Charm and strange particles production at ZEUS

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For the ZEUS Collaboration

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Outline

- ZEUS detector at the HERA
- Excited charm and charm-strange mesons
- Inclusive K0sK0s resonance production
- Summary
ZEUS detector at the HERA

- ZEUS: 56 universities and laboratories, 18 countries
- HERA - the only ep collider in the world
- HERA II (2002-2007): upgraded detectors, longitudinally polarised $e^\pm$ beams

Complete 4$\pi$ detector

Tracking:
- central tracking detector
- Silicon $\mu$-Vtx (operate in a B field of 1.43 T)

Calorimeters:
- Uranium-scintillator (CAL)
- Instrumented-iron (BAC)

Muon chambers
Motivation for study excited charm and charm strange production

Heavy-quark spectroscopy has recently undergone a renaissance with the discovery of several new states:

- Non-strange excited charm mesons $D_1(2420)^{\mp,\pm}$ and $D_2^\ast(2460)^{\mp,\pm}$
- Charm-strange excited mesons $D_{s1}(2536)^{\pm}$ and $D_{s2}(2573)^{\pm}$
- Recently, Supported Heavy Quark Effective Theory (HQET) predictions $D^{\ast\ast}(2400)^{\mp,\pm}$ and $D_1(2430)^{\circ}$
- Recent discovery charm-strange $D_{s0}^{\ast}(2317)^{\pm}$ and $D_{s1}(2460)^{\pm}$
- Predicted: broad non-strange charged excited charm meson with $JP=1^+$ has not yet been observed.
- Predicted: radially excited charm $D^\prime\rightarrow D\pi\pi$ and $D^{\ast\prime}\rightarrow D^{\ast}\pi\pi$, $\sim 2.6$ GeV. Narrow resonance at 2637 MeV with $D^{\ast\pm}\pi^+\pi^-$ reported by DELPHI, however OPAL – no evidence.

The properties of these states challenge the theoretical description of heavy-quark resonances. Further measurement of excited charm and charm-strange mesons are important!
Excited charm and charm-strange mesons

- Large charm production cross sections at HERA allow to search for excited charm states

Look for orbitally excited states:
\[ D_1(2420)^0 \rightarrow D^{*\pm}\pi^\mp \quad J^P = 1^+ \]
\[ D_2^*(2460)^0 \rightarrow D^{*\pm}\pi^\mp \quad J^P = 2^{++} \]
\[ D_2^*(2460)^0 \rightarrow D^{\pm}\pi^\mp \]
\[ J^P = 1^+ \text{ state cannot decay to } D\pi \]
\[ D_{s1}(2536)^\pm \rightarrow D^{*\mp}K^0_s, D^{*0}K^\pm \quad J^P = 1^+ \]

Search for radially excited states:
\[ D^{*d}(2640)^\pm \rightarrow D^{*\pm}\pi^+\pi^- \text{ (DELPHI)} \quad J^P = 1^- ? \]

ZEUS HERA I 1995 - 2000 (126 pb^{-1}) DIS + PHP

Study of the excited charm mesons

\[ D_1(2420)^o, D_2^*(2460)^o \]

\[ D_1(2420)^o \rightarrow D^*+ \pi^- \]
\[ D_2^*(2460)^o \rightarrow D^*+ \pi^-, D^+ \pi^- \]

combining each selected \( D^*+ \) (or \( D^+ \)) candidate with an additional track, assumed to be a pion, with a charge opposite to that of the \( D^*+ \) (or \( D^+ \)) candidate.
Reconstruction of lowest-mass charm mesons: $D^{*+}$

$D^{*+}$ mesons were identified using the two decay channels:

$D^{*+} \rightarrow D^0 \pi s^+ \rightarrow (K^- \pi^+) \pi s^+$
$\Delta M = M(K\pi \pi) - M(K\pi)$,     Signal: 39500

$D^{*+} \rightarrow D^0 \pi s^+ \rightarrow (K^- \pi^+ \pi^+ \pi^-) \pi s^+$
$\Delta M = M(K\pi\pi\pi\pi s) - M(K\pi\pi\pi)$,     Signal: 17300

Background-wrong charge combination.
Yellow band - ranges used for excited charm mesons
Reconstruction of lowest-mass charm mesons: \(D^+\) and \(D^0\)

\[D^+ \rightarrow K^−\pi^+\pi^+.\]

Width (\(D^+\)) = 12.9 MeV; (detector resolution)

**Guts:**
- \(p_T(D) > 2.8\) GeV
- |\(\eta(D)\)| < 1.6

Yellow band corresponds to ranges used for excited charm mesons

\[D^0 \rightarrow K^−\pi^+.\]

Width (\(D^0\)) = 17.4 MeV;
Excited charm mesons: $D_1(2420)^\circ$ and $D_2^{*}(2460)^\circ$

- **Decay channel** → $D^{*+} \pi^-$
  A clear enhancement in the range where contributions from $D_1(2420)^\circ$ and $D_2^{*}(2460)^\circ$ mesons are expected.

$$\Delta M^{\text{ext}} + M(D^{*\pm})_{PDG} \text{ (dots)}$$
$$\Delta M^{\text{ext}} = M(K\pi\pi_s\pi_c) - M(K\pi\pi_s)$$
$$p_T(D^{*\pm}) > 1.35 \text{ GeV, } |\eta(D^{*\pm})| < 1.6$$
$$\Delta M^{\text{ext}} = M(K\pi\pi\pi_s\pi_c) - M(K\pi\pi\pi_s)$$
$$p_T(D^{*\pm}) > 2.80 \text{ GeV, } |\eta(D^{*\pm})| < 1.6$$

- **Decay channel** → $D^+ \pi^-$
  A small excess around the nominal mass of the $D_2^{*\circ}$ meson.
$D_1^0$ and $D_2^{*0}$ in four helicity bins

Used helicity angular distribution to extract $D_1(2420)^0$ and $D_2^{*}(2460)^0$ yields and properties

$h$ -helicity parameter ( $h=3$ for pure D-wave)

$$dN/d\cos \alpha \approx 1 + h \cos^2 \alpha$$

Simultaneous fit including all contributions

<table>
<thead>
<tr>
<th>final state</th>
<th>$D^{*+}\pi_a$</th>
<th>$D^+\pi_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal yields</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N(D_1^0)$</td>
<td>3110 ± 340</td>
<td></td>
</tr>
<tr>
<td>$N(D_2^{*0})$</td>
<td>870 ± 170</td>
<td>690 ± 160</td>
</tr>
</tbody>
</table>

$M(D_1^0) = 2420.5 \pm 2.1$(stat.) $\pm 0.9$(syst.) $\pm 0.2$(PDG) MeV,

$M(D_2^{*0}) = 2469.1 \pm 3.7$(stat.) $^{+1.2}_{-1.3}$(syst.) $\pm 0.2$(PDG) MeV.

Fitted masses agree with PDG

$\Gamma(D_1^0) = 53.2 \pm 7.2^{+3.3}_{-4.9}$ MeV (PDG : 20.4 $\pm 1.7$ MeV)

$h(D_1^0) = 5.9^{+3.0}_{-1.7}$(stat.) $^{+2.4}_{-1.0}$(syst.) (CLEO: 2.74$^{+1.40}_{-0.93}$)

Roughly consistent with pure D-wave ($h=3$)
Excited charm mesons: $D_{s1}^+$

- $D_{s1}^+ \rightarrow D^{*+}(\text{both decay channels})$ with $K^0s \rightarrow \pi^+\pi^-$
- $D_{s1}^+ \rightarrow (D^{*0} \text{ with } K^\pm)$
- To extract $D_{s1}^+$ yields and properties: fit using simultaneously values of $M(D^{*0}K^\pm)$ and $M(D^{*+}K^0s)$ in four helicity intervals
- Clear $D_{s1}(2536)^+$ signals! Measured $D_{s1}^+$ mass in good agreement with the world average value!

$$M(D_{s1}^+) = 2535.57^{+0.44}_{-0.41} \text{(stat.)} \pm 0.10 \text{(syst.)} \pm 0.17 \text{ (PDG) MeV}$$

<table>
<thead>
<tr>
<th>final state</th>
<th>$D^{*+}K^0_s$</th>
<th>$D^0K_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal yields</td>
<td>100 ± 13</td>
<td>136 ± 27</td>
</tr>
</tbody>
</table>

Fitted $D_{s1}$ helicity parameter: $h(D_{s1}) = -0.74^{+0.23}_{-0.17} \text{(stat.)}^{+0.06}_{-0.05} \text{(syst.)}$

Inconsistent with pure $1^+$ D-wave ($h=3$)

Barely consistent with pure $1^+$ S-wave ($h=0$) $\rightarrow$ Significant S-D mixing
Branching ratios and fragmentation fractions

\[
\frac{B_{D_s^0 \to D^+ \pi^-}}{B_{D_s^0 \to D^{*+} \pi^-}} = 2.8 \pm 0.8 \text{(stat.)} ^{+0.5}_{-0.6} \text{(syst.)} \quad 2.3 \pm 0.6 \quad \text{(PDG)}
\]

\[
\frac{B_{D_s^+ \to D^{*0} K^+}}{B_{D_s^+ \to D^{**+} K^0}} = 2.3 \pm 0.6 \text{(stat.)} \pm 0.3 \text{(syst.)} \quad 1.27 \pm 0.21 \quad \text{(PDG)}
\]

Assuming I-spin conservation for \(D_s^0, D_s^{*0}\) and \(B_{D_s^{*0} \to D^{*+} K^0} + B_{D_s^+ \to D^{**+} K^0} = 1\) yields fragmentation functions and strangeness suppression of excited \(D\) mesons

\[
f(c \to D_s^+)/f(c \to D_s^0) = 0.31 \pm 0.06^{+0.05}_{-0.04}
\]

<table>
<thead>
<tr>
<th></th>
<th>(f(c \to D_s^0))%</th>
<th>(f(c \to D_s^{*0}))%</th>
<th>(f(c \to D_s^+))%</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEUS</td>
<td>3.5 ± 0.4^{+0.4}_{-0.6}</td>
<td>3.8 ± 0.7^{+0.5}_{-0.6}</td>
<td>1.11 ± 0.16^{+0.08}_{-0.10}</td>
</tr>
<tr>
<td>OPAL</td>
<td>2.1 ± 0.8</td>
<td>5.2 ± 2.6</td>
<td>1.6 ± 0.4 ± 0.3</td>
</tr>
<tr>
<td>ALEPH</td>
<td></td>
<td></td>
<td>0.94 ± 0.22 ± 0.07</td>
</tr>
</tbody>
</table>

⇒ Frag. fractions for excited \(D\) mesons in \(e^+e^-\) consistent
Search for radially excited charm meson $D^*(2640)\pm$

$D^*'^+ \rightarrow D^*+ \pi^+ \pi^-$

- combining each selected $D^*+$ candidate with two additional tracks with opposite charges.
- No radially excited $D^*(2640)\pm$ charm meson observed.

*Upper limit:*

$f(c \rightarrow D^{*'+}) \cdot B_{D^{*'+} \rightarrow D^*+\pi^+\pi^-} < 0.4\%$ (95\% C.L.).

*OPAL result:* < 0.9\%

$D^*'^\pm$ signal window - theoretical predictions

solid curve - fit background,

shaded histogram - Monte Carlo $D^*'^\pm$ signal,

normalised to upper limit on top of the fit.
Motivation for study $K_0sK_0s$ resonance production

- The SM allows glueballs ($gg$), hybrids ($q\bar{q}g$) and mixed states.
- The scalar meson sector ($J^P=0^+$) has too many established $l=0$ states: $f_0(980), f_0(1370), f_0(1500), f_0(1710)$
  - only two can fit into the $q\bar{q}$ nonet
- Lattice calculations predict that the lightest glueball has $J^{PC}=0^{++}$ and mass in range 1550 – 1750 MeV
- It can mix with $q\bar{q}$ ($l=0$) states close in mass
- $f_0(1710)$ is considered to be a possible glueball candidate
- The $K_s^0K_s^0$ system can couple to $J^P = 0^+$ and $2^+$

$K_s^0K_s^0$ is a good place to search for the lightest $0^+$ glueball
K0s mass distribution for events with ≥ two K0s candidates

- ZEUS data 1996-2007
- Signal window for $M(K0sK0s)$ analysis:
  $481 \leq M(\pi^+\pi^-) \leq 515$ MeV
- No. of $K0s$ candidates in signal window ~ 1,258,400
- Clean $K0s$ signal; background ~ 8%

**Cuts:**
- $pT(K0s) > 0.25$ GeV
- 2D Collinearity angle $< 0.12$ rad; (angle in $xy$-plane between $K0s$ momentum vector and vector defined by interaction point and decay vertex)
- $|Zvtx| < 50$;

$M(K_{S0}K_{S0}) = 497.49$ MeV consistent with PDG
$\sigma = 4.1$ MeV consistent with detector resolution
**K0sK0s mass spectrum (incoherent fit)**

Fit (as in L3) to background plus incoherent sum of 3 modified RBW resonance, \( R \), of the form

\[
F(m) = C_R \frac{M_R \Gamma_R}{(M_R^2 - m^2)^2 + M_R^2 \Gamma_R^2}
\]

representing the peaks \( f_2(1270)/a_2(1320), f_2'(1525), f_0(1710) \)

- \( C_R \) = Amplitude of resonance \( R \)
- \( M_R \) = Mass of resonance \( R \)
- \( \Gamma_R \) = Variable width of resonance \( R \)
- \( m = K_S^0K_S^0 \) invariant mass

\[ \chi^2/ndf = 96/95 \]

Bad fit without \( f_0(1710) \Rightarrow f_0(1710) \) required

Dip between \( f_2/a_2 \) and \( f_2' \) not reproduced
K0sK0s mass spectrum (coherent fit)

- K0sK0s invariant-mass distribution was reconstructed by combining two K0s candidates selected in the mass window;

\[ M, \Gamma \] of all resonances – free parameters in the fit.

Bottom plot background subtracted \( M(K_S^0 K_S^0) \) spectrum with fitted BW functions.

Good fit \( \chi^2/\text{ndf} = 86/97 \).

Peak around 1.3 GeV suppressed due to destructive interference between \( f_2(1270) \) and \( a_2(1320) \).

Dip between \( f_2(1270)/a_2(1320) \) and \( f_2^*(1525) \) is well reproduced.

No. of fitted \( f_0(1710) \) events: 4058±820 \( \sim 5\sigma \) significance

Fit without \( f_0(1710) \) strongly disfavoured \( \chi^2/\text{ndf} = 162/97 \)
Results

<table>
<thead>
<tr>
<th>Fit</th>
<th>No interference</th>
<th>Interference</th>
<th>PDG 2007 Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2/ndf$</td>
<td>96/95</td>
<td>86/97</td>
<td></td>
</tr>
<tr>
<td>in MeV</td>
<td>Mass Width</td>
<td>Mass Width</td>
<td>Mass Width</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>1304 ± 6 61 ± 11</td>
<td>1268 ± 10 176 ± 17</td>
<td>1275.4 ± 1.1 185.2$^{+3.1}_{-2.5}$</td>
</tr>
<tr>
<td>$a_2^0(1320)$</td>
<td>1257 ± 9 114 ± 14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f'_2(1525)$</td>
<td>1523 ± 3$^{+2}<em>{-8}$ 71 ± 5$^{+17}</em>{-2}$</td>
<td>1512 ± 3$^{+1.1}<em>{-0.5}$ 83 ± 9$^{+5}</em>{-4}$</td>
<td>1525 ± 5 73$^{+8}_{-5}$</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>1692 ± 6$^{+9}<em>{-3}$ 125 ± 12$^{+19}</em>{-32}$</td>
<td>1701 ± 5$^{+5}<em>{-3}$ 100 ± 24$^{+22}</em>{-22}$</td>
<td>1724 ± 7 137 ± 8</td>
</tr>
</tbody>
</table>

For fit with interference:
- $a_2(1320)$ mass below PDG value. Similar shift, attributed to destructive $f_2(1270)/a_2(1320)$ interference, seen by Faiman et al.
- Widths of all observed resonances close to PDG values
- $f'_2(1525)$, $f_0(1710)$ masses below PDG; uncertainties compatible with PDG
- One of the best $f_0(1710)$ reported signals: 4058±820 events ~5 s.d.
$f_2'(1525)$ and $f_0(1710)$: mass and width
Summary

- Sizeable production of the excited charm and charm-strange mesons was observed in $ep$ interactions.
- Measured masses of the $D_{1^0}$, $D_{2^*0}$ and $D_{s1^+}$ in reasonable agreement with the world average values. $D_{1^0}$ width 53.2 MeV above PDG 20.4 MeV
- Measured $D_{1^0}$ helicity parameter $h=5.9$ consistent with prediction for pure $D$-wave.
- $D_{s1^+}$ helicity parameter $h = -0.74$, inconsistent with prediction for a pure $D$- or $S$- waves. Suggests significant contributions of both waves.
- Ratios of dominant branching fractions are in agreement with the world average values.
- Fraction of $c$ quarks hadronising into $D_{1^0}$, $D_{2^*0}$ or $D_{s1^+}$ are consistent with obtained in $e^+e^-$, agreement with charm fragmentation universality;
- No radially excited $D^*(2640)^+\,$ meson was observed.
Summary(2)

- Observed three enhancements corresponding to \( f_2(1270)/a_2(1320), f_2'(1525) \) and \( f_0(1710) \);
- \( f_0(1710) \) with 5\( \sigma \) significance, has mass consistent with glueball candidate.
- No state observed heavier than \( f_0 \);
- Masses and widths of \( f_2'(1525) \) and \( f_0(1710) \) consistent with PDG;
They see 3 distinct peaks over a low background and attribute them to $f_2(1270)/a_2(1320)$, $f_2'(1525)$ and $f_0(1710)$

Spectrum dominated by the formation of the $f_2'(1525)$ tensor meson

$f_0(1710)$ signal of ~4 s.d. is seen

Maximum likelihood fit with 3 BW Functions plus 2nd order polynomial

$f_2'(1525)$ parameters consistent with PDG

<table>
<thead>
<tr>
<th></th>
<th>$f_2(1270)/a_2(1320)$</th>
<th>$f_2'(1525)$</th>
<th>$f_0(1710)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV)</td>
<td>1230 ± 6</td>
<td>1523 ± 6</td>
<td>1767 ± 14</td>
</tr>
<tr>
<td>Width (MeV)</td>
<td>78 ± 19</td>
<td>100 ± 15</td>
<td>187 ± 60</td>
</tr>
<tr>
<td>Events</td>
<td>123 ± 22</td>
<td>331 ± 37</td>
<td>221 ± 55</td>
</tr>
</tbody>
</table>
Backup- **TASSO** $\gamma\gamma \rightarrow K^+K^-, K\bar{0}sK\bar{0}s$


Results interpreted by interference effects between the 3 $J^{P}=2^+$ resonances $f_2(1270)$, $a_2(1320)$, $f_2'(1525)$

For the same spin-parity, production amplitude is sum of 3 coherent BW’s

$C_1 \cdot BW(f_2(1270)) \pm C_2 \cdot BW(a_2(1320))$

$+ C_3 \cdot BW(f_2'(1525))$

According to SU(3), sign of 2nd term is + for $K^+K^-$; - for $K_s^0K_s^0$

Backup - Coherent 2+ states

<table>
<thead>
<tr>
<th>Isospin I</th>
<th>$f_2(1270)$</th>
<th>$a_2(1320)$</th>
<th>$f'_2(1525)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Quark content</td>
<td>$(u \bar{u} + d \bar{d})/\sqrt{2}$</td>
<td>$(u \bar{u} - d \bar{d})/\sqrt{2}$</td>
<td>$s \bar{s}$</td>
</tr>
<tr>
<td>Charge factor</td>
<td>$(\frac{2}{3} \cdot \frac{2}{3} + \frac{1}{3} \cdot \frac{1}{3}) \frac{1}{2}$</td>
<td>$(\frac{2}{3} \cdot \frac{2}{3} - \frac{1}{3} \cdot \frac{1}{3}) \frac{1}{2}$</td>
<td>$\frac{1}{3} \cdot \frac{1}{3}$</td>
</tr>
<tr>
<td>Amplitude ratio</td>
<td>$C_1 = 5$</td>
<td>$C_2 = -3$</td>
<td>$C_3 = 2$</td>
</tr>
</tbody>
</table>

The appropriate function to fit the $M(K_S^0 K_S^0)$ spectra for an electromagnetic production process assuming SU(3) symmetry is H.J. Lipkin, private communication

$$F(m) = a \left[ 5 \cdot BW\left(f_2(1270)\right) - 3 \cdot BW\left(a_2(1320)\right) + 2 \cdot BW\left(f'_2(1525)\right) \right]^2$$

$$+ b \left[ BW\left(f_0(1710)\right) \right]^2 + c \cdot \text{background}$$

$a$, $b$, $c$ are free parameters

$BW$ is a relativistic $BW$ amplitude:

$$BW(R) = \frac{M_R \sqrt{\Gamma_R}}{M_R^2 - m^2 - iM_R \Gamma_R}$$