Physics impacts of Ω baryon spectroscopy

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On behalf of J-PARC K10 Beam Line Task Force

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- Features of Ω baryon (ground state)
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Features of Ω baryon (ground state)

First observation of Ω baryon

- BNL AGS K$^-$ beam
  Hydrogen bubble chamber

VOLUME 12, NUMBER 8 PHYSICAL REVIEW LETTERS 24 FEBRUARY 1964

OBSERVATION OF A HYPERON WITH STRANGENESS MINUS THREE*

V. E. Barnes, P. L. Connolly, D. J. Crennell, B. B. Culwick, W. C. Delaney, W. B. Fowler, P. E. Hagerty,† E. L. Hart, N. Horwitz,† P. V. C. Hough, J. E. Jensen, J. K. Kopp, K. W. Lai, J. Leitner,† J. L. Lloyd, G. W. London,‡ T. W. Morris, Y. Oren, R. B. Palmer, A. G. Prodell, D. Radojičić, D. C. Rahm, C. R. Richardson, N. P. Samios, J. R. Sanford, R. P. Shutt, J. R. Smith, D. L. Stonehill, R. C. Strand, A. M. Thorndike, M. S. Webster, W. J. Willis, and S. S. Yamamoto
Brookhaven National Laboratory, Upton, New York
(Received 11 February 1964)

First observation of Ω baryon

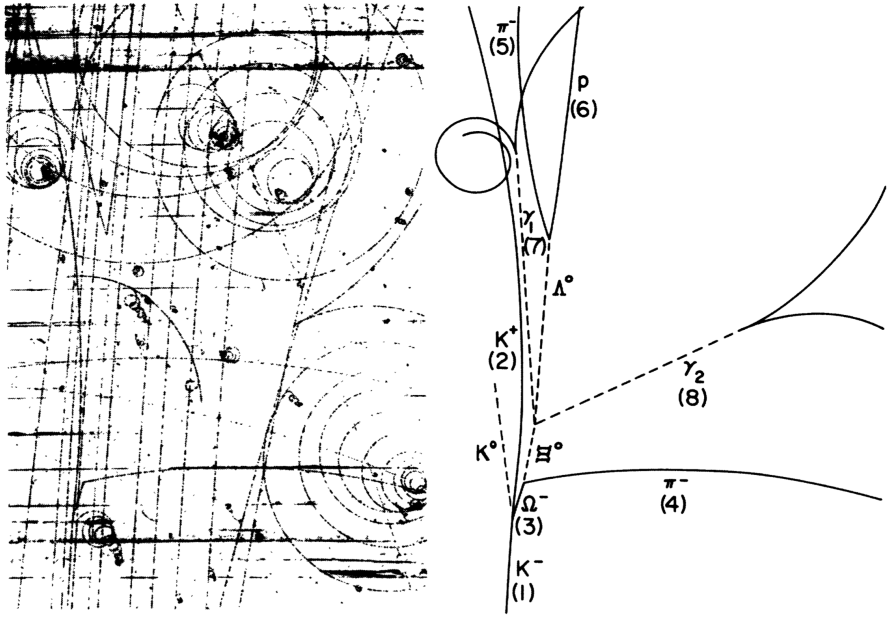
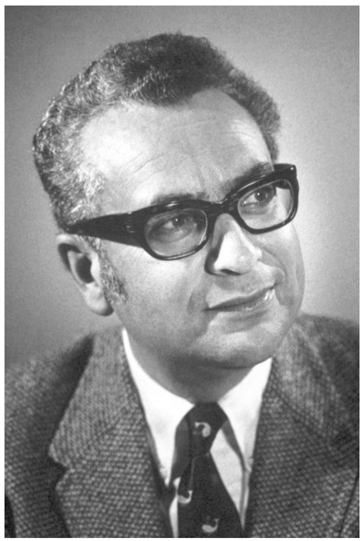


FIG. 2. Photograph and line diagram of event showing decay of Ω⁻.

Table I. Our interpretation of this event is

$$K^- + p \to \Omega^- + K^+ + K^0$$
$$\quad \hookrightarrow \Xi^0 + \pi^-$$
$$\qquad \hookrightarrow \Lambda^0 + \pi^0$$
$$\qquad\qquad \pi^0 \hookrightarrow \gamma_1 + \gamma_2$$
$$\qquad\qquad\qquad \gamma_2 \hookrightarrow e^+ + e^-$$
$$\qquad\qquad\qquad \gamma_1 \hookrightarrow e^+ + e^-$$
$$\qquad\qquad \Lambda^0 \hookrightarrow \pi^- + p.$$

- This supported Murray Gell-Man's Nobel Prize in Physics 1969.



Properties of Ω baryon

$$I\left(J^P\right) = 0\left(\frac{3}{2}^+\right)$$

Mass: 1672.45 ± 0.29 MeV [PDG2020]

Mean Life: (0.821 ± 0.011) 10^{-10} s [PDG2020]

Ω^- MAGNETIC MOMENT

VALUE (μ_N)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
−2.02 ±0.05 OUR AVERAGE					
−2.024±0.056	235k	WALLACE	95	SPEC	Ω^- 300–550 GeV
−1.94 ±0.17 ±0.14	25k	DIEHL	91	SPEC	Spin-transfer production

Properties of Ω baryon

Ω^- DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	ΛK^-		(67.8 ± 0.7) %	
Γ_2	$\Xi^0\pi^-$		(23.6 ± 0.7) %	
Γ_3	$\Xi^-\pi^0$		(8.6 ± 0.4) %	
Γ_4	$\Xi^-\pi^+\pi^-$		$(3.7^{+0.7}_{-0.6})\times10^{-4}$	
Γ_5	$\Xi(1530)^0\pi^-$		$<7\times10^{-5}$	90%
Γ_6	$\Xi^0e^-\overline{\nu}_e$		$(5.6\pm2.8)\times10^{-3}$	
Γ_7	$\Xi^-\gamma$		$<4.6\times10^{-4}$	90%
	$\Delta S = 2$ forbidden ($S2$) modes			
Γ_8	$\Lambda\pi^-$	$S2$	$<2.9\times10^{-6}$	90%

Non-leptonic weak decays

From the semi-leptonic decay: the form factor may be observed if we can produce many Ω
Size information of Ω may be obtained.

Features of Ω baryon

- Only the stable spin 3/2 state
- Valence quark component is sss.
- Flavor W.F. is symmetric -> Spin W. F. is symmetric
  -> all the diquark pairs are “bad” diquarks.
- If light (u,d) sea quark component is negligible, Ω cannot couple with the pion.
  -> no pion cloud
  -> simple structure?
  -> smaller than other hyperons?

Features of Ω baryon

- No instanton induced interaction
- Large Nc behavior may be different from Nucleon (soliton made of pion field)
- Skyrmion -> bound three kaon system?
- Clear decuplet state since no decay to octet baryon + NG boson

$\Omega(2012)^-$ (1P state)

Properties of $\Omega(2012)^-$ baryons

$\Omega(2012)^-$

$I(J^P) = 0(?^-)$ Status: ∗∗∗

J^P is not determined.

Seen in $\Xi^0 K^-$ and $\Xi^- K^0_S$ decays with a combined significance of 8.3 standard deviations.

340 MeV above Ω gs

$\Omega(2012)^-$ MASS

Observed in 2018 at Belle

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2012.4±0.7±0.6	520	YELTON	18A	BELL	In $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

$\Omega(2012)^-$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{6.4^{+2.5}_{-2.0}\pm1.6}$	520	YELTON	18A	BELL	In $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

Small width

PDG 2020

Properties of $\Omega(2012)^-$ baryons

$\Omega(2012)^-$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	ΞK		
Γ_2	$(\Xi\pi)K$		
Γ_3	$\Xi^0 K^-$	**DEFINED AS 1**	
Γ_4	$\Xi^- K^0$	0.83 ± 0.21	
Γ_5	$\Xi^- \overline{K}^0$		
Γ_6	$\Xi^0 \pi^0 K^-$	<0.30	90%
Γ_7	$\Xi^0 \pi^- \overline{K}^0$	<0.21	90%
Γ_8	$\Xi^- \pi^0 \overline{K}^0$		
Γ_9	$\Xi^- \pi^+ K^-$	<0.08	90%

PDG 2020

Properties of Ω(2012)⁻ baryons

J. Yelton et al., PRL 121, 052003

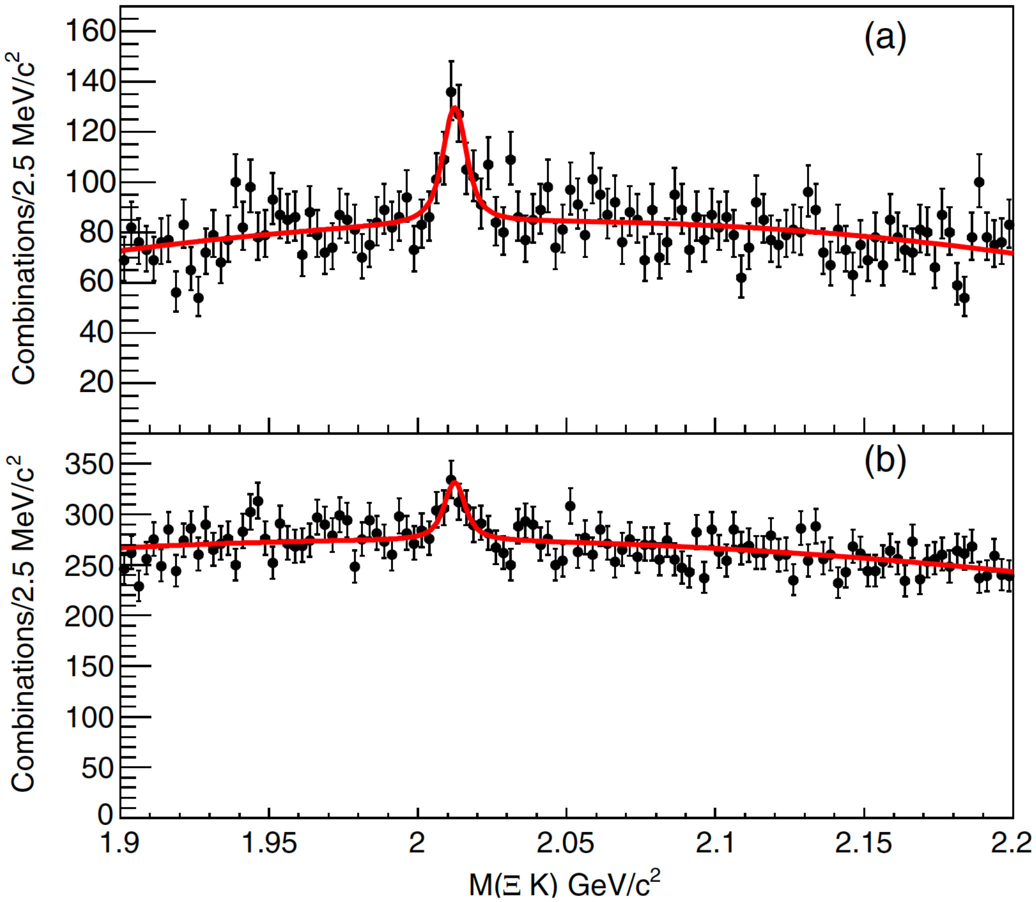


FIG. 2. The (a) $\Xi^0 K^-$ and (b) $\Xi^- K^0_S$ invariant mass distributions in data taken at the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ resonance energies. The curves show a simultaneous fit to the two distributions with a common mass and width.

J^P of $\Omega(2012)^-$ state

- Theoretical models predict a $J^P = 1/2^-$ and $J^P = 3/2^-$ pair of excited Ω^- state in this mass region.
- Ω^{*-} with $J^P = 3/2^-$ is restricted to decay to ΞK via a d wave, whereas a state with $J^P = 1/2^-$ could decay via s wave.
- The rather narrow width prefers $J^P = 3/2^-$ interpretation.

Hadronic molecule interpretation of $\Omega(2012)^-$ state

- $\Omega(2012)^-$ as a $K\Xi(1530)$ hadronic molecule

[7] Y. H. Lin and B. S. Zou, Phys. Rev. D **98**, 056013 (2018).
[8] M. P. Valderrama, Phys. Rev. D **98**, 054009 (2018).
[9] Y. Huang, M. Z. Liu, J. X. Lu, J. J. Xie, and L. S. Geng, Phys. Rev. D **98**, 076012 (2018).
[10] R. Pavao and E. Oset, Eur. Phys. J. C **78**, 857 (2018).

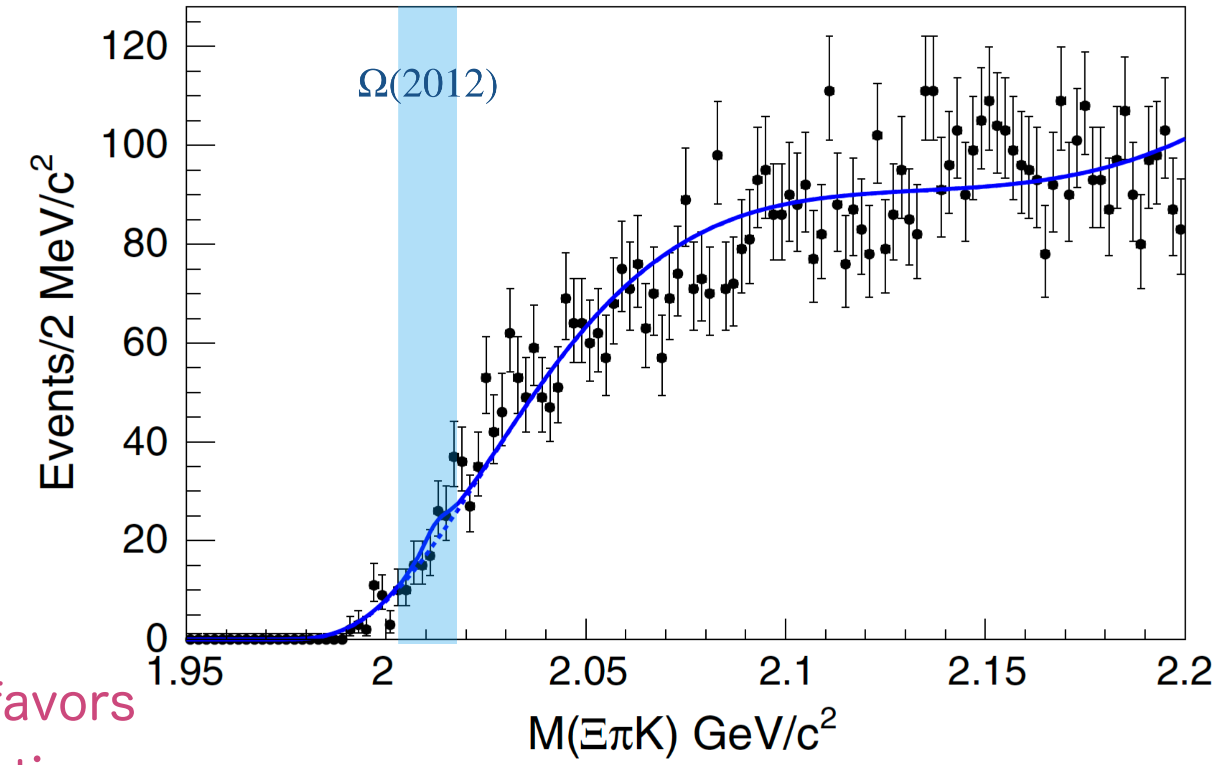
Threshold: 2025.5 MeV, 13.1 MeV above $\Omega(2012)^-$ mass

- A large decay width for $\Omega(2012)^- \to K\pi\Xi$

Properties of Ω(2012)⁻ baryons

S. Jia et al., PRD 100, 032006

Search for $\Omega(2012) \to K\Xi(1530) \to K\pi\Xi$ at Belle



No significant signals are observed.

This result strongly disfavors the molecular interpretation.

FIG. 5. The final simultaneous fit result to all three-body $\Omega(2012)$ decay modes from the combined $\Upsilon(1S, 2S, 3S)$ data samples. The solid curve is the best fit, and the dashed line represents the backgrounds.

Other Ω^{*-} states

Other Ω^{*-} states

- J^P is not fixed in any state.

State	Mass (MeV)	Width (MeV)	Decay mode
$\Omega(2250)^-$	2252±9	55±18	$\Xi^-\pi^+K^-$ $\Xi(1530)^0K^-$
$\Omega(2380)^-$	2380±9±8	26±23	$\Xi^-\pi^+K^-$ $\Xi(1530)^0K^-$ $\Xi^-\bar{K}^*(892)^0$
$\Omega(2470)^-$	2474±12	72±33	$\Omega^-\pi^+\pi^-$

Constituent Quark Model as Effective Theory of Low-Energy QCD

Revival of the constituent quark model

- Constituent quark: quasiparticle corresponding to the dynamical chiral symmetry breaking -> NJL model picture or Instanton Liquid picture
- Current quark masses give explicit chiral symmetry breaking.
- Constituent quark couples to NG bosons by Goldberger-Treiman relation
- Constituent quarks are bound to a hadron by the linear confinement + Coulomb force

Modern view of the constituent quark model

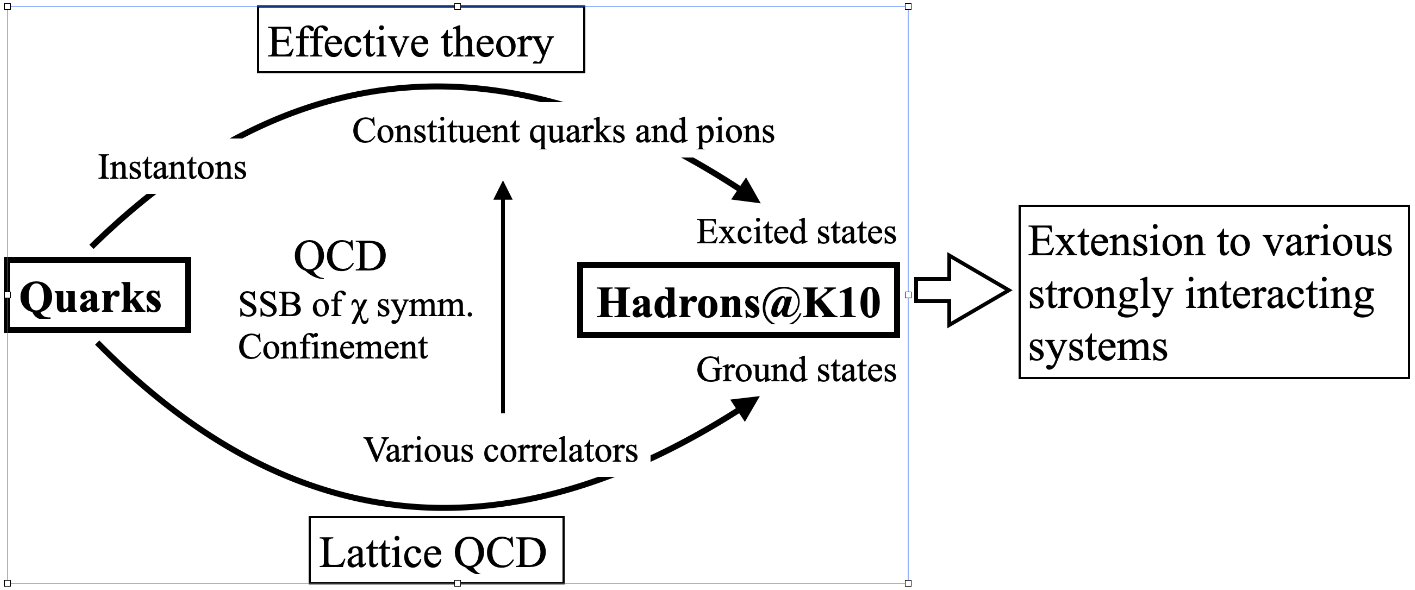
- Constituent quarks with Nambu-Goldstone bosons:
  Manohar-Georgi, NPB234 (1984) 189

$$\rightarrow \mathscr{L} = \bar{\psi}(iD + V)\psi + g_A \bar{\psi} A \gamma_5 \psi - m\bar{\psi}\psi + \frac{1}{4} f_\pi^2 \mathrm{tr}\,\partial^\mu U \partial_\mu U^\dagger - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \cdots$$

An effective theory for 0.2 fm < r < 1 fm (confinement)

with Important building blocks:

Constituent quarks in the "core region" and **pions** (cloud)



Baryon spectrum in the constituent quark model

- S. Capstick and N. Isgur, PRD34 (1986) 2809
- Relativistic Kinematics with string + Coulomb spin independent interactions + hyperfine spin-spin + tensor interactions +spin-orbit interactions

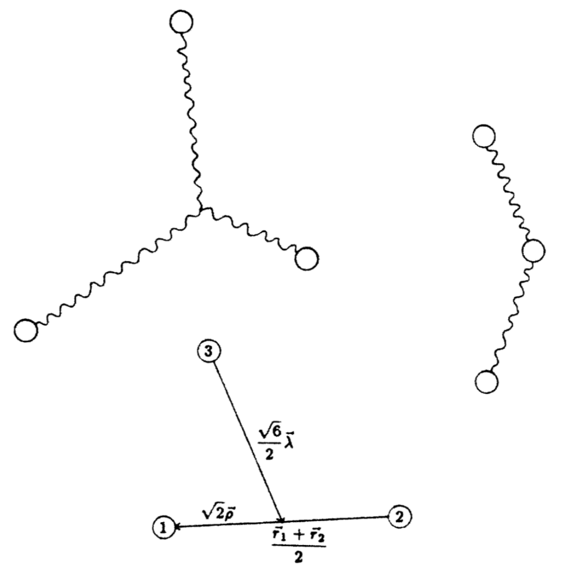


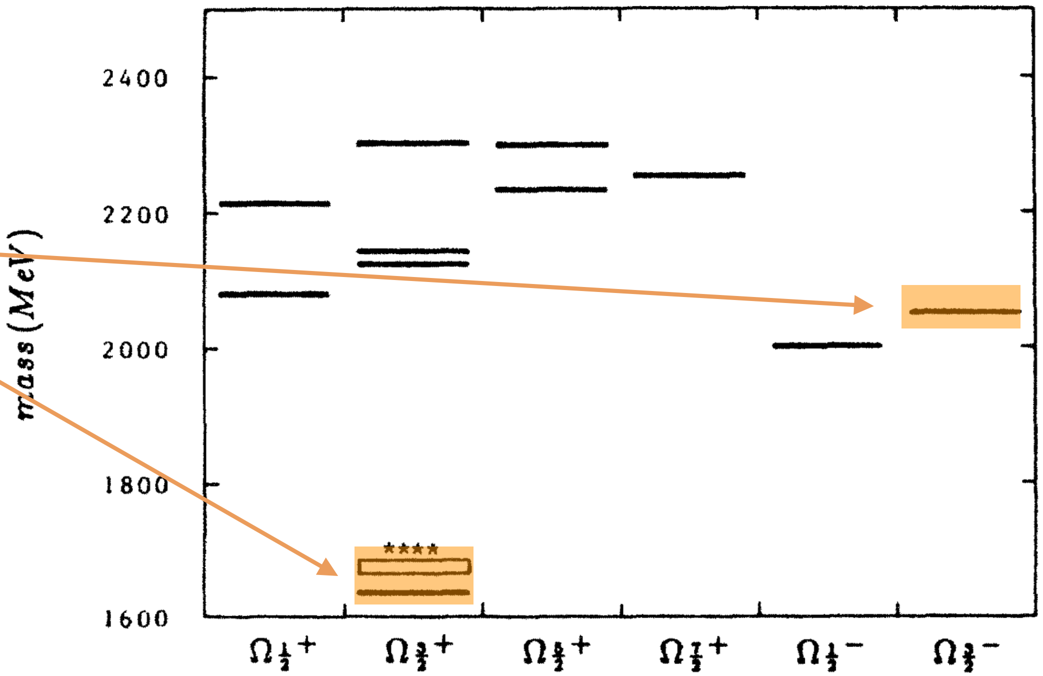
FIG. 1. The gauge-invariant string configurations and the relative coordinates $\boldsymbol{\rho}$ and $\boldsymbol{\lambda}$.

- Most of the parameters are determined from meson sector. S. Godfrey and N. Isgur, PRD 32 (1985) 189

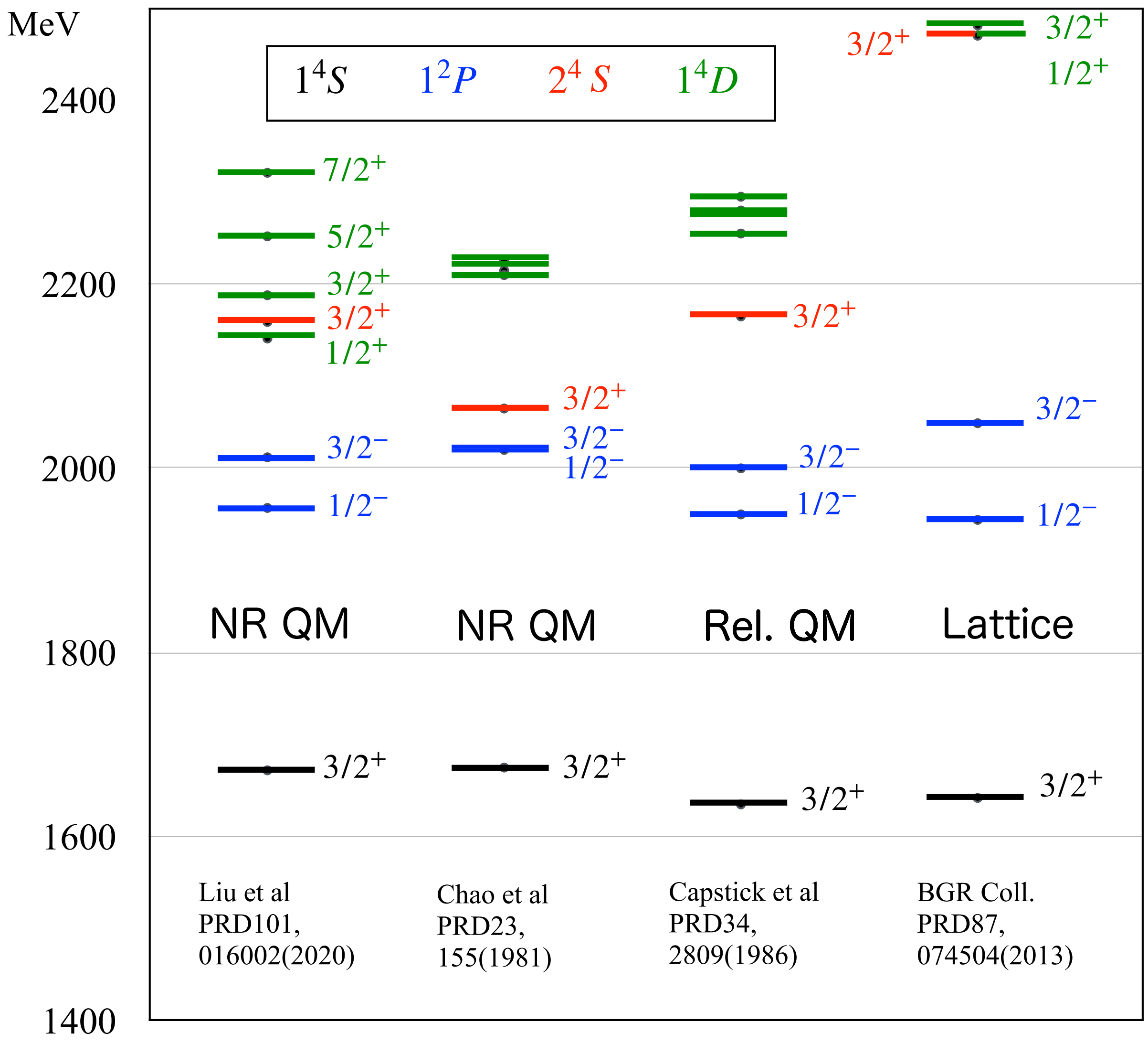
Baryon spectrum in the constituent quark model

Ω baryon mass is not used for the determination of the model parameters.

$\Omega\frac{3}{2}^+$	1635		
$\Omega^*\frac{1}{2}^-$	1950	2410	2490
$\Omega^*\frac{3}{2}^-$	2000	2440	2495
$\Omega^*\frac{5}{2}^-$	2490		
$\Omega^*\frac{1}{2}^+$	2220	2255	
$\Omega^*\frac{3}{2}^+$	2165	2280	2345
$\Omega^*\frac{5}{2}^+$	2280	2345	
$\Omega^*\frac{7}{2}^+$	2295		



Ω spectrum in the constituent quark models



Ω* strong decays in the constituent quark model

TABLE VI. The strong decay widths (MeV) of Ω baryons up to $N = 2$ shell. $\Gamma^{th}_{\text{total}}$ stands for the total decay width and $\mathcal{B}$ represents the ratio of the branching fraction $\Gamma[\Xi K]/\Gamma[\Xi(1530)K]$.

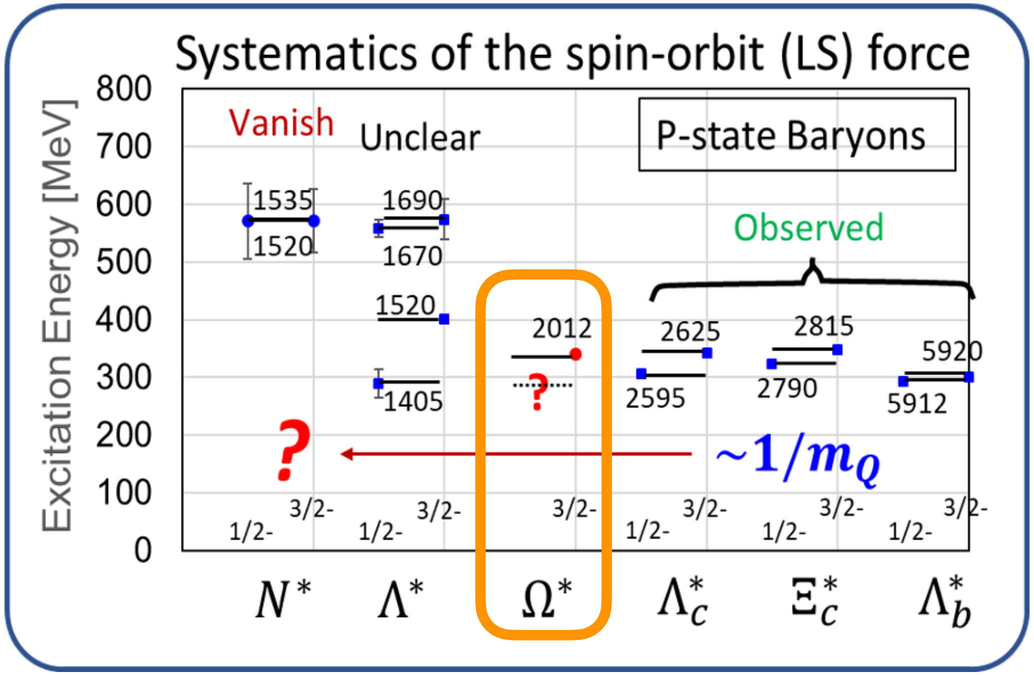
				$\Gamma[\Xi K]$		$\Gamma[\Xi(1530)K]$		$\Gamma[\Omega(1672)\eta]$		$\Gamma^{th}_{\text{total}}$		$\mathcal{B}$	
Exp.	$n^{2S+1}L_{J^P}$	Mass	α (MeV)	Ours	Ref. [16]	Ours	Ref. [16]	Ours	Ref. [16]	Ours	Ref. [16]	Ours	Ref. [16]
	$1^2P_{\frac{1}{2}^-}$	1957	428	12.43	12.64	⋯	⋯	⋯	⋯	12.43	12.64	⋯	⋯
6.4	$1^2P_{\frac{3}{2}^-}$	2012	411	5.69	5.81	⋯	⋯	⋯	⋯	5.69	5.81	⋯	⋯
	$2^2S_{\frac{1}{2}^+}$	2232	387	0.04	0.27	5.09	8.32	0.006	0.08	5.14	8.67	0.008	0.03
	$2^4S_{\frac{3}{2}^+}$	2159	381	0.99	4.72	5.12	8.96	⋯	⋯	6.11	13.68	0.19	0.53
	$1^2D_{\frac{3}{2}^+}$	2245	394	2.49	2.52	4.27	4.24	0.055	0.06	6.82	6.82	0.58	0.59
	$1^2D_{\frac{5}{2}^+}$	2303	380	3.07	3.04	14.30	14.51	1.65	1.81	19.02	19.36	0.21	0.21
	$1^4D_{\frac{1}{2}^+}$	2141	413	39.52	39.34	2.17	2.21	⋯	⋯	41.69	41.55	18.21	17.80
	$1^4D_{\frac{3}{2}^+}$	2188	399	20.25	20.26	10.93	10.92	⋯	⋯	31.18	31.18	1.85	1.86
~23	$1^4D_{\frac{5}{2}^+}$	2252	383	5.28	5.21	21.37	21.48	0.79	0.90	27.44	27.59	0.25	0.24
	$1^4D_{\frac{7}{2}^+}$	2321	367	34.38	34.36	7.17	7.00	0.066	0.13	41.62	41.49	4.79	4.91

Ming-Sheng Liu et al., PRD101, 016002 (2020)

Strong decay widths are well reproduced.

Spin-Orbit
Interaction (LS force)

LS force: Long-standing problem



- Systematics of spin-orbit interaction

  Disappears in N^*

  (OGE/Instanton Induced Interaction (III) cancelled)

  Appears in $\Lambda^*_{c(b)}$ (OGE only)

LS force in Ω*

- III: no contribution
  III is flavor antisymmetric
  wavefunction: sss flavor symmetric -> no contribution

- 2 body LS force: no contribution
  wavefunction:
  color antisymmetric
  flavor symmetric (ss)
  orbital antisymmetric (P-wave)
  -> spin should be antisymmetric (S = 0), threfore, no LS force

- 3 body LS force is introduced in some constituent quark models

$$V_{ij}^{LS} = \frac{\alpha_{\mathrm{SO}}}{\rho^2 + \lambda^2} \cdot \frac{\mathbf{L} \cdot \mathbf{S}}{3(m_1 + m_2 + m_3)^2}.$$

S: total spin of baryon,
L: total orbital angular momentum of baryon

In order to understand LS force

- Search for the LS partner of $\Omega(2012)^-$ is important

  -> missing mass spectroscopy is very strong method for the states search

- Determination of the spin-parity of $\Omega(2012)^-$ is important

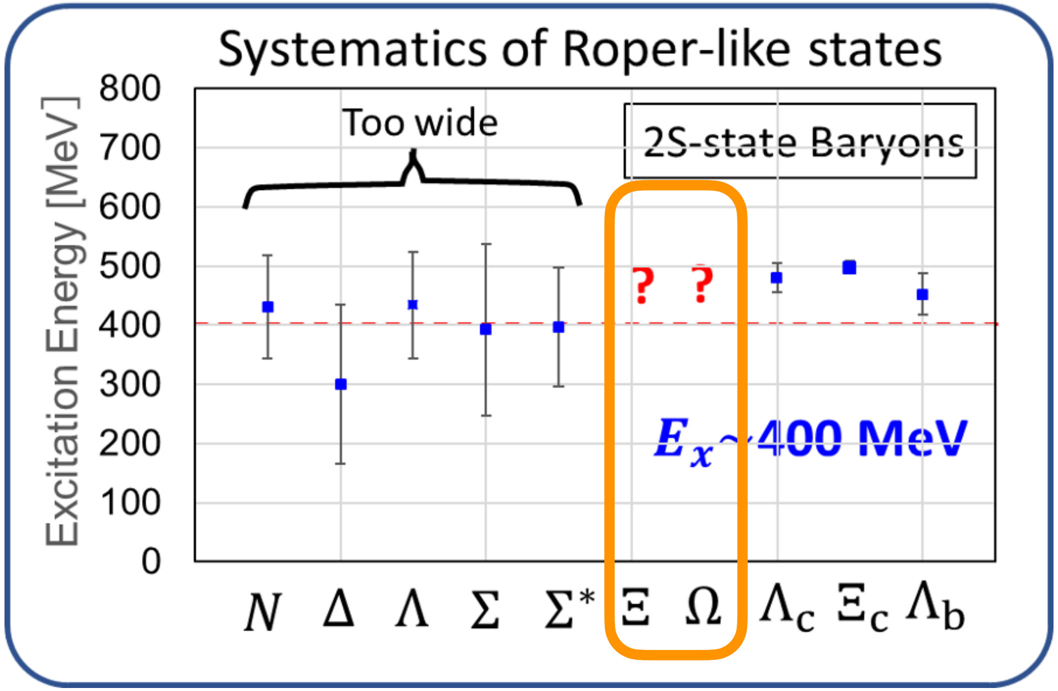
  -> high statistics, high resolution measurement is necessary

- K10 beam line is suitable for these purposes
  -> Shirotori-san's talk

Roper-like state

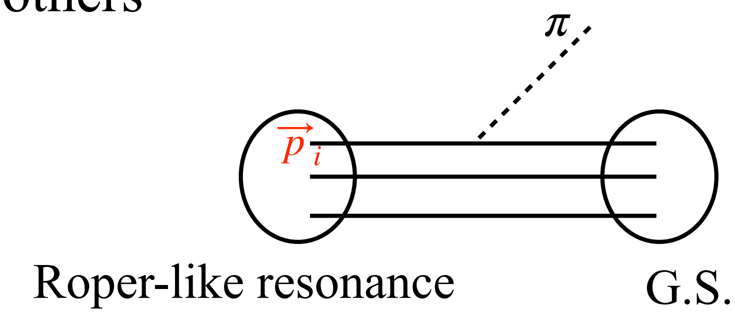
(2S state)

Roper-like state: Long-standing problem



- Systematics of Roper-like states
  (Radial excitation 2S states)
  Mass universality (independent of flavors)?
  What deteremines the width of them?

Decay width ~ Narrow in the quark model
~ 6 - 10 MeV in contrast with the others



$$\mathscr{L}_{\pi qq} = \frac{g_A^q}{f_\pi} \bar{q}\gamma_\mu\gamma_5\lambda_a q \, \partial^\mu\phi^a$$

$$\rightarrow \frac{g_A^q}{f_\pi}\left(\overbrace{\vec{\sigma}\cdot\vec{q}}^{\mathscr{O}(1)} + \overbrace{\frac{\omega_\pi}{2m_q}(\vec{\sigma}\cdot\vec{q} - 2\vec{\sigma}\cdot\vec{q})}^{\mathscr{O}(1/m_q)} \right)$$

$$+ \frac{g_A^q}{f_\pi}\left(\frac{m_\pi^2}{8m_q^2}\vec{\sigma}\cdot\vec{q} + \overbrace{\frac{1}{4m_q^2}\vec{\sigma}\cdot(\vec{q} - 2\vec{p}_i)\times(\vec{q}\times\vec{p}_i)}^{\mathscr{O}(1/m_q^2)} \right)$$

Quark internal momentum

Small in former calculations
$\mathscr{O}(1)$ Suppressed: ***selection rule***

$\mathscr{O}(1/m_q^2)$ **large** $\langle p_i^2 \rangle \sim \dfrac{1}{\langle r^2 \rangle}$

$$\Gamma_{\Omega(Roper)} \sim 50 - 100 \text{ MeV}$$ Arifi et al, *PRD* 103 (2021) 9, 094003

Roper-like state in Ω^*

- Mass ~ 1670 + 400 = 2070 MeV?

- Not observed in this mass region

  $\Omega(2012)^-$, $\Omega(2250)^-$, $\Omega(2380)^-$, $\Omega(2380)^-$, $\Omega(2470)^-$

- Width ~ 50 - 100 MeV?

  information of the baryon size.

  sensitive to the spatial extent of the wavefunction

In order to understand Roper-like states

- Search for the Roper-like states of Ω^{*-} and Ξ^{*} is important
  -> missing mass spectroscopy is very strong method
  for the states search

- Measurement of large-width (50 - 100 MeV) state
  -> high statistics, high resolution measurement is necessary

- Systematic study of Roper-like states from light flavor to heavy flavor is important
  -> high momentum beam line to K10 beam line

- K10 beam line is suitable for these purposes
  -> Shirotori-san’s talk

ΩN interaction

ΩN interaction in the quark cluster model

- No Pauli blocking effect.
- No One Pion Exchange Potential
- ΩN J=2 state decays to $\Lambda\Xi$ by D-wave.
- Origin of the attraction is Color Magnetic Interaction.

ΩN interaction

M. Oka, PRD 38 (1988) 298

Quark cluster model

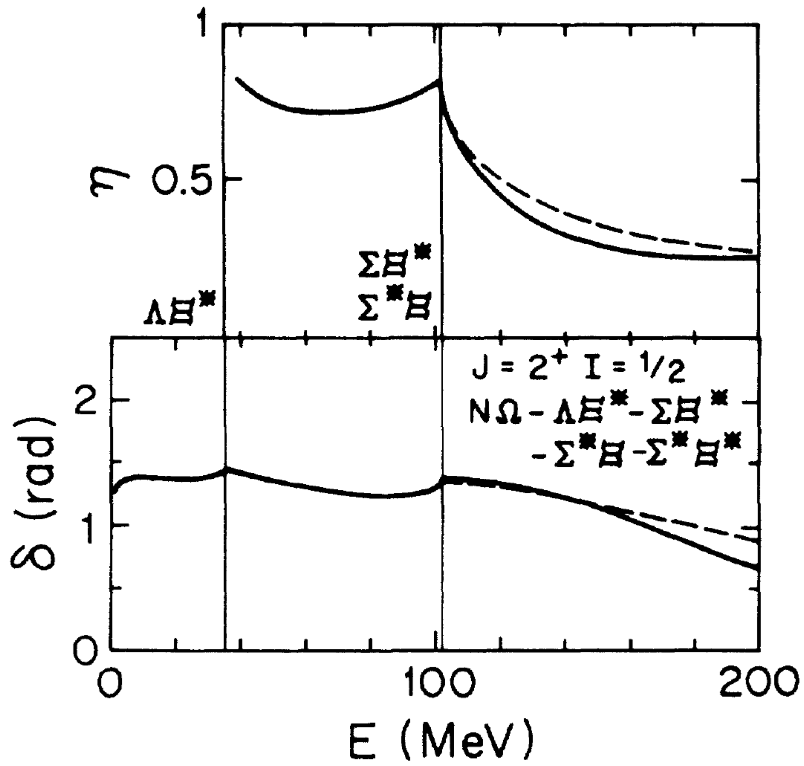
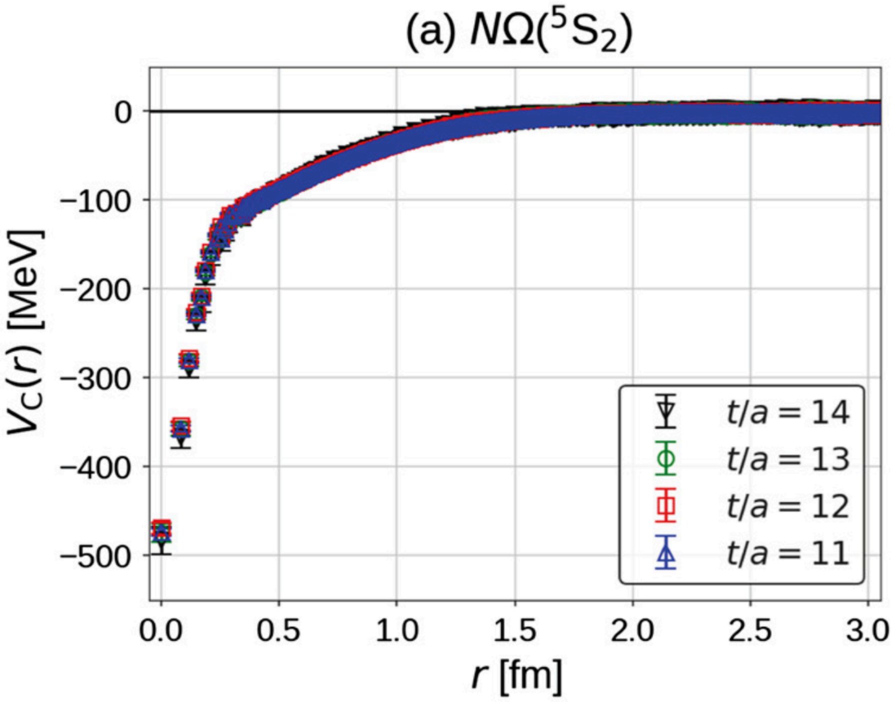
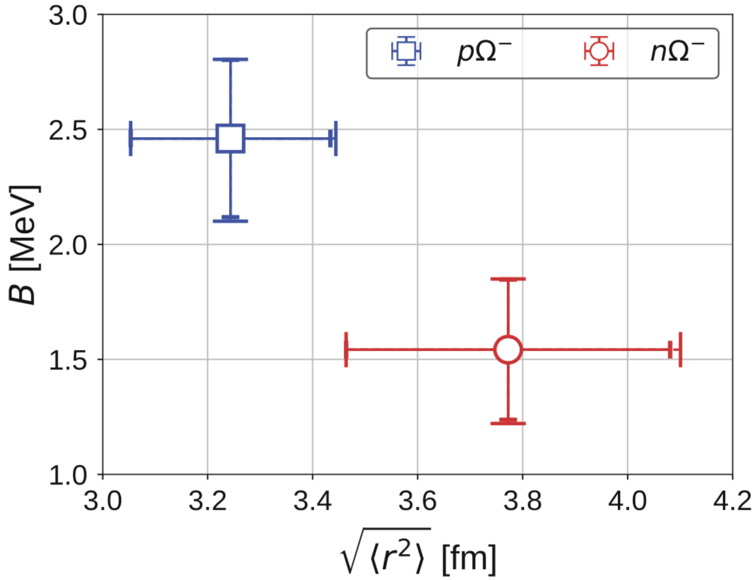


FIG. 4. Phase shift δ and elasticity η of $N-\Omega$ with $J=2^+$ and $I=\frac{1}{2}$ S-wave scattering. The solid (dashed) curve shows the $N\Omega-\Lambda\Xi^*-\Sigma\Xi^*-\Sigma^*\Xi-\Sigma^*\Xi^*(N\Omega-\Lambda\Xi^*-\Sigma\Xi^*-\Sigma^*\Xi)$ coupled-channel calculation. The $N\Omega$ single-channel calculation gives $\delta\equiv 0$ due to the absence of the exchange interaction.

ΩN interaction in lattice QCD

HAL QCD, Phys. Letts. B 792 (2019) 284



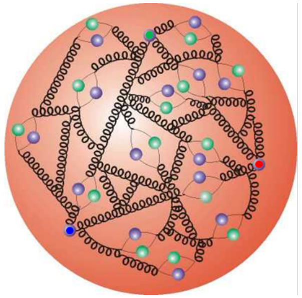


No short-range repulsion

Fig. 6. The binding energy B and the root mean square distance $\sqrt{\langle r^2 \rangle}$ for $n\Omega^-$ (red circle) and for $p\Omega^-$ (blue square). In both figures, inner bars correspond to the statistical errors, while the outer bars are obtained by the quadrature of the statistical and systematic errors.

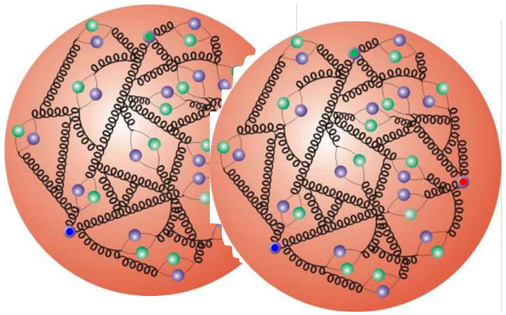
ΩN interaction

If the effective degrees of freedom of baryon is like

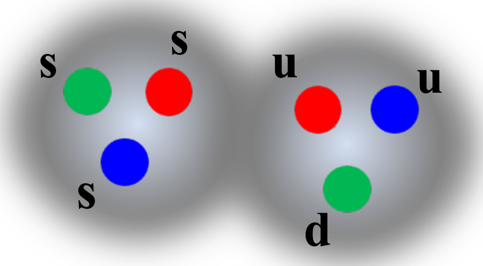


http://ppssh.phys.sci.kobeu.ac.jp/~yamazaki/lectures/07/modernphys-yamazaki07.pdf

Short range baryon-baryon interaction may be non-trivial



No short-range repulsion in $\Omega N(^5S_2)$ is understandable in the quark cluster model



Constituent quarks may be the effective degrees of freedom

Summary

Physics impacts of Ω baryon spectroscopy

- We can attack the two long-standing problems in hadron physics: Spin-Orbit interaction and Roper-like states from Ω baryon spectroscopy

- Clarify the role of a topological gluon configuration: instanton in low-energy QCD

- Clarify the effective degrees of freedom in low-energy QCD

Backup

Present Status of Hadron Spectroscopy

Observed Hadrons from PDG

Meson Summary Table

See also the table of suggested $q\overline{q}$ quark-model assignments in the Quark Model section.

• Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.

LIGHT UNFLAVORED $(S = C = B = 0)$

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(500)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	• $a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(0^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	• $\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	$a_0(1950)$	$1^-(0^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	• $f_2(1950)$	$0^+(2^{++})$
• $a_2(1320)$	$1^-(2^{++})$	• $a_4(1970)$	$1^-(4^{++})$
• $f_0(1370)$	$0^+(0^{++})$	$\rho_3(1990)$	$1^+(3^{--})$
• $\pi_1(1400)$	$1^-(1^{-+})$	$\pi_2(2005)$	$1^-(2^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
• $h_1(1415)$	$0^-(1^{+-})$	$f_0(2020)$	$0^+(0^{++})$
$a_1(1420)$	$1^-(1^{++})$	• $f_4(2050)$	$0^+(4^{++})$
• $f_1(1420)$	$0^+(1^{++})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $\omega(1420)$	$0^-(1^{--})$	$f_0(2100)$	$0^+(0^{++})$
$f_2(1430)$	$0^+(2^{++})$	$f_2(2150)$	$0^+(2^{++})$
• $a_0(1450)$	$1^-(0^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $\rho(1450)$	$1^+(1^{--})$	• $\phi(2170)$	$0^-(1^{--})$
• $\eta(1475)$	$0^+(0^{-+})$	$f_0(2200)$	$0^+(0^{++})$
• $f_0(1500)$	$0^+(0^{++})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
$f_1(1510)$	$0^+(1^{++})$		
• $f'_2(1525)$	$0^+(2^{++})$	$\eta(2225)$	$0^+(0^{-+})$
$f_2(1565)$	$0^+(2^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
$\rho(1570)$	$1^+(1^{--})$	• $f_2(2300)$	$0^+(2^{++})$
$h_1(1595)$	$0^-(1^{+-})$	$f_4(2300)$	$0^+(4^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	$f_0(2330)$	$0^+(0^{++})$
• $a_1(1640)$	$1^-(1^{++})$	• $f_2(2340)$	$0^+(2^{++})$
$f_2(1640)$	$0^+(2^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
• $\eta_2(1645)$	$0^+(2^{-+})$	$f_6(2510)$	$0^+(6^{++})$
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		

OTHER LIGHT

Further States

STRANGE $(S = \pm1, C = B = 0)$

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
• $K^*_0(700)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K^*_0(1430)$	$1/2(0^+)$
• $K^*_2(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K^*_3(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K^*_0(1950)$	$1/2(0^+)$
$K^*_2(1980)$	$1/2(2^+)$
• $K^*_4(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K^*_5(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED $(C = \pm1)$

	$I(J^P)$
• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D^*_0(2300)^0$	$1/2(0^+)$
$D^*_0(2300)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D^*_2(2460)^0$	$1/2(2^+)$
• $D^*_2(2460)^\pm$	$1/2(2^+)$
$D(2550)^0$	$1/2(?^?)$
$D^*_J(2600)$	$1/2(?^?)$
$D^*(2640)^\pm$	$1/2(?^?)$
$D(2740)^0$	$1/2(?^?)$
$D^*_3(2750)$	$1/2(3^-)$
$D(3000)^0$	$1/2(?^?)$

CHARMED, STRANGE $(C = S = \pm1)$

	$I(J^P)$
• $D^\pm_s$	$0(0^-)$
• $D^{*\pm}_s$	$0(?^?)$
• $D^*_{s0}(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D^*_{s2}(2573)$	$0(2^+)$
• $D^*_{s1}(2700)^\pm$	$0(1^-)$
$D^*_{s1}(2860)^\pm$	$0(1^-)$
$D^*_{s3}(2860)^\pm$	$0(3^-)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM $(B = \pm1)$

• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
• $B_1(5721)^+$	$1/2(1^+)$
• $B_1(5721)^0$	$1/2(1^+)$
$B^*_J(5732)$	$?(?^?)$
• $B^*_2(5747)^+$	$1/2(2^+)$
• $B^*_2(5747)^0$	$1/2(2^+)$
$B_J(5840)^+$	$1/2(?^?)$
$B_J(5840)^0$	$1/2(?^?)$
• $B_J(5970)^+$	$1/2(?^?)$
• $B_J(5970)^0$	$1/2(?^?)$

BOTTOM, STRANGE $(B = \pm1, S = \mp1)$

• B^0_s	$0(0^-)$
• B^*_s	$0(1^-)$
$X(5568)^\pm$	$?(?^?)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B^*_{s2}(5840)^0$	$0(2^+)$
$B^*_{sJ}(5850)$	$?(?^?)$

BOTTOM, CHARMED $(B = C = \pm1)$

• B^+_c	$0(0^-)$
$B_c(2S)^\pm$	$0(0^-)$

$c\overline{c}$ (+ possibly non−$q\overline{q}$ states)

• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$0^-(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$

$c\overline{c}$ continued

	$I^G(J^{PC})$
• $\psi(3770)$	$0^-(1^{--})$
• $\psi_2(3823)$	$0^-(2^{--})$
• $\psi_3(3842)$	$0^-(3^{--})$
$\chi_{c0}(3860)$	$0^+(0^{++})$
• $\chi_{c1}(3872)$	$0^+(1^{++})$
• $Z_c(3900)$	$1^+(1^{+-})$
• $X(3915)$	$0^+(0/2^{++})$
• $\chi_{c2}(3930)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $X(4020)^\pm$	$1^+(?^{?-})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$1^-(?^{?+})$
$X(4055)^\pm$	$1^+(?^{?-})$
$X(4100)^\pm$	$1^-(?^{??})$
• $\chi_{c1}(4140)$	$0^+(1^{++})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$Z_c(4200)$	$1^+(1^{+-})$
• $\psi(4230)$	$0^-(1^{--})$
$R_{c0}(4240)$	$1^+(0^{--})$
$X(4250)^\pm$	$1^-(?^{?+})$
$\psi(4260)$	$0^-(1^{--})$
• $\chi_{c1}(4274)$	$0^+(1^{++})$
$X(4350)$	$0^+(?^{?+})$
• $\psi(4360)$	$0^-(1^{--})$
$\psi(4390)$	$0^-(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
• $Z_c(4430)$	$1^+(1^{+-})$
$\chi_{c0}(4500)$	$0^+(0^{++})$
• $\psi(4660)$	$0^-(1^{--})$
$\chi_{c0}(4700)$	$0^+(0^{++})$

$b\overline{b}$ (+ possibly non-$q\overline{q}$ states)

• $\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$0^-(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon_2(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$0^-(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_{b1}(3P)$	$0^+(1^{++})$
• $\chi_{b2}(3P)$	$0^+(2^{++})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $Z_b(10610)$	$1^+(1^{+-})$
• $Z_b(10650)$	$1^+(1^{+-})$
$\Upsilon(10753)$	$?^?(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the table are not established baryons. The names with masses are of baryons that decay strongly. The spin-parity J^P (when known) is given with each particle. For the strongly decaying particles, the J^P values are considered to be part of the names.

p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	****
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	***
$N(1895)$	$1/2^-$	****
$N(1900)$	$3/2^+$	****
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	***
$N(2100)$	$1/2^+$	***
$N(2120)$	$3/2^-$	***
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	****
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	***
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	***
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
Λ	$1/2^-$	**
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	****
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1710)$	$1/2^+$	*
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$	$1/2^-$	*
$\Lambda(2050)$	$3/2^-$	*
$\Lambda(2070)$	$3/2^+$	*
$\Lambda(2080)$	$5/2^-$	*
$\Lambda(2085)$	$7/2^+$	**
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1780)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1900)$	$1/2^-$	**
$\Sigma(1910)$	$3/2^-$	***
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^+$	*
$\Sigma(2010)$	$3/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	*
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2160)$	$1/2^-$	*
$\Sigma(2230)$	$3/2^+$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
$\Omega(2012)^-$	$?^-$	***
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**
Λ^+_c	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ^+_c	$1/2^+$	***
Ξ^0_c	$1/2^+$	****
Ξ'^+_c	$1/2^+$	***
Ξ'^0_c	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		**
$\Xi_c(2970)$		***
$\Xi_c(3055)$		***
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω^0_c	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
$\Omega_c(3000)^0$		***
$\Omega_c(3050)^0$		***
$\Omega_c(3065)^0$		***
$\Omega_c(3090)^0$		***
$\Omega_c(3120)^0$		***

Ξ^{++}_{cc}		***
Λ^0_b	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
$\Lambda_b(6146)^0$	$3/2^+$	***
$\Lambda_b(6152)^0$	$5/2^+$	***
Σ_b	$1/2^+$	***
Σ^*_b	$3/2^+$	***
$\Sigma_b(6097)^+$		***
$\Sigma_b(6097)^-$		***
Ξ^0_b, Ξ^-_b	$1/2^+$	***
$\Xi'_b(5935)^-$	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
$\Xi_b(5955)^-$	$3/2^+$	***
$\Xi_b(6227)$		***
Ω^-_b	$1/2^+$	***
$P_c(4312)^+$		*
$P_c(4380)^+$		*
$P_c(4440)^+$		*
$P_c(4457)^+$		*

**** Existence is certain, and properties are at least fairly well explored.

*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

** Evidence of existence is only fair.

* Evidence of existence is poor.

Observed Mesons from PDG

- 214 mesons have been observed.
- 10% of mesons have no fixed J^P.
- 79 light flavored mesons
- 21 strange mesons
- 17 charmed mesons
- 10 charm-strange mesons
- 12 bottom mesons
- 6 bottom-strange mesons
- 2 bottom-charm mesons
- 39 cc^{bar} mesons + non qq^{bar}
- 22 bb^{bar} mesons + non qq^{bar}

Observed Baryons from PDG

- 168 baryons have been observed.
- 23% of baryons have no fixed J^P.
- 51 light flavored baryons
- 51 s = -1 baryons
- 12 s = -2 baryons
- 5 s = -3 baryons: Ω
- 10 c = 1 baryons
- 12 c = 1, s = -1 baryons
- 7 c = 1, s = -2 baryons
- 1 c = 2 baryons
- 9 b = -1 baryons
- 5 b = -1 s = -1 baryons
- 1 b = -1 s = -2 baryons

No u,d-valence quarks

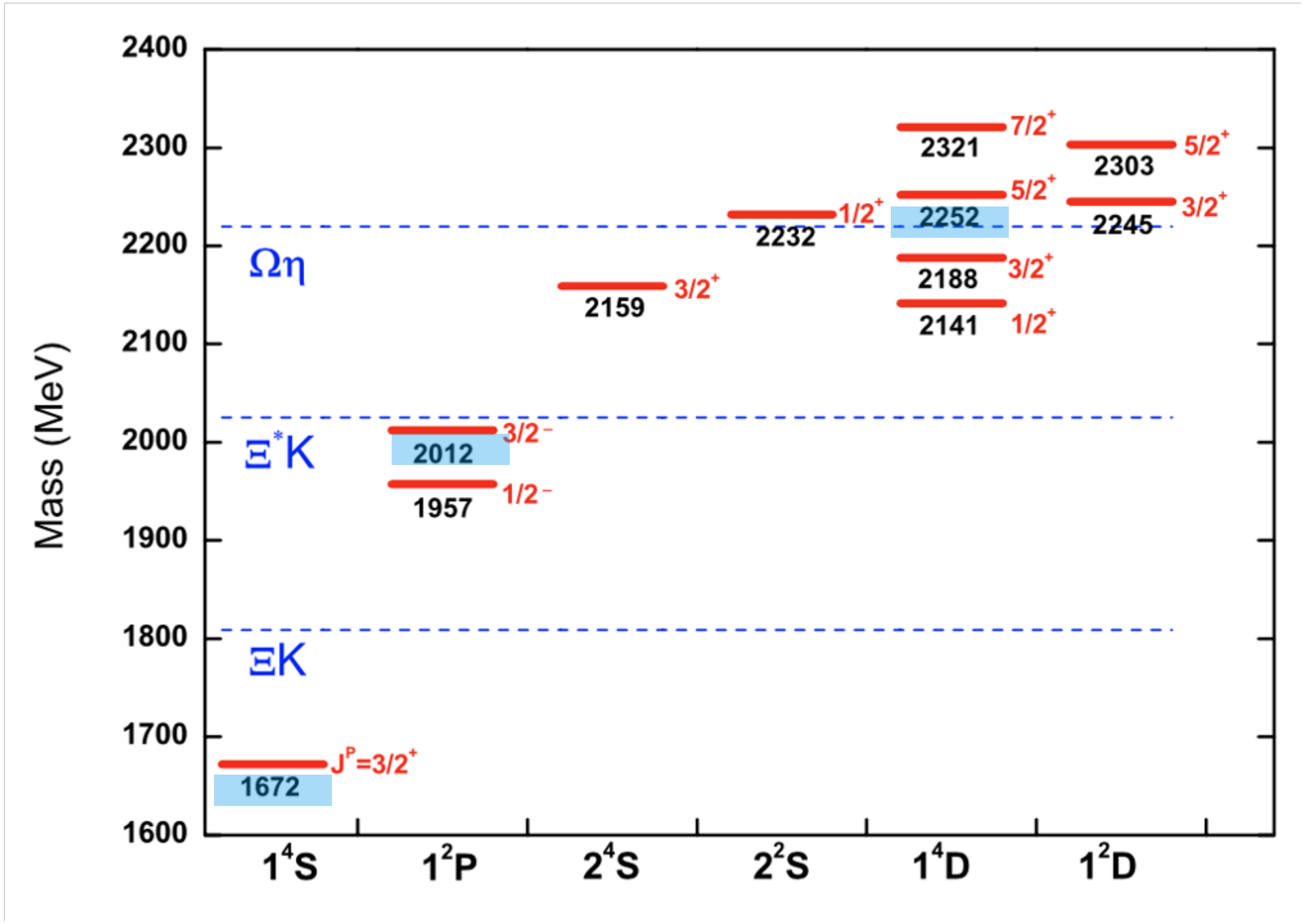
Features of Ω baryon

- Where can we observe the bad diquark properties of Ω baryon?

  -> production rate of $e^+e^- \to \Omega\overline{\Omega}$ may be smaller than usual baryon pairs.

  When the color string breaks to diquark and anti-diquark pair, bad diquark pair production less likely to happen.

Ω* spectrum in the constituent quark model



Ming-Sheng Liu et al., PRD101, 016002 (2020)

Baryon-baryon Flavor symmetry

Find spin state(s) that satisfies
F x $[f_1 f_2]$(spin) x [222](color) = $[111111]_{total}$
so that the six quarks can be in $(0s)^6$.

FxF	F	Spin	e.g.
8x8	1 [222]	J=0	H
	8S [321]	J=0	
	8A [321]	J=1	
	10bar [33]	J=1	
	10 [411]	J=1	
	27 [42]	J=0	

FxF	F	Spin	e.g.
8x10	8 [321]	J=1,2	
	10 [411]	J=1	
	27 [42]	J=2	
	35 [51]	J=1	

New Flavor Symmetry

New Spin States J = 2

FxF	F	Spin	e.g.
10x10	10bar [33]	J=1,3	d_*(2380)?
	27 [42]	J=0,2	
	35 [51]	J=1	
	28 [6]	J=0	ΩΩ