Spectrum and Quantum Numbers of Ξ Resonances

(and some EM properties of hyperons)

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KL2016 Workshop

Physics with Neutral Kaon Beams at JLab Workshop

TJNAF, VA

CONTENTS

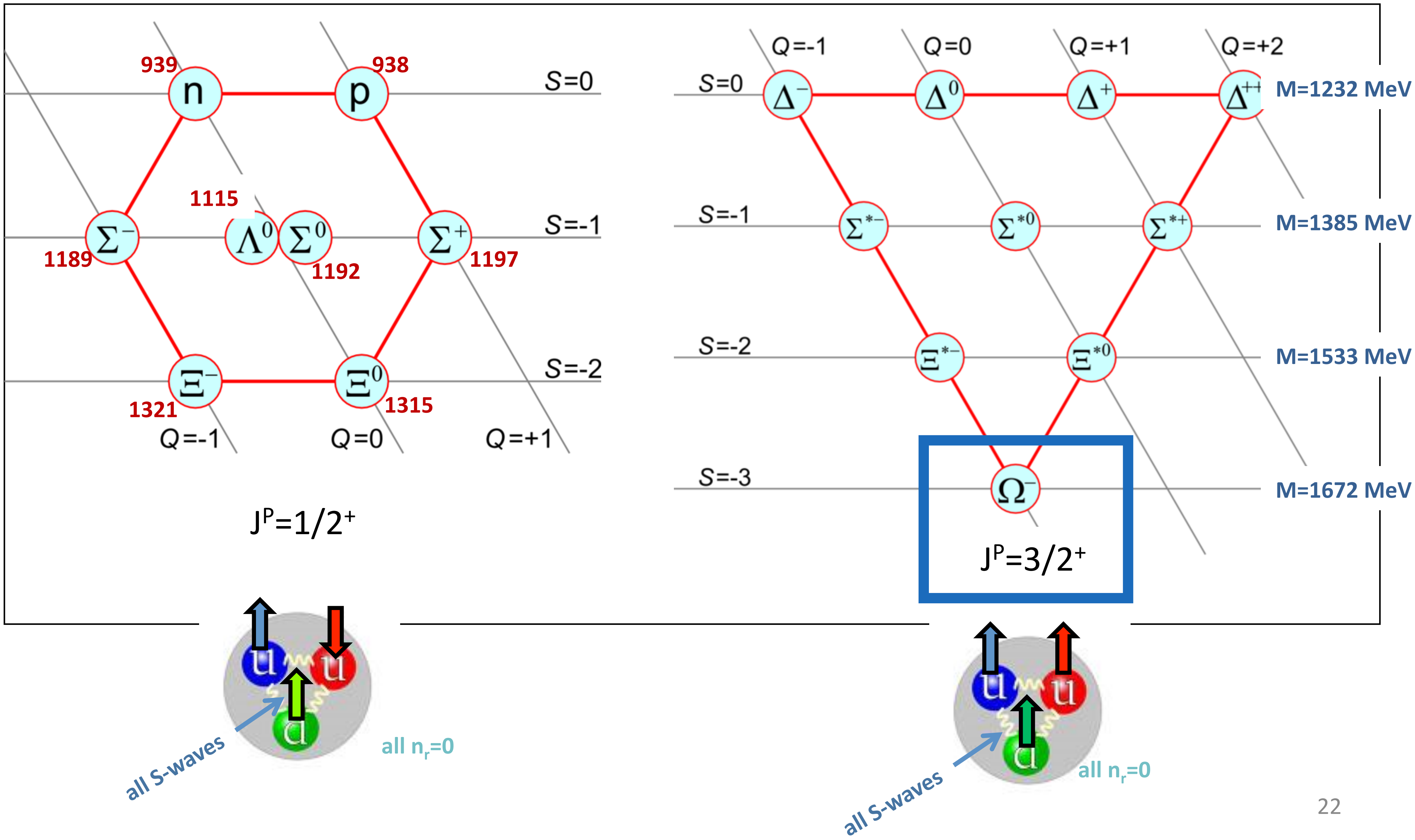
MOTIVATION

- How much do we know about multi-strangeness baryons?

- Baryons with $S = -2$
  - quark content (qss) with q being light u/d quark
  - $B = 1$, $I = 1/2$, $Q = 0$ or -1
  - name: Ξ
  - first discovery of the Ξ: about 60 years ago
- Baryons with $S = -3$
  - quark content (sss)
  - $B=1$, $I=0$, $Q = -1$
  - name: Ω
  - first discovery of the Ω: about 50 years ago

BARYONS

Ground state Baryons



THE DISCOVERY OF Ω^-

spin-3/2 Ω^-

crucial prediction of the QM

VOLUME 12, NUMBER 8 PHYSICAL REVIEW LETTERS 24 FEBRUARY 1964

OBSERVATION OF A HYPERON WITH STRANGENESS MINUS THREE*

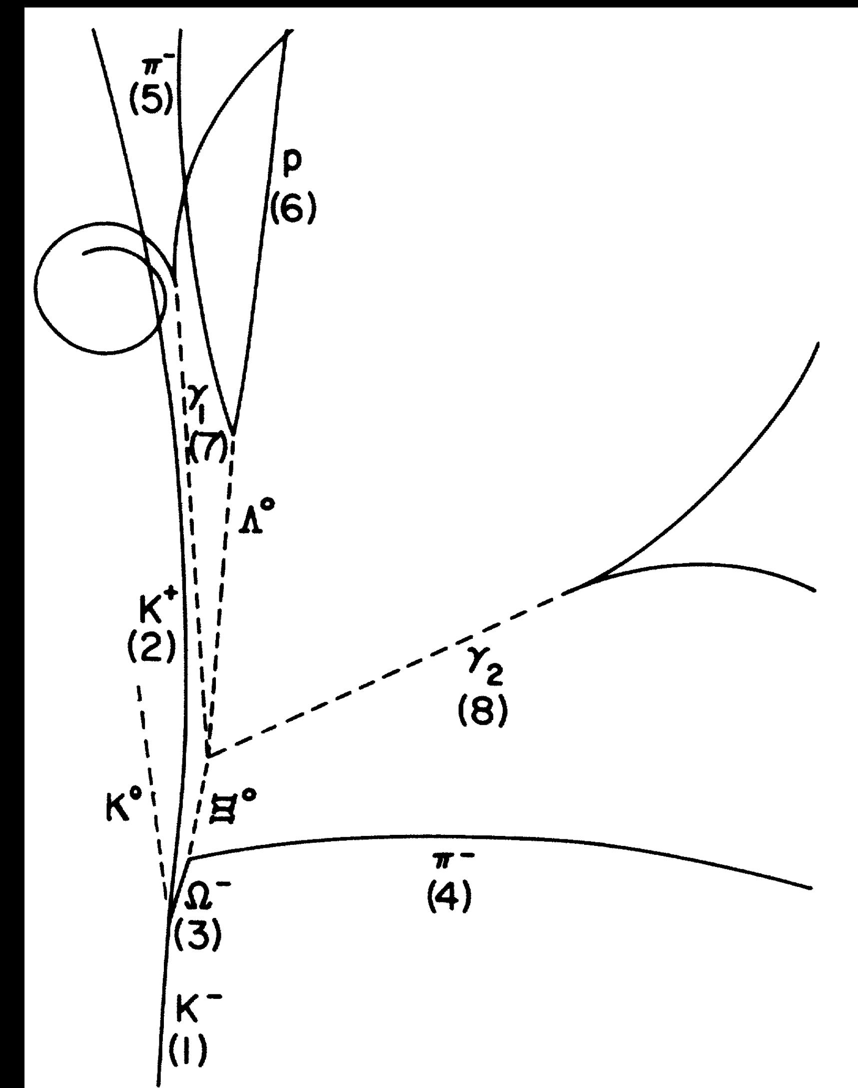
V. E. Barnes, P. L. Connolly, D. J. Crennell, B. B. Culwick, W. C. Delaney, W. B. Fowler, P. E. Hagerty,† E. L. Hart, N. Horwitz,† P. V. C. Hough, J. E. Jensen, J. K. Kopp, K. W. Lai, J. Leitner,† J. L. Lloyd, G. W. London,‡ T. W. Morris, Y. Oren, R. B. Palmer, A. G. Prodell, D. Radojičić, D. C. Rahm, 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)

It has been pointed out[1] that among the multitude of resonances which have been discovered recently, the $N_{3/2}^*(1238)$, $Y_1^*(1385)$, and $\Xi_{1/2}^*(1532)$ can be arranged as a decuplet with one member still missing. Figure 1 illustrates the position

length of ~10^6 feet. These pictures have been partially analyzed to search for the more characteristic decay modes of the Ω^-.

The event in question is shown in Fig. 2, and the pertinent measured quantities are given in



In view of the properties of charge ($Q = -1$), strangeness ($S = -3$), and mass ($M = 1686 \pm 12$ MeV/c^2) established for particle 3, we feel justified in identifying it with the sought-for Ω^-. Of course, it is expected that the Ω^- will have other observable decay modes, and we are continuing to search for them. We defer a detailed discussion of the mass of the Ω^- until we have analyzed further examples and have a better understanding of the systematic errors.

1964: the discovery of Ω^-

1969: Nobel prize to Gell-Mann "for his contributions and discoveries concerning the classification of elementary particles and their interactions"

QUANTUM NUMBERS OF HYPERONS

2006

PRL **97,** 112001 (2006) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2006

Measurement of the Spin of the Ω^- Hyperon

B. Aubert,[1] R. Barate,[1] M. Bona,[1] D. Boutigny,[1] F. Couderc,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] V. Tisserand,[1] A. Zghiche,[1] E. Grauges,[2] A. Palano,[3] J. C. Chen,[4] N. D. Qi,[4] G. Rong,[4] P. Wang,[4] Y. S. Zhu,[4] G. Eigen,[5] I. Ofte,[5] B. Stugu,[5] G. S. Abrams,[6] M. Battaglia,[6] D. N. Brown,[6] J. Button-Shafer,[6] R. N. Cahn,[6] E. Charles,[6] M. S. Gill,[6] Y. Groysman,[6] R. G. Jacobsen,[6] J. A. Kadyk,[6] L. T. Kerth,[6] Yu. G. Kolomensky,[6] G. Kukartsev,[6] G. Lynch,[6] L. M. Mir,[6] P. J. Oddone,[6] T. J. Orimoto,[6] M. Pripstein,[6] N. A. Roe,[6] M. T. Ronan,[6] W. A. Wenzel,[6] P. del Amo Sanchez,[7] M. Barrett,[7] K. E. Ford,[7]

1964 The discovery of Ω^-

1969 Nobel prize

spin of Ω^-

BaBar Collab. (2006)

2014

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

Ξ^0 $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

The parity has not actually been measured, but + is of course expected.

1952 The discovery of Ξ (cosmic ray)

1959 The discovery of Ξ (LBNL)

The parity of Ξ?

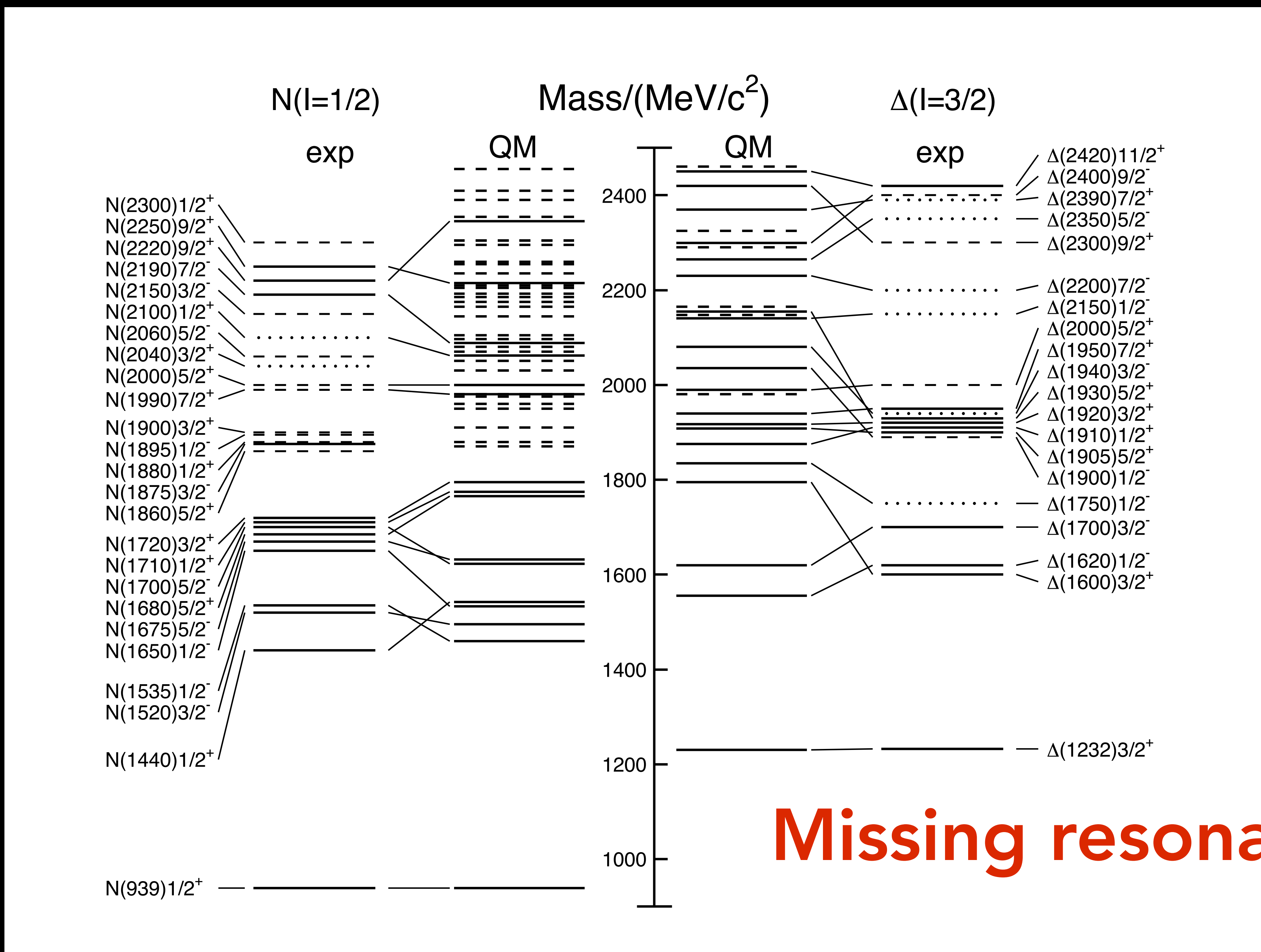
Hyperons: another way to understand strong interactions

BARYON SPECTRUM

orbital excitations, radial excitations

$J = S + L$

Excitation Spectrum of the nucleon



Missing resonances problem

PDG (2012)

- PDG List for Ξ baryons

Particle	J^P	Overall status	Status as seen in — $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
Ξ(1318)	1/2+	****					Decays weakly
Ξ(1530)	3/2+	****	****				
Ξ(1620)		*	*				
Ξ(1690)		***		***	**		
Ξ(1820)	3/2−	***	**	***	**	**	
Ξ(1950)		***	**	**		*	
Ξ(2030)		***		**	***		
Ξ(2120)		*		*			
Ξ(2250)		**					3-body decays
Ξ(2370)		**					3-body decays
Ξ(2500)		*		*	*		3-body decays

Parity is not directly measured, but assigned by the quark model

11 Ξ^*

20 N* and 20 Δ*

—— spin-parity known

$$N(\Xi^*) = N(N^*) + N(\Delta^*) \ ?$$

CURRENT STATUS

- Only $\Xi(1318)$ and $\Xi(1530)$ are four-star rated.
- Only three states with known spin-parity: those of other states should be explored.

K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014) and 2015 update

PDG 2014

Ξ RESONANCES

The accompanying table gives our evaluation of the present status of the Ξ resonances. Not much is known about Ξ resonances. This is because (1) they can only be produced as a part of a final state, and so the analysis is more complicated than if direct formation were possible, (2) the production cross sections are small (typically a few μb), and (3) the final states are topologically complicated and difficult to study with electronic techniques. Thus early information about Ξ resonances came entirely from bubble chamber experiments, where the numbers of events are small, and only in the 1980's did electronic experiments make any significant contributions. However, nothing of significance on Ξ resonances has been added since our 1988 edition.

no kaon factory

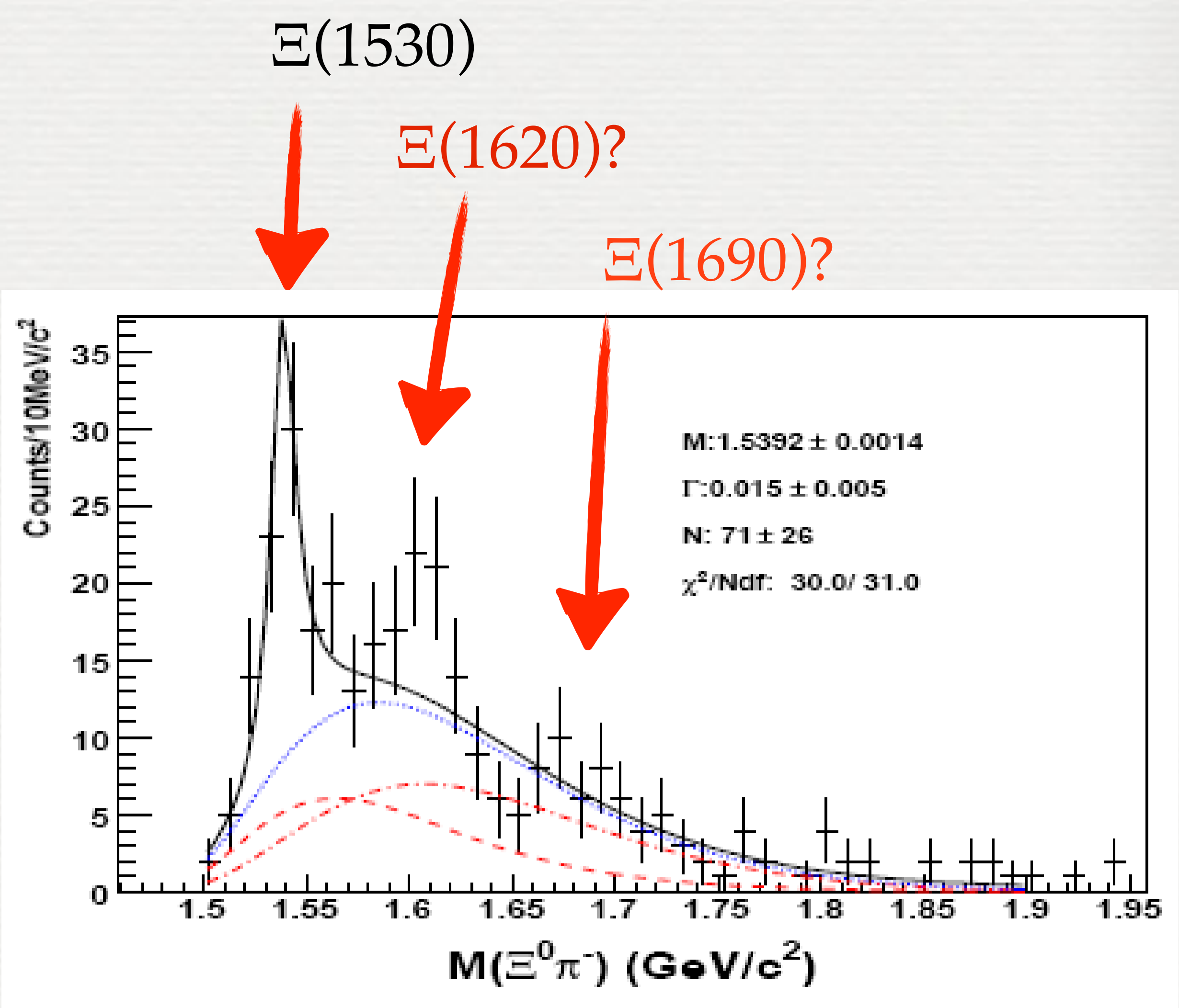
For the case of Ω, it is even worse!

Same statement in PDG for > 10 yrs

Questions

Particle	J^P	Overall status	Status as seen in — $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
$\Xi(1318)$	1/2+	****					Decays weakly
$\Xi(1530)$	3/2+	****	****				
$\Xi(1620)$		*	*				
$\Xi(1690)$		***		***	**		
$\Xi(1820)$	3/2−	***	**	***	**	**	
$\Xi(1950)$		***	**	**		*	
$\Xi(2030)$		***		**	***		
$\Xi(2120)$		*		*			
$\Xi(2250)$		**					3-body decays
$\Xi(2370)$		**					3-body decays
$\Xi(2500)$		*		*	*		3-body decays

- Where are the other resonances?
  - only 2 resonances are four-star rated
- Their quantum numbers?
  - The spin-parity quantum numbers are assigned only to 3 states



CLAS: PRC 76 (2007)

The 3rd lowest state

1. Does $\Xi(1620)$ really exist?
   Most recent report on $\Xi(1620)$: **NPB 189 (1981)**
2. The 3rd lowest state: $\Xi(1620)$ vs. $\Xi(1690)$
3. What are their spin-parity quantum numbers?
   comparison with theoretical predictions

BaBar Collab.: J^P of $\Xi(1690)$ is 1/2-
PRD 78 (2008)

Ξ(1620) vs Ξ(1690)

Citation: J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001 (2012) (URL: http://pdg.lbl.gov)

$\Xi(1620)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: $*$

J, P need confirmation.

OMITTED FROM SUMMARY TABLE

What little evidence there is consists of weak signals in the $\Xi\pi$ channel. A number of other experiments (e.g., BORENSTEIN 72 and HASSALL 81) have looked for but not seen any effect.

Citation: J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001 (2012) (URL: http://pdg.lbl.gov)

$\Xi(1690)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: $***$

AUBERT 08AK, in a study of $\Lambda_c^+ \to \Xi^- \pi^+ K^+$, finds some evidence that the $\Xi(1690)$ has $J^P = 1/2^-$.

$\Xi(1620)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
≈ 1620 OUR ESTIMATE					
1624 ± 3	31	BRIEFEL	77	HBC	$K^- p$ 2.87 GeV/c
1633 ± 12	34	DEBELLEFON	75B	HBC	$K^- p \rightarrow \Xi^- \overline{K} \pi$
1606 ± 6	29	ROSS	72	HBC	$K^- p$ 3.1–3.7 GeV/c

$\Xi(1620)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
22.5	31	[1] BRIEFEL	77	HBC	$K^- p$ 2.87 GeV/c
40 ± 15	34	DEBELLEFON	75B	HBC	$K^- p \rightarrow \Xi^- \overline{K} \pi$
21 ± 7	29	ROSS	72	HBC	$K^- p \rightarrow \Xi^- \pi^+ K^{*0}(892)$

vert hidden-variable emergence rates into quantum mechanical counting rates.

[9]It has been shown by D. Bohm and Y. Aharonov, Phys. Rev. 108, 1070 (1957), that the WS experiment is a decisive refutation of a hypothesis studied by W. H. Furry, Phys. Rev. 49, 393, 476 (1936).

[10]For details see M. A. Horne, thesis, Boston University, 1969 (unpublished).

[11]The distribution is given in H. S. Snyder, S. Pasternack, and J. Hornbostel, Phys. Rev. 73, 440 (1948).

Ξ RESONANCES IN $K^-p\to\Xi\pi K$ AT 2.87 GeV/c*

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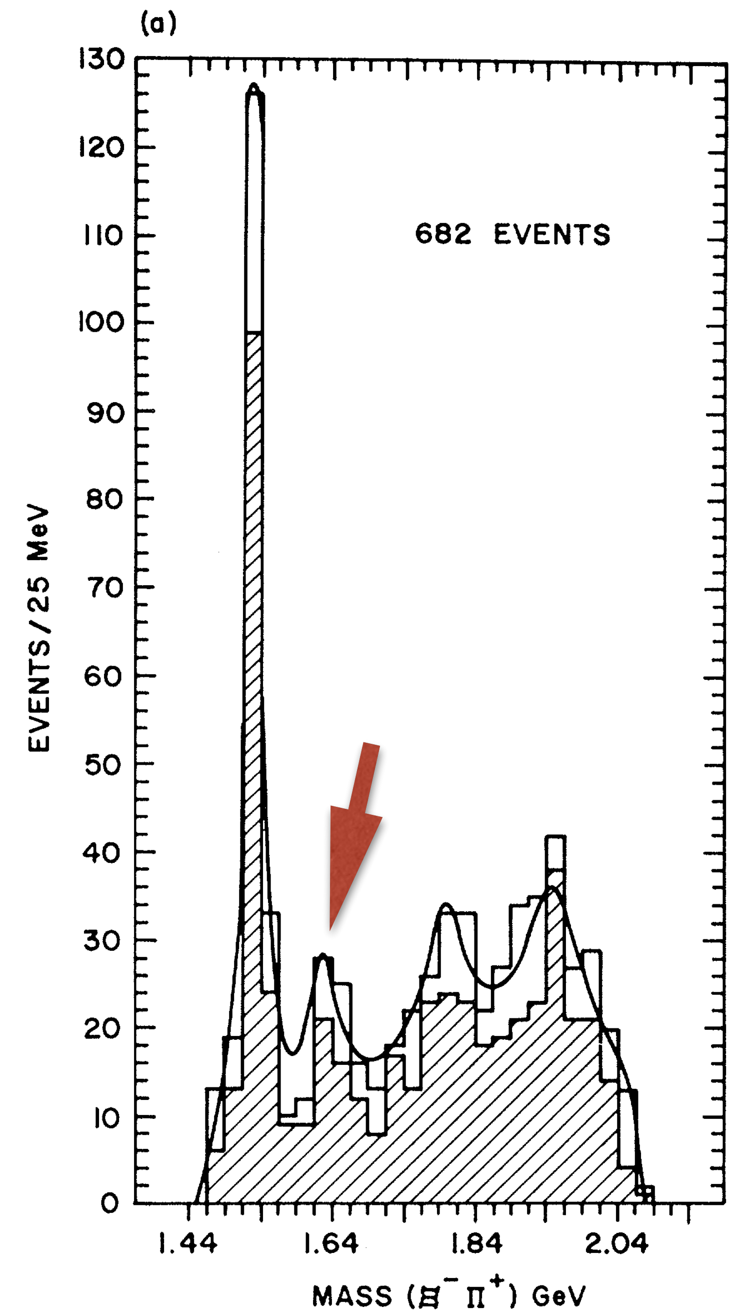
Department of Physics, Brandeis University, Waltham, Massachusetts 02154

and

C. Y. Chang, R. J. Hemingway, B. V. Khoury, A. R. Stottlemyer, H. Whiteside,† anc

Evidence is presented for four Ξ resonances in the reaction $K^-p\to\Xi^-\pi^+K^0$. In tion to the well known $\Xi(1530)$, significant structures are observed in the $\Xi\pi$ syst masses of 1630, 1800, and 1960 MeV, although the latter two are not statistically guishable from a single broad structure at 1950 MeV. No significant enhancemen these masses are observed in the $\Xi^-\pi^0K^+$ final state.

The first report on $\Xi(1620)$



PHYSICAL REVIEW D VOLUME 16, NUMBER 9 1 NOVEMBER 1977

Search for Ξ^* production in K^-p interactions at 2.87 GeV/c†

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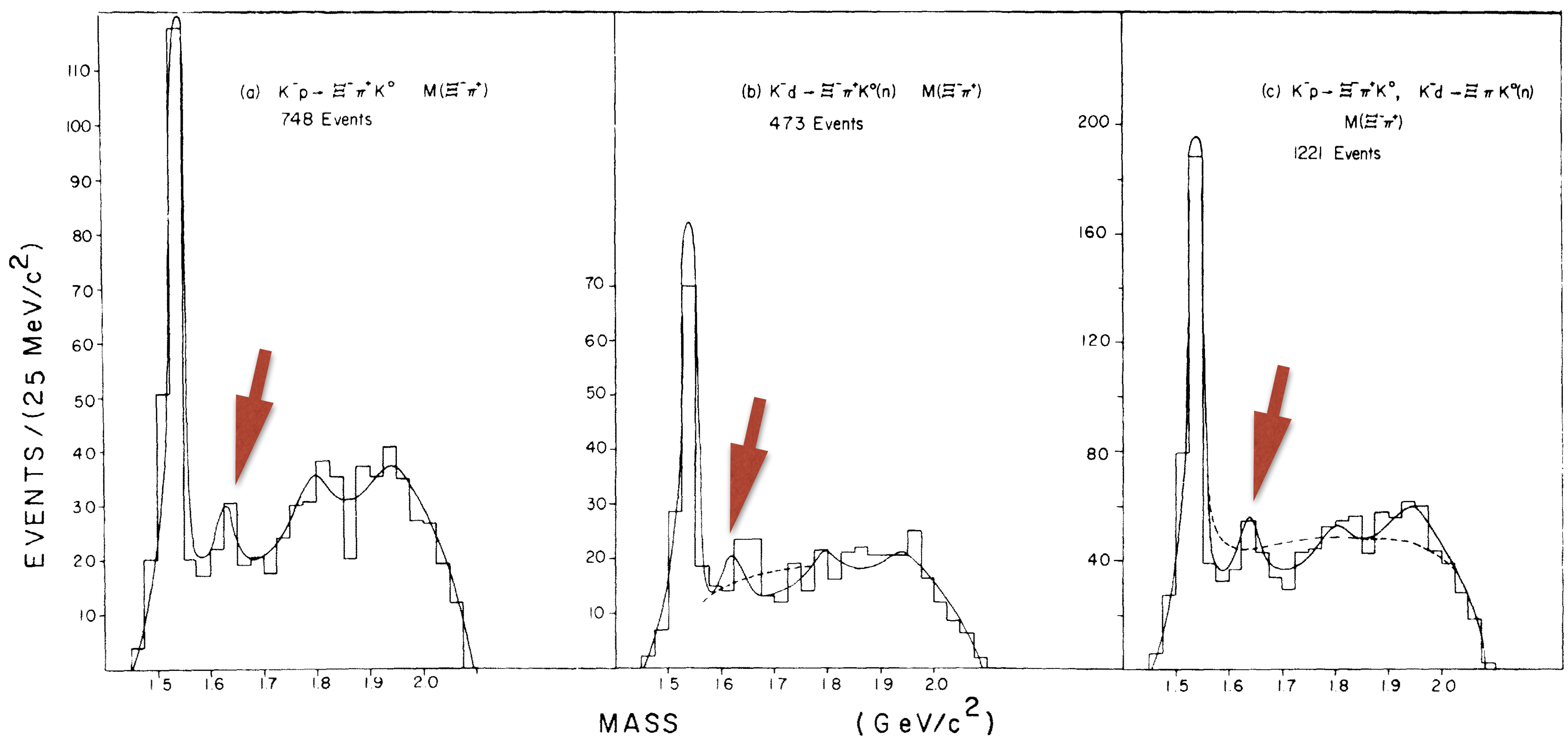
R. C. Fernow,** S. L. Glickman,†† M. Goldberg, S. M. Jacobs,†† B. T. Meadows,‡‡ G. C. Moneti, and D. P. Weygand
Syracuse University, Syracuse, New York 13210

J. Tompkins, J. Canter, E. Katsoufis,§§ W. A. Mann, J. Schneps, and G. Wolsky¶¶



Nuclear Physics B189 (1981) 397–420

PRODUCTION OF $S = -2$ AND -3 BARYON STATES IN 6.5 GeV/c K^-p INTERACTIONS

J.K. HASSALL, R.E. ANSORGE, J.R. CARTER, W.W. NEALE, J.G. RUSHBROOKE and D.R. WARD,

Cavendish Laboratory, Cambridge, UK★

B.Y. OH, M. PRATAP[1], G.A. SMITH and J. WHITMORE

Michigan State University, East Lansing 48824, USA★★

5.1. TWO-BODY MASS COMBINATIONS

The $\Xi^-\pi^+$ and $\Xi^-\pi^0$ effective mass distributions are shown in figs. 6 and 8. There is no evidence for the production of any resonance except the well known $\Xi(1530)$, and in particular we find no evidence for the production of a $\Xi(1630)$ which several previous experiments have claimed, decaying into $\Xi\pi^\star$ [24].

$\Xi(1690)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗∗

AUBERT 08AK, in a study of $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$, finds some evidence that the $\Xi(1690)$ has $J^P = 1/2^-$.

DIONISI 78 sees a threshold enhancement in both the neutral and negatively charged $\Sigma\overline{K}$ mass spectra in $K^- p \rightarrow (\Sigma\overline{K}) K \pi$ at 4.2 GeV/c. The data from the $\Sigma\overline{K}$ channels alone cannot distinguish between a resonance and a large scattering length. Weaker evidence at the same mass is seen in the corresponding $\Lambda\overline{K}$ channels, and a coupled-channel analysis yields results consistent with a new Ξ.

BIAGI 81 sees an enhancement at 1700 MeV in the diffractively produced ΛK^- system. A peak is also observed in the $\Lambda\overline{K}^0$ mass spectrum at 1660 MeV that is consistent with a 1720 MeV resonance decaying to $\Sigma^0\overline{K}^0$, with the γ from the Σ^0 decay not detected.

BIAGI 87 provides further confirmation of this state in diffractive dissociation of Ξ^- into ΛK^-. The significance claimed is 6.7 standard deviations.

ADAMOVICH 98 sees a peak of 1400 $\pm$ 300 events in the $\Xi^- \pi^+$ spectrum produced by 345 GeV/c Σ^--nucleus interactions.

$\Xi(1690)$ MASSES

MIXED CHARGES

VALUE (MeV)	*DOCUMENT ID*

1690±10 OUR ESTIMATE This is only an educated guess; the error given is larger than the error on the average of the published values.

Eur. Phys. J. C 5, 621–624 (1998)
DOI 10.1007/s100529800902

First observation of the $\Xi^- \pi^+$ decay mode of the $\Xi^0(1690)$ hyperon

WA89 Collaboration

Table 1. Mean reconstructed masses and widths of Λ^0, Ξ^-, Ω^-, Ξ^0_{1530}, Ξ^-_{1820} and Ξ^-_{1950} and mass resolutions from data and Monte Carlo. All numbers are given in units of MeV/c^2

Particle	Mass	Width	σ_{Data}	σ_{MC}
$\Lambda \to p\pi^-$	1115.7 ± 0.1		1.93	1.62
$\Xi^- \to \Lambda\pi^-$	1321.0 ± 0.1		2.68	2.32
$\Omega^- \to \Lambda K^-$	1672.5 ± 0.9		2.4	2.1
Ξ^0_{1530}	1532.2 ± 0.5	9.1	3.7	3.2
Ξ^-_{1820}	1817 ± 3	23 ± 13		3.4
Ξ^-_{1950}	1955 ± 6	68 ± 22		3.4

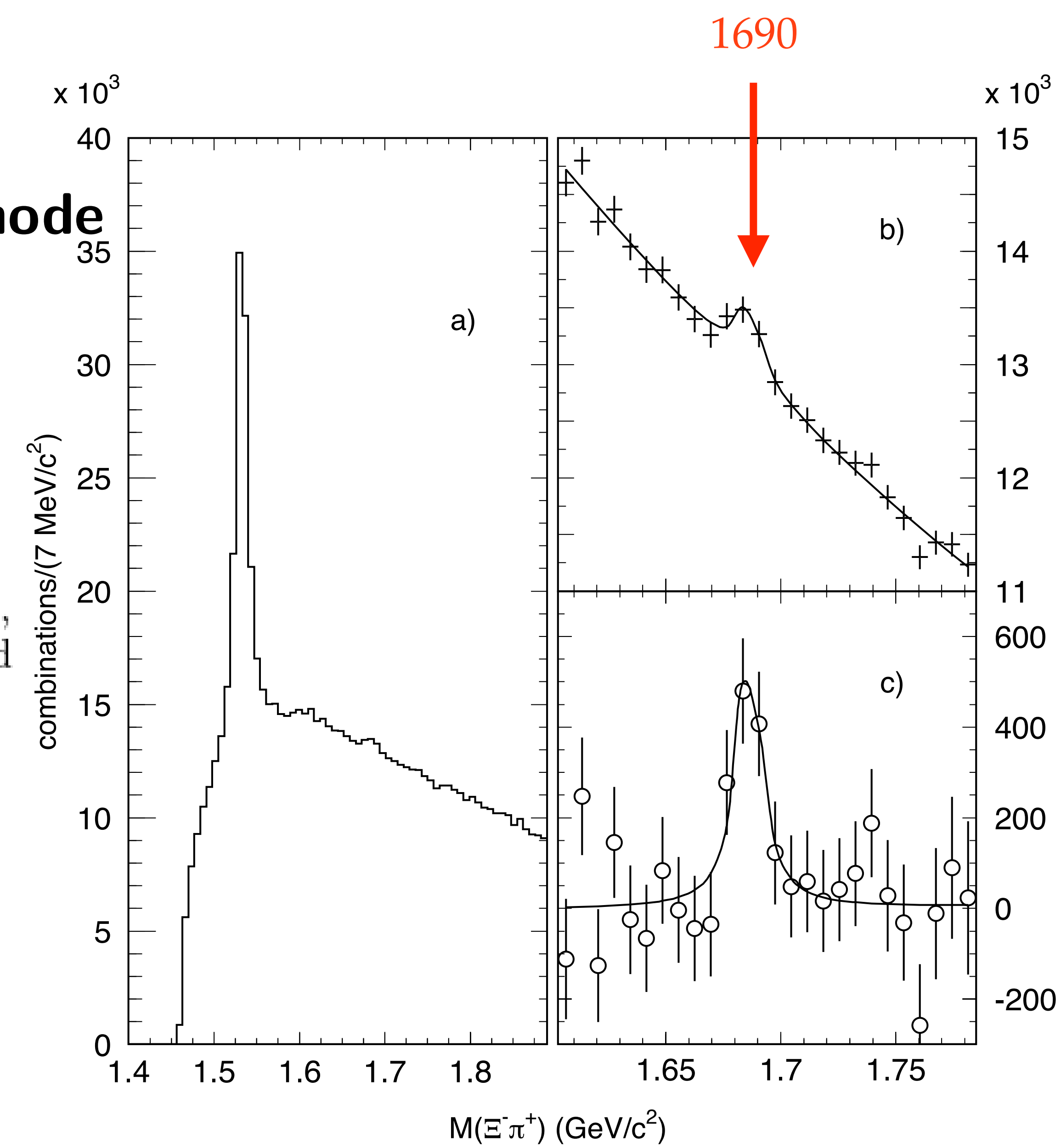


Fig. 1. Invariant mass destribution of the $\Xi^-\pi^+$ combinations. **a** the $\Xi^0(1530)$ and $\Xi^0(1690)$ mass region; **b** the $\Xi^0(1690)$ mass region only; **c** the $\Xi^0(1690)$ mass region after background subtraction

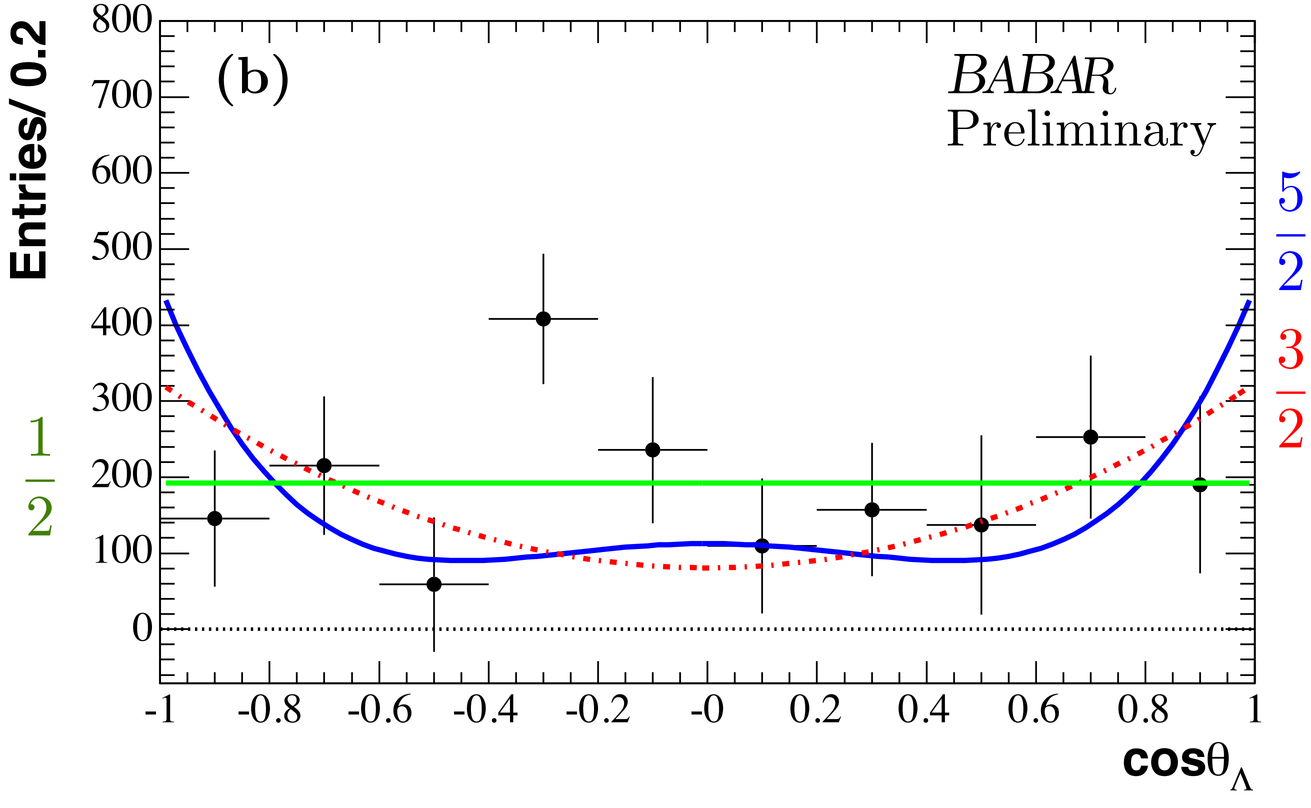
PHYSICAL REVIEW D **78,** 034008 (2008)

Measurement of the spin of the $\Xi(1530)$ resonance

B. Aubert,[1] M. Bona,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] X. Prudent,[1] V. Tisserand,[1] A. Zghiche,[1] J. Garra Tico,[2] E. Grauges,[2] L. Lopez,[3] A. Palano,[3] M. Pappagallo,[3] G. Eigen,[4] B. Stugu,[4] L. Sun,[4] G. S. Abrams,[5] M. Battaglia,[5] D. N. Brown,[5] J. Button-Shafer,[5] R. N. Cahn,[5] R. G. Jacobsen,[5] J. A. Kadyk,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Kukartsev,[5] G. Lynch,[5] I. L. Osipenkov,[5] M. T. Ronan,[5,*] K. Tackmann,[5] T. Tanabe,[5] W. A. Wenzel,[5] C. M. Hawkes,[6]

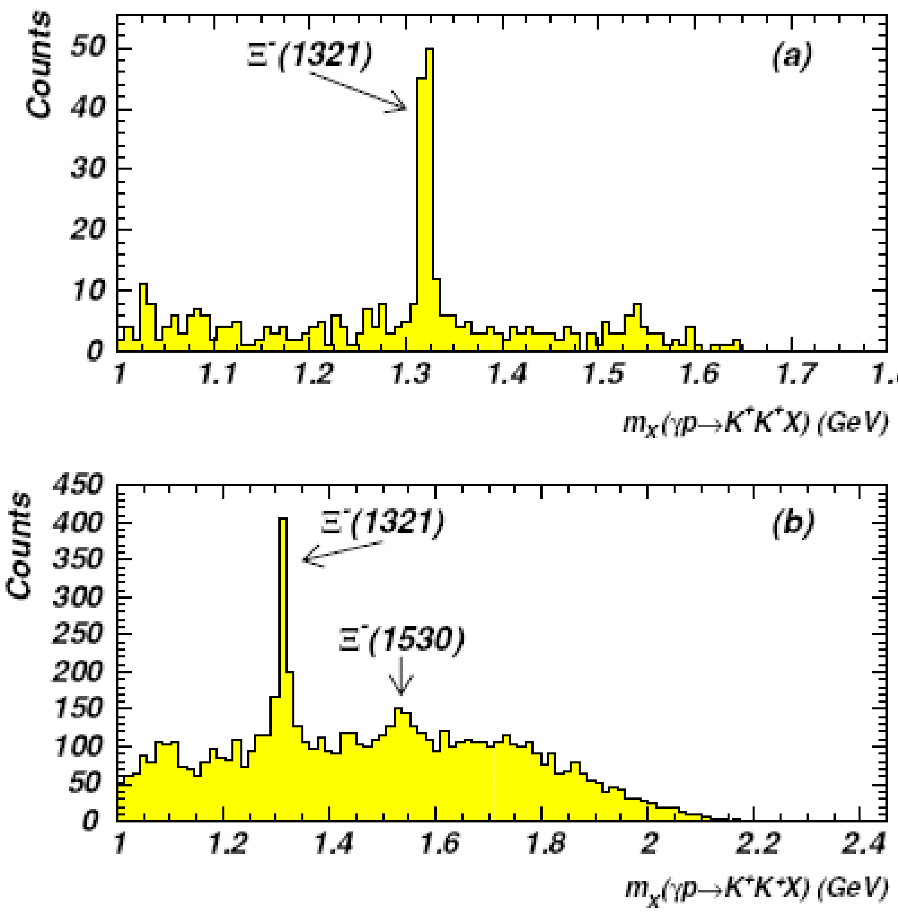
(*BABAR* Collaboration)

Legendre polynomial moment indicates the presence of a significant S-wave amplitude for $\Xi^-\pi^+$ mass values above 1.6 GeV$/c^2$, and a dip in the mass distribution at approximately 1.7 GeV$/c^2$ is interpreted as due to the coherent addition of a $\Xi(1690)^0$ contribution to this amplitude. This would imply $J^P = 1/2^-$ for the $\Xi(1690)$. Attempts at fitting the $\Xi(1530)^0$ line shape yield unsatisfactory results, and this failure is attributed to interference effects associated with the amplitudes describing the $K^+\pi^+$ and/or Ξ^-K^+ systems.

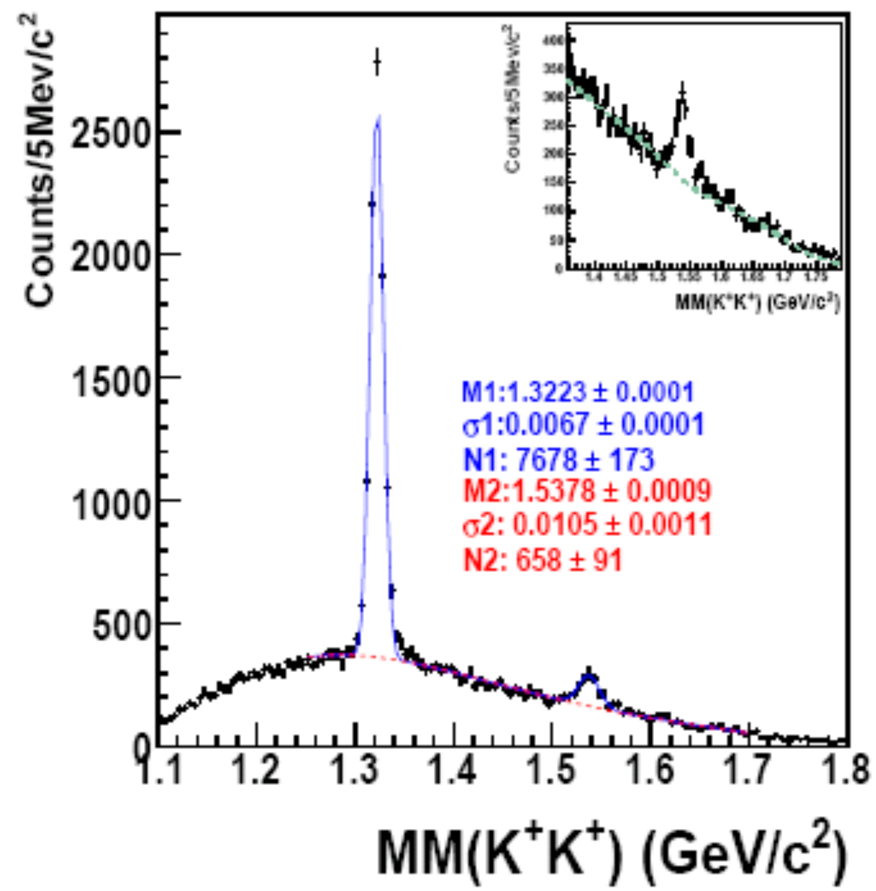


hep-ex/0607043

CLAS@JLab



PRC 71 (2005)



PRC 76 (2007)

MODELS

Direct extension of the classification in the quark model

- Classify the states as members of octet or decuplet
  - Use spin-parity (if known) and Gell-Mann—Okubo mass relation
- Works before 1975: reviewed by
  Samlos, Goldberg, Meadows *RMP* ***46*** *(1974)*
- Recent work along this line
  Guzey & Polyakov, *hep-ph/0512355 (2005)*
- *No dynamics*

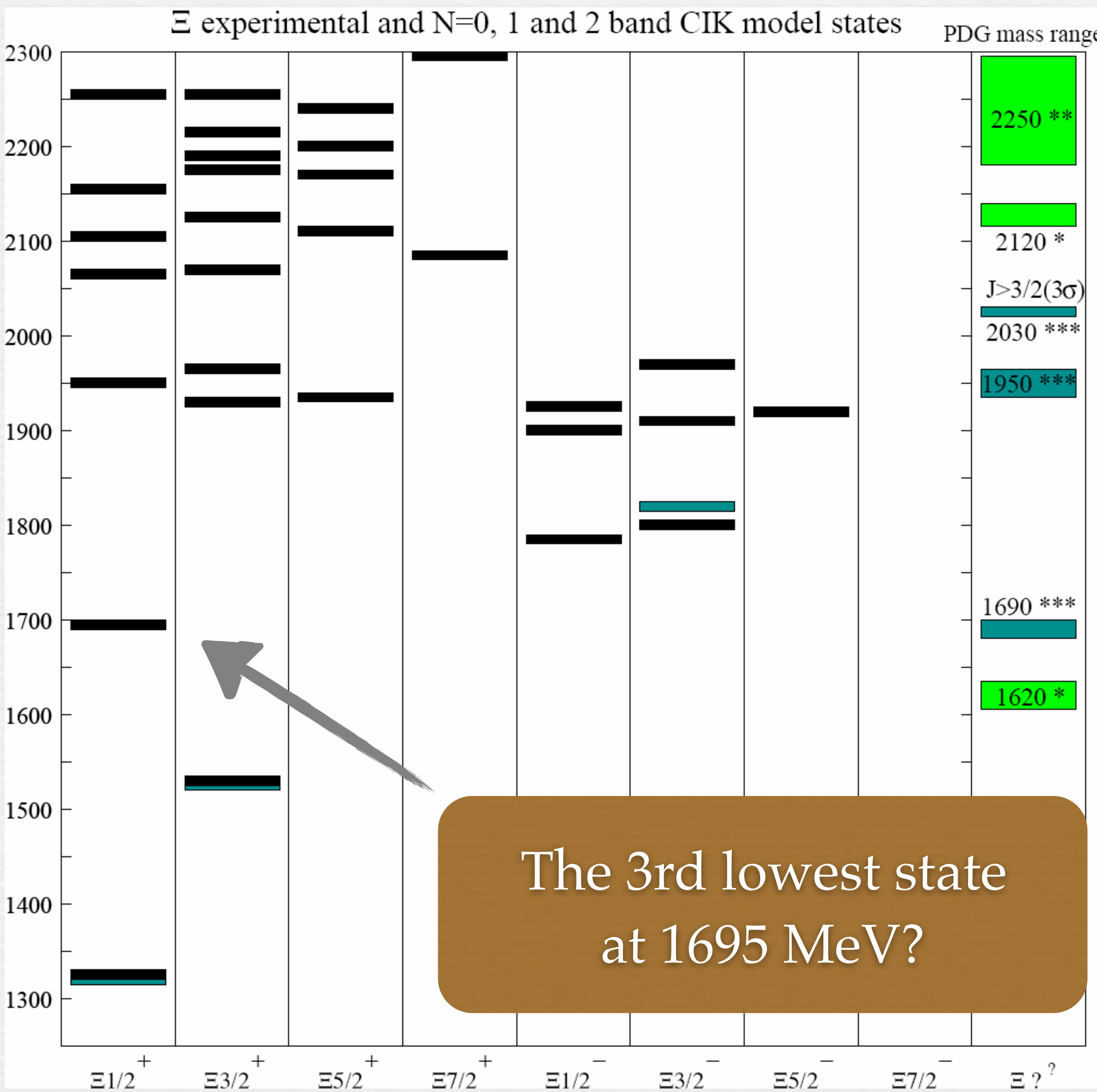
Hadron models for Ξ baryons

- Most parameters of models are fixed by the $S=0$ and $S=-1$ sector
  → in principle, no free parameter for the $S=-2, -3$
- Most models give (almost) correct masses for $\Xi(1318)$ and $\Xi(1530)$
  - ✓ Requirement to survive
  - ✓ SU(3) group structure
- But they give very different spectrum for the excited Ξ states!

경북대학교

Non-relativistic quark model

Chao, Isgur, Karl PRD 23 (1981)



The 3rd lowest state at 1695 MeV?

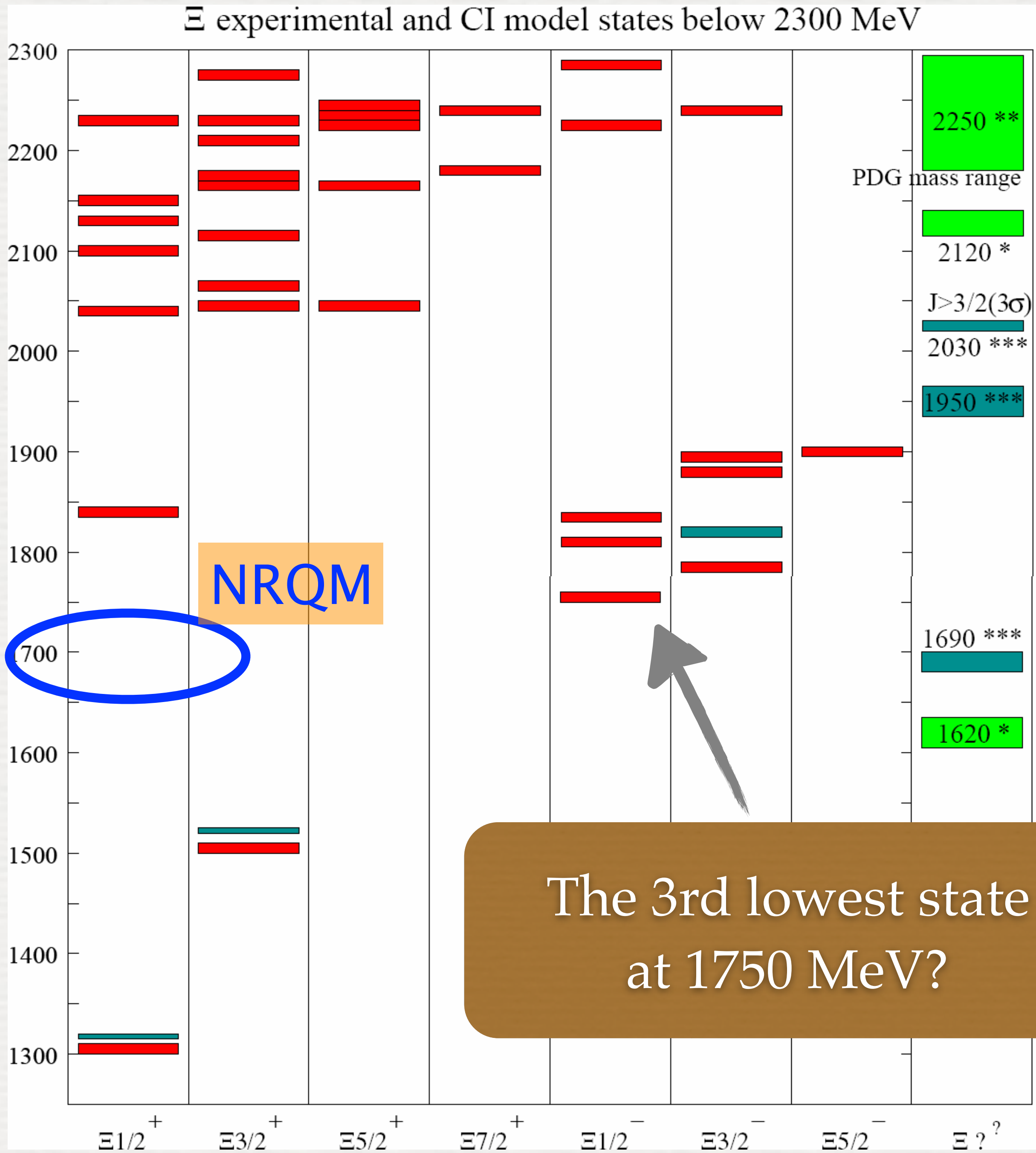
from S. Capstick

- $\Xi(1690)^{***}$ has $J^P = ½^+$?
- The first negative parity state appears at ~ 1800 MeV
- Decay widths are not fully calculated because of the limited final states (but indicates narrow widths)

경북대학교

Relativistic quark model

Capstick, Isgur PRD 34 (1986)



from S. Capstick

The 3rd lowest state at 1750 MeV?

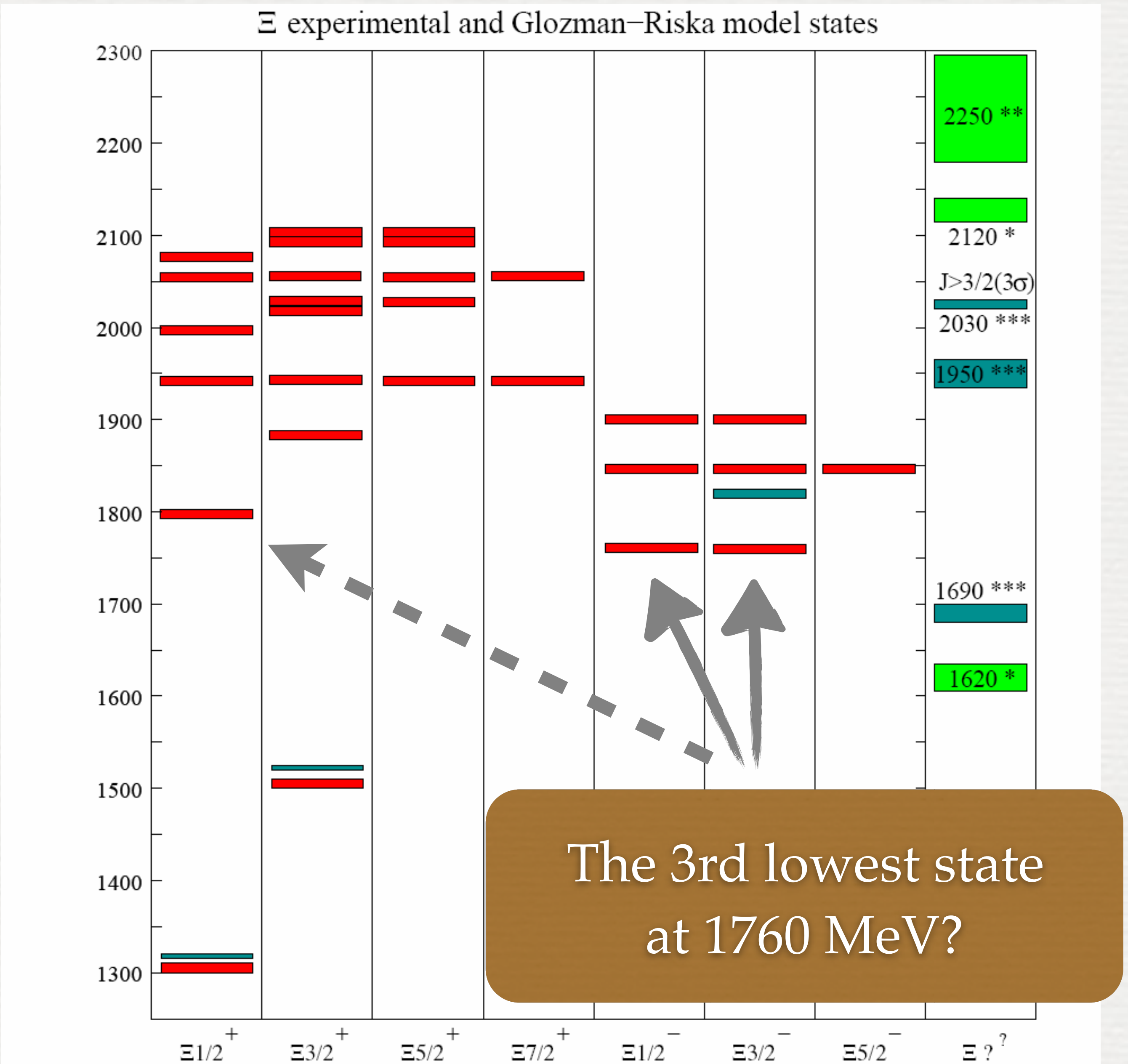
- Negative parity states have lower masses
- The 3rd lowest state has $J^P = ½^-$ at ~ 1750 MeV
- Then, where is Ξ(1690)?

경북대학교

One-boson exchange model

Glozman, Riska

Phys. Rep. 268 (1996)



Negative parity states have a lower mass

- Degeneracy pattern appears
- No clear separation between (+) and (-) parity states
- Then, where is Ξ(1690)?

from S. Capstick

경북대학교

Large Nc (Constituent QM)

Large N_C quark model

- Based on quark model
- Expand the mass operator by expansion
- Mass formula (e.g. 70-plet)

$$M = \sum_{n=0}^{11} c_n \hat{O}_n + \sum_{n=1}^{3} d_n \hat{B}_n$$

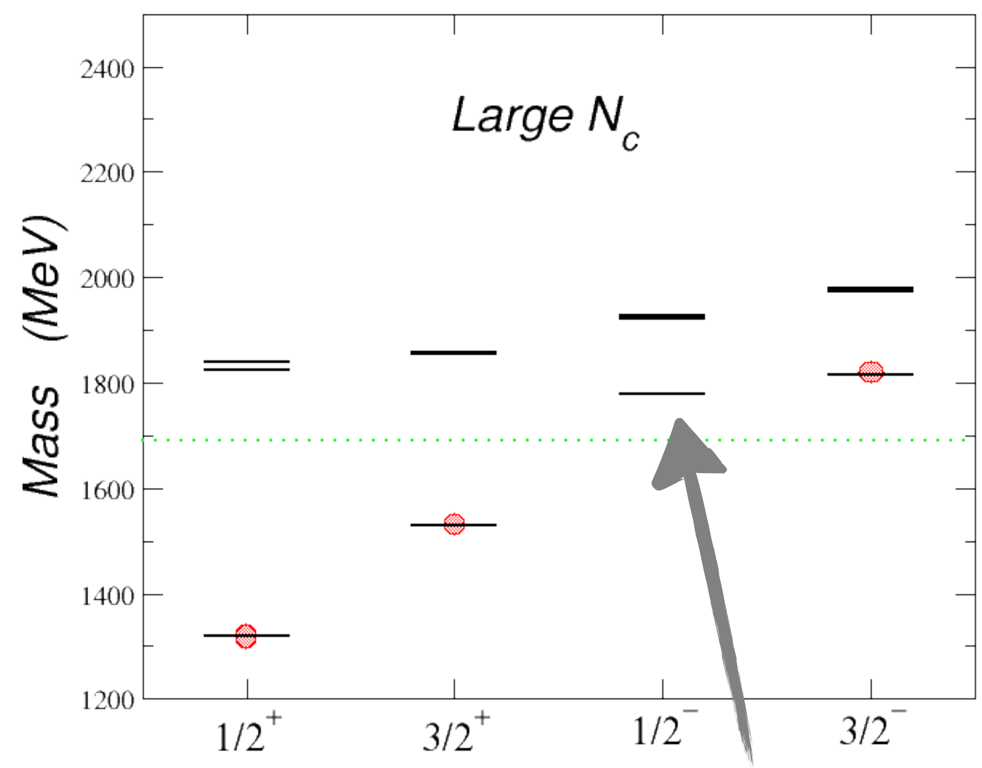
- Fit the coefficients to the known masses and predict.

Excited Ξs in $O(3) \times SU(6)$ Multiplets

$[\ell=0,56]^+$ Carlson & Carone			$[\ell=1,70]^-$ Schat, Scoccola & JLG			$[\ell=2,56]^+$ Schat, Scoccola & JLG			$[\ell=4,56]^+$ Matagne & Stancu		
State	$1/N_c$	Exp	State	$1/N_c$	Exp	State	$1/N_c$	Exp	State	$1/N_c$	Exp
$\Xi^8_{1/2}$	1825 ± 98	-	$\Xi^8_{1/2}$	1780 ± 20	-	$\Xi^8_{3/2}$	2081 ± 57	-	$\Xi^8_{7/2}$	2460 ± 166	-
$\Xi^{10}_{3/2}$	1955 ± 196	-	$\Xi^8_{3/2}$	1815 ± 20	1823 ± 5	$\Xi^8_{5/2}$	1997 ± 50	-	$\Xi^8_{9/2}$	2465 ± 165	-
			$\Xi^8_{1/2}$	1927 ± 20	-	$\Xi^{10}_{1/2}$	2237 ± 90	-	$\Xi^{10}_{5/2}$	2700 ± 266	-
			$\Xi^8_{3/2}$	1980 ± 20	-	$\Xi^{10}_{3/2}$	2216 ± 80	-	$\Xi^{10}_{7/2}$	2592 ± 203	-
			$\Xi^8_{5/2}$	1974 ± 20	-	$\Xi^{10}_{5/2}$	2181 ± 65	-	$\Xi^{10}_{9/2}$	2598 ± 250	-
			$\Xi^{10}_{1/2}$	1922 ± 20	-	$\Xi^{10}_{7/2}$	3131 ± 80	-	$\Xi^{10}_{11/2}$	2715 ± 260	-
			$\Xi^{10}_{3/2}$	1973 ± 20	-						

from J.L. Goity

Where is $\Xi(1690)$?



The 3rd lowest state at 1780 MeV?

HYPERON SPECTRUM

Baryon structure and Ξ/Ω spectra

Table 1. Low-lying *Ξ* and *Ω* baryon spectrum of spin 1/2 and 3/2 predicted by the non-relativistic quark model of Chao *et al.* (CIK), relativized quark model of Capstick and Isgur (CI), Glozman-Riska model (GR), large N_c analysis, algebraic model (BIL), and QCD sum rules (SR). The recent quark model prediction (QM) and the Skyrme model results (SK) are given as well. The mass is given in the unit of MeV.

State	CIK [4]	CI [5]	GR [6]	Large-N_c [7–11]	BIL [12]	SR [13, 14]	QM [15]	SK [1]
$\Xi(\frac{1}{2}^+)$	1325	1305	1320		1334	1320 (1320)	1325	1318
	1695	1840	1798	1825	1727		1891	1932
	1950	2040	1947	1839	1932		2014	
$\Xi(\frac{3}{2}^+)$	1530	1505	1516		1524		1520	1539
	1930	2045	1886	1854	1878		1934	2120
	1965	2065	1947	1859	1979		2020	
$\Xi(\frac{1}{2}^-)$	1785	1755	1758	1780	1869	1550 (1630)	1725	1614
	1890	1810	1849	1922	1932		1811	1660
	1925	1835	1889	1927	2076			
$\Xi(\frac{3}{2}^-)$	1800	1785	1758	1815	1828	1840	1759	1820
	1910	1880	1849	1973	1869		1826	
	1970	1895	1889	1980	1932			
$\Omega(\frac{1}{2}^+)$	2190	2220	2068	2408	2085		2175	2140
	2210	2255	2166		2219		2191	
$\Omega(\frac{3}{2}^+)$	1675	1635	1651		1670		1656	1694
	2065	2165	2020	1922	1998		2170	2282
	2215	2280	2068	2120	2219		2182	
$\Omega(\frac{1}{2}^-)$	2020	1950	1991	2061	1989		1923	1837
$\Omega(\frac{3}{2}^-)$	2020	2000	1991	2100	1989		1953	1978

Exp.

Particle	J^P
Ξ(1318)	1/2+
Ξ(1530)	3/2+
Ξ(1620)	
Ξ(1690)	1/2− ?
Ξ(1820)	3/2−
Ξ(1950)	
Ξ(2030)	
Ξ(2120)	
Ξ(2250)	
Ξ(2370)	
Ξ(2500)	

The 3rd lowest state

Highly model-dependent !

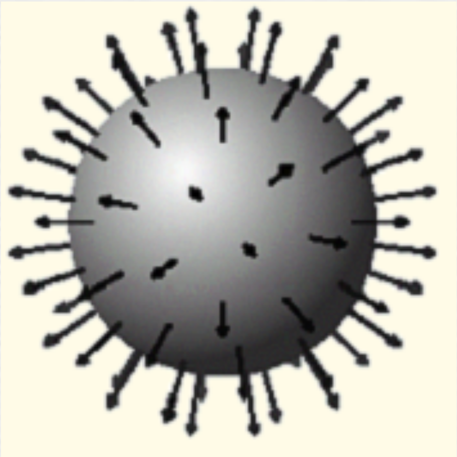
- The predicted masses for the third lowest state are higher than 1690 MeV (except NRQM)
  - How to describe $\Xi(1690)$?
- The presence of $\Xi(1620)$ is puzzling, if it exits.

Cf. similar problem in QM: $\Lambda(1405)$

Skyrme Model

- 1960s, T.H.R. Skyrme
- Baryons are topological solitons within a nonlinear theory of pions.

$$\mathcal{L} = \frac{f_\pi^2}{4} \mathrm{Tr}\left(\partial_\mu U^\dagger \partial^\mu U\right) + \frac{1}{32e^2} \mathrm{Tr}\left[U^\dagger \partial_\mu U, U^\dagger \partial_\nu U\right]^2$$



Topological soliton
winding number = integer

↑

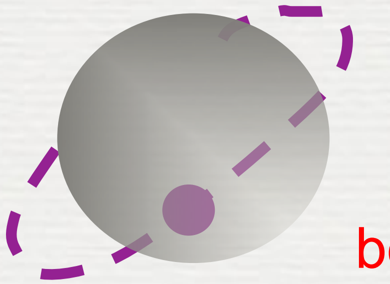
interpret as baryon number

Bound State Model

- Starting point: flavor SU(3) symmetry is badly broken
    - treats light flavors and strangeness on a different footing

      $\mathrm{SU}(3) \to \mathrm{SU}(2) \times \mathrm{U}(1)$

    - Lagrangian $\mathcal{L} = \mathcal{L}_{\mathrm{SU}(2)} + \mathcal{L}_{K/K^*}$
    - The soliton provides a background potential that traps K/K* (or heavy) mesons.



Callan, Klebanov, NPB **262** (1985)

Bound State Model

- Anomalous Lagrangian
  - Pushes up the S = +1 states to the continuum → no bound state
  - Pulls down the S = -1 states below the threshold → allows bound state → description of hyperons
- Renders two bound states with S = -1

after quantization

  - the lowest state: p-wave → gives (+)-ve parity Λ(1116)

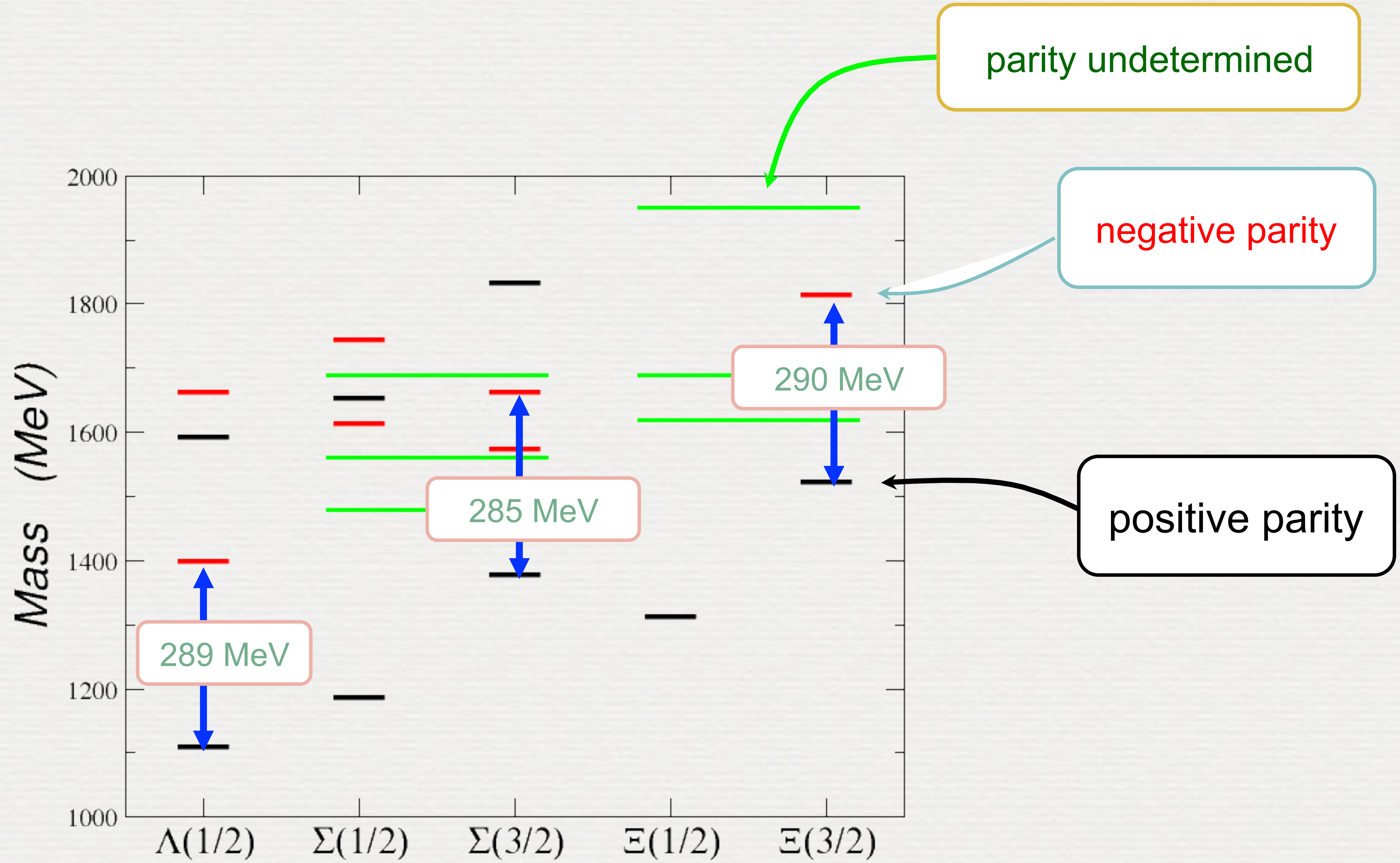
270 MeV energy difference

  - excited state: s-wave → gives (-)-ve parity Λ(1405)
- Mass formula includes parameters: depends on dynamics

  we fix them to known masses and then predict

Experimental Data

- Experimental Data



MASS FORMULA

$$M(i,j,j_m) = M_{sol} + n_1\omega_1 + n_2\omega_2 + \frac{1}{2I}\Big\{ i(i+1) + c_1c_2 j_m(j_m+1) + (\bar{c}_1 - c_1c_2) j_1(j_1+1) + (\bar{c}_2 - c_1c_2) j_2(j_2+1)$$

$$+ \frac{c_1+c_2}{2}\left[j(j+1) - j_m(j_m+1) - i(i+1) \right] + \frac{c_1-c_2}{2}\vec{R}\cdot(\vec{J}_1 - \vec{J}_2) \Big\}$$

$\Theta^2 = \bar{c}\boldsymbol{J}_K^2,$

causes mixing

8 parameters: fit to the available data

→ give predictions to the other resonances

The last term gives a mixing between the states which have same *i, j,* j_m but different *R,* J_1*,* J_2

Fitted values

$M_{sol} = 866$ MeV, $\quad I = 1.01$ fm

$\omega_1 = 211$ MeV, $\quad c_1 = 0.754, \quad \bar{c}_1 = 0.532$

$\omega_2 = 479$ MeV, $\quad c_2 = 0.641, \quad \bar{c}_2 = 0.821$

cf. $\bar{c}_1 = c_1^2, \quad \bar{c}_2 = c_2^2$ in Kaplan, Klebanov, NPB **335** (1990)

Bound State Model

- Mass sum rules
  - modification to GMO and equal spacing rule

$$3\Lambda + \Sigma - 2(N + \Xi) = 0$$

$$(\Omega - \Xi^*) = (\Xi^* - \Sigma^*) = (\Sigma^* - \Delta)$$

$$\rightarrow$$

$$3\Lambda + \Sigma - 2(N + \Xi) = \Sigma^* - \Delta - (\Omega - \Xi^*)$$

$$(\Omega - \Xi^*) - (\Xi^* - \Sigma^*) = (\Xi^* - \Sigma^*) - (\Sigma^* - \Delta)$$

  - hyperfine relation $\Sigma^* - \Sigma + \frac{3}{2}(\Sigma - \Lambda) = \Delta - N$
  - These relations are hold for

$$\Lambda(1/2^-), \Sigma(1/2^-), \Sigma(3/2^-), \Xi(1/2^+), \Xi(3/2^+), \Omega(3/2^-)$$

Bound State Model

- Best-fitted results based on the derived mass formula

Particle	Prediction (MeV)	Expt
N	939*	$N(939)$
Δ	1232*	$\Delta(1232)$
$\Lambda(1/2^+)$	1116*	$\Lambda(1116)$
$\Lambda(1/2^-)$	1405*	$\Lambda(1405)$
$\Sigma(1/2^+)$	1164	$\Sigma(1193)$
$\Sigma(3/2^+)$	1385	$\Sigma(1385)$
$\Sigma(1/2^-)$	1475	$\Sigma(1480)$?
$\Sigma(3/2^-)$	1663	$\Sigma(1670)$
$\Xi(1/2^+)$	1318*	$\Xi(1318)$
$\Xi(3/2^+)$	1539	$\Xi(1530)$
$\Xi(1/2^-)$	1658 (1660)	$\Xi(1690)$?
$\Xi(1/2^-)$	1616 (1614)	$\Xi(1620)$?
$\Xi(3/2^-)$	1820	$\Xi(1820)$
$\Xi(1/2^+)$	1932	$\Xi(1950)$?
$\Xi(3/2^+)$	2120*	$\Xi(2120)$
$\Omega(3/2^+)$	1694	$\Omega(1672)$
$\Omega(1/2^-)$	1837	
$\Omega(3/2^-)$	1978	
$\Omega(1/2^+)$	2140	
$\Omega(3/2^+)$	2282	$\Omega(2250)$?
$\Omega(3/2^-)$	2604	

Recently confirmed by COSY
*PRL **96** (2006)*

BaBar : the spin-parity of $\Xi(1690)$ is $1/2^-$
*PRD **78** (2008)*
NRQM predicts $1/2^+$

puzzle in QM

Unique prediction of this model.
The $\Xi(1620)$ should be there.
still one-star resonance

Ω's would be discovered in future.

YO, PRD **75** (2007)

More Comments

Two Ξ states

Kaons: one in p-wave and one in s-wave

$\Rightarrow \vec{J} = \vec{J}_{sol} + \vec{J}_m \qquad (\vec{J}_m = \vec{J}_1 + \vec{J}_2)$

$\vec{J}_{sol}$: soliton spin $(=1/2)$, $\vec{J}_1(\vec{J}_2)$: spin of the p(s)-wave kaon $(=1/2)$

$J_m = 0$ or 1: both of them can lead to $J^P = 1/2^-$ Ξ states

Therefore, two $J^P = 1/2^-$ Ξ states and one $J^P = 3/2^-$ Ξ states

In this model, it is natural to have two $J^P = 1/2^-$ Ξ states at 1616 MeV & 1658 MeV

Clearly, different from quark models

Other approaches

Unitary extension of chiral perturbation theory

Ramos, Oset, Bennhold, PRL 89 (2002): $1/2^-$ state at 1606 MeV

Garcia-Recio, Lutz, Nieves, PLB 582 (2004): claim tht the Ξ(1620) and Ξ(1690) are $1/2^-$ states

Recent Works

PHYSICAL REVIEW D **85,** 017502 (2012)

Are there three $\Xi(1950)$ states?

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PTEP

Prog. Theor. Exp. Phys. **2013**, 00000 (10 pages)
DOI: 10.1093/ptep/0000000000

$\Xi(1690)$ as a $\bar{K}\Sigma$ molecular state

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E&M PROPERTIES

MAGNETIC MOMENTS

✳ Magnetic moment operator

$$\hat{\mu} = \hat{\mu}_s + \hat{\mu}_v \qquad \begin{aligned} \hat{\mu}_s &= \mu_{s,0} R^z + \mu_{s,1} J_1^z + \mu_{s,2} J_2^z, \\ \hat{\mu}_v &= -2(\mu_{v,0} + \mu_{v,1} n_1 + \mu_{v,2} n_2) D^{33}, \end{aligned}$$

✳ Sum rules

$$\begin{aligned}
\mu(\Sigma^{*+}) - \mu(\Sigma^{*-}) &= \tfrac{3}{2}\{\mu(\Sigma^{+}) - \mu(\Sigma^{-})\}, \\
\mu(\Sigma^{+}) + \mu(\Sigma^{-}) &= \tfrac{4}{3}\{\mu(p) + \mu(n)\} - \tfrac{2}{3}\mu(\Lambda), \\
\mu(\Sigma^{*+}) + \mu(\Sigma^{*-}) &= 2\{\mu(p) + \mu(n)\} + 2\mu(\Lambda), \\
\mu(\Xi^{0}) + \mu(\Xi^{-}) &= -\tfrac{1}{3}\{\mu(p) + \mu(n)\} + \tfrac{8}{3}\mu(\Lambda), \\
\mu(\Xi^{*0}) + \mu(\Xi^{*-}) &= \mu(p) + \mu(n) + 4\mu(\Lambda), \\
\mu(\Xi^{*0}) - \mu(\Xi^{*-}) &= -3\{\mu(\Xi^{0}) - \mu(\Xi^{-})\}, \\
\mu(\Omega) &= 3\mu(\Lambda),
\end{aligned}$$

$$\begin{aligned}
\mu(\Omega_{1/2^-,1}) &= \tfrac{4}{3}\mu(\Lambda_{1116}) - \tfrac{1}{3}\mu(\Lambda_{1405}), \\
\mu(\Omega_{3/2^-,1}) &= 2\mu(\Lambda_{1116}) + \mu(\Lambda_{1405}), \\
\mu(\Omega_{1/2^+,1}) &= -\tfrac{1}{3}\mu(\Lambda_{1116}) + \tfrac{4}{3}\mu(\Lambda_{1405}), \\
\mu(\Omega_{3/2^+,1}) &= \tfrac{1}{3}\mu(\Lambda_{1116}) + 2\mu(\Lambda_{1405}),
\end{aligned}$$

Expt. $2.02 = 3 \times 0.163 = 1.84$

ELECTRIC QUADRUPOLE MOMENTS

Table 2. Electric quadrupole moments of the decuplet baryons in units of $10^{-2}\ \mathrm{e\cdot fm^2}$. The works (I) and (II) correspond to $\chi = 1.0$ and 1.22, respectively.

YO, MPLA **10** (1995)

Particle	Δ^{++}	Δ^{+}	Δ^{0}	Δ^{-}	Σ^{*+}	Σ^{*0}	Σ^{*-}	Ξ^{*0}	Ξ^{*-}	Ω^{-}
Ref. 3	–	–	–	–	–	–	–	–	–	1.8
Ref. 4	−6.6	−3.3	0.0	3.3	–	–	–	–	–	–
Ref. 5	−9.8	−4.9	0.0	4.9	–	–	–	–	–	3.1
Ref. 6	–	–	–	–	–	–	–	–	–	0.4
Ref. 7	−17.8	−8.9	0.0	8.9	–	–	–	–	–	–
Ref. 8	−12.6	−6.3	0.0	6.3	–	–	–	–	–	–
Ref. 9	−6.0	−2.1	1.8	5.7	−2.2	−0.01	2.0	−0.6	1.0	0.6
Ref. 10	−9.3	−4.6	0.0	4.6	−5.4	−0.7	4.0	−1.3	3.4	2.8
Ref. 11	−2.7	−1.3	0.0	1.3	0.2	0.5	1.0	0.5	0.8	0.5
Ref. 12	−8.0	−3.0	1.2	6.0	−7.0	−1.3	4.0	−3.5	2.0	0.9
Ref. 13	−8.7	−3.1	2.4	8.0	−4.2	0.5	5.2	−0.7	3.5	2.4
(I)	−8.8	−2.9	2.9	8.8	−8.2	0.0	8.2	−6.0	6.0	0.0
(II)	−8.8	−2.9	2.9	8.8	−7.1	0.0	7.1	−4.6	4.6	0.0

proportional to the baryon charge (Q) in the SU(3) limit

proportional to the baryon isospin (I_3) in the strongly broken SU(3) limit

18 August 1994

PHYSICS LETTERS B

Physics Letters B 334 (1994) 287–289

Electric quadrupole moments of the decuplet and the strangeness content of the proton

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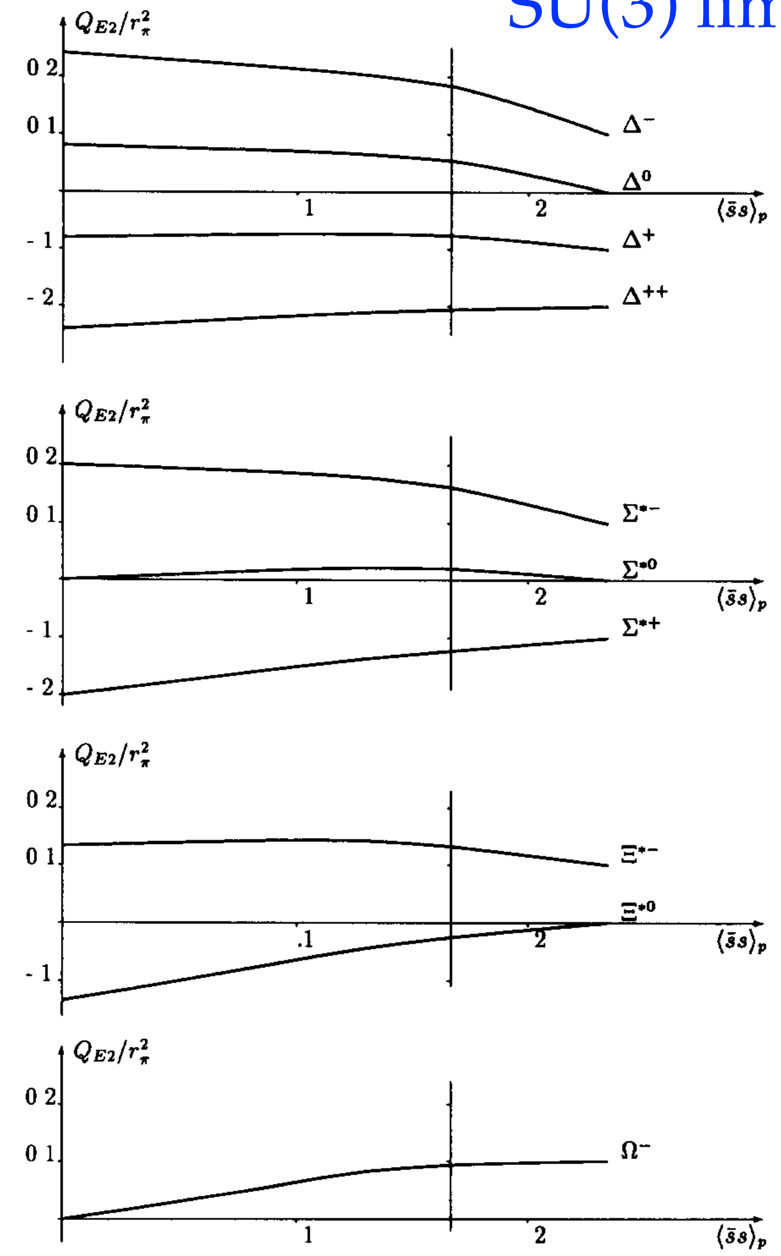
SU(3) limit



PHYSICAL REVIEW D, VOLUME 65, 073017

Quadrupole moments of baryons

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TABLE I. Two-quark (B) and three-quark (C) contributions to quadrupole moments of decuplet baryons in the SU(3) symmetry limit ($r=1$) and with broken flavor symmetry. SU(3)-flavor symmetry breaking is characterized by the ratio of u-quark and s-quark masses $r=m_u/m_s$. Two types (quadratic and cubic) of flavor symmetry breaking are considered.

	$Q(r=1)$	Q(quadratic)	Q(cubic)
Δ^-	$-4B-2C$	$-4B-2C$	$-4B-2C$
Δ^0	0	0	0
Δ^+	$4B+2C$	$4B+2C$	$4B+2C$
Δ^{++}	$8B+4C$	$8B+4C$	$8B+4C$
Σ^{*-}	$-4B-2C$	$-(4B+2C)(1+2r)/3$	$-(4B+2C)(1+r+r^2)/3$
Σ^{*0}	0	$2(B-C)(1-r)/3$	$[2B(1+r-2r^2)-C(2-r-r^2)]/3$
Σ^{*+}	$4B+2C$	$[4B(2+r)-2C(1-4r)]/3$	$[4B(2+2r-r^2)-2C(1-2r-2r^2)]/3$
Ξ^{*-}	$-4B-2C$	$-(4B+2C)(2r+r^2)/3$	$-(4B+2C)(r+r^2+r^3)/3$
Ξ^{*0}	0	$4(B-C)(r-r^2)/3$	$[4B(2r-r^2-r^3)-2C(r+r^2-2r^3)]/3$
Ω^-	$-4B-2C$	$-(4B+2C)r^2$	$-(4B+2C)r^3$

SUMMARY & OUTLOOK

Summary & Outlook

- Study on the spectrum of Ξ baryons
  - opens a new window for understanding baryon structure
- Theoretical models for Ξ spectrum
  - different and even contradictory predictions
  - mass and quantum numbers of the third lowest state
  - Skyrme model: Ξ(1620) and Ξ(1690) as analogue states of *Λ*(1405)
- Experimental side: More precise data are needed
  - existence of Ξ(1620)
  - should confirm other poorly established Ξ resonances and their quantum numbers
  - almost no information about *Ω* baryons

Summary & Outlook

- Role of Λ and Σ resonances in Ξ production processes
  - offers a chance to study these resonances
  - higher mass and high spin resonances
- J-PARC gives a new chance for Ξ physics.
  - larger yields than photoproduction
  - needs various polarization measurements
- EM properties of hyperons
- We definitely need more data.
- Omega baryons ?