The Generalized Polarizabilities of the Proton

Temple University
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On behalf of JLAB E1215-001 Collaboration
• Theoretical background
• VCS Experiment E12-15-001
• Analysis Progress
  • Elastic Data
  • Pion Preliminary Analysis
  • VCS Preliminary Analysis
• Summary
Polarizability:

- A fundamental characteristic of the proton
- Characterizes the nucleon dynamical response to an external electromagnetic field

Generalized Polarizabilities (GPs):

- Access by Virtual Compton Scattering (VCS)
- Two scaler and four vector GPs
- Fourier transform can map out the spatial distribution density of the polarization induced by an EM field

N BARYONS
\( S = 0, \ I = 1/2 \)
\[ p, N^+ = uud; \ n, N^0 = udd \]

\[ i(JF) = \frac{1}{2}(J^F) \]

<table>
<thead>
<tr>
<th>Mass</th>
<th>( m_\text{p} )</th>
<th>( m_\text{n} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_\text{p} )</td>
<td>1.00726466688 ± 0.0000000009 u</td>
<td>938.272081 ± 0.000006 MeV [3]</td>
</tr>
<tr>
<td>( m_\text{n} )</td>
<td>( \frac{m_\text{p} - m_\text{n}}{m_\text{p}} &lt; 7 \times 10^{-10}, \ CL = 90% ) [6]</td>
<td></td>
</tr>
<tr>
<td>( q_\text{p} )</td>
<td>( \frac{q_\text{p}}{m_\text{p}} = 1.0000000000 ± 0.0000000007 )</td>
<td></td>
</tr>
<tr>
<td>( q_\text{n} )</td>
<td>( q_\text{n} )</td>
<td></td>
</tr>
<tr>
<td>( q_\text{p} + q_\text{n} )</td>
<td>( q_\text{n} )</td>
<td></td>
</tr>
<tr>
<td>Magnetic moment</td>
<td>( \mu_\text{p} = 2.7928473446 ± 0.0000000008 \mu_N )</td>
<td></td>
</tr>
<tr>
<td>Electric dipole moment</td>
<td>( d &lt; 0.021 \times 10^{-23} \text{ cm} )</td>
<td></td>
</tr>
</tbody>
</table>

Electric polarizability \( \alpha = (11.2 ± 0.4) \times 10^{-4} \text{ fm}^3 \)
Magnetic polarizability \( \beta = (2.5 ± 0.4) \times 10^{-4} \text{ fm}^3 \) (\( S = 1.2 \))

Charge radius, \( r_p \) Lamb shift = 0.84037 ± 0.00039 fm [10]
Charge radius, \( r_p \) CODATA value = 0.8751 ± 0.0061 fm [14]
Magnetic radius = 0.78 ± 0.04 fm [4]
Mean life \( \tau \) > 2.1 \times 10^{34} \text{ years}, CL = 90\% [7] (\( \tau \) → invisible mode)
Mean life \( \tau \) > 10^{31} to 10^{33} \text{ years} [7] (mode dependent)
Generalized Polarizabilities

Electric Polarizability

\[ \vec{p} = \alpha_E \vec{E} \]

- Electric polarizability \( \alpha_E \) reflects the rigidity of proton

Magnetic Polarizability

\[ \vec{m} = \beta_M \vec{B} \]

- **Paramagnetic**: >0, quarks align along magnetic field;
- **Diamagnetic**: <0, pion cloud induced magnetic field in opposite direction
- Partially cancels each other, makes \( \beta_M \) value small
**Reaction & Amplitudes**

\[ \text{VCS cross-section} = \frac{d^5 \sigma}{dk'_{lab} d\Omega'_{elab} d\Omega_{p_{cm}}} \]

**Kinematics of \( ep \rightarrow ep\gamma \) reaction**

**VCS process → photon electro-production reaction**

\[ \alpha_{E1}(Q^2) = -\frac{e^2}{4\pi} \sqrt{\frac{3}{2}} P^{(L1,L1)}_0 (Q^2) \]

\[ \beta_{M1}(Q^2) = -\frac{e^2}{4\pi} \sqrt{\frac{3}{8}} P^{(M1,M1)}_0 (Q^2) \]

**Electric Scaler GP**

**Magnetic Scaler GP**

- \( \rho(\rho') \) photon longitudinal or EM nature
- \( L(L') \) angular momentum
- \([S = 1,0]\) spin flip or non-spin flip
• LEX - Low Energy Expansion  
  Below pion threshold

• DR - Dispersion Relation Formalism  
  Below & Above pion threshold

Predicted  ➔  4 spin (vector) GPs

Free parameters  ➔  2 scaler GPs

Fits to cross section of experimental data

Find best $\chi^2$

Measurement of $\alpha_E$ and $\beta_M$
World Data & Motivation

- Initial theoretical models predicted smooth fall off of $\alpha_E$
  - data at $Q^2 = 0.33$ implies non-trivial structure
- New experiment can:
  - Address puzzling $\alpha_E$ enhancement
  - Reduce error by 2

- Small values, 1/3 - 1/4 of $\alpha_E$
- Large uncertainties
- New experiment can:
  - Improve precision
  - Explore para-& dia-magnetic mechanism inside nucleon

JLab E12-15-001 Experiment

• Summer 2019: July 20 - August 5
• Beam $E = 4.56\, GeV$
• $Q^2 = 0.33\, GeV^2$, $W = 1.232\, GeV$

$\theta_e = 7.69^\circ$
$P_e = 4.034\,(GeV)$

$\theta_p = 33.73$ to $60.74^\circ$;
$P_p = 0.893$ to $0.795\,(GeV)$

$\phi = 180^\circ$;
$\phi = 0^\circ$

Asymmetries = \[\frac{d\sigma_{\phi=180^\circ} - d\sigma_{\phi=0^\circ}}{d\sigma_{\phi=180^\circ} + d\sigma_{\phi=0^\circ}}\]

- High enough $\theta_{\gamma\gamma^*}$ to avoid BH peak
- Avoid rapid cross section variation
Predicted Measurement

\[ \phi = 0^\circ \]

\[ \phi = 180^\circ \]

- Sensitivity to \( \alpha_E \)
- Sensitivity to \( \beta_M \)

- \( \epsilon \) increase to 0.98
- Doubles the sensitivity to the GPs

\[ Q^2 = 0.33 \]

\[ \alpha = 1.5, \beta = 1.1 \]

\[ \alpha = 4.8, \beta = 0.4 \]

\[ \alpha = 4.8, \beta = 1.1 \]

\[ \alpha = 4.8, \beta = 1.6 \]
**Elastic**

<table>
<thead>
<tr>
<th>Kinematic</th>
<th>$\theta_e^*$</th>
<th>$P_e$(GeV/c)</th>
<th>$\theta_p^*$</th>
<th>$P_p$(GeV/c)</th>
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<tbody>
<tr>
<td>Elastic I</td>
<td>10.76</td>
<td>4.193</td>
<td>61.16</td>
<td>0.893</td>
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<tr>
<td>Elastic II</td>
<td>10.41</td>
<td>4.214</td>
<td>61.95</td>
<td>0.863</td>
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<tr>
<td>Elastic III</td>
<td>9.64</td>
<td>4.259</td>
<td>63.76</td>
<td>0.795</td>
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</table>

**Cuts:**
- $\text{abs(HMS}_dp) < 8$
- $-10 < \text{SHMS}_dp < 22$
- $\text{g.evtyp} = 4$
- $0.85 < W < 1.05$
VCS peak and π0 peak

Coincidence Time

\[ \text{Count}_{\text{peak}} = \text{Count}_{\text{comp}} - \frac{3}{8} \times \text{Count}_{\text{acc}} \]

Reaction Vertex

\[ \text{Counts} \]

 Kin 2b Missing Mass Squared

Counts

-0.03 -0.02 -0.01 0 0.01 0.02 0.03 0.04 0.05 0.06 0.07

missing_mass^2(\text{GeV}^2)

Photon peak

π0 peak

Data

Data-acc

Data-acc-dummy

Coincidence Time

Counts

HMS reaction vertex(cm)

Data

dummy

Reaction Vertex

Counts

HMS reaction vertex(cm)
**Pion Preliminary Analysis**

Kin2b data vs. MAID

**Cuts:**
- $0.01 < m_{m2} < 0.05 \text{ (GeV}^2\text{)}$
- $\text{abs}(W - 1.232) < 0.007 \text{ (GeV)}$
- $\text{abs}(Q2-0.33) < 0.04 \text{ (GeV}^2\text{)}$
- $\text{abs}(\phi_{pq} - \phi_{center}) < 25 \text{ (deg)}$
M1 - Magnetic dipole amplitude

Very preliminary

Normalization wise good
VCS Preliminary Analysis

Cuts:

- \( \text{abs}(\text{mm2}) < 0.01 \text{ (GeV}^2\) )
- \( \text{abs}(W - W_{\text{center}}) < 0.007 \text{ (GeV) } \)
- \( \text{abs}(Q^2-0.33) < 0.035 \text{ (GeV}^2\) )
- \( \text{abs}(\theta_{pq} - \theta_{\text{center}}) < 4 \text{ (deg) } \)
- \( \text{abs}(\phi_{pq} - \phi_{\text{center}}) < 25 \text{ (deg) } \)

Data

- Pion simulation
- VCS simulation

\( W = 1220 \text{ MeV} \)

\( W = 1230 \text{ MeV} \)
Fitted polarizabilities are based on full data set for both in-plane and out-of-plane.
• Results will be extracted at $Q^2=0.28$, 0.33 and 0.4 $GeV^2$

• Preliminary results show an alphaE enhancement at Q2 region showed in previous slide

• Final results will be presented in the next few weeks

Ongoing effort: finalizing systematic uncertainties
Summary

- GPs are fundamental structure constants
- Data at $Q^2 = 0.33$ implies non-trivial structure
- JLab E12-15-001 experiment focus on exploring the mechanism of the non-trivial $Q^2$ dependence of $\alpha_E$
- Analysis status
  - Detector calibration and timing cuts – completed
  - Elastic $H(e, e')p$ data cross section comparison at same HMS central momentum – completed
  - Determination spectrometer central angle and momentum offsets – completed
  - $\pi^0$ production cross section extraction – preliminary results
  - Determination of VCS cross section and extraction of $\alpha_E$ and $\beta_M$ – preliminary results
  - Systematic uncertainty study - ongoing
# People

Zulkaida Akbar, **Hamza Atac**, Vladimir Berdnikov, Deepak Bhetuwal, Debaditya Biswas, **Marie Boer**, Alexandre Camsonne, Jian-Ping Chen, Eric Christy, Arthur Conover, Markus Diefenthaler, Burcu Duran, Dipangkar Dutta, Rolf Ent, **Dave Gaskell**, Carlos Ayerbe Gayoso, Ole Hansen, Florian Hauenstein, Nathan Heinrich, William Henry, Tanja Horn, Joshua Hoskins, Garth Huber, Shuo Jia, **Mark Jones**, Sylvester Joosten, Abishek Karki, Stephen Kay, Vijay Kumar, **Ruonan Li**, Xiaqing Li, Wenliang Li, Anusha Habarakada Liyanage, **Dave Mack**, Simona Malace, Pete Markowitz, Mike McCaughan, Hamlet Mkrtchyan, Casey Morean, Mireille Muhoza, Amrendra Narayan, **Michael Paolone**, Melanie Rehfuss, Brad Sawatzky, Andrew Smith, Greg Smith, **Nikolaos Sparveris**, Richard Trotta, Carlos Yero, Xiaochao Zheng, Jingyi Zhou

<table>
<thead>
<tr>
<th>Spokespersons</th>
<th>Run Coordinators</th>
<th>Post-docs</th>
<th>Graduate student</th>
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Thank You & Question Time

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JOINT HALL A & C SUMMER COLLABORATION MEETING 07/08/2021
Backup Slides

Temple University
Ruonan Li

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JOINT HALL A & C SUMMER COLLABORATION MEETING 07/08/2021
Energy Calibration

Spectrometer: Same momentum, Different HMS theta

<table>
<thead>
<tr>
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<th>SHMS_p</th>
<th>SHMS_th</th>
<th>HMS_p</th>
<th>HMS_th</th>
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<tbody>
<tr>
<td>Kin1a</td>
<td>4.034</td>
<td>7.69</td>
<td>0.893</td>
<td>37.33</td>
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<td>0.893</td>
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<table>
<thead>
<tr>
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<th>SHMS_th</th>
<th>HMS_p</th>
<th>HMS_th</th>
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<td>0.863</td>
<td>33.52</td>
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<tr>
<td>Kin2b</td>
<td>4.034</td>
<td>7.69</td>
<td>0.863</td>
<td>55.22</td>
</tr>
</tbody>
</table>

Kin 1a & Kin 1b

(a1) \( p_0 = 7.125 \), \( p_1 = -1.550 \)

(b1) \( p_1 = 4.110 \), \( p_1 = -0.800 \)

SHMS_p = (4.0199, 0.8946)

HMS_p = (4.034, 7.69)

Kin 2a & Kin 2b

(a2) \( p_0 = 8.2009 \), \( p_1 = 1.825 \)

(b2) \( p_1 = 3.5281 \), \( p_1 = 0.663 \)

SHMS_p = (4.0196, 0.8651)

HMS_p = (4.034, 7.69)
### Energy Calibration

#### KIN 2b MM2

![Graph showing photon peak](image)

<table>
<thead>
<tr>
<th></th>
<th>SHMS_p Cal</th>
<th>SHMS_p Exp</th>
<th>Offset</th>
<th>HMS_p Cal</th>
<th>HMS_p Exp</th>
<th>Offset</th>
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</thead>
<tbody>
<tr>
<td>Kin1a</td>
<td>4.0199</td>
<td>4.034</td>
<td>0.003</td>
<td>0.8946</td>
<td>0.893</td>
<td>0.002</td>
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<tr>
<td>Kin1b</td>
<td>4.0199</td>
<td>4.034</td>
<td>0.003</td>
<td>0.8946</td>
<td>0.893</td>
<td>0.002</td>
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<tr>
<td>Kin2a</td>
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<td>4.034</td>
<td>0.004</td>
<td>0.8651</td>
<td>0.863</td>
<td>0.002</td>
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<tr>
<td>Kin2b</td>
<td>4.0196</td>
<td>4.034</td>
<td>0.004</td>
<td>0.8651</td>
<td>0.863</td>
<td>0.002</td>
</tr>
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</table>
HMS delta

SHMS delta

HMS xp\_tar

SHMS xp\_tar

HMS yp\_tar

SHMS yp\_tar

HMS Ytar

SHMS Ytar
Old chi2>100 SHMS Run 9369

Old chi2>100 HMS Run 9369

Figure Credit: Mark Jones