The GEp-2γ Experiment at Jefferson Lab Hall-C

2011 HALL-C USERS MEETING

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OUTLINE

❖ Introduction

❖ Beyond the Born Approximation

❖ The GEp-2γ Experiment at Jlab:
  ➢ Goal
  ➢ Analysis
  ➢ Polarization Component Ratio and $P_1$ quasi-final results

❖ Determination of the 2γ amplitudes

❖ Conclusion
Over the past decade both intensive theoretical and experimental effort have been done aiming at explaining the Rosenbluth/Polarization discrepancy.

The difference between the two experimental ratios increases systematically with $Q^2$ for $Q^2 > 2$ GeV$^2$.

Two methods, two different results:

- Incomplete radiative corrections?
- Something beyond the Born Approximation? (one photon exchange)
- Possible Two-photon exchange effect? (TPEX)

This experiment is a search for a kinematical dependence in $P_t/P_\ell$ vs $\varepsilon$.

References:
- Jones et al., Phys. Rev. Lett. 84, 1398 (2000);
- Gayou et al., Phys. Rev. Lett. 88, 092301 (2002);
- Punjabi et al., Phys. Rev. C 71, 055202 (2005);
- Puckett et al., Phys. Rev. Lett 104, 242301 (2010);
Beyond the Born-Approximation formalism

\[ P_t = -\sqrt{\frac{2e(1 + \varepsilon)}{\tau}} \frac{1}{\sigma_r} \{ G_E G_M \} \]

Transverse polarization.

\[ P_l = \sqrt{1 - \varepsilon^2} \frac{1}{\sigma_r} \{ G_M^2 \} \]

Longitudinal polarization.

\[ \sigma_r = G_M^2 + \frac{\varepsilon}{\tau} G_E^2 \]

Reduced cross section.

\[ R = -\mu_p \sqrt{(1+\varepsilon)\tau} \frac{P_t}{P_l} = \mu_p \frac{G_E}{G_M} \]

Polarization component ratio.
Beyond the Born-Approximation formalism

\[ P_t = -\sqrt{\frac{2\epsilon(1 + \epsilon)}{\tau}} \frac{1}{\sigma_r} \{G_E G_M \} \]

\[ P_l = \sqrt{1 - \epsilon^2} \frac{1}{\sigma_r} \{ G_M^2 \} \]

\[ \sigma_r = G_M^2 \frac{\epsilon}{\tau} \]

\[ R = -\mu_p \sqrt{\frac{(1+\epsilon)\tau}{2\epsilon}} \frac{P_t}{P_l} = \mu_p \frac{G_E}{G_M} \]

\[ \text{Born Approx.} \]

\[ \text{Beyond Born Approx.} \]
Both theories describe Rosenbluth data but have opposite prediction for $G_{Ep}/G_{Mp}$.

**Hadronic (elastic)**

Dominated by correction to $G_M$.


**Generalized Parton Distribution**

Dominated by $F_3$ correction and correction to $G_E$.


Born value calculated from the $G_{Ep}/G_{Mp}$ fit of the polarization data.

Theoretical Estimates
Both theories describe Rosenbluth data but have opposite prediction for $G_{Ep}/G_{Mp}$.

**Hadronic (elastic)**
Dominated by correction to $G_M$.


**Generalized Parton Distribution**
Dominated by $F_3$ correction and correction to $G_E$.


Born value calculated from the $G_{Ep}/G_{Mp}$ fit of the polarization data.
The GEp-2γ Experiment

• We look for a kinematical dependence of $P_t/P_\ell$ to detect a possible two-photon exchange effect in the $ep$-scattering.

Key idea:
• fixed $Q^2$.
• same spin transport. (spin precession fixed)
• same analyzing power. ($P_p$ fixed)

precision limited only by statistics ($\sim 0.01$ for a ratio value of $0.7$)

unlike Rosenbluth, very small p.t.p systematics $\leq 0.006$ : $A_y, h$ cancel out in the $P_t/P_1$ ratio.

80μA beam current.
85% pol.
20cm LH$_2$ target.

<table>
<thead>
<tr>
<th>$E_e$, GeV</th>
<th>$p_p$</th>
<th>$E'_e$</th>
<th>$\theta_p$, deg</th>
<th>$\theta_e$</th>
<th>$\epsilon$ range</th>
<th>$&lt;Q^2&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.867</td>
<td>2.068</td>
<td>0.527</td>
<td>14.13</td>
<td>106</td>
<td>.130-.160</td>
<td>2.49</td>
</tr>
<tr>
<td>2.839</td>
<td>2.068</td>
<td>1.507</td>
<td>30.76</td>
<td>45.3</td>
<td>.611-.647</td>
<td>2.49</td>
</tr>
<tr>
<td>3.549</td>
<td>2.068</td>
<td>2.207</td>
<td>35.39</td>
<td>32.9</td>
<td>.765-.786</td>
<td>2.49</td>
</tr>
</tbody>
</table>
The polarization component ratio and $A_yP_1$ are independent of the reconstructed kinematics.

$dx/dz$ (dispersive, vertical) and $dy/dz$ (non-dispersive, horizontal) are the slopes at the target.

In each panel, result integrated over the other kinematic variables: $dx/dx$, $dy/dz$, $\delta$ or $y_{tgt}$ (target length seen from the spectrometer).

Good understanding of the spin precession calculation through the spectrometer magnets.

Good quality of the COSY Spin transport matrix.

$\epsilon=0.15$, $Q^2=2.5$ GeV$^2$
### Systematic Uncertainties on \( R \)

<table>
<thead>
<tr>
<th>Source</th>
<th>( \varepsilon=0.152 )</th>
<th>( \varepsilon=0.635 )</th>
<th>( \varepsilon=0.785 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta_{\text{bend}} ) (2 mrad)</td>
<td>0.0018</td>
<td>0.0018</td>
<td>0.0019</td>
</tr>
<tr>
<td>( \varphi_{\text{bend}} ) (0.5 mrad)</td>
<td><strong>0.0102</strong></td>
<td><strong>0.0061</strong></td>
<td><strong>0.0058</strong></td>
</tr>
<tr>
<td>( \delta ) (0.1%)</td>
<td>0.0036</td>
<td>4.402E-05</td>
<td>0.0002</td>
</tr>
<tr>
<td>( \varphi_{\text{fpp}} ) (0.14 mrad)</td>
<td>0.0039</td>
<td>0.0025</td>
<td>0.0024</td>
</tr>
<tr>
<td>( E_{\text{beam}} ) (0.05%)</td>
<td>0.0015</td>
<td>0.0001</td>
<td>5.7876E-05</td>
</tr>
<tr>
<td>False Asymmetry</td>
<td>0.0059</td>
<td>0.0063</td>
<td>0.0059</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>0.0131</strong></td>
<td><strong>0.0093</strong></td>
<td><strong>0.0088</strong></td>
</tr>
</tbody>
</table>

- Half of the false asymmetry correction as false asymmetry systematic uncertainty
- Systematics dominated by the uncertainty on \( \varphi_{\text{bend}} \) and the false asymmetry correction
Polarization Component Ratio

- No evidence of an epsilon dependence at a 0.01 level for a ratio of 0.7 in the polarization data at \( Q^2 = 2.5 \text{ GeV}^2 \).

- Models predict a bigger correction (opposite sign) at small \( \varepsilon \), not seen in the data.

- Theoretical predictions are with respect to the Born approximation. (calculated from the fit to the polarization data)

- Small point-to-point systematics

- Radiative corrections calculated with MASCARAD \(~0.01-0.02\%\) (Afanasev et.al, Phys. Rev. D 64, 113009 (2001))

\[
\]

\[
\]

\[
\]

\[
\text{Bystritskiy, Kuraev and Tomasi-Gustafsson, Phys. Rev. C75: 015207 (2007)}
\]
Zclose Dependence

- The analyzing power is not constant within the whole width of the analyzer.
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• The form factor ratio is constant within the analyzer for the 3 kinematics.
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• Dilution of the analyzing power from bad reconstructed events.
Zclose Dependence

- The analyzing power is not constant within the whole width of the analyzer.
- The form factor ratio is constant within the analyzer for the 3 kinematics.
- Dilution of the analyzing power from bad reconstructed events.

Cut in Zclose.
Longitudinal Polarization I

- Matching acceptance cut: cut to match the acceptance of the largest $\epsilon$ kinematic, to that of the $\epsilon=0.15$ one.
  
  Same spin transport, Same $A_\gamma$ to the $10^{-3}$ level

- Smallest $\epsilon$ kinematic determines the analyzing power.
• Matching acceptance cut: cut to match the acceptance of the largest ε kinematic, to that of the ε=0.15 one.

**Same spin transport, Same A_y to the 10^-3 level**

• Smallest ε kinematic determines the analyzing power: \( A_y^{\text{ave}} = 0.15079 \pm 0.00038 \)

• \( P_\ell^{\text{Born}} \) calculated from \( E_{\text{beam}} \), the momentum \( p \) and the fitted ratio value from this experiment

• 1% absolute, 0.5% point-to-point systematic errors (Möller dominated)

• Radiative corrections smaller than polarization component ratio (Afanasev et al., Phys. Rev. D 64, 113009 (2001))
Longitudinal Polarization II

\[ \varepsilon = 0.152 \]
\[ \varepsilon = 0.635 \]
\[ \varepsilon = 0.785 \]
Longitudinal Polarization II

\( \varepsilon = 0.152 \)
\( \varepsilon = 0.635 \)
\( \varepsilon = 0.785 \)

\( \text{ratio} \)
\( \varepsilon = 0.152 / \varepsilon = 0.635 \)
\( \varepsilon = 0.152 / \varepsilon = 0.785 \)
\( \varepsilon = 0.635 / \varepsilon = 0.785 \)
Longitudinal Polarization II
Longitudinal Polarization II
Longitudinal Polarization II

- Graphs showing data for different values of $\epsilon$: $0.152$, $0.635$, and $0.785$.

- Graphs depicting the ratio $\text{ratio} = \frac{\epsilon_{0.152}}{\epsilon_{0.635}}$, $\frac{\epsilon_{0.152}}{\epsilon_{0.785}}$, and $\frac{\epsilon_{0.635}}{\epsilon_{0.785}}$.

- Graphs illustrating the relationship between $\theta_{FPP}$ and $\delta$ for different $\epsilon$ values.
Empirical determination of TPEX amplitudes

- Fit the ratio

\[ \frac{\mu_p \sqrt{\tau(1 + \varepsilon)/2\varepsilon}}{p_\ell} \]

with a constant

in the OPEX
Empirical determination of TPEX amplitudes

- Fit the ratio
  \[ - \mu_p \sqrt{\frac{\tau (1 + \epsilon)}{2 \epsilon}} \frac{P_+}{P_\ell} \]
  \[ = \mu_p \frac{G_E^P}{G_M^P} \]
  in the OPEX

- Fit
  \[ \frac{P_\ell}{P_\ell \text{ Born}} \]
  with
  \[ 1 + A \epsilon^4 (1 - \epsilon)^{1/2} \]
Empirical determination of TPEX amplitudes

- Fit the ratio
  \[ \frac{\mu_p \sqrt{\frac{\tau(1 + \varepsilon)}{2\varepsilon} \frac{P_t}{P_\ell}}}{\mu_p \frac{G_E^P}{G_M^P}} \]
  in the OPEX with a constant

- Fit
  \[ \frac{P_\ell}{P_\ell \text{ Born}} \]
  with
  \[ 1 + A\varepsilon^4(1 - \varepsilon)^{1/2} \]

- Fit
  \[ \frac{\sigma_r}{\mu_p G_D} \]
  with a linear function in \( \varepsilon \):
  \[ a + b\varepsilon \]
Empirical determination of TPEX amplitudes

\[ - \mu_p \sqrt{\frac{\tau(1 + \varepsilon)^2}{2\varepsilon}} \left( \frac{P_t}{P_\ell} \right) = \mu_p \frac{G^p_E}{G^p_M} \]

in the OPEX

- Fit the ratio with a constant

\[ \frac{P_\ell}{P_Bern} \]

- Fit with a linear function in \( \varepsilon \):

\[ a + b\varepsilon \]

- Fit with \( 1 + A\varepsilon^4(1 - \varepsilon)^{1/2} \)

- Extract using the value from fit

\[ G^2_M \]

\[ \frac{G^p_E}{G^p_M} \]

and \( a, b \)

\[ \frac{P_t}{P_\ell} \]
Empirical determination of TPEX amplitudes

- Fit the ratio
  \[- \mu_p \sqrt{\frac{\tau(1 + \varepsilon)}{2 \varepsilon}} \frac{P_t}{P_\ell} \]
  \[= \mu_p \frac{G_E^p}{G_M^p} \]
  in the OPEX
  with a constant

- Fit
  \[\frac{P_\ell}{P_{\ell \text{ Born}}}\]
  with
  \[1 + A \varepsilon^4 (1 - \varepsilon)^{1/2}\]

- Fit
  \[\frac{\sigma_r}{\mu_p G_D}\]
  with a linear function in \(\varepsilon\):
  \[a + b \varepsilon\]

- Extract
  \[G_M^2\]
  using the
  \[G_E^p / G_M^p\]
  value from
  \[P_t / P_\ell\]
  fit
  and
  \[a, b\]

\[\gamma_{2\gamma}^M = \text{Re}(\delta \tilde{G}_M / G_M)\]
best constrained

are at the 3% level, opposite sign, cancel partially in the observables

\[\gamma_{2\gamma}^E = \text{Re}(\delta \tilde{G}_E / G_M)\]

\[\gamma_{2\gamma}^3 = \text{Re}(\delta \tilde{F}_3 / G_M) \nu / M^2\]

Vanderhaeghen, Kivel, Guttmann, Meziane (submitted to PRL)
• The polarization component ratio is independent of the reconstructed kinematics.

• No evidence of an epsilon dependence at a 0.01 level for a polarization component ratio of 0.7 at $Q^2$ of 2.5 GeV$^2$.

• Results show an enhancement at small $\epsilon$ for the longitudinal polarization observable.

• PRL submitted for publication.

• Determination of the TPEX amplitudes is possible

• TPEX puzzle remains:
  - Need more experimental constrains:
    - Non linearity of the cross section.
    - Single spin asymmetries.
    - Ratio $e^+/e^-$.  

To fully understand, quantify the TPEX.
BACK-UP SLIDES
"Standard" Radiative Corrections

- a) Born term
- b) vertex
- c) vacuum
- d) self energy
- e) Bremsstrahlung
- a) bremsstrahlung
- b) vertex
- c) self energy
- d) two-photon
Beyond the Born-Approximation

Parity, Wigner time reversal invariance and lepton helicity conservation give the following expansion of the hadronic vertex function (not unique):

\[ \Gamma^\mu(p, p') = \tilde{G}_M \gamma^\mu - \tilde{F}_2 \frac{P^\mu}{M} + \tilde{F}_3 \frac{\gamma \cdot k P^\mu}{M^2} \]

Beyond the Born Approximation a third complex amplitude arises.

The kinematical parameter \( \varepsilon \) is:

\[ \varepsilon = \frac{(s - u)^2 + t(4M^2 - t)}{(s - u)^2 - t(4M^2 - t)} \]
HMS with Focal Plane Polarimeter

- Two HMS drift chambers for tracking—measure proton momentum and define incident trajectory for FPP.

- Scintillator hodoscopes S0 and S1 for trigger and timing.

- Focal Plane Polarimeter
  - Two CH2 analyzers, 55 cm thick
  - Two sets of drift chambers track protons scattered in analyzer.
• 1744 channels electromagnetic calorimeter

• Measure electron angles and energy

• Separate elastic from inelastic background

• From $\frac{6.8}{\sqrt{E}}$ to $\frac{23}{\sqrt{E}}$ energy resolution
  (E in GeV) due to radiation damage

• Position resolution not very sensitive to radiation damage ~5 mm
Physical asymmetries (helicity dependent) are obtained by taking the difference between the angular distributions of events of the two helicity states: $f^+(\theta, \phi) - f^-(\theta, \phi)$

Physical asymmetries can be written as a sine function with a phase shift which is related to the polarization components ratio at the focal plane.

With the FPP, we measure the proton polarization after undergoing precession through the HMS magnets.

$$f^+(\theta - \varphi) - f^-(\theta - \varphi) = B\sin(\varphi + \Delta\varphi)$$

$$B = hA_y \sqrt{(P_t^{\text{FPP}})^2 + (P_n^{\text{FPP}})^2}$$

$$\tan\Delta\varphi = -\frac{P_t^{\text{FPP}}}{P_n^{\text{FPP}}} \quad ; \quad P_n^{\text{FPP}} \approx P_l^{\text{Tgt}} \sin \chi_\theta$$
FALSE ASYMMETRIES

• The angular distribution is given by:

\[
N^\pm(p, \theta, \varphi) = \frac{N_0^\pm \varepsilon(p, \theta)}{2\pi} \left[ 1 + (c_1 \pm A_y^{fpp} P_y^{fpp}) \cos \varphi + (s_1 \mp A_x^{fpp} P_x^{fpp}) \sin \varphi + c_2 \cos(2 \varphi) \right] + s_2 \sin(2 \varphi) + \ldots
\]

- Number of incident proton with ± helicity state.
- Fraction of proton with momentum \( p \) scattered with an angle \( \theta \).
- Analyzing power of the \( \bar{p} + CH_2 \) reaction.
- Polarization components at the focal plane.
- Fourier coefficients of helicity independent instrumental asymmetries.
  (sum of \( N^+ \) and \( N^- \), cancelled in first order)

\[ \lambda_0 = \sum_i c_i \cos \varphi_i + s_i \sin \varphi_i \]

• Maximizing the Likelihood function: \((S_{ij} \text{ COSY spin transport matrix elements})\)

\[
L(P_t, P_l) = \prod_{i=1}^{N_{\text{event}}} \left[ 1 + h \varepsilon_i A_y^{(i)} (S_y^{(i)} P_t + S_y^{(i)} P_l) \cos \varphi_i - h \varepsilon_i A_y^{(i)} (S_{xt}^{(i)} P_t + S_{xt}^{(i)} P_l) \sin \varphi_i + \lambda_0^{(i)} \right]
\]

Small negative correction at the 2\(^{nd}\) order in the P.C. ratio for the 3 kin. : \(|\Delta R| \approx 0.013\)
Other determination of TPEX amplitudes

Based on:
- The linearity of the reduced cross section $\sigma_r$
- No $\varepsilon$-dependence of the polarization transfer ratio
- TPEX amplitudes vanish at $\varepsilon=1$

The reduced cross section gives information about the amplitude $\tilde{\delta G}_M$

\[
\sigma_r = G_M^2 \{ \tau + \varepsilon R_0^2 + 2\tau \frac{\delta \tilde{G}_M}{G_M} + 2\varepsilon R_0^2 \frac{\delta \tilde{G}_E}{G_E} \} 
\]

with
\[
R_0 = \frac{G_E}{G_M}
\]

- Neglect the last term (cross check afterward)

\[
\frac{\delta \tilde{G}_M}{G_M} = a(1 - \varepsilon)
\]

- $a$ is determined by the slope of the reduced cross section

D. Borisyuk, A. Kobushkin arXiv:1012.3746v1

Elastic intermediate states
Elastic+$\Delta$ resonance

1$\sigma$ band
Other determination of TPEX amplitudes

The polarization component ratio gives information about the amplitude \( \delta \tilde{G}_E \)

\[
R = R_0 \{ 1 + \frac{\delta \tilde{G}_E}{G_E} - \frac{\delta \tilde{G}_M}{G_M} - \frac{\varepsilon (1 - \varepsilon)}{1 + \varepsilon} \frac{\delta \tilde{G}_3}{G_M} \} \]

with

\[
\delta \tilde{G}_3 = \sqrt{F_3} / 4M^2
\]

• Rough estimate of \( \delta \tilde{G}_E \)

BNk

\[ \mathcal{E} - \mathcal{E}_0 \]

Need the determination of \( \delta R = R - R_0 \)

The TPE correction to \( P_\ell \) gives information about the amplitude \( \delta \tilde{G}_3 \)

\[
\delta P_\ell = -2P_\ell \varepsilon \{ \frac{R_0^2 \delta R}{\varepsilon R_0^2 + \tau} - \frac{\varepsilon}{1 + \varepsilon} \frac{\delta \tilde{G}_3}{G_M} \}
\]

• Two few data points

• \( \delta \tilde{G}_3 \) computed at the \( \varepsilon \) value of the data points

\[ D. Borisyuk, A. Kobushkin \text{ arXiv:1012.3746v1} \]