g_{13} \gamma n \rightarrow p\pi^- \text{ Differential Cross Section, } N^* \text{ Amplitudes}

Paul Mattione, Jefferson Science Associates
N* Predictions: Quark Model

* Predictions: Capstick, Isgur†
  * Relativized quark model
  * States organized by J\(^p\)
  * Agrees well with lattice predictions below 2 GeV

* Many states missing, many others poorly understood

†S. Capstick, N. Isgur, Phys. Rev. D 34, 2809 (1986)

Legend
Black: Certain or likely: ****, ***
Blue: Fair or poor: **, *
Red: No evidence
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\( \gamma p \) vs. \( \gamma n \), Isospin

* For N* couplings to \( \gamma N \), important to study both \( \gamma p \) & \( \gamma n \)
  
  * Disentangle Isoscalar (\( A^S \)), isovector (\( A^V \)) EM amplitudes\(^\dagger\)

* \( \gamma N \rightarrow \pi N \): Primary \( \gamma N \) channel in resonance region
  
  * 4 possible reactions (below)
  
  * SAID: Sparse \( \gamma n \rightarrow \pi N \) data (3500 points) vs. \( \gamma p \rightarrow \pi N \) (35400)

\[
A_{\gamma p \rightarrow \pi^+ n} = \sqrt{\frac{1}{3}} A^V_{I=3/2} - \sqrt{\frac{2}{3}} (A^V - A^S)_{I=1/2}
\]

\[
A_{\gamma n \rightarrow \pi^- p} = \sqrt{\frac{1}{3}} A^V_{I=3/2} - \sqrt{\frac{2}{3}} (A^V + A^S)_{I=1/2}
\]

\[
A_{\gamma p \rightarrow \pi^0 p} = \sqrt{\frac{2}{3}} A^V_{I=3/2} + \sqrt{\frac{1}{3}} (A^V - A^S)_{I=1/2}
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\(^\dagger\)R. L. Walker, Phys. Rev. 182, 1729 (1969)

Paul Mattione – CLAS Collaboration Meeting – June 14, 2017
**CLAS g13 Experiment**

- g13 experiment: 2006 – 2007, LD$_2$ target
- Analysis (g13a): $E_{e^-} = 2.655, 1.990$ GeV
Final-State Interactions in $\gamma d$

* $\gamma n$: No free neutron targets
  * Deuteron target: Isotropic Fermi-motion, final-state interactions (FSI)
  * Correct for FSI to extract $\gamma n$ cross sections from $\gamma d$ measurements

* On $\gamma d$, measure “quasi-free” (QF) differential cross sections
  * QF: Cut (FSI) events with missing-$p > 200$ MeV$/c$
  * FSI corrections: Model-dependent fit to data†

†V. E. Tarasov et. al, Phys. Rev. C 84, 035203 (2011)
Reconstructed Kinematics

- Track distributions: Detector was aging
- Needed more sophisticated CLAS efficiency studies
π⁻ Triggering Efficiency

* g13: 2-sector trigger (Start-Counter x TOF)

* Study γd → ppπ⁻ events, when each track in different sector
  * Each track pair: If both fired trigger signal, study 3\textsuperscript{rd}-track signal rate
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  * Function of particle type, p, TOF scintillator, φ

Overlap between TOF panels: Forward carriage, N/S clamshells
π⁻ Triggering Efficiency

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  * Function of particle type, p, TOF scintillator, φ

* TOF thresholds: Readout = 20 mV, pre-trigger = 100 mV
  * g13 weak PMTs: Set to max voltage, gain often still too low

Overlap between TOF panels: Forward carriage, N/S clamshells
Compare Experiment, MC: \( \pi^- \)

* \( \gamma d \rightarrow p\pi^-(p) \) distributions match pretty closely
Modeling FSI in $\gamma d \rightarrow pp\pi^-$

* Must correct for FSI to extract $\gamma n \rightarrow p\pi^-$ from QF $\gamma d \rightarrow pp\pi^-$
  * GWU & ITEP Moscow

* $\gamma d \rightarrow pp\pi^-$ amplitude: $M_{\gamma d} = M_{IA} + M_{NN} + M_{\pi N}$

* Leading terms: Impulse approximation (IA), NN FSI, $\pi N$ FSI

* Fit constrained by SAID $\gamma N \rightarrow \pi N, NN \rightarrow NN, N\pi \rightarrow N\pi$

\[
\frac{d\sigma}{d\Omega}(\gamma n) = R(E_\gamma, \theta)^{-1} \frac{d\sigma}{d\Omega}(\gamma d)
\]

\[
R(E_\gamma, \theta) = M_{\gamma d}/M_{IA}
\]

†V. E. Tarasov et. al, Phys. Rev. C 84, 035203 (2011)

Paul Mattione – CLAS Collaboration Meeting – June 14, 2017
FSI Correction Factor

* Correction† < 10% except at forward angles: pp-FSI dominates
  * When pp both slow, backwards: Maximal wave function overlap
  * π⁻ faster than p: Leaves d sooner: Less FSI

\[ \frac{d\sigma}{d\Omega}(\gamma n) = R(E_\gamma, \theta)^{-1} \frac{d\sigma}{d\Omega}(\gamma d) \]

Uncertainties:
- \( E_\gamma < 1.8 \text{ GeV} \): 2%
- \( 1.8 < E_\gamma < 2.7 \): 3%
- \( E_\gamma > 2.7 \text{ GeV} \): 5%

Legend
Solid: NN + πN FSI
Dash: NN FSI

†V. E. Tarasov et. al, Phys. Rev. C 84, 035203 (2011)

Paul Mattiome – CLAS Collaboration Meeting – June 14, 2017
γn → pπ⁻ Cross Section

* CLAS g13
  * 8424 bins, ≈ 400M events
  * 157 Eγ bins (10, 20 MeV)
  * W ≈ 1.31 – 2.37 GeV: N*'s
  * σ_{Total} typically 3.5% - 15%
  * σ_{Scale} ≈ 3.4% (not shown)

Legend

γn → pπ⁻: CLAS g13, CLAS g10, SLAC, DESY, MAMI-B, Frascati
π⁻p → γn: BNL, LBL, LAMPF
Fits (lines): SAID MA27, SAID PR15, BnGa 2014-02, MAID 2007

Peaks at low-Eγ: Δ(1232), N*'s
At higher Eγ, more channels

Paul Mattione – CLAS Collaboration Meeting – June 14, 2017
\( \gamma n \rightarrow p\pi^- \) Cross Section

* **CLAS g13**
  * 8424 bins, \( \approx 400M \) events
  * 157 \( E_\gamma \) bins (10, 20 MeV)
  * \( W \approx 1.31 - 2.37 \) GeV: N*’s
  * \( \sigma_{\text{Total}} \) typically 3.5% - 15%
  * \( \sigma_{\text{Scale}} \approx 3.4\% \) (not shown)

* **New SAID fit of data: MA27**
  * Previous fit: PR15
  * BnGa, MAID: Not fit to g13

**Legend**

\( \gamma n \rightarrow p\pi^- \): **CLAS g13, CLAS g10, SLAC, DESY, MAMI-B, Frascati**

\( \pi p \rightarrow \gamma n \): **BNL, LBL, LAMPF**

Fits (lines): **SAID MA27, SAID PR15 BnGa 2014-02, MAID 2007**

Peaks at low-\( E_\gamma \): \( \Delta(1232) \), N*’s
At higher \( E_\gamma \), more channels
\( \gamma n \rightarrow p\pi^- \) Cross Section

- Peak low-\( \theta \): t-channel \( \pi^- \)
- Low energies (\( E_\gamma \leq 1 \) GeV)
  - Much old, low-stats data
  - Some \( E_\gamma \):
    - \( g_{13} < \) BNL, DESY, Frascati
  - Low-\( \theta \), Low-\( E_\gamma \):
    - Different trend than SLAC
  - Otherwise good agreement

Legend
\( \gamma n \rightarrow p\pi^- \): CLAS g13, SLAC, DESY, MAMI-B, Frascati
\( \pi^- p \rightarrow \gamma n \): BNL, LBL, LAMPF
Fits (lines): SAID MA27, SAID PR15, BnGa 2014-02, MAID 2007
$\gamma n \rightarrow p\pi^-$ Cross Section

- CLAS g10
  - $\approx 850$ bins, 1/10 g13
  - $34 E_\gamma$ bins (50, 100 MeV)
  - $\sigma_{\text{Scale}} \approx 12\%$ (not shown)
- High energies ($E_\gamma > 1$ GeV)
  - CLAS g10 systematically low
    - But has high $\sigma_{\text{Scale}}$
  - Overall excellent agreement

Legend

$\gamma n \rightarrow p\pi^-$: CLAS g13, CLAS g10, SLAC, DESY

Fits (lines): SAID MA27, SAID PR15, BnGa 2014-02, MAID 2007

Paul Mattione – CLAS Collaboration Meeting – June 14, 2017
SAID MA27 Fit

- Simultaneous fit to all 4 γN channels to extract EM multipoles
- SAID πN → πN amplitudes used to constrain γN → πN fits
- Also, resonance BW parameters fixed from πN fits

Legend

Black: PR15 vs. g13 w/o FSI correction
Blue: PR15 vs. g13 ($\chi^2$/Data = 2.1)
Red: MA27 vs. g13 ($\chi^2$/Data = 1.1)
SAID MA27 Fit

* Simultaneous fit to all 4 γN channels to extract EM multipoles
  * SAID πN → πN amplitudes used to constrain γN → πN fits
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<table>
<thead>
<tr>
<th>Channel</th>
<th>SAID PR15 (no g13)</th>
<th>SAID MA27 (w/ g13)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># Data</td>
<td>χ²/Data</td>
</tr>
<tr>
<td>γp → pn⁰</td>
<td>25540</td>
<td>2.15</td>
</tr>
<tr>
<td>γp → nn⁺</td>
<td>9859</td>
<td>2.39</td>
</tr>
<tr>
<td>γn → pn⁻</td>
<td>3162</td>
<td>2.07</td>
</tr>
<tr>
<td>γn → nn⁰</td>
<td>364</td>
<td>3.17</td>
</tr>
<tr>
<td>Sum</td>
<td>38927</td>
<td>2.22</td>
</tr>
</tbody>
</table>

Legend

Black: PR15 vs. g13 w/o FSI correction
Blue: PR15 vs. g13 (χ²/Data = 2.1)
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**γn Multipole Amplitudes**

* Where dominant resonance (N(1520)3/2⁻), all curves are similar.

* Where not (N(1720)3/2⁺ weak γn coupling), differences are starker.

**Amplitude Notation: n(E/M)L⁺I**

n: Neutron
E: Electric multipole (J⁺γ = 1⁻, 2⁺, 3⁻, …)
M: Magnetic multipole (J⁺γ = 1⁺, 2⁻, 3⁺, …)
L±: Jγn = L ± ½
I: Isospin
γn → N* Helicity Amplitudes

* Amplitudes at pole position (GeV^{-1/2}): First-ever determination†
* Previous attempts only extracted modulus

<table>
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<tr>
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<td>A_{1/2}(n)</td>
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γn → N* Helicity Amplitudes

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* MA27 vs. SAID GB12: Large change for N(1650)

* MA27 vs. PDG & BG2013: Large differences, ~agree within σ’s

\[ \gamma n \rightarrow N^* \text{ Helicity Amplitudes} \]

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* Modulus uncertainties dramatically reduced:

\[% \text{Uncertainty (Modulus)}\]

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<td>12%</td>
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<td>9.1%</td>
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<td>14%</td>
</tr>
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<td>38%</td>
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Summary & Outlook

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- Role of quark correlations in the nucleon
- Need both $\gamma p$ and $\gamma n$: Isospin decomposition of amplitudes
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* Missing N*’s: Need more precision data (especially polarized!)
Reference
N* and Δ Resonances

* PDG: 18 well-established (****) nucleon resonances: 11 N*'s, 7 Δ's
  * Most discovered through coupling to πN
  * Many wide, overlapping: Difficult to distinguish

* Measure spectra of N*'s, Δ's: Understanding of QCD in the baryon

Notation: \( L_{(2I)(2J)}(M) \)
L: Orbital angular momentum
I: Isospin
J: Spin
M: Mass

N*'s, Δ’s: \( 2I = 1, 3 \)

Evidence for N* Resonances

- N* status: Particle Data Group†
  - 27 N* states (11 ****)
  - Most evidence in πN

- Much new evidence from γN
  - JLab (CLAS), SPring-8, ELSA, GRAAL, MAMI

Legend
****: Existence is certain
***: Existence is likely
**: Evidence is fair
*: Evidence is poor

†C. Patrignani et al. (PDG), Chin. Phys. C, 40, 100001 (2016)
N* Predictions: Diquark Model

* Alternative: Diquark model\(^\dagger\)
  * Correlated quark-pair
  * Less DF: Less N* states

* “Missing” N*’s
  * Quark correlations?
  * Or N*’s couple weakly to measured channels? (Nn)

* Measure spectrum of N*’s
  * Study QCD in baryons

γn \rightarrow pπ^-, Helicity

* γN \rightarrow N^* Amplitudes: Helicity-dependent, very large errors†
* g13: Measure γn \rightarrow pπ^- dσ/dΩ: Improve helicity amplitudes

\[ \lambda = J \cdot \hat{p} = S \cdot \hat{p} \]

\[ J_\gamma = 1, J_N = \frac{1}{2} \]

\[ |\mathcal{M}_{\gamma N \rightarrow N\pi}|^2 \propto \sum_{\lambda_i \lambda_f} \sum_{J^P,L,S,\text{etc.}} A_{\gamma N \rightarrow N\pi}^2 \]

<table>
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<tr>
<th>N^* \rightarrow γN</th>
<th>( A^p_{\lambda=1/2} )</th>
<th>( A^n_{\lambda=1/2} )</th>
<th>( A^p_{\lambda=3/2} )</th>
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<td></td>
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</tr>
<tr>
<td>N (1520) ( \frac{3}{2}^- )</td>
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<td>-0.050 ± 0.010</td>
<td>0.140 ± 0.010</td>
<td>-0.115 ± 0.010</td>
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<td></td>
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<tr>
<td>N (1675) ( \frac{5}{2}^- )</td>
<td><strong>0.019 ± 0.008</strong></td>
<td>-0.060 ± 0.005</td>
<td><strong>0.020 ± 0.005</strong></td>
<td>-0.085 ± 0.010</td>
</tr>
<tr>
<td>N (1680) ( \frac{5}{2}^+ )</td>
<td><strong>-0.015 ± 0.006</strong></td>
<td><strong>0.029 ± 0.010</strong></td>
<td>0.133 ± 0.012</td>
<td><strong>-0.033 ± 0.009</strong></td>
</tr>
</tbody>
</table>

†C. Patrignani et al. (PDG), Chin. Phys. C, 40, 100001 (2016)
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Polarization Observables

* Combination of polarized beams, targets, and recoil polarization:
  * 16 observables

* Provide spin-dependent constraints for N* extraction

<table>
<thead>
<tr>
<th>Photon Beam</th>
<th>Target and/or Recoil Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neither</td>
</tr>
<tr>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Unpolarized</td>
<td>σ</td>
</tr>
<tr>
<td>Linearly Polarized</td>
<td>σ</td>
</tr>
<tr>
<td>Circularly Polarized</td>
<td>Cₓ</td>
</tr>
</tbody>
</table>

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Reconstruction Efficiencies

* Needed new, sophisticated reconstruction efficiency studies

* Select $\gamma d \rightarrow p\pi^-(p)$ events to study $p$, $\gamma d \rightarrow pp(\pi^-)$ to study $\pi^-$
  * Efficiency: See how often missing particles are reconstructed
  * Study how well simulation models CLAS efficiency
  * Function of particle type, $p$, $\theta$, $\phi$, vertex-$z$

Background present, small, ignored: Studying features
p Reconstruction Efficiency

- Efficiency: Low at edges, holes
- Cut: Where MC efficiency doesn’t match experiment
- Minimum $p = 330$ MeV/c
π⁻ Reconstruction Efficiency

- Efficiency: Low at edges, holes
- Cut: Where MC efficiency doesn’t match experiment
- Minimum $p = 100$ MeV/c
Proton Triggering Efficiency

* g13: 2-sector trigger (Start-Counter x TOF)

* Study $\gamma d \rightarrow p p \pi^-$ events, when each track in different sector
  * Each track pair: If both fired trigger signal, study 3rd-track signal rate
  * Function of particle type, $p$, TOF scintillator, $\varphi$

* Low efficiency for weak/dead TOF PMTs, TOF panel overlap
  * One PMT on each end of TOF scintillators

Overlap between TOF panels: Forward carriage, N/S clamshells
Triggering Efficiency: PMTs

* TOF thresholds: Readout = 20 mV, pre-trigger = 100 mV
* Left & right PMTs are summed for pre-trigger
* Weak PMTs: Set to max voltage, gain often still too low
* π’s worse than protons: Much less dE/dx in scintillators
* After study: Pre-trigger threshold reduced for g9b (FROST)

Thresholds set assuming MIP peak here (ADC – pedestal = 600)
Compare Experiment, MC: $p$

* After cuts: $\gamma d \rightarrow p\pi^-(p)$ distributions match VERY closely

* Need to regenerate MC with measured cross section (Used SAID)

Primary sources of holes: Triggering & drift chamber inefficiencies
†Modeling FSI in \( \gamma d \rightarrow pp\pi^- \)

* Must correct for FSI to extract \( \gamma n \rightarrow p\pi^- \) from QF \( \gamma d \rightarrow pp\pi^- \)
* Working with GWU & ITEP (Moscow)

* \( \gamma d \rightarrow pp\pi^- \) amplitude: \( \mathcal{M}_{\gamma d} = \mathcal{M}_{IA} + \mathcal{M}_{NN} + \mathcal{M}_{\pi N} \)

* Leading terms: Impulse approximation (IA), NN FSI, \( \pi N \) FSI

* Fit constrained by SAID \( \gamma N \rightarrow \pi N \), NN \( \rightarrow NN \), N\( \pi \rightarrow N\pi \)

* QF \( \gamma d \rightarrow pp\pi^- \): Slow proton is spectator: \( \mathcal{M}_{QF}^{\gamma d} = \mathcal{M}_{IA}^{(1)} \)

†V. E. Tarasov et. al, Phys. Rev. C 84, 035203 (2011)
Modeling FSI in $\gamma d \rightarrow pp\pi^-$

1st approximation: FSI $\approx$ small & IA dominates: $\gamma n$ similar to QF

Relate $\gamma n \rightarrow p\pi^-$ to QF $\gamma d \rightarrow pp\pi^-$ via correction factors:

$$\frac{d\sigma_{QF}^{\gamma d}}{d\Omega}(E_\gamma, \theta) = f_n(p_{max}) \cdot R(E_\gamma, \theta) \cdot \frac{d\sigma_{\gamma n}}{d\Omega}(\overline{E_\gamma}, \theta)$$

Where $R = R_P R_{FSI}$ and:

- $R_{FSI}$: Corrects for FSI
- $R_P$: Corrects for difference between IA, QF
- $f_n(p_{max})$: $\approx$ Fraction of $n$ with $p < p_{max}$
  * $p_{max} = 200$ MeV/c

Note $\overline{E_\gamma} \approx E_\gamma$ and $\overline{\sigma_{\gamma n}} \approx \sigma_{\gamma n}$ at low $p_{max}$

Difference: Target $d \rightarrow$ target virtual-$n$, deuteron wave function

†V. E. Tarasov et. al, Phys. Rev. C 84, 035203 (2011)
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Calculating $R, \gamma n \rightarrow p\pi^-$

* Set $R = 1$, compute $\sigma_{\gamma n}$ ($& M_{\gamma n}$) from quasi-free $\sigma_{\gamma d}$ data

* Calculate $R$ from CGLN amplitudes, using $M_{\gamma n}$

* Re-compute $\sigma_{\gamma n}$, iterate until $R$ converges

$$\frac{d\sigma_{\gamma d}^{QF}}{d\Omega}(E_\gamma, \theta) = f_n(p_{max}) R(E_\gamma, \theta) \frac{d\sigma_{\gamma n}}{d\Omega}(E_\gamma, \theta) \quad R = \frac{d\sigma_{\gamma d}}{d\Omega_1} \bigg/ \frac{d\sigma_{\gamma d}^{QF}}{d\Omega_1}$$

$$M_{\gamma d} = M_{IA} + M_{NN\text{ FSI}} + M_{\pi N\text{ FSI}} \quad M_{\gamma d}^{QF} = M_{IA}^{(1)}$$

†V. E. Tarasov et. al, Phys. Rev. C 84, 035203 (2011)