The Hadronic Molecular Interpretation of some Exotic States

——The meson sector ——

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OUTLINE

1. Introduction
2. Hadronic Molecular Candidates
3. Compositeness Condition
4. Hadronic Molecule Interpretation for $D_{s0}^{*+}(2317)$
5. Conclusions

Introduction

♠ The constituent quark model provides a convenient framework for the classification of hadrons and most of the experimentally observed hadron states fit into this scheme quite nicely.

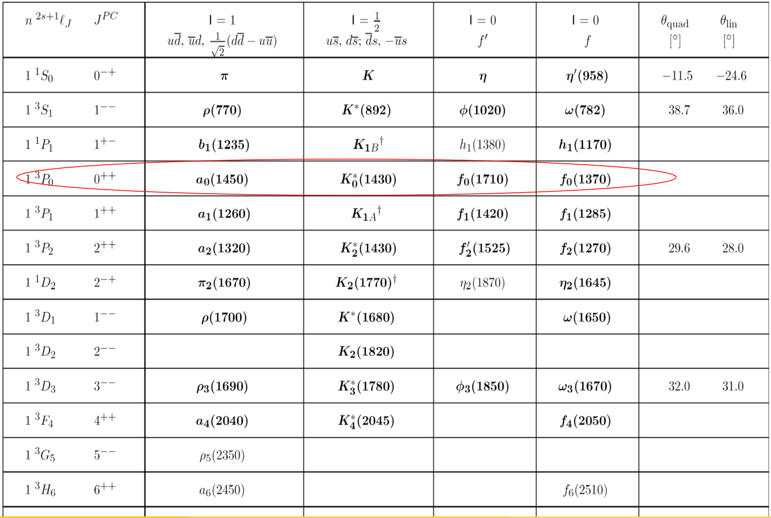
♠ In QM, mesons are $q\bar{q}'$ bound states. The parity is $P = (-1)^{l+1}$, the meson spin is given by $|l - s| \leq J \leq |l + s|$, the charged parity $C = (-1)^{l+s}$ is defined for $q\bar{q}$.

♠ Mesons are classified in J^{PC} multiplets.
$l = 0$ for pseudoscalar mesons and vector mesons.
$l = 1$ for scalar mesons, axialvector mesons and tensor mesons.

♠ States with natural spin-parity series $P = (-1)^J$ must have $CP = +1$. Thus mesons with natural spin-parity and $CP = -1$ $(0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}$, etc) are forbidden. The $J^{PC} = 0^{--}$ is forbidden as well. Mesons with such exotic quantum numbers maybe exist but would lie outside the $q\bar{q}'$ model.

Introduction

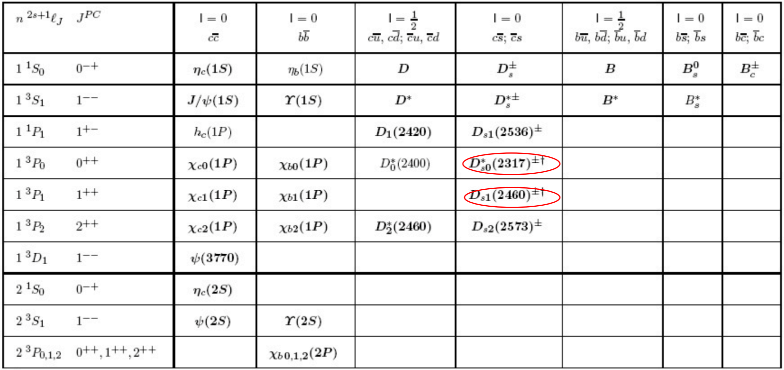
Figure 1: Quark model classification for some of the $q\bar{q}'$ states.
The light scalar meson a_0, f_0 and σ are not included.
The nature of the $f_0(1710)$ and $f_0(1370)$ is still subject to debate.



$n\ {}^{2s+1}\ell_J$	J^{PC}	I = 1 $u\bar{d}$, $\bar{u}d$, $\frac{1}{\sqrt{2}}(d\bar{d}-u\bar{u})$	I = $\frac{1}{2}$ $u\bar{s}$, $d\bar{s}$; $\bar{d}s$, $-\bar{u}s$	I = 0 f'	I = 0 f	$\theta_{\rm quad}$ [°]	$\theta_{\rm lin}$ [°]
$1\ {}^1S_0$	0^{-+}	π	K	η	$\eta'(958)$	-11.5	-24.6
$1\ {}^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$	38.7	36.0
$1\ {}^1P_1$	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1380)$	$h_1(1170)$		
$1\ {}^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$		
$1\ {}^3P_1$	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$	$f_1(1420)$	$f_1(1285)$		
$1\ {}^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$	29.6	28.0
$1\ {}^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$		
$1\ {}^3D_1$	1^{--}	$\rho(1700)$	$K^*(1680)$		$\omega(1650)$		
$1\ {}^3D_2$	2^{--}		$K_2(1820)$				
$1\ {}^3D_3$	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$	32.0	31.0
$1\ {}^3F_4$	4^{++}	$a_4(2040)$	$K_4^*(2045)$		$f_4(2050)$		
$1\ {}^3G_5$	5^{--}	$\rho_5(2350)$					
$1\ {}^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$		

Introduction

Figure 2: Quark model classification for some of the $q\bar{q}'$ states. The masses of D_{s0}^{*+} and D_{s1}^{+} are considerably smaller than most theoretical predictions. They have also been regarded as non-$q\bar{q}'$ states.



$n\ ^{2s+1}\ell_J$	J^{PC}	$\mathrm{I}=0$ $c\bar{c}$	$\mathrm{I}=0$ $b\bar{b}$	$\mathrm{I}=\frac{1}{2}$ $c\bar{u}$, $c\bar{d}$; $\bar{c}u$, $\bar{c}d$	$\mathrm{I}=0$ $c\bar{s}$; $\bar{c}s$	$\mathrm{I}=\frac{1}{2}$ $b\bar{u}$, $b\bar{d}$; $\bar{b}u$, $\bar{b}d$	$\mathrm{I}=0$ $b\bar{s}$; $\bar{b}s$	$\mathrm{I}=0$ $b\bar{c}$; $\bar{b}c$
$1\ ^1S_0$	0^{-+}	$\eta_c(1S)$	$\eta_b(1S)$	D	$D_s^\pm$	B	B_s^0	$B_c^\pm$
$1\ ^3S_1$	1^{--}	$J/\psi(1S)$	$\Upsilon(1S)$	D^*	$D_s^{*\pm}$	B^*	B_s^*	
$1\ ^1P_1$	1^{+-}	$h_c(1P)$		$D_1(2420)$	$D_{s1}(2536)^\pm$			
$1\ ^3P_0$	0^{++}	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$D_0^*(2400)$	$D_{s0}^*(2317)^{\pm\dagger}$			
$1\ ^3P_1$	1^{++}	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$		$D_{s1}(2460)^{\pm\dagger}$			
$1\ ^3P_2$	2^{++}	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$D_2^*(2460)$	$D_{s2}(2573)^\pm$			
$1\ ^3D_1$	1^{--}	$\psi(3770)$						
$2\ ^1S_0$	0^{-+}	$\eta_c(2S)$						
$2\ ^3S_1$	1^{--}	$\psi(2S)$	$\Upsilon(2S)$					
$2\ ^3P_{0,1,2}$	$0^{++}, 1^{++}, 2^{++}$		$\chi_{b0,1,2}(2P)$					

♣ Reveal the composite structures of these exotic states are necessary and important.

Introduction

Any states beyond the CQM are labelled as "exotic" hadrons. There are three classes:

(1). Mesons with "exotic" J^{PC} quantum numbers.
The possible quantum numbers of a neutral $q\bar{q}$ meson can only be $J^{PC} = 0^{++}, 0^{-+}, 1^{++}, 1^{--}, 1^{+-}, \cdots$; $q\bar{q}$ mesons cannot have $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \cdots$

(2). Mesons with "exotic" flavor content. Θ^+ pentaquark.

(3). Mesons have non-exotic quantum numbers but do not fit into the CQM spectrum.
For example, the $J^{PC} = 0^{++}$ scalar mesons. Below 2 GeV there exists the σ, $f_0(980)$, $f_0(1500)$, $f_0(1710)$, $f_0(1790)$ and $f_0(1810)$ candidate scalar meson states. Within the CQM, only two scalars are expected in this mass region, at least if we ignore the radial excitations. Including the radial excitations, the CQM could accommodate no more than four states.
$D^*_{s0}(2317), D_{s1}(2460), B_{s0}(5279), B_{s1}(5729)$.

Hadronic Molecular Candidates

Some of the exotic states can be interpreted as hadronic molecules:

♠ $|D_{s0}^{*+}\rangle = |D^{+}K^{0}\rangle + |D^{0}K^{+}\rangle$

♠ $|D_{s1}^{+}\rangle = |D^{*+}K^{0}\rangle + |D^{*0}K^{+}\rangle$

♠ $B_{s0}(5725) = |B^{+}K^{-}\rangle + |B^{0}\bar{K}^{0}\rangle$
$B_{s1}(5778) = |B^{*+}K^{-}\rangle + |B^{*0}\bar{K}^{0}\rangle$

♠ $X(1835) = |p\bar{p}\rangle + |n\bar{n}\rangle$

♠ $a_0^{+} = |K^{+}\bar{K}^{0}\rangle$
$a_0^{0} = |K^{+}K^{-}\rangle - |K^{0}\bar{K}^{0}\rangle$
$f_0 = |K^{+}K^{-}\rangle + |K^{0}\bar{K}^{0}\rangle$

♠ $X(3872) = |D^{0}\bar{D}^{*0}\rangle - |\bar{D}^{0}D^{*0}\rangle$

♠ $\cdots$

Compositeness Condition

In quantum field theory we regard a particle as a composite one provided that it is not included in the original lagrangian.

♣ Salam's criterion: The wave function renormalization constant Z_3 for boson (or Z_2 for Fermion) should be equal to zero for a composite particle.

A. Salam, Nuovo Cim.**25**:224-227,1962;Phys.Rev.**130**:1287,1963.

♣ This criterion can be proved to all orders of perturbation theory.

♣ The bound state can not arise as external state. Since each external line contributes a factor

$$Z_3(G_R) \;\;=\;\; \langle\Omega|\phi|p\rangle = 0$$

Hadronic Molecule Interpretation for $D_{s0}^{*+}(2317)$

In 2003, BABAR Collaboration at SLAC discovered a resonance in the inclusive $D_s^+\pi^0$ invariant mass distribution from the e^+e^- annihilation data at energies near 10.6 GeV.

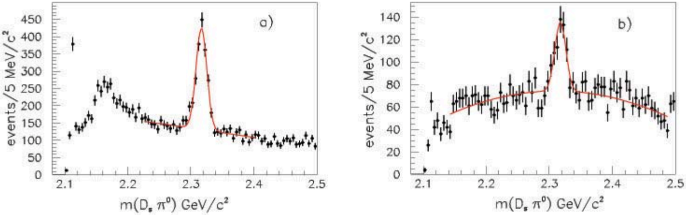


Figure 3: (color online). The $D_s^+\pi^0$ mass distribution for (a) the decay $D_s^+ \to K^+K^-\pi^+$ and (b) the decay $D_s^+ \to K^+K^-\pi^+\pi^0$.

B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **90**, 242001 (2003)

Hadronic Molecule Interpretation for $D_{s0}^{*+}(2317)$

Properties of $D_{s0}^{*+}(2317)$:

♣ $D_{s0}^{*+}(2317)$: $m = 2317.8 \pm 0.6\mathrm{MeV}$; $\Gamma < 3.8$ MeV; $I(J^P) = 0(0^+)$.

♣ Decay $D_{s0}^{*+} \to D_s^+ \pi^0$ is an isospin violating process.

♣ $D_{s0}^{*+} \to D_s^+ \gamma$ decay is excluded while $D_{s0}^{*+} \to D_s^{*+}\gamma$ is allowed.

♣ The observed mass is about 150 MeV than the QM prediction which makes it more exotic than a simple $c\bar{s}$ state.

Hadronic Molecular:

$$|D_{s0}^{*+}\rangle = |D^+ K^0\rangle + |D^0 K^+\rangle$$

A. Faessler, T. Gutsche, V. E. Lyubovitskij and Y. L. Ma, Phys. Rev. D **76**, 014005 (2007) [arXiv:0705.0254 [hep-ph]].

Hadronic Molecule Interpretation for $D_{s0}^{*+}(2317)$

$$\mathcal{L}_{D_{s0}^*}(x) = g_{D_{s0}^*} D_{s0}^{*-} \int dy \Phi_{D_{s0}^*}(y^2) D^T(x + \omega_K y) K(x - \omega_D y) + \mathrm{H.c}$$

where

$$D = \begin{pmatrix} D^0 \\ D^+ \end{pmatrix}, \quad K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}$$

$$\omega_D = \frac{m_D}{m_D + m_K}, \quad \omega_K = \frac{m_K}{m_D + m_K}$$

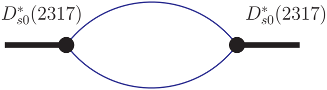
The Fourier transform of $\Phi_{D_{s0}^*}(y^2)$ can be chosen as

$$\tilde{\Phi}_{D_{s0}^*}(p_E^2) = \exp(-p_E^2/\Lambda_{D_{s0}^*}^2)$$

Note: Any choice of $\tilde{\Phi}_{D_{s0}^*}$ is appropriate as long as it falls off sufficiently fast in the ultraviolat region of Euclidean space to render the Feynman diagrams ultraviolet finite.

Hadronic Molecule Interpretation for $D_{s0}^{*+}(2317)$

Compositeness Condition



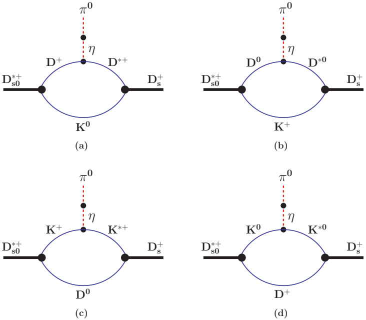
$$= -i\Sigma_{D_{s0}^*}(m_{D_{s0}^*}^2) = -i g_{D_{s0}^*}^2 \Pi_{D_{s0}^*}(m_{D_{s0}^*}^2)$$

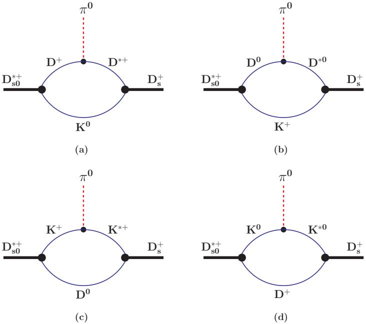
$$Z_{D_{s0}^*} = 1 - \Sigma'_{D_{s0}^*}(m_{D_{s0}^*}^2) = 0 \Rightarrow \frac{1}{g_{D_{s0}^*}^2} = \Pi'_{D_{s0}^*}(m_{D_{s0}^*}^2)$$

Approach	$g_{D_{s0}^* DK}$ (GeV)
M. Nielsen, $cq\overline{qs}$, S.R.	2.5 - 3.8
P. Colangelo, $c\bar{s}$, QCD S.R.	5.5 ± 1.8
Z.G. Wang, $c\bar{s}$, QCD S.R.	$9.3^{+2.7}_{-2.1}$
C.K.Chow, current algebra	< 9.86
NC case	$9.90 - 11.26$
LC case	8.98
NCHQL case	$11.52 - 16.22$
LCHQL case	11.52

Hadronic Molecule Interpretation for $D_{s0}^{*+}(2317)$

Strong decay $D_{s0}^{*+} \to D_s^+ + \pi^0$





Hadronic Molecule Interpretation for $D_{s0}^{*+}(2317)$

♠ In the left diagrams(LHs), π^0 meson is produced via $\eta - \pi^0$ mixing. These diagrams were mainly considered before in the literature.

♠ In the right diagrams(RHs), π^0 meson is produced directly due to the direct coupling of $D^{(*)}$ and K^* mesons to π^0.

♠ In the isospin limit, in LHs, $M_{(a)} = -M_{(b)}$ and $M_{(c)} = -M_{(d)}$. Only the use of physical masses for the $D^{(*)}$ and $K^{(*)}$ mesons gives a nontrivial contribution to the $D_{s0}^* \to D_s\pi^0$ coupling.

♠ The contribution of the RHs is of the same order as the one related to LHs involving $\eta - \pi^0$ mixing, where the $\eta - \pi^0$ transition coupling (filled black circle) is counted as the order of isospin violation.

Hadronic Molecule Interpretation for $D_{s0}^{*+}(2317)$

Numerical results at $\Lambda_{D_{s0}^*} = 1.0$ GeV:

$$\Gamma(D_{s0}^* \to D_s\pi) = 46.7 \ \mathrm{KeV}$$
$$\Gamma(D_{s0}^* \to D_s\pi)^{\mathrm{dir}} = 23.7 \ \mathrm{KeV}$$
$$\Gamma(D_{s0}^* \to D_s\pi)^{\mathrm{mix}} = 3.8 \ \mathrm{KeV}.$$

♠ Compared to the quarkonium interpretation, the strong decay width is enhanced in a molecular picture due to the inclusion of the direct π^0 coupling to the DD^* or KK^* meson pairs.

♠ In HQL, $\Gamma^{\mathrm{dir}} \simeq 0.4$ KeV, while $\Gamma^{\mathrm{mix}} \simeq 1.4$ KeV and $\Gamma \simeq 3.3$ KeV. The total result is an order smaller than the full case.

♠ In HQL, the "mixing" mode dominates over the "direct" mode. Consistent with heavy hadron ChPT.

♠ The heavy quark limit is not a good approximation for the isospin-violating strong decay $D_{s0}^* \to D_s\pi$, since some of the important isospin-breaking effects are missing.

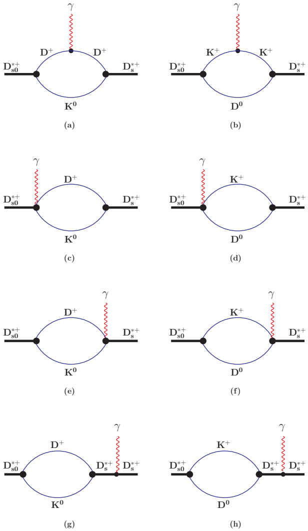
Hadronic Molecule Interpretation for $D_{s0}^{*+}(2317)$

Table 1: Decay width of $D_{s0}^{*} \to D_s\pi^0$. $\Lambda_{D_{s0}^{*}} = 1 \sim 2$ GeV.

Approach	$\Gamma(D_{s0}^{*} \to D_s\pi^0)$ (KeV)
M.Nielsen, $cq\overline{qs}$, S.R. HQ	6 ± 2
P.Colangelo, $c\bar{s}$, S.R. HQ	7 ± 1
S.Godfrey, $c\bar{s}$, Q.M.	10
Fayyazuddin, P.M.	16
W.A.Bardeen, HHχPT	21.5
S.L.Zhu, $^3P_0$ Model	32
S.L.Zhu, $c\bar{s}$, S.R. HQ	39 ± 5
H.Y.Cheng, $cq\overline{qs}$, QM	$10 - 100$
Y.I.Azimov, Phenomenology	129 ± 43 (109 ± 16)
Our result	$46.7[23.7(\mathrm{d}) + 3.8(\mathrm{m})] - 111.9$

Hadronic Molecule Interpretation for $D_{s0}^{*+}(2317)$

Electromagnetic decay:



Hadronic Molecule Interpretation for $D_{s0}^{*+}(2317)$

♠ The diagrams(a) and (b) are generated by the direct coupling of the charged D^+ and K^+ mesons to the electromagnetic field after gauging of the free Lagrangians related to these mesons.

♠ The diagrams (c) and (d) are generated after gauging of nonlocal strong Lagrangian describing the coupling of D_{s0}^* mesons to its constituents - D and K mesons.

♠ The diagrams (e) and (f) arise after gauging the strong $D_s^* DK$ interaction Lagrangian containing derivatives acting on the pseudoscalar fields.

♠ The diagrams(g) and (h) describe the sub-process where the D_{s0}^* converts into the D_s^* via a DK loop followed by the interaction of the D_s^* with the electromagnetic field.

Hadronic Molecule Interpretation for $D_{s0}^{*+}(2317)$

Nonlocal results at $\Lambda_{D_{s0}^*} = 1$ GeV:

$$
\begin{aligned}
\Gamma(D_{s0}^* \to D_s^*\gamma) &= 0.47\ \mathrm{KeV}\,,\\
\Gamma(D_{s0}^* \to D_s^*\gamma)^{\mathrm{a}} &= 0.05\ \mathrm{KeV}\,,\\
\Gamma(D_{s0}^* \to D_s^*\gamma)^{\mathrm{b}} &= 0.43\ \mathrm{KeV}\,,\\
\Gamma(D_{s0}^* \to D_s^*\gamma)^{\mathrm{c}} &= 6 \times 10^{-7}\ \mathrm{KeV}\,,\\
\Gamma(D_{s0}^* \to D_s^*\gamma)^{\mathrm{d}} &= 2 \times 10^{-4}\ \mathrm{KeV}\,,\\
\Gamma(D_{s0}^* \to D_s^*\gamma)^{\mathrm{g}} &\equiv \Gamma(D_{s0}^* \to D_s^*\gamma)^{\mathrm{h}} \equiv 0.02\ \mathrm{KeV}\,.
\end{aligned}
$$

♣ Diagrams (c) and (d) are strongly suppressed, these diagrams are kept to guarantee gauge invariance.

♣ The main contribution comes from the diagram (b). The diagram (a) is relatively suppressed as $\sim (m_K/m_D)^2$.

♣ Diagrams (e) and (f) compensate each other, the sum of them does not contribute.

Hadronic Molecule Interpretation for $D_{s0}^{*+}(2317)$

Table 2: Decay width of $D_{s0}^* \to D_s^* \gamma$. $\Lambda_{D_{s0}^*} = 1 \sim 2$ GeV.

Approach	$\Gamma(D_{s0}^* \to D_s^* \gamma)$ (KeV)
F.E.Close, $^3P_0$ model	1
X.Q.Li, C.Q.M.	1.1
Z.G.Wang, $c\bar{s}$, LCSR.	$1.3 - 9.9$
W.A.Bardeen, HHχPT	1.74
S.Godfrey, $c\bar{s}$, Q.M.	1.9
P.Colangelo, $c\bar{s}$, S.R.,H.Q.	$4 - 6$
NC case	$0.47 - 0.63$
LC case	0.66
NCHQL case	$0.71 - 1.17$
LCHQL case	1.41

Conclusion

♣ Some exotic states can be interpreted as hadronic molecules.

♣ Due to the hadronic constituents, more diagrams than the quark model structure contribute to some decay processes.

♣ Because of the extra diagrams, some of the yielded numerical results are larger than the quark model prediactions.

♣ To confirm the structure of these exotic mesons, further experiments are necessary.