Update on SAID

Bill Briscoe, Igor Strakovsky, Ron Workman
The George Washington University

- $\pi N$ 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.

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**Baryon Sector @ PDG**


- PDG18 has 109 Baryon Resonances (64 are 4* or 3*).
- In case of SU(6) X O(3), 434 states if all revealed multiplets were developed.

- First hyperon was discovered

- Pole position in complex energy plane for hyperons has been made only recently, first was \( \Lambda(1520)3/2^- \).

- Y. Qung et al, Phys Lett B 694, 123 (2010)
There are Many Ways to Study N*

Prolific source of N* & Δ* baryons

Measure many channels with different combinations of quantum numbers.

\[ \pi N \rightarrow \pi N, \pi \pi N, \ldots \]
\[ \gamma N \rightarrow \pi N, \pi \pi N, \ldots \]
\[ \gamma^* N \rightarrow \pi N, \pi \pi N, \ldots \]
\[ pp \rightarrow pp\pi^0, pp\pi\pi, \ldots \]
\[ J/\psi \rightarrow p\overline{p}\pi^0, p\overline{p}\pi^- \ldots \]

- Most of PDG info comes from these a PWA of these.
- \(\pi N\) elastic scattering is highly constrained.
- Resonance structure is highly correlated.
- Two-body final state, fewer amplitudes.
Most of our current knowledge about bound states of three light quarks has came mainly from \( \pi N \to \pi N \) PWAs:

- Karlsruhe–Helsinki,
- Carnegie–Mellon–Berkeley,
- GW & Kent State.

Main source of EM couplings is GW, MAID, BnGa, & JuBo analyses.

**Phenomenology for Baryons**

- **PWA** arose as a means to determine amplitudes by fitting scattering data.
- A **non-trivial mathematical problem** – looking for a **solution** to an **ill-posed** problem – Hadamard & Tikhonov.

- **Resonances** appeared as a **by-product**

**Standard PWA**

⇒ Reveals only **wide** Resonances, but not too wide (\( \Gamma < 500 \text{ MeV} \)) and possessing not too **small** BR (\( BR > 4\% \)).

⇒ Tends to **miss** narrow Res with \( \Gamma < 20 \text{ MeV} \).
Energy dependent SP06/WI08 and associated SES

- Energy dependent SP06/WI08 and associated SES
- $T = 0 - 2600$ MeV
- $W = 1078 - 2460$ 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 $[I=3/2]$

\[ \pi N \rightarrow \pi N \quad \pi^- p \rightarrow \eta n \]

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

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

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

10 data/MeV

Pol=28%

Pol=22%

Pol=11%
Recent for $\pi^- p \rightarrow \pi^- p$


- New precise cross section measurements:
  $\Delta \sigma = 0.5\%$ stat, $\Delta p = 1$ MeV, $\Delta \theta = \pm 1^\circ$

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

\[ \theta = 40^\circ \]
\[ \theta = 100^\circ \]
\[ \theta = 110^\circ \]

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

\[ \theta = 70^\circ \]
\[ \theta = 80^\circ \]
\[ \theta = 120^\circ \]

\[ d\sigma / d\Omega : \]
4277 MeV/c
800 – 1243 MeV/c
40 – 122 deg

\[ d\sigma / d\Omega : \]
2638 MeV/c
918 – 1240 MeV/c
40 – 122 deg

\[ I.\ Alekseev \ et\ al., \ Phys\ Rev\ C\ 91, \ 025205\ (2015) \]

- 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 not simple.

- **Resonances** found through search for Poles in complex plane and NOT put in by hand, contrary to BW parameterization.

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


- Data driven (model independent) analysis [No Adhoc resonances in]
- Energy dependent MA27
- \( E = 145 - 2700 \) MeV \( [W = 1080 - 2460] \) MeV
- PWs = 60 [EM multipoles] \( [J < 6] \)
- Prms = 210
- Constraint: Born [no free parameters to fit] \( \pi N\)-PWA [no theoretical input]

GW SAID PWA facility allows one

- To fit new data vs SAID Database.
- To calculate acceptance & flux for proposals and papers.
- To estimate systematics.
- To provide realistic event generator for MC simulations.

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

- Pion photoproduction on the neutron much less known, 35%.

\( \gamma p \rightarrow \pi^0 p \) \( 34,499 \) data

\( \gamma p \rightarrow \pi^+ n \) \( 8,959 \) data

\( \gamma n \rightarrow \pi^- p \) \( 11,950 \) data

\( \gamma n \rightarrow \pi^0 n \) \( 364 \) data

There is disbalance between \( \pi^0 \) & \( \pi^+ \) data 35%.
There is disbalance between $\pi^0p$ & $\pi^+n$ data, $\pi^+n/\pi^0p=20\%$.

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.

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

Longitudinally Polarized Nucleon Target
Transverse Polarized Nucleon Target

Nucleon Recoil Polarization
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 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 $\gamma d \rightarrow \pi pN \quad \Rightarrow \quad \gamma n \rightarrow \pi N$

V. Tarasov, A. Kudryavtsev, WJB, B. Krusche, I. Strakovsky, M. Ostrick, Phys At Nucl 79, 216 (2016)

- FSI plays critical role in state-of-the-art analysis of $\gamma n \rightarrow \pi N$ data.
- For $\gamma n \rightarrow \pi N$, effect is 5% – 60%. It depends on $(E, \theta)$.

Input: **SAID**: $\gamma N \rightarrow \pi N$, $\pi N \rightarrow \pi N$, $NN \rightarrow NN$
amplitudes for 3 leading terms.

**DWF**: full Bonn NN Potential
(there is no sensitivity to DWF).

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

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

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

- $\gamma n \rightarrow \pi^0 n$ 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
    - $A_s = 0$ or $A_v = 0$
  - isovector
    - $R_n = R_p$

$\gamma p \rightarrow \pi^0 p$ (solid curves)
$\gamma n \rightarrow \pi^0 n$ (dashed curves)

$\Delta(1232)3/2^+$

$N(1440)1/2^+$

$N(1535)1/2^-$

In general case, $R_n \neq R_p$
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.

\[ \begin{align*}
\text{Data:} & \\
\bullet & \text{MAMI-B for } \gamma n \rightarrow \pi^- p \quad \text{sys}=2\% \\
\triangle & \text{CB@BNL for } \pi^- p \rightarrow n\gamma \quad \text{sys}=5\% \\
o & \text{TRIUMF, CERN, LBL, LAMPF for } \pi^- p \rightarrow n\gamma
\end{align*} \]

- $T$-invariance is good as $2 \times 10^{-3}$

$g13$ 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.

\( \chi^2/\text{data} \)

\[ E_\gamma \text{ (GeV)} \]

- Obviously, FSI plays important role in \( \gamma n \to \pi^- p \; d\sigma/d\Omega \) determination.
- Same for \( \gamma n \to \pi^0 n \; d\sigma/d\Omega \).
**g14 Data Impact for Neutron**

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


\[ E = 730 - 2345 \ \text{MeV} \]

\[ \pi^- p: 266 \ E \]
**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.
\[ g_{13} \sum \text{ for } \vec{\gamma}n \rightarrow \pi^-p \]

D. Sokhan et al, in progress


Assumption is FSI is small
Meson Production off Deuteron with CBI

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

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

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

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

- It couples weakly to neutron.

N(1675)$5/2^- \rightarrow N\gamma$
- $pA^{3/2} = +20 \pm 5$
- $pA^{1/2} = +19 \pm 8$
- $nA^{3/2} = -85 \pm 10$
- $nA^{1/2} = -60 \pm 5$

- It couples strongly to neutron.

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 GeV @ 2009

81284

pπ^0

80004

nπ^+

801

pπ^-

New CLAS data are coming soon.

85% of them are class data

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

Pion PhotoProduction

reaction | data | χ^2
---------|------|-------
γ^* p → π^0 p     | 55,766 | 81,284
γ^* p → π^+ n    | 51,312 | 80,004
redundant         | 14,772 | 17,375
total              | 124,453| 178,663
γp → πN           | 24,888 | 50,684
all photo          | 159,341| 229,317
πN → πN           | 31,876 | 57,255
all πN             | 191,217| 286,572
**Form-Factor Measurements**

- **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

$\Lambda(1520)$

- 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.
CLAS12 Detector Systems

**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

Number of readout channels > 100,000

https://www.jlab.org/Hall-B/clas12-web/
Cross Section Estimations for (RGA)

- **Andrey Afanasev:**
  Translation hadronic into EM Xsec:
  - SLAC K^-p→Ξ^-X Xsec,
  - Φ-VMD,
  - CLAS γp→Ξ^-KK Xsec
  \[ \sigma \sim 400 \text{ pb} \]
  - CLAS γp→Ξ^-X Xsec,
  - K^-p→Ω^-X Xsec,
  - CLAS γp→Ξ^-KK Xsec
  \[ \sigma \sim 500 \text{ pb} \]

- **Vitaly Shklyar:**
  Effective Lagrangian:
  There are three additional diagrams obtained by permutations of final Kaon momenta
  \[ \sigma \sim 2000 \text{ pb} \]

- **Winston Roberts:**
  Phenomenological Lagrangian:
  - Not all couplings known
  - Born terms are in \[ \sigma \sim 200-1000 \text{ pb} \]

**E12-11-005a**
Exp sensitivity: 50 – 100 pb

No Ω-signal is seen

Expected KLF Measurements

<table>
<thead>
<tr>
<th>Resonance</th>
<th>20 days: M, Γ</th>
<th>100 days: M, Γ</th>
<th>PDG2018: M, Γ</th>
<th>LQCD: M</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma(1920),5/2^+$</td>
<td>1977±21±25 327±25±25</td>
<td>1923±10±10 321±10±10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Sigma(2030),7/2^+$</td>
<td>1981±30±30 350±80</td>
<td>1930±20±30 400±40</td>
<td>2030±10 180±30</td>
<td>2686 2709 2793 2806</td>
</tr>
</tbody>
</table>
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 the invitation and your attention