Deuteron as an Effective Neutron Target

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- Single Pion PhotoProd
- Proton Multipoles
- FSI for $\gamma n \rightarrow \pi^- p$
- CLAS $\gamma n \rightarrow \pi^- p$ data for PWA
- Neutron Multipoles
- Polarized Measurements
- Summary & Prospects
Phenomenology for non-strange Resonances
For $\pi \rightarrow 2\pi$, we use log-likelihood while for the rest – least-squares technologies.
\[ N^* \text{ and } \Delta^* \text{ States coupled to } \pi N \]

- GW SAID N* program consists of \( \pi N \rightarrow \pi N \quad \gamma N \rightarrow \pi N \quad \gamma^* N \rightarrow \pi N \)
  As was established by Dick Arndt on 1997

- Assuming dominance of 2-hadronic channels \([\pi N \text{ elastic } \& \pi p \rightarrow \eta n]\), we parameterize \( \gamma^* N \rightarrow \pi N \) in terms of \( \pi N \rightarrow \pi N \) amplitudes

- **One** of the most convincing ways to study **Spectroscopy** of \( N^* \) & \( \Delta^* \) is \( \pi N \) PWA

- Non-strange objects in the PDG Listings come mainly from: Karlsruhe-Helsinki, Carnegie-Mellon-Berkeley, & GW/VPI
- The main source of EM couplings is the GW/VPI analysis

[SAID: http://gwdac.phys.gwu.edu/]
SAID for Pion Photoproduction


- 1st generation ('60-'90)
  - 10k data [85% bremsstrahlung data]
  - 30% data is polarized [limited coverage, broad energy binning]
- 2nd generation ('90-'10) \(\rightarrow\) SAID fits
  - 25k data [60% tagged data]
  - 30% data is polarized
  - Dearth of neutron data
- 3rd generation ('10+)
  - New data will come from JLab, MAMI-C, SPring-8, CB-ELSA, MAX-lab, & LNS

### Energy dependent GB12 and associated SES

- \(E = 145 \text{ - } 2700 \text{ MeV}\)
- \(W = 1080 \text{ - } 2460 \text{ MeV}\)
- \(PWs = 60 [E \text{ & } M \text{ multipoles}] [J < 6]\)
- \(Prms = 210\)
- Constraint: \(M = (\text{Born } + A)(1+iT_{\pi p}) + BT_{\pi p} + (C+iD)(\text{Im}T_{\pi p} - |T_{\pi p}|^2)\)

### Reaction Data (Dpol)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Data</th>
<th>(Dpol)</th>
<th>(\chi^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma p \rightarrow \pi^0 p)</td>
<td>14,612</td>
<td>(3 %)</td>
<td>32,449</td>
</tr>
<tr>
<td>(\gamma p \rightarrow \pi^+ n)</td>
<td>8,510</td>
<td>(5 %)</td>
<td>16,520</td>
</tr>
<tr>
<td>(\gamma n \rightarrow \pi^- p)</td>
<td>3,058</td>
<td>(0 %)</td>
<td>6,396</td>
</tr>
<tr>
<td>(\gamma n \rightarrow \pi^0 n)</td>
<td>364</td>
<td>(0 %)</td>
<td>1,201</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>26,554</td>
<td></td>
<td>56,566</td>
</tr>
</tbody>
</table>

- Born [no free parameters to fit]
- \(\pi N\)-PWA [no theoretical input]

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**Much less known, 15%**

23,122 data

3,422 data

\((\gamma, p)\)

\((\gamma, n)\)
Recent SAID results for Pion Photoproduction

[SAID: http://gwdac.phys.gwu.edu/]

GB12: included recent CLAS $\pi^- p$ d$\sigma$/d$\Omega$

CM12: CM parameterization for $T_{\pi N}$

SN11: included recent GRAAL $\pi^- p$ & $\pi^0 n$ $\Sigma$ LEPS $\pi^0 p$ d$\sigma$/d$\Omega$

$$M = (\text{Born} + A)(1 + iT_{\pi N}) + BT_{\pi N} + (C + iD)(\text{Im}T_{\pi N} - |T_{\pi N}|^2)$$

SP09: included recent CLAS $\pi^+ n$ d$\sigma$/d$\Omega$

$$M = (\text{Born} + \alpha_R)(1 + iT_{\pi N}) + \alpha_R T_{\pi N} + \text{higher terms}$$

<table>
<thead>
<tr>
<th>Solution</th>
<th>Energy Limit (MeV)</th>
<th>$\chi^2/N_{\text{Data}}$</th>
<th>$N_{\text{Data}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB12</td>
<td>2700</td>
<td>2.09</td>
<td>26,179</td>
</tr>
<tr>
<td>CM12</td>
<td>2700</td>
<td>2.01</td>
<td>25,814</td>
</tr>
<tr>
<td>SN11</td>
<td>2700</td>
<td>2.08</td>
<td>25,553</td>
</tr>
<tr>
<td>SP09</td>
<td>2700</td>
<td>2.05</td>
<td>24,912</td>
</tr>
<tr>
<td>FA06</td>
<td>3000</td>
<td>2.18</td>
<td>25,524</td>
</tr>
<tr>
<td>SM02</td>
<td>2000</td>
<td>2.01</td>
<td>17,571</td>
</tr>
<tr>
<td>SM95</td>
<td>2000</td>
<td>2.37</td>
<td>13,415</td>
</tr>
</tbody>
</table>

- The overall SAID $\chi^2$ has remained stable against the growing database, which has increased by a factor of 2 since 1995.
  [most of this increase coming from data from photon-tagging facilities].
Minimization and Normalization Factor for Pion Prod $[\chi^2/\text{Data}]$

- In fitting the data, the stated exp syst errs have been used as an overall norm adjustment factor for the angular distribution.

- Modified $\chi^2$ function, to be minimized:

  $$
  \chi^2 = \sum_i \left( \frac{X \theta_i - \theta^\text{exp}_i}{\epsilon_i} \right)^2 + \left( \frac{X - 1}{\epsilon_X} \right)^2
  $$

  [systematics plays important role]

- $\theta^\text{exp}_i$ measured, $\epsilon_i$ stat error, $\theta_i$ calculated, $X$ norm const, $\epsilon_X$ its error.

- Modified $\chi^2$ [Norm]
  Standard $\chi^2$ [UnNorm]

  - If the systematic uncertainty varies with angle
    - This procedure may be considered as a first approximation.

- Normalization freedom provides a significant improvement for our best fit results, we cannot ignore experimental input.

<table>
<thead>
<tr>
<th>$\chi^2$/Data</th>
<th>GB12</th>
<th>SM02</th>
<th>MAID07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction</td>
<td>Norm</td>
<td>UnNorm</td>
<td>Norm</td>
</tr>
<tr>
<td>$\gamma p \rightarrow \pi^0 p$</td>
<td>2.2</td>
<td>3.6</td>
<td>3.2</td>
</tr>
<tr>
<td>$\gamma p \rightarrow \pi^+ n$</td>
<td>1.9</td>
<td>3.4</td>
<td>2.1</td>
</tr>
<tr>
<td>$\gamma n \rightarrow \pi^- p$</td>
<td>2.1</td>
<td>6.5</td>
<td>1.8</td>
</tr>
<tr>
<td>$\gamma n \rightarrow \pi^0 n$</td>
<td>3.3</td>
<td>5.3</td>
<td>2.8</td>
</tr>
</tbody>
</table>

- MAID is valid below $W = 2$ GeV
- For MAID07, the normalization constants were searched to minimize $\chi^2$ (no adjustment of the partial waves was possible).
- MAID07 does not include recent CLAS $\pi^0 p$, $\pi^+ n$, & $\pi^- p$
  - LEPS $\pi^0 p$
  - GRAAL $\pi^- p$ & $\pi^0 n$ data

Proton Multipoles
**Proton Multipoles for CM12**


- **Overall**: the difference between MAID07 or BoGa and SAID-CM12 is rather small but...
  - Resonances may be essentially different

- Significant changes have occurred at high energies
- Comparisons to earlier SAID fits and fit from the Mainz & BoGa groups show that the new CM12 solution is much more satisfactory at higher energies

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**SN11**
- $S_{31} A_{1/2} = 29 \pm 3 [66]$

**CM12**
- $P_{11} A_{1/2} = -56 \pm 1 [-61]$

**MAID07**
- $S_{11} A_{1/2} = 128.4 \pm 4.0 [66]$
  - $A_{1/2} = 55 \pm 30 [33]$
- $P_{33} A_{1/2} = -139 \pm 2 [-140]$
  - $A_{3/2} = -262 \pm 3 [-265]$

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**Subjective variables for SES are**
- Energy binning
- Strength of constraints
- Which PW to be searched

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

The radiative decay width of the neutral baryons may be extracted from π− & π0 photoproduction off a neutron, which involves a bound neutron target and requires the use of a model-dependent nuclear corrections.

The lack of γn→π−p & γn→π0n data does not allow us to be as confident about the determination of neutron couplings relative to those of the proton.
The existing $\gamma n \rightarrow \pi p$ database contains mainly differential cross sections (17% of which are from polarized measurements).

Many of these are old bremsstrahlung measurements with limited angular coverages and large energy binnings (100 - 200 MeV). In several cases, the systematic uncertainties have not been given.

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 5 to 500 times larger cross section for $\pi^- p \rightarrow \pi^0 n \rightarrow \gamma \gamma n$.

The CLAS cross section set has quadrupled the world database for $\gamma n \rightarrow \pi p$ above 1 GeV.
Some of the N* baryons [**N(1675)5/2−**, for instance] have stronger EM couplings to the neutron than to the proton but parameters are very uncertain.

**PDG** estimate for the A1/2 & A3/2 decay amplitudes of the **N(1720)3/2+** state are consistent with zero, while the recent **SAID** determination gives small but non-vanishing values.

**Other unresolved issues** relate to the second P11, **N(1710)1/2+**, that are not seen in the recent πN PWA, contrary to other PWAs used by the **PDG10**.

Most of the results published before 1975 were last included in our 1982 edition, Physics Letters **111B** 1 (1982). Some further obsolete results published before 1984 were last included in our 2006 edition, Journal of Physics, G **33** 1 (2006).

The latest GWU analysis (ARNDT 06) finds no evidence for this resonance.
Final-State Interaction
FSI and $\gamma d \rightarrow \pi^- p p \rightarrow \gamma n \rightarrow \pi^- p$

[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
- Effect: 5% - 60%

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

**DWF:** CD-Bonn

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

Fermi motion of nucleons included
\[ \gamma d \rightarrow \pi^- p p \]

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

No fit to the data

\[ \theta(\pi^-LS) \]

DESY [Bubble Chamber data]: P. Benz et al Nucl Phys B65, 158 (1973)
**FSI for CLAS γ n → π p**

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

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

**Cuts:**
- \( p_s > 200 \text{ MeV/c} \)
- \( p_f > 200 \text{ MeV/c} \)

**CLAS data:**
- \( E > 1 \text{ GeV} \)
- \( \theta > 32 \text{ deg} \)

- For CLAS data
  - The FSI correction factor \( R < 1 \)
  - The effect \((1 - R) < 10\%\)
  - The behavior is smooth vs. \( \theta \)

- Our estimation of the Glaber FSI corrections gives the value of \( 5\% \). Previous estimations gave the order of \( 15\%-30\% \).

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

- This region narrows as the \( E_\gamma \) increases.

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\[ \frac{[IA + NN_{\text{fsi}}]}{IA} \]
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\[ \frac{[IA + (NN + \pi N)_{\text{fsi}}]}{IA} \]
FSI for CLAS Data
CLAS data vs. previous Brem Measurements


- Principal $\pi^-$ experiments below 1 GeV were done at Meson Factories: LAMPF, TRIUMF, & PSI

- Previous measurements used a modified Glauber approach and the procedure of unfolding the Fermi motion of the neutron target.

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5/23/2012

Hall-B/ Physics Analysis Center Meeting, Newport News, VA, May 2012

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CLAS g10 for $\gamma n \to \pi^- p$


CLAS data appear to have fewer angular structures than the earlier fits

$\chi^2/\text{d}p = 45636/626 = 72.9$ [SN11 – no fit]

$\chi^2/\text{d}p = 1580/626 = 2.5$ [GB12 - fit]
Neutron Multipoles
**Neutron Multipoles for GB12**


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

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

CLAS g13 Data
More CLAS for $\gamma n \rightarrow \pi^- p$

[g13: P. Mattione, et al, in progress]

- Complementary measurements of $\pi^-$ Photo Prod, required for an isospin decomposition of the multipoles

- G13 vs. g10:
  - broad angular coverage
  - smaller errors

- No FSI included in both CLAS
  - g10 [50 – 100 MeV binning]
  - g13 data [2% statistics in 200 MeV binning]

[Courtesy of Paul Mattione, CLAS Meeting 2010]
MAX-lab for the Threshold
\[ \gamma n \rightarrow \pi^- p \] at Threshold

- New MAX-lab data will provide a constraint for PWA

\[ \sigma (\mu b) \] vs. \[ E (MeV) \]

\[ \frac{d\sigma}{d\theta} (\mu b/\text{sr}) \] vs. \[ \theta (\text{deg}) \]

- TRIUMF95
- SAID07
- MAID07

Stat: 2%
Syst: 7%

- \( E_{0+}(\pi^- p) \) determined on the base of these prlm TRIUMF data is off by more than 3 standard deviations while SAID has no problem with these data vs. world database.
Polarized Measurements
Complete Experiment in Pion Photo Production

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

Linear Polarized Beam

Circular Polarized Beam

Nucleon Recoil Polarization

Longitudinally Polarized Nucleon Target

Transverse Polarized Nucleon Target

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Direct Amplitude Reconstruction in Pion Photo Production

\[ \gamma \, N \rightarrow N \, \pi \]

\begin{align*}
\text{spin: } & 1 \quad \frac{1}{2} \rightarrow \frac{1}{2} \quad 0 \\
\text{helicities: } & 2 \times 2 \times 2 / 2 = 4 \\
\text{parity conservation} &
\end{align*}

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

\[ \boxed{\text{• In order to determine the pion photo production amplitude, one has to carry out 7 independent measurements at fixed (} W, t \text{) or (} E, \theta \text{)}} \]

This extra observable is necessary to eliminate a sign ambiguity
**World Neutral and Charged Pion Photo Prod Data**

JLab has a good chance to file empty spots specifically for n-target

Neutron data / Proton data = 2793/23212 = 0.12

UnP/P=10652/3987  148/216  5752/2821  1931/498

JLab has a good chance to file empty spots specifically for n-target
Recent GRAAL $\Sigma$ for $\gamma n \rightarrow \pi^0 n$


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

![Graph showing $\gamma n \rightarrow \pi^0 n$ data with various models and significance levels.]

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

\[\chi^2/\text{dp}\]

- MAID07: 100
- SP09: 223
- MA09: 3.1

No FSI included

GRAAL data are in Hall-B/Physics Analysis Center Meeting, Newport News, VA, May 2012
Recent GRAAL \[ \sum \] for \( \gamma n \rightarrow \pi^- p \)


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

No FSI included

\[ \chi^2/dp \]
- MAID07: 27
- SP09: 89
- MA09: 4.9

GRAAL data are in

Hall-B/ Physics Analysis Center Meeting, Newport News, VA, May 2012
$E_0^+$ Neutron Multipole

- The difference between SN11 & SP09 is visible above $E = 400$ MeV
- Modified MAID07 is different above $E = 1000$ MeV
- $\eta$-cusp is more pronounced for SN11


1179 new $\Sigma$ vs. 315! [That is 38% of World $\pi p$ data]

$\chi^2$ from new SAID PWA fit: 2.6

No FSI included
Preliminary $\Sigma$ Measurement II

Forward $\gamma\pi\to\pi\rho$

- No FSI included

Hall-B/Physics Analysis Center Meeting, Newport News, VA, May 2012

JLab Users’ Meeting – 8 June 2010
HD-ICE for Polarized Measurements for $\gamma n \rightarrow \pi^- p$

$$E = \frac{D_{\text{eff}}}{P_T P_\gamma} \frac{N_{1/2} - N_{3/2}}{N_{1/2} + N_{3/2}}$$

$P_D \sim 27\%$

$P_\gamma \sim 85\%$

[Courtesy of Natalie Walford, CLAS Meeting, May 2012]

--- SAID
--- MAID07

[Very, Very Preliminary]

5/23/2012

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There were several attempts to estimate FSI for $\gamma d \rightarrow \pi^- p p$.

- There are no estimations below and above the $\Delta$-region.
- The effect from FSI is small and at the lowest energy has a noticeable impact on $\Sigma$. 

Data: prlm LEGS@BNL using HD-ICE
More Neutron-Target Data
Next Step is $\gamma n \rightarrow \pi^0 n$

[M. Schwamb, Phys Rep 485, 109 (2010)]

- **INS, Tokyo:**
  [M. Asai \textit{et al} Phys Rev C 42, 837 (1990)]

- **DESY** [Bubble Chamber data]:
  [P. Benz \textit{et al} Nucl Phys B65, 158 (1973)]

- **MAMI-B:**
  [B. Krusche \textit{et al} Eur Phys J A 6, 309 (1999)]

- **IA** contribution for $\gamma d \rightarrow \pi^0 np$ is much larger than for $\gamma d \rightarrow \pi^- pp$
Pion Electroproduction on the Neutron
GW DAC for Pion Electro Prod

- Energy dependent \textit{SM08} and associated SES & SQS
- \( W = 1080 - 2000 \) MeV
- \( Q^2 = 0 - 6 \) GeV\(^2\)
- PWs = 60 [multipoles]
- Prms = 171
- Constraint: \( \pi N + \) Pion Photo Prod PWAs [no theoretical input]

- \textbf{0.85} World Electro Prod = JLab CLAS

- \textbf{PWA Problems:}
  - \( Q^2 \) dependence

- \textbf{Database Problems:}
  - Most of data are unPolarized measurements
  - There are no \( \pi^0n \) data and very few \( \pi^-p \) [no Pol measurements]
  - That does not allow to determine \( n \) couplings at \( Q^2 > 0 \)

\begin{tabular}{|c|c|c|}
\hline
\textbf{Reaction} & \textbf{Data} & \textbf{\( \chi^2 \)} \\
\hline
\( \gamma^*p \rightarrow \pi^0p \) & 55,766 & 81,284 \\
\( \gamma^*p \rightarrow \pi^-n \) & 51,312 & 80,004 \\
Redundant & 14,772 & 17,375 \\
Total & 121,850 & 178,663 \\
\( \gamma N \rightarrow \pi N \) & 25,358 & 53,458 \\
All Photo* & 148,404 & 235,229 \\
\( \pi N \rightarrow \pi N \) & 31,479 & 57,157 \\
All \( \pi N \) & 179,883 & 292,386 \\
\( \gamma^*n \rightarrow \pi^-p \) & 801 & \\
\( \gamma^*n \rightarrow \pi^0n \) & No Data & \\
\hline
\end{tabular}
CLAS for $\gamma^* n \rightarrow \pi^0 n$

BoNuS Vs Models, 5 GeV, $W = 1.525$

$Q^2 = 0.93$, $Q^2 = 1.33$, $Q^2 = 2.11$, $Q^2 = 3.59$

[Courtesy of Jixie Zhang, MENU2010]
Summary and Prospects

- Pion Photo Prod measurements on the 'neutron' target are necessary to determine neutron couplings at $Q^2 = 0 \text{ GeV}^2$

- Future experiments on the reactions $\gamma d \rightarrow \pi NN$ are welcome, especially at small angles $\theta < 30^0$, where data are absent

- JLab FROST & HD-ICE, CB@MAMI-C, LEPS II, CB-ELSA, & MAX-lab data could yield surprises

- Complete experiment would make possible a direct reconstruction of helicity amplitudes for Pseudo-Scalar Meson Photo Prod

- Pion Electro Prod measurements on the 'neutron' target are necessary to determine neutron couplings at $Q^2 > 0 \text{ GeV}^2$
THANKS

igor@gwu.edu
Pion Photoproduction with Polarized Beam and Polarized Target

\[ L = l_{\gamma N} + 1 \]

EL, ML
\[ \downarrow \]

Multipole components of the electromagnetic radiation

Angular momentum and parity conservation

\[ J^P (\gamma N) = J^P (R) = J^P (\pi N) \]

Angular momentum
\[ L \pm \frac{1}{2} = J = l_\pi \pm \frac{1}{2} \]

Parity
\[ EL : \quad (-1)^L = (-1)^{l_\pi + 1} \Rightarrow |L - l_\pi| = 1 \]

4/12/2012

Hall-B/ Physics Analysis Center Meeting, Newport News, VA, May 2012

\[ EL : \quad (-1)^{L+1} = (-1)^{l_\pi + 1} \Rightarrow L = l_\pi \]

Multipole amplitudes:
\[ E_{l \pm}, M_{l \pm} \]

\[ J = l + \frac{1}{2} \quad \quad J = l - \frac{1}{2} \]