Polarization observables in double pion photo-production with circularly polarized photons off transversely polarized protons (g9b-FROST)

CLAS Collaboration Meeting

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Outline

• g9b (FROST) Experiment
• Analysis
• Preliminary Results
• Outlook
Why $\gamma p \rightarrow p\pi^+\pi^-$?

- Biggest contribution to the photo-production cross section at higher energies
- Brings additional information to what single pion photo-production could provide

Hagiwara et al., 2002
Previous and Current Studies for Double Pion Photo-production

[Image of plots and data]

[Text: Yuqing Mao, USC]

JLab Projects (USC and FSU)

<table>
<thead>
<tr>
<th>Target</th>
<th>unpolarized</th>
<th>circular</th>
<th>linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>unpolarized</td>
<td>$I_0$</td>
<td>$I^\odot$</td>
<td>$I^s$, $I^c$</td>
</tr>
<tr>
<td>longitudinal</td>
<td>$P_z$</td>
<td>$P^\odot_z$</td>
<td>$P^c_z$, $P^s_z$</td>
</tr>
<tr>
<td>transversal</td>
<td>$P_x$, $P_y$</td>
<td>$P^\odot_x$, $P^\odot_y$</td>
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[Text:Strauch, 2005]
Polarization Observables

\[ I_0 = |M_1^-|^2 + |M_1^+|^2 + |M_2^-|^2 + |M_2^+|^2 + |M_3^-|^2 + |M_3^+|^2 + |M_4^-|^2 + |M_4^+|^2 \]

\[ I_0 P_x = 2\Re(M_1^- M_3^-* + M_1^+ M_3^+* + M_2^- M_4^-* + M_2^+ M_4^+*) \]

\[ I_0 P_y = -2\Im(M_1^- M_3^-* + M_1^+ M_3^+* + M_2^- M_4^-* + M_2^+ M_4^+*) \]

\[ I_0 I^\Diamond = -|M_1^-|^2 + |M_1^+|^2 - |M_2^-|^2 + |M_2^+|^2 - |M_3^-|^2 + |M_3^+|^2 - |M_4^-|^2 + |M_4^+|^2 \]

\[ I_0 P_x^\Diamond = 2\Re(-M_1^- M_3^-* + M_1^+ M_3^+* - M_2^- M_4^-* + M_2^+ M_4^+*) \]

\[ I_0 P_y^\Diamond = 2\Im(M_1^- M_3^-* - M_1^+ M_3^+* + M_2^- M_4^-* - M_2^+ M_4^+*) \]

[W. Roberts and T. Oed, 2005]

Reaction rate for \( \vec{\gamma}p \rightarrow p\pi^+\pi^- \) with circularly polarized photons off transversely polarized protons is written:

\[ \rho_f I = I_0[(1 + \vec{\Lambda}_i \cdot \vec{P}_i) + \delta( I^\Diamond + \vec{\Lambda}_i \cdot \vec{P}_i^\Diamond)] \quad i = x, y \]

\( \rho_f \) - spin density matrix of the recoiling nucleon
g9b( FROST) experiment

Electron beam: - longitudinally polarized; $\bar{P}_e = 87\%$
- beam energy: 3081.73 MeV

Photon beam: - circularly polarized

Targets:
- FROzen Spin Target (FROST) = transversely polarized butanol ($\text{C}_4\text{H}_9\text{OH}$) $L=5$ cm, $d=1.5$ cm
- Carbon target – $L = 0.15$ cm

CLAS Detector
g9b circularly polarized data

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<tr>
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<th>Events</th>
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The target polarization was flipped to allow a cancellation of the CLAS acceptance in the asymmetry calculations.
Reaction Selection

$$\gamma p \rightarrow p\pi^+ \pi^-$$

Final State Composition: 2 positive charges and 1 negative charge

Topology 1: \(\vec{\gamma} \vec{p} \rightarrow p\pi^+ \pi^- (X)\) nothing missing

Topology 2: \(\vec{\gamma} \vec{p} \rightarrow \pi^+ \pi^- (X)\) p missing

Topology 3: \(\vec{\gamma} \vec{p} \rightarrow p\pi^+ (X)\) \(\pi^-\) missing

Topology 4: \(\vec{\gamma} \vec{p} \rightarrow p\pi^- (X)\) \(\pi^+\) missing
Background Determination

Butanol Target ($C_4H_9OH$) - 10 free protons and 64 bound nucleons

Carbon Target - 12 bound nucleons (no free protons)

The missing mass technique is used to reconstruct the missing particle:

$$\vec{\gamma} \vec{p} \rightarrow p\pi^+ \pi^- (X)$$

$$M_X = \sqrt{(E_\gamma + m_p - E_p - E_{\pi^+} - E_{\pi^-})^2 - |\vec{p}_\gamma - \vec{p}_p - \vec{p}_{\pi^+} - \vec{p}_{\pi^-}|^2}$$
Two background subtraction methods

1) Integrated Method

Scale factor = Number of butanol events in R range divided by the number of carbon events in R range

Scale factor = 10.18

Signal = Butanol − Scale factor × Unscaled carbon
2) Event-based background subtraction

**Q-factor** = an event-based quality factor equal to the probability for one given event to come from a signal distribution

\[
Q = \frac{\text{Signal}}{\text{Signal} + \text{Background}}
\]

**Step 1** – Pre-bin data in the center-of-mass energy \(W\).

**Step 2** - Calculate the distance measure between one event \(a\) and any other random event \(b\) from our data set

\[
D^2_{a,b} = \sum_{i=1}^{5} \left( \frac{\Gamma^a_i - \Gamma^b_i}{\Delta_i} \right)^2
\]

\[\Gamma_i = \Phi^*, \cos \Theta_{CM}, \cos \Theta^*, m_{\pi^+\pi^-}, m_{p\pi^+}\]

**Step 3** - For each event \(a\) (called **seed event**), we select 5,000 kinematically nearest neighbors, which will be butanol, respectively carbon events
2) Event-based background subtraction (continuation)

Step 4 – Fit carbon and butanol distributions using $\chi^2$-minimization technique and extract the parameters needed to determine Q value.

Carbon function = Gaussian + 2$^{nd}$ order Polynomial

Butanol function = Voigt(peak) + Scale Factor $\times$ (Gaussian + 2$^{nd}$ order Polynomial)

Step 5 – After the fit is completed, the resulted fit parameters will be used to calculate the Q value, by evaluating the butanol and carbon functions at the seed event position.
2) Event-based background subtraction (continuation)

Example: 5,000 nearest neighbors distribution for topology 3

\[ Q = \frac{\text{Signal}}{\text{Signal} + \text{Background}} \]

Q value is determined:

\[ Q = \frac{145 - 51}{145} = 0.65 \]
Two methods of background subtraction comparison

Topology 3: $\vec{\gamma}p \rightarrow p\pi^+(X)$

Data is integrated over all kinematic variables!

There is a good match between the two methods within 2-sigma range of the signal!

\[ d = \frac{\text{free - proton events}}{\text{butanol events}} \]

\[ M^2_X [\text{GeV}] \]

Events

Dilution qvalue = 0.6245, Dilution integrated = 0.6136

- Butanol
- Signal (Qvalue method)
- Carbon (Qvalue method)
- Carbon (Integrated method)
- Signal (Integrated method)
Observables extraction: Moment Method

The acceptance of the detector for the two polarization directions:

\[ A(\alpha) = a_0 + a_1 \cdot \cos \alpha + b_1 \cdot \sin \alpha + a_2 \cdot \cos 2\alpha + b_2 \cdot \sin 2\alpha \]

\[ A(\alpha + \pi) = a_0 - a_1 \cdot \cos \alpha - b_1 \cdot \sin \alpha + a_2 \cdot \cos 2\alpha + b_2 \cdot \sin 2\alpha \]

The total yield for the reaction of this analysis is:

\[ Y = \frac{1}{2\pi} \int_0^{2\pi} Y_{unpol}(\alpha)(1+\Lambda P_x \cos \alpha + \Lambda P_y \sin \alpha\delta(I_0 + \Lambda P_x \cos \alpha + \Lambda P_y \sin \alpha))d\alpha \]
Different moments related to the two target polarization directions (0°, 180°) and two helicity states (+, -) of the photon beam are used to write the expressions for the polarization observables: $I^\bigcirc$, $P_x$, $P_y$, $P_x^\bigcirc$, $P_y^\bigcirc$

For example, the beam-helicity asymmetry is given by:

$$I^\bigcirc = \frac{\bar{\Lambda}^{180}(Y^+ - Y^-) + \bar{\Lambda}^0(Y^{+180} - Y^{-180})}{\delta^\bigcirc(\bar{\Lambda}^{180}Y^0 + \bar{\Lambda}^0Y^{180})}$$

All the final expressions correct for the acceptance effects and for the fact that the target polarization is slightly different for different run groups.
The results are obtained after integrating over all energies and all variables.
The text is not clearly visible due to the image quality. However, it appears to be a series of graphs showing data trends for different values of $W$ from 1450 MeV to 2450 MeV. The graphs are labeled with $P_x$ and $\phi^*$, indicating some form of projection or angle measurement. The data seems to be plotted against $\phi^*$ for each $W$ value.
$W = 1550 \text{ MeV}$

$\cos \theta^* = [-1, 1]$
$W=1550 \text{ MeV}$

$\cos \theta_{\text{CM}} = [-1, 1]$
$W = 1550 \text{ MeV}$

$
\cos\theta_{\text{CM}} = [-1, 1]
$
$W = 1550$ MeV
$\cos \theta^* = [-1, 1]$
Outlook

- overview of the methods used to analyze $\vec{\gamma}p \rightarrow p\pi^+\pi^-$ with circularly polarized photon beam off transversely polarized protons and to extract the polarization observables:

$I^\odot, P_x, P_y, P_x^\odot, P_y^\odot$

- preliminary results were shown

- next step: binning data in different ways and compare with the models, getting the systematic uncertainties
EXTRA SLIDES
L – orbital angular momentum of nucleon-pion pair
T – isospin, J – total angular momentum,

Example: $P_{11}^1$
$L=1$, $T=1/2$, $J=1/2$, $\pi=+1$

Photon selection

\[ \Delta t = t_{CLAS} - t_{TAGR} \]

\[ |\Delta t| < 1 \text{ ns} \]

Butanol events: 

\(-3 \text{ cm} < \text{mvrtZ} < +3 \text{ cm} \)

Carbon events: 

\(+6 \text{ cm} < \text{mvrtZ} < +11 \text{ cm} \)

\[ \beta_{calc} = \frac{p}{\sqrt{p^2 + m^2}} \]

\[ \Delta \beta = \beta_{meas} - \beta_{calc} \]
The moments for the two target polarization directions \(0°, 180°\) are:

\[ Y^0, Y^{180}, Y^0_{\sin \alpha}, Y^{180}_{\sin \alpha}, Y^0_{\cos \alpha}, Y^{180}_{\cos \alpha}, Y^0_{\sin 2\alpha}, Y^{180}_{\sin 2\alpha}, Y^0_{\cos 2\alpha}, Y^{180}_{\cos 2\alpha} \]

After adding and subtracting different combinations of these yields we get:

\[
\begin{align*}
P_x &= 2 \frac{[(Y^0 \bar{A}^{180} + Y^{180} \bar{A}^0) - (Y^0_{\cos 2\alpha} \bar{A}^{180} + Y^{180}_{\cos 2\alpha} \bar{A}^0)](Y^0_{\cos \alpha} + Y^{180}_{\cos \alpha}) - (Y^0_{\sin 2\alpha} \bar{A}^{180} + Y^{180}_{\sin 2\alpha} \bar{A}^0)(Y^0_{\sin \alpha} + Y^{180}_{\sin \alpha})}{(Y^0 \bar{A}^{180} + Y^{180} \bar{A}^0)^2 - (Y^0_{\cos 2\alpha} \Lambda^{180} + Y^{180}_{\cos 2\alpha} \Lambda^0)^2 - (Y^0_{\sin 2\alpha} \bar{A}^{180} + Y^{180}_{\sin 2\alpha} \bar{A}^0)^2} \\
\end{align*}
\]

\[
\begin{align*}
P_y &= 2 \frac{[(Y^0 \bar{A}^{180} + Y^{180} \bar{A}^0) + (Y^0_{\cos 2\alpha} \bar{A}^{180} + Y^{180}_{\cos 2\alpha} \bar{A}^0)](Y^0_{\cos \alpha} + Y^{180}_{\cos \alpha}) - (Y^0_{\sin 2\alpha} \bar{A}^{180} + Y^{180}_{\sin 2\alpha} \bar{A}^0)(Y^0_{\sin \alpha} + Y^{180}_{\sin \alpha})}{(Y^0 \bar{A}^{180} + Y^{180} \bar{A}^0)^2 - (Y^0_{\cos 2\alpha} \Lambda^{180} + Y^{180}_{\cos 2\alpha} \Lambda^0)^2 - (Y^0_{\sin 2\alpha} \bar{A}^{180} + Y^{180}_{\sin 2\alpha} \bar{A}^0)^2} \\
\end{align*}
\]
\[ P_x = 2 \frac{(\bar{\Lambda}^{180} Y_{\sin 2\alpha}^0 + \bar{\Lambda}^0 Y_{\sin 2\alpha}^{180})(Y_{\sin \alpha}^{+0} - Y_{\sin \alpha}^{-0} + Y_{\sin \alpha}^{+180} - Y_{\sin \alpha}^{-180}) - \delta \circ [(\bar{\Lambda}^{180} Y_{\sin 2\alpha}^0 + \bar{\Lambda}^0 Y_{\sin 2\alpha}^{180})^2 - (Y_{\cos \alpha}^0 \Lambda^{180} + Y^{180} \bar{\Lambda}^0)^2 + (Y_{\cos 2\alpha}^0 \bar{\Lambda}^{180} + Y^{180} \bar{\Lambda}^0)^2]}{\delta \circ [(\bar{\Lambda}^{180} Y_{\sin 2\alpha}^0 + \bar{\Lambda}^0 Y_{\sin 2\alpha}^{180})^2 - (Y_{\cos \alpha}^0 \Lambda^{180} + Y^{180} \bar{\Lambda}^0)^2 + (Y_{\cos 2\alpha}^0 \bar{\Lambda}^{180} + Y^{180} \bar{\Lambda}^0)^2]}\]

\[ P_y = 2 \frac{[Y_{\cos 2\alpha}^0 \bar{\Lambda}^{180} + Y^{180} \bar{\Lambda}^0] - (Y_{\cos \alpha}^0 \bar{\Lambda}^{180} + Y^{180} \bar{\Lambda}^0)(Y_{\sin \alpha}^{+0} - Y_{\sin \alpha}^{-0} + Y_{\sin \alpha}^{+180} - Y_{\sin \alpha}^{-180}) - \delta \circ [(Y_{\cos 2\alpha}^0 \bar{\Lambda}^{180} + Y^{180} \bar{\Lambda}^0)^2 - (\bar{\Lambda}^{180} Y_{\sin 2\alpha}^0 + \bar{\Lambda}^0 Y_{\sin 2\alpha}^{180})^2 - (Y_{\cos 2\alpha}^0 \bar{\Lambda}^{180} + Y^{180} \bar{\Lambda}^0)^2]}{\delta \circ [(Y_{\cos 2\alpha}^0 \bar{\Lambda}^{180} + Y^{180} \bar{\Lambda}^0)^2 - (\bar{\Lambda}^{180} Y_{\sin 2\alpha}^0 + \bar{\Lambda}^0 Y_{\sin 2\alpha}^{180})^2 - (Y_{\cos 2\alpha}^0 \bar{\Lambda}^{180} + Y^{180} \bar{\Lambda}^0)^2]}\]
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<th>Run range</th>
<th>Date range</th>
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<th>Beam current</th>
<th>Live time</th>
<th>Helicity freq.</th>
<th>H.W.P</th>
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Target polarization: (NMR_sign Holding_magnet_sign) e.g. (+ +) and (- -) means pos.sign; (+ -) and (- +) means neg.sign
Missing Mass Squared Distributions

\[ \gamma p \rightarrow p \pi^+ \pi^- (X) \]

- Butanol
- Scaled Carbon
- Free Protons

\[ \gamma p \rightarrow \pi^+ \pi^- (X) \]

\[ \gamma p \rightarrow p \pi^- (X) \]

\[ \gamma p \rightarrow p \pi^+ (X) \]
Observables odd/even behavior fit check

\[ F_{\text{even}} = a_0 + a_1 \cos(\Phi^*) + a_2 \cos(2\Phi^*) + a_3 \cos(3\Phi^*) + a_4 \cos(4\Phi^*) \]

\[ F_{\text{odd}} = b_1 \sin(\Phi^*) + b_2 \sin(2\Phi^*) + b_3 \sin(3\Phi^*) + b_4 \sin(4\Phi^*) \]
Target polarization orientation angle

\[ \Phi_0 = -63.9^\circ, 116.1^\circ \]

\[ \alpha = 180^\circ - \Phi_{lab}^p + \Phi_0 \]