Heavy-light hadrons: old laces and new pieces

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Motivation

"Solomon saith: There is no new thing upon the earth.
So that as Plato had an imagination,
that all knowledge was but remembrance;
so Solomon giveth his sentence, that
all novelty is but oblivion"

Francis Bacon: Essays, LVIII

- **Jorge Luis Borges, The Aleph and Other Stories**

Outline

- **Old Laces** - EFT (see e.g. MAN, Rho, Zahed, *Nuclear Chiral Dynamics*, WS 1995)
- **Two Revolutions** ([ex] and [th])
- **New Pieces** - Holographic approach to Exotic QCD
  Liu, Zahed; PRD95 (2017)056022; PRD95(2017) 116012.
  Liu, MAN, Zahed; PRD100 (2019)126023, PRD105 (2022)054021. (**tetraquarks**)
  Liu, MAN, Zahed; PRD104(2021)114021; PRD104(2021) 114022. (**pentaquarks: masses; decays**)
  Liu, Mamo, MAN, Zahed, PRD104(2021) 114023. (**Photoproduction of pentaquarks**)
  Liu, MAN, Zahed, PRD 105 (2022) 114021. (**Hyperons**)

Light Baryons

- Inspired by large N, we treat light baryon as Skyrme soliton. Quantization of collective modes (moduli space) from symmetries leads to
$$H_1 = \frac{\vec{I}^2}{2\Omega_{sol}} = \frac{\vec{J}^2}{2\Omega_{sol}}$$
where $\vec{I}(\vec{J})$ are isopin (angular momentum) respectively.
- Already at the level of strange quarks symmetry breaking is so bad, so collective method fails.
- Proper way is to use Born-Oppenheimer approximation - fast vibration of the kaon in the $SU(2)$ solitonic background. Then slow rotation of the bound state happens in the presence of non-Abelian Berry phase originating from kaon.
$$H = H_0 + \text{binding} + \frac{(\vec{J} - (1 - c_k) tr(K \vec{I} K^\dagger))^2}{2\Omega_{sol}}$$
([isospin-spin transmutation in Callan-Klebanov 1985])

HL Baryons

- For $c(b)$ baryons, similar picture, but with **two** Berry phases from D and D^*, so one gets

$$H_1 = \frac{[(\vec{J} - \vec{S}_H) - (1 - c_D)tr(D\vec{I}D^\dagger) - (1 - c_{D^*})tr(D^*\vec{I}D^{*\dagger})]^2}{2\Omega_{sol}}$$

- In the infinitely heavy mass Berry phases *exactly* cancel
  Then

$$H_1 = \frac{(\vec{J} - \vec{S}_H)^2}{2\Omega_{sol}} = \frac{\vec{I}^2}{2\Omega_{sol}}$$

  (Realization of **Isgur-Wise symmetry** at the baryonic level)

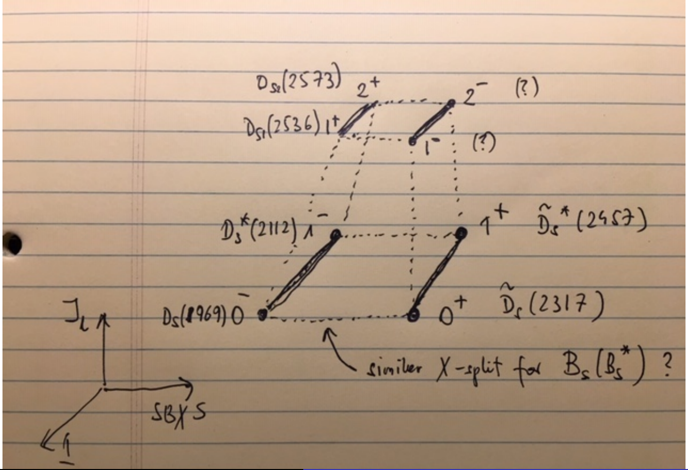
- Also, soliton can capture more than one meson (double heavy baryons, exotica).

Heavy-Light Effective Action Revisited

Combining chiral symmetry with heavy-spin symmetry leads to novel feature [MAN, Rho, Zahed (1992), Bardeen-Hill (1993)]
Both symmetries enforce the presence of opposite parity $(0^+, 1^+)$ multiplet $G = \frac{1+\not v}{2}(\tilde{D} + \gamma^\mu \gamma_5 \tilde{D}^*_\mu)$
in addition to standard $(0^-, 1^-)$ one $H = \frac{1+\not v}{2}(\gamma_5 D + \gamma^\mu D^*_\mu)$

- Consequence of chiral symmetry $[\not v, \gamma_5]_+ = 0$
- Doublers communicate only through axial current
- Physical split in axial couplings and masses, $m_G - m_H \sim O(\Sigma_I) \sim 350 MeV$
- Chiral doublers do not double the number of states in quark model, but *reorganize* them in different way.
- Similar construction for excited mesons D_1, D_2 i.e. light spin $3/2$, but the effects of chiral split are less pronounced [MAN,Zahed (1993)]

Visualization of the origin of doubling scenario based on BaBar data



Several possibilities

(i) soliton captures H meson (heavy baryon)
(ii) soliton captures G meson (doubler of heavy baryon)
(iii) soliton captured $\bar{H}$ (heavy pentaquark)
(iv) soliton captures $\bar{G}$(doubler of heavy pentaquark)
(v) soliton captures more mesons.....
Model-dependent parameters

Meson-Baryon HL "supersymmetry"

- Two identical infinitely heavy quarks QQ "sit on each other", forming diquark configuration with color $\bar{3}$, therefore colorwise, nondistinguishable form heavy antiquark $\bar{Q}$. This quark-diquark symmetry relates spin-splittings for heavy-light mesons $\bar{H}L$ to those of doubly heavy baryons HHL
- "Supersymmetric" mass relation $\Delta M_{HHL} = \frac{3}{4}\Delta M_{\bar{H}L}$ [Savage Wise (1990)]
- Iterating $HH \leftrightarrow \bar{H}$ duality leads to further dualities e.g. $HLL \leftrightarrow \bar{H}\bar{H}LL$ (heavy baryon ↔ doubly heavy tetraquark).

Experimental revolution: Post-Babar-ian era

Abundance of exotic heavy-light particles

- $\mathbf{\bar{c}du\bar{s}}$:$X(2866)$, $X_1(2904)$
- $\mathbf{c\bar{c}q\bar{q}}$: $\chi_{c1}(3872)$
- $\mathbf{c\bar{c}u\bar{d}}$: $Z_c(3900)$, $Z_c(4020)$, $Z_c(4050)$, $X(4100)$, $Z_c(3985)$, $Z_c(4430)$, $R_{c0}(4240)$
- $\mathbf{c\bar{c}u\bar{s}}$: $Z_{cs}(3985)$, $Z_{cs}(4000)$, $Z_{cs}(4220)$
- $\mathbf{b\bar{b}u\bar{d}}$: $Z_b(10610)$, $Z_b(10650)$
- $\mathbf{\bar{c}c\bar{c}c}$: $X(6900)$
- $\mathbf{cc\bar{u}\bar{d}}$: $T^+_{cc}(3875)$, also T^0_{cc}, T^{++}_{cc} (preliminary)
- Pentaquarks $\mathbf{c\bar{c}uud}$: $P_c((4380),(4450)$
  $\rightarrow [(4440),(4457)],(4312)]$, $P_c(4337)$ (3σ) significance
- $\mathbf{c\bar{c}uds}$: $P_{cs}(4459)$
- possibilities of further **heavy-light "chemistry": many more expected (?)**

Input from lattice

Theoretical revolution: Gravity/Gauge duality (holography, AdS/CFT)

- In the 70' QCD became **fundamental theory of quarks and gluons**, strings (flux tubes) appear as **effective**, e.g. Lund model
- Maldacena pointed that gauge theory is 4 dim is equivalent to string theory in higher dimensions: **Two fundamental theories of strong interactions (!)**
- Various versions - conformal window, lower-dimensions (solid state physics)
- Witten (1998) applied duality to QCD: pure YM in $3+1$ at large N and $\lambda = g_{YM}^2 N$
  Surprising similarity to spectrum of glueballs al large N lattice

Sakai-Sugimoto breakthrough 2005

- Adding N_f massless fermions - geometric SBχS
- Low energy limit $S = S_{YM} + S_{CS}$ where $S_{YM} \sim \int d^4xdz\mathrm{Tr}\left(\frac{1}{2}k(z)^{-1/3}F_{\mu\nu}^2 + k(z)F_{\mu z}^2\right)$ where $k(z) = 1 + z^2$
- Mode expansion: $A_\mu(x^\mu, z) = \sum_n B_\mu^{(n)}(x_\mu)\Psi_n(z)$, $A_5(x^\mu, z) = \sum_n \phi^{(n)}(x^\mu)\Phi_n(z)$
- Keeping only $\phi^{(0)}$ give $L = L_\sigma + L_{Skyrme} + L_{WZ}$. Adding $B_\mu^{(1)} \sim \rho$ and $B_\mu^{(2)} \sim a_1$ give hidden gauge model
- **Successful phenomenology with very few parameters**

Baryon in Sakai-Sugimoto scenario

- 4 dim pion - Skyrmion (static solution)
- 5 dim gauge field - **BPST instanton in** x_1, x_2, x_3, z **in flavor**
- Topological number $\equiv$ baryon number
- Direct realization of 1989 Atiyah-Manton idea $U(\vec{x}) = P\exp(i\int dz A_z(\vec{x}, z))$
- 8 zero modes lead to moduli space quantization $M = M_0 + \left(\sqrt{\frac{(l+1)^2}{6} + \frac{2}{15}N^2} + \sqrt{\frac{2}{3}}(n_\rho + n_z + 1)\right) M_{KK}$ where $l = 2I = 2J = 1, 3, 5...$

HL baryons in holographic scenario: Liu, Zahed, 2017

- CK-like scheme with heavy-spin symmetry
- $M = M_0 + (N_Q + N_{\bar{Q}})m_H + \left(\sqrt{\frac{(l+1)^2}{6} + \frac{2}{15}N^2\left(1 - \frac{15(N_Q - N_{\bar{Q}})}{4N} + \frac{5(N_Q - N_{\bar{Q}})^2}{3N^2}\right)^2}\right)M_{KK} + \sqrt{\frac{2}{3}}(n_\rho + n_z + 1))M_{KK}$
- Various combinations of q-numbers give all types of HL hadrons
  $N_Q = 1, N_{\bar{Q}} = 0$ yield HLL
  $N_Q = 2, N_{\bar{Q}} = 0$ yield HHL
  $N_Q = N_{\bar{Q}} = 1$ yield pentaquarks $H\bar{H}LLL$
  $n_z \neq 0$ yield excited (Roper-like), $n_\rho \neq 0$ yield odd parity
- **Three parameters**: $M_{KK}, M_0, m_H \sim M_D(M_B)$

Adding spin effect (subleading in m_H^{-1}) Liu, MAN, Zahed, 2021

- 3 parameters, $M_0 \to m_N$, $M_{KK} \to m_{\Lambda_c}$, $m_H \sim M_D(M_B)$ for $c(b)$
- 3 pentaquarks $\frac{1}{2}, \frac{1}{2}^-(S=1)$, $\frac{1}{2}, \frac{1}{2}^-(S=0)$,$\frac{1}{2}, \frac{3}{2}^-(S=1)$, IJ^π ($\frac{1}{2}, \frac{5}{2}^\pm$ ruled out), consistent with $P_c(4312, 4440, 4457)$ [LHCb]
- Recently reported $P_c(4337)$ at 3σ significance is not supported
- Open and hidden decay widths (Liu, MAN, Zahed, 2021) e.g. $P_c \to \Lambda_c + \bar{D}$, $\Gamma(S=0, J=\frac{1}{2}) : \Gamma(S=1, J=\frac{1}{2}) : \Gamma(S=1, J=\frac{3}{2}) = \frac{1}{2} : \frac{5}{6} : \frac{1}{3}$
- Formfactors (Liu, Mamo, MAN, Zahed; 2021), consistent with recent GLUEX results on $\gamma p \to (P_c^+) \to J/\psi p$

Charmed baryons and Pentaquarks

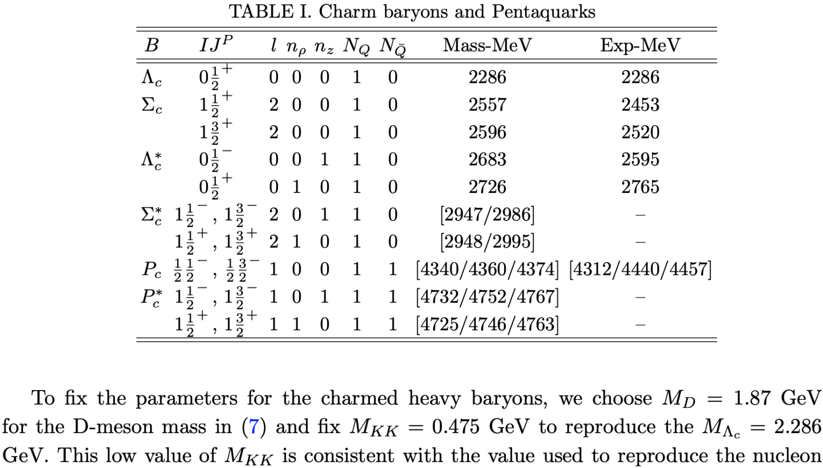


TABLE I. Charm baryons and Pentaquarks

B	IJ^P	l	n_ρ	n_z	N_Q	$N_{\bar{Q}}$	Mass-MeV	Exp-MeV
Λ_c	$0\frac{1}{2}^+$	0	0	0	1	0	2286	2286
Σ_c	$1\frac{1}{2}^+$	2	0	0	1	0	2557	2453
	$1\frac{3}{2}^+$	2	0	0	1	0	2596	2520
Λ_c^*	$0\frac{1}{2}^-$	0	0	1	1	0	2683	2595
	$0\frac{1}{2}^+$	0	1	0	1	0	2726	2765
Σ_c^*	$1\frac{1}{2}^-, 1\frac{3}{2}^-$	2	0	1	1	0	[2947/2986]	–
	$1\frac{1}{2}^+, 1\frac{3}{2}^+$	2	1	0	1	0	[2948/2995]	–
P_c	$\frac{1}{2}\frac{1}{2}^-, \frac{1}{2}\frac{3}{2}^-$	1	0	0	1	1	[4340/4360/4374]	[4312/4440/4457]
P_c^*	$1\frac{1}{2}^-, 1\frac{3}{2}^-$	1	0	1	1	1	[4732/4752/4767]	–
	$1\frac{1}{2}^+, 1\frac{3}{2}^+$	1	1	0	1	1	[4725/4746/4763]	–

To fix the parameters for the charmed heavy baryons, we choose $M_D = 1.87$ GeV for the D-meson mass in (7) and fix $M_{KK} = 0.475$ GeV to reproduce the $M_{\Lambda_c} = 2.286$ GeV. This low value of M_{KK} is consistent with the value used to reproduce the nucleon

Bottom baryons and Pentaquarks

TABLE II. Bottom baryons and Pentaquarks

B	IJ^P	l	n_ρ	n_z	N_Q	$N_{\bar{Q}}$	Mass-MeV	Exp-MeV
Λ_b	$0\frac{1}{2}^+$	0	0	0	1	0	5608	5620
Σ_b	$1\frac{1}{2}^+$	2	0	0	1	0	5962	5810
	$1\frac{3}{2}^+$	2	0	0	1	0	5978	5830
Λ_b^*	$0\frac{1}{2}^-$	0	0	1	1	0	5998	5912
	$0\frac{1}{2}^+$	0	1	0	1	0	6029	(6072)
Σ_b^*	$1\frac{1}{2}^-, 1\frac{3}{2}^-$	2	0	1	1	0	[6351/6367]	–
	$1\frac{1}{2}^+, 1\frac{3}{2}^+$	2	1	0	1	0	[6344/6367]	–
P_b	$\frac{1}{2}\frac{1}{2}^-, \frac{1}{2}\frac{3}{2}^-$	1	0	0	1	1	[11155/11163/11167]	–
P_b^*	$1\frac{1}{2}^-, 1\frac{3}{2}^-$	1	0	1	1	1	[11544/11553/11556]	–
	$1\frac{1}{2}^+, 1\frac{3}{2}^+$	1	1	0	1	1	[11532 /11543/11579]	–

T_{cc}^+ Tetraquark

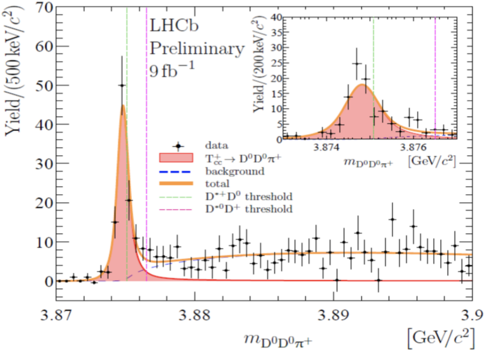


FIG. 1. Newly measured isoscalar charmed T_{cc}^+ tetraquark by LHCb [48].

Tetraquark puzzle

- $HH\bar{L}\bar{L}$ - several predictions (positive/negative $\pm 200\ MeV$)
- Measurement of $\Xi_{cc}^{++}(3621)$ fixed the normalization for $\bar{b}\bar{b}ud$ tetraquark
  (Karliner, Rosner (2017); Eichten, Quigg (2017)), bound up to $200 MeV$ (!)
- T_{cc}^{+} (01^{+}) (LHCb), narrow, bounded at $-360 keV$, $\Gamma \sim 50 keV$
- Holographic picture: instanton-antiinstanton "molecule" binds two mesons (Liu, MAN, Zahed (2019)), $b(c)$ tetraquarks bounded by 80(40) MeV
- Normalizing mass to T_{cc}^{+}, (Liu, MAN, Zahed (2022)) predict mass of T_{bc} and T_{bb}, and calculate very narrow width.

Binding energies for tetraquarks

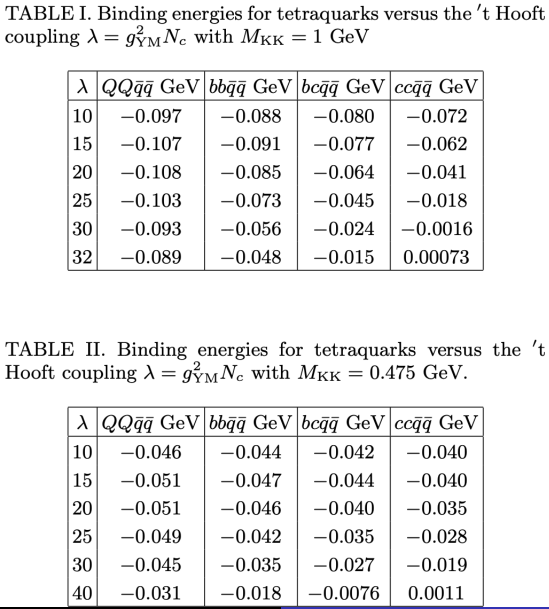


TABLE I. Binding energies for tetraquarks versus the ′t Hooft coupling $\lambda = g_{\mathrm{YM}}^2 N_c$ with $M_{\mathrm{KK}} = 1$ GeV

λ	$QQ\bar{q}\bar{q}$ GeV	$bb\bar{q}\bar{q}$ GeV	$bc\bar{q}\bar{q}$ GeV	$cc\bar{q}\bar{q}$ GeV
10	−0.097	−0.088	−0.080	−0.072
15	−0.107	−0.091	−0.077	−0.062
20	−0.108	−0.085	−0.064	−0.041
25	−0.103	−0.073	−0.045	−0.018
30	−0.093	−0.056	−0.024	−0.0016
32	−0.089	−0.048	−0.015	0.00073

TABLE II. Binding energies for tetraquarks versus the ′t Hooft coupling $\lambda = g_{\mathrm{YM}}^2 N_c$ with $M_{\mathrm{KK}} = 0.475$ GeV.

λ	$QQ\bar{q}\bar{q}$ GeV	$bb\bar{q}\bar{q}$ GeV	$bc\bar{q}\bar{q}$ GeV	$cc\bar{q}\bar{q}$ GeV
10	−0.046	−0.044	−0.042	−0.040
15	−0.051	−0.047	−0.044	−0.040
20	−0.051	−0.046	−0.040	−0.035
25	−0.049	−0.042	−0.035	−0.028
30	−0.045	−0.035	−0.027	−0.019
40	−0.031	−0.018	−0.0076	0.0011

Summary

- **Strongly coupled QCD could be approached via duality from string theory in large N and large λ limit, including spectra of heavy-light hadrons**
- **Few parameters and very restrictive predictions, so models are confutable**
- Approach based on confinement, SBχS and heavy spin symmetry, in the limit of large N and λ.
- "High brow" theory boils down to relatively simple QM in moduli space (top-down approach)
- **Astonishing and deep analogies to "old" physics**