Spin Asymmetries and Helicity Amplitudes from Pion Production from Polarized Neutrons at Jefferson Lab

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(for the g14 analysis team and the CLAS Collaboration, together with the GWU-SAID and Bonn-Gatchina PWA groups)
Unfolding and interpreting the N* spectrum

- low energy structure of QCD lies encoded in the excited N* spectrum, a complex overlap of resonances with “dressed” vertices

- only lowest few in each band “seen” with 4★ or 3★ PDG status

⇔ need to understand the structure of the states that are observed and find the ones that aren’t!
the physics of “dressed” QCD

\[ N^* \text{ resonance } \leftrightarrow s\text{-channel pole} \]

- meson-loop “dressings” of the Electromagnetic vertex affect the dynamical properties (excitation mechanism) and determine \( Q^2 \) evolution, but do not affect the \( N^* \) spectral properties

- coupled-channel “dressings” of the strong vertex determine the \( N^* \) spectral properties (mass/pole positions, widths)

- dressings are beyond the current sophistication of LQCD or DSE field theories
  \( \Leftrightarrow \) we rely on models, constrained by the spectrum and its couplings
data needed to unravel the N* spectrum

\[ \gamma + N \Leftrightarrow (J^\pi=0^-) + N/\Lambda/\Sigma \]

spin states: \( 2 + 2 \Rightarrow 0 + 2 \Rightarrow 8 \) spin combinations
\( \Rightarrow 4 \) unique (parity)
\( \Rightarrow 4 \) complex amplitudes describe photo-production \( \Leftrightarrow 8 \) unknowns

New goal: (Jlab, Bonn, Mainz)
• measure many polarization observables (of 16) \( \Leftrightarrow \) lots of proton data
• the electromagnetic interactions do not conserve isospin

\[
\begin{align*}
A_{\gamma p \rightarrow \pi^+ n} &= \sqrt{2} \left\{ A_{p}^{I=1/2} - \frac{1}{3} A_{I}^{I=3/2} \right\} \\
A_{\gamma n \rightarrow \pi^- p} &= \sqrt{2} \left\{ A_{n}^{I=1/2} + \frac{1}{3} A_{I}^{I=3/2} \right\}
\end{align*}
\]

\( \Rightarrow \) both proton and neutron target data needed for the \( I=\frac{1}{2} \) amplitudes

• \( \gamma+n \) data base is very sparse
\( \Leftrightarrow \gamma n N^* \) couplings very poorly determined

Dec’2011 – to May’2012

tagged photons with circular and linear polarization on polarized HD, $E_\gamma$: 700 – 2400 MeV

PRL 118 (2017) 242002:
the beam-target "E" asymmetry in $\gamma D \rightarrow \pi^- p(p)$
with circularly polarized photons and longitudinally polarized Deuterons, $W$: 1500 – 2300 MeV

\[
E = \left( \frac{1}{P_\gamma P_T} \sigma_A - \sigma_P \right) \left( \sigma_A + \sigma_P \right)
\]

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g14 ... with the last breath of the CLAS(6) detector

- **Torus magnet**: 6 superconducting coils
- **Electromagnetic calorimeters**: Lead/scintillator, 1296 photomultipliers
- **polarized target + start counter**
- **Drift chambers**: argon/CO₂ gas, 35,000 cells
- **Time-of-flight counters**: plastic scintillators, 684 photomultipliers
- **Gas Cherenkov counters**: e/π separation, 256 PMTs

**DAQ limit**: ~6kHz (~1.5TB/day)
**HDice Frozen-Spin Target**

- **Target:** Ø 15 mm × 50 mm
- **Material:** Solid HD
- **Dilution factors:** 1/1 for $\bar{n}$, 1/2 for $\bar{p}$
- **$< P(D) >$** = 25% (ave in g14)
- **$T_1$ (1/e relaxation time)** ~ years
- **HDice-I:** NIM A737 (2014) 107
- **HDice-II:** NIM A815 (2016) 31

- Moved while polarized to Hall B
parallel analyses of $\gamma D \rightarrow \pi^- p (p)$

- **Bksub** – conventional application of sequential cuts, with **empty subtraction**

- **KinFit** – energy & momentum conservation used in **Kinematic fitting** to improve accuracy of measured quantities

- **BDT** – “**Boosted Decision Trees**” used to place simultaneous (rather than sequential) requirements

- Vertex preselection:
  
  - **Bksub**
  - **KinFit**
  - **BDT**
  - **empty cell yield**

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Select events for which the proton in Deuterium is a passive “spectator”
⇔ key variable is the momentum of the undetected proton in $\gamma + n(p) \rightarrow \pi^- p(p)$

⇔ use the data itself to determine the kinematic region in which the result is stable

$|P_{miss}| < 0.1$ GeV/c

⇔ applied in all three analyses

Theory perspective:
FSI have negligible effect on E asymmetry in $\pi^- p p$ final state
⇔ $I = 1$ pp final state is orthogonal to the initial deuteron wavefunction
   (in contrast with $\pi^0 n p$ final state, where FSI are essentially required)

⇔ more details in talks by Satoshi Nakamura (B3) and Igor Strakovsky (B5)
Impact of the Deuteron’s D-state on the effective neutron polarization

- T.-S. H. Lee: impulse calculation, extended to include all relativistic spin transformations of the moving neutron
- effect of deuteron’s D-state is negligible after $|P_{\text{miss}}| < 0.1$ requirement
Combining analyses into the final results

- asymmetries from the three analyses are statistically consistent
- weighted mean is taken as the best estimate of the asymmetry
- correlated errors are fitted to the expected $\chi^2$ 

$E_{(g14_v2.4)} \ W_{2220}, E_{2152}$

Advantages
- reduces hidden bias
- acceptance at extreme angles is different for the 3 methods; averaging improves reliability where PWA interference is large
The $g_{14}$ beam-target "E" asymmetries for $\gamma n \rightarrow \pi^- p$

The diagram shows the asymmetries for various $W$ values, with $W$ ranging from 1500 MeV to 2300 MeV. The asymmetry $E$ is plotted against the angle $\cos \theta_{c.m.}$ for each $W$ value. The asymmetry $E$ is defined as the ratio of the number of events in one direction to the number in the opposite direction, normalized to a reference value.

The calculations are performed using the SAID and BnGa models, with and without the $g_{14}$ effect.

The data is compared with the CLAS (g14) results, and the models are shown with different line styles for SAID and BnGa.

The figures show the variation of the asymmetry with $W$ and the angular distribution, highlighting the impact of the $g_{14}$ effect on the asymmetry.

PRL 118 (2017) 242002
The $g_{14}$ beam-target “E” asymmetries for $\gamma n \rightarrow \pi^- p$
The $g_{14}$ beam-target “E” asymmetries for $\gamma n \rightarrow \pi^- p$

**SAID**

- $W = 1620$ MeV
- $W = 1660$ MeV
- $W = 1700$ MeV
- $W = 1740$ MeV
- $W = 1780$ MeV
- $W = 1820$ MeV
- $W = 1860$ MeV
- $W = 1900$ MeV
- $W = 1940$ MeV
- $W = 1980$ MeV
- $W = 2020$ MeV
- $W = 2060$ MeV
- $W = 2100$ MeV
- $W = 2140$ MeV
- $W = 2180$ MeV
- $W = 2220$ MeV
- $W = 2260$ MeV
- $W = 2300$ MeV

**BnGa**

- $W = 1620$ MeV
- $W = 1900$ MeV
- $W = 1940$ MeV
- $W = 1980$ MeV
- $W = 2020$ MeV
- $W = 2060$ MeV
- $W = 2100$ MeV
- $W = 2140$ MeV
- $W = 2180$ MeV
- $W = 2220$ MeV
- $W = 2260$ MeV
- $W = 2300$ MeV

**Jefferson Lab**

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The $g_{14}$ beam-target “E” asymmetries for $\gamma n \rightarrow \pi^- p$

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The g14 beam-target “E” asymmetries for $\gamma n \rightarrow \pi^- p$
Partial Wave Analyses

\[ T_{\alpha\gamma} = \sum_{\sigma} \frac{\bar{K}_{\sigma\gamma}}{1 - c\bar{K}} \]

SAID (R. Workman, A. Švarc, I. Strakovsky, …)
• sequential, unitary fit to all \( \pi N \) scattering and \( \pi \)-photoproduction data
  - fit \( 1 - c\bar{K} \) to \( \pi N \rightarrow \pi N \)
  - vary \( K(W) \) as polynomials in \( W \) to fit photo-production
  - fits \( \pi N \rightarrow \eta N \)
  - determines all poles \( \Leftrightarrow \) no new resonances

BnGa (E. Klempt, V. Nikonov, A. Sarantsev, …)
• simultaneous, coupled-channel analysis of \( \pi N \) and \( \gamma N \rightarrow \pi N, \pi\pi N, KY \)
  - fit to SAID amplitudes for \( \pi N \rightarrow \pi N \)
  - include new resonances as needed to improve fits for \( \gamma N \) channels

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Status of $\gamma n \rightarrow \pi N$ data base

- 4 complex amplitudes describe photo-production $\Leftrightarrow$ 8 unknowns
- 8 carefully chosen observables (out of 16) for a “mathematical soln”
  - Chiang & Tabakin, PR C55, (1997)
- in practice, ie. with realistically achievable uncertainties, even more

- $\gamma n \rightarrow \pi^- p$ Data Base:
  $d\sigma$ (2322 pts), $\Sigma$ (315 pts), $T$ (105 pts), $P$ (75 pts), and now $E$ (263 pts)
  (even less for $\pi^0 n$)

- insufficient to completely remove ambiguities:
  $\Leftrightarrow$ deduced couplings can change with new data;
  $\Leftrightarrow$ attach a higher significance when there is agreement btw very different PWA approaches
PWA: phase motion of a resonance

- expectation for an isolated resonance:
  - ideal single isolated resonance (Breit-Wigner)
  - Argand plots:
    - counter-clockwise rotating amplitude
      - characteristic resonance behavior

- caveat:
  every resonance produces a loop; but not every loop is a resonance

- amplitude decomposed into \((L^{\pi N})_{IJ}(n/p)E/M\) partial waves

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PWA: $I = 1/2 \ (N^*)$ P-waves

e.g. SAID P13nM

BnGa P13nM

N(1720)3/2$^+$ (PDG ****)
PWA: \( I = 1/2 \) (\( N^* \)) G-waves

---

\[ \text{SAID G17nM} \]

\[ \text{BnGa G17nM} \]

---

\[ \text{N}(2190)^{7/2}^- \]

(PDG ****)
\( h_\gamma = 1 \), \( h_N = \frac{1}{2} \) \( \Leftrightarrow \) \( A^{1/2} \), \( A^{3/2} \)

- residues from analytic continuation to a pole in the complex \( W \) plane

- Breit-Wigner parameterization,

\[
T_{\alpha \gamma} = \sum_\sigma \frac{\overline{K}_{\sigma \gamma}}{[1 - c \overline{K}]_{\alpha \sigma}} \quad \Rightarrow \quad \sum \frac{A^h g_\alpha(s)}{[M^2 - s - i \sum c_j g_j^2(s)]}
\]

\( \gamma n N^* \) couplings \( \Leftrightarrow \) transverse helicity amplitudes
### Revisions to $\gamma nN^*$ couplings

<table>
<thead>
<tr>
<th></th>
<th>$A_n^{1/2}$ (10$^{-3}$ GeV$^{-1/2}$)</th>
<th>$A_n^{3/2}$ (10$^{-3}$ GeV$^{-1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SAID</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N(1720)3/2$^+$</td>
<td>$-9 \pm 2$</td>
<td>$-21 \pm 4$</td>
</tr>
<tr>
<td>N(2190)7/2$^-$</td>
<td>$-6 \pm 9$</td>
<td>---</td>
</tr>
<tr>
<td><strong>BnGa</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N(1720)3/2$^+$</td>
<td>$-(28 +40/-15)$</td>
<td>$-80 \pm 50$</td>
</tr>
<tr>
<td>N(2190)7/2$^-$</td>
<td>$+30 \pm 7$</td>
<td>$-15 \pm 12$</td>
</tr>
</tbody>
</table>

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Sensitivities to new data

- new $\sigma(\pi p)$ data from CLAS/g13
  - $D(\gamma, \pi p)p$ with FSI correction
  - 8424 kinematic bins

Paul Mattione’s talk (A2)
Convergence of $\gamma pN^*$ couplings with new data

<table>
<thead>
<tr>
<th>$(10^{-3} \text{ GeV}^{-1/2})$</th>
<th>Last published</th>
<th>$+ \text{CLAS/g14 (E)}$</th>
<th>$+ \text{CLAS/g13 (}\sigma)$</th>
<th>$+ \text{CLAS/g13 (}\sigma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_n^{1/2}$</td>
<td></td>
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<tr>
<td>$N(1720)3/2^+$</td>
<td>$-21 \pm 4$</td>
<td>$-9 \pm 2$</td>
<td>$-16 \pm 6$</td>
<td>$-15 \pm 5$</td>
</tr>
<tr>
<td>$N(2190)7/2^-$</td>
<td>$- -$</td>
<td>$-6 \pm 9$</td>
<td></td>
<td>$-16 \pm 5$</td>
</tr>
<tr>
<td>$A_n^{3/2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N(1720)3/2^+$</td>
<td>$-38 \pm 7$</td>
<td>$+19 \pm 2$</td>
<td>$+17 \pm 5$</td>
<td>$13 \pm 4$</td>
</tr>
<tr>
<td>$N(2190)7/2^-$</td>
<td>$- -$</td>
<td>$-28 \pm 10$</td>
<td></td>
<td>$-35 \pm 5$</td>
</tr>
</tbody>
</table>

[3] CLAS/g13 (\sigma) - arXiv1706.01963
**PWA: $I = 1/2 \ (N^*)$ P-waves**

**BnGa:**

- N(1720)$3/2^+$ & PDG ****
- N(1900)$3/2^+$ & PDG ****
- (but weakly coupled to πN)

- N(2040)$3/2^+$ & PDG * ??? (PRL 118)
PWA: \( l = 1/2 \) (\( N^* \)) P-waves

BnGa:

\[
\begin{align*}
\text{Re[P13nM]} & \quad \text{(mF)} \\
\text{Im[P13nM]} & \quad \text{(mF)}
\end{align*}
\]

- N(1720)\(^{3/2}^+\) ↔ PDG ****
- N(1900)\(^{3/2}^+\) ↔ PDG ****
  (but weakly coupled to \( \pi N \))

- new BnGa PWA (submitted to PRC):
  \( \Rightarrow \) highest \( 3/2^+ \) at \( W=1975 \) MeV
  \( \Leftrightarrow \) possible \( N(1975)3/2^+ \)

\[
A_{1/2} = -26 \pm 13, \quad A_{3/2} = -77 \pm 15
\]
PWA: $l = 1/2 \ (N^*) \ S$-waves

N(1895)1/2-
(PDG **)

N(1650)1/2-
(PDG ****)

N(1535)1/2-
(PDG ****)

<table>
<thead>
<tr>
<th>BnGa[Jan17, w g14(E)]</th>
<th>BnGa[Jan17, no g14]</th>
<th>BnGa[2014_02]</th>
</tr>
</thead>
</table>

Re[S11nE] (mF) | Im[S11nE] (mF)

N(1895) | N(1650) | N(1535)

Born

E 0+
(n)
**PWA: \( l = 1/2 \) (\( N^* \)) S-waves**

- \( N(1895)1/2^- \) (PDG ***)
- \( N(1650)1/2^- \) (PDG ****)
- \( N(1535)1/2^- \) (PDG ****)

- **new BnGa PWA** (submitted -PRC):
  - highest \( 1/2^- \) at \( W=1895 \) MeV
  - required \( N(1895)1/2^- \)
  - \( A_n^{1/2} = -15 \pm 10 \)
**PWA: \( I = 1/2 \ (N^*) \) S-waves**

- **N(1895)1/2-** (PDG ***)
- **N(1650)1/2-** (PDG ****)
- **N(1535)1/2-** (PDG ****)

- similar phase motion in SAID fits to \( \gamma N \rightarrow \pi N \), but not seen in \( \pi N \rightarrow \pi N \)
  \( \Leftrightarrow \) not able to confirm

- **new BnGa PWA** (submitted -PRC):
  \( \rightarrow \) highest \( 1/2^- \) at \( W=1895 \) MeV
  \( \Leftrightarrow \) required \( N(1895)1/2^- \)
  \( A_n^{1/2} = -15 \pm 10 \)
### $\gamma nN^* \text{ vs } \gamma pN^* \text{ couplings}$

<table>
<thead>
<tr>
<th>$(10^{-3} \text{ GeV}^{-1/2})$</th>
<th>$A_n^{1/2}$</th>
<th>$A_p^{1/2}$</th>
<th>$A_n^{3/2}$</th>
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<tr>
<td><strong>SAID</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$N(1895)1/2^-$</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>$N(1975)3/2^+$</td>
<td>----</td>
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<td>----</td>
<td>----</td>
</tr>
<tr>
<td>$N(2190)7/2^-$</td>
<td>$\bf{-16 \pm 5}$ [4]</td>
<td>- -</td>
<td>$\bf{-35 \pm 5}$ [4]</td>
<td>- -</td>
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<td>$N(1720)3/2^+$</td>
<td>$\bf{-28 +40/-15}$ [3]</td>
<td>$110 \pm 45$ [5]</td>
<td>$\pm(103 \pm 35)$ [3]</td>
<td>$150 \pm 30$ [5]</td>
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<td>$N(1975)3/2^+$</td>
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<td></td>
</tr>
<tr>
<td>$N(2190)7/2^-$</td>
<td>$+30 \pm 7$ [1]</td>
<td>$-65 \pm 8$ [5]</td>
<td>$-23 \pm 8$ [1]</td>
<td>$+35 \pm 17$ [5]</td>
</tr>
</tbody>
</table>

Couplings can only be as certain as the multipoles could be impacted by data on new observable

E06-101 (g14 run with CLAS – 2012)
- linearly-polarized photons on $\vec{HD}$
- $E_\gamma$: 1600 – 2200 MeV
- $\gamma n (p) \rightarrow \pi^- p (p)$

$W= 2020 \pm 40$ MeV

SAID[TS21]: fit to new $E$, $d\sigma$

$G = \frac{1}{P_\gamma P_T} \frac{\sigma_{+\pi/4,+z} - \sigma_{-\pi/4,+z}}{\sigma_{+\pi/4,+z} + \sigma_{-\pi/4,+z}}$

$\Leftrightarrow$ Haiyun Lu’s talk (A2)
Summary

- **Beam-Target helicity asymmetries (E) for \( \gamma n \to \pi^- p \) just out in PRL**
  - 1st data on this observable and spans the full N* energy range

- **significant addition to the sparse \( \gamma n \) data base**
  - inclusion in PWA have resulted in significant changes to \( I = \frac{1}{2} \) multipoles
  - improved determination of helicity amplitudes (\( \gamma n N^* \) couplings),
    with SAID and BnGa agreement for \( A_{n}^{1/2} [N(1720)3/2^+] \) and \( A_{n}^{3/2} [N(2190)7/2^-] \)
  - potential signals in BnGa PWA from PDG* and PDG** resonances

- **next observables in the g14 pipeline:**
  - beam asymmetry \( \Sigma \) and beam-target asymmetry \( G \) for \( \gamma n \to \pi^- p \)
clean deuteron target

- sources of neutrons: D in HD and the target cell
- evaporate and pump away HD: residual backgrounds are small

⇒ after empty cell subtraction, all neutrons are polarizable
\[ \pi^- p \]
\[ \pi\pi p \]

\[ \text{Missing Mass}^2 (\text{GeV}^2) \]

Entries 27398
Mean 0.9774
RMS 0.1743

Entries 275424
Mean 1.478
RMS 0.5065

Entries 708655
Mean 1.576
RMS 0.5226

\[ \phi_p - \phi_\pi = 180 \pm 20 \] (coplanarity)

\[ |P_{miss}| < 0.1 \]

\( \gamma D \rightarrow \pi p (p) \) Missing Mass squared, with sequential 2-body requirements, followed by empty cell subtraction.
• Kinematic Fitting carried out on candidates for $\gamma + (n) \rightarrow \pi^- p$

$\Leftrightarrow$ target assumed to have the neutron mass, but unknown momentum

$\Leftrightarrow$ amounts to a 1C fit

• $2\pi$ & reactions on target cell nucleons fail with Confidence Level < 0.05
• accept events with Confidence Level > 0.05
• apply $|P_{\text{miss}}| < 0.1$ GeV/c to accepted events
multivariate Boosted Decision Trees
view the data in a higher dimension
creates a forest of if-then-else logical tests on all kinematic variables simultaneously
algorithm categorizes events as either signal or background
- signal trained on $\gamma D \rightarrow \pi^- p(p)$ from CLAS MC
- background trained on empty-cell data
apply $|P_{miss}| < 0.1$ GeV/c to signal events

Dao Ho (2015)
Select events for which the proton in Deuterium is a passive "spectator"

\[ \Leftrightarrow \text{key variable is the momentum of the undetected proton in } \gamma + n(p) \rightarrow \pi^- p(p) \]
\( E(\pi^- p) \) vs \( |P_{\text{miss}}| \)

\[(1560.00<W<1600.00), \text{E asym. vs. } \theta_z \]

\(|P_{\text{miss}}| \leq 300 \text{ MeV/c} \)

\(|P_{\text{miss}}| \leq 200 \text{ MeV/c} \)

\(|P_{\text{miss}}| \leq 150 \text{ MeV/c} \)

\(|P_{\text{miss}}| \leq 75 \text{ MeV/c} \)

\(|P_{\text{miss}}| \leq 100 \text{ MeV/c} \)
$E_\gamma = 1890$ MeV; $W = 2105$ MeV

- CLAS/g13 $\sigma$
- SAID fits with CLAS[g13 $(\sigma)$ + g14 (E)]
- SAID fit with CLAS[g13 $(\sigma)$]
PWA: $I = 3/2 (\Delta^*)$ partial waves

e.g. $I=3/2, P$ wave

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

$\Delta(1950) 7/2^+$ (PDG ***)

$I = 3/2$ waves ~ unchanged $\Leftrightarrow$ determined by proton data