Observation of the decay $D_s^+ \to \eta' \pi^+$

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Using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY, we have observed the decay $D_s^+ \to \eta'\pi^+$ in two decay modes of the η'. We measure the ratio of branching ratios $BR(D_s^+ \to \eta'\pi^+)/BR(D_s^+ \to \phi\pi^+)$ to be $2.5 \pm 0.5 \pm 0.3$.

Recently, there has been considerable interest in the decay $D_s^+ \to \eta'\pi^+$ [#1] due to conflicting measurements of the branching ratio relative to the decay $D_s^+ \to \phi\pi^+$ [1–4]. A precise measurement of this decay rate is of interest since a large $D_s^+ \to \eta'\pi^+$ branching ratio poses problems for current models, which predict values of $BR(D_s^+ \to \eta'\pi^+)/BR(D_s^+ \to \phi\pi^+)$ of less than 2 [5,6]. Among the mechanisms offered as possible explanations for larger values are final-state interactions and even the presence of a nearby scalar resonance [5,7].

Several experiments have searched for evidence of the decay $D_s^+ \to \eta'\pi^+$. An indication for a signal was reported by Mark II [1], with a value of 4.8 ± 2.1 for the ratio $BR(D_s^+ \to \eta'\pi^+)/BR(D_s^+ \to \phi\pi^+)$. Subsequently, NA14′ also claimed evidence for this channel, with a value of $5.0 \pm 1.8 \pm 1.2$ for the same ratio [3]. However, in considerable disagreement with these results are the upper limits reported by Mark III and E691. These experiments have determined $BR(D_s^+ \to \eta'\pi^+)/BR(D_s^+ \to \phi\pi^+)$ to be less than 1.9 [2] and less than 1.7 [4] respectively, both at the 90% confidence level. Given the low significance of the claimed signals, and the incompatibility of the existing measurements, it is clearly of interest to examine this channel once more with the large data sample available to ARGUS.

In this letter, a new determination of the ratio $BR(D_s^+ \to \eta'\pi^+)/BR(D_s^+ \to \phi\pi^+)$ is presented using the ARGUS detector at the e^+e^- storage ring DORIS II. This analysis is based on a data sample of 388 pb^{-1} taken at an average center-of-mass energy of 10.4 GeV on the $\Upsilon(4S)$ and $\Upsilon(2S)$ resonances and in the nearby continuum. The ARGUS detector is a 4π spectrometer described in detail elsewhere [8]. For this study, photons were identified as neutral energy deposits of more than 60 MeV in the electromagnetic calorimeter. Charged particle identification was made on the basis of specific ionization in the drift chamber and time of flight measurements. This information was used to calculate, for all charge tracks, a likelihood ratio for each of the particle hypotheses (e, μ, π, K and p). All particle assignments with a likelihood ratio greater than 1% were accepted.

The search for $D_s^+ \to \eta'\pi^+$ was made using two decay modes of the η' meson,

$$\eta' \to \rho^0\gamma \quad (\rho^0 \to \pi^+\pi^-) \qquad \text{and} \qquad \eta' \to \eta\pi^+\pi^- \quad (\eta \to \gamma\gamma),$$

which are discussed separately below.

For the decay $\eta' \to \rho^0\gamma$, all $\pi^+\pi^-$ combinations with an invariant mass between 520 MeV/c^2 and 850 MeV/c^2 were accepted as ρ^0 mesons. This asymmetric cut around the nominal ρ^0 mass of 770 MeV/c^2 [9] takes into account the shift of the ρ^0 line shape due to the electric-dipole nature of the $\eta' \to \rho^0\gamma$ transition [10]. Those $\rho^0\gamma$ combinations having an invariant mass within ± 50 MeV/c^2 of the η' mass, and agreeing with the η' mass hypothesis with a χ^2 less than 9, were accepted as η' mesons. For the surviving candidates, a kinematic fit was performed which constrained the mass to its nominal value of 957.5 MeV/c^2 [9].

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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.

The large background from soft photons was reduced by requiring that $\cos\theta_\gamma$ be greater than -0.5, where θ_γ is defined as the angle between the direction of the η' boost and the photon flight direction, as measured in the η' rest frame. The distribution of $\cos\theta_\gamma$ from real η' decays is expected to be isotropic, while background from soft photons is peaked strongly in the backward direction.

In the search for $D_s^+ \to \eta'\pi^+$, we required that $|\cos\theta_\pi|$ be less than 0.5, where θ_π is the angle between the D_s^+ boost direction and the π^+ flight direction, as measured in the D_s^+ rest frame. This requirement reduces the background from combinations of η' mesons with slow pions, which is peaked in the backward direction, as well as from slow forward-going η' mesons. Also, since the momentum spectrum for charmed particles produced in the continuum is known to be hard, $\eta'\pi^+$ combinations were further required to have $x_p > 0.6$, where $x_p = p(\eta'\pi^+)/p_{max}$ and $p_{max} = \sqrt{E_{beam}^2 - m(\eta'\pi^+)^2}$.

The mass spectrum of all accepted $\eta'\pi^+$ combinations, where $\eta' \to \rho^0\gamma$, is shown in fig. 1a. A clear signal at the D_s^+ mass is observed. Superimposed on fig. 1a is the result of a fit using a gaussian to parametrize the signal and a third-order polynomial to describe the combinatorial background. The width of the gaussian as fixed to 18.1 MeV/c^2, as determined by Monte Carlo studies. A signal of 164 ± 34 events was obtained at a mass of 1969 ± 5 MeV/c^2, in excellent agreement with the accepted D_s^+ mass [9].

No D_s^+ signal is observed in the corresponding plot made with $\rho^0\gamma$ combinations from 50 MeV/c^2 wide sidebands immediately above and below the accepted η' mass region. The $\rho^0\gamma$ combinations were constrained to the central mass of the appropriate sideband. This distribution, shown in fig. 1b, agrees well in shape with the background in fig. 1a.

For the decay mode $\eta' \to \eta\pi^+\pi^-$, candidates for η mesons were defined as $\gamma\gamma$ combinations having an invariant mass within ± 200 MeV/c^2 of the nominal η mass of 548.8 MeV/c^2 [9] and having a χ^2 of less than 16 for the η mass hypothesis. All $\eta\pi^+\pi^-$ combinations having an invariant mass within ± 50 MeV/c^2 of the η' mass, and a χ^2 of less than 9 for the η' mass hypothesis, were accepted as η' candidates. Both the η and η' candidates were kinematically fit, constraining them to their nominal masses.

The background from soft photons in the decay of the η was reduced by requiring that $|\cos\theta_\gamma|$ be less than 0.6, where θ_γ is the angle between the direction of the η boost and the flight direction of one photon, was measured in the rest frame of the η. In the $\eta\pi^+\pi^-$ mass spectrum, background from slow η candidates was reduced by accepting only those combinations with $\cos\theta_\eta > -0.8$, where θ_η is the angle between the η' boost direction and the η flight direction, as measured in the rest frame of the η'. Finally, only those $\eta'\pi^+$ combinations with $|\cos\theta_\pi| < 0.8$ and $x_p > 0.6$

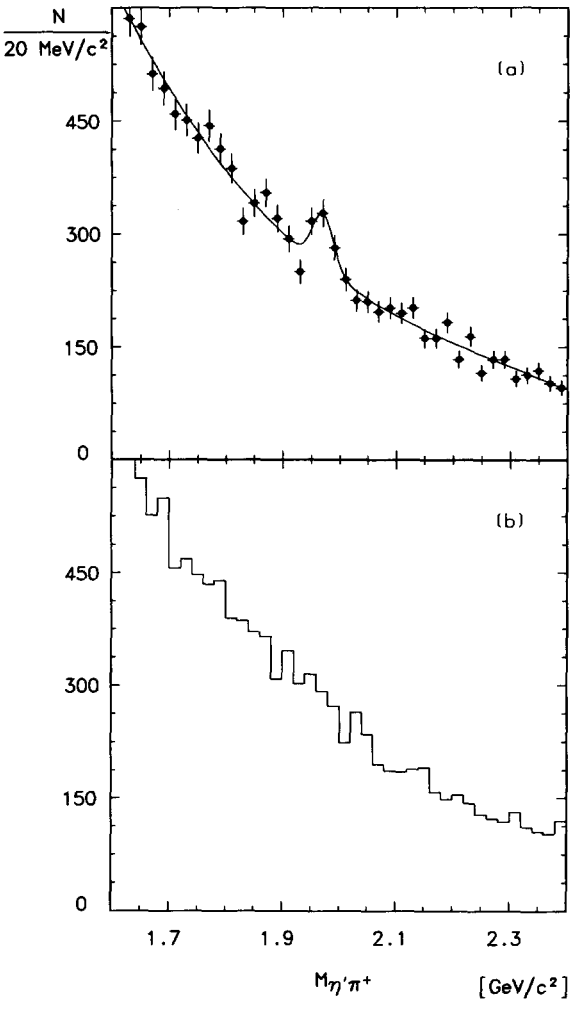

Fig. 1. (a) Mass spectrum of $\eta'\pi^+$ candidates for the decay $\eta' \to \rho^0\gamma$, together with (b) the corresponding distribution obtained using the η' sidebands. The curve shows the result of the fit described in the text.

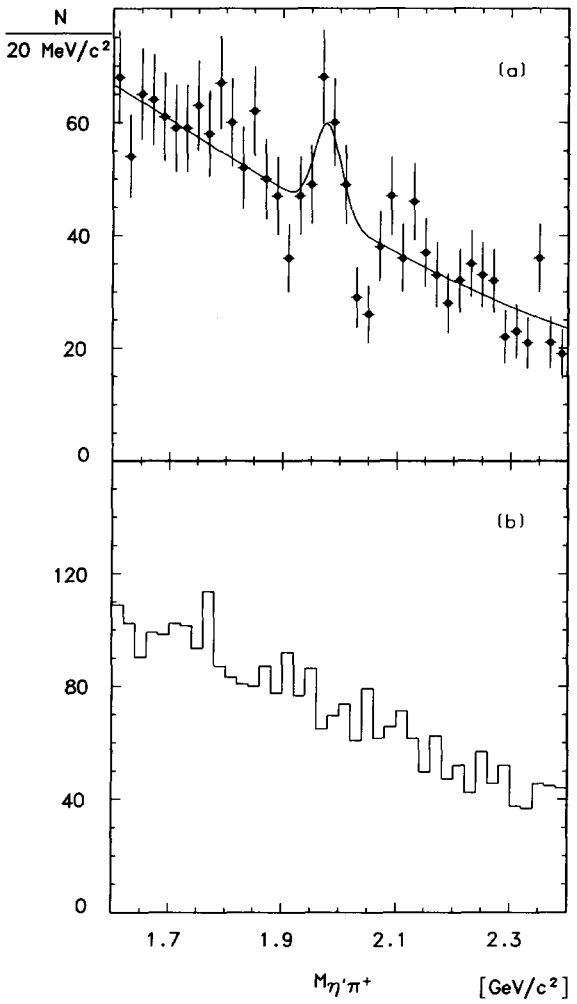

Fig. 2. (a) Mass spectrum of $\eta'\pi^+$ candidates for the decay $\eta' \to \eta\pi^+\pi^-$, and (b) the corresponding distribution for the η' sidebands. The curve corresponds to the fit described in the text.

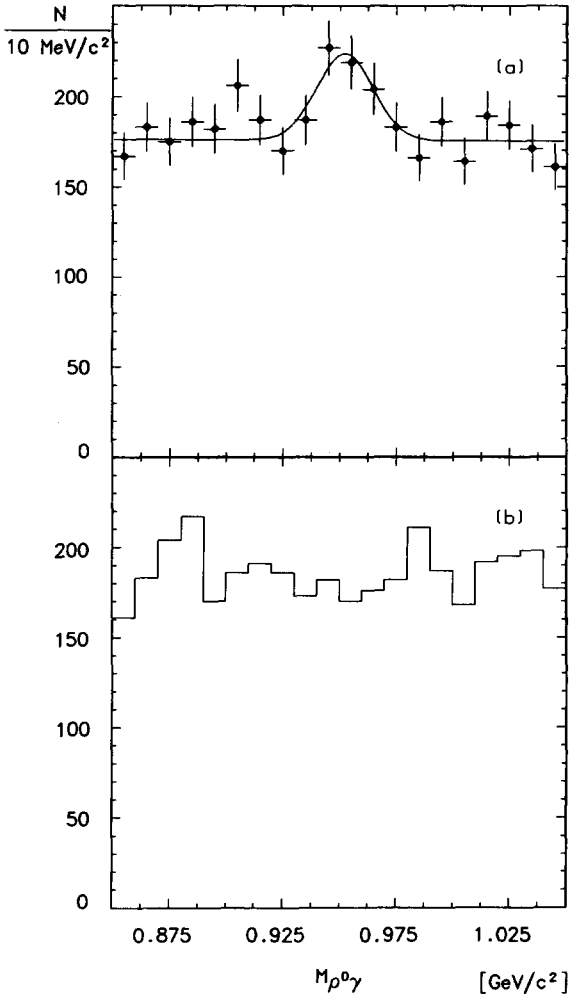

Fig. 3. (a) Mass spectrum of $\rho^0\gamma$ candidates obtained after fitting the mass of the $\rho^0\gamma\pi^+$ system to the D_s^+ mass, and (b) the corresponding spectrum from the D_s^+ sidebands. The curve shows the result of the fit described in the text.

were selected, analogous to the previous search using $\eta' \to \rho^0\gamma$.

Shown in fig. 2a is the mass spectrum of surviving $\eta'\pi^+$ combinations, where $\eta' \to \eta\pi^+\pi^-$. A peak in the region of the D_s^+ can be seen. The spectrum was fitted with the sum of a third-order polynomial and a gaussian with a width fixed to 24.5 MeV/c^2, as determined from Monte Carlo studies. A signal of 51 ± 17 events was obtained at a mass of 1975 ± 10 MeV/c^2, in good agreement with the accepted D_s^+ mass. The histogram in fig. 2b shows the mass spectrum from 50 MeV/c^2 wide sidebands immediately above and below the accepted η' mass region. There is no enhancement in the region of the D_s^+ mass and the shape agrees well with that of the background underneath the signal in fig. 2a.

As a check of these results, figs. 3a and 4a show the invariant mass distribution of $\rho^0\gamma$ and $\eta\pi^+\pi^-$ combinations respectively, from a region of width ± 50 MeV/c^2 ($\pm 1.5\sigma$) centered on the D_s^+ mass. These spectra were obtained by kinematically fitting the

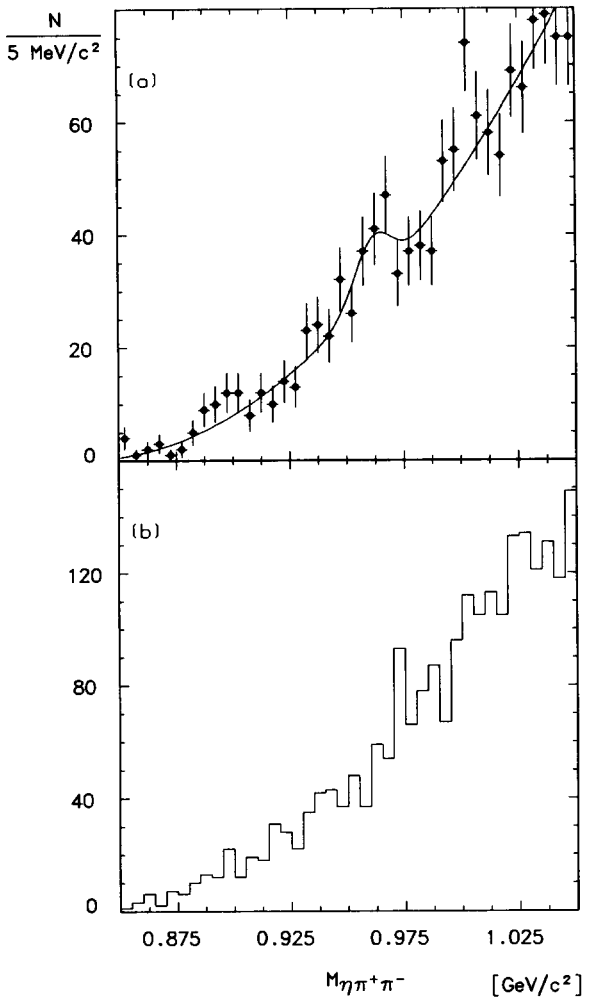

Fig. 4. (a) Mass spectrum of $\eta\pi^+\pi^-$ candidates after constraining the $\eta\pi^+\pi^+\pi^-$ combinations to the D_s^+ mass, and (b) the corresponding distribution for the D_s^+ sidebands. The curve shows the result of the fit described in the text.

$\rho\gamma\pi^+$ and $\eta\pi^+\pi^+\pi^-$ combinations to the accepted D_s^+ mass of 1969 MeV/c^2, after removing the η' mass constraint. Visible in both distributions is a clear enhancement at a mass consistent with the accepted value for the η'. The signals contain 150 ± 34 and 40 ± 18 events respectively, consistent with the number of D_s^+ mesons observed. Figs. 3b and 4b show the corresponding spectra form the 50 MeV/c^2 wide sidebands immediately above and below the accepted D_s^+ region, where the $\rho^0\gamma\pi^+$ and $\eta\pi^+\pi^+\pi^-$ combinations were constrained to have the central mass of the appropriate sideband. No evidence for an η' is seen in the D_s^+ sidebands.

A Monte Carlo study was made to determine the acceptance for $D_s^+\to\eta'\pi^+$. In both η' decay modes, the reconstruction efficiency is independent of momentum for $x_p>0.6$. The results of a previous analysis [11], which found a value of $\epsilon=0.09\pm0.02$ from a fit of the fragmentation function of Peterson et al. [12] to the x_p distribution of the D_s^+, has been used to extrapolate the present measurement to zero momentum.

The results after correcting for acceptances are summarized in table 1. The ARGUS measurement [11] of $\sigma(D_s^-+D_s^+)\cdot BR(D_s^+\to\phi\pi^+)=7.8\pm0.8\pm1.3$ pb at 10.15 GeV, scaled to the appropriate center-of-mass energy, was used to calculate the ratio of branching ratios. Systematic errors were determined by varying the cuts, the background parameterization, the ϵ parameter of the Peterson fragmentation function, the single-track reconstruction efficiency, and the widths of the signals. In taking the ratio, the systematic error of $\pm10\%$ due to extrapolation to zero momentum cancels.

In conclusion, the first significant evidence of the mode $D_s^+\to\eta'\pi^+$ has been obtained, using both the

Table 1
Summary of the results for $D_s^+\to\eta'\pi^+$.

η' decay mode	Number of events	$\sigma(D_s^-+D_s^+)\cdot BR(D_s^+\to\eta'\pi^+)$ (pb at 10.4 GeV)	$\frac{BR(D_s^+\to\eta'\pi^+)}{BR(D_s^+\to\phi\pi^+)}$
$\eta'\to\rho^0\gamma$	164 ± 34	$23.6\pm4.9\pm3.3$	$3.2\pm0.7\pm0.5$
$\eta'\to\eta\pi^+\pi^-$	51 ± 17	$14.4\pm4.8\pm2.3$	$1.9\pm0.7\pm0.3$
weighted mean	–	–	$2.5\pm0.5\pm0.3$

$\eta\pi^+\pi^-$ and $\rho^0\gamma$ decay channels of the η'. The weighted average of the two measurements is $2.5 \pm 0.5 \pm 0.3$ for the ratio $BR(D_s^+ \to \eta'\pi^+)/BR(D_s^+ \to \phi\pi^+)$. This is somewhat larger than the limits quoted by Mark III and E691, but is about a factor of two smaller than the large values reported by Mark II and NA14'. Our result is too large to be explained by most theoretical models.

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