Exotic hadrons and emergent long range correlation in QCD

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Introduction

Classification of hadrons

Observed hadrons

PDG2018: http://pdg.lbl.gov/

~ 150 baryons

~ 210 mesons

All ~ 360 hadrons emerge from single QCD Lagrangian.
Introduction

**Hadron clusters**

**Hadrons near an s-wave two-body threshold**

- $f_0(980)$: ~2 MeV
- $\Lambda(1405)$: ~15 MeV
- $D_{s0}(2317)$: ~45 MeV
- $X(3872)$: ~200 keV?
- $K$, $\bar{K}$: ~2 MeV
- $D$, $\bar{D}^*$: ~2 MeV
- $N$, $\bar{N}$: ~2 MeV
- $K$, $\bar{K}$: ~15 MeV

“hadronic molecules” (various flavors, baryon numbers, ...
Two-body universal physics

Near-threshold s-wave state: universal physics

E. Braaten, H.-W. Hammer, Phys. Rept. 428, 259 (2006);
P. Naidon, S. Endo, Rept. Prog. Phys. 80, 056001 (2017)

- scattering length $|a| \gg $ interaction range $r_e$
- size of (quasi-)bound state $\sim |a|$: loosely bound
- relation with eigenenergy $E$

$$a(E) \sim \frac{i}{k} = \frac{i}{\sqrt{2\mu E}}$$

Examples: $d$, $\Lambda(1405)$, $^4$He dimer

<table>
<thead>
<tr>
<th></th>
<th>NN [fm]</th>
<th>$\bar{K}$N [fm]</th>
<th>$^4$He [$a_0$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a(E)$</td>
<td>4.3</td>
<td>1.2-0.8i</td>
<td>178</td>
</tr>
<tr>
<td>$a_{emp}$</td>
<td>5.1</td>
<td>1.4-0.9i</td>
<td>189</td>
</tr>
<tr>
<td>$r_e$</td>
<td>1.4</td>
<td>0.4</td>
<td>10</td>
</tr>
</tbody>
</table>
Only **color singlet** states are observed.

-> Color confinement problem

Flavor quantum numbers are described by $qqq/q\bar{q}$.

Why no $qq\bar{q}\bar{q}$, $qqqq\bar{q}\bar{q}$, ... states (**exotic hadrons**)?

-> Exotic hadron problem, as not trivial as confinement!

~ 150 baryons

~ 210 mesons

All ~ 360 hadrons emerge from single QCD Lagrangian.
Introduction

Two-body potential

\[ V(r) \propto \frac{1}{r} \quad \text{: long (infinite) range} \]

\[ V(r) \propto \frac{e^{-mr}}{r} \quad \text{: finite (~1/m) range} \]

Hadron-hadron interaction is considered to be finite range.

- Longest interaction range
  
  \( \leftarrow \) exchange of lightest particle \((\pi) \sim 1 \text{ fm}\)

- Absence of the long range force is the basis for the (standard) scattering theory, Lüscher/HALQCD method, etc.

There can be (quasi) long range force beyond \(1 \text{ fm}\).

Emergence of long range correlation

**Low energy NN interaction : \( \pi \) exchange**

\[
\begin{align*}
N(k) & \quad \rightarrow \quad \bullet \quad \rightarrow \quad N(k') \\
N(p) & \quad \rightarrow \quad \bullet \quad \rightarrow \quad N(p') \\
\pi(q) &
\end{align*}
\]

- **Static approx.**
  \[ p^\mu = (M_N, p), \quad p'^\mu = (M_N, p'), \quad q^\mu = p'^\mu - p^\mu = (0, q) \]

- **Coupling**
  \[ g\bar{N}i \gamma_5 \pi N \sim g\chi^\dagger \sigma \cdot q\chi \]  
  *(isospin ignored)*

**Potential**

\[
V(r) \sim \text{F.T.} \left\{ g^2 \frac{\sigma_1 \cdot q}{q^2 + m^2_\pi} \frac{1}{(q^0)^2 - q^2 - m^2_\pi} \right\}
\]

**Tensor op.**

\[
\text{Yukawa} \quad \frac{e^{-m_\pi r}}{r}
\]
Emergence of long range correlation

**NN* potential (exchange)**

NN*(J^P=1/2-) interaction

\[ N^*(k) \rightarrow N(k') \]
\[ \pi(q) \]
\[ N(p) \rightarrow N^*(p') \]
\[ N^*(k) \rightarrow N^*(k') \]

Mass difference = energy transfer

\[ \Delta = M_{N^*} - M_N \]

- Static approx.

\[ p^\mu = (M_N, p), \quad p'^\mu = (M_{N^*}, p'), \quad q^\mu = (\Delta, q) \]

- Coupling

\[ \tilde{g} \ N^* \pi N \ + \ h.c. \sim \tilde{g} \ \chi^\dagger 1 \chi \]

Potential (\(P_\sigma\): spin exchange factor)

\[ V(r) \sim \text{F.T.} \left\{ \tilde{g}^2 \frac{1}{\Delta^2 - q^2 - m_\pi^2} \right\} P_\sigma = \text{F.T.} \left\{ \tilde{g}^2 \frac{-1}{q^2 + \mu^2} \right\} P_\sigma \sim \tilde{g}^2 P_\sigma \frac{e^{-\mu r}}{r} \]

- Sign of \(V(r)\) is fixed and attractive (c.f. \(\sigma\) exchange in NN)

- Effective mass \(\mu=0\) \(\rightarrow\) long range force (Coulomb like)
Emergence of long range correlation

What does $\mu = (m_\pi^2 - \Delta^2)^{1/2} = 0 \iff \Delta = m_\pi$ mean?

- $\Delta = m_\pi$: $N^*$ lies on top of the $\pi N$ threshold $\implies a_{\pi N} = \infty$

Unitary limit and zero-energy resonance

$\pi N$ wave function in $N^*$

Interaction range
Emergence of long range correlation

Remarks and toward physical realization

\(N^*N \sim \pi NN\) : effective description of three-body system

- No system with exact \(\mu = 0\) (\(N^*\): \(\Delta \sim 595\) MeV / \(m_\pi \sim 140\) MeV)
- Is there any system with small \(\mu\)?
Strange dibaryon

\( \Lambda(1405) = \Lambda^* : \bar{K}N \) quasibound state near the threshold


- \( \bar{K} \) exchange between \( \Lambda^* \) and \( N \)

\( \Lambda^* \) (at 1420 MeV), \( \bar{K}N \) threshold

\[ \Lambda^* \]

\[ \bar{K}N \]

\[ \Delta \sim 482 \]

\[ m_K \sim 495 \]

- \( \mu \sim 91 \) MeV: \( \bar{K} \) exchange has longer tail than expected

- attractive in spin singlet channel \( \rightarrow \bar{K}NN \) as \( \Lambda^*N \) system

We consider $D_{s0}(c\bar{s}, 0^+)D(c\bar{q}, 0^-)$ system via $K$ exchange

- Charm $C=2$: manifestly exotic $(cc\bar{q}\bar{s})$

$D_{s0}(2317)$, $KD$ threshold

$\Delta \sim 450$ $m_K \sim 495$

- $K$ exchange gives quasi-long range $(\mu \sim 200 \text{ MeV})$ attraction

Can the attraction generate a bound state?
Prediction of binding energy

Effective Lagrangian for $D_{s0}D^*K$ (and HQ partners) coupling

$$\mathcal{L} = \frac{h}{2} \text{Tr} [\bar{H}_a S_b A_{ab} \gamma_5] + \text{C.C.}$$

- coupling constant $h : D_0 \longrightarrow D^*\pi$ decay + SU(3) symmetry
- Short range cutoff $R_c \leftarrow$ hadron size

- $R_c \sim 0.5 \text{ fm} \rightarrow \sim 6 \text{ MeV binding}$
Long range correlation among hadrons emerges when the mass difference $\Delta$ matches with the mass of the exchange particle $m$.

$K$ exchange in $D_{s0}(0^+)D(0^-)$ system: $\mu \sim 200$ MeV

$\Rightarrow$ prediction of exotic charmed tetraquark