D_s^+ Decays to $\eta\rho^+$, $\eta'\rho^+$, and $\phi\rho^+$

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We have observed the previously unseen $\eta\rho^+$ and $\eta'\rho^+$ decay modes of the D_s^+, and measured branching ratios relative to the $\phi\pi^+$ mode of $2.86 \pm 0.38^{+0.36}_{-0.38}$ and $3.44 \pm 0.62^{+0.44}_{-0.46}$, respectively. In addition, the relative branching ratio for the decay into $\phi\rho^+$ is measured as $1.86 \pm 0.26^{+0.29}_{-0.40}$. Combining these new measurements with previous results and those in the adjoining Letter, we account for $\approx (79 \pm 26)\%$ of D_s decays.

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In this Letter we report measurements of D_s^+ decays to the previously unseen $\eta\rho^+$ and $\eta'\rho^+$ modes as well as the $\phi\rho^+$ mode. These modes are important since, as we will show, they represent a substantial fraction of D_s decays. The data were collected with the CLEO II detector at the Cornell Electron Storage Ring (CESR). The analysis uses the same data sample, a total of 689 pb^{-1}, and the same detection techniques as described in the adjoining Letter. More details of event selection and analysis can be found elsewhere [1]. The selection criteria for the different D_s modes considered here are listed in Table I. These include mass cuts, decay angle cuts, and a mini-

TABLE I. Cuts used in forming D_s candidates.

Mode	$s\bar{s}$ decay (ϕ,η,η')	$P>0.3$ (GeV)	Mass [a] (MeV)	Decay angle
$\phi\pi^+$	K^+K^-		± 8	$\cos\alpha_\phi < 0.8$
$\eta\rho^+$	$\gamma\gamma$	π^0	$\pm(34-37)$	$\lvert\cos\alpha_{\rho^+}\rvert < 0.8$
	$\pi^+\pi^-\pi^0$	π^0 [b]	± 15	$\lvert\cos\alpha_{\rho^+}\rvert < 0.8$
$\eta'\rho^+$	$\eta\pi^+\pi^-$	η	$\pm 15, \pm 23$ [c]	$\lvert\cos\alpha_{\rho^+}\rvert < 0.8$
$\phi\rho^+$	K^+K^-	π^0	± 8	

[a]Mass cut on the primary $s\bar{s}$ system.
[b]Applies to both the π^0 from the ρ^+ decay and from the η decay.
[c]For $\eta\to\gamma\gamma$ and $\eta\to\pi^+\pi^-\pi^0$, respectively.

mum momentum requirement of 0.3 GeV/c that is imposed on the listed particles to reduce backgrounds. For $\eta\to\gamma\gamma$ and $\pi^0\to\gamma\gamma$ decays we require that the decay angle cosine between both of the γ's and the $\gamma\gamma$ direction in the laboratory transformed into the $\gamma\gamma$ rest frame be smaller than 0.8. In addition, when there is a vector-pseudoscalar final state, the helicity angle distribution must be $\cos^2\theta$ and we apply a helicity angle cut of $|\cos\theta|>0.45$ to the positively charged decay product of the vector. For ρ^+ selection the $\pi^+\pi^0$ invariant mass $M(\pi^+\pi^0)$ is required to be within ± 170 MeV of the ρ^+ mass M_ρ.

The $\eta\pi^+\pi^0$ mass spectrum, for $|M(\pi^+\pi^0)-M_\rho|<170$ MeV, is shown in Fig. 1, for the subsequent decay $\eta\to\gamma\gamma$. The peak at the D_s mass contains 158 ± 22 events. To show that this peak is associated with a ρ^+ signal, we plot in Fig. 2(a) the $\pi^+\pi^0$ mass spectrum for events in the D_s peak (histogram) and sidebands (solid points). The peak region is defined as $2.02>M(\eta\pi^+\pi^0)>1.92$ GeV, while the sidebands are comprised of two regions $1.905>M(\eta\pi^+\pi^0)>1.880$ GeV and $2.035>M(\eta\pi^+\pi^0)>2.060$ GeV. The data are fitted well by a Breit-Wigner form for the ρ^+ plus background, giving 204 ± 57 ρ^+ events. [This larger number results from not imposing an $M(\pi^+\pi^0)$ cut.] Further evidence for ρ^+ is obtained by plotting the helicity angle distribution, shown in Fig. 2(b). The curve shows the fit of a $\cos^2\theta_{\pi^+}$ distribution to the data, the confidence level (C.L.) for the fit being 38%. The isotropic component is $<20\%$ at 90% C.L.

We can make a more stringent estimate of the maximum amount of nonresonant $\pi^+\pi^0$ by dividing our sample into two regions, one rich in ρ^+ content and the other ρ^+ poor, and then comparing the number of $D_s\to\eta\pi^+\pi^0$ events in these two regions. We assume that the nonresonant component has $M(\pi^+\pi^0)$ and $\cos\theta_{\pi^+}$ distributions given by phase space. The ρ-rich region is defined by having $|M(\pi^+\pi^0)-M_\rho|<170$ MeV and $|\cos\theta_{\pi^+}|>0.4$, while the ρ-poor region is defined by not being in the ρ-rich region. The relationship between the number of events in the ρ-rich region, N_r, and the ρ-poor region, N_ρ, and the number of nonresonant events $N_{\rm NR}$ is given

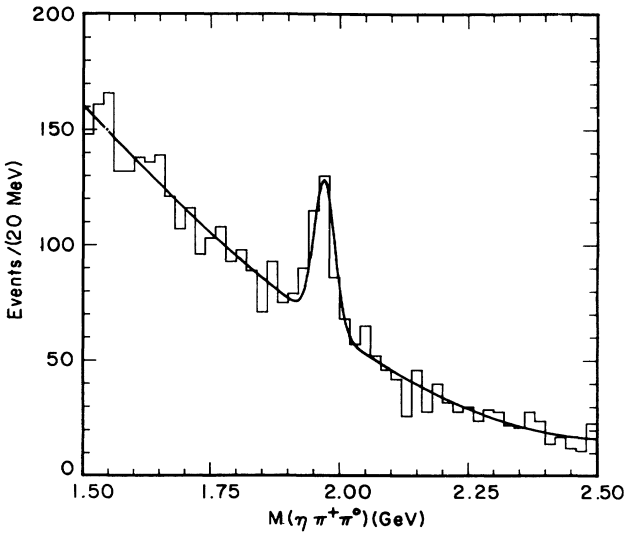

FIG. 1. The $\eta\pi^+\pi^0$ invariant-mass spectrum, for the subsequent decay $\eta\to\gamma\gamma$. Helicity and ρ^+ mass cuts are used.

by

$$N_\rho=[N_r-(1-\beta)N_{\rm NR}]\epsilon'/(1-\epsilon')+\beta N_{\rm NR}\,, \qquad (1)$$

where ϵ' is the probability that real ρ^+ events fall into the ρ-poor region and β is the fraction of the phase space in the ρ-poor region; these are found by Monte Carlo simulation. For this decay mode $\epsilon'=0.24$, $\beta=0.8$, and N_r and N_ρ are 164 ± 23 and 34 ± 30 events, respectively. Solv-

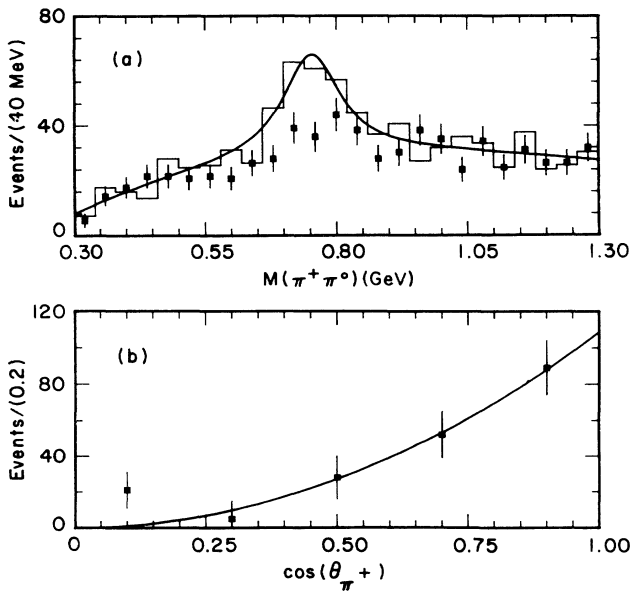

FIG. 2. (a) The $\pi^+\pi^0$ mass spectrum for events in the D_s peak for the $\eta\pi^+\pi^0$ channel (histogram) and sidebands (solid points), both for the case $\eta\to\gamma\gamma$. The helicity cut is used. (b) The number of D_s events in the ρ^+ mass peak as a function of helicity angle θ_{π^+}. The curve is a fit by the form $\cos^2\theta_{\pi^+}$.

TABLE II. Relative branching ratios for D_s modes.

Mode	$s\bar{s}$	Events	$\epsilon\mathcal{B}$ (%)	$\Gamma/\Gamma(\phi\pi^+)$
$\phi\pi^+$	K^+K^-	453 ± 28	17.0	1
$\eta\rho^+$	$\gamma\gamma$	158 ± 22	2.02	$2.93\pm0.45\pm0.39$
	$\pi^+\pi^-\pi^0$	59 ± 15	0.82	$2.70\pm0.68\pm0.38$
$\eta'\rho^+$	$\eta\pi^+\pi^-$ [a]	53 ± 10	0.56	$3.55\pm0.71\pm0.53$
	$\eta\pi^+\pi^-$ [b]	15 ± 6	0.18	$3.10\pm1.24\pm0.45$
$\phi\rho^+$	K^+K^-	253 ± 32	5.10	$1.86\pm0.26\pm0.29$

[a] $\eta\to\gamma\gamma$ is used. [b] $\eta\to\pi^+\pi^-\pi^0$ is used.

ing the equation gives $N_{NR}<55$ at 90% C.L., or <11 events in the ρ-rich region. Thus, under the assumption that the non-ρ^+ decay follows phase space, the nonresonant content is $<7\%$ at 90% C.L. The branching ratio is presented in Table II, along with the detection efficiency ϵ times the product branching ratios of the decay products, $\mathcal{B}$. The average branching ratio for the two η decay modes, relative to $\phi\pi^+$ is $2.86\pm0.38^{+0.36}_{-0.38}$. The systematic errors have the same components and magnitudes as discussed in the preceding Letter [2], with the exception that we have added the uncertainty in our estimate of the non-ρ component in quadrature to the negative systematic error.

For our analysis of the $\eta'\rho^+$ mode, we use the $\eta'\to\eta\pi^+\pi^-$ decay mode. The decay chains and cuts are listed in Table I. The $\eta'\pi^+\pi^0$ mass spectrum is shown in Fig. 3 for $\eta\to\gamma\gamma$. The peak at the D_s mass contains 53 ± 10 events. The solid points are for $\pi^+\pi^0$ masses below 500 MeV. We show in Fig. 4(a) the $\pi^+\pi^0$ mass spectrum for events in the D_s peak (histogram) and D_s sidebands (solid points). [These mass intervals are the same as defined for Fig. 2(a).] There is peaking in the ρ^+ mass region for the sample from the D_s peak, but not from the D_s sidebands. In Fig. 4(b), we show the helicity angle distribution of the ρ^+ candidates. The fit to the $\cos^2\theta_{\pi^+}$ distribution has a C.L. of 10%. Using only the helicity angle we limit the nonresonant background to $<20\%$. To find a more stringent limit we again use Eq. (1) for this decay channel. We set an upper limit of $<8\%$ at 90% C.L. on the amount of nonresonant $\pi^+\pi^0$ in the ρ^+ region. Averaging the two decays modes (see Table II) [3], we find a rather large relative branching ratio of $3.44\pm0.62^{+0.44}_{-0.46}$.

We now consider the $\phi\rho^+$ mode. The $\phi\pi^+\pi^0$ mass distribution is shown as the histogram in Fig. 5. The curve is a fit with two signal Gaussians with means fixed at the D_s^+ and D^+ masses and widths fixed from Monte Carlo studies, and a background polynomial. A clear peak with 253 ± 32 events is observed at the D_s^+ mass. Also shown is the mass spectrum for events with $M(\pi^+\pi^0)<500$ MeV (solid points). Assuming all the events are $\phi\rho^+$, we find a branching ratio, relative to $\phi\pi^+$, of $1.86\pm0.26\pm0.29$. Our result is consistent with a previous E691 observation [4], which was based on a sample of 11 ± 3.6 events.

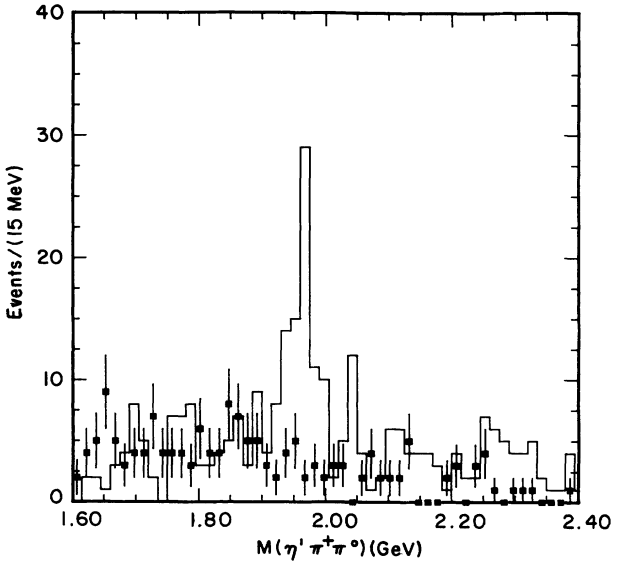

FIG. 3. The $\eta'\pi^+\pi^0$ invariant-mass spectrum, for the decay $\eta'\to\eta\pi^+\pi^-$, with $\eta\to\gamma\gamma$. Helicity and ρ^+ mass cuts are used. The solid points are for the lower sideband of the ρ, defined as $M(\pi^+\pi^0)<500$ MeV.

To ascertain the maximum amount of nonresonant $\pi^+\pi^0$ allowed by the data, we again use Eq. (1); however, in this case, the $\cos\theta_{\pi^+}$ distribution is not predetermined by angular momentum considerations, and thus not used. The ρ-rich region has $M(\pi^+\pi^0)>0.6$ GeV, while the ρ-

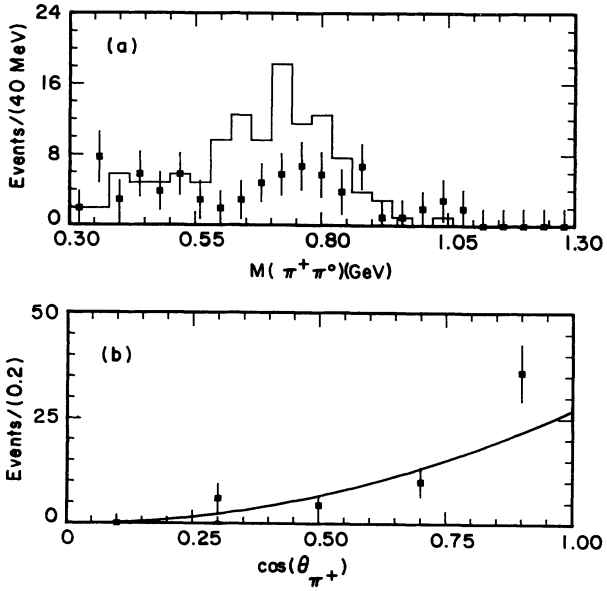

FIG. 4. (a) The $\pi^+\pi^0$ mass spectrum for events in the D_s mass peak in the channel $\eta'\pi^+\pi^0$ and $\eta\to\gamma\gamma$ (histogram) and in the D_s sidebands (solid points). The helicity cut is applied. (b) The helicity angle distribution from the ρ^+ band.

TABLE III. $\Gamma/\Gamma(\phi\pi^+)$ compared with theory.

Mode	This experiment	BSW	BS
$\eta\rho^+$	$2.86\pm0.38^{+0.36}_{-0.38}$	1.96	2.33
$\eta'\rho^+$	$3.44\pm0.62^{+0.44}_{-0.46}$	0.56	
$\phi\rho^+$	$1.86\pm0.26^{+0.29}_{-0.40}$	6.30	

poor region has $M(\pi^+\pi^0)<0.5$ GeV. The upper limit at 90% C.L. on the amount of nonresonant $\pi^+\pi^0$ is 20%.

Model comparisons are given in Table III. Bauer, Stech, and Wirbel (BSW) [5] use form factors calculated from $q\bar{q}$ wave functions and consider color-allowed and color-suppressed decays. Blok and Shifman (BS) [6] make predictions using QCD sum rules. The discrepancy with the BSW theory for the vector-vector mode, $\phi\rho^+$, may be related to the small form factors observed in the semileptonic decay $D\to K^*lv$ [7].

We now assess the known fraction of D_s decays. The sum of the widths of the modes measured in this paper and the adjoining paper relative to $\phi\pi^+$ is 9.9 ± 1.1. In addition, well-established decays into modes such as $\bar{K}^0K^+$ sum up to 7.0 ± 0.7 times $\phi\pi^+$ [8–10].

The absolute $D_s\to\phi\pi^+$ branching ratio can be estimated by using the measured ratio $\Gamma(\phi\pi^+)/\Gamma(\phi l^+\nu)$. Using an average of CLEO [11] and ARGUS [12] results yields a value of $\mathcal{B}(D_s\to\phi\pi^+)$ of $(3.7\pm1.2)\%$ [1]. $\mathcal{B}(D_s\to Xe^+\nu)=(8\pm1)\%$ is found by assuming equal semileptonic widths of charmed mesons and using the measured charmed meson lifetimes [8]. Thus the sum total of known D_s decays is $\approx(79\pm26)\%$, where the error is dominated by the error on the $D_s^+\to\phi\pi^+$ branching ratio.

In conclusion, the $\eta\rho^+$ and $\eta'\rho^+$ modes have been seen for the first time and the $\phi\rho^+$ mode has been confirmed. These decay modes have significantly larger rates than the $\phi\pi^+$ mode.

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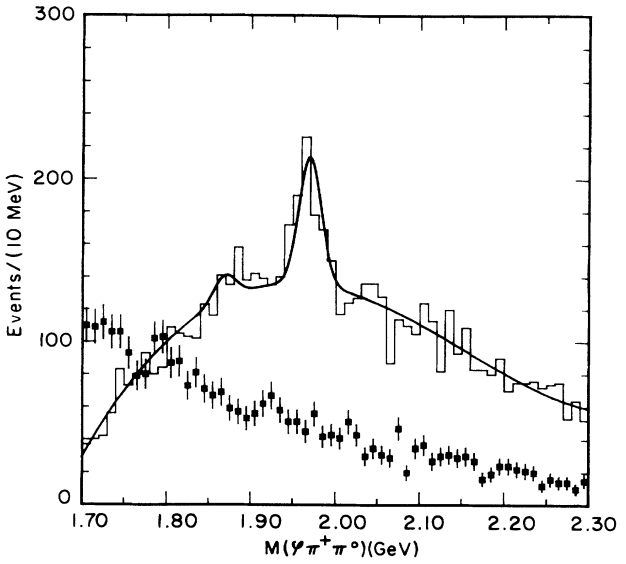

FIG. 5. The $\phi\pi^+\pi^0$ invariant-mass spectrum (histogram) for $|M(\pi^+\pi^0)-M_\rho|<170$ MeV. The solid points are for $M(\pi^+\pi^0)<500$ MeV.

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[3] The ratio $\epsilon\mathcal{B}(\eta\to\gamma\gamma)/\epsilon\mathcal{B}(\eta\to\pi^+\pi^-\pi^0)$ varies between the $\eta\rho^+$ mode and the $\eta'\rho^+$ mode because of the different momentum distributions of the η coupled with the minimum imposed η momentum cut.

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[10] The large size of the modes we have measured with respect to the modes having kaons is consistent with the observation that the fraction of D_s decays which do not include kaons is $(64\pm17\pm3)\%$ from D. Coffman *et al.*, Phys. Lett. B **262**, 135 (1991).

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