Study of D_s mesons

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Outline

- Theoretical study of D_s
- "New" D_s
- Interpretation of $D_{sJ}(2632)^+$, $D_{s1}(2700)^{\pm}$, $D_{sJ}(2860)$ and $D_{sJ}(3040)^+$
- Discussions and questions

Theoretical study of D_s

D_s ($c\bar{s}$ or $\bar{c}s$): heavy-light systems

Features of strong interaction: Heavy quark symmetry, Chiral symmetry, Symmetry breaking

♠ References

- Relativized quark model:

  Spectrum, Decay

  S. Godfrey and N.Isgur, Phys. Rev. **D32**, 189(1985)

  S. Godfrey and R. Kokoski, Phys. Rev. **D43**, 1679(1991)

  F.E. Close and E.S. Swanson, Phys. Rev. **D72**, 094004(2005)

- Heavy quark symmetry theory:

  Spectrum, Decay

  E.J. Eichten, C.T. Hill and C. Quigg, Phys. Rev. Lett. **71**, 4116(1993)

- Relativistic quark model:

  Spectrum, Decay

  D. Ebert, V.O. Galkin and R.N. Faustov, Phys. Rev. **D57**, 5663(1998); Erratum-ibid. **D59**, 019902(1999)

- Lattice QCD:

  J. Hein, S. Collins, C.T.H. Davies, A.A. Khan, H. Newton, C. Morningstar, J. Shigemitsu and J. Sloan, Phys. Rev. **D62**, 074503(2000)

- Chiral quark model

  Spectrum, Decay

  M.Di Pierro and E. Eichten, Phys. Rev. **D64**, 114004(2001)

- Constituent quark model(heavy quark symmetry + light quark chiral symmetry)

  M.A. Nowak, M. Rho and I. Zahed , Phys. Rev. **D48**, 4730(1993)

  W.A. Bardeen and C.T. Hill, Phys. Rev. **D49**, 409(1994)

  W.A. Bardeen, E.J. Eichten and C.T. Hill, Phys. Rev. **D68**, 054024(2003)

- Mass loaded flux tube model:

  T.J. Allen, T. Coleman, M.G. Olsson and S. Veleli, Phys. Rev. **D69**, 074010(2004)

  Hong-Yun Shan and Ailin Zhang, Chin. Phys. **C34**, 1(2010), [arXiv: 0805.4764]

  Bing Chen, Deng-Xia Wang and Ailin Zhang, Phys. Rev. **D80**, 071502(R)(2009)

- Coupled channels models:

  Eef van Beveren and George Rupp, Phys. Rev. Lett. **91**, 012003(2003)

  Yu.A. Simonov and J.A. Tjon, Phys. Rev. **D70**, 114013(2004)

  Eef van Beveren and George Rupp, Phys. Rev. Lett. **97**, 202001(2006)

- Other models:

  T. Matsuki and T. Morii, Phys. Rev. **D56**, 5646(1997)

  J. L. Goity and W. Roberts, Phys. Rev. **D60**, 034001 (1999)

  Yu.S. Kalashnikova, A.V. Nefediev and Yu. A. Simonov, Phys. Rev. **D64**, 014037(2001)

  J. Erdmenger, N. Evans and J. Grosse, **JHEP** 0701, 098(2007)

  Xian-Hui Zhong and Qiang Zhao, Phys. Rev. **D78**, 014029 (2008)

- Reviews:

  P. Colangelo, F. De Fazio and R. Ferrandes, Mod. Phys. Lett. **A19**, 2083(2004)

  E.S. Swanson, Phys. Rept. **429**, 243(2006)

  J.L. Rosner, J. Phys. **G34**, S127(2007)

  Shi-Lin Zhu, Int. J. Mod. Phys. **E17**, 28(2008)

♠ Spectrum of D_s mesons

♢ Heavy quark symmetry

$$SU(2N_f)$$

Vanishing hyperfine splitting effects, degenerate spin multiplets

Ground state: $j^P = \frac{1}{2}^-$

Doublet: $J^P = (0^-, 1^-)(^1S_0, ^3S_1)$

The first excited states(a P-wave excitation): $j^P = \frac{1}{2}^+$ or $\frac{3}{2}^+$

Two doublets: $J^P = (0^+, 1^+)$ and $J^P = (1^+, 2^+)$

$\diamondsuit$ Light quark chiral symmetry

$$SU(2)_L \times SU(2)_R \;\; (1994), \qquad SU(3)_L \times SU(3)_R \;\; (2003)$$

Parity degeneracy

$j^P = \frac{1}{2}^-$ multiplet degenerate with $j^P = \frac{1}{2}^+$ multiplet

$(0^+, 1^+)$ degenerate with $(0^-, 1^-)$

Chiral symmetry breaking

elevating $(0^+, 1^+)$ while depressing $(0^-, 1^-)$

Mass splitting between these parity partners (the even and the odd parity multiplets)

$$\Delta M$$

$\diamondsuit$ Heavy quark symmetry + Light quark chiral symmetry

Two kinds of classification schemes:

Nonrelativistic $n^{2S+1}L_J$:

[1], S. Godfrey and N.Isgur, Phys. Rev. **D32**, 189(1985)

Candidates	J^P	$n^{2S+1}L_J$	[1]
$D_s^{\pm}(1969)$	0^-	1^1S_0	1.98
$D_s^{\star\pm}(2112)^0$	1^-	1^3S_1	2.13
$D_{s0}^{\star}(2317)^{\pm}$	0^+	1^3P_0	2.48
$D_{s1}(2536)^{\pm}$	1^+	1^3P_1	2.57
$D_{s1}(2460)^{\pm}$	1^+	1^1P_1	2.53
$D_{s2}(2573)^{\pm}$	2^+	1^3P_2	2.59
$D_{sJ}(2632)$	1^-	1^3D_1	2.90
?	2^-	1^3D_2	-
?	2^-	1^1D_2	-
$D_{sJ}(2860)$	3^-	1^3D_3	2.92
?	0^-	2^1S_0	2.67
$D_{s1}(2700)^{\pm}$	1^-	2^3S_1	2.73

Tab. 1: Spectrum of D_s mesons (GeV).

Heavy quark symmetric nj^P:

[2], S. Godfrey and R. Kokoski, Phys. Rev. **D43**, 1679(1991)

[3], D. Ebert, V.O. Galkin and R.N. Faustov, Phys. Rev. **D57**, 5663(1998); Erratum-ibid. **D59**, 019902(1999)

[4], M.Di Pierro and E. Eichten, Phys. Rev. **D64**, 114004(2001)

Candidates	J^P	nj^P	[3]	[4]
$D_s^{\pm}(1969)$	0^-	$1\frac{1}{2}^-$	1.981	1.965
$D_s^{\star\pm}(2112)^0$	1^-	$1\frac{1}{2}^-$	2.111	2.113
$D_{s0}^{\star}(2317)^{\pm}$	0^+	$1\frac{1}{2}^+$	2.508	2.487
$D_{s1}(2536)^{\pm}$	1^+	$1\frac{3}{2}^+$	2.515	2.535
$D_{s1}(2460)^{\pm}$	1^+	$1\frac{1}{2}^+$	2.569	2.605
$D_{s2}(2573)^{\pm}$	2^+	$1\frac{3}{2}^+$	2.56	2.581
$D_{sJ}(2632)$	1^-	$1\frac{3}{2}^-$	-	2.913
?	2^-	$1\frac{5}{2}^-$	-	2.900
?	2^-	$1\frac{3}{2}^-$	-	2.953
$D_{sJ}(2860)$	3^-	$1\frac{5}{2}^-$	-	2.925

Candidates	J^P	nj^P	[3]	[4]
?	0^-	$2\frac{1}{2}^-$	2.670	2.700
$D_{s1}(2700)^{\pm}$	1^-	$2\frac{1}{2}^-$	2.716	2.806
?	0^+	$2\frac{1}{2}^+$	-	3.067
?	1^+	$2\frac{3}{2}^+$	-	3.114
$D_{sJ}(3040)^+$	1^+	$2\frac{1}{2}^+$	-	3.165
?	2^+	$2\frac{3}{2}^+$	-	3.157

Tab. 2: Spectrum of D_s mesons (GeV).

◇ Mixing

Relations among the ${}^{2S+1}L_J$ eigenstates and the j^P eigenstates (C-G coefficients):

$$|\frac{1}{2}^+\rangle = \sqrt{\frac{2}{3}}\,{}^3P_1 - \sqrt{\frac{1}{3}}\,{}^1P_1$$

$$|\frac{3}{2}^+\rangle = \sqrt{\frac{1}{3}}\,{}^3P_1 + \sqrt{\frac{2}{3}}\,{}^1P_1$$

$$|\frac{3}{2}^-\rangle = \sqrt{\frac{3}{5}}\,{}^3D_2 - \sqrt{\frac{2}{5}}\,{}^1D_2$$

$$|\frac{5}{2}^-\rangle = \sqrt{\frac{2}{5}}\,{}^3D_2 + \sqrt{\frac{3}{5}}\,{}^1D_2$$

Physical states may not be the $^{2S+1}L_J$ or the j^P eigenstates!

Mixing between orbital P-wave $|1^+\rangle$:

mixing between $^3P_1$ and $^1P_1$:

$$|1^+\rangle = a|^3P_1\rangle + b|^1P_1\rangle$$

mixing between $|\frac{1}{2}^+\rangle$ and $|\frac{3}{2}^+\rangle$

$$|1^+\rangle = a'|\frac{1}{2}^+\rangle + b'|\frac{3}{2}^+\rangle$$

Mixing between orbital D-wave $|2^-\rangle$:

mixing between $^3D_2$ and $^1D_2$

$$|2^-\rangle = a|^3D_2\rangle + b|^1D_2\rangle$$

mixing between $|\frac{3}{2}^-\rangle$ and $|\frac{5}{2}^-\rangle$

$$|2^-\rangle = a'|\frac{3}{2}^-\rangle + b'|\frac{5}{2}^-\rangle$$

Mixing between the orbital D-wave $|1^-\rangle$ and the first radial S-wave $|1^-\rangle$:

mixing between 1^3D_1 and 2^3S_1

$$|1^-\rangle = a|1^3D_1\rangle + b|2^3S_1\rangle$$

mixing between $|\frac{3}{2}^-\rangle$ and $|2\ \frac{1}{2}^-\rangle$

$$|1^-\rangle = a'|\frac{3}{2}^-\rangle + b'|2\frac{1}{2}^-\rangle$$

Mixing among other states

♢ Physical states under mixing? (Experimental distinction?)

Spectrum?

Decay modes? Mixing angle?

Mechanism of Mixing?

♠ Strong decay of D_s mesons

Relativized quark model: meson decay proceeds through a single quark transition via the emission of a pseudoscalar meson(S. Godfrey and N. Isgur(1985))

Chiral quark model: transition is mediated by an effective interaction (M. Di Pierro and E. Eichten(2001))

$^3P_0$ model: the elementary process is described by the creation of a $q\bar{q}$ pair with the quantum numbers of the vacuum, $J^{PC} = 0^{++}$, in the final state (A. Le Yaouanc, L. Oliver, O. Pene and J.C. Raynal, Phys. Rev. **D8**, 2223(1973); **D 11**, 1272(1975))

Other models

The difference among the decay widths in different models may be very large!

$\diamondsuit$ $nj^P = 1\ \frac{1}{2}^+$:

Large width

S. Godfrey and R. Kokoski(1991)

$$D_0^{\star}(1\ ^{\frac{1}{2}}P_0) \rightarrow D(1\ ^{\frac{1}{2}}S_0)K \approx 310\ \ MeV$$

M. Di Pierro and E. Eichten(2001)

$$D_s(1\ ^{\frac{1}{2}}P_{0,1}) \rightarrow D(1\ ^{\frac{1}{2}}S_{0/1})K \approx 236/224\ \ MeV$$

$\diamondsuit\ nj^P = 1\ \frac{3}{2}^+$:

Small width

S. Godfrey and R. Kokoski(1991)

$$D^{\star}_{s2}(1\ ^{\frac{3}{2}}P_2) \to D/D^{\star}K = 20/1.0\ \ MeV$$

M. Di Pierro and E. Eichten(2001)

$$\Gamma(D_s(1\ ^{\frac{3}{2}}P_{1/2})) = 2.0/10.9\ \ MeV$$

$\diamondsuit \; nj^P = 1\,\frac{3}{2}^-$:

M. Di Pierro and E. Eichten(2001)

$$D_s(1\;\tfrac{3}{2}D_1) \to D(1\;\tfrac{1}{2}S_{0/1})K = 26.1/10.7 \;\; MeV$$

$$D_s(1\;\tfrac{3}{2}D_1) \to D(1\;\tfrac{3}{2}P_1)K/D_s(1\;\tfrac{1}{2}S_0)\eta = 39.7/15.2 \;\; MeV$$

F.E. Close and E.S. Swanson(2005)

$$D_s(1\;{}^3D_1) \to D/D^\star K = 120/74 \;\; MeV$$

$$D_s(1\;{}^3D_1) \to D_s/D_s^\star\eta = 39/17 \;\; MeV$$

with $\Gamma_{total} = 331$ MeV

$\diamondsuit \ nj^P = 1\ \frac{5}{2}^-$:

M. Di Pierro and E. Eichten(2001), small width

$$D_s(1\ ^{\frac{5}{2}}D_3) \rightarrow D(1\ ^{\frac{1}{2}}S_{0/1})K = 11.4/7.3\ \ MeV$$

$$D_s(1\ ^{\frac{5}{2}}D_3) \rightarrow D_s(1\ ^{\frac{1}{2}}S_{0/1})\eta = 3.1/7.3\ \ MeV$$

F.E. Close and E.S. Swanson(2005), large width!

$$D_s(1\ ^3D_3) \rightarrow D/D^\star K = 82/67\ \ MeV$$

$$D_s(1\ ^3D_3) \rightarrow D_s/D_s^\star \eta = 4.5/2.2\ \ MeV$$

with $\Gamma_{total} = 222$ MeV

$\diamondsuit\ nj^p = 2\ \frac{1}{2}^-$:

M. Di Pierro and E. Eichten(2001), small width

$$D_s(2\ ^{\frac{1}{2}}S_0) \rightarrow D(1\ ^{\frac{1}{2}}S_1)K/D_s(1\ ^{\frac{1}{2}}S_1)\eta = 3.12/0.04 \quad MeV$$

$$D_s(2\ ^{\frac{1}{2}}S_1) \rightarrow D(1\ ^{\frac{1}{2}}S_{0/1})K = 21.1/12.2 \quad MeV$$

$$D_s(2\ ^{\frac{1}{2}}S_1) \rightarrow D_s(1\ ^{\frac{1}{2}}S_{0/1})\eta = 6.2/1.5 \quad MeV$$

F.E. Close and E.S. Swanson(2005), not small width!

$$D_s^{\star\prime}(2\ ^3S_1) \rightarrow D/D^\star K = 17/81 \quad MeV$$

$$D_s^{\star\prime}(2\ ^3S_1) \rightarrow D_s/D_s^\star\eta = 2.6/4.1 \quad MeV$$

with $\Gamma_{total} = 105$ MeV

$\diamondsuit\ nj^p = 2\ \frac{1}{2}^+$:

M. Di Pierro and E. Eichten(2001)

$$D_s(2\ ^{\frac{1}{2}}P_0) \longrightarrow D(1\ ^{\frac{1}{2}}S_0)K/D_s(1\ ^{\frac{1}{2}}S_0)\eta = 74.1/49.1\quad MeV$$

$$D_s(2\ ^{\frac{1}{2}}P_0) \longrightarrow D(1\ ^{\frac{1}{2}/\frac{3}{2}}P_1)K = 17.8/32.3\quad MeV$$

$$D_s(2\ ^{\frac{1}{2}}P_1) \longrightarrow D(1\ ^{\frac{1}{2}}S_1)K/D_s(1\ ^{\frac{1}{2}}S_1)\eta = 72.1/45.1\quad MeV$$

$$D_s(2\ ^{\frac{1}{2}}P_1) \longrightarrow D(1\ ^{\frac{1}{2}/\frac{3}{2}}P_1)K = 17.8/32.3\quad MeV$$

$$D_s(2\ ^{\frac{1}{2}}P_1) \longrightarrow D(1\ ^{\frac{1}{2}}P_{0/1})K = 42.6/28.7\quad MeV$$

$$D_s(2\ ^{\frac{1}{2}}P_1) \longrightarrow D(1\ ^{\frac{3}{2}}P_{1/2})K = 12.6/41.3\quad MeV$$

F.E. Close, C.E. Thomas, Olga Lakhina and E.S. Swanson, Phys. Lett. **B647**, 159(2007)

$$D_s(2\ ^3P_0) \rightarrow DK = 80 \ \ MeV$$
$$D_s(2\ ^3P_0) \rightarrow D_s\eta = 10 \ \ MeV$$

with $\Gamma_{total} = 90$ MeV

$\diamondsuit\ nj^p = 2\ \frac{3}{2}^+$

Small width

"New" D_s

So far, there seems no confusion for the charmed mesons $c\bar{q}$, but the case is different for the charmed strange mesons $c\bar{s}$

♠ $D^{\star}_{s0}(2317)^{\pm}$

$D^{\star}_{s0}(2317)^{\pm}$ was first observed by BaBar (PRL, **90**, 242001(2003)) in

$$D^{\star}_{s0}(2317) \to D_s^+\pi^0$$

with mass near $2.32\ GeV$

Confirmed by CLEO(PR, **D68**, 032002(2003)) and BELLE(PRL, **92**, 012002(2004))

PDG: 2317.8 ± 0.6 MeV, ≈ 40 MeV below DK threshold
full width $\Gamma < 3.8$ MeV at 95% confidence level
J, P need confirmation

$\diamondsuit$ Conventional $0^+(\frac{1}{2}^+)$ D_s:

Phys. Rev. Lett. **90**, 242001(2003) $\surd$

Lower mass? Narrower width? Isospin violation

W.A. Bardeen, E.J. Eichten and C.T. Hill, Phys. Rev. **D68**, 054024(2003) $\surd$

$\diamondsuit$ DK, $D\pi$ molecules:

T. Barnes, F.E. Close and H.J. Lipkin, Phys. Rev. **D 68**, 054006(2003) $\surd$

Electromagnetic decay mode $D_{s0/1} \longrightarrow D_s^\star\gamma$? Other partners($\approx$ 2500 MeV)?

♢ Baryonium:

V. Dmitrasinovic, Phys. Rev. **D70**, 096011(2004)

Yu-Qi Chen and Xue-Qian Li, Phys. Rev. Lett. **93**, 232001(2004)

Narrower width? Other partners?

♢ Coupled channels:

Eef van Beveren and George Rupp, Phys. Rev. Lett. **91**, 012003(2003)

♠ $D_{s1}(2460)^{\pm}$

$D_{s1}(2460)^{\pm}$ was first reported by CLEO(PR, **D68**, 032002(2003))

$$D_{s1}(2460)^{\pm} \longrightarrow D_s^{\star}\pi^0$$

Observed by BELLE(PRL, **92**, 012002(2004)) and BaBar(PR, **D69**, 031101(2004))

PDG: 2459.6 ± 0.6 MeV, ≈ 50 MeV below $D^{\star}K$ threshold

Full width $\Gamma < 3.5$ MeV at 95% CL

♢ Conventional $1^+(\frac{1}{2}^+)$ D_s:

Phys. Rev, **D68**, 032002(2003) $\surd$

Lower mass? Narrower width?

In the chiral quark model, the new observed $D^\star_{s0}(2317)^\pm$, $D_{s1}(2460)^\pm$ are suggested to be $(0^+, 1^+)$ states, the chiral doubler of $(0^-, 1^-)$ states: $D_s(1969)^\pm$ and $D^\star_s(2112)^\pm$. They have similar splitting ≈ 348 MeV:

$$D_{s1}(2460)^\pm - D^\star_s(2112)^\pm \approx D^\star_{s0}(2317)^\pm - D_s(1969)^\pm$$

Eur. Phys. J. **C32**, 493(2004) $\surd$

Strong OZI-allowed $^3P_0$ coupling to the nearby threshold

$\diamondsuit$ Baryonium:

V. Dmitrasinovic, Phys. Rev. **D70**, 096011(2004)

$\diamondsuit$ $\frac{1}{2}^+$ and $\frac{3}{2}^+$ mixing?

Width?

Relative branching ratio?

♠ $D_{s1}(2700)^{\pm}$

$D_{s1}(2700)^{\pm}$ was first observed by Belle (K. Abe, *et al.*, Belle Collaboration, hep-ex/0608031) in

$$B^+ \to \bar{D}^0 D_{s1} \to \bar{D}^0 D^0 K^+$$

with $M = 2715 \pm 11^{+11}_{-14}$ and $\Gamma = 115 \pm 20^{36}_{-32}$ MeV. The mass and the decay width change a little in their published version(J. Brodzicka *et al.*, Belle Collaboration, Phys. Rev. Lett. **100**, 092001 (2008))

$X(2690)$ was also reported by BaBar(B. Aubert, *et al.*, BaBar Collaboration, Phys. Rev. Lett. **97**, 222001 (2006)), but the significance of the signal was not stated!

$D_{s1}^{\star}(2710)^{+}$ was recently observed by BaBar (B. Aubert, *et al.*, BaBar Collaboration, Phys. Rev. **D80**, 092003(2009) in

$$e^{+} + e^{-} \rightarrow D_{s1}^{\star}(2710)^{+}X \rightarrow D^{\star}KX,$$

with mass and width

$$\begin{aligned} m(D_{s1}^{\star}(2710)^{+}) &= 2710 \pm 2_{stat}(^{+12}_{-7})_{syst}\ MeV, \\ \Gamma &= 149 \pm 7_{stat}(^{+39}_{-52})_{syst}\ MeV. \end{aligned}$$

PDG: 2690 ± 7 MeV

Full width: $\Gamma = 110 \pm 27$ MeV

$J^{p} = 1^{-}$

$\diamondsuit$ Conventional $1^-(2^3S_1)$ D_s:

F.E. Close, C.E. Thomas, O. Lakhina and E.S. Swanson, Phys. Lett. **B647**, 159 (2007)

Hong-Yun Shan and Ailin Zhang, Chin. Phys. **C34**, 1(2010)

Bing Chen, Deng-Xia Wang and Ailin Zhang, Phys. Rev. **D80**, 071502(R) (2009)

Mass $\surd$

Broader width?

$\diamondsuit$ Conventional $1^-(1^3D_1)$ D_s:

Bo Zhang, Xiang Liu, Wei-Zhen Deng and Shi-Lin Zhu, Eur. Phys. J. **C50**, 617 (2007)

Lower mass?

Broader width?

♢ Other interpretation?

♠ $D_{sJ}(2860)$

$D_{sJ}(2860)$ was first reported by BaBar(B. Aubert, *et al.*, BaBar Collaboration, Phys. Rev. Lett. **97**, 222001 (2006)) in

$$D_{sJ}(2860) \to D^0 K^+ \ , \ D^+ K_s^0$$

with $M = 2856.6 \pm 1.5(stat) \pm 5.0(syst)$ and $\Gamma = 48 \pm 7(stat) \pm 10(syst)$ MeV

Natural spin-parity: $J^P = 0^+, \ 1^-, \ \cdots$

The observation of $D_{sJ}(2860) \to D^\star K$ by BaBar rules out the possibility of 0^+

$D_{sJ}^{\star}(2860)^{+}$ was recently observed by BaBar (B. Aubert, *et al.*, BaBar Collaboration, Phys. Rev. **D80**, 092003(2009) in

$$e^{+} + e^{-} \rightarrow D_{sJ}^{\star}(2860)^{+} X \rightarrow D^{\star} K X,$$

with mass and width

$$\begin{aligned} m(D_{sJ}^{\star}(2860)^{+}) &= 2862 \pm 2_{stat} (^{+5}_{-2})_{syst}\ MeV, \\ \Gamma &= 48 \pm 3_{stat} \pm 6_{syst}\ MeV. \end{aligned}$$

Branching ratio

$$\frac{B(D_{sJ}^{\star}(2860)^{+} \rightarrow D^{\star} K)}{B(D_{sJ}^{\star}(2860)^{+} \rightarrow D K)} = 1.10 \pm 0.15_{stat} \pm 0.19_{syst}.$$

$\diamondsuit$ Conventional $0^+(2^3P_0)$ D_s:

Eef van Beveren and George Rupp, Phys. Rev. Lett. **97**(2006), 202001

Bo Zhang, Xiang Liu, Wei-Zhen Deng and Shi-Lin Zhu, Eur. Phys. J. **C50**, 617 (2007)

Width $\surd$

Lower mass?

$\diamondsuit$ Conventional $3^-(1^3D_3)$ D_s:

P. Colangelo,F.De. Fazio and S. Nicotri, Phys. lett. **B642**(2006), 48

Bo Zhang, Xiang Liu, Wei-Zhen Deng and Shi-Lin Zhu, Eur.

Phys. J. **C50**, 617 (2007)

Hong-Yun Shan and Ailin Zhang, Chin. Phys. **C34**, 1(2010)

Bing Chen, Deng-Xia Wang and Ailin Zhang, Phys. Rev. **D80**, 071502(R) (2009)

Mass $\surd$

Broader width?

$\diamondsuit$ Other interpretation:

♠ $D_{sJ}(2632)^+$

A surprisingly narrow charmed strange meson, $D_{sJ}(2632)^+$, was reported by SELEX (A. Evdokimov et al, SELEX Collaboration, Phys. Rev. Lett. **93**, 242001(2004)) some years ago in

$$D_{sJ}^+(2632) \to D_s^+\eta \;, \;\; D^0K^+$$

with $M = 2632.5 \pm 1.7(stat) \pm 5.0(syst)$ and $\Gamma < 17$ MeV with 90% confidence level

About 274 MeV and 116 MeV above D^0K^+ and $D_s\eta$ threshold

This state has an exotic relative branching ratio $\Gamma(D^0K^+)/\Gamma(D_s^+\eta) = 0.16 \pm 0.06$

The decay favors the $D_s\eta$ mode over the DK mode, but the two channels share the same quark flavors and phase space

It is not observed by BaBar, FOCUS or Belle, it seems that this state is excluded!

$\diamondsuit$ Conventional $1^-(2^3S_1)$ D_s:

Kuang-Ta Chao, Phys. Lett. **B599**,43(2004)

T. Barnes, F.E. Close, J.J. Dudek, S. Godfrey and E.S. Swanson, Phys. Lett. **B600**,223(2004)

Width $\surd$

Lower mass?

Ailin Zhang, Phys. Rev. **D72**, 017902(2005): it seems not a conventional $1^-(2^3S_1)$ D_s

$\diamondsuit$ Four-quark states:

$[cd][\bar{d}\bar{s}]$

L.Maiani, F. Piccinini, A.D. Polosa and V. Riquer, Phys. Rev. **D70**, 054009(2004)

$$\frac{1}{2\sqrt{2}}(ds\bar{d}+sd\bar{d}+su\bar{u}+us\bar{u}-2ss\bar{s})\bar{c}$$

Y.R. Liu, Shi-Lin Zhu, Y.B. Dai and C. Liu, Phys. Rev. **D70**, 094009(2004)

$\diamondsuit$ Conventional $1^- \ (1\ ^3D_1)\ D_s$:

Bing Chen, Deng-Xia Wang and Ailin Zhang, Phys. Rev. **D80**, 071502(R) (2009)

Mass $\surd$

Width $\surd$

♠ $D_{sJ}(3040)^+$

$D^{\star}_{sJ}(3040)^+$ was first observed by BaBar (B. Aubert, *et al.*, BaBar Collaboration, Phys. Rev. **D80**, 092003(2009) in

$$e^+ + e^- \to D^{\star}_{sJ}(3040)^+ X \to D^{\star} K X,$$

with mass and width

$$\begin{aligned} m(D^{\star}_{sJ}(3040)^+) &= 3044 \pm 8_{stat}(^{+30}_{-5})_{syst}\ MeV, \\ \Gamma &= 239 \pm 35_{stat} \pm (^{+46}_{-42})_{syst}\ MeV. \end{aligned}$$

The nonobservation of $D_{sJ}(3040)^+ \to DK$ and the angular analysis suggest an unnatural parity $J^P = 0^-,\ 1^+,\ 2^-,\ \cdots$

♢ Conventional $1^+(2\frac{1}{2}^+)$ D_s:

Bing Chen, Deng-Xia Wang and Ailin Zhang, Phys. Rev. **D80**, 071502(R) (2009)
Zhi-Feng Sun and Xiang Liu, Phys. Rev. **D80**, 074037 (2009)

♠ Regge trajectory on (L, M^2)-plots

S. Filipponi, G. Pancheri and Y. Srivastava, Phys. Rev. Lett. **80**, 1838(1998)

Ailin Zhang, Phys. Rev. **D72**, 017902(2005)

$$\alpha(m_1+m_2,t)=\alpha_I(m_1+m_2,0)+\alpha'(m_1+m_2)t, \quad (1)$$

where

$$\begin{aligned}\alpha_I(m_1+m_2,0) &= 0.57-\frac{(m_1+m_2)}{GeV}, \\ \alpha'(m_1+m_2) &= \frac{0.9\ GeV^{-2}}{[1+0.22(\frac{m_1+m_2}{GeV})^{3/2}]}\end{aligned} \quad (2)$$

♠ Semiclassic flux tube model:

Two masses m_1 and m_2 are connected by a flux tube or relativistic string with constant tension T rotating with angular momentum L. The flux tube or string carries both angular momentum and energy, and is responsible for the color confinement

D. Lacourse and M.G. Olsson, Phys. Rev. **D39**, 2751 (1989)

Alexander Selem and Frank Wilczek, hep-ph/0602128, Ringberg 2005, New trends in HERA physics, 337-356

Heavy-light system:

Hong-Yun Shan and Ailin Zhang, Chin. Phys. **C34**, 1(2010)

$$E = M + \sqrt{\frac{\sigma L}{2}} + 2^{\frac{1}{4}}\kappa L^{-\frac{1}{4}} m^{\frac{3}{2}} + a\vec{L}\cdot\vec{S} \qquad (3)$$

Bing Chen, Deng-Xia Wang and Ailin Zhang, Phys. Rev. **D80**, 071502(R) (2009)

$$E = M + \sqrt{\frac{\sigma L}{2}} + 2^{\frac{1}{4}}\kappa L^{-\frac{1}{4}} m^{\frac{3}{2}} + a\xi(L,S) \qquad (4)$$

where $\xi(L,S)$ is calculable coefficient from Schrödinger equation.

Spin-orbit interaction: $a\vec{L}\cdot\vec{S} \rightarrow a\xi(L,S)$

♠ Regge trajectory on (n, M^2)-plots

A.V. Anisovich, V.V. Anisovich, and A.V. Sarantsev, Phys. Rev. **D62**, 051502(R)(2000)

In the mass region up to $M < 2400$ MeV, radially excited mesons (trajectories on (n, M^2)-plots):

$$M^2 = M_0^2 + (n-1)\mu^2$$

where M_0 is the mass of basic meson, n is the radial quantum number, and μ^2 is the slope parameter of the trajectory(approximately the same for all trajectories)

♠ Interpretation of $D_{sJ}(2632)^+$, $D_{s1}(2700)^{\pm}$, $D_{sJ}(2860)$ and $D_{sJ}(3040)^+$

♢ $D_{sJ}(2632)^+$

If $D_{sJ}(2632)^+$ exists, it seems not the radially excited 1^- 2^3S_1 D_s

It is very possibly the orbitally excited 1^- (1^3D_1) D_s

♢ $D_{s1}(2700)^{\pm}$

$D_{s1}(2700)^{\pm}$ is very possibly the radially excited $1^-(2^3S_1)$ D_s!

$\diamondsuit$ $D_{sJ}(2860)$

If $D_{sJ}(2860)$ and its decay modes are confirmed by experiment, it must be the orbitally excited 3^- 1^3D_3 D_s! (no mixing)

$\diamondsuit$ $D_{sJ}(3040)^+$

$D_{sJ}(3040)^+$ is very likely the radially excited 1^+ $\frac{1}{2}^+$ D_s

♠ Implications of the interpretation of the "New" D_s

Ailin Zhang, **arXiv: 0904.2453**

♢ Partners of the D-wave 2^- D_s

2^- D_{s2}: $\approx 2700 - 2800$ MeV

♢ Partners of the radially excited D_s

0^- D'_s: ≈ 2600 MeV
1^+ D'_{s1}: ≈ 2970 MeV

♢ Higher excited D_s have lower masses (compared with most previous predictions)

Discussions and questions

♢ Conclusions

- D_s mesons seem to have different features from D (few data)! the truth? or the reason?

- It seems that the P-wave D_s mesons have been established

- It seems that the higher excited D_s have lower masses

- Mixing effects are important to both the mass and the width determination

♢ Discussions and questions

- Where are the orbitally excited D-wave and the radially excited D_s mesons (supernumerary)?
- Why do the higher excited D_s have lower masses?
- Are exotic explanations outside normal meson models necessary?
- What is the mechanism of mixing? How the mixing effects affect the mass and the width of D_s?
- Too many "seem"s, more experiments and theoretical studies required

Thank you!