Exotic hadrons and emergent long range force in QCD

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Introduction

Classification of hadrons

Observed hadrons

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

Only **color singlet** states are observed.

→ Color confinement problem

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

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

→ Exotic hadron problem, as not trivial as confinement!

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**~ 150 baryons**

**~ 210 mesons**

All ~ 360 hadrons emerge from single QCD Lagrangian.
Two-body potential

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

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

Hadron-hadron interaction is considered to be finite range.

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

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

There can be (quasi) long range force beyond 1 fm.

Emergence of long range force

Low energy NN interaction: $\pi$ exchange

- 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

$$V(r) \sim \text{F.T.} \left\{ g^2 (\sigma_1 \cdot q)(\sigma_2 \cdot q) \frac{-1}{q^2 + m^2_{\pi}} \right\}$$

Tensor op. Yukawa $e^{-m_{\pi}r} \frac{r}{r}$
Emergence of long range force

**NN* potential (exchange)**

\[ \text{NN}^*(J^P=1/2^-) \text{ interaction} \]

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

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

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

- **Coupling**
\[ \tilde{\varepsilon} \bar{N}^* \pi N + \text{h.c.} \sim \tilde{\varepsilon} \chi^\dagger 1 \chi \]

**Potential** (\( P_\sigma : \text{spin exchange factor} \))
\[ V(r) \sim \text{F.T.} \left\{ \tilde{\varepsilon}^2 \frac{1}{\Delta^2 - q^2 - m^2_\pi} \right\} P_\sigma = \text{F.T.} \left\{ \tilde{\varepsilon}^2 \frac{-1}{q^2 + \mu^2} \right\} P_\sigma \sim \tilde{\varepsilon}^2 P_\sigma \frac{e^{-\mu r}}{r} \]

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

- **Effective mass** \( \mu = 0 \rightarrow \text{long range force (Coulomb like)} \)
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

s-wave resonance at threshold: unitary limit of $\pi N$ system

- Scattering length diverges $\rightarrow$ universal physics


- completely composite: w.f. of $N^*$ spreads to infinity.

Emergence of long range force

Origin of the long range force

Origin of the long range force

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

Realization in physical hadron systems

- No system with exact \( \mu = 0 \) \( (N^*: \Delta \sim 595 \text{ MeV} / m_\pi \sim 140 \text{ MeV}) \)
- Is there any system with small \( \mu \)? \( (c.f. \overline{KNN} \sim \Lambda^*N) \)

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 ($\mu \sim 200$ MeV) attraction

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

Effective Lagrangian for $D_{s0}DK$ (and HQ partner) coupling

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

- coupling constant $h : D_0 \rightarrow D\pi$ 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 force among hadrons emerges when the mass difference $\Delta$ matches with the mass of the exchange particle $m$.

\[ V(r) \sim e^{-\mu r} , \quad \mu = \sqrt{m^2 - \Delta^2} \]

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

$\rightarrow$ prediction of exotic charmed tetraquark