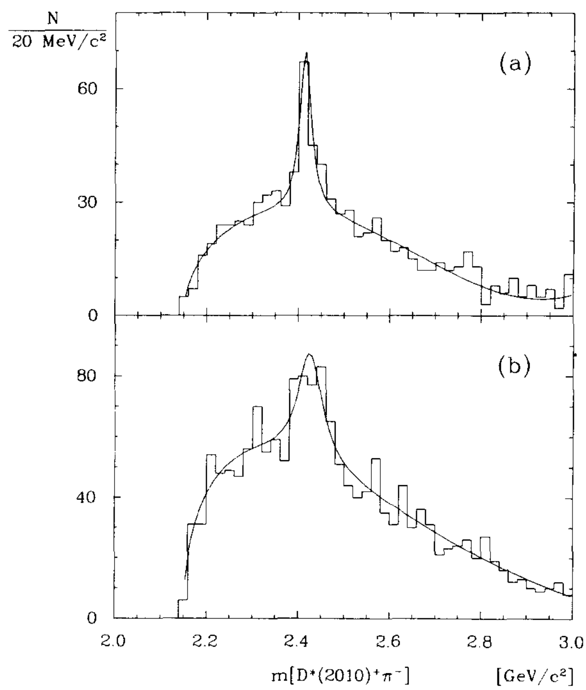

Fig. 2. Invariant mass spectra of all accepted $D^*(2010)^+\pi^-$ combinations satisfying the additional requirement that (a) $|\cos\alpha| > 0.75$ and (b) $|\cos\alpha| < 0.50$. The curves correspond to the results of the single-resonance fits described in the text.

Table 1
Measured mass and width of the $D^*(2420)^0$ for two different ranges of $|\cos\alpha|$.

$\|\cos\alpha\|$ range	Mass (MeV/c^2)	Width (MeV/c^2)
>0.75	2415.2±2.7	30.1±10.1
<0.50	2427.3±6.9	68.5±24.2

dence on $|\cos\alpha|$. A Monte Carlo simulation was performed, and both the detector resolution and acceptance were determined to be independent of $|\cos\alpha|$. Thus, the mass and width shifts seen in table 1 do not reflect differences in detector response, but instead provide strong evidence that the "$D^*(2420)^0$" is not a single state, but a superposition of more than one resonance.

The predicted angular distributions outlined previously can then be used in an attempt to separate the underlying resonances contributing to the broad enhancement seen in fig. 1. In order to clearly resolve the 1^+ contribution, it is possible to remove most of any 2^+ component by requiring $|\cos\alpha|>0.75$. We fitted the resultant spectrum, shown in fig. 3, with a function which now had a sum of two Breit–Wigners convoluted with a gaussian resolution function to parametrize the signal. As before, the background underneath the signal was described by a third order polynomial multiplied by a threshold factor. The mass resolution was fixed to 5.5 MeV/c^2, as determined by Monte Carlo simulation. The mass and width of one of the Breit–Wigners was constrained to the measured values [5] of the $D^*(2459)^0$, while the parameters of the other were left free. The result of the fit, shown superimposed on fig. 3, gave a mass and width of the second Breit–Wigner of $(2414\pm2\pm5)$ MeV/c^2 and $(13\pm6^{+10}_{-5})$ MeV/c^2 respectively. The systematic uncertainties were determined by varying the parameters of the $D^*(2459)^0$. We will refer to this lower mass state as the $D^*(2414)^0$.

Both masses and widths were then fixed to these measured values, and the $D^*(2010)^+\pi^-$ mass spectrum was fitted in bins of $|\cos\alpha|$ in order to check the observed angular distributions against the expectations outlined previously. The results are shown in fig. 4. Fitting the distribution for the $D^*(2459)^0$ to the form $A(1+B\cos^2\alpha)$ gave a result of $B=-0.4\pm0.7$. This is in agreement with the $\sin^2\alpha$ expectation for the 2^+ decay. Fitting with the same functional form to the $D^*(2414)^0$ distribution yielded $B=2.8\pm1.7$, with a χ^2 per degree of freedom

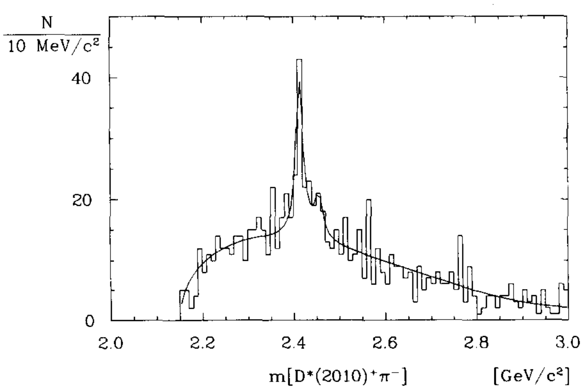

Fig. 3. Invariant mass spectrum, as in fig. 2a, of all accepted $D^*(2010)^+\pi^-$ combinations satisfying the additional requirement that $|\cos\alpha|>0.75$. The curve is the result of the two-resonance fit described in the text.

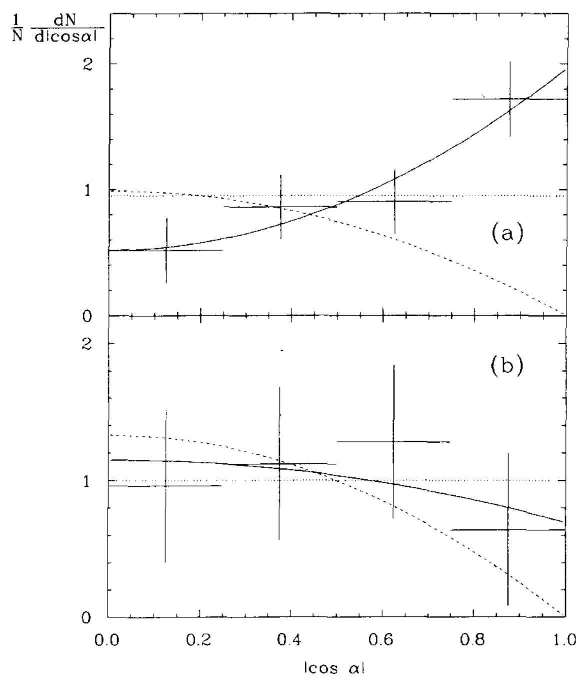

Fig. 4. Angular distributions for (a) the $D^*(2414)^0$ and (b) the $D^*(2459)^0$. The curves correspond to the results of fits to the forms $A(1+B\cos^2\alpha)$ (solid lines), $A\sin^2\alpha$ (dashed lines) and to an isotropic distribution (dotted lines).

(χ^2/df) of 0.9/2. This result is in agreement with the prediction for a 1^+ pure D-wave decay. Fits to isotropic and $\sin^2\alpha$ distributions, on the other hand, gave poorer results, with χ^2/df of 9.5/3 and 28.9/3 respectively. The fitted curves are shown superimposed on fig. 4.

Finally, the invariant mass spectrum of fig. 1 was fitted with the function previously described. The result of the fit is shown superimposed on fig. 5. The fit yielded signals of 171 ± 22 and 94 ± 21 events for the $D^*(2414)^0$ and $D^*(2459)^0$ respectively.

The momentum spectra of the two resonances were investigated by fitting the mass spectrum in bins of x_p. The two masses and widths were fixed, and the mass resolution was obtained by Monte Carlo for the relevant x_p range. The two x_p spectra are in agreement, within errors, and are shown in fig. 6. Fitting with the fragmentation function of Peterson et al. [15], a value of 0.040 ± 0.010 [0.054 ± 0.027] for the fragmentation parameter, ϵ, was obtained for the $D^*(2414)^0$ [$D^*(2459)^0$]. The result for the $D^*(2459)^0$ is in excellent agreement with the value of 0.06 ± 0.03 determined in the analysis of its decay to $D^+\pi^-$ [5].

Using the Peterson et al. fragmentation function to extrapolate to zero momentum, we obtain, after correcting for the relevant D^0 [14] and $D^*(2010)^+$ [16] branching ratios,

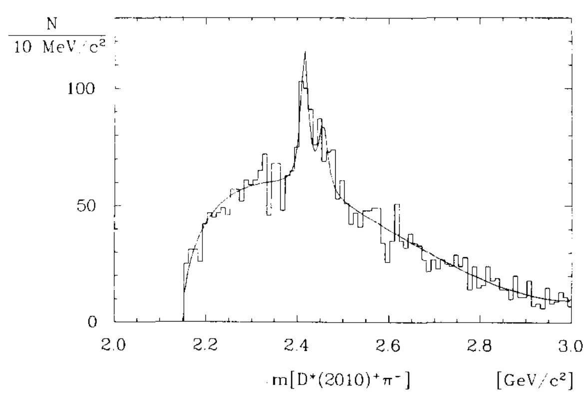

Fig. 5. Invariant mass spectrum of all accepted $D^*(2010)^+\pi^-$ combinations. The curve is the result of the fit described in the text.

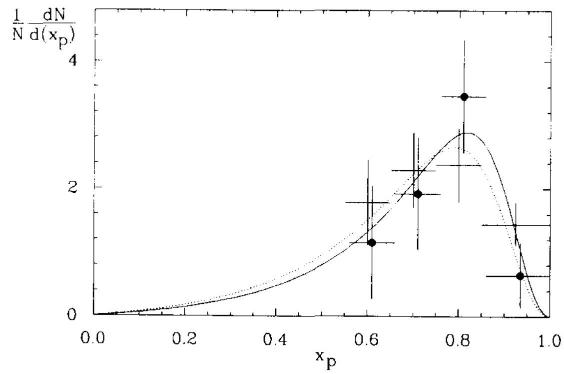

Fig. 6. Measured x_p spectra for the $D^*(2414)^0$ (crosses) and the $D^*(2459)^0$ (solid points). The solid [dotted] curve corresponds to the result of the fit of the Peterson et al. fragmentation function to the $D^*(2414)^0$ [$D^*(2459)^0$] spectrum. The $D^*(2459)^0$ data points have been shifted by $\delta x_p=0.01$ for display purposes.

$$\sigma[D^*(2414)^0]\times Br[D^*(2414)^0\to D^*(2010)^+\pi^-]$$
$$=(40\pm5\pm11)\text{ pb},$$
$$\sigma[D^*(2459)^0]\times Br[D^*(2459)^0\to D^*(2010)^+\pi^-]$$
$$=(23\pm5\pm8)\text{ pb}.$$

The systematic errors are dominated by the uncertainties in the masses and widths of the two states, in the momentum extrapolation, and in the $D^*(2010)^+$ branching ratio.

Comparing the $D^*(2459)^0$ signal with $x_p>0.55$ with the previously measured result [5] for the decay $D^*(2459)^0\to D^+\pi^-$, we find

$$R=\frac{Br[D^*(2459)^0\to D^+\pi^-]}{Br[D^*(2459)^0\to D^*(2010)^+\pi^-]}$$
$$=3.0\pm1.1\pm1.5.$$

This result is in good agreement with the prediction for the decays of the 2^+ $L=1$ D meson of R in the range from 1.5 to 3.5, as discussed previously.

It is also of interest to compare the production rates for the 1^+ and the 2^+ states. For this purpose, we assume isospin invariance, and also assume that decays to $D\pi$ and $D^*(2010)\pi$ saturate the total widths. We obtain, under these assumptions,

$$\frac{\sigma[D^*(2459)^0]}{\sigma[D^*(2414)^0]}=2.3\pm0.6\pm1.0,$$

in good agreement with the value of 5/3 predicted by naive spin-statistics.

In summary, we have performed a decay angular analysis of the enhancement seen around a mass of 2420 MeV/c^2 in the $D^*(2010)^+\pi^-$ final state, and have demonstrated the presence of a substructure due to two resonances. One of the underlying resonances is identified as the $D^*(2459)^0$. The mass and width of the other have been measured to be $(2414 \pm 2 \pm 5)$ MeV/c^2 and $(13 \pm 6^{+10}_{-5})$ MeV/c^2 respectively. The observed helicity angle distributions are in good agreement with the expectations for the decays of the $L=1$ D mesons of spin–parities 2^+ and 1^+, which would then be identified as the $D_2^*(2459)^0$ and the $D_1(2414)^0$ respectively.

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