New Results in Charm Meson Spectroscopy from FOCUS and SELEX

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Outline

FOCUS  (thanks to Rob Kutschke and Eric Vaandering)
Masses and Widths of $D_2^{*+}$ $D_2^{*0}$ mesons
Evidence for $D_0^{*+}$ and $D_0^{*0}$ broad states
Confirmation of $D_s^+(2317)$ and others

SELEX
Evidence for $D_{sJ}^+(2632)$ in $D_s^+\eta$ and $D^0K^+$
FOCUS Spectrometer

Highlights:

- Segmented target
- Silicon vertexing
- MWPC tracking
- ~200 GeV Photon Beam
- Threshold Čerenkov
- EM/hadronic calorimeters
- Muon detectors
- Charm Photo-production
Selex Experiment at Fermilab
Charmed Hadroproduction with $\pi^-$, p and $\Sigma^-$ beams

SELEX Experiment
- Forward charm hadro-production $x_F > 0.1$
- $\pi^-$, p and $\Sigma^-$ beams @ 600 GeV/c
- Typical boost ~100
- RICH PID above 22 GeV/c
- 20 plane – 4 view SVX $\sigma > 4 \, \mu m$
- data taken in 1996-7
$L = 1$ Charm Decays

3 Hydrogenic (heavy-light) systems: $D^0(c\bar{u})$ $D^+(c\bar{d})$ $D_s^+(c\bar{s})$
**D Samples for $D_2$ Measurement**

Photoproduction gives sizable yields with low multiplicity.

Processes studied:

- $\gamma N \rightarrow D^0 \pi^+ + X$
- $D^0 \rightarrow K^- \pi^+$
- $D^0 \rightarrow K\pi\pi\pi$
- $\gamma N \rightarrow D^+ \pi^- + X$
- $D^+ \rightarrow K\pi\pi$

Remove any $D^0$ candidate with $D^* < 3\sigma$.
(Cleans up $D^0 \pi^+$.)
Fitting without $D^*_0$ Broad States

Perform a free fit just of $D^*_2$ parameters. Feed-downs are calculated from PDG values. Still very poor agreement ($\chi^2$/d.o.f $\approx 3$) between $D^*_2$ signal region and the feed-down region. $D^*_2$ parameters are far from expected values.
Adding $D_0^*$ Broad States

Add $S$-wave contribution for $D_0^*$ state ($j_\ell = \frac{1}{2}$). Fit is much improved, especially problem region before. CL = 22%. Also could be $D_1^* (j_\ell = \frac{1}{2}) \to D^* \pi$ with an unreconstructed $\pi^0$. 
### FOCUS $D_{J^*}$ Fit Results

<table>
<thead>
<tr>
<th></th>
<th>$D_2^{*0}$</th>
<th>$D_2^{*+}$</th>
<th>$D_2^{*+} - D_2^{*0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>5776 ± 869 ± 696</td>
<td>3474 ± 670 ± 656</td>
<td>—</td>
</tr>
<tr>
<td>Mass</td>
<td>2464.5 ± 1.1 ± 1.9</td>
<td>2467.6 ± 1.5 ± 0.8</td>
<td>3.1 ± 1.9 ± 0.9</td>
</tr>
<tr>
<td>PDG03</td>
<td>2458.9 ± 2.0</td>
<td>2459 ± 4</td>
<td>0.0 ± 3.3</td>
</tr>
<tr>
<td>Belle03</td>
<td>2461.6 ± 3.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>38.7 ± 5.3 ± 2.9</td>
<td>34.1 ± 6.5 ± 4.2</td>
<td></td>
</tr>
<tr>
<td>PDG03</td>
<td>23 ± 5</td>
<td>25^{+8}_{-7}</td>
<td></td>
</tr>
<tr>
<td>Belle03</td>
<td>45.6 ± 8.0</td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$D_0^{*0}(j_\ell = \frac{1}{2})$</th>
<th>$D_0^{*+}(j_\ell = \frac{1}{2})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>9810 ± 2657</td>
<td>18754 ± 2189</td>
</tr>
<tr>
<td>Mass</td>
<td>2407 ± 21 ± 35</td>
<td>2403 ± 14 ± 35</td>
</tr>
<tr>
<td>Belle03</td>
<td>2308 ± 36</td>
<td>2308 ± 36</td>
</tr>
<tr>
<td>Width</td>
<td>240 ± 55 ± 59</td>
<td>283 ± 24 ± 34</td>
</tr>
<tr>
<td>Belle03</td>
<td>276 ± 66</td>
<td>276 ± 66</td>
</tr>
</tbody>
</table>

Errors on $D_2^*$ masses and widths smaller than or same as PDG03 and agree with recent Belle report (hep-ex/0307021).
Excited $D_s$ Mesons

Until spring 2003, this pattern was expected to be repeated in the $D_s$ sector. Two relatively narrow $j_{\text{light}} = 3/2$ states had been observed and broad $j_{\text{light}} = 1/2$ were expected to be there too.

Instead, two new, very narrow states have been observed by the $B$ factories decaying to $D_s^{(*)}\pi^0$.

The first, dubbed $D_{sJ}^{*}(2317)$, was discovered by BABAR and later confirmed by CLEO and Belle.

The second, $D_{sJ}^{*}(2463)$, was discovered by CLEO and confirmed by BABAR and Belle.

$D_{sJ}^{*}(2317)$ also seen by FOCUS

For $j_{\ell} = 3/2$ states, analysis is very similar to $D$ sector; replace $\pi$ with $K^+/K_s^0$. 

$D_s^+(2317)$ Observation

- Reconstructed in $D_s^+(\rightarrow K^- K^+ \pi^+) \pi^0$ (58 events, inner EM Cal only)
- Correction to $\pi^0$ energy based on $D_s^* \rightarrow D_s^+ \pi^0$ and $D^0 \rightarrow K^- \pi^+ \pi^0$.
- Mass (using PDG $D_s^+$ value) found to be 2323 ± 2 MeV/$c^2$. BABAR/Belle/CLEO avg. ~ 2317
$D_{sJ}^+(2573) \rightarrow D^0 K^+$ and $D^+ K_S^0$

Simultaneous fit to $D^0 K^+$ and $D^+ K_S^0$. Terms:

- $D_{s2}^*$ signal: D-wave Rel. BW
- Smooth BG shape
- $D_{s1}^*$ & $D_{s2}^*$ feed-down shapes

Common $M$ and $\Gamma$, stat. only.

- $M = 2567.3^{+1.3}_{-1.2}$ MeV/c$^2$
- $\Gamma = 28.5^{+4.8}_{-4.0}$ MeV/c$^2$

PDG values are:

- $M = 2572.4 \pm 1.5$ MeV/c$^2$
- $\Gamma = 15 \pm 5$ MeV/c$^2$

First observation of $D^+ K_S^0$ decay mode. Comparable errors to PDG averages
Summary Of FOCUS Results

- Same paper presents evidence for broad ($D^{*0}_0$) states in $D^+\pi^-$ and $D^0\pi^+$ final states (first evidence in $D^0\pi^+$).
- Combined paper on excited $D_s$ states in preparation.
- $D^{*}\pi^{\pm}$ under study for other $L = 1$ states.
- Renewed interest in sector due to “strange” charmed mesons
Heavy-light spectroscopy

- Model predicts mass and widths – works well for $D(c\bar{d})$, but not for all $D_s(c\bar{s})$
- 2003 – $e^+e^-$ found $D_s(2317), D_s(2463)$ – below $DK$ threshold, inconsistent with model
- Higher states – expected above $D^{(*)}K$ threshold – therefore broad and hard to observe
SELEX search for $D_{sJ^+} \rightarrow D_s^+ \eta^0, D^0 K^+$

SELEX single charm samples (few % FOCUS)

This analysis uses $D^0$ and $D_s$ data
η⁰ signal in CHARM trigger

- Eγ > 2 GeV,
- Eγγ > 10 GeV,
- Nγ < 10
- Fit to: exp + Gaussian + constant
- good fit

Fit M(η⁰)  544.8 ± 2.9
PDG M(η⁰)  547.3 ± 0.12
Fit resolution  27.8 ± 4.3
MC resolution  30.2 ± 1.2

- η⁰ mass agrees with PDG value.
- MC represents resolution well.
η and Ds selection

- Eγ > 2 GeV, Eγγ > 15 GeV
- η0 mass region: M_{PDG}(η0) ± 60 MeV
- 5M η0 in 150M candidates
  S/N ~ 1/30
- 0.15 η0 candidates /event

- L/σ > 8, pvtx < 8
- |M(KKπ) – 1968.5| < 25 MeV
- ~1.2 η0 candidate / Ds candidate
New charm-strange meson

- Combined clean sample of $D_s$ with $\eta^0$ candidates

- $\eta$ mass constrained $p_\eta = [M_{PDG}(\eta), p]$

- 615 $\eta^0$ cand in 554 $D_s$ cand

- $103 \pm 27 \eta^0$ signal events

Clear peak near 2635 MeV/c$^2$

Event mixed background technique

$\eta^0$s from previous 25 events + $D_s$ candidates

Background consistent with just combinatorics – all sidebands flat.
Heavy-light spectroscopy now

New state lies above $D^{(0)} K$ threshold

Look for $D_s(2632) \Rightarrow D^0 K^+$
Fitting $D_s (2632) \rightarrow D^0 K^+$

- Strong selection criteria on $D^0$ & $K^+$
  - $D^0 \rightarrow K^- \pi^+$ only (S/N 4/1)
  - $L/\sigma > 6$, svtx $\chi^2 < 3$, pointback $\chi^2 < 5$
  - $\text{Prob}(K^+) > 10 \text{ Prob(any other)}$
- Wrong sign background constant
- Fit with 2 [ BW convolved with Gaussian ] + constant background
- Fix resolution from MC (4.9 MeV)
- New state is narrow (resolution only)

Count $S = 21$, $B = 7.0 \pm 0.6$, $(S-B)/\sqrt{B} = 5.3 \sigma$

3 bin Poisson excess probability = $2.5 \times 10^{-5}$

Fit events: $13.2 \pm 4.9$, Mass $2631.5 \pm 2.0$ MeV/c$^2$

A 90% CL upper limit $\Gamma < 17$ MeV/c$^2$
D_{sJ}(2632) Branching Ratios

- Most models say that D^0K^+ coupling should be much bigger than D_s^+ \eta^0
- Phase space favors D^0K^+ mode by 2.3x
- Acceptances given a detected D(s) meson are comparable
- We see 3x as many D_s^+ \eta^0 decays as D^0K^+

**SURPRISE:** \( \Gamma(D^0 K^+)/ \Gamma(D_s^+ \eta^0) = 0.14 \pm 0.06 \)
# D_s (2632) summary

<table>
<thead>
<tr>
<th>State</th>
<th>D_s (2632) $\rightarrow D_s\eta$</th>
<th>D_s(2632) $\rightarrow D^0K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>$2635.4 \pm 3.3$</td>
<td>$2631.5 \pm 2.0$</td>
</tr>
<tr>
<td>Sign.</td>
<td>$6.2 \sigma$</td>
<td>$5.3 \sigma$</td>
</tr>
<tr>
<td>Events</td>
<td>$43.4 \pm 9.1$</td>
<td>$13.2 \pm 4.9$</td>
</tr>
<tr>
<td>$\chi^2 / n_d$</td>
<td>$1.10$</td>
<td>$0.77$</td>
</tr>
</tbody>
</table>

- ✔ Average D_{sJ}^+(2632) mass $2632.5 \pm 1.7$ MeV/c^2
- ✔ $\Gamma<17$ MeV/c^2 @ 90% CL(D^0K^+)
- ✔ $\Gamma(D^0K^+)/\Gamma(D_s^+\eta^0) = 0.14 \pm 0.06$
Not seen in $e^+e^-$ or photoproduction

CLEO Preliminary
20 fb$^{-1}$

Thanks to Rich Galik (Cornell)

FOCUS (unpub) Thanks to Rob Kutschke (FNAL)

Babar hep-ex/04080087

• Not Made?
• Not there?
• Babar only sees $\sim 0.4\%$ $D_s\eta / D_s$

Are any of the higher mass $D_s$ states being produced in $e^+e^-$?

Figure 4: (a) The $D_s^+\eta$ invariant mass distribution. The unshaded distribution ($m_S$) corresponds to the central region of Fig. 3a while the shaded distribution is obtained using Eq. 4. (b) The $D_s^+\eta$ mass distribution obtained by subtracting the distributions of (a).
Summary of Selex Result

$D_s^+ \eta^0$ Observed a clear peak of $43.4 \pm 9.1$ events with a significance of $6.2 \sigma$ at a mass difference $666.9 \pm 3.3$ MeV/c$^2$ above ground state

$D^0 K^+$ Observed a clear peak of $13.2 \pm 4.9$ events with a significance of $5.3 \sigma$ at a mass difference $767.0 \pm 2.0$ MeV/c$^2$ above ground state

Clear evidence for a new state $D_{sJ}^+(2632)$ at $2632.5 \pm 1.7$ MeV/c$^2$ with $\Gamma < 17$ MeV/c$^2$!

Result accepted for publication in PRL (after much hand-wringing on both sides)

This state is definitely NOT seen in $e^+e^-$ (CLEO, Babar) or in photo-production (FOCUS)?

CONCLUSIONS

Heavy-Light systems still require exploration and explanation

Can $D_{sJ}^+(2632)$ be confirmed?

Are there other states to be found; wide or narrow?

Who are these guys ($I^G J^\pi$, etc.)?

Exotica? (21 cites for the $D_s^+$ (2632) preprint include some eclectic explanations)

Will we have a descriptive “post-diction” of this spectroscopy to build on the relatively successful predictions?