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Scattering theory, effective field theory, and chiral dynamics

§0. Introduction

• Observed hadrons in PDG 2016

- ~150 baryons ($p, n, \Lambda, \cdots$)
- ~210 mesons ($\pi, K, \eta, \cdots$)

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

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \bar{q}(i\not{D} - m_q) q$$

($G^a_{\mu\nu}$: gluons; q: 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 qqq or $q\bar{q}$

  No rule to forbid $qqq\bar{q}\bar{q}$ (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)

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• Exotic candidates (recent, heavy sector)

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

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

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

  $Z_b^{\pm} \to \Upsilon\,(b\bar{b}) + \pi^{\pm}\,(u\bar{d}/d\bar{u})$

- Only a few (~ 8) out of ~ 360

- Internal structure is not yet clarified.

• Exotic candidates (traditional, light sector)

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

  quark model $\to \ell = 1$ uds state $\to$ mass is too heavy

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

- Scalar mesons σ, κ, $f_0(980)$, $a_0(980)$: $J^P = 0^+$

  quark model $\to \ell = 1$ $q\bar{q}$ state $\to$ mass ordering problem
  $\sigma > \kappa > f_0, a_0$

  $\pi\pi$ molecule? tetraquark?

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

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• Unstable nature

$P_c \to J/\psi\, p$, $Z_b^{\pm} \to \Upsilon\, \pi^{\pm}$

$\Lambda(1405) \to \pi\Sigma$, $\sigma \to \pi\pi$, $\kappa \to K, \pi$, ---

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]