Non-Strange & Strange Baryon Spectroscopy @ GW

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- $\pi N$ elastic for Baryon Spectroscopy.
- Pion PhotoProd for Baryon Spectroscopy.
- Pion ElectroProd for Baryon Spectroscopy.
- First pole for hyperons from Hall A.
- Very Strange study with CLAS12.
- KLF study with GlueX.
- Summary.

Supported by DE-SC0016583
**Baryon Sector**

*GW Contribution for* M. Tanabashi *et al, Phys Rev D 98, 030001 (2018)*

- **PDG18** has 109 Baryon Resonances (64 of them are 4* & 3*).
- In case of **SU(6) X O(3)**, 434 states would be present if all revealed multiplets were fleshed out (three 70 and four 56).

- **First hyperon was discovered**

- **Pole position in complex energy plane for hyperons** has been made only recently, first of all for Λ(1520)3/2−.

Y. Qung *et al, Phys Lett B 694, 123 (2010)*
Phenomenology for Baryons

• Originally PWA arose as technology to determine amplitude of reaction via fitting scattering data. That is non-trivial mathematical problem – looking for solution of ill-posed problem following to Hadamard & Tikhonov.

• Resonances appeared as by-product [bound states objects with definite quantum numbers, mass, lifetime, & so on].

• Standard PWA
  ⇒ Reveals only wide Resonances, but not too wide ($\Gamma < 500$ MeV) & possessing not too small BR ($\text{BR} > 4\%$).
  ⇒ Tends (by construction) to miss narrow Res with $\Gamma < 20$ MeV.

Most of our current knowledge about bound states of three light quarks has come mainly from $\pi N \rightarrow \pi N$ PWAs:

Karlsruhe–Helsinki,
Carnegie–Mellon–Berkeley,
GW & KentState.

Main source of EM couplings is GW, MAID, BnGa, & JuBo analyses.
for $\pi N \rightarrow \pi N$, $\pi^- p \rightarrow \eta n$

- Energy dependent SP06/WI08 and associated SES
- $T = 0 - 2600$ MeV
- 4-channel Chew-Mandelstam $K$-matrix parameterization
- DR constraint
- 3 mapping variables: $g^2/4\pi$, $a[\pi p]$, $\eta$–th
- PWs = 30 $\pi N \{15 [I=1/2] + 15 [I=3/2]\} + 4 \eta N$
- Prms = 99 [I=1/2] + 89 [I=3/2]

$[W = 1078 - 2460$ MeV$]$
$[\pi N, \pi\Delta, \rho N, \eta N]$

$\pi^+ p \rightarrow \pi^+ p$

$\pi^- p \rightarrow \pi^- p$

$\pi^- p \rightarrow \pi^0 n$

$Pol=28\%$

$Pol=22\%$

$Pol=11\%$

$10$ data/MeV
Recent for $\pi^+ p \rightarrow \pi^+ p$

- New precise cross section measurements:
  \[\Delta\sigma = 0.5\% \text{ stat, } \Delta p = 1 \text{ MeV, } \Delta\theta = \pm 1^\circ\]

\[\pi^- p \rightarrow \pi^- p\]

\[\theta = 40^\circ, 70^\circ, 80^\circ\]

\[4277 \, d\sigma/d\Omega:\]
\[800 - 1243 \text{ MeV/c}\]
\[40 - 122 \text{ deg}\]

\[\pi^+ p \rightarrow \pi^+ p\]

\[\theta = 100^\circ, 110^\circ, 120^\circ\]

\[2638 \, d\sigma/d\Omega:\]
\[918 - 1240 \text{ MeV/c}\]
\[40 - 122 \text{ deg}\]

- CMB analysis significantly more predictive when compared to versions of KH analyses.

Predictions: WI08, KH80, KA84, CMB

Determination Pole Positions & Residues for $\pi N$ scattering amplitudes


- Interpretation of PW amplitudes may appear not simple.

- Resonances found through search for Poles in complex plane are not put in by hand, contrary to BW parameterization.

- There is shift between Pole & BW mass (0 – 10%) & width.
SAID for Pion Photoproduction


GW SAID PWA facility allows
- To fit new data vs World Database.
- To validate acceptance & flux of new measurements.
- To validate systematics.
- To provide realistic event generator for MC simulations.

Data driven (model independent) analysis [No Adhoc resonances in]
- Energy dependent MA27
- $E = 145 - 2700$ MeV
- $W = 1080 - 2460$ MeV
- PWs = 60 [EM multipoles]
- Prms = 210
- Constraint: Born [no free parameters to fit] $\pi N$-PWA [no theoretical input]

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Data (Pol)</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma p \rightarrow p^0 p$</td>
<td>25,540 (23 %)</td>
<td>55,529</td>
</tr>
<tr>
<td>$\gamma p \rightarrow p^+ n$</td>
<td>8,959 (38 %)</td>
<td>20,736</td>
</tr>
<tr>
<td>$\gamma n \rightarrow p^- p$</td>
<td>11,590 (4 %)</td>
<td>16,453</td>
</tr>
<tr>
<td>$\gamma n \rightarrow p^0 n$</td>
<td>364 (59 %)</td>
<td>1,540</td>
</tr>
<tr>
<td>Total</td>
<td>46,453</td>
<td>94,258</td>
</tr>
</tbody>
</table>

- Pion photoproduction on the neutron much less known, 35%.
- There is disbalance between $p^0$ & $p^+$ data, 35%.

4/8/2019
8th GHP Workshop, Denver, Colorado, April 2019
Igor Strakovsky
There is disbalance between $\pi^0 p$ & $\pi^+ n$ data, $\pi^+ n / \pi^0 p = 20\%$.

Pion photoproduction on neutron much less known, $n / p = 31\%$.
Complete Experiment for Pion PhotoProduction

- There are 16 non-redundant observables.
- They are not completely independent from each other.

There are 16 non-redundant observables. They are not completely independent from each other.

1 un-pol measurement: $d\sigma/d\Omega$
3 single pol measurements: $\Sigma$, $T$, $P$
12 double pol measurements: $E$, $F$, $G$, $H$, $C_x$, $C_z$, $O_x$, $O_z$, $L_x$, $L_z$, $T_x$, $T_z$
18 triple polarization asymmetries
  [9 for linear pol beam]
  [9 for circular pol beam]
13 of them are non-vanishing

K. Nakayama, arXiv:1903.05015, 2019
Single Pion PhotoProduction on “Neutron” Target

- Accurate evaluation of EM couplings $N^*\rightarrow\gamma N$ & $\Delta^*\rightarrow\gamma N$ from meson photoproduction data remains paramount task in hadron physics.

- Only with good data on both proton & neutron targets, one can hope to disentangle isoscalar & isovector EM couplings of various $N^*$ & $\Delta^*$ resonances, as well as isospin properties of non-resonant background amplitudes.

- The lack of $\gamma n\rightarrow\pi^- p$ & $\gamma n\rightarrow\pi^0 n$ data does not allow us to be as confident about determination of neutron couplings relative to those of proton.

- Radiative decay width of neutral baryons may be extracted from $\pi^-$ & $\pi^0$ photoproduction off neutron, which involves bound neutron target & needs use of model-dependent nuclear (FSI) corrections.


A.B. Migdal, JETP 1, 2 (1955); K.M. Watson, Phys Rev 95, 228 (1954)
**FSI for γd → πpN ↔ γn → πN**

**FSI plays critical role in state-of-the-art analysis of γn→πN data.**

- For γn→πN, effect is 5% – 60%.
- It depends on (E, θ).

**Input:** SAI: γN→πN, πN→πN, NN→NN amplitudes for 3 leading terms.

**DWF:** full Bonn NN Potential

(there is no sensitivity to DWF).

\[
R = \frac{d\sigma}{d\Omega_{\pi p}} / \left( \frac{d\sigma^{IA}}{d\Omega_{\pi p}} \right)
\]

\[
\frac{d\sigma}{d\Omega} (\gamma n) = R^{-1} \frac{d\sigma}{d\Omega} (\gamma d)
\]
FSI for $\gamma d \rightarrow \pi^0 np$ $\rightarrow$ $\gamma n \rightarrow \pi^0 n$ & $\gamma p \rightarrow \pi^0 p$

$R = \frac{d\sigma/d\Omega_{\pi p}}{d\sigma^{IA}/d\Omega_{\pi p}}$

- $\gamma n \rightarrow \pi^0 n$ case is much more complicated vs. $\gamma n \rightarrow \pi^- p$ because $\pi^0$ can come from both $\gamma n$ & $\gamma p$ initial interactions.

- The corrections for both target nucleons are practically identical for $\pi^0$ production in energy range of $\Delta(1232)3/2^+$ due to isospin structure of $\gamma N \rightarrow \pi N$ amplitude:
  - isoscalar
  - isovector

  $A_s = 0$ or $A_v = 0$

  \[ R_n = R_p \]

- In general case, $R_n \neq R_p$

\[\Delta(1232)3/2^+\]
\[N(1440)1/2^+\]
\[N(1535)1/2^-\]
$g_{13}$ for $\gamma n \rightarrow \pi^- p$ above 0.5 GeV


$E = 445 - 2510$ MeV
$\pi^- p: 8428 \, d\sigma/d\Omega$

- These data a factor of nearly three increase in world statistics for this channel in this kinematic range.

FSI included
Comparison of Previous & New Fits for $g_{13}$

- Recent SAID PR15 applied to $g_{13}$ data without & with FSI corrections.
- New SAID MA27 fit obtained after adding new $g_{13}$ data with FSI corrections.

- Obviously, FSI plays important role in $\gamma n \rightarrow \pi^- p \frac{d\sigma}{d\Omega}$ determination.
- Same for $\gamma n \rightarrow \pi^0 n \frac{d\sigma}{d\Omega}$.

$g_{14}$ Data Impact for Neutron $S = 0$ & $I = \frac{1}{2}$ Couplings


$E = 730 - 2345$ MeV

$\pi^- p$: 266 $E$
**g13 Impact for Neutron**

\[ S = 0 \& I = \frac{1}{2} \] **Couplings**


- Selected photon decay amplitudes \( N^* \rightarrow \gamma n \) at resonance poles are determined for the first time.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Coupling</th>
<th><strong>MA27</strong> Moduli, Phase</th>
<th>GB12 [g10]</th>
<th>BG2013 [g10]</th>
<th>MAID2007</th>
<th>Capstick</th>
<th>PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1440)1/2^+</td>
<td>A_{1/2}(n)</td>
<td>0.065±0.005, 5°±3°</td>
<td>0.048±0.004</td>
<td>0.043±0.012</td>
<td>0.054</td>
<td>-0.006</td>
<td>0.040±0.010</td>
</tr>
<tr>
<td>N(1535)1/2^-</td>
<td>A_{1/2}(n)</td>
<td>-0.055±0.005, 5°±2°</td>
<td>-0.058±0.006</td>
<td>-0.093±0.011</td>
<td>-0.051</td>
<td>-0.063</td>
<td>-0.075±0.020</td>
</tr>
<tr>
<td>N(1650)1/2^-</td>
<td>A_{1/2}(n)</td>
<td>0.014±0.002, -30°±10°</td>
<td>-0.040±0.010</td>
<td>0.025±0.020</td>
<td>0.009</td>
<td>-0.035</td>
<td>-0.050±0.020</td>
</tr>
<tr>
<td>N(1720)3/2^-</td>
<td>A_{1/2}(n)</td>
<td>-0.016±0.006, 10°±5°</td>
<td>-0.080±0.050</td>
<td>-0.003</td>
<td>0.004</td>
<td>-0.080±0.050</td>
<td></td>
</tr>
<tr>
<td>N(1720)3/2^-</td>
<td>A_{3/2}(n)</td>
<td>0.017±0.005, 90°±10°</td>
<td>-0.140±0.065</td>
<td>-0.031</td>
<td>0.011</td>
<td>-0.140±0.065</td>
<td></td>
</tr>
</tbody>
</table>
Meson Production off Deuteron with CB @

- Differential cross sections for $\gamma n \rightarrow \pi^0 n$.

$E = 200 - 800$ MeV
$\pi^0 n$: 523 $d\sigma/d\Omega$

- $\pi^0 n$: 523 $d\sigma/d\Omega$

- Data up to $E = 1500$ MeV are coming.

- New $d\sigma/d\Omega$s by A2 contribution is 200% to previous world $\pi^0 n$ data.

- It couples weakly to neutron.

- It couples strongly to neutron.

M. Martemianov et al, in progress

PDG

$N(1680)5/2^+ \rightarrow N\gamma$
$pA^{3/2} = +133 \pm 12$  $pA^{1/2} = -15 \pm 6$
$nA^{3/2} = -33 \pm 9$  $nA^{1/2} = +29 \pm 10$

- New $d\sigma/d\Omega$s by A2 contribution is 200% to previous world $\pi^0 n$ data.
World Neutral & Charged Pion EPR Data


\( W < 2 \text{ GeV @ 2009} \)

\[ p\pi^0, n\pi^+, p\pi^- \]

- 85\% of them are CLAS data

\[ \begin{array}{c|c|c}
\text{reaction} & \text{data} & \chi^2 \\
\hline
\gamma^* p \rightarrow \pi^0 p & 55,766 & 81,284 \\
\gamma^* p \rightarrow \pi^+ n & 51,312 & 80,004 \\
\text{redundant} & 14,772 & 17,375 \\
\text{total} & 124,453 & 178,663 \\
\gamma p \rightarrow \pi N & 24,888 & 50,684 \\
\text{all photo} & 159,341 & 229,317 \\
\pi N \rightarrow \pi N & 31,876 & 57,255 \\
\text{all } \pi N & 191,217 & 286,572 \\
\end{array} \]

- Problem 1: 18 new Multipoles. [Parameterization as \( E, M \)]
- Problem 2: \( Q^2 \) dependence.

New CLAS data are coming soon.

Pion PhotoProduction

4/8/2019

8th GHP Workshop, Denver, Colorado, April 2019

Igor Strakovsky 18
• **Inverse Pion Electroproduction** is only process which allows determination of EM nucleon & pion form factors in intervals:

\[
0 < k^2 < 4 M^2 \quad \text{and} \quad 0 < k^2 < 4 m_\pi^2
\]

which are kinematically **unattainable** from \(e^+e^-\) initial states.

\[\pi^- p \rightarrow e^+ e^- n\] measurements will significantly complement current electroproduction.

\[\gamma^* N \rightarrow \pi N\] study for evolution of baryon properties with increasing momentum transfer by investigation of case for **time-like virtual photon**.
Hall A Results for $\Lambda(1520)$

- $e + p \rightarrow e' + K^+ (\pi^+, K^-) + MM$ [Hall A: $E = 5.09$ GeV $Q^2 \sim 0.1$ (GeV/c)$^2$  Statistics = 13k]
- In fitting, we applied MM resolution, $\sigma = 1.5$ MeV
- We did not take into account any Res with $M > 1670$ MeV

**BW with Least-Squares & Log-Likelihood**

$M = 1520.4 \pm 0.6 \pm 1.0$ MeV
$\Gamma = 18.6 \pm 1.9 \pm 1.0$ MeV

**Pole position**

$M = 1518.3$ MeV
$\Gamma = 17.2$ MeV

- Having BW mass & width, we also give first estimate of pole parameters for $\Lambda(1520)$.
- Pole values for both mass & width tend to be lower than BW values.
Cross Section Estimations for (RGA)

**Andrey Afanasev:**
Translation hadronic into EM Xsec:
- SLAC $K^-p \rightarrow \Xi^- X$ Xsec,
- $\phi$-VMD,
- CLAS $\gamma p \rightarrow \Xi^- KK$ Xsec
  $\sigma \sim 0.4$ nb

- SLAC $K^-p \rightarrow \Xi^- X$,
- $K^-p \rightarrow \Omega^- X$ Xsec,
- CLAS $\gamma p \rightarrow \Xi^- KK$ Xsec
  $\sigma \sim 0.5$ nb

**Vitaly Shklyar:**
Effective Lagrangian:
There are three additional diagrams obtained by permutations of final Kaon momenta
$\sigma \sim 2$ nb

**Winston Roberts:**
Phenomenological Lagrangian:
- Not all couplings known
- Born terms are in
  $\sigma \sim 0.2–1$ nb


**Alternative Xsec estimation**
recently, it resulted in $\sim 1$ pb.

Why We Have to Measure Double-Strange Cascades in 

- Heavy quark symmetry (Isgur–Wise symmetry) suggests that multiplet splittings in strange, charm, & bottom hyperons should scale as approximately inverses of corresponding quark masses:
  \[ \frac{1}{m_s} : \frac{1}{m_c} : \frac{1}{m_b} \]

- If they don’t, that scaling failure implies that structures of corresponding states are anomalous, & very different from one another.

- So far only hyperon resonance multiplet, where this scaling can be ``tested” & seen is lowest negative parity multiplet:
  \[ \Lambda(1405)1/2^- \rightarrow \Lambda(1520)3/2^-, \ \Lambda_c(2595)1/2^- \rightarrow \Lambda_c(2625)3/2^-, \ \Lambda_b(5912)1/2^- \rightarrow \Lambda_b(5920)3/2^- \]

- It works approximately (30%) well for those Λ-splitting. It would work even better for Ξ, Ξ_c, Ξ_b splittings, & should be very good for Ω, Ω_c, Ω_b splittings.

- **Jefferson Lab** can do double cascade spectrum. As is doing double charm cascade spectrum.
  \[ \Xi_c(2790)1/2^- \rightarrow \Xi_c(2815)3/2^- \]


See Moskov Amaryan’s talk
It is clear that we still need much more information about the existence and parameters of many baryon states, especially in the $N=2$ mass region, before this question of non-minimal SU(6) x O(3) super-multiplet can be settled. Richard Dalitz, 1976.

The first problem is the notion of a resonance is not well defined. The ideal case is a narrow resonance far away from the thresholds, superimposed on slowly varying background. It can be described by a Breit-Wigner formula and is characterized by a pole in the analytic continuation of the partial wave amplitude into the low half of energy plane. Gerhard Höhler, 1987.

Why $N^*$s are important – The first is that nucleons are the stuff of which our world is made. My second reason is that they are simplest system in which the quintessentially non-Abelian character of QCD is manifest. The third reason is that history has taught us that, while relatively simple, Baryons are sufficiently complex to reveal physics hidden from us in the mesons. Nathan Isgur, 2000.
Thank you for invitation & your attention
First Baryon Resonance Discovery

**Total Cross Sections of Positive Pions in Hydrogen**

H. L. Anderson, E. Fermi, E. A. Long,† and D. E. Nagle

Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 21, 1952)

![Image of a scientific graph showing cross sections of pion interactions](image)

- **π⁺p → π⁺p**
- **π⁻p → π⁻p**
- **Δ(1232)3/2⁺**

**Notes:**
- Then, since 1952 many states were discovered.
- Charged Pions were discovered in 1947.
There are Many Ways to Study $N^*$

Prolific source of $N^*$ & $\Delta^*$ baryons

Measure many channels with different combinations of quantum numbers.

- $\pi N \rightarrow \pi N$, $\pi \pi N$, ...
- $\gamma N \rightarrow \pi N$, $\pi \pi N$, ...
- $\gamma^* N \rightarrow \pi N$, $\pi \pi N$, ...
- $pp \rightarrow p\pi^0$, $pp\pi^\pi$, ...
- $J/\psi \rightarrow p\bar{p}\pi^0$, $p\bar{p}\pi^-$, ...

- Most of PDG info comes from these sources & PWA is main of them.
- $\pi N$ elastic scattering is highly constrained.
- Resonance structure is correlated.
- Two-body final state, fewer amplitudes.

$\text{CLAS}$
Double Polarized Measurements

• πN scattering data:

\[
\frac{d\sigma}{d\Omega} \quad \text{(unpolarized)}
\]
\[
P \quad \text{(polarized target or recoil nucleon)}
\]
\[
R \text{ and } A \quad \text{(polarized target and recoil measured)}
\]

Not Independent: \(P^2 + R^2 + A^2 = 1\)

• Old PWA solutions may be not able to reproduce New measurements.

Data:

- ITEP: \(\pi^+p \rightarrow \pi^+p\) @ 1300 MeV

PWA:

- KA84: Karlsruhe-Helsinki fit, 1984
- KB84: KH Barrelet corrected solution, 1997
- SP06: GW fit, 2006

• Polarized measurements would also be important part of hadron program.

\(\pi^+p: 1300\) MeV
**Forced Fit for Double-Polarization Measurements**

- For $\gamma p \rightarrow \pi^0 p$ at 1900 MeV

- SAID Forced Fit has weighted data by factor of $4 - 5$.
- By weighting data, we magnify changes in multipole amplitudes, & more clearly see where data conflicts occur.
- Forced Fit results indicate that what more measurements require for constraint solution.

- DNPL: $T$ measurements
  P.J. Bussey et al, Nucl Phys B 159, 383 (1979)

- JLab Hall A:
  There are 22 $C_x$ & 21 $C_z$ below 2 GeV

- That is not artifact as was possible to think a while ago!
- Hall A data do allow to reproduce previous $T$ measurements well.
MAMI-B for $\gamma n \rightarrow \pi^- p$ around $\Delta$


- MAMI-B data for $\gamma n \rightarrow \pi^- p$ (including FSI corrections) & previous hadronic data for $\pi^- p \rightarrow n \gamma$ appear to agree well.

Data:
- MAMI-B for $\gamma n \rightarrow \pi^- p$ sys=2%
- CB@BNL for $\pi^- p \rightarrow n \gamma$ sys=5%
- TRIUMF, CERN, LBL, LAMPF for $\pi^- p \rightarrow n \gamma$

$T$-invariance is good as $2 \times 10^{-3}$
$g_{13}$ for $\gamma n \to \pi^- p$

D. Sokhan et al, in progress


Assumption is FSI is small

Preliminary
**Forward Detector (FD)**
- TORUS magnet
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Pre-shower calorimeter
- E.M. calorimeter
- Forward Tagger
- RICH detector

**Central Detector (CD)**
- Solenoid magnet
- Silicon Vertex Tracker
- Central Time-of-Flight
- Central Neutron Detector
- MicroMegas

**Beamline**
- Diagnostics
- Shielding
- Targets
- Polarimeter
- Faraday Cup

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Number of readout channels > 100,000

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https://www.jlab.org/Hall-B/clas12-web/