SAID Analysis of Meson Photoproduction

Igor Strakovsky
The George Washington University

• A Bit of History.
• Pion Photoproduction Database.
• Phenomenology for Pion Photoproduction.
• SAID for Pion Photoproduction.
• SAID Features & Benefits.
• SAID for Charged Baryon.
• FSI for $\gamma n \rightarrow \pi N$.
• SAID for Neutral Baryons.
• Summary.

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A bit of History
Discovery of Pion

NATURE May 24, 1947 Vol. 159

PROCESSES INVOLVING CHARGED MESONS

By Dr. C. M. G. LATTES, H. MUIRHEAD, Dr. G. P. S. OCCHIALINI and Dr. C. F. POWELL

H. H. Wills Physical Laboratory, University of Bristol

IN recent investigations with the photographic method, it has been shown that slow charged particles of small mass, present as a component of the cosmic radiation at high altitudes, can enter nuclei and produce disintegrations with the emission of heavy particles. It is convenient to apply the term 'meson' to any particle with a mass intermediate between that of a proton and an electron.

\[ \pi^+ \text{ and } \pi^- \]

A classic Bristol pion. The track of the positively-charged pion produced in the interaction 'star' (top left) has been cut in two to facilitate presentation. Bottom right, the pion eventually decays into a muon, which after some 600 microns itself subsequently decays, producing an electron. This full decay chain was recorded in electron-sensitive emulsion, available from 1948, even more sensitive than the specially-developed nuclear research emulsions in which the pion was discovered in 1947.

5/8/2017 Space-like & time-like electromagnetic baryonic transitions, Trento, Italy, May 2017 Igor Strakovsky
Production of Mesons by X-Rays

Edwin M. McMillan, Jack M. Peterson, and R. Stephen White

Radiation Laboratory, Department of Physics, University of California, Berkeley

At the 1949 Spring Meeting of the National Academy of Sciences (2) a preliminary account was given of some observations of mesons produced by the 335-Mev x-ray beam from the Berkeley synchrotron. The present

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**FIG. 4.** Distribution of meson energies from x-ray energy of 335 Mev. The apparent lower limit on the energy is caused by the fact that the energies are computed as if the mesons originated in the center of the carbon block. The dotted line is simply a guess as to the trend of the distribution at low energies, which was used in the integration leading to the total cross section.
The First Baryon Resonance Discovery

Total Cross Sections of Positive Pions in Hydrogen*

H. L. Anderson, E. Fermi, E. A. Long,† and D. E. Nagle
Institute for Nuclear Studies, University of Chicago,
Chicago, Illinois
(Received January 21 1952)

Then, since 1952 many states were discovered.
**Baryon Sector at PDG16**

**GW Contribution**


**PDG16 has 109 Baryon Resonances**
(58 of them are 4* & 3*).

• In case of SU(6) x O(3),
it would be required 434 baryons,
if all revealed multiplets were completed
(three 70 & four 56).

**Pole position in complex energy plane for hyperons** has been made only recently,
first of all for Λ(1520)3/2−.

Pion Photoproduction Database

Screenshot of SAID Website usage
http://gwdac.phys.gwu.edu/
World Neutral and Charged Pion PR Data


\(W < 2.5\ \text{GeV}\)

\(\gamma p \rightarrow \pi^0 p\)

\(\gamma p \rightarrow \pi^+ n\)

\(\gamma n \rightarrow \pi^- p\)

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

Full

UnPol

Pol

2017

W < 2.5 GeV

\(\gamma p \rightarrow \pi^0 p\)

\(\gamma p \rightarrow \pi^+ n\)

\(\gamma n \rightarrow \pi^- p\)

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

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Space-like & time-like electromagnetic baryonic transitions, Trento, Italy, May 2017

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Many of $\gamma n \rightarrow \pi^- p$ data are old bremsstrahlung measurements with limited angular ($\theta = 40 - 140^\circ$) coverage & large energy binning ($E = 100 - 200$ MeV). In several cases, systematic uncertainties have not been given.

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

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

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

$\gamma n \rightarrow \pi^0 n$ measurement is very small fraction of $\gamma n \rightarrow \pi N$ database.
Phenomenology for Pion Photoproduction
Most of our current knowledge about bound states of three light quarks has come mainly from \( \pi N \rightarrow \pi N \) PWA:

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

Main source of EM couplings is GW, BnGa, & JuBo analyses.
Complete Experiment for Pion PhotoProduction

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

Linear Polarized Beam

Circular Polarized Beam

Nucleon Recoil Polarization

Longitudinally Polarized Nucleon Target

Transverse Polarized Nucleon Target

1 un-pol measurement: \(d\sigma/d\Omega\)

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

[K. Nakayama, private communication, 2014]
Importance of Neutron Data

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

**Proton**

\[
A_{\gamma p \to K^0_p} = -\left[ \frac{1}{3} A^{(0)} - \frac{1}{3} A^{(1)} \right]^{L-\frac{1}{2}} + \frac{2}{3} A^{(J-\frac{3}{2})} \\
A_{\gamma p \to K^+} = \frac{1}{\sqrt{2}} \left[ \frac{1}{3} A^{(0)} - \frac{1}{3} A^{(1)} \right]^{L-\frac{1}{2}} + \frac{\sqrt{2}}{3} A^{(J-\frac{3}{2})}
\]

**Neutron**

\[
A_{\gamma n \to K^0_n} = \left[ -\frac{1}{3} A^{(0)} + \frac{1}{3} A^{(1)} \right]^{L-\frac{1}{2}} + \frac{2}{3} A^{(J-\frac{3}{2})} \\
A_{\gamma n \to K^-} = \frac{1}{\sqrt{2}} \left[ \frac{1}{3} A^{(0)} + \frac{1}{3} A^{(1)} \right]^{L-\frac{1}{2}} + \frac{\sqrt{2}}{3} A^{(J-\frac{3}{2})}
\]

- Proton data alone does not allow separation of isoscalar & isovector components.

Q: Can we avoid?  A: NO!

- Need data on both proton & neutron!
Accurate evaluation of EM couplings $N^* \rightarrow \gamma N$ & $\Delta^* \rightarrow \gamma N$ from meson photoproduction data remains paramount task 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 and needs use of model-dependent nuclear (FSI) corrections.
SAID for Pion Photoproduction
**SAID Progress in PionPR**

- Overall **SAID $\chi^2$** has remained **stable** against growing database, which has increased by **factor of 5** since **1989**.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Energy (MeV)</th>
<th>$\chi^2$/Data</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>MA27</td>
<td>2700</td>
<td>2.02</td>
<td>46,453</td>
</tr>
<tr>
<td>PR15</td>
<td>2700</td>
<td>2.20</td>
<td>37,550</td>
</tr>
<tr>
<td>ST14</td>
<td>2700</td>
<td>2.21</td>
<td>29,720</td>
</tr>
<tr>
<td>DU13</td>
<td>2700</td>
<td>2.09</td>
<td>27,265</td>
</tr>
<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>SM02</td>
<td>2700</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>
<tr>
<td>SP93</td>
<td>1800</td>
<td>3.62</td>
<td>12,466</td>
</tr>
<tr>
<td>SP89</td>
<td>1000</td>
<td>3.31</td>
<td>8,936</td>
</tr>
</tbody>
</table>
SAID for Pion Photoproduction

[P. Mattione et al, to be submitted to Phys Rev C]

- Energy dependent MA27
- $E = 145 - 2700$ MeV  \[W = 1080 - 2460\text{ MeV}\]
- PWs = 60 [EM multipoles] \[J < 6\]
- $Prms = 210$
- Constraint: Born [no free parameters to fit] $\pi N$-PWA [no theoretical input]

<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>Total</td>
<td>46,453</td>
<td>94,258</td>
</tr>
</tbody>
</table>

- There is disbalance between $\pi^+$ & $\pi^0$ data, 35%.
- Pion photoproduction on the neutron much less known, 35%.

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Space-like & time-like electromagnetic baryonic transitions, Trento, Italy, May 2017

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Photo-Decay Amplitudes in BW & Pole Forms

\[ A_{h}^{BW} = C \sqrt{\frac{q_{r} \pi (2J + 1) M_{r} \Gamma^2}{m_{N} \Gamma_{\pi,r}}} A_{h}^{h} \]

\[ A_{h}^{pole} = C \sqrt{\frac{q_{p} 2\pi (2J + 1) W_{p}}{m_{N} \text{Res}_{\pi N}}} \text{Res} A_{h}^{h} \]

Pole is main signature of resonance.

Evaluated at Res Energy

Evaluated at Pole

TABLE I. Breit-Wigner and pole values for selected nucleon resonances. Masses, widths, and residues are given in units of MeV, the helicity 1/2 and 3/2 photo-decay amplitudes in units of $10^{-3} \text{(GeV)}^{-1/2}$. Errors on the phases are generally 2–5 degrees. For isospin 1/2 resonances the values of the proton target are given.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Breit-Wigner values</th>
<th>Pole values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Mass, width)</td>
<td>(Re $W_{p}$, $-2\text{ Im }W_{p}$)</td>
</tr>
<tr>
<td>$\Delta(1232)\ 3/2^{+}$</td>
<td>(1233, 119)</td>
<td>(1211, 99)</td>
</tr>
<tr>
<td>$N(1440)\ 1/2^{+}$</td>
<td>(1485, 284)</td>
<td>(1359, 162)</td>
</tr>
<tr>
<td>$N(1520)\ 3/2^{-}$</td>
<td>(1515, 104)</td>
<td>(1515, 113)</td>
</tr>
<tr>
<td>$N(1535)\ 1/2^{-}$</td>
<td>(1547, 188)</td>
<td>(1502, 95)</td>
</tr>
<tr>
<td>$N(1650)\ 1/2^{-}$</td>
<td>(1635, 115)</td>
<td>(1648, 80)</td>
</tr>
</tbody>
</table>

[R.L. Workman et al, Phys Rev C 87, 068201 (2013)]
[A. Svarc et al, Phys Rev C 89, 065208 (2014)]
SAID
Features & Benefits

• Minimization & Normalization Fact.
• Single-Energy Solutions.
• Forced Fit.
• Narrow Resonances in PWA.
• Quasi-Data.
Minimization & Normalization Factor for Pion Prod $[\chi^2/\text{Data}]$

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

\[
\chi^2 = \sum_i \left( \frac{N\Theta_i - \Theta_i^{\exp}}{\epsilon_i} \right)^2 + \left( \frac{N - 1}{\epsilon_N} \right)^2
\]

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

\begin{table}[h]
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
\textbf{Reaction} & \textbf{SP09} & \textbf{SM02} & \textbf{MAID07} \\
\hline
$\gamma p \rightarrow \pi^0 p$ & 2.2 & 3.6 & 3.2 & 5.7 & 7.7 & 12.3 \\
$\gamma p \rightarrow \pi^+ n$ & 1.9 & 3.3 & 2.1 & 3.9 & 8.1 & 11.7 \\
$\gamma n \rightarrow \pi^- p$ & 1.8 & 2.6 & 1.8 & 2.5 & 2.9 & 3.8 \\
$\gamma n \rightarrow \pi^0 n$ & 2.1 & 2.1 & 2.8 & 2.8 & 6.4 & 6.4 \\
\hline
\end{tabular}
\end{table}

- SAID solutions look more stable vs. MAID.

- For MAID07, normalization constants were searched to minimize $\chi^2$ (no adjustment of partial waves was possible).

- MAID is valid below $W = 2$ GeV.

- CLAS $\pi^+$ & $\pi^0$ & LEPS $\pi^0$ data included.

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

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

- $\chi^2$ measured, $\epsilon_i$ stat error, $\Theta_i$ calculated, $N$ norm const, $\epsilon_N$ its error.

- SAID $< 2500$ MeV
- MAID $< 2000$ MeV

[D. Drechsel et al, Eur Phys J A 34, 69 (2007)]
**Single-Energy Solutions (SES)**

- **SAID** has employed both single-energy (SES) & energy-dependent (Global) solutions over variety of energy ranges in order to estimate uncertainties.

- **SES**: based on bin of data spanning narrow $E$ range $[5 – 75\text{ MeV}]$ searches 2 to 29 prms. 110 SES have been generated with central $E = 147$ to 2650 MeV. # of data in bin varies from 80 to 1100.

- **Systematic deviation** between SES & global fits is indication of
  - Missing structure in global fit.
  - Possible problems with particular dataset.

- **Diagonal Error Matrix** generated in SES fits. It can be used to estimate the overall uncertainties for Global solution.

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**Space-like & time-like electromagnetic baryonic transitions, Trento, Italy, May 2017**

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Forced Fit for Double-Polarization Measurements

[R. Arndt, IS, R. Workman, Phys Rev C 67, 048201 (2003)]

- For $\gamma p \rightarrow \pi^0 p$ at 1900 MeV

- SAID Forced Fit has weighted data by factor of 4 – 5.
- By weighting data, we magnify changes in multipole amplitudes, & more clearly see where data conflicts occur.
- Forced Fit results indicate that what more measurements require for constraint solution.

- DNPL: T measurements
  [P.J. Bussey et al, Nucl Phys B 159, 383 (1979)]
- JLab Hall A:
  There are 22 $C_x$ & 21 $C_z$ below 2 GeV
  [K. Wijesooriya et al, Phys Rev C 66, 034614 (2002)]

- That is not artifact as was possible to think a while ago!
- Hall A data do allow to reproduce previous T measurements well.
**Narrow Resonances in PWA**


- Conventional PWA (by construction) tends to miss narrow Res with $\Gamma < 30$ MeV.

- We assume existence of narrower Res, add it to amplitude, then re-fit over the whole database.

**Refitting**

- If worse description:
  - Resonance with corresponding $M$ & $\Gamma$ is not supported.
- If better description:
  - Resonance may exist.
  - Effect can be due to various corrections (eg, thresholds).
  - Both possibilities can contribute.
- Some additional checks are necessary.

- **True Resonance** should provide the effect only in single particular PW.

- While non-Resonance source may show similar effects in various PWs.
Quasi-Data: What to Expect When you’re Expecting

- Prove motivation of JLab Proposal JLab E-03-105
  Pion Photoproduction from Polarized Target for FROST Project.

\[ R = \frac{u(A_{MC})}{u(A_{world})} \]

Average ratio of uncertainties of amplitudes w/o expected FROST data.

- The data generated by this work will fill number of gaps in existing database of single & double meson photoproduction.

- Greatest effect naturally requires measurement of all possible quantities as accomplished by FROST.

\[ \eta p \quad E: \text{[I. Senderovich et al, Phys Lett B 755, 64 (2016)]} \]
\[ \pi^n p \quad E: \text{[S. Strauch et al, Phys Lett B 750, 53 (2015)]} \]

More results are coming...

Transverse Polarization [H, P, T, F]  Longitudinal Polarization [G, E]

SAID for Charged Baryon Spectroscopy
**CLAS for \( \vec{\gamma}p \rightarrow \pi^0p \) above 1 GeV**

[M. Dugger et al, Phys Rev C 88, 065203 (2013)]

\[ E = 1100-1860 \text{ MeV} \]

\( \pi^0p: 700 \Sigma \]

\( \pi^+n: 386 \Sigma \]

\[ \theta = \text{angles} \]

\[ W (\text{MeV}) \]

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CLAS $\Sigma$ Data Impact for Proton

$S = 0 \& I = \frac{1}{2}$ Couplings

[M. Dugger et al, Phys Rev C 88, 065203 (2013)]

- Largest change is found for $\Delta(1700)3/2^-$ & $\Delta(1905)5/2^+$ states, for which various analyses disagree significantly in terms of photo-decay amplitudes.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$pA_{1/2}$</th>
<th>$pA_{3/2}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta(1700)3/2^-$</td>
<td>132 ± 5</td>
<td>108 ± 5</td>
<td>SAID DU13 [8]</td>
</tr>
<tr>
<td></td>
<td>105 ± 5</td>
<td>92 ± 4</td>
<td>SAID CM12 [2]</td>
</tr>
<tr>
<td></td>
<td>160 ± 20</td>
<td>165 ± 25</td>
<td>BnGa12 [10]</td>
</tr>
<tr>
<td></td>
<td>58 ± 10</td>
<td>97 ± 8</td>
<td>Kent12 [11]</td>
</tr>
<tr>
<td></td>
<td>226</td>
<td>210</td>
<td>MAID [9]</td>
</tr>
<tr>
<td></td>
<td>104 ± 15</td>
<td>85 ± 22</td>
<td>PDG2 [1]</td>
</tr>
<tr>
<td>$\Delta(1905)5/2^+$</td>
<td>20 ± 2</td>
<td>−49 ± 5</td>
<td>SAID DU13 [8]</td>
</tr>
<tr>
<td></td>
<td>19 ± 2</td>
<td>−38 ± 4</td>
<td>SAID CM12 [2]</td>
</tr>
<tr>
<td></td>
<td>25 ± 5</td>
<td>−49 ± 4</td>
<td>BnGa12 [10]</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>−28</td>
<td>MAID [9]</td>
</tr>
<tr>
<td></td>
<td>26 ± 11</td>
<td>−45 ± 20</td>
<td>PDG2 [1]</td>
</tr>
</tbody>
</table>

Relativized Quark Model:
[S. Capstick, Phys Rev D 46, 2864 (1992)]
A2 at MAMI for $\gamma p \rightarrow \pi^0 p$ below 1.6 GeV

[P. Adlarson et al, Phys Rev C 92, 024617 (2015)]

$E = 220–1570$ MeV

$\pi^0 p$: 7978 $d\sigma/d\Omega$
$E_2/M_1$ Ratio for $\Delta(1232) \rightarrow N\gamma$

- Non-relativistic Constituent quark model gives $E_2/M_1 = 0$ [up to relativistic corrections].
- Any solid evidence for deviation would demonstrate necessity of those corrections.

**SAID SES** [E = 335 – 345 MeV] associated with PR15 allows determine E/M ratio.

- The new E/M value by A2 close to 2006 E/M value by previous A2 (there are no new $\Sigma$ data around $\Delta(1232)$) while uncertainty for E/M is smaller now.
- Now A2 is collecting data around $\Delta$-isobar for $\Sigma$.

**E/M estimation on base of**

- G. Blanpied et al, Phys Rev C 64, 025203 (2001)

• The critical role plays 353 MAMI-B $\Sigma$-data $E = 240 – 440$ MeV $\theta = 11 – 170$ deg

$R \simeq ReM = \frac{\Im E_1^{3/2}}{\Im M_1^{3/2}}_{W=M_\Delta}$
CB-ELSA for $\vec{\gamma} \vec{p} \rightarrow \pi^0 p$ around 1 GeV

[A. Thiel et al, Phys Rev Lett 109, 102001 (2012)]

E = 633–1300 MeV
\( \pi^0 p: 318 \text{ G} \)

Linearly pol Beam
Longitudinally pol Target

\[ G(\pi^0 p) \]

\[ E = E_{\text{MeV}} \]

\[ E = 633, 667, 700, 733, 767, 800, 833, 867, 900, 933, 967, 1000, 1033, 1067, 1100, 1150, 1200, 1250, 1300 \]

\[ \theta (\text{deg}) \]

DU12
GU12
GFI2
MAID07
BnGa12

[including CLAS $\Sigma$ for $\pi^0$ & $\pi^+$]
[including CLAS $\Sigma$ and Bonn $\pi^0 G$]
[including CLAS $\Sigma$ and Bonn $\pi^0 G^*4$]
Impact of New Polarization Data


- Independent PWA fits by BnGa, JuBo, & SAID

- Work together with:
  BnGa: A. Sarantsev, ....
  JuBo: D. Rönchen, M. Döring
  SAID: R. Workman, ....

- Clear convergence between different PWA’s.
Previous neutron measurements used modified Glauber approach & procedure of unfolding Fermi motion of “neutron” target.
FSI and $\gamma d \rightarrow \pi pN \rightarrow \gamma n \rightarrow \pi N$

- 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 $(E, \theta)$.

Fermi motion of nucleons included

\begin{align*}
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)
\end{align*}
**FSI for \( \gamma d \to \pi^- \eta \to \pi p \)**

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

- There is no large sensitivity to cuts.

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

- Previous estimations gave order of 15-30%.

- For CLAS data
  - FSI correction factor \( R < 1 \).
  - Behavior is smooth vs. \( \theta \).
  - Effect: \( \Delta \sigma / \sigma \leq 10\% \).

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

- Region narrows as \( E_\gamma \) increases.

For CLAS data:
- FSI correction factor \( R < 1 \).
- Behavior is smooth vs. \( \theta \).
- Effect: \( \Delta \sigma / \sigma \leq 10\% \).
FSI for $\gamma d \rightarrow \pi^0 np \leftrightarrow \gamma n \rightarrow \pi^0 n$

[V. Tarasov, A. Kudryavtsev, W. Briscoe, B. Krusche, IS, M. Ostrick, Phys At Nucl 79, 216 (2016)]

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

- In general case,

$$R_n = R_p$$

$$R_n \neq R_p$$
SAID for Neutral Baryon Spectroscopy
**CLAS g10 for γn → π−p above 1 GeV**


- The CLAS g10 cross sections have quadrupled world database for γn → π−p above Eγ = 1 GeV.

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

\[ \chi^2/dp = 45636/626 = 72.9 \quad [SN11 – no fit] \]
\[ \chi^2/dp = 1580/626 = 2.5 \quad [GB12 – fit] \]

- The CLAS g10 cross sections have quadrupled world database for γn → π−p above Eγ = 1 GeV.

**FSI included**

\[ E = 1050–2700 \text{ MeV} \]
\[ π−p: 626 \text{ dσ/dΩ} \]

- CLAS data appear to have fewer angular structures than the earlier fits.
**CLAS Data Impact for Neutron $S = 0$ & $I = \frac{1}{2}$ Couplings**

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

<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>
</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>
</tr>
<tr>
<td></td>
<td>−60±3</td>
<td></td>
<td>−47±2</td>
<td>−125±2</td>
<td>SAID SN11 [25]</td>
</tr>
<tr>
<td>S$_{11}$</td>
<td>−93±11</td>
<td>D$_{13}$</td>
<td>−49±8</td>
<td>−113±12</td>
<td>BnGa13 [26]</td>
</tr>
<tr>
<td></td>
<td>−49±3</td>
<td></td>
<td>−38±3</td>
<td>−101±4</td>
<td>Kent12 [11]</td>
</tr>
<tr>
<td></td>
<td>−46±27</td>
<td></td>
<td>−59±9</td>
<td>−139±11</td>
<td>PDG [1]</td>
</tr>
<tr>
<td>$N(1650)1/2^-$</td>
<td>−40±10</td>
<td>$N(1675)5/2^-$</td>
<td>−58±2</td>
<td>−80±5</td>
<td>SAID GB12 [17]</td>
</tr>
<tr>
<td></td>
<td>−26±8</td>
<td></td>
<td>−42±2</td>
<td>−60±2</td>
<td>SAID SN11 [25]</td>
</tr>
<tr>
<td>S$_{11}$</td>
<td>25±20</td>
<td>D$_{15}$</td>
<td>−60±7</td>
<td>−88±10</td>
<td>BnGa13 [26]</td>
</tr>
<tr>
<td></td>
<td>11±2</td>
<td></td>
<td>−40±4</td>
<td>−68±4</td>
<td>Kent12 [11]</td>
</tr>
<tr>
<td></td>
<td>−15±21</td>
<td></td>
<td>−43±12</td>
<td>−58±13</td>
<td>PDG [1]</td>
</tr>
<tr>
<td>$N(1440)1/2^+$</td>
<td>48±4</td>
<td>$N(1680)5/2^+$</td>
<td>26±4</td>
<td>−29±2</td>
<td>SAID GB12 [17]</td>
</tr>
<tr>
<td></td>
<td>45±15</td>
<td></td>
<td>50±4</td>
<td>−47±2</td>
<td>SAID SN11 [25]</td>
</tr>
<tr>
<td>P$_{11}$</td>
<td>43±12</td>
<td>F$_{15}$</td>
<td>34±6</td>
<td>−44±9</td>
<td>BnGa13 [26]</td>
</tr>
<tr>
<td></td>
<td>40±5</td>
<td></td>
<td>29±2</td>
<td>−59±2</td>
<td>Kent12 [11]</td>
</tr>
<tr>
<td></td>
<td>40±10</td>
<td></td>
<td>29±10</td>
<td>−33±9</td>
<td>PDG [1]</td>
</tr>
</tbody>
</table>

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

- **New GB12** $nA_{1/2}$ & $nA_{3/2}$ couplings shown sometimes significant deviation from our previous SAID determination (**SN11** & **PDG12**) average values, eg, for $N(1650)1/2^-$, $N(1675)5/2^-$, & $N(1680)5/2^+$.  

- **Fresh BnGa13** has some difference vs. **GB12**, **PDG12**, & relativized quark model, eg, for $N(1650)1/2^-$, $N(1650)1/2^-$, & $N(1680)5/2^+$.  

---

S. Capstick, Phys Rev D 46, 2864 (1992)
CLAS \( g_{13} \) for \( \gamma n \rightarrow \pi^- p \) above 0.5 GeV

\[ E = 445 - 2510 \text{ MeV} \]
\[ \pi^- p: 8428 \frac{d\sigma}{d\Omega} \]

These data a factor of nearly three increase in world statistics for this channel in this kinematic range.

FSI included
Comparison of Previous & New SAID Fits

[P. Mattione et al, to be submitted to Phys Rev C]

- Recent SAID PR15 applied to g13 data without & with FSI corrections.
- New SAID MA27 fit obtained after adding new g13 data with FSI corrections.
**CLAS Data Impact for Neutron**

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

[P. Mattione et al, to be submitted to Phys Rev C]

- Selected photon decay amplitudes \( N^* \rightarrow \gamma n \) at resonance poles are determined for the first time.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1440)1/2^+</td>
<td>A_{1/2}(n)</td>
<td>0.065±0.005, 5°±3°</td>
<td>0.048±0.004</td>
<td>0.043±0.012</td>
<td>0.054</td>
<td>-0.006</td>
<td>0.040±0.010</td>
</tr>
<tr>
<td>N(1535)1/2^-</td>
<td>A_{1/2}(n)</td>
<td>-0.055±0.005, 5°±2°</td>
<td>-0.058±0.006</td>
<td>-0.093±0.011</td>
<td>-0.051</td>
<td>-0.063</td>
<td>-0.075±0.020</td>
</tr>
<tr>
<td>N(1650)1/2^-</td>
<td>A_{1/2}(n)</td>
<td>0.014±0.002, -30°±10°</td>
<td>-0.040±0.010</td>
<td>0.025±0.020</td>
<td>0.009</td>
<td>-0.035</td>
<td>-0.050±0.020</td>
</tr>
<tr>
<td>N(1720)3/2^+</td>
<td>A_{1/2}(n)</td>
<td>-0.016±0.006, 10°±5°</td>
<td>-0.080±0.050</td>
<td>-0.003</td>
<td>0.004</td>
<td>0.004</td>
<td>-0.080±0.050</td>
</tr>
<tr>
<td>N(1720)3/2^+</td>
<td>A_{3/2}(n)</td>
<td>0.017±0.005, 90°±10°</td>
<td>-0.140±0.065</td>
<td>-0.031</td>
<td>0.011</td>
<td>0.011</td>
<td>-0.140±0.065</td>
</tr>
</tbody>
</table>

**BW** neutron photo-decay amplitudes

- Moduli & phases

**GW**

- Data Analytics Center
- Institute for Nuclear Studies
- POSTECH, Korea University

**MAID**

- M A I D

**PDG**

- Particle Data Group
CLAS Data Impact for Neutron

$S = 0 \& I = \frac{1}{2}$ Couplings

[D. Ho et al, submitted to Phys Rev Lett]

- Inclusion of these $g_{14}$ data in new PWA calculations has resulted in revised $\gamma n N^*$ couplings & in case of $N(2190)7/2^-$, convergence among different PWA groups.

- Such couplings are sensitive to dynamical process of $N^*$ excitation & provide important guides to nucleon structure models.

$E = 730–2345$ MeV

$\pi^- p$: 266 E

No FSI included

Courtesy of Andy Sandorfi, 2017
• Differential cross sections for $\gamma n \rightarrow \pi^0 n$.

$E = 180 - 800$ MeV

$\pi^0 n$: $589 \, \text{d}\sigma/\text{d}\Omega$

New $\text{d}\sigma/\text{d}\Omega$ by A2 contribution is 160% to previous world $\pi^0 n$ data.
Summary for Pion Photoproduction Study

• Since 1989 pion photoproduction database below $W = 2.5$ GeV was increased by factor of 5 (most of new data came for $\gamma p \rightarrow \pi^0 p$) & is compatible with $\pi N \rightarrow \pi N$ database now.

• Pion photoproduction on proton with $\pi^+ n$ final state much less known than with $\pi^0 p$ one (35%).

• Pion photoproduction on "neutron" much less known than on proton (35%) & "neutron" database grows.
  FSI tool is available for diff. cross sections for both $\pi^- p$ & $\pi^0 n$ final states.

• Now we are able to extract pole positions on complex energy plane for both $N^* \rightarrow \gamma p$ & $\gamma n$ photo-decay amplitudes.

Thanks!
This is just the beginning of the story... We don't know yet which way it will go

“Would you tell me, please, which way I ought to go from here?”
“ That depends a good deal on where you want to get to,” said the Cat.
“I don't much care where ---” said Alice.
“Then it doesn't matter which way you go,” said the Cat.
“--- so long as I get somewhere,” Alice added as an explanation.
“Oh, you're sure to do that,” said the Cat “if you only go long enough.”
A Letter of Intent to Jefferson Lab PAC-43.

Physics Opportunities with a Secondary $K_L^0$ Beam at JLab.

Moskov J. Amaryan (spokesperson),¹ • Yakov I. Azimov,² William J. Briscoe,³ Eugene Chudakov,⁴ Pavel Degtyarenko,⁴ Gail Dodge,¹ Michael Döring,³ Helmut Haberzettl,³ Charles E. Hyde,¹ Benjamin C. Jackson,⁵ Christopher D. Keith,⁴ Ilya Larin,¹ Dave J. Mack,⁴ D. Mark Manley,⁶ Kanzo Nakayama,⁵ Yongseok Oh,⁷ Emilie Passemard,⁸ Diane Schott,³ Alexander Somov,⁴ Igor Strakovsky,³ and Ronald Workman³

¹ Old Dominion University, Norfolk, VA 23529
² Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg 188300, Russia
³ The George Washington University, Washington, DC 20052
⁴ Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606
⁵ The University of Georgia, Athens, GA 30602
⁶ Kent State University, Kent, OH 44242
⁷ Kyungpook National University, Daegu 702-761, Korea
⁸ Indiana University, Bloomington, IN 47405

(Dated: May 14, 2015)

We will submit full Proposal for JLab PAC45 in 2 weeks.
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) & 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 $2 \times 10^{-3}$

SAID-PE12
SAID-SN11
MAID07
Double Polarization Observable $E$ for $\pi^+ n$

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0(1 - P_zP_\phi E)$$

$W = 1240 - 2260$ MeV

$-0.9 \leq \cos(\theta_{\pi}) \leq +0.9$

$E = 360 - 2180$ MeV

$\pi^+ n$: 900 $E$

$W = 1650$ MeV

$W = 1920$ MeV

$W = 2170$ MeV

Courtesy of Steffen Strauch, CIPANP 2015
## CLAS Data Impact for Neutron \( S = 0 \) \& \( I = \frac{1}{2} \) Couplings

[S. Strauch et al, Phys Lett B 750, 53 (2015)]

Fits to the new CLAS data (labeled E) and previous results. Breit-Wigner helicity amplitudes for the SAID (ST14 based on CM12 [11]) and Bonn-Gatchina ([12]; \(^\dagger\): entries from Ref. [9]) analyses. Values from Jülich-Bonn (JUB014 based on Ref. [10]) are quoted at the \( T \)-matrix pole including the complex phase in parentheses. Helicity amplitudes \( A_{1/2} \) and \( A_{3/2} \) are given in units of (GeV\(^{-1}\))^\(1/2\) \(\times 10^{-3}\).

<table>
<thead>
<tr>
<th></th>
<th>ST14</th>
<th>ST14E</th>
<th>JUB014</th>
<th>JUB014E</th>
<th>BnGa11E</th>
<th>BnGa14E</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1440)1/2(^+)</td>
<td>( A_{1/2} )</td>
<td>(-65 \pm 5)</td>
<td>(-60 \pm 5)</td>
<td>(-56(\pm 5^\circ))</td>
<td>(-53(\pm 6^\circ))</td>
<td>(-62 \pm 8)</td>
</tr>
<tr>
<td>N(1520)3/2(^-)</td>
<td>( A_{1/2} )</td>
<td>(-22 \pm 2)</td>
<td>(-24 \pm 2)</td>
<td>(-25(\pm 13^\circ))</td>
<td>(-22(\pm 14^\circ))</td>
<td>(-20 \pm 3)</td>
</tr>
<tr>
<td>N(1535)1/2(^-)</td>
<td>( A_{1/2} )</td>
<td>(142 \pm 5)</td>
<td>(138 \pm 3)</td>
<td>(112(\pm 28^\circ))</td>
<td>(104(\pm 22^\circ))</td>
<td>(131 \pm 7)</td>
</tr>
<tr>
<td>N(1650)1/2(^-)</td>
<td>( A_{1/2} )</td>
<td>(115 \pm 10)</td>
<td>(120 \pm 10)</td>
<td>(52(\pm 14^\circ))</td>
<td>(51(\pm 20^\circ))</td>
<td>(105 \pm 9)</td>
</tr>
<tr>
<td>( \Delta(1620)1/2(^-) )</td>
<td>( A_{1/2} )</td>
<td>(55 \pm 30)</td>
<td>(60 \pm 30)</td>
<td>(28(\pm 7^\circ))</td>
<td>(30(\pm 21^\circ))</td>
<td>(33 \pm 7)</td>
</tr>
<tr>
<td>( \Delta(1700)3/2(^-) )</td>
<td>( A_{1/2} )</td>
<td>(35 \pm 5)</td>
<td>(30 \pm 5)</td>
<td>(23(\pm 14^\circ))</td>
<td>(25(\pm 13^\circ))</td>
<td>(52 \pm 5)</td>
</tr>
<tr>
<td>( \Delta(1905)5/2(^+) )</td>
<td>( A_{1/2} )</td>
<td>(128 \pm 20)</td>
<td>(150 \pm 20)</td>
<td>(118(\pm 6^\circ))</td>
<td>(121(\pm 14^\circ))</td>
<td>(160 \pm 20^\dagger)</td>
</tr>
<tr>
<td>( \Delta(1905)7/2(^+) )</td>
<td>( A_{3/2} )</td>
<td>(91 \pm 30)</td>
<td>(110 \pm 30)</td>
<td>(106(\pm 20^\circ))</td>
<td>(116(\pm 52^\circ))</td>
<td>(165 \pm 25^\dagger)</td>
</tr>
<tr>
<td>( \Delta(1950)3/2(^+) )</td>
<td>( A_{1/2} )</td>
<td>(30 \pm 6)</td>
<td>(30 \pm 5)</td>
<td>(13(\pm 17^\circ))</td>
<td>(39(\pm 26^\circ))</td>
<td>(25 \pm 5^\dagger)</td>
</tr>
<tr>
<td>( \Delta(1950)3/2(^+) )</td>
<td>( A_{3/2} )</td>
<td>(-70 \pm 10)</td>
<td>(-50 \pm 10)</td>
<td>(-79(\pm 59^\circ))</td>
<td>(-49(\pm 67^\circ))</td>
<td>(-49 \pm 4^\dagger)</td>
</tr>
<tr>
<td>( \Delta(1950)7/2(^+) )</td>
<td>( A_{1/2} )</td>
<td>(-70 \pm 5)</td>
<td>(-80 \pm 5)</td>
<td>(-70(\pm 15^\circ))</td>
<td>(-64(\pm 16^\circ))</td>
<td>(-70 \pm 5)</td>
</tr>
<tr>
<td>( \Delta(1950)7/2(^+) )</td>
<td>( A_{3/2} )</td>
<td>(-90 \pm 5)</td>
<td>(-90 \pm 5)</td>
<td>(-86(\pm 8^\circ))</td>
<td>(-91(\pm 7^\circ))</td>
<td>(-93 \pm 5)</td>
</tr>
</tbody>
</table>
\[ \Sigma \text{ for } \gamma n \rightarrow p \pi^- \]

- SAID can fit CLAS $\Sigma$s with $\chi^2/dp = 2.6$

- No FSI included

9 out of 40 angular bins are shown
Bins 0.04 in $\cos \theta$ and 20 MeV in $W$

Courtesy of Daria Sokhan, 2013

D. Sokhan

5/8/2017

Space-like & time-like electromagnetic baryonic transitions, Trento, Italy, May 2017

Igor Strakovsky
Recent GRAAL $\Sigma$ for $\gamma n \rightarrow \pi^- p$

[G. Mandaglio et al, Phys Rev C 82, 045209 (2010)]

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

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

- $\chi^2$/dp
  - MAID07: 100
  - SP09: 223
  - MA09: 3.1

No FSI included

- GRAAL data are in

- MA09
- SP09
- MAID07
- DTM

5/8/2017  Space-like & time-like electromagnetic baryonic transitions, Trento, Italy, May 2017  Igor Strakovsky  52
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 $\gamma n \rightarrow \pi^- p \rightarrow \pi^0 n$.

---

**Projected results**

- MAID07
- FA07
- TRIUMF data

- 2.1% stat, 7.1% syst
- 32 X 650 keV bins

---

**FSI**

- Average Ratio
- $E$ (MeV)

---

**MAX-lab for $\gamma n \rightarrow \pi^- p$ at Threshold**

---

**Photon detectors**

- Onsite: 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 $E_\gamma \approx 130$ MeV (endpoint is 131.4 MeV)
  - $\Delta E_\gamma / E_\gamma \approx 2\%$
  - $\varepsilon_\gamma \approx 98\%$
- $\Delta \Omega \approx 40$ msr at nominal distances
\( \gamma d \rightarrow \pi^- pp \) from **DESY Bubble Chamber**

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

**No fit to data**

DESY [Bubble Chamber data]:
[P. Benz et al, Nucl Phys B 65, 158 (1973)]
No fit to data

MAMI-B data:
[B. Krusche et al, Eur Phys J A 6, 309 (1999)]
FSI for $\gamma n \rightarrow \pi^0 n$

[V. Tarasov, A. Kudryavtsev, W. Briscoe, B. Krusche, IS, M. Ostrick, Phys At Nucl 79, 216 (2016)]

- FSI corrections for $\gamma n \rightarrow \pi^0 n$ using full MC simulations for Crystal Ball setting.
The Production of Charged Photomesons from Deuterium and Hydrogen. I*

R. S. White, M. J. Jacobson, and A. G. Schulz
Radiation Laboratory, Department of Physics, University of California, Berkeley, California
(Received June 30, 1952)

These free nucleon reactions are thought to be

\[ \gamma + p \rightarrow n + \pi^+ , \]
\[ \gamma + n \rightarrow p + \pi^- . \]

The first reaction has been studied by Steinberger, Bishop, and Cook\textsuperscript{4-6} and by Feld \textit{et al.}\textsuperscript{11} and the second has not been investigated because of the lack of a concentrated target of neutrons. As an alternative to the free nucleon reactions, this experiment has utilized the loosely bound neutron and proton in the deuteron to compare the above production cross sections.
**Complete Experiment for Pion Photoproduction**

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

**Spin:** 1\
\[ \frac{1}{2} \rightarrow \frac{1}{2} \ \ 0 \]

**Helicities:** 2 \times 2 \times 2 / 2 = 4

**Parity conservation**

Therefore, there are 4 independent invariant amplitudes

- In order to determine pion photoproduction amplitude [4 modules & 3 relative phases], one has to carry out 7 independent measurements at fixed \((s, t)\) or \((E, \theta)\).

Extra observable is necessary to eliminate sign ambiguity.

**In particle physics, helicity** is projection of spin \(\vec{S}\) onto direction of momentum, \(\hat{p}\):

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

\[ \hat{p} = \frac{\vec{p}}{|\vec{p}|} \]
We update **SAID** databases, develop & study PWAs, & keep current versions of phenomenological & theoretical models, both those of CNS/DAC & other research groups, on continual basis for relevant two- & three-body reactions of interest.

In the **full database**, one will occasionally find experiments which give conflicting results.

**Some data** with very large $\chi^2$ contributions have been excluded from our fits.

**Redundant data** are also excluded [these include $\sigma_{\text{tot}}$ based on $d\sigma/d\Omega$ already contained in database]

**Measurements of pol observables** ($P$, for instance) with uncertainties more than 0.2 are not included as they have little influence in our fits.

However, all available data have been **retained** in database (excluded data labeled as “flagged”) so that comparisons can be made through our on-line facility

For $\pi\to2\pi$, we use **log-likelihood** while for rest – **least-squares** technologies.

---

**SAID Database below 4 GeV**

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

**Partially-Wave Analyses at GW**

- Pion-Nucleon
- Pi-Pi-N
- Kaon(+)-Nucleon
- Nucleon-Nucleon
- Pion Photoproduction
- Pion Electroproduction
- Kaon Photoproduction
- Eta Photoproduction
- Eta-Prime Photoproduction
- Pion-Deuteron (elastic)
- Pion-Deuteron to Proton+Proton

[W = 1320 to 1930 MeV]

- 50,650
- 5,576
- 47,353
- 12,864
- 852
- 4,398

- 241,214 evts+
- 38,414
- 107,915
- 6,502
- 2,736

---


Igor Strakovsky
Pion Photoproduction with Polarized Beam and Polarized Target

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

\[ E_{l\pm}, M_{l\pm} \]

- Multipole components of EM 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

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

\[ ML : \quad (-1)^{L+1} = (-1)^{l_{\pi} + 1} \Rightarrow L = l_{\pi} \]
Watson’s Theorem
• Connection between **scattering** & **decay processes** provides solid theoretical ground for describing some hadronic effects – “**Watson’s theorem.**”

• For **pion photoproduction**, **isospin amplitudes** have to satisfy **Watson’s theorem** below **$2\pi$-threshold** allowing for smooth departure from constraint at high energies.

\[
\arctan\left(\frac{\text{Im}A}{\text{Re}A}\right) = \delta_I(\pi N)
\]

• Above **$2\pi$-threshold**, rule may still be true, if **inelasticity** of corresponding **$\pi N$-elastic** amplitude is small (as, eg, for $P_{33}$.)
Evaluation of PionPR Amplitudes below 2π-Threshold

- **SAID** uses $\pi N$ PWA results as constraint for analysis of PionPR data.

- Most of PionPR analyses are doing the same & uses SAID $\pi N$ outcome or its modification as input.

- Let us evaluate several PionPR analyses such as **SAID**, **MAID**, **EBAC**, **Giessen**, & **BnGa** and compare $\pi N$ phases coming from $\pi N$ & PionPR amplitudes on proton target.

- **SAID database** has all these amplitudes which came from authors or we used WebSites.

<table>
<thead>
<tr>
<th>reaction</th>
<th>W(GeV)</th>
<th>E_g(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g p \rightarrow p^0 p$</td>
<td>1.073</td>
<td>144.7</td>
</tr>
<tr>
<td>$g p \rightarrow \pi^0 n$</td>
<td>1.079</td>
<td>151.4</td>
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</table>

<table>
<thead>
<tr>
<th>Amplitude Source</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAID</strong></td>
<td>L. Tiator <em>et al</em>, PC 2008.</td>
</tr>
<tr>
<td><strong>BnGa</strong></td>
<td>A. Sarantsev <em>et al</em>, PC 2009.</td>
</tr>
<tr>
<td><strong>PionPR</strong></td>
<td>R. Workman <em>et al</em>, PC 2012.</td>
</tr>
</tbody>
</table>
3/2 Isospin Amplitudes for $E$ & $M$

![Graphs showing isospin amplitudes](image)

- $S_{31}pE$
- $P_{31}pM$
- $P_{33}pE$
- $P_{33}pM$

**Legend:**
- SAID
- MAID
- EBAC
- Giessen
- BnGa

**Plot Details:**
- $W$ (MeV) on the x-axis.
- Amplitudes on the y-axis.
- Data points and lines represent different models for $E$ and $M$ transitions.
Summary for Watson’s Theorem for Proton Amplitudes

- Phases coming from $\pi N$ amplitudes of different analyses are consistent.

- Some phases coming from different PionPR analyses are consistent to each other & phases coming from $\pi N$ amplitudes:
  
  **3/2 Isospin Amplitudes**: E0+, E1+, & M1+.

- Some phases coming from different PionPR analyses are inconsistent to each other & phases coming from $\pi N$ amplitudes:
  
  **3/2 Isospin Amplitudes**: M1−, E2−, M2−, E2+, & M2+.

  **1/2 Isospin Amplitudes**: E0+, M1−, E1+, M1+, E2−, M2−, E2+, & M2+.

- Some phases coming from E & M multipoles are inconsistent to each other & phases coming from $\pi N$ amplitudes.