Substructure of Multiquark Hadrons

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Outline

- quarks are fundamental building blocks of protons, neutrons and all hadrons
- all quarks are equal, but heavy quarks are more equal than others

new combinations with heavy quarks, incl. exotics:

- newly discovered T_{cc}^{+} tetraquark $= (cc\bar{u}\bar{d})$
- stable $bb\bar{u}\bar{d}$ tetraquark
- hadronic molecules, esp. LHCb pentaquark
- *"like a new layer in the periodic table"*

- exotic, multiquark (m.q.) states predicted long before QCD: $\bar{q}\bar{q}qq$ mesons & $\bar{q}qqqq$ baryons (Gell-Mann & Zweig)
- at that early stage purely group-theoretical insights, $\equiv$ condition for color singlet
- first dynamical model by Jaffe in 1970-s
- no clear exp results for many years
- exp breakthrough in 2003, discovery of X(3872), first unambiguosly multiquark hadron
- in retrospective clear why no evidence in early searches for m.q. states:
  – to be observed, m.q. state needs to:
  – be narrow enough to stand out on bkg
  – have decay modes unavailable to ordinary hadrons

- m.q. with light quarks only:
  – many decay channels $\Longrightarrow$ wide
  – share decay channels
    & mix with excited ordinary hadrons

  $\Longrightarrow$ extremely difficult to pin down

- m.q. with heavy quarks ($Q = c, b$):

  very different

m.q. with heavy quarks ($Q = c, b$) very different,

$\bar{Q}Q\bar{q}q$, $QQ\bar{q}\bar{q}$, $\bar{Q}Qqqq$: heavy-light

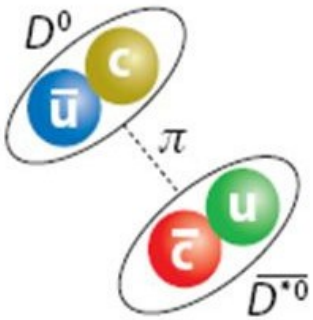
- $m_Q/\Lambda_{QCD} \gg 1 \Longrightarrow$ reduced E_k, easier binding
- unambiguous decay modes, e.g.
  $Z_b^+ \to \Upsilon\pi^+ \Rightarrow (\bar{b}b\bar{d}u)$,
  $T_{cc} \to D^0D^0\pi^+$, peaking at $D^0D^{*+} \Rightarrow (cc\bar{u}\bar{d})$
- due to their internal structure, many such systems have anomalously small $\Gamma \Rightarrow$ v. conspicuous
- $V_{QQ} \sim \alpha_s^2 m_Q \propto m_Q$.
  $\Rightarrow$ at least in one case have a
  $bb\bar{u}\bar{d}$ tetraquark below two meson threshold
  stable under strong interactions, only weak decay

Indeed, in recent years $\exists$ rapidly growing exp. evidence for exotic, *multiquark hadrons*, 4q mesons and 5q baryons. All cases with robust evidence contain at least one Q, the majority including $\bar{Q}Q$ or QQ.

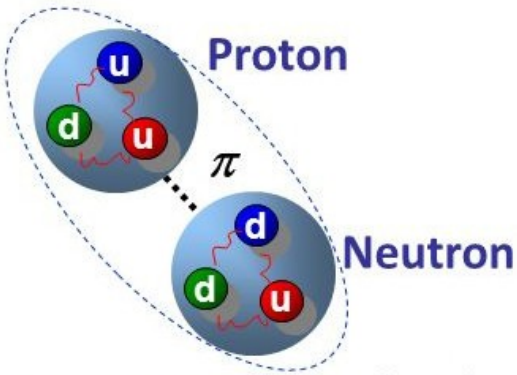
$\Longrightarrow$ two key questions:

- How are quarks organized inside them –
  as compact objects, w. all quarks in one confinement volume, perhaps with an important role played by diquarks, or as deuteron-like hadronic molecules?
- What additional multiquark states should we expect?

Hadronic molecules: deuteron-like



D^0–$\overline{D^{*0}}$ "molecule"

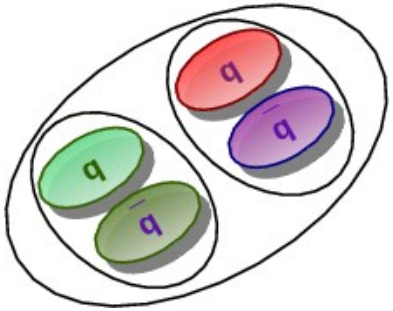


Deuteron: p-n molecule

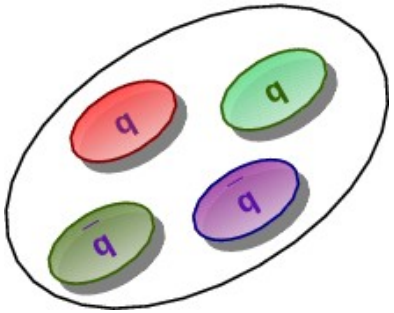
Tetraquarks: same 4 quarks, but tightly bound:

Hadronic Molecule

two color singlets attract through residual forces



Tetraquark



each quark sees color charges of all the other quarks

The two questions are tightly intertwined.

- Each interpretation provides a natural explanation of parts of the data, but neither explains all of the data.
- Quite possible that both kinds of structures appear in Nature.
- Certain states might be superpositions of the compact and molecular configurations.

robust research program combining EXP, TH & lattice

- now & in future: LHCb, Belle II, BESIII, GlueX
  hopefully also ATLAS, CMS & heavy ions
  in future: $\overline{\text{P}}$ANDA, EIC, super τ-charm factory, JLab exps
  v. high E resolution, v. high $\mathcal{L}$, superb particle id
  new algorithms for bkg reduction

- TH toolboxes, e.g.
  – S-matrix: JPAC Collaboration
  (Joint Physics Analysis Center, JLab & Indiana U.)
  – identify specific diffs btw models' predictions
  – instantons, effective string theory,...

- lattice QCD: (cf. 2203.03230)
  – treatment of unstable states, including width
  – decay to 3 or more hadrons
  – two baryon systems
  – $1/m_Q \ll a \;\Rightarrow$ algorithms for heavy Q, esp. b