The Generalized Polarizabilities of the Proton

Temple University
Ruonan Li

On behalf of JLAB E12-15-001 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
\[ \vec{p} = \alpha_E \vec{E} \]

Electric Polarizability

- Electric polarizability $\alpha_E$ reflects the **rigidity** of proton
• **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

\[ \frac{d\sigma}{dk'd\Omega'} \]

\[ = d^5\sigma / (dk_{lab}'d\Omega'_{lab}d\Omega_{p_{cm}}) \]

Kinematics of \( ep \to e\gamma \) reaction
Amplitudes for photon electroproduction process:

\[ T^{ep \to ep\gamma} = T^{BH} + T^{Born} + T^{NB} = T^{BH} + T^{VCS} \]

- \( \rho(\rho') \) photon longitudinal or EM nature
- \( L(L') \) angular momentum
- \( [S = 1,0] \) spin flip or non spin flip

\[ P^{(\rho'L',\rho L)S}(Q^2) \]
**LEX & DR Formalism**

**LEX - Low Energy Expansion**

Below pion threshold

\[ d\sigma = d\sigma_{BH+Born} + (\Phi \cdot q'_cm) \cdot \Psi_0 + O(q'^2_{cm}) \]

\[ \Psi_0 = V_{LL} \cdot (P_{LL} - P_{TT}/\epsilon) + V_{LT} \cdot P_{LT} \]

\[ P_{LL} \sim P^{(L1,L1)}(Q^2) \]

\[ P_{LT} \sim P^{(M1,M1)}(Q^2) + P^{(L1,L1)}(Q^2) \]

\[ P_{TT} \sim (P^{(M1,M1)}(Q^2) - \sqrt{2}q^0P^{(L1,M1)}(Q^2)) \]

**DR - Dispersion Relation Formalism**

Below & Above pion threshold

Predicted

\[ 4 \text{ spin (vector) GPs} \]

Free parameters

\[ 2 \text{ scaler GPs} \]

Fits to cross section of experimental data

Find best \( \chi^2 \)

Measurement of \( \alpha_E \) and \( \beta_M \)
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

Summer 2019: July 20 - August 5

Beam $E = 4.56 GeV$

$Q^2 = 0.33 GeV^2$, $W = 1.232 GeV$

- High enough $\theta_{\gamma\gamma}$ to avoid BH peak
- Avoid rapid cross section variation
\( \phi = 0^\circ \)

\( Q^2 = 0.33 \)

- \( \alpha = 1.5, \beta = 1.1 \)
- \( \alpha = 4.8, \beta = 0.4 \)
- \( \alpha = 4.8, \beta = 1.1 \)
- \( \alpha = 4.8, \beta = 1.6 \)

\( \phi = 180^\circ \)

\( Q^2 = 0.33 \)

- \( \alpha = 1.5, \beta = 1.1 \)
- \( \alpha = 4.8, \beta = 0.4 \)
- \( \alpha = 4.8, \beta = 1.1 \)
- \( \alpha = 4.8, \beta = 1.6 \)

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

- \( \epsilon \) increases to 0.98
- Doubles the sensitivity to the GPs
Elastic II data vs. simulation

<table>
<thead>
<tr>
<th>Kinematic</th>
<th>$\theta_e^o$</th>
<th>$P_e$(GeV/c)</th>
<th>$\theta_p^o$</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>
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<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>

Agreement in 3 %
VCS peak and π0 peak

Missing Mass Squared

Coincidence Time

Reaction Vertex

Photon peak

π⁰ peak

\[ \text{Count}_{\text{peak}} = \text{Count}_{\text{coin}} - \frac{3}{8} \text{Count}_{\text{acc}} \]
Pion Preliminary Analysis

W

Q2

MM2

\[0.0025 < m^2 < 0.06\]

\[0.0025 < m^2 < 0.06\]

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**Pion Preliminary Analysis**

**Cuts:**

- $0.0025 < \text{mm}^2 < 0.06$
- $\text{abs}(W-1.260) < 0.01$
- $\text{abs}(W-0.33) < 0.05$
- $\text{abs}(\theta_{pq} - \theta_{\text{center}}) < 5$
- $\text{abs}(\phi_{pq} - \phi_{\text{center}}) < 70$

\[ \phi_{pq} = 50 \]  
\[ \phi_{pq} = 230 \]
Pion Preliminary Analysis

Figure Credit: Hamza Atac
Cuts:

\[ -0.01 < m_{m2} < 0.01 \]
\[ \theta_{gg} > 140 \]
\[ 1.075 < W < 1.3 \]

Data vs. DR

\[ Q^2 = 0.33(GeV^2) \]
\[ \lambda_\alpha = 0.7(GeV), \lambda_\beta = 0.5(GeV) \]

Cuts:

\[ -0.01 < m_{m2} < 0.01 \]
\[ \theta_{gg} > 140 \]
\[ 1.075 < W < 1.3 \]
VCS Preliminary Analysis

Missing Mass Squared

Counts

<table>
<thead>
<tr>
<th>mm2</th>
<th>Entries</th>
<th>Mean</th>
<th>Std Dev</th>
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<tr>
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<td>5790</td>
<td>0.003</td>
<td>0.005061</td>
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Cuts:

- mm2 < 0.06
- ABS(theta_gg-140) < 6
- ABS(W-1.232) < 0.008
- ABS(Q2-0.33) < 0.05

VCS data vs. DR comparison

ONGOING…

Pion contamination
• 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
    • Agreement with world data at 3% level
  • Determination spectrometer central angle and momentum offsets – nearly complete
  • $\pi^0$ production cross section extraction – preliminary results
  • Determination of VCS cross section and extraction of $\alpha_E$ and $\beta_M$ – ongoing
People


Spokespersons    Run Coordinators    Post-docs    Graduate student
Thank You & Question Time

Temple University
Ruonan Li

On behalf of JLAB E12-15-001 Collaboration
Backup Slides

Temple University
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JLAB HALLC COLLABORATION MEETING  1/29/2021
Energy Calibration

Spectrometer: Same momentum, Different HMS theta

<table>
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<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>
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<td>55.22</td>
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Kin 1a & Kin 1b

Kin 2a & Kin 2b

(4.0268, 0.8949)

(4.0231, 0.8690)
Energy Calibration

KIN 2b MM2

Photon peak

<table>
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<th>SHMS_p Cal</th>
<th>SHMS_p Exp</th>
<th>Offset</th>
<th>HMS_p Cal</th>
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Pion Preliminary Analysis

HMS delta

SHMS delta

HMS xp_tar

SHMS xp_tar

HMS yp_tar

SHMS yp_tar

HMS Ytar

SHMS Ytar (cm)