All-Heavy Tetraquarks: The Dynamical Diquark Model and Other Approaches

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Although This Talk Is About Heavy Tetraquarks in General...

- In this talk, we focus on developments to study interesting structure observed by LHCb in the di-*J*/ψ channel [Sci. Bull. 65, 1983 (2020)]
- After a false alarm of bbbb state (→ μ⁺μ⁻μ⁺μ⁻) at 18.4 GeV using CMS data [http://meetings.aps.org/Meeting/APR18/Session/U09.6],
- LHCb [JHEP **10**, 086 (2018)] studied $\Upsilon(1S) \mu^+\mu^$ and found no significant structures
- No structures reported yet in $b\overline{b}c\overline{c}$, $b\overline{c}b\overline{c}$, etc.

How All-Heavy Tetraquarks Are Made

• Mostly gluon-gluon fusion (but both single- and double-parton scattering important for nonresonant $Q\bar{Q}Q\bar{Q}$ production)

[R. Maciuła, W. Schäfer, A. Szczurek, Phys. Lett. B 812, 136010 (2021)]



Neutral charmoniumlike sector, August 2021



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Charged charmoniumlike sector, August 2021



The heavy exotics scorecard: August 2021

- **51** observed exotics
 - 41 in charmoniumlike sector (incl. pentaquarks)
 - 1 decaying to di- J/ψ
 - 5 in the (much less explored) bottomonium sector
 - 1 with a single b quark (and an s, a u, and a d)
 - 2 with a single c quark (and an s, a u, and a d)
 - 1 with two *c* quarks
- 15 established [PDG] (& none of other 36 disproved)
- My naïve count estimates over 100 more exotics are waiting to be discovered

The Plot That Launched 100 Theory Papers

LHCb Collaboration, Sci. Bull. 65, 1983 (2020) [2006.16957]



The Eye Immediately Notices...



The Most Important Apparent Features

- X(6900), the only obvious peak, lies about 700 MeV above $2m_{J/\psi}$ but is likely not wider than the ρ (≤ 200 MeV, & perhaps much narrower)
- A cccc state, if a traditional di-meson molecule, would be bound through exchanging conventional charmonium which for expected ≤ 0(10 MeV) molecular binding energies is very far off mass shell
- Typical $c\bar{c}$ mean charge radii from potential models: 1S: 0.35 fm 1P: 0.63 fm 2S: 0.78 fm $\Rightarrow J/\psi$ exchange in particular would be very short-ranged
- So what about *nontraditional* di-meson molecules?
 - Pomeron (multi-gluon) exchanges [C. Gong *et al.*, 2011.11374]
 - Soft gluons hadronizing into light-meson exchanges (π , K) [X.-K. Dong *et al.*, 2107.03946]

The Most Important Apparent Features

- J^{PC} for $J/\psi(1^{--})$ identical boson pair restricted: C = + and: $0^{++}, 2^{++}$ (S wave), $0^{-+}, 1^{-+}, 2^{-+}$ (P wave)
- J^{PC} for system made of *cc* and *cc* identical fermion pairs also restricted: In their *S* wave: [color-**3**, spin-1] or [color-**6**, spin-0]

History of $c\bar{c}c\bar{c}$ Theory Studies

- 11 November 1974: Discovery of *J*/ψ

 [J. Aubert *et al.*, Phys. Rev. Lett. **33**, 1404 (1974);
 J. Augustin *et al.*, Phys. Rev. Lett. **33**, 1406 (1974)]
- First di- J/ψ theory paper: Y. Iwasaki, Prog. Theor. Phys. 54, 492 (1975) (!)
- **5** theory papers in the **1980**s, **1** in the **1990**s, **3** in the **2000**s ("All the states are unbounded and consequently rather uninteresting")
- 2010: First physics from LHC. Very soon afterwards pointed out that: Lots of gg → J/ψ-J/ψ being produced, and can be reconstructed by LHCb: [A. Berezhnoy, A. Likhoded, A. Luchinsky, and A. Novoselov, Phys. Rev. D 84, 094023 (2011); 86, 034004 (2012)]
- And then...nothing else until 2016, and 12 papers from then until the middle of 2020

History of $c\bar{c}c\bar{c}$ Theory Studies

- **16 June 2020**: CERN-LHC Seminar, Liupan An (LHCb Collaboration), "Latest Results on Exotic Hadrons at LHCb"
- Then 8 more theory papers just in the following two weeks
- 30 June 2020: Posting of arXiv:2006.16957,
 R. Aaij *et al.* (LHCb Collaboration), Sci. Bull. 65, 1983 (2020),
 "Observation of Structure in the J/ψ-pair Mass Spectrum"
- Since then: 53 theory papers posted on arXiv discussing cccc structure (as of 21 August 2021)

What Has Been Tried?

(with apologies to the many authors whose names are not listed here!)

- String junction model
- Quark model, chromomagnetic interactions
- Quark potential model
- Chiral quark model
- Diquark model
- Effective theory with light-meson exchanges
- Threshold effects with coupled charmonium channels
- Threshold effects plus compact tetraquark
- QCD sum rules
- Lattice
- Regge phenomenology, including Pomeron exchange
- Holography
- Spin-chain (Bethe Ansatz) algebraic methods
- X(6900) might even be a Higgs-like boson!

The Relevant Charmonium Thresholds



- X(6900) seems to be genuine resonance, even within the presence of multiple threshold effects that might explain other cccc structure: [e.g., X.-K. Dong et al., Phys. Rev. Lett. 126, 132001 (2021);
 Z.-H. Guo and J.A. Oller, Phys. Rev. D 103, 034024 (2020)]
- Others [e.g., J.-Z. Wang, X. Liu, and T. Matsuki, Phys. Rev. D 103, L071503 (2021)] suggest X(6900) itself might be generated by χ_{c0}-χ_{c1} threshold
- Virtually all models predict ground-state 1*S* resonances to be much lower than *X*(6900), typically from 6.0-6.4 GeV (ever since Iwasaki [1975])
- So then, is *X*(6900) ...

a 1*P* state (*e.g.*, M.-S. Liu *et al.*, 2006.11952) or a 2*S* state [*e.g.*, J.F. Giron and RFL, Phys. Rev. D **102**, 074003 (2020); M. Karliner and J.L. Rosner, Phys. Rev. D **102**, 114039 (2020)]? (Measuring parity will answer this question)

- The broad structure around 6400-6500 MeV is about the upper limit of where models predict ground-states (1*S*) to occur
 [*e.g.*, B.-C. Yang, L. Tang, and C.-F. Qiao, Eur. Phys. J. C 81, 324 (2021);
 Z. Zhao *et al.*, Phys. Rev. D 103, 116207 (2021)]
- LHCb's Model I [Sci. Bull. **65**, 1983 (2020)]: Broad structure is a superposition of (at least) two resonances
- And what do we mean by "1S", which suggests a 2-body description? Since molecules are problematic for cccc, and no good thresholds are in the 6400-6500 MeV range, then diquark (cc)₃(cc)₃ structure is natural
- But not everyone agrees!

C. Deng, H. Chen, J. Ping, Phys. Rev. D **103**, 014001 (2021) note that $6-\overline{6}$ attraction stronger than $\overline{3}-3$ (despite quark repulsion in a 6 diquark!), and find that the ground states mix both configurations, but that $\overline{3}-3$ dominates excited states

- The dip around 6750 MeV suggests destructive interference with X(6900)
- LHCb's Model II [Sci. Bull. 65, 1983 (2020)]: Interference between broad 6400-6500 MeV structure and a resonance
- χ_{c0}-χ_{c0} threshold effect?
 [e.g., M. Karliner and J.L. Rosner, Phys. Rev. D 102, 114039 (2020)]?
- If X(6900) is 2S (P = +), then 6750 MeV is where 1P states (P = -) expected [e.g., Giron & RFL] But of course P = + and P = - configurations do not have interference with each other

Again, determining the parity of these events is crucial

- LHCb [Sci. Bull. 65, 1983 (2020)] notes structure near 7200 MeV
- Open-flavor decays of $c\bar{c}c\bar{c}$ first allowed at $\overline{\Xi}_{cc}$ - Ξ_{cc} (ccu)($c\bar{c}\bar{u}$) threshold, 7242.4(1.0) MeV
- Likely no observably narrow *cccc* structures above this point
- Giron & RFL: "where the color flux tube breaks in a diquark model"
- J. Sonnenschein and D. Weissman, Eur. Phys. J. C **81**, 1 (2021): "where new string junctions become possible in a holographic model"

How Many States?

- If both 3 and 6 diquarks both allowed, one finds a *lot* of states
 [M.A. Bedolla, J. Ferretti, C. Roberts, and E. Santopinto,
 Eur. Phys. J. C 80, 1004 (2020)]:
 17 with C = + & J ≤ 2 predicted below Ξ_{cc}-Ξ_{cc} threshold (see next slide)
- Adopt minimal ansatz, of $\overline{3}$ diquarks only: about half as many states Take spin couplings to be large only within diquarks [Defining properties of **dynamical diquark model**: Giron & RFL]: All *S* wave multiplets: **3** degenerate states 0⁺⁺, 2⁺⁺ (and 1⁺⁻) In *P* wave multiplets: **7** states (**3** with *C* = +), equal-spacing mass rule if tensor couplings negligible $J^{PC} \Delta M_{LS} \Delta M_T$ $1^{--} -3V_{LS} -\frac{28}{5}V_T$ $0^{-+} -2V_{LS} -8V_T$ $1^{-+} -V_{LS} +4V_T$

 $2^{--} -V_{LS} + \frac{28}{5}V_T$ $1^{--} 0V_{LS} 0V_T$ $2^{-+} +V_{LS} - \frac{4}{5}V_T$

 $3^{--} + 2V_{LS} - \frac{8}{5}V_T$

	ccēē	
J^{PC}	$N[(S_D, S_{\bar{D}})S, L]J$	E^{th} [MeV]
0++	1[(1,1)0,0]0	5883
0++	2[(1,1)0,0]0	6573
0++	1[(1, 1)2, 2]0	6835
0++	3[(1,1)0,0]0	6948
0++	2[(1,1)2,2]0	7133
0++	3[(1,1)2,2]0	7387
1+-	1[(1,1)1,0]1	6120
1+-	2[(1,1)1,0]1	6669
1+-	1[(1, 1)1, 2]1	6829
1+-	3[(1,1)1,0]1	7016
1+-	2[(1,1)1,2]1	7128
1+-	3[(1,1)1,2]1	7382
1	1[(1,1)0,1]1	6580
1	1[(1, 1)2, 1]1	6584
1	2[(1,1)0,1]1	6940
1	2[(1,1)2,1]1	6943
1	3[(1,1)0,1]1	7226
1	3[(1,1)2,1]1	7229
0^-+	1[(1,1)1,1]0	6596
0^-+	2[(1,1)1,1]0	6953
0^-+	3[(1,1)1,1]0	7236
1++	1[(1,1)2,2]1	6832
1++	2[(1,1)2,2]1	7130
1++	3[(1,1)2,2]1	7384
2++	1[(1,1)2,0]2	6246
2++	1[(1, 1)2, 2]2	6827
2++	1[(1,1)0,2]2	6827
2++	2[(1,1)2,0]2	6739
2++	3[(1,1)2,0]2	7071
2++	2[(1,1)2,2]2	7125
2++	2[(1,1)0,2]2	7126
2++	3[(1,1)2,2]2	7380
2++	3[(1,1)0,2]2	7380

Some Parting Thoughts

- Desperately need J^P information to disentangle spectrum
- An excellent suggestion: Look at J/ψ-ψ(2S) spectrum
 [e.g., J.-M. Richard, Sci. Bull. 65, 1954 (2020);
 Q.-F. Cao et al., Chin. Phys. C 45, 093113 (2021)], even though its threshold
 is 700 MeV higher, and ψ(2S) production is lower than that of J/ψ
 Also note that BESIII sees different Y states via J/ψ or ψ(2S) decays
- $gg \operatorname{producing} J/\psi$ is C = +; is there much ggg (C = -) production? Could find 1^{+-} resonance via $J/\psi - \eta_c$, although η_c harder to reconstruct [but note B.R. $(\eta_c \rightarrow p\bar{p}) = 1.45 \times 10^{-3}$] Alternately, $J/\psi - \chi_{cJ}$ also has C = -, but less phase space (> 6512 MeV)
- And don't forget about ccbb and bbbb production!
 ccbb (e.g., J/ψ-Y) should have more resonances:
 evades identical fermions constraint
 - → Important tests of quark flavor universality

Backup slides