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

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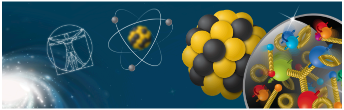
Jefferson Lab, Newport News



06/11/2024

Outline

1. Brief Review and Motivation
    - Experimental Studies of Baryons
2. Baryon Spectroscopy at GlueX
    - The GlueX Experiment
    - Spectroscopy of Ξ Resonances
    - Magnetic Moments of Baryons
3. Heavy-Flavor Resonances
4. Summary and Conclusions

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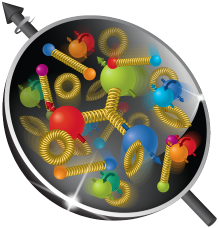
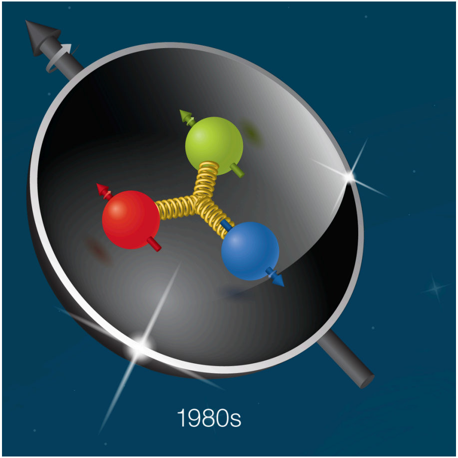


The Structure of the Nucleon



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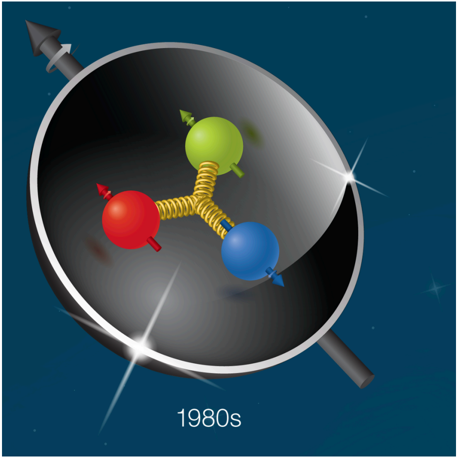
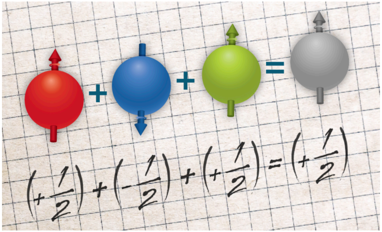
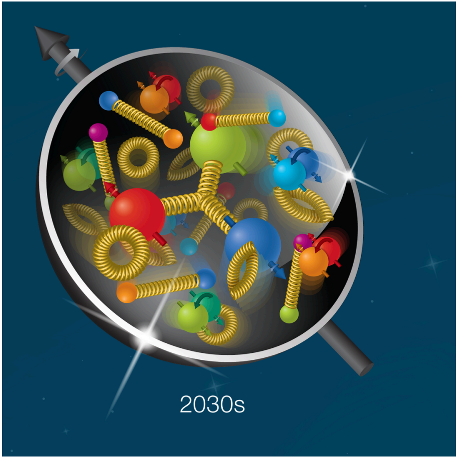
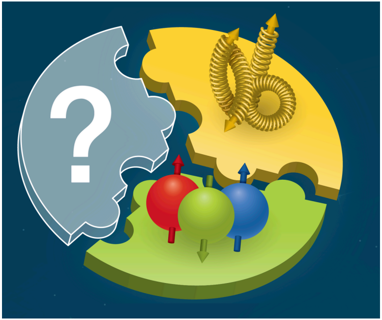




The Structure of the Nucleon





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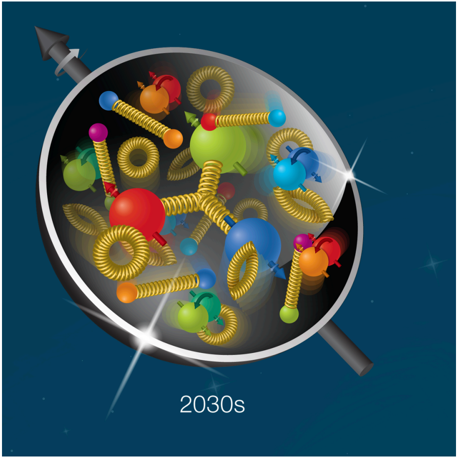


The unknown beast ...

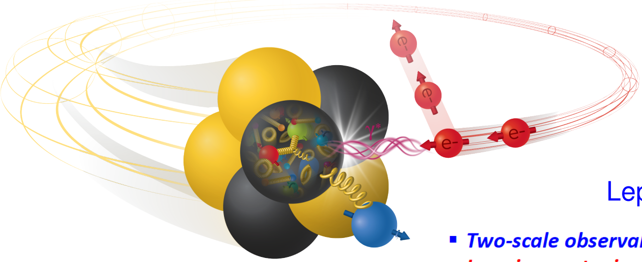
- Origin of nucleon mass
- Origin of nucleon spin
- Confinement
- Behavior of quarks / gluons in nucleon as compared to nuclei

etc.

The Electron-Ion Collider (EIC)

World’s first polarized electron-proton collider:

➜ The spins of both colliding particles can be aligned in a controlled way.



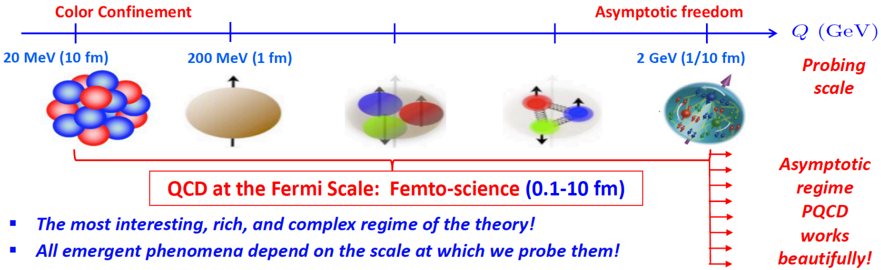
Lepton-hadron facilities:

- ***Two-scale observables are natural***
- ***Imaging partonic structure without breaking it!***
- ***Emergence of hadrons***
- ***Heavy ion target or beam***

HERA discovery:

Hadron stays intact 10-15 % time.

Nuclear Femtography: Non-Perturbative QCD



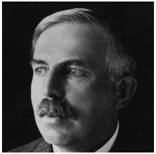
QCD at the Fermi Scale: Femto-science (0.1-10 fm)

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

How does QCD give rise to excited nucleons?

- Relevant degrees of freedom
- Quark-quark interactions

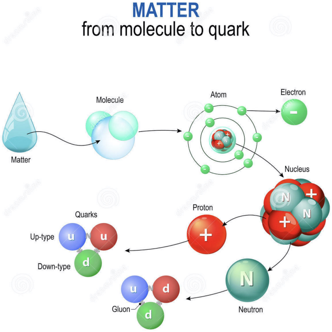
Particle Zoo



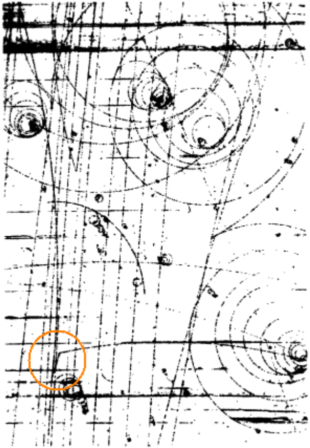
Name “proton” given to H nucleus by Rutherford in 1920

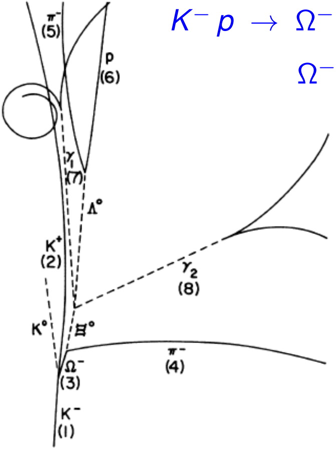
He had discovered earlier that proton was a candidate to be a fundamental particle & building block of nitrogen, and all other heavier atomic nuclei.

1932	Neutron
1947	First Mesons: π^+, π^-, K^+, K^-
1951	Strange baryons: Λ with $\lvert uds\rangle$
1964	Ω^- with $\lvert sss\rangle$
1964	Quark model
1968	Discovery of “partons” at SLAC
	after 1970: Quantum Chromodynamics



1964: Discovery of the Ω Baryon at BNL

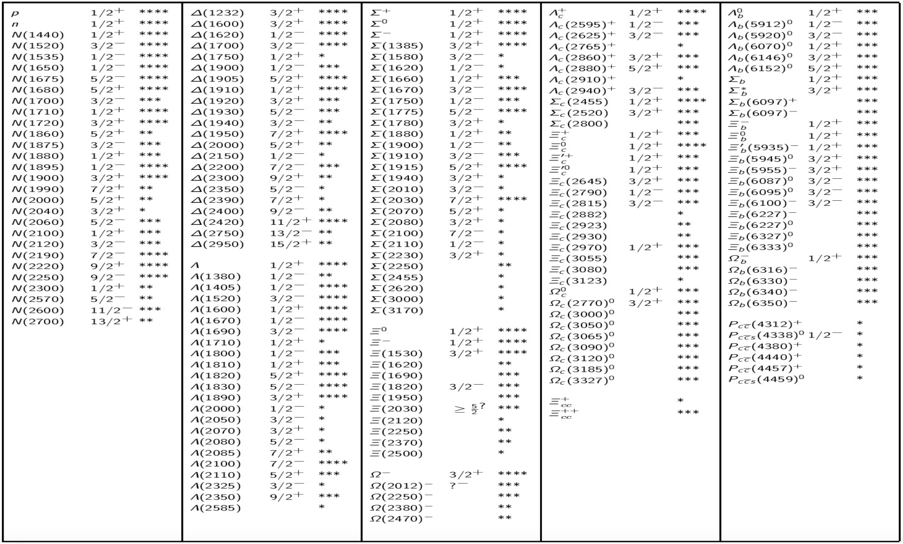




$$K^- p \rightarrow \Omega^- K^+ K^0$$

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

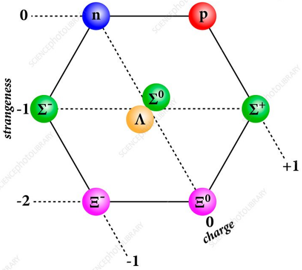
$$\Xi^0 \rightarrow \Lambda^0 \pi^0$$

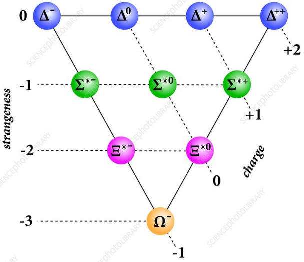


p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	****
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	***
$N(1895)$	$1/2^-$	****
$N(1900)$	$3/2^+$	****
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	***
$N(2100)$	$1/2^+$	***
$N(2120)$	$3/2^-$	***
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**
$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	****
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	***
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	***
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
$\Lambda(1380)$	$1/2^-$	**
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	****
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1710)$	$1/2^+$	*
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$	$1/2^-$	*
$\Lambda(2050)$	$3/2^-$	*
$\Lambda(2070)$	$3/2^+$	*
$\Lambda(2080)$	$5/2^-$	*
$\Lambda(2085)$	$7/2^+$	**
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		*
Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1780)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1900)$	$1/2^-$	**
$\Sigma(1910)$	$3/2^-$	***
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^+$	*
$\Sigma(2010)$	$3/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	*
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2110)$	$1/2^-$	*
$\Sigma(2230)$	$3/2^+$	*
$\Sigma(2250)$		**
$\Sigma(2455)$		*
$\Sigma(2620)$		*
$\Sigma(3000)$		*
$\Sigma(3170)$		*
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^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2910)^+$		*
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	****
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2882)$		*
$\Xi_c(2923)$		**
$\Xi_c(2930)$		**
$\Xi_c(2970)$	$1/2^+$	***
$\Xi_c(3055)$		***
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
$\Omega_c(3000)^0$		***
$\Omega_c(3050)^0$		***
$\Omega_c(3065)^0$		***
$\Omega_c(3090)^0$		***
$\Omega_c(3120)^0$		***
$\Omega_c(3185)^0$		***
$\Omega_c(3327)^0$		***
Ξ_{cc}^+		*
Ξ_{cc}^{++}		***
Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
$\Lambda_b(6070)^0$	$1/2^+$	***
$\Lambda_b(6146)^0$	$3/2^+$	***
$\Lambda_b(6152)^0$	$5/2^+$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
$\Sigma_b(6097)^+$		***
$\Sigma_b(6097)^-$		***
Ξ_b^-	$1/2^+$	***
Ξ_b^0	$1/2^+$	***
$\Xi'_b(5935)^-$	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
$\Xi_b(5955)^-$	$3/2^+$	***
$\Xi_b(6087)^0$	$3/2^-$	***
$\Xi_b(6095)^0$	$3/2^-$	***
$\Xi_b(6100)^-$	$3/2^-$	***
$\Xi_b(6227)^-$		***
$\Xi_b(6227)^0$		***
$\Xi_b(6327)^0$		***
$\Xi_b(6333)^0$		***
Ω_b^-	$1/2^+$	***
$\Omega_b(6316)^-$		***
$\Omega_b(6330)^-$		***
$\Omega_b(6340)^-$		***
$\Omega_b(6350)^-$		***
$P_{c\overline{c}}(4312)^+$		*
$P_{c\overline{c}s}(4338)^0$	$1/2^-$	*
$P_{c\overline{c}}(4380)^+$		*
$P_{c\overline{c}}(4440)^+$		*
$P_{c\overline{c}}(4457)^+$		*
$P_{c\overline{c}s}(4459)^0$		*

The Status of very strange Baryons

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^-	$3/2^+$	****
$\Omega(2012)^-$	$?^-$	***
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

****	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.

The Status of very strange Baryons

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$\Xi(2500)$		*

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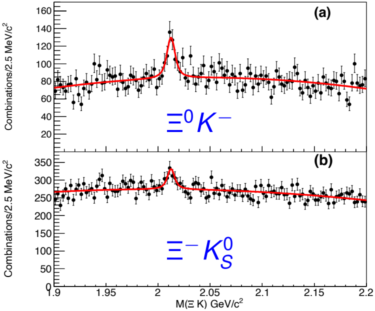
$\Omega(2012)^-$	$?^-$	***
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

Belle Collaboration, PRL **121** (2018) 052003



$L = 1$: $J^P = \frac{3}{2}^-$?

Where is $J^P = \frac{1}{2}^-$?

Dynamically generated?

****	Existence is certain, and properties are at least fairly well explored.
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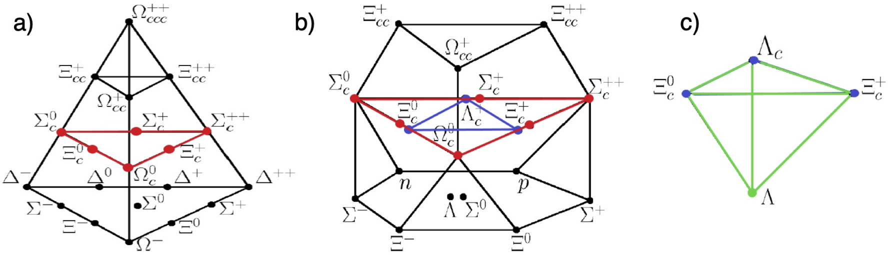
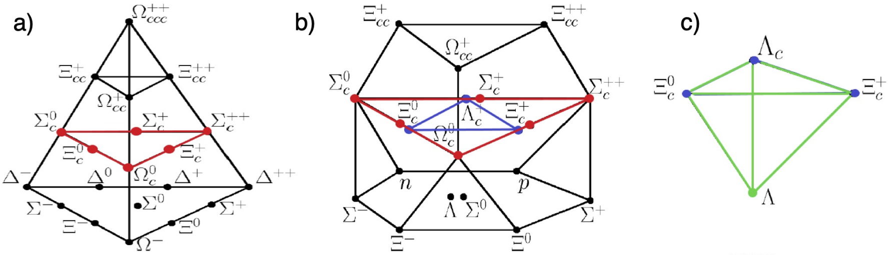
SU(4) Multiplet Structure of Baryons



Multiplet structure for flavor SU(3):

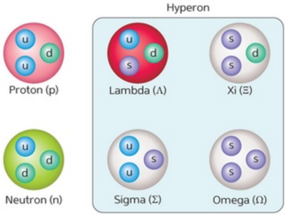
$$3 \otimes 3 \otimes 3 = 10_S \oplus 8_M \oplus 8_M \oplus 1_A$$

SU(4) Multiplet Structure of Baryons

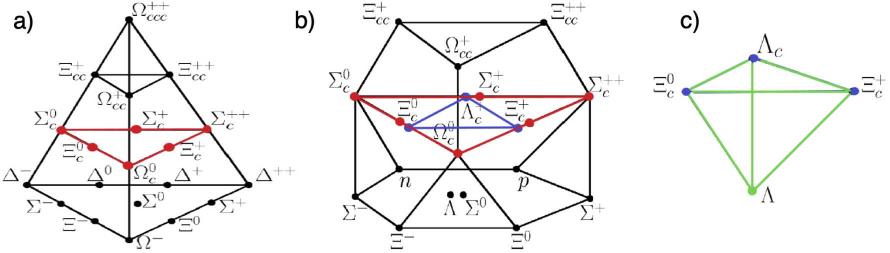


Multiplet structure for flavor SU(3):

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



SU(4) Multiplet Structure of Baryons



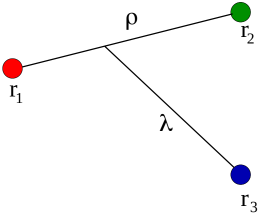
Multiplet structure for flavor SU(4):

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

➜ Great progress also for charmed and bottom baryons (Belle, LHCb).

Description of a Baryon

Simple quark model depiction of a baryon



$$\vec{\rho} = \frac{1}{\sqrt{2}}\,(\,\vec{r}_1 - \vec{r}_2\,)$$

$$\vec{\lambda} = \frac{1}{\sqrt{6}}\,(\,\vec{r}_1 + \vec{r}_2 + 2\vec{r}_3\,)$$

The reduced masses of ρ and λ are defined in terms of the kinetic energy:

$$T \propto \frac{\vec{p}_\rho^{\,2}}{2\mu_\rho} + \frac{\vec{p}_\lambda^{\,2}}{2\mu_\lambda} + \frac{\vec{P}^{\,2}}{2M} = \frac{\vec{p}_1^{\,2}}{2m_q} + \frac{\vec{p}_2^{\,2}}{2m_q} + \frac{\vec{p}_3^{\,2}}{2m_Q}\,,$$

where $M = 2m_q + m_Q$ and $\vec{P} = \vec{p}_q + \vec{p}_q + \vec{p}_Q$.

Description of a Baryon

The reduced masses of the two oscillators are then given as:

$$\mu_\rho = m_q \quad \text{and} \quad \mu_\lambda = \frac{3m_q m_Q}{2m_q + m_Q}\,,$$

where $q = s$ and $Q = u, d$ for the doubly strange Ξ system, and $q = u, d$ and $Q = c, b$ for the singly heavy charmed or bottom baryons.

The ratio of the harmonic oscillator frequencies is given by:

$$\frac{\omega_\lambda}{\omega_\rho} = \sqrt{\frac{1}{3}\,(1 + 2m_q/m_Q)} \;\leq\; 1\,.$$

In the limit of $m_q \approx m_Q$, e.g. for N^* & Δ^* states, the excitation energies in the ρ and λ oscillators are about the same, whereas the excitation energies in the λ oscillator are reduced by a factor of $\sqrt{3}$ in the heavy-quark limit, $m_Q \to \infty$.

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. $\gamma N\,(e^-\,N) \to (e^-)\,N^*/\Delta^*$

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

   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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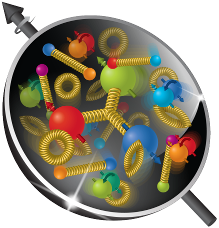
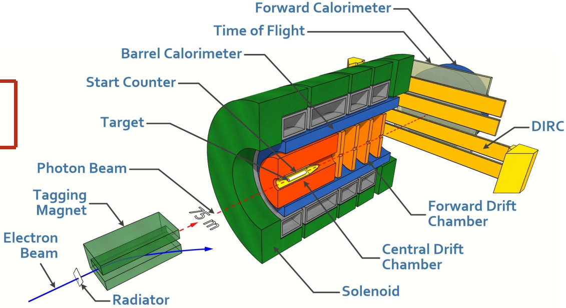
   - The GlueX Experiment
   - Spectroscopy of Ξ Resonances
   - Magnetic Moments of Baryons
3. Heavy-Flavor Resonances
4. Summary and Conclusions



Hadron Spectroscopy

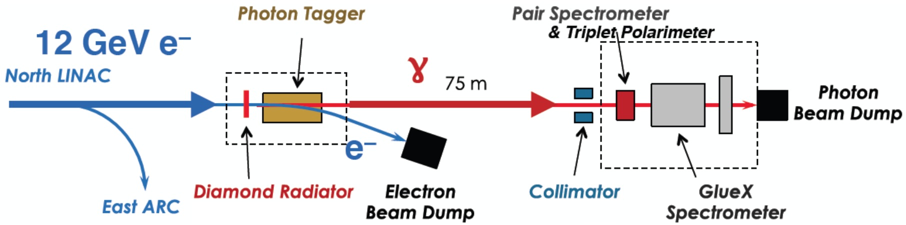
- π + Nucleus
- $\gamma\, p$ *Photoproduction*
- $e^+ e^-$
- $\bar{p}\, p$



The GlueX Collaboration

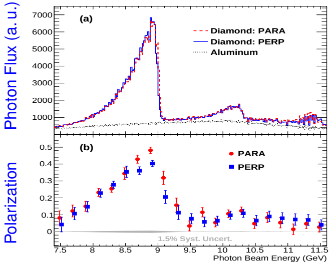
- $\sim$135 members, 29 institutions
  (Armenia, Canada, Chile, China, Germany, Greece, Russia, UK, USA)
- GlueX phase-I complete (120 PAC days)
- First physics published in 2017

The GlueX Experiment: Photon Beamline

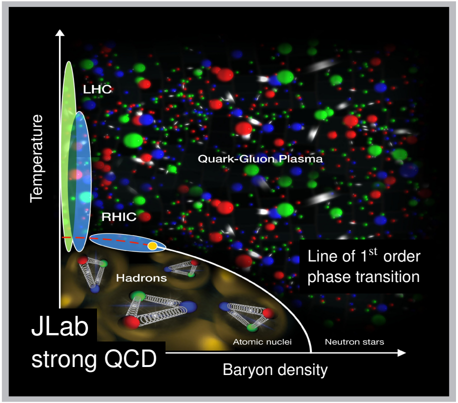


Polarized photon beam produced via coherent bremsstrahlung off thin diamond radiator:

- Tagging system with $\Delta E < 25$ MeV.
- Linear photon polarization of $P_\gamma \approx 40\,\%$ in the coherent peak.
- Phase-I intensity of 5×10^7 γ/s in peak.



QCD Phases and the Study of Baryon Resonances

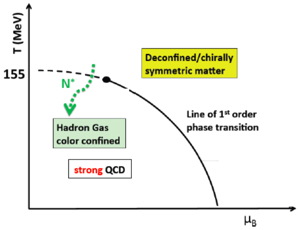


QGP

↓

hadron phase

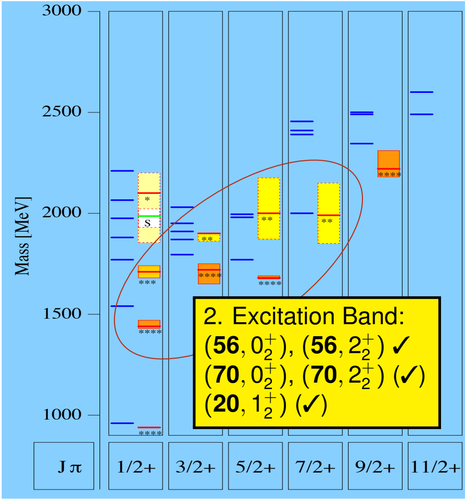
- Chiral symmetry is broken
- Quarks acquire mass
- Baryon resonances occur
- Color confinement emerges



RPP (u, d, s, c) baryons not sufficient to describe freeze-out behavior.

(e. g. A. Bazavov *et al.*, PRL **113** (2014) 7, 072001)

Spectrum of N^* Resonances

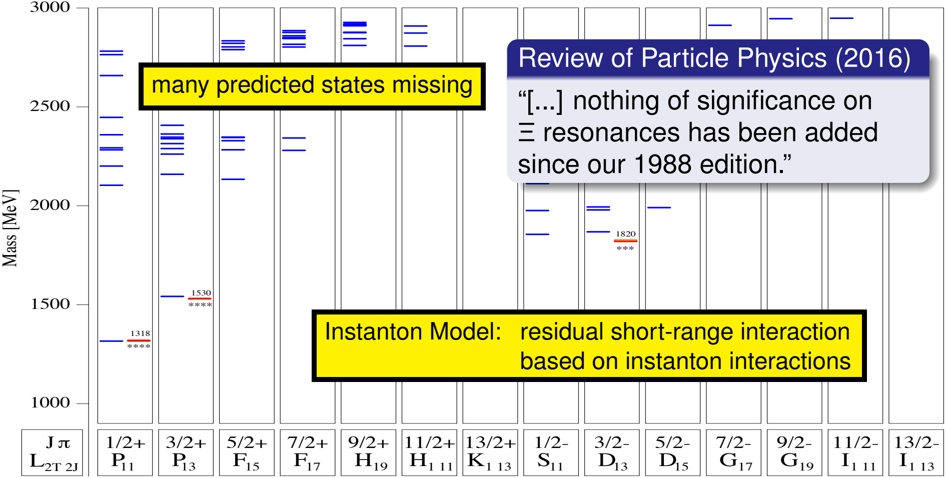


2. Excitation Band:
$(\mathbf{56}, 0_2^+)$, $(\mathbf{56}, 2_2^+)$ ✓
$(\mathbf{70}, 0_2^+)$, $(\mathbf{70}, 2_2^+)$ (✓)
$(\mathbf{20}, 1_2^+)$ (✓)

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	$(56, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$		–
	$(70, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(1710)$	$\Lambda(1810)^\dagger$	$\Sigma(1770)^\dagger$		
		$\frac{3}{2}$	$\frac{3}{2}^+$					–
	$(56, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$	$N(1720)^\dagger$	$\Lambda(1890)^\dagger$	$\Sigma(1840)^\dagger$		–
			$\frac{5}{2}^+$	$N(1680)$	$\Lambda(1820)^\dagger$	$\Sigma(1915)^\dagger$		–
	$(70, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$					
			$\frac{5}{2}^+$	$N(1860)$				
		$\frac{3}{2}$	$\frac{1}{2}^+$	$N(1880)$				–
			$\frac{3}{2}^+$	$N(1900)^\dagger$		$\Sigma(2080)^\dagger$		–
			$\frac{5}{2}^+$	$N(2000)$	$\Lambda(2110)^\dagger$	$\Sigma(2070)^\dagger$		–
			$\frac{7}{2}^+$	$N(1990)$	$\Lambda(2020)$	$\Sigma(2030)^\dagger$		–
	$(20, 1_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(2100)^\dagger$				
			$\frac{3}{2}^+$	$N(2040)^\dagger$				
			$\frac{5}{2}^+$	–	–	–	–	

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

Cascade Resonances: Status as of 2018



many predicted states missing

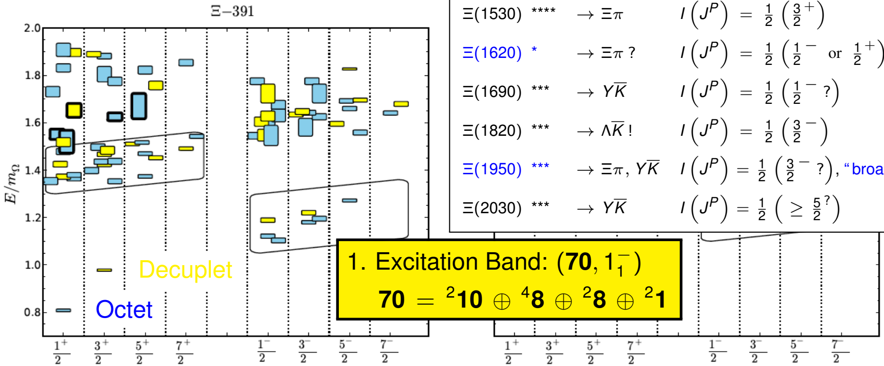
Review of Particle Physics (2016)

"[...] nothing of significance on Ξ resonances has been added since our 1988 edition."

Instanton Model: residual short-range interaction based on instanton interactions

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

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



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

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

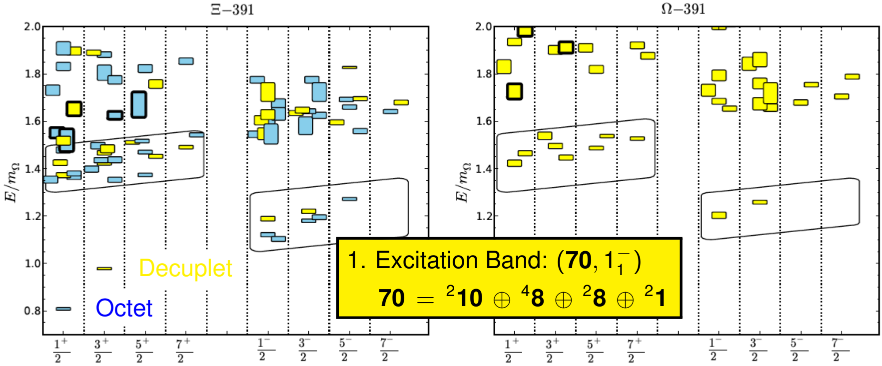
$$\mathbf{70} = {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1}$$

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.

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

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



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

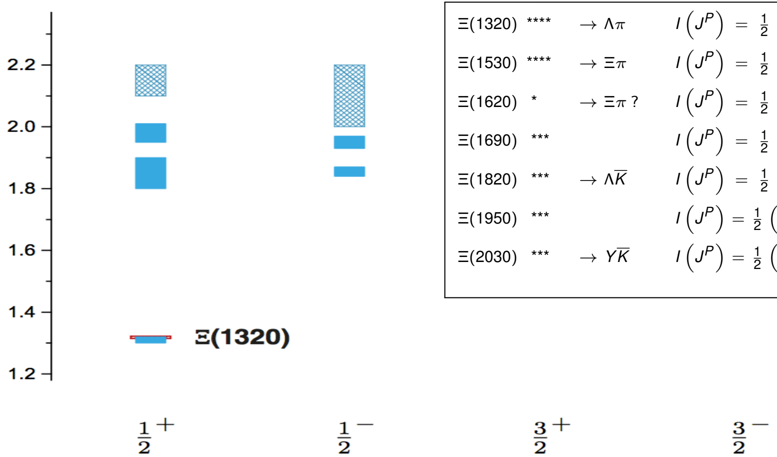
$$\mathbf{70} = {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1}$$

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.

The Ξ* Spectrum in a Dyson-Schwinger Approach

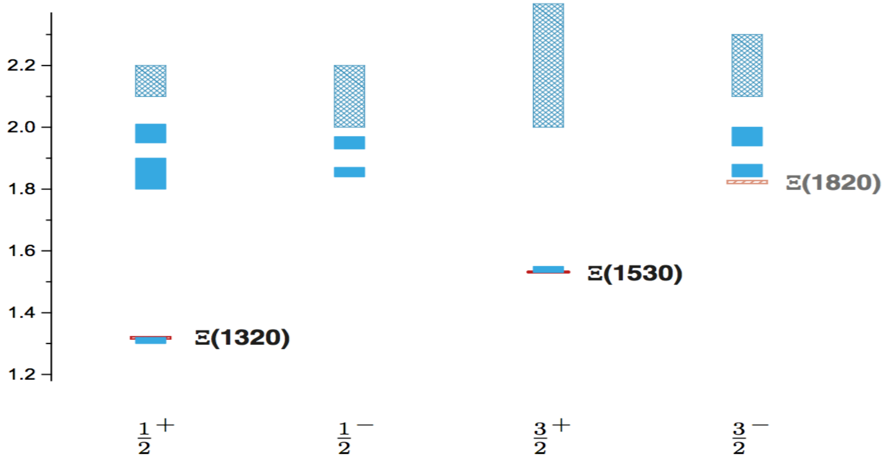
C. Fischer *et al.*, PoS Hadron 2017 (2018) 007



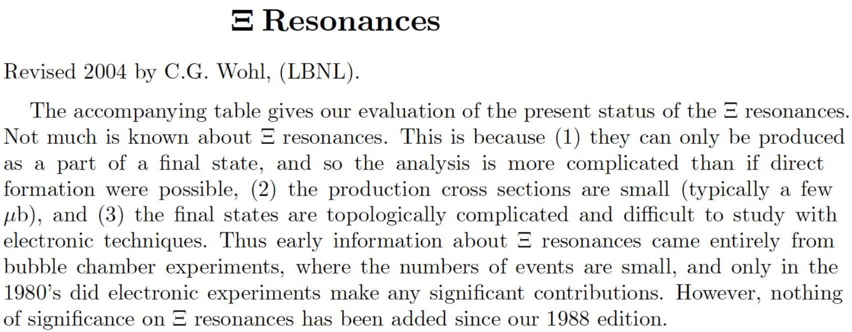
Ξ(1320)	****	$\to \Lambda\pi$	$I\left(J^P\right) = \frac{1}{2}\left(\frac{1}{2}^+\right)$
Ξ(1530)	****	$\to \Xi\pi$	$I\left(J^P\right) = \frac{1}{2}\left(\frac{3}{2}^+\right)$
Ξ(1620)	*	$\to \Xi\pi$?	$I\left(J^P\right) = \frac{1}{2}\left(\frac{1}{2}^+ \text{ or } \frac{1}{2}^+\right)$
Ξ(1690)	***		$I\left(J^P\right)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

The Ξ^* Spectrum in a Dyson-Schwinger Approach

C. Fischer *et al.*, PoS Hadron 2017 (2018) 007



PDG 2022 Mini-Review

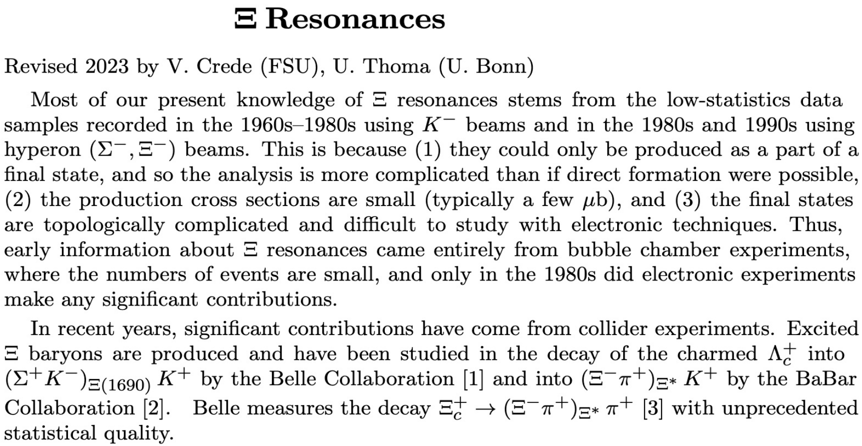


Ξ Resonances

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



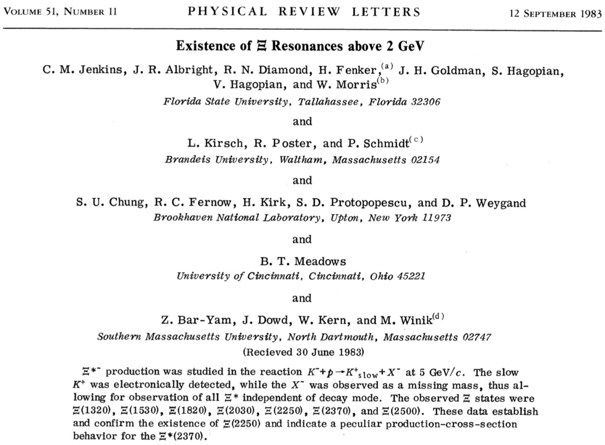
Ξ Resonances

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.

Hyperons in Florida



VOLUME 51, NUMBER 11 PHYSICAL REVIEW LETTERS 12 SEPTEMBER 1983

Existence of Ξ Resonances above 2 GeV

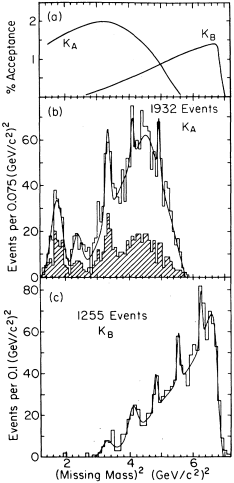
C. M. Jenkins, J. R. Albright, R. N. Diamond, H. Fenker,(a) J. H. Goldman, S. Hagopian, V. Hagopian, and W. Morris(b)
Florida State University, Tallahassee, Florida 32306
and
L. Kirsch, R. Poster, and P. Schmidt(c)
Brandeis University, Waltham, Massachusetts 02154
and
S. U. Chung, R. C. Fernow, H. Kirk, 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 $K^-+p\to K^+_{\rm slow}+X^-$ 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 $\Xi^*(2370)$.

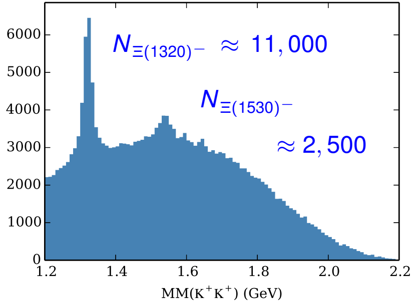
PACS numbers: 14.20.Jn, 13.75.Jz

$K^- p \to K^+ X^-$ ➜

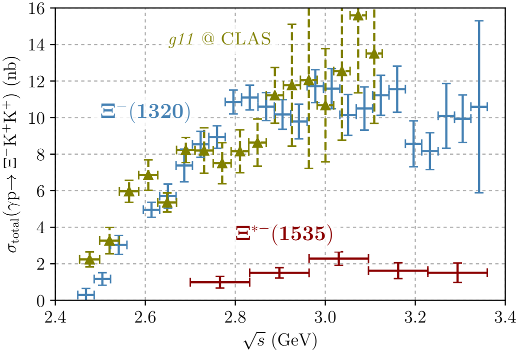


CLAS g12: Total Cross Sections of $(\Xi^-)^*$

$2.31 < \sqrt{s} < 3.4$ GeV



J. T. Goetz *et al.* [CLAS Collaboration], Phys. Rev. C **98**, 062201 (2018)



No statistically significant structures beyond Ξ(1530) peak: Different reaction (production) mechanism for Ξ^* states?

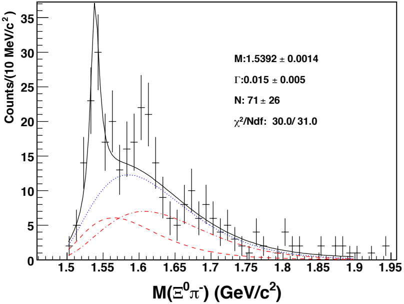
CLAS g11a: Excited States in $\gamma p \to K^+ K^+ \pi^-\,(X)$

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.*
Phys. Rev. C **76**, 025208 (2007)

Need high-statistics, high-energy data from an experiment designed to see Ξ states:

- 3- or 4-track trigger
- Reconstruction of full decay chain
- Higher photon energy
- Improved detectors

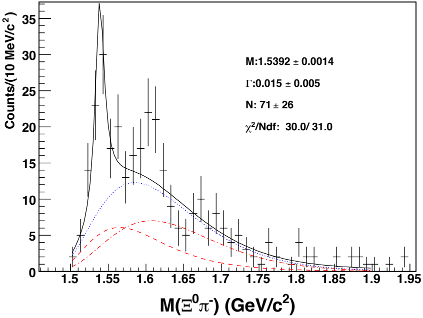
➜ CLAS 12 and GlueX at Jefferson Lab



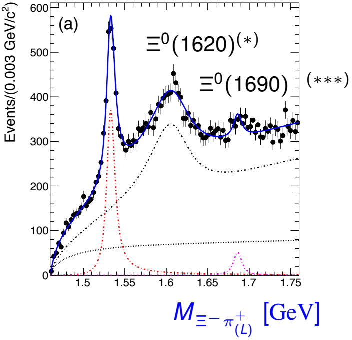
Excited Ξ^* States: 1500 - 1750 Mass Region

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.*

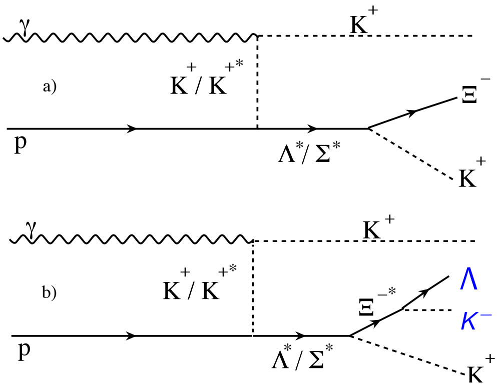
[CLAS], Phys. Rev. C **76**, 025208 (2007)



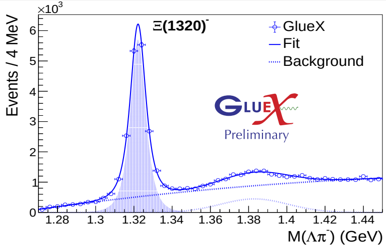
Belle: PRL **122**, 072501 (2019)

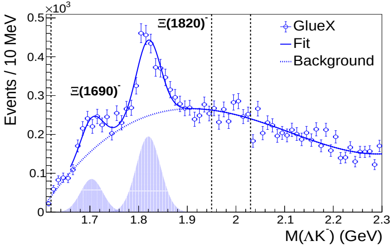


Possible Production Mechanisms



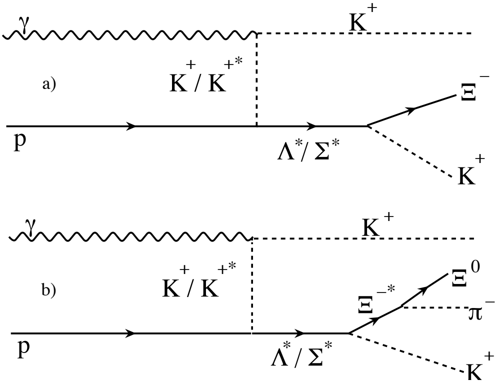
$$\gamma p \rightarrow K^+ \, (K^+ \, \Xi^{-*}) \rightarrow K^+ \, (p \, \pi^- \, K^-) \, K^+$$





Courtesy of Jesse Hernandez, Chandra Akondi (FSU)

Possible Production Mechanisms



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

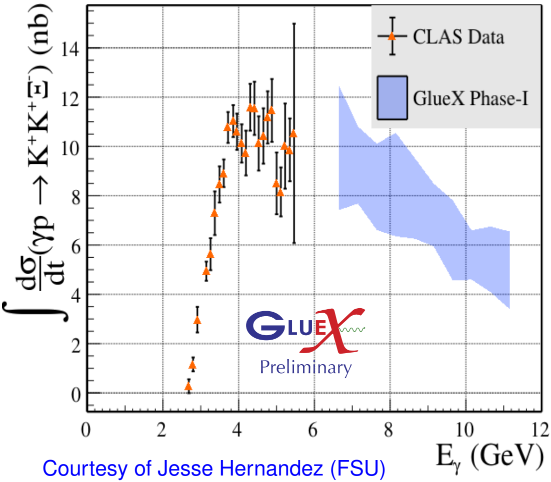
➜ Cross sections, beam asymmetries (similar to $p\,\pi\pi$ & $p\,KK^*$)

At other facilities (for comparison):

$K^- p \to K^+ \Xi^{*-}$	J-PARC (2029?)
$K_L p \to K^+ \Xi^{*0}$	Hall D (2026/30?)
$p p \to \Xi^* X$	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 $\gamma p \to K^+ K^+ \Xi(1320)^-$



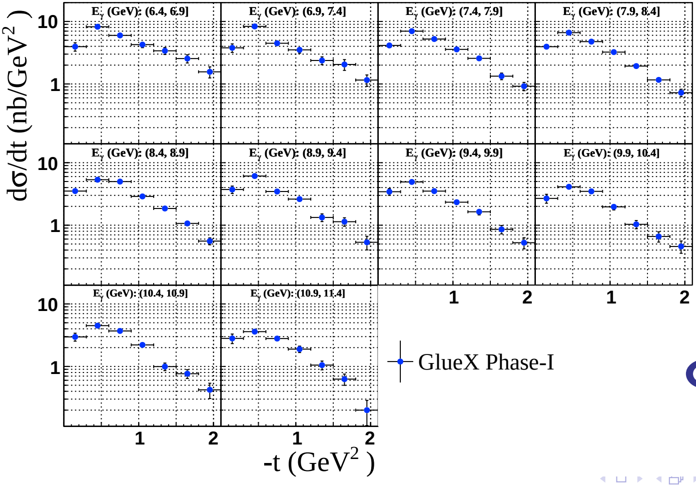
Courtesy of Jesse Hernandez (FSU)

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)



Preliminary

Magnetic Moment

The magnetic moment of a magnet is a quantity that determines the torque it will experience in an external magnetic field:

$$\vec{\tau} \,=\, \vec{\mu} \times \vec{B}$$

Torque on a current-carrying loop:

$$\tau \,=\, I\,A\,B \sin\phi \quad \text{with } I\,A \,=\, \mu$$

Remember: $L = I\,\omega = (mR^2)\,(\frac{2\pi}{\Delta t})$

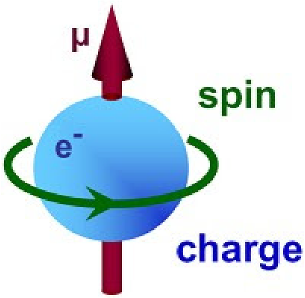
(for a point charge moving in a circle):

$$I\,A \,=\, \frac{\Delta Q}{\Delta t} \cdot \pi R^2 \,=\, \frac{\Delta Q}{\Delta t}\,\frac{2m_e}{2m_e}\,\pi R^2 \,=\, \frac{\Delta Q}{2m_e}\,L$$

Electron: $\vec{\mu} = -q/2m_e\,\vec{L}$

Magnetic Moment & Spin

For spin: $\vec{\mu} = -q/2m_e\,\vec{S}$ (according to the classical theory).



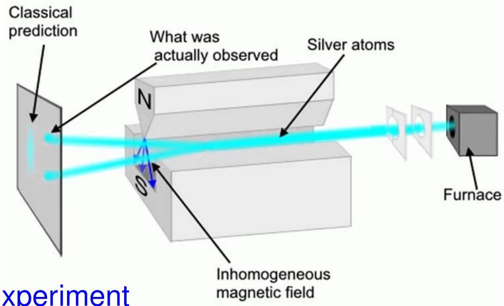
Particle Properties

Mass, electric charge, “spin” (permanent ang. momentum), ...

1924: Experimental evidence of e^- spin (spin-magn. moment)

➜ Two orientations relative to external magnetic field.

Spin: $S_z = m_S\hbar \; (\hbar = h/2\pi)$ with $(2m_S + 1)$ orientations



Stern-Gerlach Experiment

Magnetic Moment & Spin

For spin: $\vec{\mu} = -q/2m_e\,\vec{S}$ (according to the classical theory).

Stern-Gerlach experiment involves sending a beam of particles through an inhomogeneous magnetic field and observing their deflection. Results show that particles possess intrinsic angular momentum that is closely analogous to the angular momentum of a classically-spinning object,

1. But that takes only certain quantized values,
2. And is off by a factor for the spin-magnetic moment:

$$\vec{\mu} = -g\,\frac{e}{2m_e}\,\vec{S} = -g\,\mu_B\,\frac{\vec{S}}{\hbar}$$

with the Bohr magneton (defined in SI units) $\mu_B = \frac{e\,\hbar}{2m_e}$.

Spin I

Existence of spin ang. momentum is inferred from experiments. Spin is like a vector quantity, it has:

- Definite magnitude and “direction,” spin orientation.

Spin has peculiar properties different from orbital ang. mom.:

- Spin quantum numbers (QN) may take half-integer values.
- Direction of spin can be changed but a particle cannot be made to spin faster or slower.
- Spin of charged particle associated with magn. dipole moment:

$$\vec{\mu} = -g_S \frac{q}{2m} \vec{S} \quad \text{with} \quad g_S = \text{spin g factor}$$

Classically, $g_S \neq 1$ only if mass & charge fill volumes with diff. radii.

Spin II

Existence of spin ang. momentum is inferred from experiments.
Spin is like a vector quantity, it has:

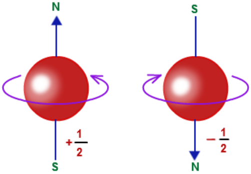
- Definite magnitude and "direction," spin orientation.

For electrons:

1. $S^2 = s\,(s+1)\,\hbar^2 = 3/4\,\hbar^2$ for spin $S = 1/2$.
2. $S_z = m_s\hbar$ with $m_S = \pm 1/2$ (for electrons in units of $\hbar$).

$$\rightarrow |\vec{\mu}_{S_z}| = \mu_B = \frac{q\,\hbar}{2m} \text{ and } |\vec{\mu}_S| = \sqrt{3}\,\mu_B$$

(total spin magnetic moment)



Baryon Magnetic Moments

1. Meson: quark-antiquark pair ($q\bar{q}$) $\pi,\ \eta$, etc.
2. Baryon: three-quark state (qqq) $p,\ n,\ \Delta$, etc.

Charged particles with spin have intrinsic magnetic moment:

$$\vec{\mu}_S = (q/m)\,\vec{S}$$

Dirac equation describes point-like spin-$\frac{1}{2}$ particle (q, m):

$$|\vec{\mu}_z| = \frac{q\,\hbar}{2m} = -g_S\,\mu_B\,m_S \approx \mu_B \text{ (Bohr magneton for electron)}$$

In general:

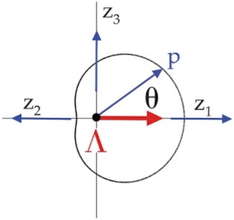
$g_S \approx 2$ for e^-, $g_S \approx -3.83$ for neutron, $g_S \approx +5.59$ for proton

Decay of the Λ Baryon

Magnetic moment of $\Lambda\,|uds\rangle$ in the quark model:
$(I = \frac{1}{2}$ u and d quarks couple to total $I = 0)$

$$\mu_\Lambda = \mu_s = \frac{e}{2m_s}\left(-\frac{1}{3}\right) = \left(-\frac{1}{3}\right)\frac{M_p}{m_s}\,\mu_N$$

Decay: $\Lambda \to p\,\pi^-$ with $L = 0, 1$, and parity not conserved.



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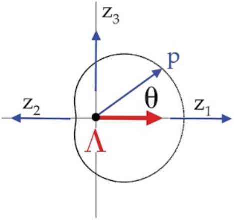


Decay: $\Lambda \to p\,\pi^-$ with $L = 0, 1$, and parity not conserved.

- In Λ rest frame: proton along z_1 and $m_s = +\frac{1}{2}$

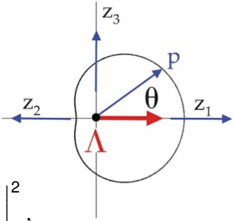
$$|\pi^- p\rangle = \alpha_0 \left\langle \frac{1}{2}\,\frac{1}{2}\,|\,0\,\frac{1}{2}\,0 + \frac{1}{2}\right\rangle + \alpha_1 \left\langle \frac{1}{2}\,\frac{1}{2}\,|\,1\,\frac{1}{2}\,0 + \frac{1}{2}\right\rangle = \begin{pmatrix} \alpha_0 - \frac{1}{\sqrt{3}}\,\alpha_1 \\ 0 \end{pmatrix}$$

- In Λ rest frame: proton along z_2 and $m_s = -\frac{1}{2}$

$$|\pi^- p\rangle = \alpha_0 \left\langle \frac{1}{2}\, -\frac{1}{2}\,|\,0\,\frac{1}{2}\,0 - \frac{1}{2}\right\rangle + \alpha_1 \left\langle \frac{1}{2}\, -\frac{1}{2}\,|\,1\,\frac{1}{2}\,0 - \frac{1}{2}\right\rangle = \begin{pmatrix} 0 \\ \alpha_0 + \frac{1}{\sqrt{3}}\,\alpha_1 \end{pmatrix}$$

Decay of the Λ Baryon

- In Λ rest frame: proton along z_3 with $\theta = 90^\circ$
  ➜ Equal superposition of the other two cases.



The decay intensity for any proton and angle θ is then proportional to (α_0 and α_1 are complex constants):

$$w(\theta) = \langle \pi^- p \,|\, \pi^- p \rangle = \cos^2\frac{\theta}{2}\left|\alpha_0 - \frac{\alpha_1}{\sqrt{3}}\right|^2 + \sin^2\frac{\theta}{2}\left|\alpha_0 + \frac{\alpha_1}{\sqrt{3}}\right|^2,$$

describing angular distribution of proton in rest frame of 100 % polarized Λ along z_1.

$$w(\theta) = |\alpha_0|^2 + \frac{|\alpha_1|^2}{3} - 2\mathrm{Re}\,\frac{\alpha_0^*\alpha_1}{\sqrt{3}}\left(\cos^2\frac{\theta}{2} - \sin^2\frac{\theta}{2}\right) \qquad S \equiv \alpha_0 \text{ and } P \equiv -\frac{\alpha_1}{\sqrt{3}}$$

$$= \left(|S|^2 + |P|^2\right)\left(1 + \underbrace{\left[\frac{2\mathrm{Re}(S^* P)}{|S|^2 + |P|^2}\right]}_{\equiv \alpha_\Lambda}\cos\theta\right) = \frac{1}{4\pi}\left(1 + \alpha_\Lambda \cos\theta\right).$$

Decay of the Λ Baryon

$$w(\theta) \;=\; \left(\,|S|^2 + |P|^2\,\right)\left(1 + \underbrace{\left[\frac{2\mathrm{Re}(S^*P)}{|S|^2+|P|^2}\right]}_{\equiv\alpha_\Lambda}\cos\theta\right) \;=\; \frac{1}{4\pi}\left(\,1 + \alpha_\Lambda\cos\theta\,\right).$$

The parity-violating forward-backward asymmetry is due to the interference of the S ($L = 0$) and P ($L = 1$) waves.

For hyperons with partial polarization P_Λ:

$$w(\theta) \;=\; \frac{1}{4\pi}\left(\,1 + \alpha_\Lambda\,P_\Lambda\cos\theta\,\right).$$

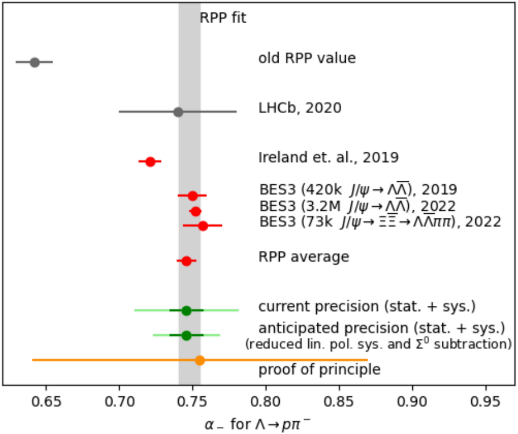
For an unpolarized hyperon, the proton is longitudinally polarized with the number of protons flying in the $+z$ direction proportional to $(1+\alpha_\Lambda)$ and $(1-\alpha_\Lambda)$, respectively:

$$P_{\mathrm{proton}} \;=\; \frac{1+\alpha_\Lambda-(1-\alpha_\Lambda)}{1+\alpha_\Lambda+(1-\alpha_\Lambda)} \;=\; \alpha_\Lambda\,.$$

This property was used to measure α_Λ, e.g. at BNL in the reaction $\pi^- p \to K^0\Lambda$.

Decay of the Λ Baryon: Data Situation in 2024

Decay parameter α_- of the parity-violating weak decay $\Lambda \to p\pi^-$ describes the interference between parity-violating *S* and parity-conserving *P* waves.



- Important for any kind of experiment that involves the polarization of the Λ.
- A comparison of α_- and α_+ provides a test of CP symmetry for strange baryons.

➜ GlueX Proposal to JLab 2024 PAC.

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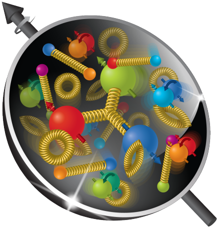
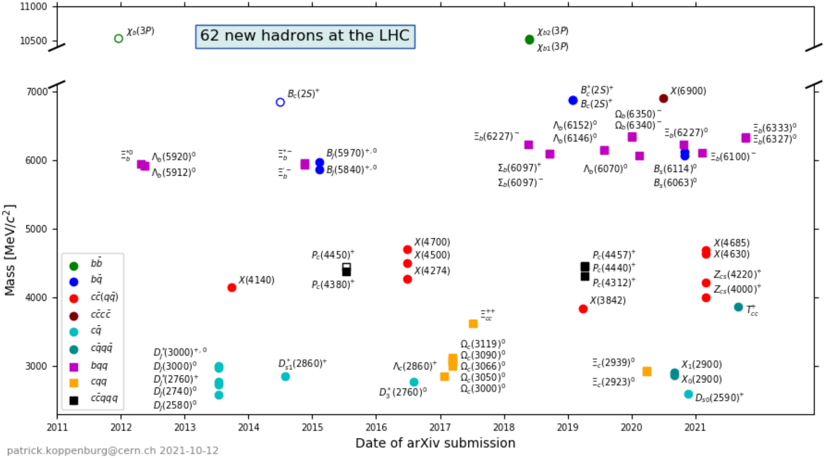
    - Spectroscopy of Ξ Resonances
    - Magnetic Moments of Baryons
3. **Heavy-Flavor Resonances**
4. Summary and Conclusions



Peak Hunting for Heavy-Flavor States



https://www.nikhef.nl/ pkoppenb/particles.html

Description of a Baryon

The reduced masses of the two oscillators are then given as:

$$\mu_\rho = m_q \quad \text{and} \quad \mu_\lambda = \frac{3m_q\, m_Q}{2m_q + m_Q}\,,$$

where $q = s$ and $Q = u, d$ for the doubly strange Ξ system, and $q = u, d$ and $Q = c, b$ for the singly heavy charmed or bottom baryons.

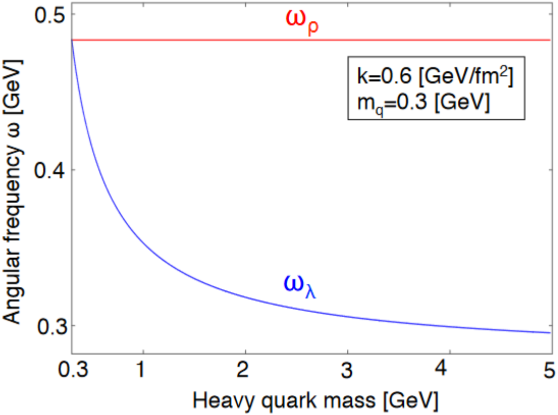
The ratio of the harmonic oscillator frequencies is given by:

$$\frac{\omega_\lambda}{\omega_\rho} = \sqrt{\frac{1}{3}\,(1 + 2m_q/m_Q)} \leq 1\,.$$

In the limit of $m_q \approx m_Q$, e.g. for N^* & Δ^* states, the excitation energies in the ρ and λ oscillators are about the same, whereas the excitation energies in the λ oscillator are reduced by a factor of $\sqrt{3}$ in the heavy-quark limit, $m_Q \to \infty$.

Excitation Energy as Function of Heavy Quark Mass

Phys. Rev. D **92**, no.11, 114029 (2015)

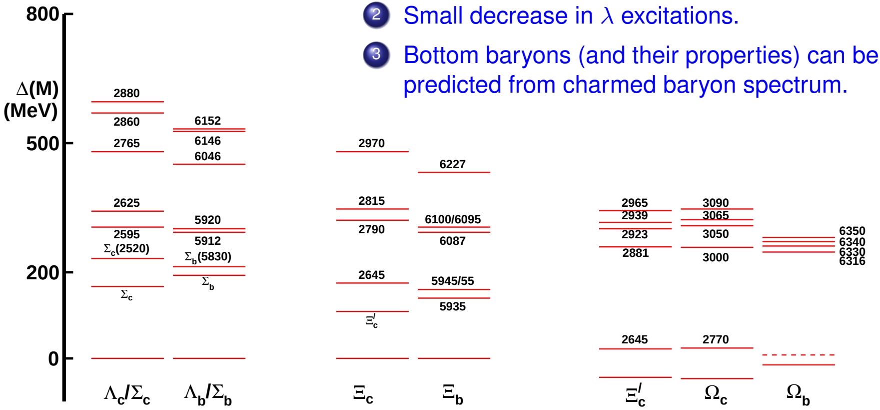


Excitation energy of ρ mode depends only on light quarks.

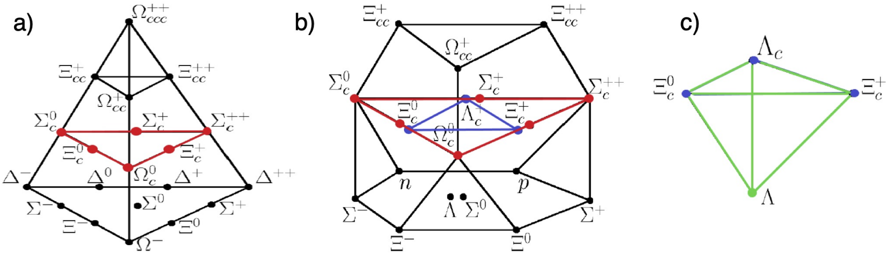
Excitation energy of λ mode lowered with increasing heavy-quark mass.

Comparison of Charmed and Bottom Baryons

1. Hyperfine splitting inversely proportional to the heavy quark mass.
2. Small decrease in λ excitations.
3. Bottom baryons (and their properties) can be predicted from charmed baryon spectrum.



SU(4) Multiplet Structure of Baryons

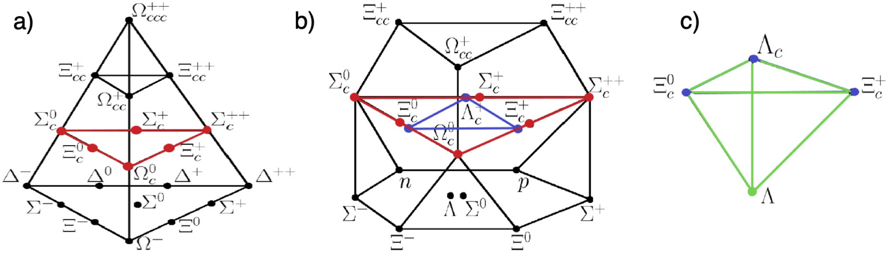


Multiplet structure for flavor SU(4):

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

➜ Great progress also for charmed and bottom baryons (Belle, LHCb).

SU(4) Multiplet Structure of Baryons



Singly heavy baryons particularly amenable to potential models, and states can be classified according to multiplet structure of the light diquark:

$$3 \otimes 3 = \overline{3}_A \oplus 6_S \,.$$

These diquarks are sometimes called *good* and *bad* diquarks for $s_{qq} = 1$ and $s_{qq} = 0$, respectively.

Light Diquark Structure for Singly Heavy Baryons

$$l_\rho = 0\ (S) = \begin{cases} s_{qq} = 0\ (A), & \bar{\mathbf{3}}_F\ (A) \quad j_{qq} = 0\,, \\ s_{qq} = 1\ (S), & \mathbf{6}_F\ (S) \quad j_{qq} = 1\,, \end{cases}$$

$$l_\rho = 1\ (A) = \begin{cases} s_{qq} = 0\ (A), & \mathbf{6}_F\ (S) \quad j_{qq} = 1\,, \\ s_{qq} = 1\ (S), & \bar{\mathbf{3}}_F\ (A) \quad j_{qq} = 0/1/2\,, \end{cases}$$

$$l_\rho = 2\ (S) = \begin{cases} s_{qq} = 0\ (A), & \bar{\mathbf{3}}_F\ (A) \quad j_{qq} = 2\,, \\ s_{qq} = 1\ (S), & \mathbf{6}_F\ (S) \quad j_{qq} = 1/2/3\,, \end{cases}$$

where the total angular momentum of the singly heavy baryon is then

$$J = s_Q \otimes (j_{qq} \otimes l_\lambda)\,.$$

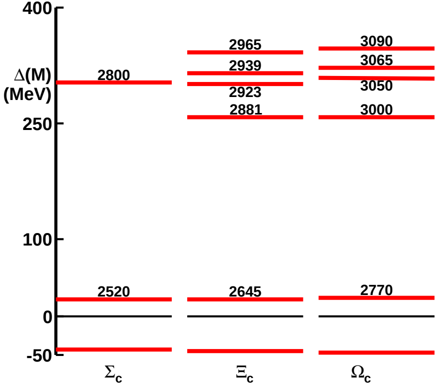
Example of ρ and λ Classification Scheme

	L	l_ρ	l_λ	s_{qq}	j_{qq}	J^P	(nL)	Observed Candidates
	0	0	0	0	0	$\frac{1}{2}^+$	$(1S)$	$\Lambda_c\ \frac{1}{2}^+$, $(\,\Xi_c^+, \Xi_c^0\,)\ \frac{1}{2}^+$
	0	0	0	0	0	$\frac{1}{2}^+$	$(2S)$	$*\,\Lambda_c(2765)\ \frac{1}{2}^+\ (?)^\dagger$, $\Xi_c(2970)\ \frac{1}{2}^+$
	1	0	1	0	1	$\frac{1}{2}^-,\ \frac{3}{2}^-$	$(1P)$	$\Lambda_c(2595)\ \frac{1}{2}^-$, $\Lambda_c(2625)\ \frac{3}{2}^-$ $\Xi_c(2790)\ \frac{1}{2}^-$, $\Xi_c(2815)\ \frac{3}{2}^-$
$\mathbf{\bar{3}_F}$	1	1	0	1	0	$\frac{1}{2}^-$	$(1P)$	
$\Lambda_c^{(*)}$	1	1	0	1	1	$\frac{1}{2}^-,\ \frac{3}{2}^-$	$(1P)$	$\Big\}\ \left(\Lambda_c(2940)\ \frac{3}{2}^-\right)^?$ ”possibly a $2P$ state”
$\Xi_c^{(*)}$	1	1	0	1	2	$\frac{3}{2}^-,\ \frac{5}{2}^-$	$(1P)$	
	2	0	2	0	2	$\frac{3}{2}^+,\ \frac{5}{2}^+$	$(1D)$	$\Lambda_c(2860)\ \frac{3}{2}^+$, $\Lambda_c(2880)\ \frac{5}{2}^+$ $\Xi_c(3055)\ \frac{3}{2}^+\ (?)^\dagger$, $\Xi_c(3080)\ \frac{5}{2}^+\ (?)^\dagger$
	2	2	0	0	2	$\frac{3}{2}^+,\ \frac{5}{2}^+$	$(1D)$	

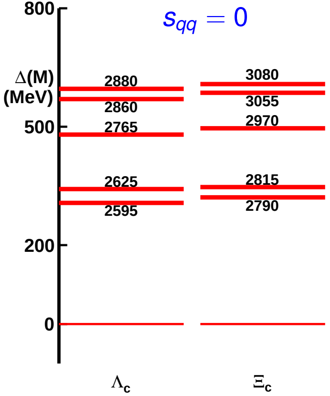
Comparison of Charmed Baryon Spectra

V.C. and J. Yelton, *70 Years of Hyperon Spectroscopy*, submitted to Rept. Prog. Phys. (2024)

Σ-like resonances

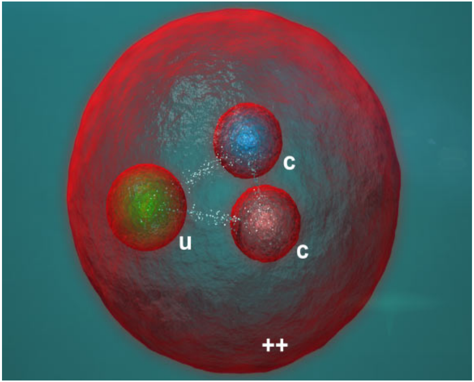


Λ-like resonances



Doubly-Heavy (Charmed) Resonances

2017: The LHCb (Large Hadron Collider beauty) collaboration at CERN's Large Hadron Collider in Switzerland has reported the observation of a doubly charmed particle, $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$.



Discovery will improve the predictive power of theories.

"In contrast to other baryons, in which the three quarks perform an elaborate dance around each other, a doubly heavy baryon is expected to act like a planetary system, where the two heavy quarks play the role of two heavy stars orbiting one around the other, with the lighter quark orbiting around this binary system."

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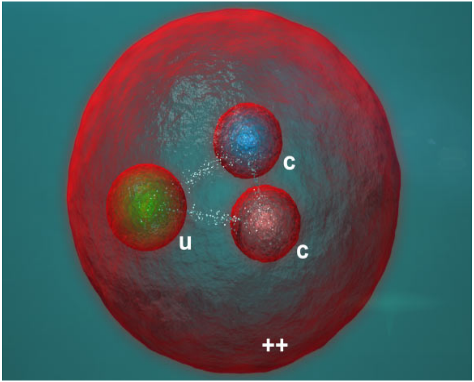
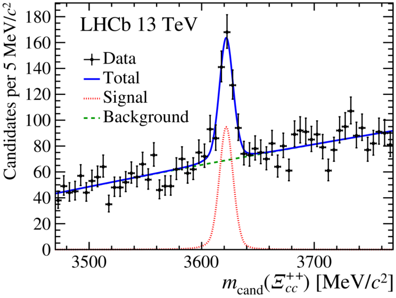
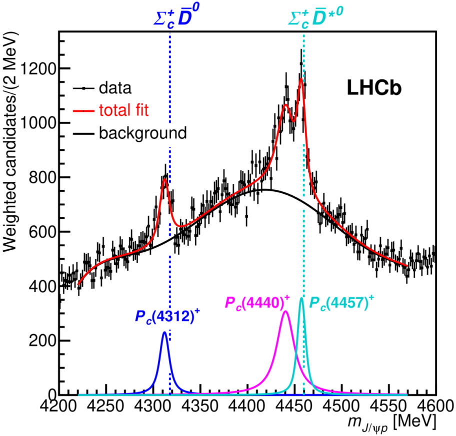




R. Aaij *et al.*, PRL **119** (2017) 112001

Observation of a Narrow Pentaquark State



A narrow pentaquark state, $P_c(4312)^+$, decaying to $J/\psi\, p$ was discovered by the LHCb Collaboration with statistical significance of 7.3σ in a data sample of $\Lambda_b^0 \to (J/\psi\, p)\, K^-$ decays.

A higher-mass $P_c(4450)^+$ pentaquark structure formerly reported by LHCb confirmed and observed to consist of two narrow overlapping peaks, $P_c(4440)^+$ and $P_c(4457)^+$.

R. Aaij *et al.*, PRL **122**, 222001 (2019)

J/ψ Photoproduction Near Threshold

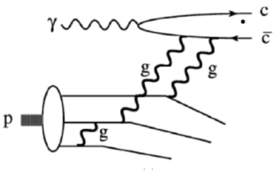
Photoproduction of J/ψ (near threshold) provides clean laboratory to study $c\bar{c}$:

- Probes gluon distribution in proton

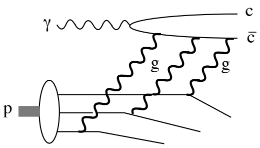
  (D. Kharzeev *et al.*, Nucl. Phys. A **661**, 568 (1999))

- Sensitive to multi-quark correlations

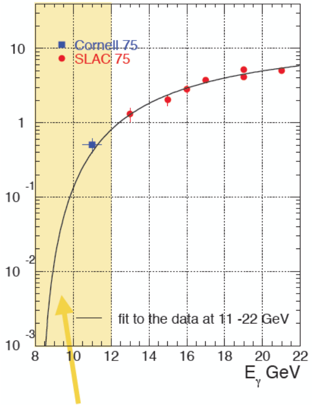
  (S. Brodsky *et al.*, Phys. Lett. B **498**, 23 (2001))



leading twist



higher twist

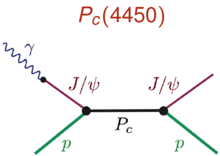


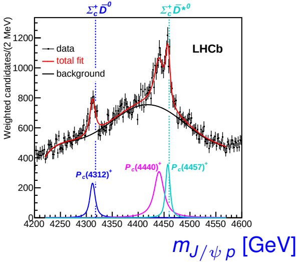
GlueX energy range

J/ψ Photoproduction Near Threshold

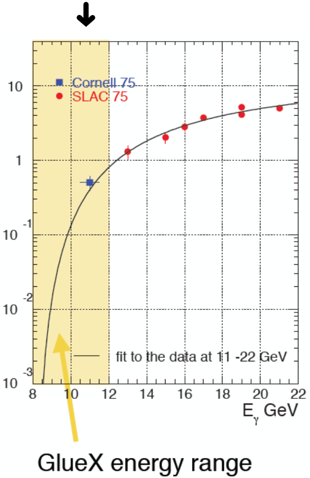
Photoproduction of J/ψ (near threshold) provides clean laboratory to study $c\bar{c}$:

- Probes gluon distribution in proton
- Sensitive to multi-quark correlations
- Intriguing possibility of five-quark interaction





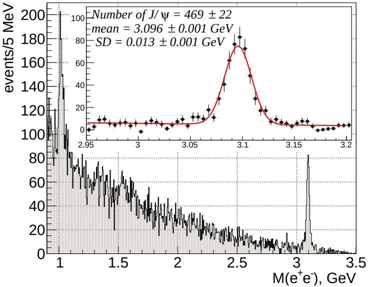
R. Aaij *et al.*, PRL **122**, 222001 (2019)



GlueX energy range

Observation of J/ψ at GlueX

A. Ali *et al.* [GlueX Collaboration], Phys. Rev. Lett. **123**, no.7, 072001 (2019)

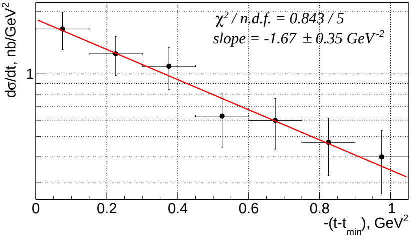


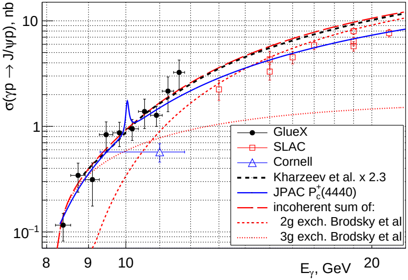
First observation of J/ψ at Jefferson Lab in $\gamma p \rightarrow p\, J/\psi \rightarrow p\, e^+ e^-$

- First detailed look at cross section near threshold

Observation of J/ψ at GlueX

A. Ali *et al.* [GlueX], Phys. Rev. Lett. **123**, no.7, 072001 (2019)





First observation of J/ψ at Jefferson Lab in $\gamma p \rightarrow p\,J/\psi \rightarrow p\,e^+e^-$

- First detailed look at cross section near threshold
- Measurement of t slope (at 10.7 GeV avg. E_γ): (-1.67 ± 0.39) GeV^{-2}
- Limits on pentaquark production

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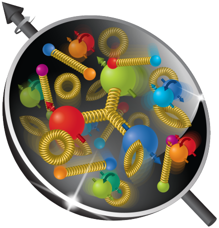
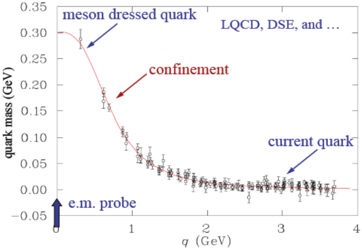


Open Issues in (Light) Baryon Spectroscopy

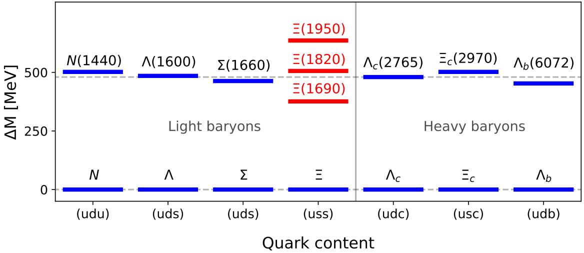
1. What are the relevant degrees of freedom in (excited) baryons?
   - ➜ Can the high-mass states be described by the dynamics of three flavored quarks? To what extent are diquark correlations, gluonic modes or hadronic degrees of freedom important in this physics?
2. Can we identify unconventional states in the strangeness sector, e. g. a $\Lambda(1405)$ or $N(1440)$? What is the situation with the $(\mathbf{20}, 1_2^+)$?
3. What is the nature of non-quark contributions, e. g. meson-baryon cloud or dynamically-generated states?
   - ➜ Probe the running quark mass and determine the relevant degrees of freedom at different distance scales.
4. How do nearly massless quarks acquire mass? (as predicted in DSE and LQCD)



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?
- Is the Ξ(1620) more than one state? Is the Ξ(1620) the doubly strange partner of the Λ(1405)?
- Where is the radial excitation of the Ξ(1320)?



Radial Excitations
(Roper-like states)

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

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

Summary and Conclusions

Quantum Chromodynamics (QCD) is (most likely) the correct theory of strong interactions. However, the theory remains still fairly untested and not very well understood at low energies (spectra and properties of hadrons).

Hadron spectroscopy is a powerful tool to scrutinize ideas on the effective degrees of freedom that govern hadron dynamics.

- QCD-inspired models have been very successful at describing the overall features of the spectrum of mesons and baryons, and also their decays, form factors, transition form factors, magnetic moments, etc.
- However, these models have also exhibited important failures:
  - Link between partonic degrees of freedom seen in deep inelastic scattering and constituent quarks remains poorly understood.
  - Experiments have yet to provide compelling evidence for gluonic excitations (glueballs, hybrids, etc.)

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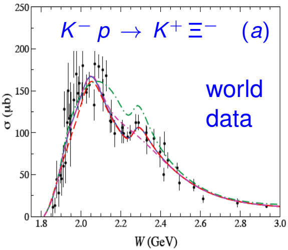
Opportunities with Secondary K_L^0 Beams in Hall D

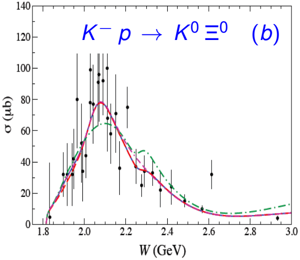
Possible reactions to be studied (elastic and charge-exchange reactions):

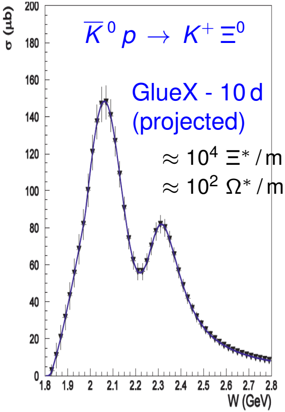
- 2- & 3-body reactions producing $S = -1$ hyperons
- 2-body reactions producing $S = -2$ hyperons

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

  ➜ $K_L^0\, p \to K^+ K^+\,\Omega^-;\; K^+ K^+\,\Omega^{-*}$







$\approx 10^4\;\Xi^*$ / m

$\approx 10^2\;\Omega^*$ / m