(Light) Baryon phenomenology and partial-wave analyses – recent developments in Germany

KHuK annual meeting 2023, Bad Honnef

December 8, 2023 | Deborah Rönchen | Institute for Advanced Simulation, Forschungszentrum Jülich

Supported by DFG, NSFC, MKW NRW

HPC support by Jülich Supercomputing Centre

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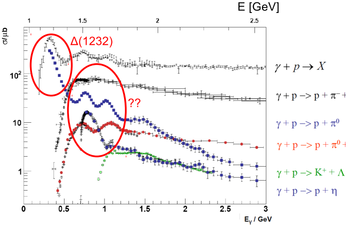
The excited baryon spectrum:

Connection between experiment and QCD in the non-perturbative regime

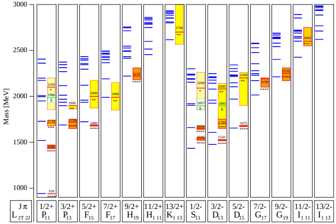
Experimental study of hadronic reactions



source: ELSA; data: ELSA, JLab, MAMI

$\Longleftrightarrow$

Theoretical predictions of excited baryons
e.g. from relativistic quark models:



Löring *et al.* EPJ A 10, 395 (2001), experimental spectrum: PDG 2000

Major source of information:

In the past: **elastic or charge exchange πN scattering**

- “missing resonance problem”

In recent years: **photoproduction reactions** (also: $\pi N \to \pi\pi N$)

- large data base, high quality (double) polarization observables (from ELSA, MAMI, JLab...)
  Reviews: Prog.Part.Nucl.Phys. 125, 103949 (2022), Prog.Part.Nucl.Phys. 111 (2020) 103752

In the future: **electroproduction reactions**

- 10^5 data points for πN, ηN, KY, $\pi\pi N$ Review: e.g. Prog.Part.Nucl.Phys. 67 (2012)

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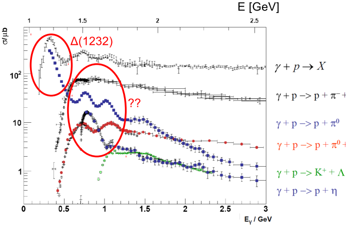

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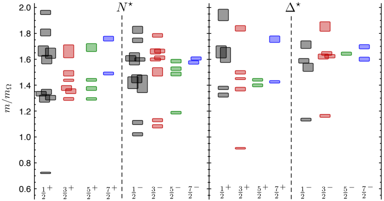
$\Longleftrightarrow$

Theoretical predictions of excited baryons
... or lattice calculations:
(with some limitations)



$m_\pi = 396$ MeV [Edwards *et al.*, Phys.Rev. D84 (2011)]

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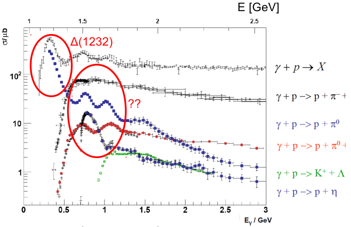
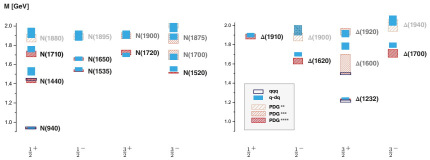


source: ELSA; data: ELSA, JLab, MAMI

Theoretical predictions of excited baryons

... or Dyson-Schwinger approaches:

$\Longleftrightarrow$



[Eichmann *et al.*, Phys.Rev. D94 (2016), fig. from PoS LC2019 (2019) 003]

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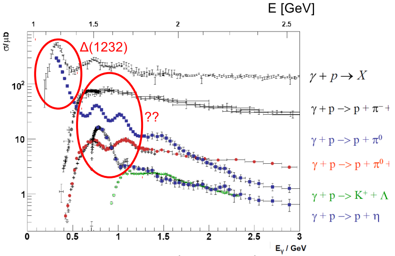
From experimental data to the resonance spectrum



source: ELSA; data: ELSA, JLab, MAMI

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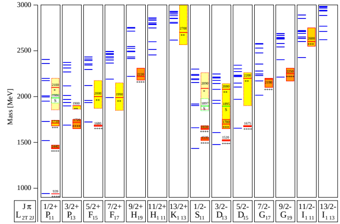

Löring *et al.* EPJ A 10, 395 (2001), experimental spectrum: PDG 2000

Different modern analyses frameworks:

- **(multi-channel)** ***K*-matrix:** GWU/SAID, BnGa (phenomenological),
  Gießen (microscopic Bgd)
- **dynamical coupled-channel (DCC):** 3d scattering eq., off-shell intermediate states
  ANL-Osaka (EBAC), Dubna-Mainz-Taipeh, Jülich-Bonn
- **unitary isobar models:** unitary amplitudes + Breit-Wigner resonances
  MAID, Yerevan/JLab, KSU
- **other groups:** Mainz-Tuzla-Zagreb PWA (MAID + fixed-t dispersion relations, L+P), JPAC (amplitude analysis with Regge phenomenology), Ghent (Regge-plus-resonance), truncated PWA
- …

Detailed comparison of MAID, GWU/SAID, BnGa and JüBo: EPJ A 52, 284 (2016)

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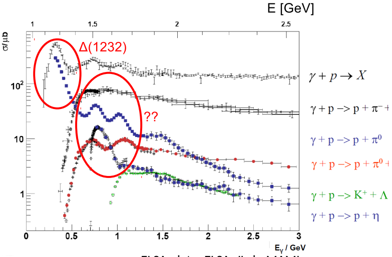

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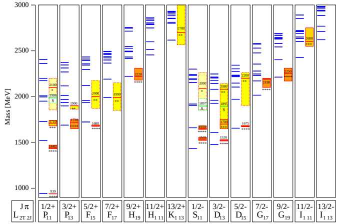

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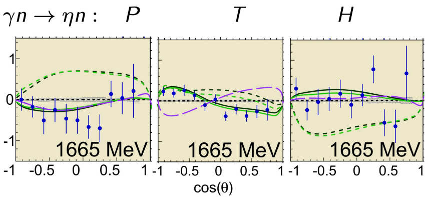
Recent results Bonn-Gatchina `pwa.hiskp.uni-bonn.de`

- new photoproducion data are constantly included (e.g. T, E, P, H, and G in $\gamma p \to \eta p$ (CBELSA/TAPS PLB 803 (2020)) $\to$ BnGa2019 solution, new value for ηN residue of $N(1650)1/2^-$)
- photoproduction off neutrons: T, P, H for $\gamma p \to \pi^0 p$, ηp and $\gamma \boldsymbol{n} \to \pi^0 n$, ηn (CBELSA/TAPS EPJ A 59 (2023))

Previously observed narrow structure in ηn at W ∼1.68 GeV:

- previously attributed to a new narrow $P_{11}(1680)$ (e.g. Witthauer *et al.* PRL 117 (2016))
- here: $S_{11}(1535)$–$S_{11}(1650)$ interference (green solid),
- no need for $P_{11}(1680)$ (green dashed lines)



(Figs. from CBELSA/TAPS EPJ A 59 (2023))

$\to$ situation even for lower N^* not yet absolutely clear!

- Analysis of 3 body final states (with quasi 2-particle unitarity): study of sequential decays of high mass resonances via, e.g.,:
  - $\gamma p \to \pi^0\pi^0 p$ CBELSA/TAPS (2022) arXiv:2207.01981
  - $\pi^- p \to \pi^+\pi^- n$, $\pi^0\pi^- p$ HADES PRC 102 (2020)

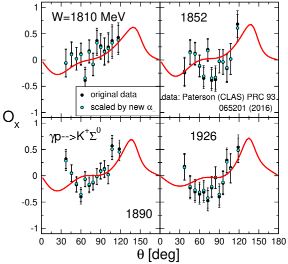
  $\Rightarrow$ charged pions: ρN branching ratios of $N(1535)1/2^-$, $N(1520)3/2^-$ (poorly known so far)

Recent results Jülich-Bonn-Washington

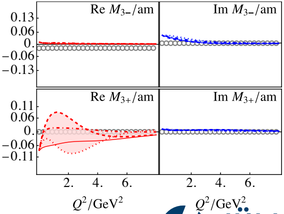
collaborations.fz-juelich.de/ikp/meson-baryon/main, jbw.phys.gwu.edu

- extension to include $K\Sigma$ photoproduction off the proton:
  D. Rönchen *et al.* ("JüBo2022") Eur.Phys.J.A 58 (2022) 229
  - Simultaneous analysis of $\pi N \to \pi N, \eta N, K\Lambda, K\Sigma$ and $\gamma p \to \pi N, \eta N, K\Lambda, K\Sigma$
  - all 4-star N and Δ states up to $J = 9/2$ seen (exception: $N(1895)1/2^-$) + some states with less stars
  - indications for new dyn. gen. poles
  - new value for ηN residue of $N(1650)1/2^-$
- $\pi N \to \omega N$ channel included: Y.-F. Wang *et al.* PRD 106 (2022)
  prerequisite for ω photoproduction
- extension of JBW approach to $K\Lambda$ electroproduction:
  M. Mai *et al.* PRC 103 (2021), PRC 106 (2022), EPJ A 59 (2023)
  - simultaneous fit to $\gamma^* p \to \pi N, \eta N, K\Lambda$ ($W < 1.8$ GeV, $Q^2 < 8$ GeV^2)
  - Input from JüBo: amplitude at $Q^2 = 0$
    $\to$ universal pole positions and residues (fixed here)
  - long-term goal: fit pion-, photo- & electron-induced reactions simultaneously
- study on compositeness/elementariness of resonances
  within JüBo DCC, spectral density function method Y.-F. Wang *et al.* 2307.06799 [nucl-th]

Selected fit results



$\gamma^* p \to K\Lambda$ at $W = 1.7$ GeV



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Further analyses efforts (selected examples)

- Recent results Mainz-Tuzla-Zagreb:
  - coupled channels analysis of η, η' photoproduction: "EtaMAID2018" (Tiator *et al.* EPJ A54 (2018) 210)
    evidence for $N(1895)1/2^-$ (among other things)
  - SE PWA of $\gamma p \to \pi^0 p, \pi^+ n$ and $\gamma n \to \pi^- p, \pi^0 n$
    Osmanovic *et al.* (PRC 104 (2021))
    multipoles with min. model depend., constraints from unitarity & fixed-t analyticity

$\gamma p \to \eta p$

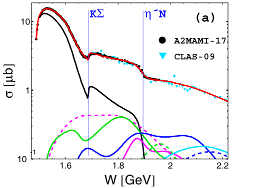


figure: EPJ A 54, 210. Red: EtaMAID2018. Black: S_{11}

- Truncated partial-wave analysis (TPWA):
  - Single-channel SE PWA with "AA/PWA"
    aim: extraction of multipole in almost model indep. way (phase fixed to BnGa multipoles)
    - $\gamma p \to \eta p$ (Svarc, Wunderlich, Tiator PRC 102 (2020))
    - $\gamma p \to K\Lambda$ (Svarc, Wunderlich, Tiator PRC 105 (2022)):
      $\to$ BnGa M_{1-} reproduced,
      but $N(1880)1/2^+$ not confirmed

$\gamma p \to K^+\Lambda$

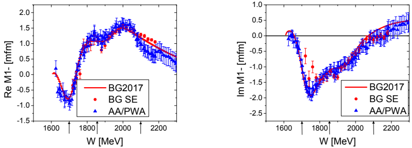


figure from PRC 105 (2022)

$\to$ situation even for lower N^* not yet absolutely clear!

- TPWA of η photoproduction combined with Bayesian statistics (Kroenert *et al.* arXiv:2305.10367)
  quantify the uncertainty of multipole amplitudes with a high level of detail

Challenges and Perspectives

Extraction of the N^* and Δ spectrum from experimental data: major progress in last decade

- new information from photoproduction data $\rightarrow$ new and upgraded states in PDG table
- γn reactions, multi meson final states: valuable information, data base is filling up
- wealth of high-quality electroproduction data, more at high Q^2 in the future (CLAS12)
  $\rightarrow$ to be included in modern coupled-channel analyses (in progress)

Challenges:

- πN scattering: improved data situation highly desirable
- γN scattering: "complete experiment"
- thorough determination of uncertainties of resonance parameters:
  - error propagation data $\rightarrow$ fit parameters $\rightarrow$ derived quantities
  - model selection: significance of resonance signals with Bayesian evidence (PRL 108, 182002; PRC 86, 015212 (2012)) or LASSO (PRC 95, 015203 (2017); J. R. Stat. Soc. B 58, 267 (1996))

$\rightarrow$ need for refined analysis tools that match in precision the nowadays available data!
(Huge numerical effort)

Λ^* and Σ^* spectrum:

- rather poorly known (data situation)
- prospects for new data: K_L facility at JLab, planned experiment at ELSA, PANDA at FAIR

Thank you for your attention!

Appendix

The Hyperon Spectrum (Λ^*'s and Σ^*'s)

- Very little new experimental data in the last decades for the complete resonance region

$\rightarrow$ spectrum much less known than N^* or Δ
but equally important to understand QCD at low energies!

- 4 groups world-wide re-analyzed old $K^- p$ data over the complete resonance region
  - BnGa: multi-channel PWA based on a modified K-matrix approach EPJA 55,179 & 180 (2019)
  - JüBo: DCC analysis of $\bar{K}N$ reactions in progress

Particle	J^P	Overall status	$N\overline{K}$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	$1/2^+$	****			$N\pi$ (weak decay)
$\Lambda(1380)$	$1/2^-$	**	**	**	
$\Lambda(1405)$	$1/2^-$	****	****	****	
$\Lambda(1520)$	$3/2^-$	****	****	****	$\Lambda\pi\pi$, $\Lambda\gamma$, $\Sigma\pi\pi$
$\Lambda(1600)$	$1/2^+$	****	***	****	$\Lambda\pi\pi$, $\Sigma(1385)\pi$
$\Lambda(1670)$	$1/2^-$	****	****	****	$\Lambda\eta$
$\Lambda(1690)$	$3/2^-$	****	****	***	$\Lambda\pi\pi$, $\Sigma(1385)\pi$
$\Lambda(1710)$	$1/2^+$	*	*	*	
$\Lambda(1800)$	$1/2^-$	***	***	**	$\Lambda\pi\pi$, $N\overline{K}^*$
$\Lambda(1810)$	$1/2^+$	***	**	**	$N\overline{K}^*$
$\Lambda(1820)$	$5/2^+$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	$5/2^-$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	$3/2^+$	****	****	**	$\Sigma(1385)\pi$, $N\overline{K}^*$
$\Lambda(2000)$	$1/2^-$	*	*	*	
$\Lambda(2050)$	$3/2^-$	*	*	*	
$\Lambda(2070)$	$3/2^+$	*	*	*	
$\Lambda(2080)$	$5/2^-$	*	*	*	
$\Lambda(2085)$	$7/2^+$	**	**	*	
$\Lambda(2100)$	$7/2^-$	****	****	**	$N\overline{K}^*$
$\Lambda(2110)$	$5/2^+$	***	**	**	$N\overline{K}^*$
$\Lambda(2325)$	$3/2^-$	*	*		
$\Lambda(2350)$	$9/2^+$	***	***	*	
$\Lambda(2585)$		*	*		

(Status as seen in — $N\overline{K}$, $\Sigma\pi$, Other channels)

R. L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

Status updated   Quantum numbers updated   New

Prospects for new data:

- K_L facility at JLab: Strange Hadron Spectroscopy with a secondary K_L Beam at GlueX (approved) 2008.08215 [nucl-ex]
- planned new experiment at ELSA in Bonn: $\gamma p \rightarrow K^+\Lambda^* \rightarrow K^+\Sigma^0\pi^0$, $\gamma p \rightarrow K^+\Sigma^* \rightarrow K^+\Lambda\pi^0$
- PANDA at FAIR: $\bar{p}p \rightarrow \bar{Y}Y^*$: besides Ξ^* and Ω^* also Λ^* and Σ^* spectrum accessible 0903.3905 [hep-ex]

Jülich-Bonn-Washington parametrization

M. Mai *et al.* PRC 103 (2021), PRC 106 (2022), arXiv:2307.10051 [nucl-th]

$$\mathcal{M}_{\mu\gamma^*}(k, W, Q^2) = R_{\ell'}(\lambda, q/q_\gamma) \left(V_{\mu\gamma^*}(k, W, Q^2) + \sum_\kappa \int_0^\infty dp\, p^2\, T_{\mu\kappa}(k, p, W) G_\kappa(p, W) V_{\kappa\gamma^*}(p, W, Q^2) \right)$$

(Pseudo)-threshold behavior with meson/photon momenta

$$lim_{k\to 0} E_{\ell+} = k^\ell$$
$$lim_{q\to 0} L_{\ell+} = q^\ell$$
$$\dots$$

For $Q^2=0$ (real photons) identical to Jülich-Bonn photoproduction amplitude

$$V_{\mu\gamma^*}(k, W, Q^2) = V_{\mu\gamma}^{\text{JUBO}}(k, W) \cdot \tilde{F}_D(Q^2) \cdot e^{-\beta_\mu^0 Q^2/m_p^2} \left(1 + Q^2/m_p^2 \beta_\mu^1 + (Q^2/m_p^2)^2 \beta_\mu^2\right)$$

$\leftarrow$ Siegerts's theorem Siegert(1973) Amaldi et al.(1979) Tiator(2016)

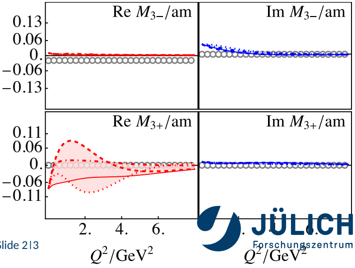
$$V^{L_{\ell\pm}} = (\text{const.}) \cdot V^{E_{\ell\pm}}$$

...at pseudo-threshold

- simultaneous fit to πN, ηN, $K\Lambda$ electroproduction off proton $(W < 1.8$ GeV, $Q^2 < 8$ GeV$^2)$
- 533 fit parameters, 110.281 data points
- Input from JüBo: $V_{\mu\gamma}(k, W, Q^2 = 0)$, $T_{\mu\kappa}(k, p, W)$, $G_\kappa(p, W)$

  $\rightarrow$ universal pole positions and residues (fixed in this study)
- long-term goal: fit pion-, photo- and electron-induced reactions simultaneously

$\gamma^* p \rightarrow K\Lambda$ at $W = 1.7$ GeV



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Different methods to extract the spectrum from data

Detailed comparison: EPJ A 52, 284 (2016)

Bonn-Gatchina (BnGa) PWA

(pwa.hiskp.uni-bonn.de)

Multi-channel PWA based on K-matrix (N/D)

- mostly phenomenological model
- resonances added by hand
- resonance parameters determined from large experimental data base:
  pion-, photon-induced reactions, 3-body final states
- PWA of $\bar{K}N$ scattering, hyperon spectrum EPJA 55,179 & 180 (2019)

Jülich-Bonn (JüBo) DCC model

(collaborations.fz-juelich.de/ikp/meson-baryon/main)

Lippmann-Schwinger eq. formulated in TOPT

- hadronic potential from effective Lagrangians
- photoproduction as energy-dependent polynomials
- resonances as s-channel states (“by hand”), dynamical generation possible
- resonance parameters from pion- and photon-induced data
- Jülich-Bonn-Washington model: CC electroproduction analysis (jbw.phys.gwu.edu)

MAID PWA

(maid.kph.uni-mainz.de)

unitary isobar model

- resonances as multi-channel Breit-Wigner amplitudes
- background: Born terms + Regge exchanges
- photo- and electroproduction of pions, etas & kaons
- Mainz-Tuzla-Zagreb collaboration: MAID + fixed-t dispersion relations, L+P (pwatuzla.com/p/mtz-collab.html)