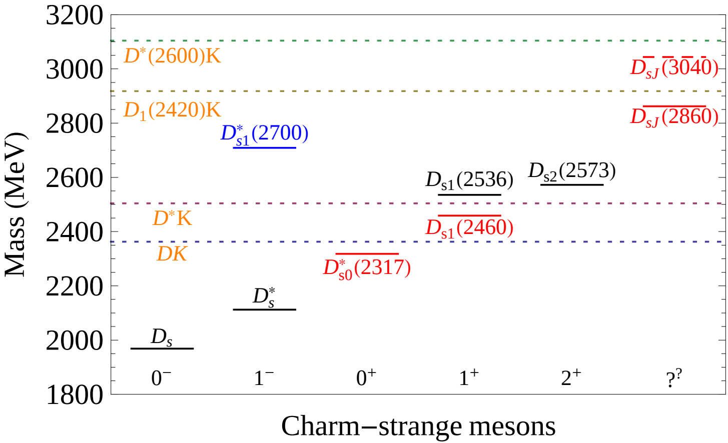
A comprehensive interpretation of the D_{sJ} states

Feng-Kun Guo

Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn

Hadron 2011, München, June 13-17, 2011

Based on: F.-K.G., U.-G. Meißner, **arXiv:1002.3536 [hep-ph]**



All are listed in PDG 2010

See F. De Fazio's talk.

$D_{s0}^*(2317)$, $D_{s1}(2460)$ and $D_{s1}^*(2700)$

$D_{s0}^*(2317)$ and $D_{s1}(2460)$: hadronic decay modes $D_s\pi^0$ and $D_s^*\pi^0$ break isospin symmetry

- Masses much lower than quark model predictions

	Measured mass (MeV)	Godfrey-Isgur quark model (MeV)
$D_{s0}^*(2317)$	2317.8 ± 0.6	2480
$D_{s1}(2460)$	2459.5 ± 0.6	2530, 2570

- They could be DK and D^*K bound states Barnes, Close, Lipkin, PRD68(2003)054006
  van Bevaren, Rupp, Kolomeistsev, Lutz, Hofmann, F.K.G., Shen, Gammermann, Oset, Faessler, Gutsche, ...

  Explains naturally why $M_{D^*} - M_D = M_{D_{s1}} - M_{D_{s0}^*}$ F.K.G., Hanhart, Meißner, PRL102(2009)242004

$D_{s0}^*(2317)$, $D_{s1}(2460)$ and $D_{s1}^*(2700)$

$D_{s0}^*(2317)$ and $D_{s1}(2460)$: hadronic decay modes $D_s\pi^0$ and $D_s^*\pi^0$ break isospin symmetry

- Masses much lower than quark model predictions

	Measured mass (MeV)	Godfrey-Isgur quark model (MeV)
$D_{s0}^*(2317)$	2317.8 ± 0.6	2480
$D_{s1}(2460)$	2459.5 ± 0.6	2530, 2570

- They could be DK and D^*K bound states — Barnes, Close, Lipkin, PRD68(2003)054006
  van Bevaren, Rupp, Kolomeistsev, Lutz, Hofmann, F.K.G., Shen, Gammermann, Oset, Faessler, Gutsche, ...

  Explains naturally why $M_{D^*} - M_D = M_{D_{s1}} - M_{D_{s0}^*}$ — F.K.G., Hanhart, Meißner, PRL102(2009)242004

$D_{s1}^*(2700)$: discovered by Belle in B decays $B^+ \to \bar{D}^0 DK$ — PRL100(2008)092001

- $M = 2709^{+9}_{-6}$ MeV, $\Gamma = 125 \pm 30$ MeV
- Decays into $DK \Rightarrow$ natural parity: positive (negative) parity for even (odd) spin
- Helicity angular distribution consistent with $J = 1 \Rightarrow J^P = 1^-$
- $\Gamma(D^*K)/\Gamma(DK) = 0.91 \pm 0.18$ — BABAR, PRD80(2009)092003

$D_{s0}^*(2317)$, $D_{s1}(2460)$ and $D_{s1}^*(2700)$

$D_{s0}^*(2317)$ and $D_{s1}(2460)$: hadronic decay modes $D_s\pi^0$ and $D_s^*\pi^0$ break isospin symmetry

- Masses much lower than quark model predictions

	Measured mass (MeV)	Godfrey-Isgur quark model (MeV)
$D_{s0}^*(2317)$	2317.8 ± 0.6	2480
$D_{s1}(2460)$	2459.5 ± 0.6	2530, 2570

- They could be DK and D^*K bound states — Barnes, Close, Lipkin, PRD68(2003)054006

  van Bevaren, Rupp, Kolomeistsev, Lutz, Hofmann, F.K.G., Shen, Gammermann, Oset, Faessler, Gutsche, ...

  Explains naturally why $M_{D^*} - M_D = M_{D_{s1}} - M_{D_{s0}^*}$ — F.K.G., Hanhart, Meißner, PRL102(2009)242004

$D_{s1}^*(2700)$: discovered by Belle in B decays $B^+ \to \bar{D}^0 DK$ — PRL100(2008)092001

- $M = 2709^{+9}_{-6}$ MeV, $\Gamma = 125 \pm 30$ MeV
- Decays into $DK \Rightarrow$ natural parity: positive (negative) parity for even (odd) spin
- Helicity angular distribution consistent with $J = 1 \Rightarrow J^P = 1^-$
- $\Gamma(D^*K)/\Gamma(DK) = 0.91 \pm 0.18$ — BABAR, PRD80(2009)092003

☞ Mass consistent with quark model prediction for the $2S\ 1^-$ state

2.73 GeV in Godfrey-Isgur quark model — S.Godfrey,N.Isgur,PRD32(1985)189

☞ Leading order HMChPT predicts for $2S\ 1^-$:

$\Gamma(D^*K)/\Gamma(DK) = 0.91 \pm 0.04$ — P.Colangelo et al.,PRD77(2008)014012

$D_{sJ}(2860)$ and $D_{sJ}(3040)$

Both discovered by BABAR. PRL97(2006)222001; PRD80(2009)092003

	$D_{sJ}(2860)$	$D_{sJ}(3040)$
Mass [width] (MeV)	$2862^{+5.4}_{-2.8}$ [48 ± 7]	3044^{+31}_{-9} [239 ± 60]
Decay modes	DK, D^*K	D^*K, so far not seen in DK
	$\Gamma(D^*K)/\Gamma(DK) = 1.10 \pm 0.24$	
Quantum numbers	natural parity	?

$D_{sJ}(2860)$ and $D_{sJ}(3040)$

Both discovered by BABAR. PRL97(2006)222001; PRD80(2009)092003

	$D_{sJ}(2860)$	$D_{sJ}(3040)$
Mass [width] (MeV)	$2862^{+5.4}_{-2.8}$ [48 ± 7]	3044^{+31}_{-9} [239 ± 60]
Decay modes	DK, D^*K	D^*K, so far not seen in DK
	$\Gamma(D^*K)/\Gamma(DK) = 1.10 \pm 0.24$	
Quantum numbers	natural parity	?

☞ LO HMChPT predictions: P.Colangelo et al.,PRD77(2008)014012

$D_{sJ}(2860)$	$D_{sJ}(2860) \to DK$	$\frac{\Gamma(D_{sJ}\to D^*K)}{\Gamma(D_{sJ}\to DK)}$
$s_\ell^P = \frac{1}{2}^-$, $J^P = 1^-$, $n = 1$	p-wave	1.23
$s_\ell^P = \frac{1}{2}^+$, $J^P = 0^+$, $n = 1$	s-wave	0
$s_\ell^P = \frac{3}{2}^+$, $J^P = 2^+$, $n = 1$	d-wave	0.63
$s_\ell^P = \frac{3}{2}^-$, $J^P = 1^-$, $n = 0$	p-wave	0.06
$s_\ell^P = \frac{5}{2}^-$, $J^P = 3^-$, $n = 0$	f-wave	0.39

☞ However, $(2S, 1^-)$ has been assigned to $D_{s1}^*(2700)$

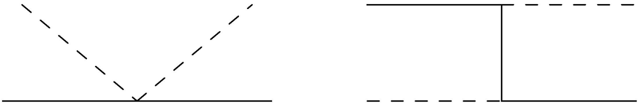
☞ $M(2P, 2^+) \sim 3.16$ GeV, $M(1F, 3^-) \sim 3.25$ GeV $\gg M[D_{sJ}(2860)]$

M.Di Pierro, E.Eichten, PRD64(2001)114004

☞ $n = 2, J^P_{s_\ell} = 1^+_{1/2}$ is the most possible assignment for $D_{sJ}(3040)$ in the $c\bar{s}$ picture.

P.Colangelo, F.De Fazio, PRD81(2010)094001

Resummation of the Weinberg-Tomozawa term



- Leading order interaction:
  - ☞ Weinberg-Tomozawa term: chiral symmetric kinetic term Burdman, Donoghue, Wise, Yan,...

$$-i\,\mathrm{Tr}[\bar{H}_a v\cdot D_{ba} H_b] \Rightarrow -\frac{i}{4F_\pi^2}\mathrm{Tr}[\bar{H}_a v_\mu H_b][\Phi, \partial^\mu \Phi]_{ba}$$

  - ☞ Heavy meson exchange: *S* wave projection vanishes or is tiny.

Resummation of the Weinberg-Tomozawa term

- Leading order interaction:
  - ☞ Weinberg-Tomozawa term: chiral symmetric kinetic term Burdman, Donoghue, Wise, Yan,...

$$-i\,\mathrm{Tr}[\bar{H}_a v\cdot D_{ba} H_b] \Rightarrow -\frac{i}{4F_\pi^2}\mathrm{Tr}[\bar{H}_a v_\mu H_b][\Phi,\partial^\mu\Phi]_{ba}$$

  - ☞ Heavy meson exchange: S wave projection vanishes or is tiny.
- Resummation: Oller, Oset, Pelaez, Meißner, ...

$$T(s) = V(s)[1-G(s)V(s)]^{-1}$$

$$G(s) = \frac{1}{16\pi^2 M}\left\{E_K\left[a(\mu)+\log\left(\frac{M_K^2}{\mu^2}\right)\right]+2|\vec{p}_K|\cosh^{-1}\left(\frac{E_K}{M_K}\right)-2\pi i|\vec{p}_K|\right\}$$

- Bound states and resonances as poles of the resummed amplitudes

  $D_{s0}^*(2317)$ is an S wave isoscalar DK bound state (using as an input to fix $a(\mu)$)

  $D_{s1}(2460)$ is an S wave isoscalar D^*K bound state

Narrow charmed mesons

Excited states have nonvanishing widths, invalidate the use of WT term?

The WT term can also be used for other narrow heavy hadrons, whose width is much smaller than the inverse of range of forces $\Gamma \ll M_\rho$ or more conservatively $2M_\pi$.

J^P	Nonstrange	Width (MeV)	Strange	Width (MeV)
0^-	D	0	D_s	0
1^-	D^*	0.1	D_s^*	< 1.9
1^+	$D_1(2420)$	20.4 ± 1.7	$D_{s1}(2536)$	< 2.3
2^+	$D_2^*(2460)$	42.9 ± 3.1	$D_{s2}^*(2573)$	20 ± 5
$0^-(2S)$	$D(2550)$	130 ± 18	$D_s(?)$	Not observed
$1^-(2S)$	$D^*(2600)$	93 ± 14	$D_{s1}^*(2700)$	125 ± 30

$D(2550)$ and $D^*(2600)$ were discovered in BABAR, PRD82(2010)111101R

Generated states

Constituents	DK	D^*K	$D_1(2420)K$	$D^*(2600)K$
J^P	0^+	1^+	1^-	1^+
Predictions	2317.8(input)	2458 ± 3	2870 ± 9	3052 ± 11
Data	2317.8 ± 0.6	2459.5 ± 0.6	$2862 \pm 2^{+5}_{-2}$	$3044 \pm 8^{+30}_{-5}$
Decays	$D_s\pi$	$D_s^*\pi$	$D^{(*)}K, D_s^{(*)}\eta$	$D^*K, D_s^*\eta, D_s\omega, DK^*, D\phi$

Generated states

Constituents	DK	D^*K	$D_1(2420)K$	$D^*(2600)K$
J^P	0^+	1^+	1^-	1^+
Predictions	2317.8(input)	2458 ± 3	2870 ± 9	3052 ± 11
Data	2317.8 ± 0.6	2459.5 ± 0.6	$2862 \pm 2^{+5}_{-2}$	$3044 \pm 8^{+30}_{-5}$
Decays	$D_s\pi$	$D_s^*\pi$	$D^{(*)}K, D_s^{(*)}\eta$	$D^*K, D_s^*\eta, D_s\omega, DK^*, D\phi$

Heavy flavor hadronic molecules should have their spin partners

Spin partners of the $D_{sJ}(2860)$ and $D_{sJ}(3040)$:

Constituents	$D_2(2460)K$	$D(2550)K$
J^P	2^-	0^+
Predictions	2910 ± 9	2984 ± 10
Data	?	?
Decays	$D^*K, D_s^*\eta$	$DK, D_s\eta$

Generated states

Constituents	DK	D^*K	$D_1(2420)K$	$D^*(2600)K$
J^P	0^+	1^+	1^-	1^+
Predictions	2317.8(input)	2458 ± 3	2870 ± 9	3052 ± 11
Data	2317.8 ± 0.6	2459.5 ± 0.6	$2862 \pm 2^{+5}_{-2}$	$3044 \pm 8^{+30}_{-5}$
Decays	$D_s\pi$	$D_s^*\pi$	$D^{(*)}K, D_s^{(*)}\eta$	$D^*K, D_s^*\eta, D_s\omega, DK^*, D\phi$

Heavy flavor hadronic molecules should have their spin partners

Spin partners of the $D_{sJ}(2860)$ and $D_{sJ}(3040)$:

Constituents	$D_2(2460)K$	$D(2550)K$
J^P	2^-	0^+
Predictions	2910 ± 9	2984 ± 10
Data	?	?
Decays	$D^*K, D_s^*\eta$	$DK, D_s\eta$

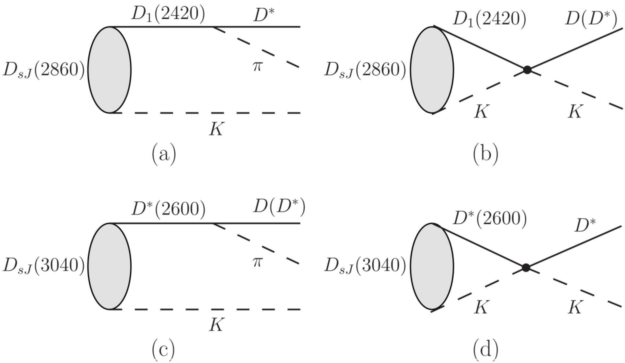
Very important question:

Can we understand the decay patterns of $D_{sJ}(2860)$ and $D_{sJ}(3040)$?

Decays of $D_{sJ}(2860)$ and $D_{sJ}(3040)$

Sequential decays

Rescattering



Decays of $D_{sJ}(2860)$ and $D_{sJ}(3040)$: qualitative features

- Three-body decays are suppressed:
  - $D_{sJ}(2860) \to D_1(2420)K \to D^*\pi K$: $D_1(2420) \to D^*\pi$ is in a D wave.
    $[s_\ell^P = \frac{3}{2}^+$ couples to $s_\ell^P = \frac{1}{2}^-(D^*)$ and $J^P = 0^-(\pi)]$
  - $D_{sJ}(3040) \to D^*(2600)K \to D^{(*)}\pi K$: $D^*(2600) \to D^{(*)}\pi$ is in a P wave.
    $[s_\ell^P = \frac{1}{2}^-$ couples to $s_\ell^P = \frac{1}{2}^-(D^{(*)})$ and $J^P = 0^-(\pi)]$
  - Three-body phase space

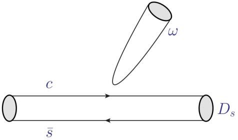
Decays of $D_{sJ}(2860)$ and $D_{sJ}(3040)$: qualitative features

- Three-body decays are suppressed:
  - $D_{sJ}(2860) \to D_1(2420)K \to D^*\pi K$: $D_1(2420) \to D^*\pi$ is in a D wave.
    [$s_\ell^P = \frac{3}{2}^+$ couples to $s_\ell^P = \frac{1}{2}^-(D^*)$ and $J^P = 0^-(\pi)$]
  - $D_{sJ}(3040) \to D^*(2600)K \to D^{(*)}\pi K$: $D^*(2600) \to D^{(*)}\pi$ is in a P wave.
    [$s_\ell^P = \frac{1}{2}^-$ couples to $s_\ell^P = \frac{1}{2}^-(D^{(*)})$ and $J^P = 0^-(\pi)$]
  - Three-body phase space
- $\Gamma[D_{sJ}(3040)] \gg \Gamma[D_{sJ}(2860)]$ Data: 239 ± 60 MeV $\gg 48 \pm 7$ MeV
  - $J^P = 1^+, \quad D_{sJ}(3040) \to D^*P, DV \quad : \quad$ S wave
  - $J^P = 1^-, \quad D_{sJ}(2860) \to D^*P, DP \quad : \quad$ P wave

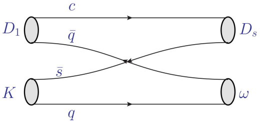
- Three-body decays are suppressed:
  - ☞ $D_{sJ}(2860) \to D_1(2420)K \to D^*\pi K$: $D_1(2420) \to D^*\pi$ is in a D wave.
    $[s_\ell^P = \frac{3}{2}^+$ couples to $s_\ell^P = \frac{1}{2}^-(D^*)$ and $J^P = 0^-(\pi)]$
  - ☞ $D_{sJ}(3040) \to D^*(2600)K \to D^{(*)}\pi K$: $D^*(2600) \to D^{(*)}\pi$ is in a P wave.
    $[s_\ell^P = \frac{1}{2}^-$ couples to $s_\ell^P = \frac{1}{2}^-(D^{(*)})$ and $J^P = 0^-(\pi)]$
  - ☞ Three-body phase space
- $\Gamma[D_{sJ}(3040)] \gg \Gamma[D_{sJ}(2860)]$ Data: 239 ± 60 MeV $\gg 48 \pm 7$ MeV
  - ☞ $J^P = 1^+, \quad D_{sJ}(3040) \to D^*P, DV \;:\;$ S wave
  - ☞ $J^P = 1^-, \quad D_{sJ}(2860) \to D^*P, DP \;:\;$ P wave
- $D_{sJ}(3040)$ with $J^P = 1^+$ cannot decay into DK
  (so far observed only in D^*K)

Decays of $D_{sJ}(2860)$ and $D_{sJ}(3040)$: qualitative features

- Three-body decays are suppressed:
  - ☞ $D_{sJ}(2860) \to D_1(2420)K \to D^*\pi K$: $D_1(2420) \to D^*\pi$ is in a D wave. $[s_\ell^P = \frac{3}{2}^+$ couples to $s_\ell^P = \frac{1}{2}^-(D^*)$ and $J^P = 0^-(\pi)]$
  - ☞ $D_{sJ}(3040) \to D^*(2600)K \to D^{(*)}\pi K$: $D^*(2600) \to D^{(*)}\pi$ is in a P wave. $[s_\ell^P = \frac{1}{2}^-$ couples to $s_\ell^P = \frac{1}{2}^-(D^{(*)})$ and $J^P = 0^-(\pi)]$
  - ☞ Three-body phase space
- $\Gamma[D_{sJ}(3040)] \gg \Gamma[D_{sJ}(2860)]$ Data: 239 ± 60 MeV $\gg 48 \pm 7$ MeV
  - ☞ $J^P = 1^+, \quad D_{sJ}(3040) \to D^*P, DV \;:\;$ S wave
  - ☞ $J^P = 1^-, \quad D_{sJ}(2860) \to D^*P, DP \;:\;$ P wave
- $D_{sJ}(3040)$ with $J^P = 1^+$ cannot decay into DK (so far observed only in D^*K)
- $D_s\omega$ is a signature channel of non-$c\bar{s}$ nature of the $D_{sJ}(3040)$.
  - ☞ $c\bar{s} \to D_s\omega$: disconnected, OZI violating.



  - ☞ $D^*(2600)K \to D_s\omega$: OZI allowed.



Decays of $D_{sJ}(2860)$ and $D_{sJ}(3040)$: quantitative predictions

General structure of the *P*-wave decay amplitudes:

$$\begin{aligned} \mathcal{M}(D_{sJ}(2860) \to DK) &= g_D G_{D_1 K} \vec{\varepsilon}_{D_{sJ}} \cdot \vec{k}_D, \\ \mathcal{M}(D_{sJ}(2860) \to D^* K) &= g_{D^*} G_{D_1 K} \epsilon^{ijk} k^i_{D^*} \varepsilon^j_{D_{sJ}} \varepsilon^{*k}_{D^*} \end{aligned}$$

Heavy quark spin symmetry $\Rightarrow$

$$\begin{aligned} R_{D_{sJ}(2860)} &= 2 \frac{M_{D^*}}{M_D} \left| \frac{\vec{k}_{D^*}}{\vec{k}_D} \right|^3 \\ &= 1.23 \end{aligned}$$

Data $\quad 1.10 \pm 0.24 \quad$ Amazing agreement!

Predictions for the spin partners:

$$\frac{\Gamma_{D^*_{s2}(2910)}}{\Gamma_{D_{sJ}(2860)}} \simeq 0.2, \qquad \frac{\Gamma_{D^*_{s0}(2985)}}{\Gamma_{D_{sJ}(3040)}} < 1$$

Summary

- Assuming dominance of the WT term for interaction between light pseudoscalar mesons and narrow heavy mesons, a family of kaonic bound states can be generated.
- Wonderful agreement with both the mass and decay pattern of $D_{sJ}(2860)$ supports strongly the $D_1(2420)K$ bound state interpretation
- $D_s\omega$ can be used to distinguish the hadronic molecular picture of the $D_{sJ}(3040)$ from the $c\bar{s}$ one.
- Their spin partners and more states are predicted:

Constituents	$\bar{B}K$	$\bar{B}^*K$	$\bar{B}_1(5720)K$	$\bar{B}_2(5747)K$
J^P	0^+	1^+	1^-	2^-
Predicted masses	5705 ± 31	5751 ± 32	6151 ± 33	6169 ± 33
Dominant decays	$\bar{B}_s\pi$	$\bar{B}_s^*\pi$	$\bar{B}^{(*)}K, \bar{B}_s^{(*)}\eta$	$\bar{B}^*K, \bar{B}_s^*\eta$

Heavy quark spin symmetry

For a heavy quark, spin-dependent quark gluon interaction suppressed by $1/m_Q$

$\Rightarrow$ heavy quark spin symmetry

- The heavy quark spin and the total momentum of light degrees of freedom s_ℓ ($\vec{s}_\ell = \vec{s} + \vec{l}$) are conserved in the heavy quark limit $m_Q \to \infty$
- Heavy hadrons can be classified as spin multiplets

s_ℓ^P	$n\,^{2s+1}l_J$	J^P	Nonstrange	Strange	Nonstrange decays
$\frac{1}{2}^-$	$1\,^1S_0$	0^-	D	D_s	Weak
	$1\,^3S_1$	1^-	D^*	D_s^*	$D\pi$ P wave; radiative
	$2\,^1S_0$	0^-	$D(2550)$	?	$D^*\pi$ P wave
	$2\,^3S_1$	1^-	$D^*(2600)$	$D_{s1}^*(2700)$	$D^{(*)}\pi$ P wave
$\frac{1}{2}^+$	$1\,^3P_0$	0^+	$D_0^*(2400)$	?	$D\pi$ S wave
	$1\,^3P_1$(mixing)	1^+	$D_1(2430)$	?	$D^*\pi$ S wave
$\frac{3}{2}^+$	$1\,^1P_1$(mixing)	1^+	$D_1(2420)$	$D_{s1}(2536)$	$D^*\pi$ D wave
	$1\,^3P_2$	2^+	$D_2^*(2460)$	$D_{s2}^*(2573)$	$D\pi$ D wave