Progress in Neutron EM Couplings

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- Pion photoproduction.
- FSI for unpol $\gamma n \rightarrow \pi^- p$ and $\gamma n \rightarrow \pi^0 n$.
- **CLAS** and **A2** for unpol $\gamma n \rightarrow \pi^- p$.
- Amplitudes and couplings.
- $\gamma n \rightarrow \pi^- p$ coming from **CLAS** and **MAX-lab** with $\gamma n \rightarrow \pi^0 n$ coming from **A2** and **ELPH**.
- **GRAAL** for polarized $\gamma n \rightarrow \pi^- p$ and $\gamma n \rightarrow \pi^0 n$.
- Coming polarized data.
- Summary.

Thank you:
Bill Briscoe
Sasha Kudryavtsev
Slava Kulikov
Maxim Martemianov
Vladimir Tarasov
Ron Workman
Only with good data on both the proton and neutron targets, one can hope to disentangle the isoscalar & isovector EM couplings of various $N^*$ and $\Delta^*$ resonances.
Many of $\gamma n \rightarrow \pi^- p$ data are old bremsstrahlung measurements with limited angular ($\theta = 40 - 140^\circ$) coverage and large energy binning ($E_\gamma = 100 - 200$ MeV). In several cases, the systematic uncertainties have not been given.

The existing $\gamma n \rightarrow \pi^- p$ database contains mainly differential cross sections (15% of which are from polarized measurements.)

At lower energies ($E_\gamma < 700$ MeV,) there are data sets for the inverse $\pi^-$ photoproduction reaction: $\pi^- p \rightarrow \gamma n$. This process is free from complications associated with a deuteron target.

However, the disadvantage of using $\pi^- p \rightarrow \gamma n$ is the large background because of the 5 to 500 times larger cross section for $\pi^- p \rightarrow \pi^0 n \rightarrow \gamma \gamma n$ and there were no ``tagging'' high flux pion beams ($\Delta p/p=6\%$).

$\gamma n \rightarrow \pi^0 n$ measurement is a small fraction of $\gamma n \rightarrow \pi N$ database.
The existing $\gamma n \rightarrow \pi^- p$ data contains mainly differential cross sections, 15% of which are from polarized measurements.

Future experiments will fill empty spots specifically for n-target which is 15% of p-target measurements.

Meson Factories

$\gamma p \rightarrow p\pi^0$

$\gamma p \rightarrow n\pi^+$

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

$\gamma n \rightarrow n\pi^0$

W < 2.5 GeV

SAID: http://gwdac.phys.gwu.edu/
Pion Photoproduction: Phenomenological Point of View

I'm creating an imaginary world in which I would like to live.

William Burroughs
In particle physics, helicity is the projection of the spin $\vec{s}$ onto the direction of momentum, $\hat{p}$:

$$h = \vec{J} \cdot \hat{p} = \vec{L} \cdot \hat{p} + \vec{S} \cdot \hat{p} = \vec{S} \cdot \hat{p}$$

$$\hat{p} = \frac{\vec{p}}{|\vec{p}|}$$

Therefore, there are 4 independent invariant amplitudes.

In order to determine the pion photoproduction amplitude [4 modules and 3 relative phases], one has to carry out 7 independent measurements at fixed $(W, t)$ or $(E_γ, θ)$.

This extra observable is necessary to eliminate a sign ambiguity.
Complete Experiment in Pion PhotoProduction

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

Linear Polarized Beam
Circular Polarized Beam

Longitudinallly Polarized Nucleon Target
Transverse Polarized Nucleon Target

\[ \gamma \rightarrow \bar{N} \rightarrow \bar{N} \pi \]

1 un-pol measurement: \( \frac{d\sigma}{d\Omega} \)
3 single pol measurements: \( \Sigma, T, P \)
12 double pol measurements: \( E, F, G, H, Cx, Cz, Ox, Oz, Lx, Lz, Tx, Tz \)
18 triple polarization asymmetries
[9 for linear pol beam]
[9 for circular pol beam]
13 of them are non-vanishing

Q: Can we avoid? A: NO!

K. Nakayama, private communication, 2014.
Single Pion PhotoProduction on Neutron Target

- An accurate evaluation of the EM couplings $N^* \rightarrow \gamma N$ and $\Delta^* \rightarrow \gamma N$ from meson photoproduction data remains a paramount task in hadron physics.

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

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

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


A.B. Migdal, JETP 1, 2 (1955); K.M. Watson, Phys Rev 95, 228 (1954)
The Importance of the Neutron

- EM interaction do not conserve **isospin**, so multipole amplitudes contain **isoscalar** and **isovector** contributions of EM current.

- **Proton** data alone does not allow separation of **isoscalar**, $A^{(0)}$, and **isovector**, $A^{(1)}$, components.

  - **Need data** on both **proton** and **neutron**!

- **Q: Can we avoid?**  **A: NO!**
### Uncertainties for $A_{1/2}$ & $A_{3/2}$ Decay Amplitudes

**Neutron** coupling quality are generally as **bad** or **worse** than **proton** one.

<table>
<thead>
<tr>
<th>$N^* \rightarrow N\gamma$</th>
<th>$\delta A_{1/2}(p)$</th>
<th>$\delta A_{1/2}(n)$</th>
<th>$\delta A_{3/2}(p)$</th>
<th>$\delta A_{3/2}(n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1440)1/2+</td>
<td>0.07</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N(1520)3/2−</td>
<td>0.38</td>
<td>0.15</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>N(1535)1/2−</td>
<td>0.33</td>
<td>0.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N(1650)1/2−</td>
<td>0.30</td>
<td>1.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N(1675)5/2−</td>
<td>0.42</td>
<td>0.28</td>
<td>0.60</td>
<td>0.22</td>
</tr>
<tr>
<td>N(1680)5/2+</td>
<td>0.40</td>
<td>0.35</td>
<td>0.09</td>
<td>0.27</td>
</tr>
<tr>
<td>N(1720)3/2+</td>
<td>1.20</td>
<td>3.75</td>
<td>1.05</td>
<td>3.00</td>
</tr>
</tbody>
</table>

One of reasons of that is simple – the **neutron** database is much less than **proton**.
Previous neutron measurements used a modified Glauber approach and the procedure of unfolding the Fermi motion of the `neutron’ target.
FSI and $\gamma d \rightarrow \pi pN \rightarrow \gamma n \rightarrow \pi N$

[V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C 84, 035203 (2011)]

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

**Input:** SAI[D]: $\gamma N \rightarrow \pi N$, $\pi N \rightarrow \pi N$, $NN \rightarrow NN$
amplitudes for 3 leading terms.

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

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

$\frac{d\sigma}{d\Omega} (\gamma n) = R^{-1} \frac{d\sigma}{d\Omega} (\gamma d)$
FSI for $\gamma d \rightarrow \pi pp \rightarrow \gamma n \rightarrow \pi^+ p$

[V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C 84, 035203 (2011)]

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

Cuts:
$p_s > 200 \text{ MeV/c}$
$p_f > 200 \text{ MeV/c}$

CLAS data:
$E > 1 \text{ GeV}$
$\theta > 32 \text{ deg}$

- There is no large sensitivity to cuts.

- Our estimation of the Glauber FSI corrections gives the value of 5%.

- Previous estimations gave the order of 15-30%.

- For CLAS data
  - The FSI correction factor $R < 1$.
  - The behavior is smooth vs. $\theta$.
  - The effect $\Delta \sigma/\sigma \leq 10\%$.

- There is a sizeable FSI effect from S-wave part of $pp$-FSI at small angles.

- This region narrows as the $E_\gamma$ increases.

Hadron 2015, Newport News, VA, Sept 2015
FSI for $\gamma d \rightarrow \pi^0 np \rightarrow \gamma n \rightarrow \pi^0 n$


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

- The corrections for both target nucleons are practically identical for $\pi^0$ production in the energy range of the $\Delta(1232)_{3/2}^+$.

- In general, $R_n \neq R_p$.
CLAS & MAMI-B

for $\gamma n \rightarrow \pi^- p$
**CLAS for γn→π−p above 1 GeV**


- The **CLAS** g10 cross sections have quadrupled the world database for γn→π−p above \( E_\gamma = 1 \) GeV.

**Systematics:**
- Exp: 6-9%
- FSI: 2-3%

\[
\chi^2/d\nu = 45636/626 = 72.9 \quad \text{[SN11 – no fit]}
\]
\[
\chi^2/d\nu = 1580/626 = 2.5 \quad \text{[GB12 – fit]}
\]

- The **CLAS** data appear to have fewer angular structures than the earlier fits.

**SAID-GB12**
**SAID-SN11**
**MAID07**
MAMI-B for $\gamma n \rightarrow \pi^- p$ around the $\Delta$

[W.J. Briscoe et al, Phys Rev C 86, 065207 (2012)]

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

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

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

Amplitudes & Couplings
**Neutron Multipoles from SAID GB12 & SN11**

- **Overall**: the difference between MAID07 with BnGa13 and SAID GB12 is rather small but... Resonances may be essentially different.

- Significant changes have occurred at high energies.
- Comparisons to earlier SAID and fits from the Mainz and BnGa groups show that the new GB12 solution is much more satisfactory at higher energies.

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<table>
<thead>
<tr>
<th>Multipole</th>
<th>SAID GB12</th>
<th>SAID SN11</th>
<th>MAID07</th>
<th>BnGa13</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{11}$</td>
<td>$A_{1/2} = -58 \pm 6$ [−51−93±11]</td>
<td>$A_{1/2} = -40 \pm 10$ [9 25±20]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_{13}$</td>
<td>$A_{1/2} = -46 \pm 6$ [−77−49±8]</td>
<td>$A_{1/2} = -115 \pm 5$ [−154−113±12]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{11}$</td>
<td>$A_{1/2} = 48 ± 4$ [54 43±12]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{15}$</td>
<td>$A_{1/2} = 26 ± 4$ [28 34±6]</td>
<td>$A_{3/2} = -29 ± 2$ [−38−44±9]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


**CLAS Impact for Neutral \( S = 0 \) \& \( I = \frac{1}{2} \) Couplings**

[W. Chen et al, Phys Rev C 86, 015206 (2012)]

- BnGa13 and SAID GB12 used the same (almost) data to fit them while BnGa13 has several new *Ad hoc* resonances.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>( nA_{1/2} )</th>
<th>Resonance</th>
<th>( nA_{1/2} )</th>
<th>( nA_{3/2} )</th>
<th>Ref.</th>
<th>([(\text{GeV})^{-1/2} \times 10^{-3}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N(1535)1/2^- )</td>
<td>-58±6</td>
<td>( N(1520)3/2^- )</td>
<td>-46±6</td>
<td>-115±5</td>
<td>SAID GB12 [17]</td>
<td>12.21, 12.22, 12.23</td>
</tr>
<tr>
<td>( S_{11} )</td>
<td>-60±3</td>
<td>( D_{13} )</td>
<td>-47±2</td>
<td>-125±2</td>
<td>SAID SN11 [25]</td>
<td>12.21, 12.22, 12.23</td>
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<tr>
<td></td>
<td>-93±11</td>
<td></td>
<td>-49±8</td>
<td>-113±12</td>
<td>BnGa13 [26]</td>
<td>12.21, 12.22, 12.23</td>
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<tr>
<td>( S_{11} )</td>
<td>-46±27</td>
<td>( F_{15} )</td>
<td>-59±9</td>
<td>-139±11</td>
<td>[PDG14]</td>
<td>12.21, 12.22, 12.23</td>
</tr>
<tr>
<td>( -35 )</td>
<td>-26±8</td>
<td></td>
<td>-58±2</td>
<td>-80±5</td>
<td>[PDG14]</td>
<td>12.21, 12.22, 12.23</td>
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<tr>
<td>( N(1650)1/2^- )</td>
<td>-40±16</td>
<td>( N(1675)5/2^- )</td>
<td>-42±2</td>
<td>-60±2</td>
<td>[PDG14]</td>
<td>12.21, 12.22, 12.23</td>
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<tr>
<td>( S_{11} )</td>
<td>25±20</td>
<td>( N(1675)5/2^- )</td>
<td>-40±7</td>
<td>-88±10</td>
<td>[PDG14]</td>
<td>12.21, 12.22, 12.23</td>
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<tr>
<td></td>
<td>11±2</td>
<td>( N(1680)5/2^+ )</td>
<td>-40±4</td>
<td>-68±4</td>
<td>[PDG14]</td>
<td>12.21, 12.22, 12.23</td>
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<tr>
<td>( -35 )</td>
<td>-15±21</td>
<td>( N(1680)5/2^+ )</td>
<td>-43±12</td>
<td>-58±13</td>
<td>[PDG14]</td>
<td>12.21, 12.22, 12.23</td>
</tr>
<tr>
<td>( P_{11} )</td>
<td>48±4</td>
<td>( N(1680)5/2^+ )</td>
<td>26±4</td>
<td>-29±2</td>
<td>[PDG14]</td>
<td>12.21, 12.22, 12.23</td>
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<tr>
<td></td>
<td>45±15</td>
<td></td>
<td>50±4</td>
<td>-47±2</td>
<td>[PDG14]</td>
<td>12.21, 12.22, 12.23</td>
</tr>
<tr>
<td>( P_{11} )</td>
<td>43±12</td>
<td></td>
<td>34±6</td>
<td>-44±9</td>
<td>[PDG14]</td>
<td>12.21, 12.22, 12.23</td>
</tr>
<tr>
<td></td>
<td>40±5</td>
<td></td>
<td>29±2</td>
<td>-59±2</td>
<td>[PDG14]</td>
<td>12.21, 12.22, 12.23</td>
</tr>
<tr>
<td>( P_{11} )</td>
<td>40±10</td>
<td></td>
<td>29±10</td>
<td>-33±9</td>
<td>[PDG14]</td>
<td>12.21, 12.22, 12.23</td>
</tr>
</tbody>
</table>

- Recent GB12 \( nA_{1/2} \) & \( nA_{3/2} \) couplings shown sometimes a significant deviation from our previous SAID determination (SN11) and PDG14 average values, e.g., for \( N(1650)1/2^- \), \( N(1675)5/2^- \), and \( N(1680)5/2^+ \).

- Recent BnGa13 has some difference vs. GB12, PDG12, and the relativized quark model, e.g., for \( N(1650)1/2^- \), \( N(1650)1/2^- \), and \( N(1680)5/2^+ \).
• The differential cross section for the processes $\gamma n \rightarrow \pi^- p$ was extracted from recent CLAS and MAMI-B measurements accounting for Fermi motion effects in the IA as well as NN- and $\pi N$-FSI effects beyond the IA.

• Consequential calculations of the FSI corrections, as developed by the GW-ITEP Collaboration, was applied.

• New cross sections departed significantly from our predictions, at the higher energies, and greatly modified the fit result.

• New $\gamma n \rightarrow \pi^- p$ and $\gamma n \rightarrow \pi^0 n$ data will provide a critical constraint on the determination of the multipoles and couplings of low-lying baryon resonances using the PWA and coupled channel techniques.

• Polarized measurements from JLab/JLab12, A2, LEPS/LEPS2, ELSA, and ELPH will help to bring more physics in.

• FSI corrections need to apply.
Thank you for the invitation and your attention.
Work in Progress
More CLAS for $\gamma n \rightarrow \pi^- p$ above 0.4 GeV

$\gamma d \rightarrow p \pi^-(p)$ Cross Section

* CLAS g13: Preliminary, high statistics: $\sim$300 million events in $\sim$9000 bins:
  * 10- & 20-MeV-wide bins from 0.395 < $E_\gamma$ (GeV) < 2.51
  * Significant increase in statistics: CLAS g10 had $\sim$3000 bins

No FSI included for both g13 and g10

Legend
Black: CLAS g13
Red: CLAS g10
Blue: SAID CM12

Courtesy of Paul Mattione
MAX-lab for $\gamma n \rightarrow \pi^- p$ at Threshold

It is a difficult task to measure $\pi^- p$ final state close to the threshold.

We measured $\pi^0$ decay in to $2\gamma$ from $\gamma n \rightarrow \pi^- p \rightarrow \pi^0 n$.

Max-lab photon detectors:
- 3 of the largest (single-crystal) NaI(Tl) detectors ever built
  - BUNI (Boston University, USA)
  - CATS (University of Mainz, Germany)
  - DIANA (University of Kentucky, USA)
- at $E_\gamma \sim 130$ MeV (endpoint is 131.4 MeV)
- $\Delta E_\gamma / E_\gamma \sim 2\%$
- $\varepsilon_\gamma \sim 98\%$
- $\Delta \Omega \sim 40$ msr

Projected results:
- MAID07, FA07 TRIUMF data
- 2.1% stat, 7.1% syst
- 32 x 650 keV bins

DIANA
CATS
BUNI

Courtesy of Kevin Fissum
Meson Production off the Deuteron at CB@MAMI

[Spokespersons: W. Briscoe, IS, MAMI-A2-02/12; W. Briscoe, V. Kulikov, K. Livingstone, IS, MAMI-A2-02/13]

- New A2 data will provide a critical constraint on the determination of multipoles and EM couplings of low-laying baryon resonances using the PWA techniques developed by the SAID group.

![Total Cross Section of γn→π0n](image)

- For dσ/dΩ:
  \[ W = 1105 - 1545 \text{ MeV}, \quad \Delta W \sim 10 \text{ MeV}, \quad n_W = 31 \]
  \[ E_\gamma = 180 - 800 \text{ MeV}, \quad \Delta E_\gamma \sim 20 \text{ MeV} \]
  \[-0.9 \leq \cos(\theta) \leq +1, \quad \Delta \cos(\theta) = 0.01, \quad n_{\cos \theta} = 19 \]

Relative error of our measurement has a level of 1.5 – 3 %.

- Comparison of our A2 exp data with MAID07 predictions gives more reasonable agreement vs. SAID CM12, especially at higher energies.

- New 589 dσ/dΩs by the A2 contribution is 160% to the previous world π⁰n database.
Exclusive Analysis for $\gamma N' \rightarrow \eta N$, $\gamma N' \rightarrow \pi^0 N$

Differential and total cross sections for $\gamma N' \rightarrow \pi^0 N$

Proton and neutron cross sections for 1200 MeV and 930 MeV.

No FSI included.

Ishikawa, 05 Nov. 2013
Polarized Measurements

for $\gamma n \rightarrow \pi^0 p$ & for $\gamma n \rightarrow \pi p$

Situation is more complicate. We have no FSI tool yet.
Recent GRAAL $\sum$ for $\gamma n \rightarrow \pi^0 n$


- The difference between previous Pion Prod and new GRAAL measurements result in significant changes in the neutron couplings.

GRAAL data are in Hadron 2015, Newport News, VA, Sept 2015

- 216 GRAAL $\sum$s are 60% of the World $\pi^0 n$ data

$\chi^2/dp$
- MAID07: 100
- SP09: 223
- MAID09: 3.1

No FSI included
Recent GRAAL data are in

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

Previous $\gamma n \rightarrow \pi^- p$ measurements provided a better constraint vs. $\gamma n \rightarrow \pi^0 n$ case.

- $\chi^2/dp$
  - MA09: 4.9
  - SP09: 89
  - MA09: 27

No FSI included

GRAAL data are in

MA09
SP09
MAID07
DTM
\[ \Sigma \text{ for } \gamma n \rightarrow p \pi^- \]

\begin{align*}
\text{CLAS} & \quad \cos \theta = 0.34 \\
\text{GRAAL} & \quad \cos \theta = 0.62 \\
\text{SAID CM12} & \quad \cos \theta = 0.50 \\
\text{W (MeV)} & \quad \cos \theta = 0.78 \\
\text{W (MeV)} & \quad \cos \theta = 0.90 \\
\end{align*}

\[ \text{Courtesy of Daria Sokhan} \]

\[ \text{D. Sokhan} \]

\[ \text{No FSI included} \]

\[ \chi^2/dp = 2.6 \]

\[ \text{SAID can fit CLAS } \Sigma \text{s with } \chi^2/dp = 2.6 \]
Beam-Target Helicity asymmetry $E(\pi^+p)$ - T. Kageya (Jlab)

$E(\pi^+p) = \frac{\bar{Y}_c \bar{n}(p) - Y_c n(p)}{\bar{Y}_c \bar{n}(p) + Y_c n(p)}$

SAID[CM12]  
BoGa[2011-02]

No FSI included

Σ & G data are coming

Courtesy of Andy Sandorfi