$D_s^+$ 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 $\phi \rho^+$ mode of $2.86 \pm 0.38 \pm 0.08$ and $3.44 \pm 0.62 \pm 0.10$, respectively. In addition, the relative branching ratio for the decay into $\phi \rho^+$ is measured as $1.86 \pm 0.26 \pm 0.09$. 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 [11]. 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.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$s\bar{s}$ decay</th>
<th>$P &gt; 0.3$</th>
<th>Mass $^a$</th>
<th>Decay angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi\pi^+$</td>
<td>$K^+K^-$</td>
<td>$\pm 8$</td>
<td>$\cos\theta &lt; 0.8$</td>
<td></td>
</tr>
<tr>
<td>$\eta\rho^+$</td>
<td>$\gamma\gamma$</td>
<td>$\pi^0$</td>
<td>$\pm (34-37)$</td>
<td>$\cos\theta &lt; 0.8$</td>
</tr>
<tr>
<td>$\eta\rho^+$</td>
<td>$\pi^+\pi^-\pi^0$</td>
<td>$\pi^0$</td>
<td>$\pm 15$</td>
<td>$\cos\theta &lt; 0.8$</td>
</tr>
<tr>
<td>$\eta\rho^+$</td>
<td>$\pi^+\pi^-\pi^0$</td>
<td>$\eta$</td>
<td>$\pm 15, \pm 23^c$</td>
<td>$\cos\theta &lt; 0.8$</td>
</tr>
<tr>
<td>$\phi\rho^+$</td>
<td>$K^+K^-\pi^0$</td>
<td>$\pm 8$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$Mass cut on the primary $s\bar{s}$ system.
$^b$Applys to both the $\pi^0$ from the $\rho^+$ decay and from the $\eta$ decay.
$^c$For $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$, respectively.

The 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 $\gamma$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 $\cos\theta$ and we apply a helicity angle cut of $|\cos\theta| > 0.45$ to the positively charged decay product of the vector. For $\rho^+$ selection the $\pi^+\pi^0$ invariant mass $M(\pi^+\pi^0)$ is required to be within $\pm 170$ MeV of the $\rho^+$ mass $M_{\rho}$.

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 $158 \pm 22$ events. To show that this peak is associated with a $\rho^+$ 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 $\rho^+$ plus background, giving $204 \pm 57$ $\rho^+$ events. [This larger number results from not imposing an $M(\pi^+\pi^0)$ cut.] Further evidence for $\rho^+$ is obtained by plotting the helicity angle distribution, shown in Fig. 2(b). The curve shows the fit of a $\cos^2\theta_{\rho^+}$ 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 $\rho^+$ content and the other $\rho^+$ 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 $\cos\theta_{\rho^+}$ distributions given by phase space. The $\rho$-rich region is defined by having $|M(\pi^+\pi^0) - M_{\rho}| < 170$ MeV and $|\cos\theta_{\rho^+}| > 0.4$, while the $\rho$-poor region is defined by not being in the $\rho$-rich region. The relationship between the number of events in the $\rho$-rich region, $N_r$, and the $\rho$-poor region, $N_p$, and the number of nonresonant events $N_{NR}$ is given by

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

where $\epsilon'$ is the probability that real $\rho^+$ events fall into the $\rho$-poor region and $\beta$ is the fraction of the phase space in the $\rho$-poor region; these are found by Monte Carlo simulation. For this decay mode $\epsilon' = 0.24, \beta = 0.8$, and $N_r$ and $N_p$ are $164 \pm 23$ and $34 \pm 30$ events, respectively. Solv-
TABLE II. Relative branching ratios for $D^*$ modes.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\bar{s} \bar{s}$</th>
<th>Events</th>
<th>$\epsilon \bar{B}$ (%)</th>
<th>$\Gamma/\Gamma(\phi \pi^*)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi \pi^*$</td>
<td>$K^+ K^-$</td>
<td>453 ± 28</td>
<td>17.0</td>
<td>1</td>
</tr>
<tr>
<td>$\eta \rho^*$</td>
<td>$\gamma \gamma$</td>
<td>158 ± 22</td>
<td>2.02</td>
<td>2.93 ± 0.45 ± 0.39</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^0$</td>
<td>59 ± 15</td>
<td>0.82</td>
<td>2.70 ± 0.68 ± 0.38</td>
<td></td>
</tr>
<tr>
<td>$\eta^* \rho^+$</td>
<td>$\pi^+ \pi^- \pi^0$</td>
<td>53 ± 10</td>
<td>0.56</td>
<td>3.55 ± 0.71 ± 0.53</td>
</tr>
<tr>
<td>$\eta^* \rho^+$</td>
<td>$\pi^+ \pi^- \pi^0$</td>
<td>15 ± 6</td>
<td>0.18</td>
<td>3.10 ± 1.24 ± 0.45</td>
</tr>
<tr>
<td>$\phi \rho^+$</td>
<td>$K^+ K^-$</td>
<td>253 ± 32</td>
<td>5.10</td>
<td>1.86 ± 0.26 ± 0.29</td>
</tr>
</tbody>
</table>

$^a$ $\eta \rightarrow \gamma \gamma$ is used.  
$^b$ $\eta \rightarrow \pi^+ \pi^- \pi^0$ is used.

ing the equation gives $N_{NR} < 55$ at 90% C.L., or < 11 events in the $\rho^+$-rich region. Thus, under the assumption that the non-$\rho^+$ 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 $\epsilon$ times the product branching ratios of the decay products, $\bar{B}$. The average branching ratio for the two $\eta$ decay modes, relative to $\phi \pi^*$, is $2.86 \pm 0.38 \pm 0.13$. 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-$\rho$ component in quadrature to the negative systematic error.

For our analysis of the $\eta^* \rho^+$ mode, we use the $\eta^* \rightarrow \pi^+ \pi^- \pi^0$ decay mode. The decay chains and cuts are listed in Table I. The $\pi^+ \pi^- \pi^0$ mass spectrum is shown in Fig. 3 for $\eta \rightarrow \gamma \gamma$. 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 $\rho^+$ 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 $\rho^+$ candidates. The fit to the $\cos^2 \theta_{\rho^+}$ 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 $\rho^+$ region. Averaging the two decays modes (see Table II) [3], we find a rather large relative branching ratio of $3.44 \pm 0.62 \pm 0.44$.

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 $1.86 \pm 0.26 \pm 0.29$. Our result is consistent with a previous E691 observation [4], which was based on a sample of 11 ± 3.6

![FIG. 3. The $\eta^* \pi^+ \pi^0$ invariant-mass spectrum, for the decay $\eta^* \rightarrow \pi^+ \pi^- \pi^0$, with $\eta \rightarrow \gamma \gamma$. Helicity and $\rho^+$ mass cuts are used. The solid points are for the lower sideband of the $\rho^s$ defined as $M(\pi^+ \pi^0) < 500$ MeV.](image)

![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 $\eta \rightarrow \gamma \gamma$ (histogram) and in the $D_s$ sidebands (solid points). The helicity cut is applied. (b) The helicity angle distribution from the $\rho^+$ band.](image)
TABLE III. $\Gamma/\Gamma(\phi\pi^+)$ compared with theory.

<table>
<thead>
<tr>
<th>Mode</th>
<th>This experiment</th>
<th>BSW</th>
<th>BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta\pi^+$</td>
<td>$2.86 \pm 0.38^{+0.30}_{-0.33}$</td>
<td>1.96</td>
<td>2.33</td>
</tr>
<tr>
<td>$\eta'\pi^+$</td>
<td>$3.44 \pm 0.62^{+0.46}_{-0.46}$</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>$\phi\pi^+$</td>
<td>$1.86 \pm 0.26^{+0.20}_{-0.20}$</td>
<td>6.30</td>
<td></td>
</tr>
</tbody>
</table>

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, $\phi\pi^+$, may be related to the small form factors observed in the semileptonic decay $D \to K^*\nu$ [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 $9.9 \pm 1.1$. In addition, well-established decays into modes such as $K^0\bar{K}^0$ sum up to $7.0 \pm 0.7$ times $\phi\pi^+$ [8-10].

The absolute $D_s \to \phi\pi^+$ branching ratio can be estimated by using the measured ratio $\Gamma(\phi\pi^+)/\Gamma(\phi\ell^+\nu)$. Using an average of CLEO [11] and ARGUS [12] results yields a value of $B(D_s \to \phi\pi^+) = (3.7 \pm 1.2)^%$ [1]. $B(D_s \to X_{\pi^+}\nu) = (8 \pm 1)^%$ 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 $\approx (79 \pm 26)^%$, where the error is dominated by the error on the $D_s \to \phi\pi^+$ branching ratio.

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

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[1] M. Daoudi et al., Cornell University Report No. CLNS

[3] The ratio $eB(\eta \to \gamma\gamma)/eB(\eta \to \pi^+\pi^-\pi^0)$ varies between the $\eta\pi^+$ mode and the $\eta'\pi^+$ mode because of the different momentum distributions of the $\eta$ coupled with the minimum imposed $\eta$ momentum cut.
[9] We have included a recent result from ARGUS that $\Gamma(K^{*-}\pi^+)/\Gamma(\phi\pi^+) = 1.6 \pm 0.6$; ARGUS Collaboration, H. Albrecht et al., DESY Report No. DESY 91-066, 1991 (unpublished).
[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 $(64 \pm 17 \pm 3)^%$ from D. Coffman et al., Phys. Lett. B 262, 135 (1991).