

## Scattering theory, effective field theory, and chiral dynamics

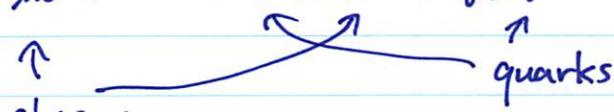
## § 0. Introduction

• Observed hadrons in PDG 2016

$$\left\{ \begin{array}{l} \sim 150 \text{ baryons } (\text{p}, \text{n}, \Lambda, \dots) \\ \sim 210 \text{ mesons } (\pi, K, \eta, \dots) \end{array} \right.$$

← All from QCD Lagrangian (color SU(3) gauge theory)

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \bar{q} (i\cancel{D} - m_q) q$$


  
 ↑                      ↗              ↑  
 gluons              quarks

• Experimental facts on hadron spectrum

- Hadrons are color singlet

No rule to forbid the existence of colored states in QCD

→ confinement problem

- Flavor quantum numbers can be expressed by  $qq\bar{q}\bar{q}$  or  $q\bar{q}$

No rule to forbid  $qq\bar{q}\bar{q}$  (or multiquarks) states in QCD

→ exotic hadron problem, as nontrivial as confinement!

(N.B. This is an experimental fact, nothing to do with quark model)

• Exotic candidates (recent, heavy sector)

- Pentaquark  $P_c(4450)$ ,  $P_c(4380)$  by LHCb, 2015

$$P_c \rightarrow J/\psi(c\bar{c}) + p(uud)$$

- Tetraquark  $Z_b(10610)$ ,  $Z_b(10650)$  by Belle, 2012

$$Z_b^\pm \rightarrow \gamma(b\bar{b}) + \pi^\pm(u\bar{d}/d\bar{u})$$

- Only a few ( $\sim 8$ ) out of  $\sim 360$

- Internal structure is not yet clarified.

• Exotic candidates (traditional, light sector)

- $\Lambda(1405)$ :  $S=-1$ ,  $I=0$ ,  $J^P=\frac{1}{2}^-$

quark model  $\rightarrow l=1$  uds state  $\rightarrow$  mass is too heavy

$\bar{K}N$  molecule? pentaquark? How can we distinguish?

- Scalar mesons  $\sigma$ ,  $K$ ,  $f_0(980)$ ,  $a_0(980)$ :  $J^P=0^+$

quark model  $\rightarrow l=1$   $g\bar{g}$  state  $\rightarrow$  mass ordering problem  
 $\sigma > K > f_0, a_0$

$\pi\pi$  molecule? tetraquark?

Study of structure of hadrons  $\Leftrightarrow$  How they are formed in QCD

- Unstable nature

$$P_c \rightarrow J/\psi p , Z_b^\pm \rightarrow \gamma \pi^\pm$$

$$\Lambda(1405) \rightarrow \pi \Sigma , \sigma \rightarrow \pi \pi , K \rightarrow K, \pi , \dots$$

All interesting hadrons are unstable against the strong decay,

→ They should be formulated as resonances in hadron scattering.

PDG 2017 update puts more weight on pole positions

rather than Breit-Wigner mass and width (see  $\Lambda(1405)$ ).

- Plan of this lecture

1. Scattering theory

Ref. J.R. Taylor, "Scattering theory" 1972

2. Effective field theory

Ref. E. Braaten, M. Kusunoki, D. Zhang

Ann. Phys. 323, 1770 (2008)

arXiv: 0709.0499 [cond-mat.other]

3. Chiral dynamics for meson-baryon scattering →  $\Lambda(1405)$

Ref. T. Hyodo, D. Jido

Prog. Part. Nucl. Phys. 67, 55 (2012)

arXiv: 1104.4474 [nucl-th]