70 Years of Hyperon Spectroscopy: The Exploration of Very Strange Baryons

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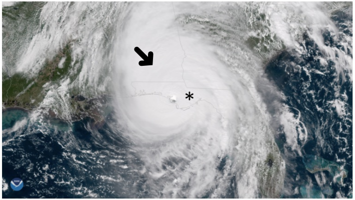
Excited QCD 2024 Workshop

Benasque, Spain

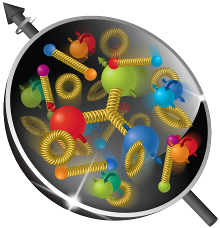
01/17/2024

Outline

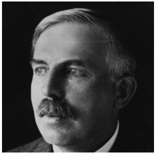
1. Introduction and Motivation
   - Experimental Studies of Baryons
2. Baryon Spectroscopy
   - Nucleon Resonances at GlueX
   - Spectroscopy of Ξ Resonances
3. Summary and Conclusions



Outline



Particle Zoo



Name "proton" given to H nucleus by Rutherford in 1920

He had discovered earlier that proton was a candidate to be a fundamental particle & building block of nitrogen, and all other heavier atomic nuclei.

1932 Neutron

1947 First Mesons: π^+, π^-, K^+, K^-

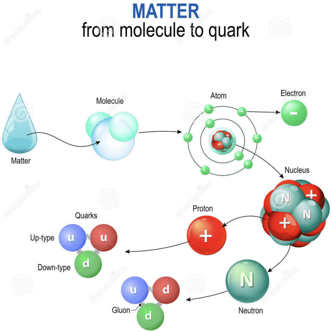
1951 Strange baryons: Λ with $|uds\rangle$

1964 Ω^- with $|sss\rangle$

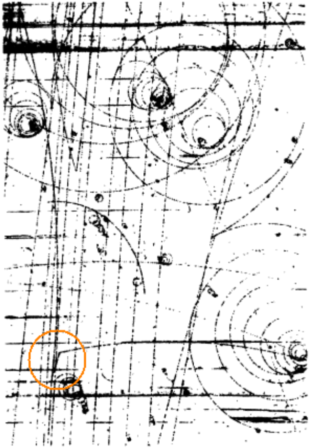
1964 Quark model

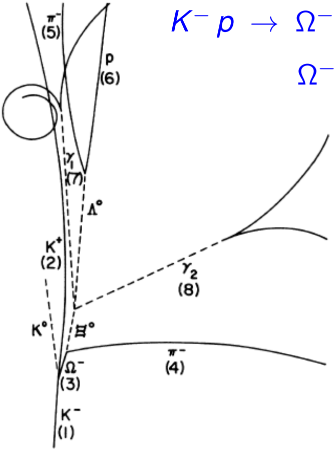
1968 Discovery of "partons" at SLAC

after 1970:
Quantum Chromodynamics



1964: Discovery of the Ω Baryon at BNL





$$K^- p \rightarrow \Omega^- K^+ K^0$$

$$\Omega^- \rightarrow \Xi^0 \pi^-$$

$$\Xi^0 \rightarrow \Lambda^0 \pi^0$$

Nuclear Femtography: Non-Perturbative QCD

Color Confinement — Asymptotic freedom — Q (GeV)

20 MeV (10 fm) — 200 MeV (1 fm) — 2 GeV (1/10 fm)

Probing scale

QCD at the Fermi Scale: Femto-science (0.1-10 fm)

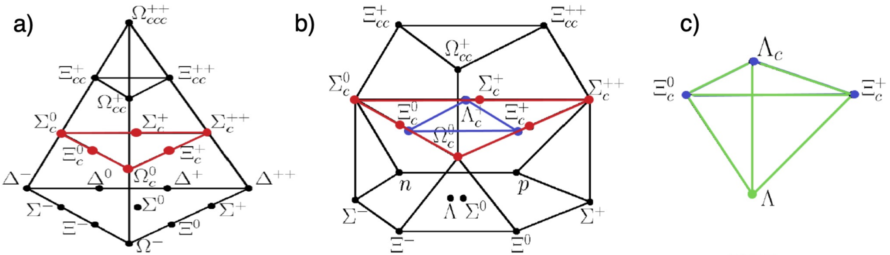
- ***The most interesting, rich, and complex regime of the theory!***
- ***All emergent phenomena depend on the scale at which we probe them!***

Asymptotic regime PQCD works beautifully!

How does QCD give rise to excited nucleons?

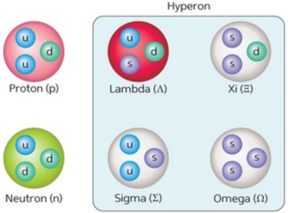
- Relevant degrees of freedom
- Quark-quark interactions

SU(4) Multiplet Structure of Baryons

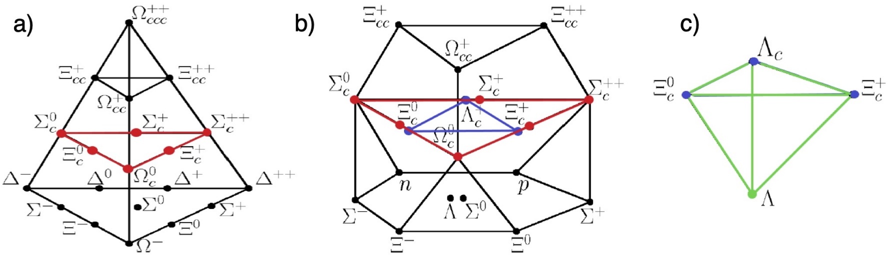


Multiplet structure for flavor SU(3):

$$3 \otimes 3 \otimes 3 = 10_S \oplus 8_M \oplus 8_M \oplus 1_A$$



SU(4) Multiplet Structure of Baryons



Multiplet structure for flavor SU(4):

$$4 \otimes 4 \otimes 4 = 20_S \oplus 20_M \oplus 20_M \oplus 4_A$$

➜ Great progress also for charmed and bottom baryons (Belle, LHCb).
V.C. and J. Yelton, review submitted to Reports on Progress in Physics

How do we study baryons experimentally?

Light-flavor baryons are typically studied in fixed-target experiments (nuclear physics), heavy-flavor baryons are studied at colliders (high-energy physics).

1. Fixed-Target Experiments

   Photo-/electroproduction, e. g. Jefferson Lab, ELSA, MAMI, etc.

   e. g. $\gamma N\,(\mathrm{e}^-\,N) \to (\mathrm{e}^-)\,N^*/\Delta^*$

   $\gamma N\,(\mathrm{e}^-\,N) \to (\mathrm{e}^-)\,K\,Y^*\,(Y^{ast} = \Lambda^*, \Sigma^*)$

   π / K-induced production, e. g. HADES@GSI, (future J-PARC, JLab)

   e. g. $\pi N \to N^*/\Delta^*$

2. Collider Experiments

   at e^+e^- machines, e. g. BES III, Belle, BaBar, etc.

   e. g. $\Xi_c^+\,(\Lambda_c^+) \to [\Xi^-\pi^+]_{\Xi^*}\,\pi^+\,(K^+)$ or $e^+e^- \to J/\psi \to N^*\bar{N}$

   at pp machines, e. g. LHC

   e. g. $\Xi_b^{*\,-} \to \Xi_b^-\,\pi^+\pi^-$ (LHCb, CMS)

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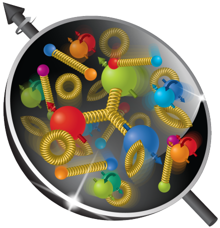


Spectrum of N^* Resonances

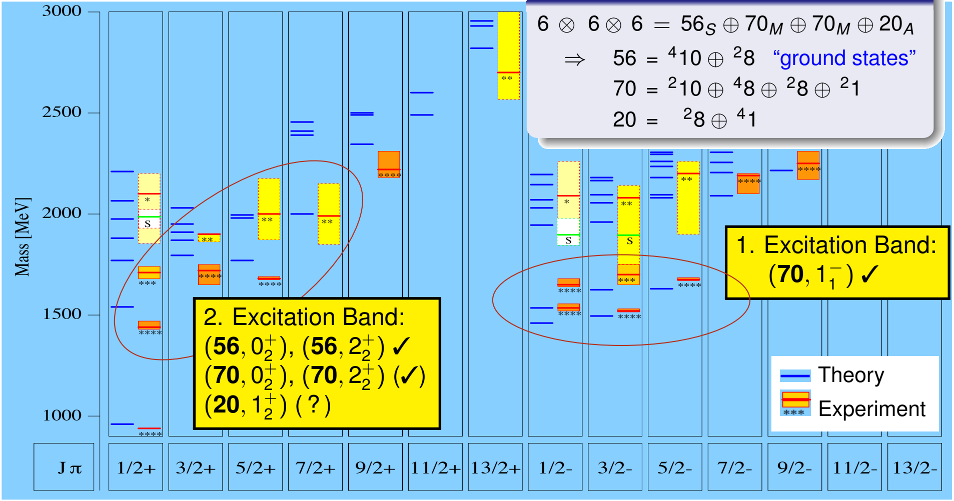
SU(6) ($^{2S+1}$multiplets; u, d, s, spin)

$$6 \otimes 6 \otimes 6 = 56_S \oplus 70_M \oplus 70_M \oplus 20_A$$

$$\Rightarrow \quad 56 = {}^4 10 \oplus {}^2 8 \quad \text{“ground states”}$$

$$70 = {}^2 10 \oplus {}^4 8 \oplus {}^2 8 \oplus {}^2 1$$

$$20 = {}^2 8 \oplus {}^4 1$$

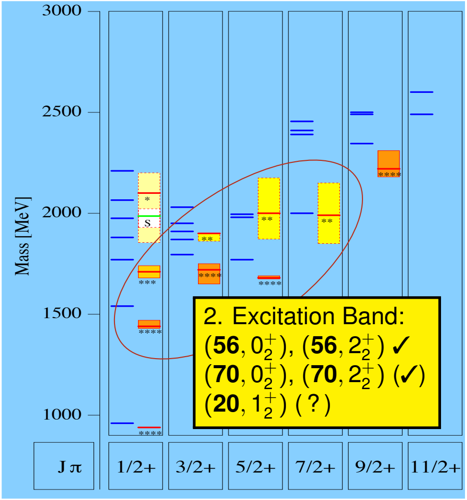


1. Excitation Band: $(\mathbf{70}, 1_1^-)$ ✓

2. Excitation Band:
$(\mathbf{56}, 0_2^+)$, $(\mathbf{56}, 2_2^+)$ ✓
$(\mathbf{70}, 0_2^+)$, $(\mathbf{70}, 2_2^+)$ (✓)
$(\mathbf{20}, 1_2^+)$ (?)

S. Capstick & N. Isgur, Phys. Rev. **D34** (1986) 2809

Spectrum of N^* Resonances

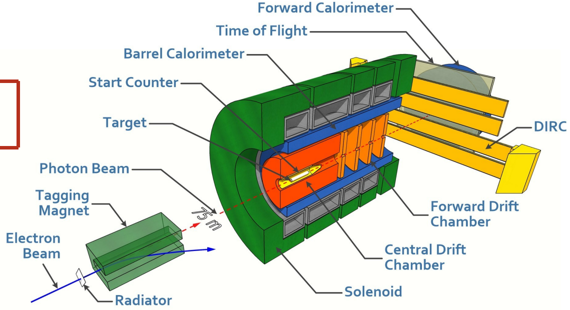


V. C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

N	(D, L_N^P)	S	J^P	Octet Members				Singlets
0	$(56, 0_0^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	–
1	$(70, 1_1^-)$	$\frac{1}{2}$	$\frac{1}{2}^-$	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	~~$\Xi(1690)$~~	$\Lambda(1405)$
			$\frac{3}{2}^-$	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
		$\frac{3}{2}$	$\frac{1}{2}^-$	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$		–
			$\frac{3}{2}^-$	$N(1700)$				–
			$\frac{5}{2}^-$	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$		–
2	$(56, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$		–
	$(70, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(1710)$	$\Lambda(1810)^\dagger$	$\Sigma(1770)^\dagger$		
		$\frac{3}{2}$	$\frac{3}{2}^+$					–
	$(56, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$	$N(1720)^\dagger$	$\Lambda(1890)^\dagger$	$\Sigma(1840)^\dagger$		–
			$\frac{5}{2}^+$	$N(1680)$	$\Lambda(1820)^\dagger$	$\Sigma(1915)^\dagger$		–
	$(70, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$					
			$\frac{5}{2}^+$	$N(1860)$				
		$\frac{3}{2}$	$\frac{1}{2}^+$	$N(1880)$				–
			$\frac{3}{2}^+$	$N(1900)^\dagger$		$\Sigma(2080)^\dagger$		–
			$\frac{5}{2}^+$	$N(2000)$	$\Lambda(2110)^\dagger$	$\Sigma(2070)^\dagger$		–
			$\frac{7}{2}^+$	$N(1990)$	$\Lambda(2020)$	$\Sigma(2030)^\dagger$		–
	$(20, 1_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(2100)^\dagger$				
			$\frac{3}{2}^+$	$N(2040)^\dagger$				
			$\frac{5}{2}^+$	–	–	–	–	

Hadron Spectroscopy

- π + Nucleus
- $\gamma\, p$ *Photoproduction*
- $e^+ e^-$
- $\bar{p}\, p$



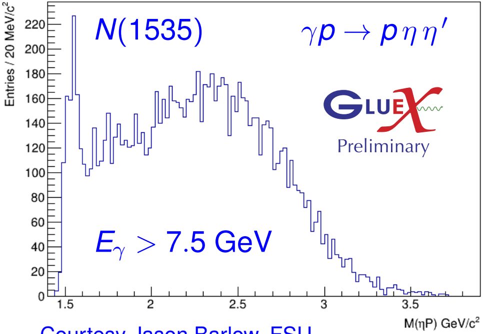
The GlueX Collaboration

- $\sim$135 members, 29 institutions
  (Armenia, Canada, Chile, China, Germany, Greece, Russia, UK, USA)
- GlueX phase-I complete (120 PAC days)
- First physics published in 2017

N^* Spectroscopy at GlueX

GlueX is not the ideal experiment for N^* spectroscopy without a polarized target. However,

- N^* resonances are abundantly produced at $E_\gamma > 7$ GeV.
- Interesting program on N^* physics is possible.



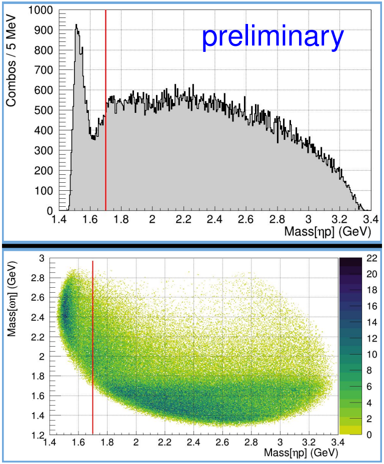
Courtesy Jason Barlow, FSU

Data selection:

- General cuts to improve overall event kinematics (CL, missing mass, etc.).
- No cuts (yet) to enhance $\gamma p \to \eta' N(1535)$ production.

Possibly, direct access to $N(1535)\,\frac{1}{2}^-$ due to t-channel production.

N^* Spectroscopy at GlueX



Courtesy Edmundo Barriga, FSU

Reaction: $\gamma p \to p\,\eta\,\omega$

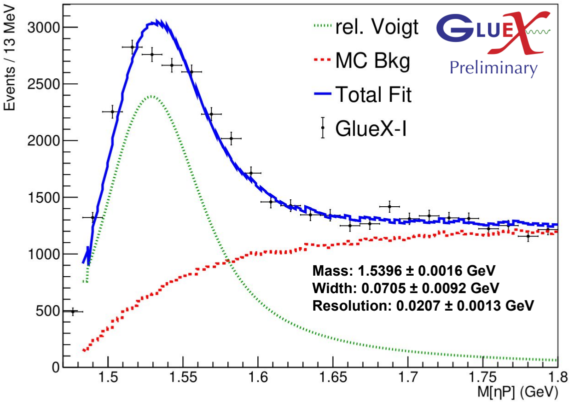
Data selection:

- General cuts to improve overall event kinematics (CL, missing mass, etc.).
- $8.2\ \mathrm{GeV} < E_\gamma < 8.8\ \mathrm{GeV}$
- $-t < 0.6$ GeV^2
- No cuts (yet) to enhance $\gamma p \to \omega\, N(1535)$ production.

Possibly, direct access to $N(1535)\,\frac{1}{2}$ due to t-channel production.

N^* Spectroscopy at GlueX

V. C. *et al.* [GlueX], Few Body Syst. **64** (2023) 2, 32



Courtesy Edmundo Barriga, FSU

$N(1535)$ BREIT-WIGNER WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
125 to 175 (≈ 150) OUR ESTIMATE				
147 ± 5	[6] HUNT	19	DPWA	Multichannel
163 ± 25	KASHEVAROV	17	DPWA	$\gamma p \to \eta p, \eta' p$
120 ± 10	SOKHOYAN	15A	DPWA	Multichannel
131 ± 12	[6] SHKLYAR	13	DPWA	Multichannel
188.4 ± 3.8	[6] ARNDT	06	DPWA	$\pi N \to \pi N, \eta N$
240 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
120 ± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
128 ± 14	ANISOVICH	12A	DPWA	Multichannel
141 ± 4	[6] SHRESTHA	12A	DPWA	Multichannel
182 ± 25	BATINIC	10	DPWA	$\pi N \to N\pi, N\eta$
129 ± 8	PENNER	02C	DPWA	Multichannel
95 ± 25	BAI	01B	BES	$J/\psi \to p\bar{p}\eta$
143 ± 18	THOMPSON	01	CLAS	$\gamma^* p \to p\eta$

Description with rel. Voigtian

Barrier factor of $L = 1$

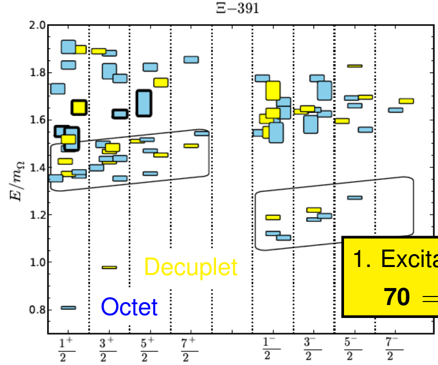
$\eta\omega$ MC background

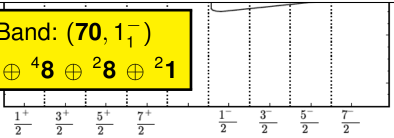
$M_{\eta\omega} < 2$ GeV/c^2

➜ $\Gamma = 70.5 \pm 9.2$ MeV

The Ξ^* and Ω^* Spectrum from Lattice QCD

R. Edwards *et al.*, PRD **87**, 054506 (2013)





Ξ(1320)	****	$\to \Lambda\pi$	$I\left(J^P\right) = \frac{1}{2}\left(\frac{1}{2}^+\right)$
Ξ(1530)	****	$\to \Xi\pi$	$I\left(J^P\right) = \frac{1}{2}\left(\frac{3}{2}^+\right)$
Ξ(1620)	**	$\to \Xi\pi$?	$I\left(J^P\right) = \frac{1}{2}\left(\frac{1}{2}^- \text{ or } \frac{1}{2}^+\right)$
Ξ(1690)	***	$\to Y\bar{K}$	$I\left(J^P\right) = \frac{1}{2}\left(\frac{1}{2}^- ?\right)$
Ξ(1820)	***	$\to \Lambda\bar{K}$!	$I\left(J^P\right) = \frac{1}{2}\left(\frac{3}{2}^-\right)$
Ξ(1950)	***	$\to \Xi\pi,\ Y\bar{K}$	$I\left(J^P\right) = \frac{1}{2}\left(\frac{3}{2}^- ?\right)$, "broad"
Ξ(2030)	***	$\to Y\bar{K}$	$I\left(J^P\right) = \frac{1}{2}\left(\geq \frac{5}{2}^?\right)$

1. Excitation Band: $(\mathbf{70}, 1_1^-)$

$$\mathbf{70} = {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1}$$

Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

➜ Counting of states of each flavor and spin consistent with QM for the lowest negative- and positive-parity bands.

Particle Data Group: Unstable (Light-Flavor) Baryons





Philosophy: descriptive vs. prescriptive (generally descriptive)

descriptive: maintain listings and reviews

prescriptive: collect standards (e.g. naming scheme) and best practices (e.g. moving beyond BW parameters)

$S_{11}(1535) \longleftrightarrow N(1535)\,\frac{1}{2}^{-}$

PDG 2022 Mini-Review

Ξ Resonances

Revised 2004 by C.G. Wohl, (LBNL).

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.

PDG 2023 Mini-Review

Ξ Resonances

Revised 2023 by V. Crede (FSU), U. Thoma (U. Bonn)

Most of our present knowledge of Ξ resonances stems from the low-statistics data samples recorded in the 1960s–1980s using K^- beams and in the 1980s and 1990s using hyperon (Σ^-, Ξ^-) beams. This is because (1) they could 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 1980s did electronic experiments make any significant contributions.

In recent years, significant contributions have come from collider experiments. Excited Ξ baryons are produced and have been studied in the decay of the charmed Λ_c^+ into $(\Sigma^+ K^-)_{\Xi(1690)}\, K^+$ by the Belle Collaboration [1] and into $(\Xi^- \pi^+)_{\Xi^*}\, K^+$ by the BaBar Collaboration [2]. Belle measures the decay $\Xi_c^+ \to (\Xi^- \pi^+)_{\Xi^*}\, \pi^+$ [3] with unprecedented statistical quality.

Ξ Resonances using K^- Beams

VOLUME 51, NUMBER 11 PHYSICAL REVIEW LETTERS 12 SEPTEMBER 1983

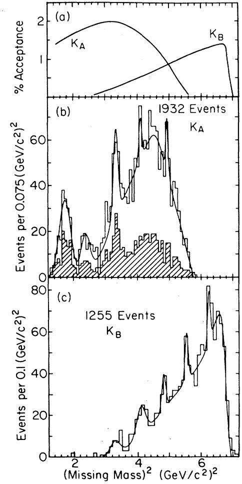
Existence of Ξ Resonances above 2 GeV

C. M. Jenkins, J. R. Albright, R. N. Diamond, H. Fenker,[(a)] J. H. Goldman, S. Hagopian, V. Hagopian, and W. Morris[(b)]
Florida State University, Tallahassee, Florida 32306
and
L. Kirsch, R. Poster, and P. Schmidt[(c)]
Brandeis University, Waltham, Massachusetts 02154
and
S. U. Chung, R. C. Fernow, H. Kirk, S. D. Protopopescu, and D. P. Weygand
Brookhaven National Laboratory, Upton, New York 11973
and
B. T. Meadows
University of Cincinnati, Cincinnati, Ohio 45221
and
Z. Bar-Yam, J. Dowd, W. Kern, and M. Winik[(d)]
Southern Massachusetts University, North Dartmouth, Massachusetts 02747
(Recieved 30 June 1983)

Ξ^{*-} production was studied in the reaction $K^- + p \to K^+_{slow} + X^-$ at 5 GeV/c. The slow K^+ was electronically detected, while the X^- was observed as a missing mass, thus allowing for observation of all Ξ^* independent of decay mode. The observed Ξ states were Ξ(1320), Ξ(1530), Ξ(1820), Ξ(2030), Ξ(2250), Ξ(2370), and Ξ(2500). These data establish and confirm the existence of Ξ(2250) and indicate a peculiar production-cross-section behavior for the $\Xi^*(2370)$.

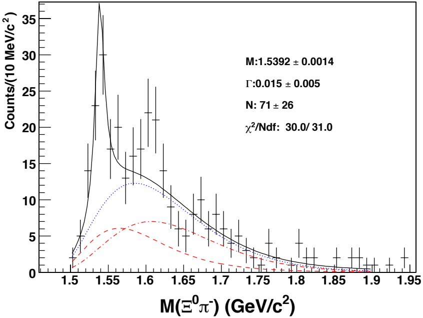
PACS numbers: 14.20.Jn, 13.75.Jz

$K^- p \to K^+ X^-$ ➜

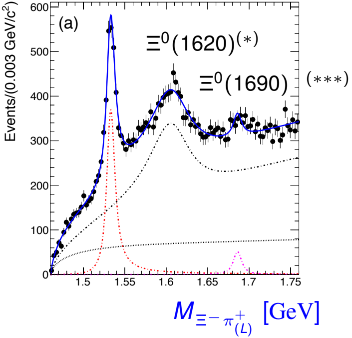


Excited Ξ^* States: 1500 - 1750 Mass Region

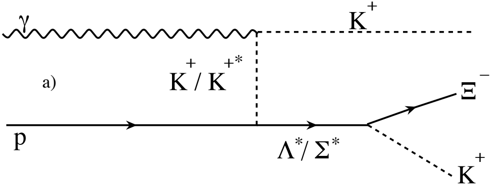
From the paper: *Although a small enhancement is observed in the $\Xi^0\pi^-$ invariant mass spectrum near the controversial 1-star $\Xi^-(1620)$ resonance, it is not possible to determine its exact nature without a full partial wave analysis.*
[CLAS], Phys. Rev. C **76**, 025208 (2007)

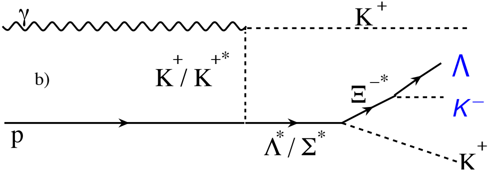


Belle: PRL **122**, 072501 (2019)

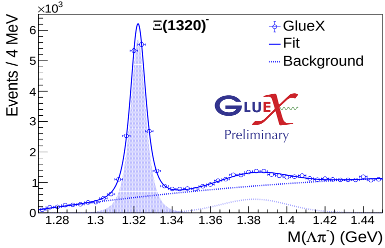


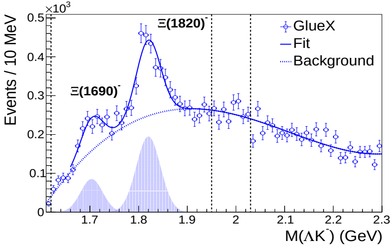
Possible Production Mechanisms





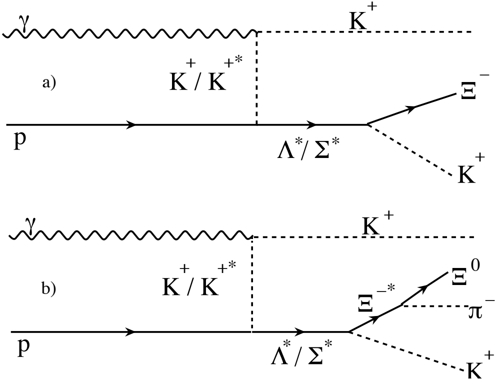
$$\gamma p \rightarrow K^+ (K^+ \Xi^{-*}) \rightarrow K^+ (p \pi^- K^-) K^+$$





Courtesy of Jesse Hernandez, Chandra Akondi (FSU)

Possible Production Mechanisms



$K^+(\Xi^- K^+)$, $K^+(\Xi^0 K^0)$, $K^0(\Xi^0 K^+)$

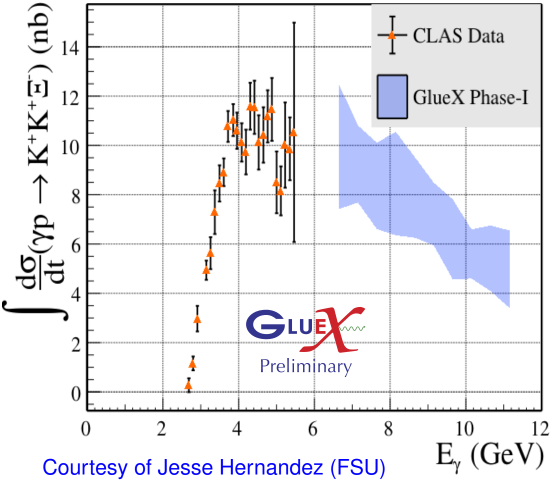
➜ Cross sections, beam asymmetries (similar to $p\pi\pi$ & pKK^*)

At other facilities (for comparison):

$K^- p \to K^+ \Xi^{*-}$	J-PARC (2029?)
$K_L p \to K^+ \Xi^{*0}$	Hall D (2026/30?)
$pp \to \Xi^* X$	LHCb
$\bar{p}p \to \Xi^* \bar{\Xi}$	$\overline{\text{P}}$ANDA ?
$e^+ e^- \to \Xi^* X$	Belle II, BES III

* W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

GlueX: Cross Sections in $\gamma p \to K^+ K^+ \Xi(1320)^-$



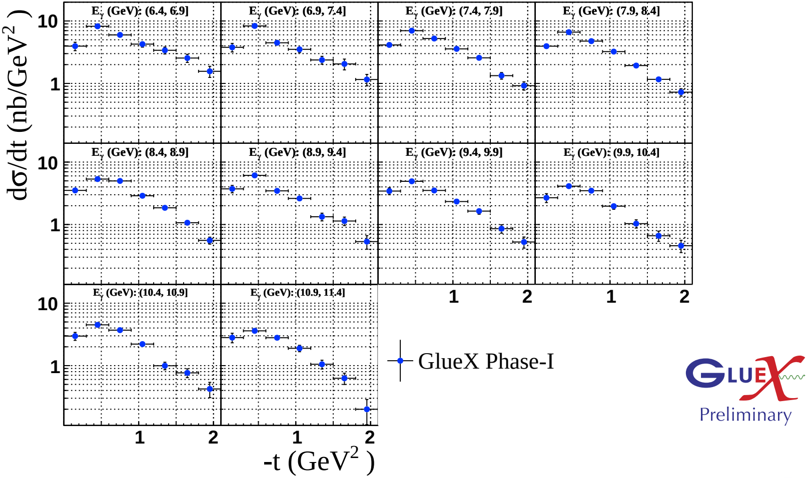
Courtesy of Jesse Hernandez (FSU)

Measurements of

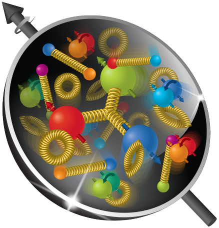
- Differential cross sections
- Polarization observables
- Mass, width, spin

GlueX: Cross Sections in $\gamma p \to K^+ K^+ \Xi(1320)^-$

Courtesy of Jesse Hernandez (FSU)



Outline



Summary and Conclusions

Spectroscopy of (low-mass) Ξ resonances very important to understand the systematics of the baryon spectrum:

- What about the properties of the Ξ(1620) / Ξ(1690) states?

N	(D, L_N^P)	S	J^P	Octet Members				Singlets
0	$(56, 0_0^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	–
1	$(70, 1_1^-)$	$\frac{1}{2}$	$\frac{1}{2}^-$	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(1620)^\dagger$	$\Lambda(1405)$
			$\frac{3}{2}^-$	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
		$\frac{3}{2}$	$\frac{1}{2}^-$	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(1690)^\dagger$	–
			$\frac{3}{2}^-$	$N(1700)$				–
			$\frac{5}{2}^-$	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(2030)^\dagger$	–

Summary and Conclusions

Spectroscopy of (low-mass) Ξ resonances very important to understand the systematics of the baryon spectrum:

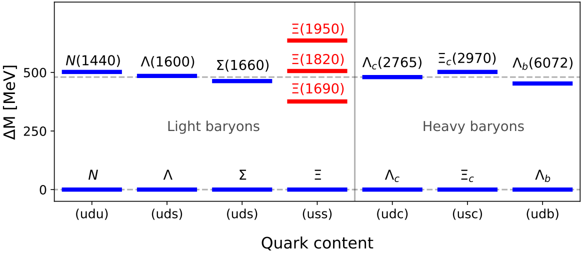
- What about the properties of the Ξ(1620) / Ξ(1690) states?

N	$(D,\, L_N^P)$	Spin, S	J^P	Decuplet Members			
0	$(56,\, 0_0^+)$	$\frac{3}{2}$	$\frac{3}{2}^+$	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$
1	$(70,\, 1_1^-)$	$\frac{1}{2}$	$\frac{1}{2}^-$ $\frac{3}{2}^-$	$\Delta(1620)$ $\Delta(1700)$			$\Omega(2012)^\dagger$

Summary and Conclusions

Spectroscopy of (low-mass) Ξ resonances very important to understand the systematics of the baryon spectrum:

- What about the properties of the $\Xi(1620)$ / $\Xi(1690)$ states?
- Is the $\Xi(1620)$ more than one state? Is the $\Xi(1620)$ the doubly strange partner of the $\Lambda(1405)$?
- Where is the radial excitation of the $\Xi(1320)$?



Radial Excitations
(Roper-like states)

for the octet members with $J^P = \frac{1}{2}^+$

Arifi *et al.*, PRD **105**, 094006

Opportunities with Secondary K_L^0 Beams in Hall D

Possible reactions to be studied (elastic and charge-exchange reactions):

- 2- & 3-body reactions producing $S = -1$ hyperons
- 2-body reactions producing $S = -2$ hyperons
  ➜ $K_L^0\, p \to K^+\, \Xi^0;\ \pi^+ K^+\, \Xi^-;\ K^+\, \Xi^{0*};\ \pi^+ K^+\, \Xi^{-*}$
- 3-body reactions producing $S = -3$ hyperons
  ➜ $K_L^0\, p \to K^+ K^+\, \Omega^-;\ K^+ K^+\, \Omega^{-*}$