Systematic study of the heavy-light meson spectrum

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Outline

- Mass loaded flux tube model
- Spectrum of heavy-light mesons
- Some new observations
- Conclusions and discussions

Mass loaded flux tube model

Hadron spectroscopy, Heavy-light meson spectrum

- Relativized quark model: S. Godfrey and N.Isgur, Phys. Rev. **D32**, 189 (1985)
- Heavy quark symmetry theory: E.J. Eichten, C.T. Hill and C. Quigg, Phys. Rev. Lett. **71**, 4116(1993)
- Relativistic quark model: 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: M.Di Pierro and E. Eichten, Phys. Rev. **D64**, 114004 (2001)

- Other models:
  W.A. Bardeen, E.J. Eichten and C.T. Hill, Phys. Rev. **D68**, 054024 (2003) (chiral+relativstic);
  Eef van Beveren and George Rupp, Phys. Rev. Lett. **91**, 012003(2003); Eef van Beveren and George Rupp, Phys. Rev. Lett. **93**, 202001(2004); Eef van Beveren and George Rupp, Phys. Rev. Lett. **97**, 202001 (2006) (coupled channel);
  J. Erdmenger, N. Evans and J. Grosse, **JHEP** 0701, 098 (2007) (ADS/CFT)

Computation of the meson spectrum of higher orbital excitation is a challenge!

Idea

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

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

Meson: quark m_1 and anti-quark m_2

Baryon: quark m_1 and diquark m_2

For light systems (mesons and baryons), an approximate mass

$$E \approx \sqrt{\sigma L} + \kappa L^{-\frac{1}{4}} \mu^{\frac{3}{2}}, \tag{1}$$

where L is the orbital angular momentum, and $\frac{\sigma}{2\pi}$ is the string tension. $\kappa \equiv \frac{2}{3}\frac{\pi^{\frac{1}{2}}}{\sigma^{\frac{1}{4}}}$, and $\mu^{\frac{3}{2}} \equiv m_1^{\frac{3}{2}} + m_2^{\frac{3}{2}}$.

For heavy-light systems, the energy E

$$E = M + \sqrt{\frac{\sigma L}{2}} + 2^{\frac{1}{4}} \kappa L^{-\frac{1}{4}} m^{\frac{3}{2}}, \tag{2}$$

M: heavy quark mass

m: $m_u = m_d$, m_s, $m_{[ud]}$, light quark/diquark mass

♠ Charmed mesons and baryons: three and a half lines in their original work:

"We will discuss this subject in more detail elsewhere. Existing data is sparse,but certainly consistent with the ideas discussed here. For example, the series $\Lambda_c(2285)$, $\Lambda_c(2625)$, $\Lambda_c(2880)$ at $J^P = \frac{1}{2}^+, \frac{3}{2}^-, \frac{5}{2}^+$ is well fit using the mass-loaded string formulae with $M_c = 1600$, $m_{[ud]} = 180$ MeV^2, and $\sigma = .974$ GeV^2"

No "elsewhere" yet!

♠ Problems

- Spin-Orbit forces were ignored!
- Heavy-light systems were not analyzed!
- Good diquark-antiquark degeneracy hypothesis?

♠ Improvements

Spin-Orbit forces

A. De. Rujula, H. Georgi and S. L. Glashow, Phys. Rev. **D12**, 147 (1977)

E. Eichten, K. Gottfried, T. Kinoshita, K.D. Lane and Tung-Mow Yan, Phys. Rev. **D 17**, 3090 (1978); Erratum-ibid. **D21**, 313 (1980)

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

T. Barnes, F. E. Close, P. R. Page and E.S. Swanson, Phys. Rev. **D 55**, 4157 (1997)

Spin-orbit interaction: color-magnetic piece + Thomas-procession piece

Spin-Orbital correction is dominant

Spin-orbit interaction $\approx a\vec{L}\cdot\vec{S}$

- Spin-triplet and spin-singlet hyperfine splitting relation!

$$\Delta M_{hf}(1P) =< M(1^3P_J) > -M(1^1P_1) \approx 0,$$
$$\Delta M_{hf}(1D) =< M(1^3D_J) > -M(1^1D_2) \approx 0,$$

- experimental data of charmonium and D mesons!

- Our results!

Heavy quark symmetry: j^P

Spin-orbit interaction $\approx a\vec{l}\cdot\vec{s}$? our analysis: $\times$

- Experimental data of D mesons!

- Spin-orbit inversion!

♠ Heavy quark symmetry seems a little difficult to be accommodated in the present flux tube picture in a simple way.
Open question!

Spectrum of heavy-light mesons

Hong-Yun Shan and Ailin Zhang, arXiv: 0805.4764 [hep-ph]

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

a: fitted constant, S: Spin

$M_c = 1.6$ GeV $\sigma = 0.974$ GeV^2

Good diquark-antiquark degeneracy hypothesis:
$m_{u,d} = m_{[ud]} = 180$ MeV

1^1P_1 charmed meson: 2.406 GeV $\approx D_1(2430)^0$

Other charmed and charmed strange mesons: $a = 24.6$ MeV, $m_s = 320$ MeV.

- charmed mesons and baryons are successfully described by the same formula and parameters!

- Good diquark-antiquark degeneracy hypothesis!

  σ is a little different!(spin-orbit interaction?)

♠ Prescription:

Charmed mesons (four $1P$ charmed mesons)$\rightarrow$ parameters ($\sigma = 1.10$ GeV^2, $a = 37.9$ MeV) $\rightarrow$ $1D$ and $1F$ charmed mesons

Parameters of charmed mesons ($\sigma = 1.10$ GeV^2, $a = 37.9$ MeV)+charmed strange mesons ($D_{s1}(2536)^{\pm}$ and $D_{s2}(2573)^{\pm}$)$\rightarrow$ parameter $m_s = 288$ MeV $\rightarrow$ charmed strange mesons ($1P$, $1D$, $1F$)

Candidates(PDG)	J^P	j^P	$n^{2S+1}L_J$	GI	PE	our paper
D^0	0^-	$\frac{1}{2}^-$	1^1S_0	1.88	1.868	-
$D^\star(2007)^0$	1^-	$\frac{1}{2}^-$	1^3S_1	2.04	2.005	-
$D_0^\star(2400)^0$	0^+	$\frac{1}{2}^+$	1^3P_0	2.40	2.377	2.370
$D_1(2420)^0$	1^+	$\frac{1}{2}^+$	1^3P_1	2.49	2.417	2.408
$D_1(2430)^0$	1^+	$\frac{3}{2}^+$	1^1P_1	2.44	2.49	2.446
$D_2^\star(2460)^0$	2^+	$\frac{3}{2}^+$	1^3P_2	2.50	2.46	2.484
?	1^-	$\frac{3}{2}^-$	1^3D_1	2.82	2.775	2.623
?	2^-	$\frac{3}{2}^-$	1^3D_2	-	2.795	2.699
?	2^-	$\frac{5}{2}^-$	1^1D_2	-	2.799	2.737
?	3^-	$\frac{5}{2}^-$	1^3D_3	2.83	2.833	2.775

Tab. 1: Spectrum of charmed mesons(GeV) with parameters $\sigma = 1.10$ GeV^2, $m_c = 1.6$ GeV, $m_{u,d} = 180$ MeV and $a = 37.9$ MeV.

Candidates(PDG)	J^P	j^P	$n^{2S+1}L_J$	GI	PE	our paper
?	2^+	$\frac{5}{2}^+$	1^3F_2	-	-	2.812
?	3^+	$\frac{5}{2}^+$	1^3F_3	-	-	2.926
?	3^+	$\frac{7}{2}^+$	1^1F_3	-	-	2.964
?	4^+	$\frac{7}{2}^+$	1^3F_4	3.11	-	3.078

Spectrum of charmed mesons(GeV)

Candidates(PDG)	J^P	j^P	$n^{2S+1}L_J$	GI	PE	our paper
$D_s^{\pm}(1969)$	0^-	$\frac{1}{2}^-$	1^1S_0	1.98	1.965	-
$D_s^{\star\pm}(2112)^0$	1^-	$\frac{1}{2}^-$	1^3S_1	2.13	2.113	-
$D_{s0}^{\star}(2317)^{\pm}$	0^+	$\frac{1}{2}^+$	1^3P_0	2.48	2.487	2.478
$D_{s1}(2536)^{\pm}$	1^+	$\frac{1}{2}^+$	1^3P_1	2.57	2.535	2.516
$D_{s1}(2460)^{\pm}$	1^+	$\frac{3}{2}^+$	1^1P_1	2.53	2.605	2.554
$D_{s2}(2573)^{\pm}$	2^+	$\frac{3}{2}^+$	1^3P_2	2.59	2.581	2.592
$D_{sJ}(2700)$	1^-	$\frac{3}{2}^-$	1^3D_1	2.90	2.900	2.714
?	2^-	$\frac{3}{2}^-$	1^3D_2	-	2.913	2.789
?	2^-	$\frac{5}{2}^-$	1^1D_2	-	2.925	2.827
$D_{sJ}(2860)$	3^-	$\frac{5}{2}^-$	1^3D_3	2.92	2.953	2.865

Tab. 2: Spectrum of charmed strange mesons(GeV) with parameters $\sigma = 1.10$ GeV^2, $m_c = 1.6$ GeV, $m_s = 288$ MeV and $a = 37.9$ MeV.

Candidates(PDG)	J^P	j^P	$n^{2S+1}L_J$	GI	PE	our paper
?	2^+	$\frac{5}{2}^+$	1^3F_2	-	-	2.894
?	3^+	$\frac{5}{2}^+$	1^3F_3	-	-	3.008
?	3^+	$\frac{7}{2}^+$	1^1F_3	-	-	3.046
?	4^+	$\frac{7}{2}^+$	1^3F_4	3.19	-	3.160

Spectrum of charmed strange mesons(GeV).

GI: S. Godfrey and N. Isgur, Phys. Rev. D32: 189(1985); Relativized quark model

PE: M.Di Pierro and E. Eichten, Phys. Rev. D64: 114004(2001); Chiral quark model

PDG: W.-M.Yao, *et al.*, J. Phys. **G33**, 1 (2006).

String tension: $\frac{\sigma}{2\pi} = 0.175$ GeV^2, reasonable!

Uncertainty of experiments: several MeV $\rightarrow 50$ MeV

Assuming each $1P$: ± 30 MeV

$1D$: ± 44 MeV
$1F$: ± 54 MeV

♠ Our results:

- $1P$: comparable with other theoretical predictions and experiments
- $1D$: much lower in comparison with other theoretical predictions
- $1F$: new predictions
- $D_{s0}^{\star}(2317)^{\pm}$, $D_{s1}(2460)^{\pm}$
- $D_{sJ}(2700)$, $D_{sJ}(2860)$

Mesons with b quark are in preparation!

Some new observations

♠ $D_{sJ}(2700)$

K. Abe, et al., Belle Collaboration, hep-ex/0608031

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

with $M = 2715 \pm 11^{+11}_{-14}$ and $\Gamma = 115 \pm 20^{36}_{-32}$ MeV

J. Brodzicka et al., Belle Collaboration, Phys. Rev. Lett. **100**, 092001(2008)

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

with $M = 2708 \pm 9^{+11}_{-10}$ and $\Gamma = 108 \pm 23^{36}_{-31}$ MeV

$J^P = 1^-$, 2^3S_1

Possible explanations:

- $c\bar{s}$, mixture of 2^3S_1 and 1^3D_1; F.E. Close, C.E. Thomas, O. Lakhina and E.S. Swanson, Phys. Lett. B647: 159(2007)

- $1^-(1^3D_1)$, Bo Zhang, Xiang Liu, Wei-Zhen Deng and Shi-Lin Zhu, Eur. Phys. J. C50: 617(2007)

♠ $D_{SJ}(2860)$

B. Aubert, et al, BABAR Collaboration, Phys. Rev. Lett. **97**, 222001 (2006)

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

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: $J^P = 0^0, \ 1^-, \ \cdots$

Possible explanations:

- First radial excitation of the $D^{\star}_{s0}(2317)$; E. Beveren and G. Rupp, Phys. Rev. Lett. 97: 202001(2006)
- 3^- $\frac{5}{2}^-$ $c\bar{s}$; P. Colangelo,F.De. Fazio and S. Nicotri, Phys. lett. **B642**, 48 (2006)
- $c\bar{s}(2p)$; F.E. Close, C.E. Thomas, O. Lakhina and E.S. Swanson, Phys. Lett. B647: 159(2007)
- $0^+(2^3P_0)$ or $3^-(1^3D_3)$, unlikely $1^-(2^3S_1)$ and $1^-(1^3D_1)$, Bo Zhang, Xiang Liu, Wei-Zhen Deng and Shi-Lin Zhu, Eur. Phys. J. C50: 617(2007)

♠ $X(2690)$

B. Aubert, et al, BABAR Collaboration, Phys. Rev. Lett. **97**, 222001 (2006)

Broad enhancement: not possible to associate with any known reflection or background

$$X(2690) \to D^0 K^+ \ , \ D^+ K_s^0$$

with $M = 2688 \pm 4(stat) \pm 3(syst)$ and $\Gamma = 112 \pm 7(stat) \pm 36(syst)$ MeV

Conclusions and discussions

Conclusions:

* Semi-classical mass loaded flux tube
  Simple model, predictable!
  4 parameters $\longrightarrow$ charmed mesons
* $1P$: comparable with other models
* $1D$: much lower

* Other two $1D$ $c\bar{s}/\bar{c}s$ mesons:
  ≈ 2800 MeV, **Where?**

* $D^{\star}_{s0}(2317)^{\pm}$? 1^3P_0
  $D_{s1}(2460)^{\pm}$? 1^1P_1

* $D_{sJ}(2700) \approx 1^3D_1$
  $D_{sJ}(2860) \approx 1^3D_3$

Heavy-light baryons are under analysis

Discussions:

* Heavy quarkonium?
* radial excitation?
* mixing?
* production and decays?

Thank you!