First measurements of parity-violating excitation of the $\Delta$ and pion photoproduction

New results from $G^0$

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College of William & Mary

(for the $G^0$ Collaboration)

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Rome, Italy
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Outline

- $G^0$ experiment
- Inelastic processes in parity-violating electron scattering
- Results from $N \rightarrow \Delta$
- Results from $(\gamma, \pi^-)$ on deuteron
- Interpretation

Inelastic analysis: Carissa Capuano (W&M)
Pion analysis: Alex Coppens (U. Manitoba)

Thanks to Carissa, Alex, Jeff Martin (U. Winnipeg) for figures...
Parity-Violating Electron Scattering
Weak NC Amplitudes

Interference: \( \sigma \sim |M^{EM}|^2 + |M^{NC}|^2 + 2\text{Re}(M^{EM*}M^{NC}) \)

Interference with EM amplitude makes Neutral Current (NC) amplitude accessible

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \left| \frac{M^{NC}}{M^{EM}} \right| \sim \frac{Q^2}{(M_Z)^2} \]

Small (~10^{-6}) cross section asymmetry isolates weak interaction
Superconducting toroidal magnetic spectrometer – counting expt.

**Forward angle mode:**

\[ \text{LH}_2: \ E = 3.0 \text{ GeV} \]

Recoil proton detection

\[ 0.12 \leq Q^2 \leq 1.0 \text{ (GeV/c)}^2 \]

**Backward angle mode:**

\[ E = 362, 687 \text{ MeV} \]

\[ \text{LH}_2, \text{ LD}_2 \quad \text{electron, pion detection} \]

(quasi)elastic at \( \sim 108^\circ \)

\[ Q^2 = 0.22 \text{ GeV}^2, \ 0.63 \text{ GeV}^2 \]

**Main Goal: Strange Form Factors of Nucleon**

*PRL 95 (2005) 092001*

*PRL 104 (2010) 012001*

*NIM A 646 (2011) 59*
G⁰: Ancillary measurements

- In the backward angle mode:
  Also measured (in parallel with elastic data) asymmetry for inelastically scattered electrons in the Δ(1232) region (from hydrogen and deuterium targets)

  as well as π⁻ produced from deuterium target.

- Backgrounds for main (elastic) measurement, but have physics interest in their own right…

- Experiment was not optimized for these processes!
**$G^0 N-\Delta$: Introduction**

- **First look at $G^A_{NA}$ in neutral current process**
  - $Q^2 = 0.34 \text{ GeV/c}^2$.

- **What does $G^A_{NA}$ describe?**
  - $G^A(Q^2) \rightarrow$ Axial elastic form factor for $N$
    - How is the spin distributed?
  - $G^A_{NA}(Q^2) \rightarrow$ Axial transition form factor for $N \rightarrow \Delta$
    - How is the spin redistributed during transition?

- **Measure Parity-violating asymmetry $A_{inel}$**
  - Allows a direct measure of the axial response during $N \rightarrow \Delta$

- **Accessing $G^A_{NA}$:**
  - Previous Measurements: Charged current process
    - Both quark flavor change and spin flip
  - $G^0 N-\Delta$ Measurement: Neutral current process
    - Quark spin flip only

PV $N \rightarrow \Delta$ first considered by Cahn & Gilman  
PRD 17(1978) 1313

...proposed as a Standard Model test!
\[ A_{inel} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left[ \Delta^{\pi}_{(1)} + \Delta^{\pi}_{(2)} + \Delta^{\pi}_{(3)} \right] \]

\[ \Delta^{\pi}_{(1)} = 2(1-2\sin^2\theta_W) \approx 1 \]

\[ \Delta^{\pi}_{(2)} = \text{non-resonant contribution} \]

\[ \Delta^{\pi}_{(3)} = 2(1-4\sin^2\theta_W) F(Q^2, s) \]

(resonant term)

At tree-level:

\[ F(Q^2, s) \rightarrow G^A_{NA}(Q^2) \]

- \( F \) contains kinematic information & weak and electromagnetic transition form factors
  
- \( \rightarrow \) Extract \( G^A_{NA} \) from \( F \)
**G⁰ Backward angle: Detectors**

Detector System (one octant shown):

**Scintillators:**
Kinematic separation of elastic and inelastic electrons

*Cryostat Exit Detectors (CED)*
*Focal Plane Detectors (FPD)*

**Cerenkov Detectors:**
Distinguish pions from electrons; one per octant

Coincidences send to scalers, accumulated during helicity states
G^0 Backward angle

Detector package

Target system installation

Superconducting Magnet

FPD (1 octant)
\( G^0 N-\Delta: \text{ Data} \)

\[ A_{\text{meas}} = -22.3 \pm 2.2 \text{ (stat) ppm (before background correction)} \]
$G^0 N-\Delta$: Data

LD$_2$

Matrix Space Cuts - 687 MeV

Electron Yield (Octant2)

CED

FPD

Background

Elastic

Inelastic

Super-elastic

inelastics

elastics

Asymmetry vs Octant

<table>
<thead>
<tr>
<th>Asymmetry ppm</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>-10</td>
<td>![Graph]</td>
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<td>-20</td>
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<tr>
<td>70</td>
<td>![Graph]</td>
</tr>
<tr>
<td>80</td>
<td>![Graph]</td>
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</table>

$A_{\text{meas}} = -26.4 \pm 5.9 \text{ (stat) ppm (before background correction)}$
**$G^0 N-\Delta$: Corrections (all except backgrounds)**

<table>
<thead>
<tr>
<th>Pass 1: Raw</th>
<th>A</th>
<th>$\sigma_{stat}$</th>
<th>$\sigma_{sys}$</th>
<th>$\sigma_{cor}$</th>
<th>dA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pass 2: Scalar Correction</td>
<td>-20.23</td>
<td>2.00</td>
<td>0.00</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Pass 3: Rate Corrections</td>
<td>-20.00</td>
<td>1.99</td>
<td>0.00</td>
<td>0.00</td>
<td>+0.23</td>
</tr>
<tr>
<td>Pass 4: Linear Regression</td>
<td>-22.17</td>
<td>2.25</td>
<td>0.16</td>
<td>0.16</td>
<td>-2.17</td>
</tr>
<tr>
<td>Beam Polarization</td>
<td>-22.33</td>
<td>2.24</td>
<td>0.23</td>
<td>0.16</td>
<td>-0.16</td>
</tr>
<tr>
<td>Transverse Polarization</td>
<td>-26.27</td>
<td>2.64</td>
<td>0.43</td>
<td>0.36</td>
<td>-3.91</td>
</tr>
</tbody>
</table>

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<tr>
<th>Pass 1: Raw</th>
<th>A</th>
<th>$\sigma_{stat}$</th>
<th>$\sigma_{sys}$</th>
<th>$\sigma_{cor}$</th>
<th>dA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pass 2: Scalar Correction</td>
<td>-14.11</td>
<td>2.62</td>
<td>0.00</td>
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<td>—</td>
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<td>1.23</td>
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<td>+0.25</td>
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<tr>
<td>Transverse Polarization</td>
<td>-31.07</td>
<td>6.92</td>
<td>1.30</td>
<td>0.43</td>
<td>-4.66</td>
</tr>
</tbody>
</table>

*All values in ppm*

Corrections well understood, statistical error dominates
$G^0 \text{ N-Δ: Inelastic locus}$
$G^0 N-\Delta$: Pion locus

Misidentified pions a significant background
\textbf{G}^0 N-\Delta: Background Correction

- **Correcting the Asymmetry:**
  - Extract \( A_{\text{inel}} \) from \( A_{\text{meas}} \) by subtracting backgrounds:

\[
A_{\text{inel}} = \frac{A_{\text{meas}} - \sum f_i^{bg} A_i^{bg}}{1 - \sum f_i^{bg}}
\]

- **Backgrounds:**
  - Electrons scattered elastically from target
  - Electrons scattered from Al target walls
  - Electrons from \( \pi^0 \) decay
  - Misidentified \( \pi^- \)

- **Background Asymmetries:**
  - Background from Al target walls: \textit{Dominated by inelastics}
    - Inelastic Al asymmetry unmeasured \( \rightarrow \) use D asymmetry
  - Pion contamination:
    - Negligible in H target, but significant for D; use direct pion measurement
  - Elastic contribution:
    - Mostly comes from radiative tail: use elastic data & simulation to extrapolate
**G^0 N-Δ: Background Dilutions**

- **Scale Yield vs. FPD for each CED**
  - Before fitting, subtract π^- contamination and Al target-wall yield

  Target wall yield: use separate low-density Gas target measurement; scale to remove gas contribution & account for kinematic differences between liquid and gas target

  - Scale the remaining contributions independently to fit the data
  - Require scale factors to vary smoothly across CEDs
  - Constrain scale factors same for all octants
\textbf{G^0 N-Δ: Background Dilutions LH2}
$G^0 N-\Delta$: Background Dilutions LH2
$G^0 N-\Delta$: Background Dilutions  LD2
$G^0 N-\Delta$: **Background Dilutions (by cell)**

**Total Inelastic Background, Locus Cells**

For each cell, all octants separately plotted
**G^0 N-Δ:** Background Dilutions (by octant)

**Inelastic Locus: Elastic Contribution**

**Inelastic Locus: Inelastic Contribution**

**Inelastic Locus: π^0 decay Contribution**

**Inelastic Locus: Empty Target Contribution**
Asymmetry of elastic radiative tail varies strongly over inelastic region.

Use GEANT 3, scaled to our own elastic backward angle results, make cell-by-cell correction.
$G^0 N-\Delta$: Result

### $A_{inel}$ for H 687 MeV

<table>
<thead>
<tr>
<th>Source</th>
<th>$A$</th>
<th>$\sigma_{stat}$</th>
<th>$\sigma_{sys}$</th>
<th>$\sigma_{cor}$</th>
<th>dA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam &amp; Instrumentation</td>
<td>-26.27</td>
<td>2.64</td>
<td>0.43</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>-33.60</td>
<td>5.30</td>
<td>5.10</td>
<td>4.93</td>
<td>-7.33</td>
</tr>
<tr>
<td>EM Radiative Effects</td>
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<td>5.30</td>
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<td>0.20</td>
<td>-0.39</td>
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<tr>
<td>Acceptance Averaging</td>
<td>-33.44</td>
<td>5.30</td>
<td>5.11</td>
<td>0.20</td>
<td>-0.55</td>
</tr>
</tbody>
</table>

### $A_{inel}$ for D 687 MeV

<table>
<thead>
<tr>
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<th>$\sigma_{cor}$</th>
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<tr>
<td>Beam &amp; Instrumentation</td>
<td>-31.07</td>
<td>6.92</td>
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<td>Backgrounds</td>
<td>-43.57</td>
<td>14.64</td>
<td>6.23</td>
<td>5.52</td>
<td>-12.5</td>
</tr>
</tbody>
</table>

All values in ppm

Acceptance Averaging: $\langle A(Q^2, W) \rangle \rightarrow A(\langle Q^2 \rangle, \langle W \rangle)$
Axial radiative corrections can be large and uncertain…


Found in particular: “many-quark” axial r.c. leads to new PV $\gamma^{}N\Delta$ coupling $d^-_\Delta$

$$A^-_\gamma \equiv \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = -\frac{2d^-_\Delta}{C^V_3}\frac{M_N}{\Lambda_{\chi}}$$  

Inelastic asymmetry does not vanish at $Q^2=0$!

“Natural” scale $d^\pm_\Delta \sim g\pi$

Enhancement mechanism proposed: $|d^\pm_\Delta| = 25g\pi$ (or larger)

would help solve puzzle of large asymmetries in Hyperon radiative decays

Enhanced values would lead to measurable (few ppm) asymmetries in $(\gamma,p^-)$

Would confuse extraction of $G^A_{N\Delta}(Q^2)$ from inelastic data
**G⁰: Pion photoproduction**

362 MeV LD2 data

Misidentified electrons a background:
Use TOF spectra from pulsed-beam runs to determine Cerenkov detector inefficiency ➔ 2.6% background.

Target wall background: 2%

Corrections for:
- rate-effects
- polarization,
- helicity-correlated beam properties

➔ under good control
Result: $A^{-\gamma} = - (0.36 \pm 1.1 \pm 0.4) \text{ ppm}$

Implies: \[ d_{\Delta}^- = (8.4 \pm 24 \pm 8.3) \ g_\pi \]

*Will neglect this contribution in the following…*
1) “Default” model:

- MAID for $\Delta_{(2)}$
- use dipole form for $G_{NA}(Q^2)$ with $M_A = 1.03$ GeV
- $F(Q^2)$ from Adler parameterization (S.L. Adler PRD 12(1975)2644)

3) Dynamical Model of electroweak pion production:

and T.S.H. Lee (private communication)
- hadronic effective chiral Lagrangian; field operators: N,Δ,π,ω,ρ and
  effective Lagrangians for πNN,πNΔ,ωNN…

- $\Delta_{(3)}$ uses alternate form: $G_{N,\Delta}(Q^2) = (1 + aQ^2)\exp(-bQ^2)G_A(Q^2)$,

  with $a = 0.154$ GeV$^{-2}$  $b = 0.166$ GeV$^2$ and $M_A = 1.02$ GeV
  (from fit to neutrino charged-current pion production data)
$G^0 N-\Delta$: Result (default model)

$A$ vs. $Q^2$, $E = 0.680$ GeV, $W = 1.178$ GeV, $\theta = 94.81^\circ$

$G^0$ result: $A = -(33.4 \pm 7.4)$ ppm
$G^0 N-\Delta$: Dynamical Model of Matsui, Sato and Lee

A vs. $Q^2$, $E = 0.680\text{ GeV}$, $W = 1.178\text{ GeV}$, $\theta = 94.81^\circ$
$G^0 N - \Delta$: extracting $\Delta^{\pi}_{(3)}$

$A_3$ vs. $Q^2$, $E = 0.680$ GeV, $W = 1.178$ GeV, $\theta = 94.81^\circ$

Subtract off $\Delta_{(1)}$ and $\Delta_{(2)}$

$\Delta^{\pi}_{(3)}$ consistent with theory, but data not precise enough to provide $G^{A}_{N\Delta}$
One would need a precision of about ± 0.5 ppm to say anything significant about $M_A$ …

Recall: $G^0$ error bar: ±7.4 ppm
Summary

• First measurement of PV asymmetry in inelastic scattering to the Δ
• First measurement of PV asymmetry in (γ, π−)

• $N \rightarrow \Delta$ consistent with theory, but not precise enough to give useful information on $G_{NA}^A(Q^2)$ or on axial mass $M_A$

• $(γ, π−)$ consistent with theory; does not favor very enhanced $d^{-}_\Delta$
  but still room for sizable values

• Qweak has data in-hand on asymmetry at very low $Q^2$; analysis underway & more data likely will be taken…
  improve precision on $d^{-}_\Delta$?