QCD and the Strange Baryon Spectrum

M. Niiyama (Kyoto Sangyo Univ.)
QCD and the Strange Baryon Spectrum

Contents

1. Recent results and exotic candidates
   S=-1, -2, -3
2. Λ(1405)
   1. molecular picture
   2. two pole structure
   3. γp→K(890)Λ(1405) at SPring-8/LEPS2 in Japan
3. Summary
Quantum Chromo-Dynamics (QCD) and hadron physics

Running coupling constant of strong interaction
Quantum Chromo-Dynamics (QCD) and hadron physics

Running coupling constant of strong interaction

Low energy: non-perturbative region

High energy: perturbative region
Degrees-of-freedom for hadron

- Constituent quark model
  - guiding principle
- “Exotic” non-3q/q̅q hadrons
- Hadronic molecules
  - hadrons as building blocks of a hadron
  - most candidates appear near the threshold
    - \( \Lambda(1405): \overline{K}N, \chi(3872): \overline{D}D^*, P_{cc}: \overline{D}\Sigma_c, \overline{D}^*\Sigma_c \)
- Compact exotic hadron
  - 3<quarks in a confinement bag
  - diquark DOF may appear
Spectroscopy of hyperon resonances

4 star (⭐️) rating by PDG

S=-1

- 10 Λ states, 6 Σ states

Several exotic candidates
- Λ(1380)/Λ(1405)
- K\bar{N}, πΣ
- Λ’s around 1.67 GeV
- and more ...
Two pole structure for $\Lambda$ below KN threshold

$\Lambda(1405)$:

- pole $\sim 1420$ MeV (Kaonic Hydrogen)

$\Lambda(1380)$:

- newly assigned state

T. Hyodo, D. Jido, Prog. Part. Nucl. Phys. 67, 55 (2012)

T. Hyodo, M. Niiyama, PPNP 120, 103868 (2021)
**Λ’s around 1.67 GeV**

- Belle observed narrow peaking structure in $M(K^- p)$ of $Λ_c → pK^- π^+$ around 1663 MeV ($Λ_η = 1663.5$ MeV) (PRL117,011801, Workshop on singly and doubly charmed baryons)

- ~10 MeV width: narrower than known resonances (25~200 MeV).

- Two groups claim narrow resonances from $K^- p → Λ_η$ data
  - $J^P=3/2^+, M=1671^{+2,-8}$ MeV, $Γ=10^{+22,-4}$ MeV (Kamano et al., PRC90.065204, PRC92.025205)
  - $J^P=3/2^-, M=1668.5±0.5$ MeV, $Γ=1.5±0.5$ MeV (Liu&Xie, PRC85.038201, PRC86.055202)

- New experiment at J-PARC (E72)
Spectroscopy of hyperon resonances

$S=-2$

- $\Xi, \Xi(1530)$ : ★★★★★
- $\Xi(1690), \Xi(1820), \Xi(1950), \Xi(2030)$ : ★★★★

$S=-3$

- only 5 states in PDG
- $\Omega(2012), \Omega(2250)$ : ★★★★

Exotic candidates

- $\Xi(1620), \Xi(1690), \Xi(1820)$
- $\Omega(2012)$ ...
Excited Ξ states

- **Belle**: \( \Xi(1620), \Xi(1690) \) in \( \Xi_c^+ \rightarrow \Xi^+ \pi^+ \pi^+ \), (PRL122, 072501 (2019))
  - \( \Xi(1620) \) @ \( 1610.4 \pm 6.0^{+6.1}_{-4.2} \) MeV, \( \Gamma \sim 60 \) MeV

- **BES III**: \( \Xi(1690), \Xi(1820) \) in \( \psi(3686) \rightarrow K^- \Lambda \Xi^+ \) (PRD 91, 092006 (2015), PRD 109, 072008 (2024))
  - \( \Xi(1690) \) \( 1/2^- \) @ \( 1685^{+3}_{-2} \pm 12 \) MeV, \( \Gamma \sim 81 \) MeV
  - \( \Xi(1820) \) \( 3/2^- \) @ \( 1821^{+2}_{-3} \pm 3 \) MeV, \( \Gamma \sim 73 \) MeV

![Graphs showing Belle and BES III data](image_url)
• Low-lying states, $\Xi(1620), \Xi(1690)$ 1/2-
• Constituent quark model predicts heavier states
• Lattice QCD also predicts heavier states
  R.G. Edwards et al., PRD87, 054506 (2013)
• Discussions on the internal structure, mostly based on meson-baryon molecular picture ($\pi\Xi, \bar{K}\Lambda, \bar{K}\Sigma$)
  • K.Miyahara et al., PRC 95, 035212 (2017)
  • H.P.Li et al., Eur. Phys. J. C (2023) 83:954
  • and ...
• Large width of $\Xi(1820), \Gamma=73^{+6.5}\pm 9$ MeV
• two states may overlap? M.Y. Duan et al., Eur. Phys. J. C (2024) 84:947
Excited $\Omega$ state

- Belle: $\Omega(2012)$ in $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ decay (PRL121, 052003 (2018), arXiv:2207.03090)
  and $\Omega_c \to \pi^+ (\Xi\overline{\Xi})^-$ (PRD 104, 052005 (2021))
- $M = 2012.4 \pm 0.7$ (stat) $\pm 0.6$ (syst),
- $\Gamma \sim 6.4$ MeV
- Lattice: $3/2^-$
  (R.J. Hudspith et al., (arXiv:2404.02769))
  $1/2^-$ or $3/2^-$
  (L. Hockley et al., (arXiv:2408.16281))
- QCD sum rule: $1/2^-$ or $3/2^-$
  (N. Su et al., (NPPP 347 (2024)))
- Meson-baryon ($\Xi\overline{\Xi}(1530)$, $\eta\Omega$, $\Xi\overline{\Xi}$) molecular picture
  - J.X Lu et al., (EPJ C (2020) 80:361)
  - N. Ikeno et al., (PRD 101, 094016 (2020))
  - and ...
• Meson baryon molecule?
• Two pole structure?

Λ(1380)/Λ(1405)

T. Hyodo, M. Niiyama, PPNP 120, 103868 (2021)
3 quark or hadron molecule? (I) Lattice QCD

- Magnetic form factor (J.M.M. Hall et al., PRL 114, 132002 (2015))
  - contribution from strange quark vanish
  - strange quark spin is hidden in the kaon
  → evidence as $\bar{K}N$ molecule
3 quark or hadron molecule? (II)

- Constituent quark counting rule for hard exclusive reaction
  - $\gamma p \rightarrow K^+ Y$ reactions (J-Lab CLAS) (W.C. Chang et al. PRD93 034006)

$$\frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(t/s) \quad n = n_\gamma + n_b + n_c + n_d$$

- $n=9$ for 3q hyperons
- $n=9$ for ground state $\Lambda$, $\Sigma$
- Not conclusive for excited states
- Higher energy data, J-LAB, J-PARC?
Two pole structure

- $\Lambda(1405)$:
  - pole $\sim 1420$ MeV
  - strongly couples to $\bar{K}N$

- $\Lambda(1380)$:
  - newly assigned state
  - $\pi\Sigma$ resonance?

D. Jido, et al. NPA725 (2003)

V.K. Magas, E. Oset and A. Ramos, PRL 95

LEPS, M.Niiyama et al., PRC78
Two pole structure

- $\Lambda(1405)$: ⭐⭐⭐⭐⭐
  - pole $\sim 1420$ MeV
  - strongly couples to $\bar{K}N$
- $\Lambda(1380)$: ⭐⭐
  - newly assigned state
  - $\pi\Sigma$ resonance?

D. Jido, et al. NPA725(2003)

V.K. Magas, E. Oset and A. Ramos, PRL 95
$\Lambda(1405)/\Lambda(1380)$ using linearly polarized photon beam

Linear pol $\gamma +$ vector $K^*$ meson : Parity filter

$\gamma p \rightarrow K(890)^+ \Lambda^*$
$\Lambda(1405)/\Lambda(1380)$ using linearly polarized photon beam

T. Hyodo et al, PLB593
Solenoid spectrometer at LEPS2/SPring-8 in Japan

• 1.4-2.9 GeV photon beam with 1 Mcps
• Charged particle, photon, neutron counters
Summary

• Many new measurements of strange baryons
  • $S=-1$, $\Lambda(1380), \Lambda(1405)$, $\Lambda$’s around 1.67 GeV
  • $S=-2$, $\Xi(1620), \Xi(1690), \Xi(1820)$
  • $S=-3$, $\Omega(2012)$

• non-3q exotic candidates
  • meson-baryon picture

• $\Lambda(1405)$
  • magnetic FF from lattice: $\bar{K}N$ molecule
  • constituent quark counting

• $\Lambda(1380)/\Lambda(1405)$
  • Parity filter using linear pol. $\gamma$ and $K^*$ associate production using solenoid spectrometer at SPring-8 in Japan