SAID Analysis of Meson Photoproduction: Determination of Neutron and Proton EM Couplings

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Based on work in collaboration with Dick Arndt, Bill Briscoe & Ron Workman, Alexander Kudryavtsev & Vladimir Tarasov

- SAID for Baryon Spectroscopy.
- Pion photoproduction off the proton.
- Recent proton data for EM couplings.
- Pion photoproduction off the neutron.
- FSI for $\gamma n \rightarrow \pi^- p$.
- Recent GW-ITEP FSI for $\gamma n \rightarrow \pi^- p$.
- New neutron EM couplings.
- Polarized Measurements.
SAID for Baryon Spectroscopy
Original: PWA arose as the technology to determine amplitude of the reaction via fitting scattering data which is a non-trivial mathematical problem

[Solution of ill-posed problem
– Hadamard, Tikhonov, et al]

Resonances appeared as a by-product
[Bound states objects with definite quantum numbers, mass, lifetime, etc]

That is the strategy of the GW/VPI πN PWA since 1987

For π→2π, we use log-likelihood while for the rest – least-squares technologies.

Below 4 GeV

[\(W = 1320\) to 1930 MeV]

241,214 evts
38,162
113,900
6,235
1,914


Igor Strakovsky
$N^*$ and $\Delta^*$ States coupled to $\pi N$

Assuming dominance of 2-hadronic channels [$\pi N$ 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 a non-strange baryon Spectroscopy [a key to our understanding of QCD] is $\pi N$ PWA.


- The main source of EM couplings is the GW & BnGa analyses.

GW SAID $N^*$ program consists of $\pi N \rightarrow \pi N \rightarrow \gamma N \rightarrow \pi N \rightarrow \gamma^* N \rightarrow \pi N$

As was established by Dick Arndt on 1997.
### Status of Non-strange Resonances: PDG12

- More than half of states have poor evidence.
- Most of states need more work to do.
- Most of QCD models predict more states than observed.
- Where are missing resonances?

#### GW SAID Contribution

**I = 1/2**

<table>
<thead>
<tr>
<th>Particle</th>
<th>J^P</th>
<th>Status as seen in —</th>
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</thead>
<tbody>
<tr>
<td>N(1440) 1/2^+</td>
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<tr>
<td>N(1520) 3/2^-</td>
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<tr>
<td>N(1535) 1/2^-</td>
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<td>N(1685) ??</td>
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<td>N(1900) 3/2^-</td>
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<td>N(1990) 7/2^+</td>
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<td>N(2000) 5/2+</td>
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<td>N(2040) 3/2+</td>
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<td>N(2060) 5/2-</td>
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<tr>
<td>N(2100) 1/2^-</td>
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<td>N(2150) 3/2^-</td>
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<td>N(2190) 7/2^+</td>
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<td>N(2220) 9/2^-</td>
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<tr>
<td>N(2250) 9/2^-</td>
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<tr>
<td>N(2600) 11/2^-</td>
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<td></td>
</tr>
<tr>
<td>N(2700) 13/2^+</td>
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**I = 3/2**

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<td>Δ(1700) 3/2^-</td>
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<td></td>
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<tr>
<td>Δ(1750) 1/2^+</td>
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<tr>
<td>Δ(1900) 1/2^-</td>
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<tr>
<td>Δ(1905) 5/2+</td>
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<td>Δ(1910) 1/2^-</td>
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<td>Δ(1920) 3/2^-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δ(1930) 5/2^-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δ(1940) 3/2^-</td>
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<td>Δ(1950) 3/2^-</td>
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<tr>
<td>Δ(2150) 1/2^-</td>
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<tr>
<td>Δ(2200) 7/2^-</td>
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<td>Δ(2300) 9/2^-</td>
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<tr>
<td>Δ(2750) 13/2^-</td>
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<tr>
<td>Δ(2950) 15/2^+</td>
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</tbody>
</table>

**SAID:**
- Tends (by construction) to miss narrow N* s with \( \Gamma < 30 \) MeV
- Reveals only wide N* s, but not too wide \( \Gamma < 500 \) MeV and possessing not too small BR \( BR > 0.04 \)
Where We Are Now

- Some of the N* baryons [N(1675)D_{15}, for instance] have stronger EM coupling to the neutron than to the proton but parameters are very uncertain.

\[ N(1675) \, 5/2^- \quad \ell(J^P) = \frac{1}{2}(\frac{3}{2}^-) \quad \text{Status: ****} \]

- PDG estimates for the A_{1/2} & A_{3/2} decay amplitudes of the N(1720)P_{13} state are consistent with zero, while the recent SAID determination gives small but non-vanishing values.

\[ N(1720) \, 3/2^- \quad \ell(J^P) = \frac{1}{2}(\frac{3}{2}^+) \quad \text{Status: *** P}_{13} \]

- Other unresolved issues relate to the second P_{11}, N(1710)P_{11}, that are not seen in the recent πN PWA, contrary to other PWAs used by the PDG12.

\[ N(1710) \, 1/2^+ \quad \ell(J^P) = \frac{1}{2}(\frac{3}{2}^+) \quad \text{Status: *** P}_{11} \]

The latest GWU analysis (ARNDT 06) finds no evidence for this resonance.

• Energy dependent **SP06/WI08** and associated SES
  - \( T = 0 - 2600 \text{ MeV} \)
  - 4-channel Chew-Mandelstam **K-matrix** parameterization
  - 3 mapping variables: \( g^2/4\pi, a[\pi p], \text{Eth} \)
  - PWs = 30 \( \pi N \) \{15 \([I=1/2]\) + 15 \([I=3/2]\)\} + 4 \( \eta N \)
  - Prms = \[99 \([I=1/2]\) + 89 \([I=3/2]\)\]

**Reaction Data**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Data</th>
<th>( \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^+ p \rightarrow \pi^+ p )</td>
<td>13,354</td>
<td>27,136</td>
</tr>
<tr>
<td>( \pi^- p \rightarrow \pi^- p )</td>
<td>11,978</td>
<td>22,632</td>
</tr>
<tr>
<td>( \pi^- p \rightarrow p^0 n )</td>
<td>3,115</td>
<td>6,068</td>
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<tr>
<td>( \pi^- p \rightarrow \eta n )</td>
<td>257</td>
<td>650</td>
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<tr>
<td><strong>DR constraint</strong></td>
<td>2,775</td>
<td>671</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>31,479</td>
<td>57,157</td>
</tr>
</tbody>
</table>

[\( W = 1078 - 2460 \text{ MeV} \)  
\( \pi N, \pi \Delta, \rho N, \eta N \)]

[\( I < 9 \) ]

- **1st generation** (‘57–’79)
  - Used by CMB79 and KH84 analyses.
  - \( 10k \) \( \pi \pm p \) each & \( 1.5k \) CXS.
  - 17% data is polarized.

- **2nd generation** (‘80–’06)
  - SAID fits:
    - \( 13k \) \( \pi \pm p \) each, \( 3k \) CXS & \( 0.3k \) \( \pi^- p \rightarrow \eta n \)
  - 25% data is polarized.
  - Meson Factories [LAMPF, TRIUMF, & PSI] are the main source of new measurements.
  - There is no discrimination against data

- **3rd generation** (07+)
  - New data may come from J-PARC, HADES, EPECUR, etc

\( 27 \sigma_{\text{tot}} \) & \( 37 \) \( p \) data above \( 800 \text{ MeV} \) \( \rightarrow 0.03 \text{ data/MeV} \)
Pion Photoproduction: Phenomenological Point of View Shot
Single Pion Photoproduction

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

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

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

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


A.B. Migdal, JETP 1, 2 (1955); K.M. Watson, Phys Rev 95, 228 (1954)
SAID for Pion Photoproduction

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

- Energy dependent GB12 and associated SES
- \( E = 145 - 2700 \ \text{MeV} \) \( [W = 1080 - 2460 \ \text{MeV}] \)
- PWs = 60 [E & M multipoles] \( [J < 6] \)
- Prms = 210
- Constraint: \( M = (\text{Born} + A)(1+iT_{\pi N}) + BT_{\pi N} + (C+iD)(\text{Im}T_{\pi N} - |T_{\pi N}|^2) \)

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

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

Much less known, 15%

23,122 data
3,422 data
Recent \textit{SAID} Progress in Pion\textit{PR}

\begin{itemize}
  \item DU13: included recent \textit{CLAS}  $\pi^0 p$ \& $\pi^+ n$ $\Sigma$ [M. Dugger \textit{et al}, arXiv:1308.4028[nucl-ex]]
  \item GB12/GZ12: included recent \textit{CLAS}  $\pi^- p$ $d\sigma/d\Omega$ [W. Chen \textit{et al}, Phys Rev C \textbf{86}, 015206 (2012)]
  \item CM12: \textit{CM} parameterization for $T_{\pi N}$ [R. Workman \textit{et al}, Phys Rev C \textbf{86}, 015202 (2012)]
  \item SN11/SK11: included recent \textit{GRAAL}  $\pi^- p$ \& $\pi^0 n$ $\Sigma$
  \item LEPS  $\pi^0 p$ $d\sigma/d\Omega$ [R. Workman \textit{et al}, Phys Rev C \textbf{85}, 025201 (2012)]
  \item SP12: included recent \textit{CLAS}  $\pi^+ n$ $d\sigma/d\Omega$ [M. Dugger \textit{et al}, Phys Rev C \textbf{79}, 065206 (2009)]
  \item M = \((\text{Born} + A)(1 + iT_{\pi N}) + BT_{\pi N} + (C + iD)(|T_{\pi N}|^2 - |T_{\pi N}|^2))$$
  \item M = \((\text{Born} + \alpha_R)(1 + iT_{\pi N}) + \alpha_R T_{\pi N} + \text{higher terms}$$
\end{itemize}

\begin{tabular}{|c|c|c|c|}
\hline
Solution & Energy Limit (MeV) & $\chi^2/N_{\text{Data}}$ & $N_{\text{Data}}$ \\
\hline
DU13 & 2700 & 2.23 & 27,265 \\
GB12 & 2700 & 2.09 & 26,179 \\
CM12 & 2700 & 2.01 & 25,814 \\
SN11 & 2700 & 2.08 & 25,553 \\
SP09 & 2700 & 2.05 & 24,912 \\
FA06 & 3000 & 2.18 & 25,524 \\
SM02 & 2000 & 2.01 & 17,571 \\
SM95 & 2000 & 2.37 & 13,415 \\
\hline
\end{tabular}

\begin{itemize}
  \item The overall \textit{SAID} $\chi^2$ has remained stable against the growing database, which has increased by a factor of 2 since 1995.
  \item Most of this increase coming from photon-tagging facilities.
\end{itemize}
CLAS for $\vec{p} \rightarrow p^0 p$ above 1 GeV


SAID DU13
SAID CM12
BnGa11-2
MAID07
CLAS for $\vec{p} \rightarrow \pi^+ n$ above 1 GeV


SAID DU13
SAID CM12
BnGa11-2
MAID07
CB-ELSA for $\gamma \vec{p} \rightarrow \pi^0 p$ around 1 GeV

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

Preliminary

G(\pi^0 p)

Lin. pol Beam
Longitudinally pol Target
CB@MAMI for $\gamma p \rightarrow \pi^0 p$

[M. Sikora et al, arXiv:1309.xxxx]

- SAID CM12
- SAID SN11
- BnGa11-2
- MAID07

No fit to the CB data

- CM12 is favorite

Circular pol Beam
Recoil Nucleon

Hall A

CB@MAMI

A2
Proton Multipoles from DU13 & CM12


- Overall: the difference between MAID07 or BnGa and SAID DU13 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 & BnGa groups show that the new DU13 & CM12 solutions is much more satisfactory at higher energies.
CLAS $\Sigma$ Data Impact for Proton $S = 0$ & $I = 1/2$ Couplings


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

<table>
<thead>
<tr>
<th>$\Delta^*$</th>
<th>Solution</th>
<th>$A_{1/2}$</th>
<th>$A_{3/2}$</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>(GeV$^{1/2}$ $\times 10^{-3}$)</td>
<td>(GeV$^{1/2}$ $\times 10^{-3}$)</td>
</tr>
<tr>
<td>CM12</td>
<td>105±5</td>
<td>92±4</td>
<td></td>
</tr>
<tr>
<td>DU13</td>
<td>132±5</td>
<td>108±5</td>
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<tr>
<td>BnGa</td>
<td>160±20</td>
<td>165±20</td>
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<tr>
<td>MD07</td>
<td>226</td>
<td>210</td>
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<tr>
<td>PDG12</td>
<td>104±15</td>
<td>85±22</td>
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Relativized Quark Model:
S. Capstick, Phys Rev D 46, 2864 (1992)
γn → π⁻ p Measurements

Bernd Krusche’s talk
Victor Nikonov’s talk
Daria Sokhan’s talk
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 ($\theta = 40 - 140^\circ$) coverage and large energy binning ($E_\gamma = 100 - 200$ 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 large background because of the 5 to 500 times larger cross section for $\pi^- p \rightarrow \pi^0 n \rightarrow \gamma \gamma n$. 

eg, CB@BNL: A. Shafi, et al, PRC70, 035204 (2004)
The existing $\gamma p \to p\pi^0$ data contains mainly differential cross sections (17% of which are from polarized measurements.)

Future exp activity will fill empty spots specifically for n-target.

The existing $\gamma n \to n\pi^0$ data contains mainly differential cross sections (17% of which are from polarized measurements.)

The existing $\gamma p \to n\pi^+$ data contains mainly differential cross sections (17% of which are from polarized measurements.)

The existing $\gamma n \to p\pi^-$ data contains mainly differential cross sections (17% of which are from polarized measurements.)

\[ \text{UnP/P} = \frac{10954}{3400} = \frac{216}{148} = \frac{5787}{2435} = \frac{2484}{498} \]
FSI and $\gamma d \to \pi^- p p \to \gamma n \to \pi^- p$

[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 of $\gamma n \to \pi N$ data.
- For $\gamma n \to \pi^- p$ the effect: 5% - 60%. It depends on $(E, \theta)$.

Fermi motion of nucleons included.

Input: SAID $\gamma N \to \pi N$, $\pi N \to \pi N$, $NN \to NN$ amplitudes for 3 leading terms.

DWF: Bonn Potential.

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

\[ \frac{d\sigma}{d\Omega} (\gamma n) = R^{-1} \frac{d\sigma}{d\Omega} (\gamma d) \]
CLAS & MAMI-B

for $\gamma n \rightarrow \pi^- p$
The new CLAS cross sections have quadrupled the world database for $\gamma n \rightarrow \pi^- p$ above $E_\gamma = 1$ GeV.

Systematics:

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

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

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

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

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

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

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**Data:**

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

**Neutron Multipoles from SAID GB12 & SN11**


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

- Significant changes have occurred at high energies.

- Comparisons to earlier SAID and fit from the Mainz and BnGa groups show that the new GB12 solution is much more satisfactory at higher energies.

\[ S_{11} \]
\[ A_{1/2} = -58 \pm 6 [-51 - 93] \]
\[ A_{1/2} = -40 \pm 10 [9 - 25] \]

\[ D_{13} \]
\[ A_{1/2} = -46 \pm 6 [-77 - 49] \]
\[ A_{1/2} = -115 \pm 5 [-154 - 113] \]

\[ P_{11} \]
\[ A_{1/2} = 48 \pm 4 [54 43] \]

\[ F_{15} \]
\[ A_{1/2} = 26 \pm 4 [28 34] \]
\[ A_{3/2} = -29 \pm 2 [-38 -44] \]

BW for πN SP06

SAID GB12
SAID SN11
MAID07
BnGa13

CLAS Data Impact for Neutron $S = 0$ & $I = \frac{1}{2}$ Couplings

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

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

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$\pi N$ SAI\D</th>
<th>$nA_{1/2}$</th>
<th>Resonance</th>
<th>$\pi N$ SAI\D</th>
<th>$nA_{1/2}$</th>
<th>$nA_{3/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N(1535)1/2^-$</td>
<td>$W_R = 1547$ MeV</td>
<td>$-58 \pm 6$</td>
<td>$N(1520)3/2^-$</td>
<td>$W_R = 1515$ MeV</td>
<td>$-46 \pm 6$</td>
<td>$-115 \pm 5$</td>
</tr>
<tr>
<td>$\Gamma = 188$ MeV</td>
<td>$-60 \pm 3$</td>
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<td>$\Gamma_{\pi N}/\Gamma = 0.63$</td>
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- New **GB12** $nA_{1/2}$ & $nA_{3/2}$ couplings shown sometimes a significant deviation from our previous SAID determination (**SN11**) and **PDG12** average values, e.g., for $N(1650)1/2^-$, $N(1675)5/2^-$, and $N(1680)5/2^+$.

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

Status of Non-strange Resonances

- More than half of states have poor evidence.
- Most of states need more work to do.
- Most of QCD models predict more states than observed.
- Where are missing resonances?

### GW SAID Contribution

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### BnGa Additional States

The latest GWU analysis (ARNET 06) finds no evidence for this resonance.
• The differential cross section for the processes $\gamma n \rightarrow \pi^- p$ was extracted from new CLAS and MAMI-B measurements accounting for Fermi motion effects in the IA as well as NN- and $\pi N$-FSI effects beyond the IA.

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

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

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

• **Polarized measurements** [JLab, CB@MAMI, Spring-8, CB-ELSA...] will help to bring more physics in. FSI corrections need to apply.
For Tomorrow
Meson Production off the Deuteron at CB@MAMI

[Spokespersons: W.J. Briscoe and IS, MAMI-A2-02/12]

- We proposed to perform a precision measurement of \( \frac{d\sigma}{d\Omega} \) in the reactions \( \gamma d \to \pi^- p p \) and \( \gamma d \to \pi^0 n p \) in the tagged-photon energy region from threshold to 800 MeV.

- The \( \frac{d\sigma}{d\Omega} \) for the processes \( \gamma n \to p^- p \) and \( \gamma n \to \pi^0 n \) will be extracted from these CB@MAMI-C measurements accounting for Fermi motion effects in IA as well as NN- and \( \pi N-FSI \) effects beyond the IA.

- Data were taken in March 2013 and Analysis in progress.

- Consequential calculations of the FSI corrections, as developed by the GW-ITEP Collab., will be applied. We have \( \pi^- p \) FSI already while \( \pi^0 n \) FSI in progress.

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

igor@gwu.edu
Polarized Measurements for $\bar{\nu}_n \rightarrow \pi N$
**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.

No FSI included

GRAAL data are in Menu 2013 Workshop, Rome, Italy, Sept. – Oct. 2013

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

- $\Sigma$
  - 53.7 deg
  - 67.7 deg
  - 80.1 deg
  - 91.3 deg

### $W$ (MeV)

- 1550
- 1750
- 1950
- 2150
- 2350
- 2550

- 105.5 deg
- 123.5 deg
- 144.2 deg
- 163.4 deg

### $\chi^2/dp$

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

---

- 216 GRAAL $\Sigma$s are 60% of the World $\pi^0 n$ data
Recent GRAAL \( \sum \) 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.
$\Sigma$ for $\gamma n \rightarrow p \pi^-$

Curve - SAID
Red GRAAL
Magenta and Blue - Erevan

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

No FSI included
$\Sigma$-beam Asymmetry & FSI

$[\text{M.I. Levchuk et al, Phys Rev C 74, 014004 (2006)}]$
Watson’s Theorem
Connection between scattering and decay processes provides a solid theoretical ground for describing some hadronic effects – "Watson’s theorem."

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

Above $2\pi$-threshold, the rule may still be true, if inelasticity of the corresponding $\pi N$-elastic amplitude is small (as, eg, for $P_{33}$.)

$\tan(\frac{\text{Im}A}{\text{Re}A}) = \delta_i(\pi N)$
Evaluation of **PionPR** Amplitudes below 2π-Threshold

- **SAID** uses πN PWA results as a constraint for analysis of PionPR data. [see pg 10]

- Most of PionPR analyses are doing the same and uses SAID πN outcome or its modification as input.

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

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

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**Thresholds**

\[ \gamma p \rightarrow \pi^0 p \quad 1.073 \quad 144.7 \]

\[ \gamma p \rightarrow \pi^+ n \quad 1.079 \quad 151.4 \]
3/2 Isospin Amplitudes for $E$ & $M$

Graphs showing variations of $\delta[E_{3/2}^3/2]$ and $\delta[M_{1/2}^3/2]$ with $W$ (MeV) for different amplitudes and models.
1/2 Isospin Amplitudes for $E$ & $M$
3/2 & 1/2 Isospin Amplitudes for E & M

Isospin Amplitudes for E & M

D_{33}pE

D_{13}pE

D_{33}pM

D_{13}pM

SAID
MAID
EBAC
Giessen
BnGa
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 and 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 and 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 and phases coming from $\pi N$ amplitudes.
$\gamma d \rightarrow \pi^- pp$ from DESY Bubble Chamber

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

No fit to the data

DESY Bubble Chamber data:
[P. Benz et al, Nucl Phys B65, 158 (1973)]
FSI for $\gamma n \rightarrow \pi^- p$

[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:**
- $p_s > 200$ MeV/c
- $p_f > 200$ MeV/c

**CLAS data:**
- $E > 1$ GeV
- $\theta > 32$ deg

- There is no large sensitivity to cuts.

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

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

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

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

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

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$I_A + NN_{fsi} / I_A$

$I_A + (NN + \pi N)_{fsi} / I_A$