Discoveries of Exotic Hadrons

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• Don’t we know about quarks from mid 1960s?

• …and don’t we have exact theory of strong interactions since early 1970s?
Strongly coupled theory

Hadron spectroscopy

- Lattice QCD is doing very well for lower excitations of $q\bar{q}$ and $qqq$ hadrons
- Still in its infancy when dealing with unstable and multiquark states $qq\bar{q}\bar{q}$, $qqqq\bar{q}$, …

- QCD-motivated phenomenology, with often uncontrollable errors due to model assumptions
Many open questions in hadron spectroscopy

• We know the lightest hadrons in each quark configuration are predominantly bound states of $q\bar{q}$ or $qqq$, but

• We don’t know if diquarks, strongly motivated by QCD, are good building blocks for more complex quark structures: $(qq)(\bar{q}\bar{q})?, (qq)(qq)\bar{q}?$, …, and under which circumstances?

• We are not even sure about the role of diquarks in baryons $q(qq)$?

• We don’t know if gluon can be among dominant hadron constituents, as motivated by QCD: glueballs $gg$? hybrids $gq\bar{q}?$, $gqqq$?

• We are not sure if nuclear-type forces can bind mesons to other mesons or baryons (“molecular” states)
Heavy hadrons often lead the way

“Eightfold Way” symmetry – Gell-Mann 1961

Fractional elementary charge? Why can’t we see them? No way!

Why can’t we see them?

No way!
Heavy hadrons often lead the way

November revolution of 1974

pBe → e⁺e⁻ X

Non-relativistic bound states of heavy fermion pair (c̅c) carrying new quantum number (charm) conserved in strong interactions

Separation of interaction energies and the masses of constituents helps!

Source of effective theories.
Heavy hadrons often lead the way

Belle 2003: discovery of X(3872)

PRL 91, 262001 (2003)

\[ e^+ e^- \rightarrow B + \cdots \]

\[ B \rightarrow (\pi^+ \pi^- J/\psi) K \]

\(~36\) signal events

\[ \psi(2S) \]

\[ D\bar{D}^* \]

\[ j^{PC} = 1^{++} \]

\[ I^G = 0^+ \]

\[ X(3872) \]

\[ \Gamma = 1.2 \pm 0.2 \text{ MeV (PDG 2021)} \]

Large isospin violation rules out pure \( c\bar{c} \) interpretation


arXiv:2204.12597 (accepted by PRD Letters)

\[ p p \rightarrow B^+ + \cdots \]

\[ B^+ \rightarrow (\pi^+ \pi^- J/\psi) K^+ \]

\(~6,800\) signal events

\[ \text{Candidates} / \text{1 MeV} \]

\[ \text{Decays / 5 MeV} \]

LHCb 9 fb\(^{-1}\)

\[ \rho \sim 79\% \]

\[ \omega - \rho \sim 19\% \]

\[ \omega \sim 2\% \]

\[ \text{Isospin-violating / Isospin-conserving couplings} \]

\[ \frac{g_{\chi c1(3872)\rightarrow \rho^0 J/\psi}}{g_{\chi c1(3872)\rightarrow \omega J/\psi}} = 0.29 \pm 0.04 \]

\[ \frac{g_{\psi(2S)\rightarrow \rho^0 J/\psi}}{g_{\psi(2S)\rightarrow \eta J/\psi}} = 0.045 \pm 0.001 \]

Natural explanation via large \( D^0\bar{D}^{*0} \) component (the mass 8 MeV below \( D^+\bar{D}^{*-} \))
Dual nature of X(3872)?

- X(3872) mixes features expected for a loosely bound \textit{molecular} state (mass coincidence with the $D^0 \bar{D}^{0*}$ threshold, “right” $J^P=1^+$, narrow width, large fall-apart rate to $D^0 \bar{D}^{0*}$, large isospin violation in decays) with features expected for a tightly bound quark state i.e. \textbf{P-wave $c\bar{c}$} (production in many different reactions, usually following the rate pattern not too different from well-behaved $c\bar{c}$ state – $\psi(2S)$, pattern of radiative decays (?))

- If coincidence of $\chi_{c1}(2^3P_1)$ with the $D^0 \bar{D}^{0*}$ threshold is responsible for it, then there is no narrow analog of it in bottomonium

- \textbf{P-wave $c\bar{s}$} states, $D_{s0}^*(2317)^-$ and $D_{s1}(2460)^-$ also believed to be predominantly $D^0 K^-$, $D^0 K^{*-}$ molecules
Narrow $Z^+_b,0$ and $Z^+_c,0$ states

Belle 2012

$e^+e^- \rightarrow \pi^+\pi^-\Upsilon(n^3S_1)$

Charged and neutral versions detected $I^G=1^+$

no confusion with $(b\bar{b})$!

Mass

MeV

10400
10500
10600
10700

$3^{3}S_1$

$4^{3}S_1$

$2^{3}S_1$

$2^{1}P_1$

$2^{1}P_{1,0}$

$1^{3}P_1$

$1^{3}P_{0,1,2}$

$Y(4260)$

$Z_c(3900)$

$Z_c(4020)$

$e^+e^- \rightarrow \pi^+\pi^-\Upsilon(1^{3}S_1)$

$e^+e^- \rightarrow \pi^+\pi^-\Upsilon(1^{3}S_1)$

$\Upsilon(3S)$

$\Upsilon(2S)$

$\Upsilon(1S)$

$\pi$

$\pi$

$\pi$

$\Upsilon$(3S)

$\Upsilon$(2S)

$\Upsilon$(1S)

$\Gamma = 13 \pm 5 \text{ MeV}$

$\Gamma = 28 \pm 3 \text{ MeV}$

$\Gamma = 18 \pm 2 \text{ MeV} \quad 11 \pm 2 \text{ MeV}$

Narrow! Masses peak slightly above thresholds. Coupled-channel fits (with $D\bar{D}$ data) for $Z_c(3900)^+$, give its pole mass slightly below the threshold. $J^P=1^+$ states. Large fall-apart decay rates.

BES-III and Belle 2013

$e^+e^- \rightarrow \pi^+\pi^- h_c(1^{1}P_1)$
Narrow $Z_{cs}^{+,0}$ states

- Strange SU(3)$_f$ partners of the narrow $Z_c (3900)^{+,0}$ state have been recently discovered by BESIII:

$M(D_s^- D^{(*)0})$ via Recoil Mass against $K^+$

$$m_{Z_{cs}} = 3982.5^{+1.8}_{-2.6} \pm 2.1 \text{ MeV}$$

$$\Gamma_{Z_{cs}} = 12.8^{+5.3}_{-4.4} \pm 3.0 \text{ MeV}$$

$m_{D_s^-} + m_{D^{*0}} = 3975.2 \pm 0.1 \text{ MeV}$

$m_{D_s^0} + m_{D^{*0}} = 3977.0 \pm 0.4 \text{ MeV}$

$M(D_s^- D^{(*)+}, D_s^{(*)-} D^0)$ via Recoil Mass against $K_s^0$

$$m_{Z_{cs}^0} = 3902.2 \pm 1.7 \pm 1.6 \text{ MeV}$$

$$\Gamma_{Z_{cs}^0} = 7.7^{+4.1}_{-3.8} \pm 4.3 \text{ MeV}$$
Narrow $P_{c(s)}^{+(0)}$ states

LHCb 2019 PRL 122, 222001

$p p \rightarrow \Lambda_b + \cdots$

$246k \Lambda_b \rightarrow J/\psi p K^-$

$\Lambda_b \rightarrow (J/\psi p)K^+$


$pp \rightarrow \Xi_b^- + \cdots$

$1.8k \ Xi_b^- \rightarrow J/\psi \Lambda K^-$

$\Xi_b^- \rightarrow (J/\psi \Lambda)K^-$

Expected in molecular model:

\[ J^P = \frac{1}{2}^- \text{ for } \Sigma^+_c \bar{D}^0 \quad (J^P_{\Sigma^+_c} = \frac{1}{2}^- \text{, } J^P_{\bar{D}^0} = 0^-) \]

\[ J^P = \frac{1}{2}^+ , \frac{3}{2}^- \text{ for } \Sigma^+_c \bar{D}^{*0} \quad (J^P_{\Sigma^+_c} = \frac{1}{2}^+ \text{, } J^P_{\bar{D}^{*0}} = 1^-) \]

Also expect 4 relatively narrow states $\Sigma^+_c \bar{D}^{(*)0}$

Data 9 fb$^{-1}$

Predicted $J^P$: $\frac{1}{2}^- , \frac{3}{2}^-$

Fit without $P_{cs}$

Fit with $P_{cs}$

3σ evidence for a $J/\psi \Lambda$ mass structure

one or two states?

Need more data!
Another narrow $P_{cs}^0$ state

6D amplitude analysis of masses and decay angles


$4.6k B^- \rightarrow J/\psi \Lambda \bar{p}$

- $P_{cs}^0(4338)^0 \leftrightarrow \Xi_c^0 \bar{D}^0$ is likely an analog of $P_c(4312)^+ \leftrightarrow \Sigma_c^0 \bar{D}^0$

$\Xi_c^0 \bar{D}^0, 10\sigma$

M. Karliner, J. Rosner PRD106, 036024 (2022)
Narrow states near hadron-hadron thresholds

- Coincidence with hadron-hadron thresholds hard to deny.

- However, origin of all these states does not need to be the same and is not settled.

Expect many more narrow near-threshold states to be discovered, also involving other quark combinations!
Not all heavy exotic hadrons are near hadron-hadron thresholds

LHCb 2022

$pp \rightarrow B_s^0 + \cdots$  
$0.8k B_s^0 \rightarrow J/\psi p\bar{p}$

$B_s^0 \rightarrow J/\psi p\bar{p}$

4D amplitude analysis

$m_{P_c^+} = 4337^{+7}_{-4} \pm 2 \text{ MeV}$

$\Gamma_{P_c^+} = 29^{+26+14}_{-12-14} \text{ MeV}$

Not near any baryon-meson threshold

More than one mechanism to bind pentaquarks?

Need more data!
Many broader exotic states not near thresholds

\[ B^+ \to (J/\psi \phi)K^+ \]

(cs)(\bar{c}\bar{s}) tetraquarks? 
3,43P_{1,0} (c\bar{c}) in the mix?

CDF 2008

0.06k \( B^+ \) decays

PRL127, 082001 (2021)

24k \( B^+ \) decays

CDF 2008

\[ B \to (\psi(2S)\pi^+)K \]

(cu)(\bar{c}\bar{d}) tetraquark?

Belle 2008

2k \( B \) decays

Γ ~ 181 ± 31 MeV

LHCb 2014

3 fb^{-1} decays

\[ Z_{cs}(4000)^+ \] significantly wider than \[ Z_{cs}(3985)^+ \] from BESIII.
Likely different states with different dynamics.

\[ Z_{cs}(4000)^+ \] significantly wider than \[ Z_{cs}(3985)^+ \] from BESIII.
Likely different states with different dynamics.

Amplitude analysis reveals large number of \( J/\psi \phi \) states, 
and two \( J/\psi K^+ \) states \( (Z_{cs}^+(4000), Z_{cs}^+(4216)) \)
A lot of \( c\bar{c}q\bar{q} \) structures. Amplitude analyses very complex, but still naïve, since coupled-channels \( (D(s)) \) (s) neglected.
Anomalous charmonium-like vector states

Decays via

\( Y(4260) \rightarrow Y(4230) \)
\( Y(4320) \rightarrow Z_c^{+0}\pi^{-0} \)
\( e^+e^- \rightarrow \pi^+\pi^- J/\psi \)

4225.3 \( \pm \) 2.3 \( \pm \) 21.5 MeV
\( \Gamma = 72.9 \pm 6.1 \pm 30.8 \) MeV

4484.7 \( \pm \) 13.3 \( \pm \) 24.1 MeV
\( \Gamma = 111.1 \pm 30.1 \pm 15.2 \) MeV

4406.9 \( \pm \) 17.2 \( \pm \) 4.5 MeV
\( \Gamma = 128.1 \pm 37.2 \pm 2.3 \) MeV

4647.9 \( \pm \) 8.6 \( \pm \) 0.8 MeV
\( \Gamma = 33.1 \pm 18.6 \pm 4.1 \) MeV

\( g\bar{c}\bar{c} \) hybrid states?,
\( (c\bar{q})(\bar{c}q) \) tetraquarks,...?
Charming and strange exotic states

The $0^+ T_{cs0}(2900)^0$ state is a good candidate for a "nearly"-doubly-heavy tetraquark.

Amplitude analysis

Proximity of the thresholds motivates other explanations - molecular or triangle diagrams.
Charming and anti-strange exotic state

4.8\(k\)

\[ B^0 \rightarrow \bar{D}^0 D_s^+ \pi^- \]

\[ M^2(D_s^+ \pi^-)(\text{GeV}^2) \]

\[ \text{LHCb} \]

9 fb\(^{-1} \]

preliminary

3.8\(k\)

\[ B^+ \rightarrow D^- D_s^+ \pi^+ \]

\[ M^2(D^- \pi^+)(\text{GeV}^2) \]

\[ \text{LHCb} \]

9 fb\(^{-1} \]

preliminary

LHC seminar “Particle Zoo 2.0: New tetra- and pentaquarks at LHCb”, July 5, 2022, https://indico.cern.ch/event/1176505/

\[ M = 2.908 \pm 0.011 \pm 0.020 \text{ GeV} \]

\[ \Gamma = 0.136 \pm 0.023 \pm 0.011 \text{ GeV} \]

\[ J^P = 0^+ \]

\[ M(D_s \pi) \] well described by adding a \( J^P = 0^+ T_{c\bar{s}0}^q(2900) \) in each channel
Hidden double-charm tetraquarks?

- Very significant structures in J/ψJ/ψ mass
- Interpretation of data is not clear:
  - Likely many (interfering?) resonances
  - X(6900) peak seems too wide to be loosely-bound (Γ≈80 MeV or more), tightly-bound tetraquark state?
  - Possible effects due to nearby J/ψJ/ψ’, J/ψJ/ψ’’ thresholds via coupled channel effects, see Dong, Baru, Fen-Kun Guo, Hanhart, Nefediev PRL 126, 132001 (2021)
- Likely theoretical interpretation: (cc)(c̅c̅) tetraquark state(s), but the coupled channel effects may be important in shaping the mass spectrum

$pp \rightarrow (J/ψ \rightarrow μ^+μ^-)(J/ψ \rightarrow μ^+μ^-) + \cdots$  

$T_{cc}(6900)$

CMS Preliminary

ATLAS Preliminary

9 fb⁻¹

J/ψJ/ψ’ J/ψJ/ψ’’

9 fb⁻¹

J/ψJ/ψ’ J/ψJ/ψ’’

$J/ψ \rightarrow μ^+μ^- J/ψ \rightarrow μ^+μ^- + \cdots$

$J/ψ \rightarrow μ^+μ^- J/ψ \rightarrow μ^+μ^- + \cdots$

$J/ψ \rightarrow μ^+μ^- J/ψ \rightarrow μ^+μ^- + \cdots$

$J/ψ \rightarrow μ^+μ^- J/ψ \rightarrow μ^+μ^- + \cdots$

$J/ψ \rightarrow μ^+μ^- J/ψ \rightarrow μ^+μ^- + \cdots$
Stable tightly-bound $(bb)(\bar{u}\bar{d})$ tetraquark?

The lightest $1^+$ state for hadronic decay

Karliner's slide from 2017

Stable tetraquark, will decay weakly

$\Xi_{cc}^{++}$ baryon observed by LHCb in 2017

consistent results predicted by LQCD:
Francis,Hudspith,Lewis,Maltman
PRL 1118,142001 (2017)
Double-charm tetraquark

\[ pp \rightarrow D^0 (\rightarrow K^- \pi^+) D^0 (\rightarrow K^- \pi^+) \pi^+ + \cdots \]

\[ D^{*+} D^0 D^0 D^+ \]

\[ T_{cc}(3875)^+ \]

\[ l=0 \text{ favored} \]

\[ \Gamma \sim 0.4 \text{ MeV} \]

\[ M_{T_{cc}^+} = 2M_{D^0} + M_{\pi^+} + \sim 6\text{MeV} \]

Very small phase-space for \( D^0 D^0 \pi^+ \), or any other strong decay

- Very little phase-space for any strong decay! It could also be a tightly-bound \((cc)(\bar{u}\bar{d})\) diquark state!
- Very narrow state, very close to the meson-meson threshold. It could be a loosely-bound \(D^{*+/0} D^{0+/0}\) state.
- Detecting \( bb\bar{u}\bar{d} \) can separate these two mechanisms, but it will be very challenging experimentally. \( bc\bar{u}\bar{d} \) easier?
Hadron Spectroscopy is in crisis

- Internal structure of the new particle Zoo is poorly understood
It is time to stop pretending that we understand hadrons

S. Godfrey, N. Isgur
PR,D32,189 (1985)

Mesons in a relativized quark model with chromodynamics

Excited kaons $q\bar{s}$

$K^*\omega, K^*\rho$

$K\omega, K\rho$

$K^*\pi$

$K\pi$

New Zoo is likely also here!

$K^* (892)$

$\Lambda^*\pi, \Lambda^*\rho, \Lambda^*\omega, \Lambda^*\rho_0, \Lambda^*\omega_0, \Lambda^*\rho_1, \Lambda^*\omega_1, \Lambda^*\rho_2, \Lambda^*\omega_2, \Lambda^*\rho_3, \Lambda^*\omega_3$ Mass predictions by Loring-Metsch-Petry EPJ, A10, 447 (2001) vs Well-established $\Lambda^*$

Didn’t Gell-Mann tell us so?
Experimental prospects for heavy hadrons in the next decade

• Unique features of LHC:
  – enormous strong production rates (before trigger)
  – access to b-baryons (also serves pathway to charm pentaquarks)
  – access to doubly-flavored states (\(b\bar{c}, ccq, cc\bar{q}, cc\bar{c}\bar{c}, \ldots\))

• Expect many new measurements/discoveries from LHCb
  – triggering optimized to flavor physics
  – good hadrons ID (\(\pi/K/p\) separation)

• ATLAS/CMS potential:
  – best flavor rates, but triggering on them is a challenge, no hadron ID
  – can be competitive in certain channels (\(\mu^+\mu^-\mu^+\mu^-\))
  – the only experiments which may have a chance to confirm some of LHCb claims

• Expect many new measurements/discoveries from Belle II. Unique features:
  – good \(\gamma, \pi^0, \eta\) detection
  – access to precision \(bb\) spectroscopy below and above \(BB\) threshold (via dedicated runs)
  – production also via \(\gamma\gamma\) collisions, and \(e^+e^-\rightarrow c\bar{c}c\bar{c}\bar{c}\)
Past and future: dedicated $c$–quark experiments

Energy & lumi upgrade
\[ \sqrt{s} \sim 5 \rightarrow 5.6 \text{ GeV} \]
\[ \sqrt{s} \sim 10 \text{ GeV} \]
\[ \sqrt{s} \sim 4 \text{ GeV} \]

Super Tau-Charm Factory
Proposed at Hefei and Novosibirsk
(in R&D phase)
energy up to $\sqrt{s} \sim 7 \text{ GeV}$

BES-III: highest luminosity $e^+e^- \rightarrow c\bar{c}$ experiment near the charm threshold
(precision $c\bar{c}$ spectroscopy below and above $D\bar{D}$ threshold, light-hadron spectroscopy including glue-rich $J/\psi \rightarrow \gamma g\bar{g}$)

PANDA: highest luminosity $p\bar{p} \rightarrow c\bar{c}$ experiment near the charm threshold
(2025- ?)
Precision scans of charmonium-like states?
Experimental prospects at JLab and EIC

**JLab: 12 GeV e⁻ beam (2017-...)**

Photoproduction of charmonium(-like) states
If detected offers a good insight into their substructure

**Electron Ion Collider e⁻p, e⁻A (2030-...)**

Photoproduction of charmonium exotics possible

JLab upgrade to 20-24 GeV e⁻ beam?
Would greatly increase a chance to detect charmonium-like states

Search for light hybrid mesons

- Statistical errors will be improved
- Search for $P_c$ states
Summary

• The experimental discoveries in the last two decades in the heavy flavor sector showed us that we understand very little from hadron spectroscopy.
• Many heavy hadron exotics are narrow, and near hadron-hadron thresholds, pointing to hadron-hadron interactions playing an important role in their creation (molecular states?)
• There are also many exotic hadron candidates not fitting this pattern, leaving room for tetraquark and pentaquark states tightly bound directly by color interactions (diquarks or other color schemes?)
• The states of mixed nature, certainly must exist too
• We need a broad spectroscopy program to continue:
  – in the coming decade LHCb upgrades are likely to produce the largest amount of experimental information in the biggest variety of heavy quark configurations
  – the BESIII, and later new tau-charm factory, have their own variety of charmonium-like states to study above the open charm threshold. They also have unique access to light hadron spectroscopy, including glueballs.
  – Belle II has similar unique access to bottomonium-like states
  – Photoproduction of charmonium-like states at JLab or EIC can play an important role, if such states are produced with sufficient rates
  – Light hadron spectroscopy is not a settled subject and deserves a fresh look with beyond $q\bar{q},qqq$ models
• Improved confinement phenomenology would be an important tool is sorting out nature of all hadronic states observed in the data already, and predicting ones yet to be discovered