Spectroscopy of Strange Baryons
Future Perspectives

May 16, 2016       | Albrecht Gillitzer,  IKP Forschungszentrum Jülich
Baryons 2016, Talahassee, May 16-20, 2016
Outline

- Introductory Remarks
- The $\Xi$ and $\Omega$ spectrum
  - experimental status
  - theoretical studies
- Experimental Prospects:
  - photo-induced
  - high-energy $pp$
  - $\bar{p}p$
- Summary
Why to be Interested in Baryons?

- No understanding of strong interaction without understanding the excitation pattern of baryons!
- Strong worldwide activity in „Baryon Spectroscopy“ with in photo-induced reactions
### Achievements in N* Spectroscopy

**N*(1875)$^{3\text{−}}_{2}$** or **N*(1875)$D_{13}$**

### N*(1875)$^{3\text{−}}_{2}$ pole parameters (MeV)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{pole}}$</td>
<td>1860±25</td>
<td>MeV</td>
</tr>
<tr>
<td>$\Gamma_{\text{pole}}$</td>
<td>200±20</td>
<td>MeV</td>
</tr>
<tr>
<td>Elastic pole residue</td>
<td>2.5±1.0</td>
<td>MeV</td>
</tr>
<tr>
<td>2 Res$_{\Sigma K}$</td>
<td>4±2%</td>
<td>MeV</td>
</tr>
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<td>2 Res$_{\Sigma K}$</td>
<td>4±2%</td>
<td>MeV</td>
</tr>
<tr>
<td>2 Res$_{\Sigma N}$</td>
<td>8±3%</td>
<td>MeV</td>
</tr>
<tr>
<td>Phase</td>
<td>(170±65)$^\circ$</td>
<td></td>
</tr>
</tbody>
</table>

### N*(1875)$^{3\text{−}}_{2}$ Breit-Wigner parameters (MeV)

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<tr>
<th>Parameter</th>
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<tr>
<td>$M_{\text{BW}}$</td>
<td>1880±20</td>
<td>MeV</td>
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<tr>
<td>$\Gamma_{\text{BW}}$</td>
<td>200±25</td>
<td>MeV</td>
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<tr>
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<td>3±2%</td>
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<td>MeV</td>
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<tr>
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<td>60±12%</td>
<td>MeV</td>
</tr>
<tr>
<td>$A^{1/2}_{\text{BW}}$ (GeV$^{-1/2}$)</td>
<td>0.018±0.001</td>
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</tr>
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**BnGa PWA:**

A.V. Anisovich et al., EPJA 48 (2012) 15
Open Questions

- Missing resonances
- Wrong masses, wrong sequence
- Relevant degrees of freedom?
  - 3-quark?
  - quark-diquark?
  - meson-baryon dynamics

from RPP 2014 / QM: S. Capstick, W. Roberts
Strange Partners

- Approximate SU(3) flavor symmetry
- N* & Δ states have partners in the strange sector
- Focus on Ξ and Ω
  - Ξ: as many states as N* & Δ together
  - Ω: as many states as Δ
- Scrutinize our understanding of the baryon excitation pattern
Table 1. The status of the Ξ resonances. Only those with an overall status of *** or **** are included in the Baryon Summary Table.

<table>
<thead>
<tr>
<th>Particle</th>
<th>$J^P$</th>
<th>Overall status</th>
<th>$\Xi\pi$</th>
<th>$\Lambda K$</th>
<th>$\Sigma K$</th>
<th>$\Xi(1530)\pi$</th>
<th>Other channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ξ(1318)</td>
<td>1/2+</td>
<td>?</td>
<td>****</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ξ(1530)</td>
<td>3/2+</td>
<td>****</td>
<td>****</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ξ(1620)</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ξ(1690)</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ξ(1820)</td>
<td>3/2−</td>
<td>?</td>
<td>***</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>Ξ(1950)</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>**</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ξ(2030)</td>
<td>***</td>
<td>**</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ξ(2120)</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ξ(2250)</td>
<td>**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3-body decays</td>
</tr>
<tr>
<td>Ξ(2370)</td>
<td>**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3-body decays</td>
</tr>
<tr>
<td>Ξ(2500)</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>3-body decays</td>
</tr>
</tbody>
</table>

****  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.

Ξ(1820):

Teodoro78 favors $J = 3/2$, but cannot make a parity discrimination. Biagi 87c is consistent with $J = 3/2$ and favors negative parity for this $J$ value.
SU(6) x O(3) Classification


"Assignments for \(\Xi(1820)\) and \(\Xi(2030)\), are merely educated guesses."

\(\Xi(1690),\ \Xi(1950): \ ?\)

T. Melde \textit{et al.}, PRD 77 (2008) 114002

decuplet: no \(\Xi^*\), no \(\Omega^*\)

"… nothing of significance on \(\Xi\) resonances has been added since our 1988 edition."

<table>
<thead>
<tr>
<th>(J^P)</th>
<th>((D, L^P_N))</th>
<th>(S)</th>
<th>Octet members</th>
<th>Singlets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2(^+)</td>
<td>((56,0^+_{0}))</td>
<td>1/2 (N(939))</td>
<td>(\Lambda(1116))</td>
<td>(\Sigma(1193))</td>
</tr>
<tr>
<td>1/2(^+)</td>
<td>((56,0^+_{2}))</td>
<td>1/2 (N(1440))</td>
<td>(\Lambda(1600))</td>
<td>(\Sigma(1660))</td>
</tr>
<tr>
<td>1/2(^-)</td>
<td>((70,1^-_{1}))</td>
<td>1/2 (N(1535))</td>
<td>(\Lambda(1670))</td>
<td>(\Sigma(1620))</td>
</tr>
<tr>
<td>3/2(^-)</td>
<td>((70,1^-_{1}))</td>
<td>1/2 (N(1520))</td>
<td>(\Lambda(1690))</td>
<td>(\Sigma(1670))</td>
</tr>
<tr>
<td>1/2(^-)</td>
<td>((70,1^-_{1}))</td>
<td>3/2 (N(1650))</td>
<td>(\Lambda(1800))</td>
<td>(\Sigma(1750))</td>
</tr>
<tr>
<td>3/2(^-)</td>
<td>((70,1^-_{2}))</td>
<td>3/2 (N(1700))</td>
<td>(\Lambda(?))</td>
<td>(\Sigma(1940)) (^\dagger)</td>
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<tr>
<td>5/2(^-)</td>
<td>((70,1^-_{1}))</td>
<td>3/2 (N(1675))</td>
<td>(\Lambda(1830))</td>
<td>(\Sigma(1775))</td>
</tr>
<tr>
<td>1/2(^+)</td>
<td>((70,0^+_{2}))</td>
<td>1/2 (N(1710))</td>
<td>(\Lambda(1810))</td>
<td>(\Sigma(1880))</td>
</tr>
<tr>
<td>3/2(^+)</td>
<td>((56,2^+_{2}))</td>
<td>1/2 (N(1720))</td>
<td>(\Lambda(1890))</td>
<td>(\Sigma(?))</td>
</tr>
<tr>
<td>5/2(^+)</td>
<td>((56,2^+_{2}))</td>
<td>1/2 (N(1680))</td>
<td>(\Lambda(1820))</td>
<td>(\Sigma(1915))</td>
</tr>
<tr>
<td>7/2(^-)</td>
<td>((70,3^-_{3}))</td>
<td>1/2 (N(2190))</td>
<td>(\Lambda(?))</td>
<td>(\Sigma(?))</td>
</tr>
<tr>
<td>9/2(^-)</td>
<td>((70,3^-_{3}))</td>
<td>3/2 (N(2250))</td>
<td>(\Lambda(?))</td>
<td>(\Sigma(?))</td>
</tr>
<tr>
<td>9/2(^+)</td>
<td>((56,4^+_{4}))</td>
<td>1/2 (N(2220))</td>
<td>(\Lambda(2350))</td>
<td>(\Sigma(?))</td>
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<tr>
<td>3/2(^+)</td>
<td>((56,0^+_{0}))</td>
<td>3/2 (\Delta(1232))</td>
<td>(\Sigma(1385))</td>
<td>(\Xi(1530))</td>
</tr>
<tr>
<td>3/2(^+)</td>
<td>((56,0^+_{2}))</td>
<td>3/2 (\Delta(1600))</td>
<td>(\Sigma(1690))</td>
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<td>5/2(^+)</td>
<td>((56,2^+_{2}))</td>
<td>3/2 (\Delta(1905))</td>
<td>(\Sigma(?))</td>
<td>(\Xi(?))</td>
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<tr>
<td>7/2(^+)</td>
<td>((56,2^+_{2}))</td>
<td>3/2 (\Delta(1950))</td>
<td>(\Sigma(2030))</td>
<td>(\Xi(?))</td>
</tr>
<tr>
<td>11/2(^+)</td>
<td>((56,4^+_{4}))</td>
<td>3/2 (\Delta(2420))</td>
<td>(\Sigma(?))</td>
<td>(\Xi(?))</td>
</tr>
</tbody>
</table>
Data on $\Xi^*$ States: $\Xi(1530)$

- The only reasonably well studied $\Xi$ resonance:
- $\Xi(1530)$ - decuplet g.s. $J^P = 3/2^+$
- $\Gamma = 9\ldots10$ MeV \textit{Compare to $\Delta$!!}
- decay: $\sim100\%$ $\Xi\pi$
- BaBar measured the $\Xi(1530)^0$ spin $J = 3/2$ in $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$
- favor $J^P = 1/2^-$ for $\Xi(1690)$

BaBar: B. Aubert et al., PRD 78 (2008) 034008
Quark Model

Ξ:
• many states predicted below 3 GeV
• compare 1/2\(^+\) and 1/2\(^-\) excitation

Ω:
• several states predicted between 2 GeV and 3 GeV
• compare 3/2\(^+\) and 3/2\(^-\) excitation

U. Löring et al., EPJA 10 (2001) 447
s.a.: M. Pervin, W. Roberts, PRC 77 (2008) 025202
Lattice Calculations

$m_{\pi^*} = 391$ MeV

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

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

D. Leinweber, this session
Experimental Prospects

Invitation to give a talk on „Strange Baryons … with reference to the programs at PANDA, GlueX, and LHCb”

- $pp \rightarrow \Xi^*\chi$ (prompt or delayed)  
  - LHCb  
  - P. Spradlin, Wednesday

- $\gamma p \rightarrow K^+K^+\Xi^*$  
  - GlueX, CLAS12  
  - L. Guo, Tuesday

- $\bar{p}p \rightarrow \Xi^*\Xi$ & c.c.  
  - PANDA

- $e^+e^- \rightarrow \Xi^*\chi$ (prompt or delayed)  
  - Belle II

- $K^-p \rightarrow K^+\Xi^*$  
  - J-PARC

- $K_Lp \rightarrow K^+\Xi^{*0}$  
  - Hall D $K_L$ beam

- M. Naruki, Tuesday

- J. Yelton, Thursday

- M. Destefanis, Thursday

- S. Taylor, Tuesday
Production in $\gamma p$: CLAS

Runs g6a, g6b:
- first exclusive photoproduction of $\Xi^-$
- reaction $\gamma p \rightarrow K^+K^+X$

J. Price et al., PRC 71 (2005) 058201
Production in $\gamma p$: CLAS

Run g11a:
- higher statistics
- differential cross sections
- excitation function

$\Xi(1620)$ signal?

peaking background:
$\gamma p \rightarrow K^+ K^0 \Xi^0$, $K^0 \rightarrow K^+ \pi^-$

K. Nakayama et al., PRC 74 (2006) 035205

K. Nakayama, Tuesday
Ξ Production at CLAS

Run g12:
- more statistics
- higher photon energies
- upper limits for higher Ξ states 
  (3.5 GeV < $E_\gamma$ < 5.4 GeV):
  - $\Xi(1620)$: 0.78 nb
  - $\Xi(1690)$: 0.97 nb
  - $\Xi(1820)$: 1.09 nb

J.T. Goetz, PhD thesis UCLA 2010
生产在GlueX

\[ \gamma p \rightarrow K^+\Xi^- (1320) K^+ \]
\[ \Xi^- (1320) \rightarrow \pi^- \Lambda \]
\[ \Lambda \rightarrow p\pi^- \]

现有的TOF
4σ K/π分离

\[ \gamma p \rightarrow K^+\Xi^- (1820) K^+ \]
\[ \Xi^- (1820) \rightarrow K^- \Lambda \]
\[ \Lambda \rightarrow p\pi^- \]

A. AlekSejevs et al., arXiv:1305.1523
GlueX proposal to PAC 40

- GlueX Proposal (JLAB PAC 39, 40 & 42): „Decays to Strange Final States“
- Study excited Ξ states
- parity measurement of the g.s. Ξ-
- will probably need enhanced kaon identification in forward region
- Components of BaBar DIRC for GlueX
Expected yields of \( \Xi \) states using (PAC 40 proposal):

\[
N = \epsilon \sigma \ n_\gamma \ n_t \ T \quad \text{where}
\]

\[
\sigma_{\Xi(1320)} = 15 \text{ nb} \quad \text{and} \quad \sigma_{\Xi(1530)} = 2 \text{ nb} \quad \text{at} \quad E_\gamma = 5 \text{ GeV}
\]

\[
\epsilon_{\Xi(1820)} \approx 30\% \quad (\text{BDT: signal purity 0.9})
\]

→ 800,000 \( \Xi^- (1320) \) events

100,000 \( \Xi^- (1530) \) events

90,000 \( K^+ K^+ K^- \Lambda \) events (based on PYTHIA)

→ At least x10 more statistics than previous CLAS result.
### Strange Baryons at LHCb

<table>
<thead>
<tr>
<th>Run</th>
<th>Year</th>
<th>$\sqrt{s}$ [TeV]</th>
<th>$\int L dt$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2011</td>
<td>7</td>
<td>1 fb$^{-1}$</td>
</tr>
<tr>
<td>I</td>
<td>2012</td>
<td>8</td>
<td>2 fb$^{-1}$</td>
</tr>
<tr>
<td>II</td>
<td>2015</td>
<td>13</td>
<td>320 pb$^{-1}$</td>
</tr>
</tbody>
</table>

**LHCb track types**

- Patrick Spradlin, Wednesday
- Sebastian Neubert, Thursday

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*Albrecht Gillitzer*
Why Light Spectroscopy?

**Extended Λ* model**

**Extended Λ* model**

**Reduced Λ* model + 2 Pc’s**

---

More reliable model for the Λ* sector would implies more precise measurements of $P_c$ properties

$Λ_b \to K P_c \to K J/ψ p$

$Λ_b \to J/ψ Λ^* \to J/ψ K p$

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EMMI: Resonances in QCD

M. Pappagallo
Strange Baryons at LHCb

- 2015 Run II data: $\sqrt{s} = 13$ TeV
- first analysis to study prompt $\Xi$ and $\Omega$ production

* communicated by M. Pappagallo
The PANDA Experiment

Antiproton Beam at HESR:

- 1.5 – 15 GeV/c
- $\delta p/p = 3 \cdot 10^{-5} / 10^{-4}$
- $L = 2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ (final)

Physics Program:

- hadron spectroscopy
- reaction dynamics
- proton structure
- hadrons in nuclei
- $\Lambda\Lambda$ hypernuclei (modified setup)
The PANDA Experiment

Detector capabilities

- $4\pi$ acceptance
- High tracking resolution
- Good particle identification
- Software-based trigger system
• characteristic event topology
• $\sigma \sim \mu b$: $\sim 10^7 \Xi/d$ produced
• final states to be studied: $\Xi^* \to \Xi \pi, \Xi \eta, \Lambda \bar{K}, \Sigma \bar{K}$, $\Xi(1530) \pi, \Xi \pi \pi$, ...
• benchmark channel: 6.57 GeV/c $\bar{p}p \to \Xi^- \Xi^+ \pi^0$
• no empty regions or discontinuities in Dalitz plot
• $\Xi^- \pi^0$ mass resolution < 4 MeV; rec. eff. $\sim 15\%$, S/B $>19^*$
  *DPM generated background

(#) $L = 10^{32}$ cm$^{-2}$s$^{-1}$
Early Physics: Expected Rates for Strange Baryons

- initial phase: \( L \equiv 10^{31} \text{cm}^{-2} \text{s}^{-1} \) instead of \( L \equiv 2 \cdot 10^{32} \text{cm}^{-2} \text{s}^{-1} \)
- nevertheless the \( \Xi\Xi \) production rate will be \( R_{\Xi\Xi} \equiv 10/\text{s} \equiv 10^6/\text{d} \)
- for \( \Omega\Omega \) production we expect \( R_{\Omega\Omega} \equiv 0.3/\text{s} \equiv 3 \cdot 10^4/\text{d} \)
- for excited states the cross section should be of the same order of magnitude as for the ground state for given \( \sqrt{s} - \sqrt{s_{\text{thr}}} \)
- the detected rate depends on the specific decay mode (branching & reconstruction efficiency)
- e.g. \( \bar{p}p \rightarrow \Xi^+\Xi^*^- \rightarrow \Xi^+\Xi^-\pi^0 \rightarrow \bar{\Lambda}\pi^+\Lambda\pi^-\pi^0 \rightarrow \bar{p}\pi^+\pi^+p\pi^-\pi^-\pi^0 \)
  assume \( b = 0.5 \cdot 0.64^2 = 0.2 \) and \( \epsilon = 5\% \) \( \rightarrow R_{\text{det}} \equiv 10^4/\text{d} \)
PANDA: $\Xi^*$ Spectroscopy

new MC simulations & analyses:

- André Zambanini, completed, PhD thesis U Bochum 2015
- $4.1 \text{ GeV/c } \bar{p}p \rightarrow \Xi(1690)^-\bar{\Xi}^+ \rightarrow K^-\Lambda\bar{\Xi}^+$
- $\sim 0.5 \cdot 10^6$ signal events, $\sim 50 \cdot 10^6$ DPM background events
- Jennifer Pütz, PhD thesis fully devoted to $\Xi$ spectroscopy
- $4.6 \text{ GeV/c } \bar{p}p \rightarrow \Xi(1820)^-\bar{\Xi}^+ \rightarrow K^-\Lambda\bar{\Xi}^+$ & c.c.
- $1.5 \cdot 10^6$ signal events, $15 \cdot 10^6$ DPM background events so far
**Ξ⁺Ξ⁻ System — Dalitz-Plot**

\[ \Xi^+ \Lambda K^- \text{ final state: } M^2(\Lambda K^-) \text{ vs. } M^2(\bar{\Xi}^+ \Lambda) \]

**Reconstructed** (bef. 4C kin. fit)

\[ \sigma_M(\Xi^+) = 3.2 \text{ MeV} \]
\[ f_{\text{rec}} \times \text{BR} \sim 2.5\%, \quad f_{\text{bckg}} \sim 0.2 \cdot 10^{-7} \]

**Simulation input**

\[
\bar{p}p \rightarrow \Xi^+(1820)^- \rightarrow \Xi^+\Lambda K^-
\]

\[\Xi^+\Lambda K^- \text{ final state: } M^2(\Xi^+K^-) \text{ vs } M^2(\Lambda K^-)\]

\[
\sigma_M(\Xi^+) = 4.0 \text{ MeV} \\
\text{f}_{\text{rec}} \sim 5\% \\
\text{background suppression under study}
\]

Jenny Pütz, Talk at FAIRNESS 2016
Studies within the PANDA Physics Program

- good case for initial phase with lower L
- \(\Lambda\) & \(\Sigma\) spectroscopy can be done in parallel
- long runs to measure the \(X(3872)\) width in energy scan planned:
  - parallel trigger for \(\Xi^*\) and \(\Omega^*\)
  - \(p \approx 7.0\) GeV/c
  - \(M_{\text{max}}(\Xi^*) \approx 2.55\) GeV \(M_{\text{max}}(\Omega^*) \approx 2.20\) GeV

- later: long runs for threshold scan of \(D_s^+D_s(2317)^\mp\)
  - \(p \approx 8.8\) GeV/c
  - \(M_{\text{max}}(\Omega^*) \approx 2.61\) GeV
Summary

- Spectroscopy of (multi-)strange baryons has lagged very much behind the study of the N*/Δ spectrum
- Deficit particularly large for excited Ξ and Ω states
- Without knowledge of the Ξ and Ω spectrum our understanding of baryon excitation will remain incomplete
- Various experiments will contribute in the near or intermediate future

- Ξ and Ω spectroscopy has a bright perspective!