Measurement of the Helicity Difference in Double - Pion Photoproduction using the CLAS Spectrometer at Jefferson Laboratory

Sungkyun Park
Graduate Student
Florida State University

Prospectus of Dissertation
November 18, 2008
Outline

1. Introduction
   - Problems in Hadron Spectroscopy
   - Motivation for this work

2. The concept of physics for my dissertation

3. FROST Experiment
   - Experimental Setup
   - The FROST Data
   - Summary
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Sungkyun Park
Measurement of the Helicity Difference using CLAS
What are hadrons?

Hadrons are composed of quarks bound by the strong interaction.

- **Baryon**: $qqq$
- **Meson**: $q\bar{q}$

Quantum Chromodynamics (QCD)
- The theory of how quarks and gluons interact with themselves and each other

Constituent quark models (QCD-based models)
- as the short-range interaction between quarks.
  - Gluon-exchange models
  - One-boson exchange models
  - Instanton-based models
The excited states of the nucleon

Constituent quark models based on instanton

- The number of *'s indicates the ranking of the state according to the particle data group (PDG).
- The four-star is a well established resonance.

U. Lohring et al., EPJ A10 395 (2001)
The excited states of the nucleon

Constituent quark models: $N^*$ resonances (Isospin $\frac{1}{2}$)

The left part of each column - model predictions
The right part of each column - experimental findings

$L^J_{2T2\ell}$

- $T$ Isospin
- $\pi$ Parity
- $J$ Total spin

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<table>
<thead>
<tr>
<th>$J^\pi_T$</th>
<th>$L^2_{J^\pi_T}$</th>
<th>Model Predictions</th>
<th>Experimental Findings</th>
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<td>3/2+</td>
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The left part of each column:
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The left part of each column represents the model predictions, and the right part represents the experimental findings.

$L^J_{2T2J}$

- $T$: Isospin
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Constituent quark models: $N^*$ resonances (Isospin $\frac{1}{2}$)

The left part of each column - model predictions
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$L^J_{2T_2J}$
- $T$ Isospin
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- $J$ Total spin

The missing resonances is experimentally not established baryon states which are predicted by constituent quark models.

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- The four-star is a well established resonance.
**Introduction**

The concept of physics for my dissertation

**FROST Experiment**

**Problems in Hadron Spectroscopy**

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**Why have we not found these missing resonances?**

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<th>$L_{2I-2J}$ Status</th>
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<th>$N\pi$</th>
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<th>$\Delta K$</th>
<th>$\Sigma K$</th>
<th>$\Delta \pi$</th>
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(A) Most experiments have been $N\pi$ elastic scattering experiments.
Why have we not found these missing resonances?

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The modes used in this work: $\gamma N \rightarrow N^* \rightarrow \Delta \pi \rightarrow N\pi^+\pi^-$

- $N\rho$
- $N\gamma$
Why have we not found these missing resonances?

(B) Most channels explored until now include one meson in the final state.

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\[ N\rho \]

\[ N\gamma \]
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(C) Photoproduction data accumulated in recent years mainly cover masses up to 1800 MeV/c². The CLAS-FROST experiment covers above 1800 MeV/c².
Why have we not found these missing resonances?

projection along the mass axis

The excited states are found as broadly overlapping resonances.

- We can isolate single resonances from these other interference terms by determining the polarization observables.
The cross section of 3-body final states dominates above $W \approx 1.7$ GeV. The dominant resonant decay modes leading to $\gamma p \rightarrow p\pi^+\pi^-$ include $\Delta\pi$, $N\rho$, and $N\gamma$. 

$$
\begin{align*}
\gamma N \rightarrow N^* &\rightarrow \Delta\pi \rightarrow N\pi^+\pi^- \\
\gamma N \rightarrow N^* &\rightarrow N\rho \rightarrow N\pi^+\pi^- \\
\gamma N \rightarrow N^* &\rightarrow N\gamma \rightarrow N\pi^+\pi-
\end{align*}
$$

These modes are difficult to detect.

- The need of detectors with a large angular acceptance
- The contribution of the large non-resonant background

The CLAS-FROST experiment can be a solution of these problems.

- The CLAS spectrometer is nearly-4$\pi$ detector
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The 3-particle final state for $\gamma p \rightarrow p\pi\pi$

The $\pi^-\pi^+$ final state requires 5 independent invariable.

The differential cross section for $\gamma p \rightarrow p\pi^+\pi^-$ (without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{dx_i} = \sigma_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I_\odot + \vec{\Lambda}_i \cdot \vec{P}_\odot) + \delta_i \left[ \sin 2\beta (I_\odot + \vec{\Lambda}_i \cdot \vec{P}_\odot) + \cos 2\beta (I_\odot + \vec{\Lambda}_i \cdot \vec{P}_\odot) \right]\right\}$$

- $\sigma_0$: The unpolarized cross section
- $\beta$: The angle between the direction of polarization and the x-axis
- $\delta_\odot, \delta_i$: The degree of polarization of the photon beam
- $\vec{\Lambda}_i$: The polarization of the initial nucleon
- $I_\odot, I_\odot, I_\odot$: The observable arising from use of polarized photons
- $\vec{P}$: The polarization observable

Sungkyun Park Measurement of the Helicity Difference using CLAS
The concept of physics for my dissertation

The 3-particle final state for $\gamma p \rightarrow p\pi\pi$

The center of mass system

The $\pi^-\pi^+$ final state requires 5 independent invariables.

$\gamma p \rightarrow N^* \rightarrow \bar{p} \rho \rightarrow \bar{p} \pi^+\pi^-$

$\phi, \theta_{cm}, k, m_{\rho\pi^+},$ and $m_{\pi^+\pi^-}$

The differential cross section for $\gamma p \rightarrow p\pi^+\pi^-$ (without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{dx_i} = \sigma_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) + \delta_I \left[ \sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c) \right] \right\}$$

- $\sigma_0$: The unpolarized cross section
- $\beta$: The angle between the direction of polarization and the $x$-axis
- $\delta_\odot, I$: The degree of polarization of the photon beam
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- $\sigma_0$: The unpolarized cross section
- $\beta$: The angle between the direction of polarization and the x-axis
- $\delta_\odot, I$: The degree of polarization of the photon beam $\Rightarrow \delta_\odot, I$
- $\vec{\Lambda}_i$: The polarization of the initial nucleon
- $I^\odot, S, C$: The observable arising from use of polarized photons
- $\vec{P}$: The polarization observable
The 3-particle final state for $\gamma p \rightarrow p \pi \pi$

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$\gamma p \rightarrow N^* \rightarrow \not{p} \rho \rightarrow \not{p} \pi^+ \pi^-$

$\phi, \theta_{cm}, k, m_{\pi^+},$ and $m_{\pi^+}$

The differential cross section for $\gamma p \rightarrow p \pi^+ \pi^-$ (without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{dx_i} = \sigma_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta \odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) + \delta_I \left[ \sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c) \right] \right\}$$

- $\sigma_0$: The unpolarized cross section
- $\beta$: The angle between the direction of polarization and the x-axis
- $\delta \odot, \delta_I$: The degree of polarization of the photon beam $\Rightarrow \delta \odot$, and $\delta_I$
- $\vec{\Lambda}_i$: The polarization of the initial nucleon $\Rightarrow (\Lambda_x, \Lambda_y, \Lambda_z)$
- $I^\odot, s, c$: The observable arising from use of polarized photons
- $\vec{P}$: The polarization observable
The 3-particle final state for $\gamma p \rightarrow p\pi\pi$

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$\phi$, $\theta_{cm}$, $k$, $m_{p\pi^+}$, and $m_{\pi^+\pi^-}$

The differential cross section for $\gamma p \rightarrow p\pi^+\pi^-$ (without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{dx_i} = \sigma_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) + \delta_I \left[ \sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c) \right] \right\}$$

- $\sigma_0$: The unpolarized cross section
- $\beta$: The angle between the direction of polarization and the x-axis
- $\delta_\odot$, $I$: The degree of polarizaton of the photon beam $\Rightarrow \delta_\odot$, and $I$
- $\vec{\Lambda}_i$: The polarization of the initial nucleon $\Rightarrow (\Lambda_x, \Lambda_y, \Lambda_z)$
- $I^\odot$, $I^s$, $I^c$: The observable arising from use of polarized photons $\Rightarrow I^\odot$, $I^s$, $I^c$
- $\vec{P}$: The polarization observable
The concept of physics for my dissertation

The 3-particle final state for \( \gamma p \rightarrow p\pi\pi \)

The center of mass system

The \( \pi^-\pi^+ \) final state requires 5 independent invariables.
\[ \gamma p \rightarrow N^* \rightarrow \hat{p} \rho \rightarrow \hat{p} \pi^+\pi^- \]
\[ \phi, \theta_{cm}, k, m_{\pi^+}, \text{and} m_{\pi^+\pi^-} \]

The differential cross section for \( \gamma p \rightarrow p\pi^+\pi^- \) (without measuring the polarization of the recoiling nucleon)

\[
\frac{d\sigma}{dx_i} = \sigma_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I_\odot + \vec{\Lambda}_i \cdot \vec{P}_\odot) + \delta_l \left[ \sin 2\beta (I_s + \vec{\Lambda}_i \cdot \vec{P}_s) + \cos 2\beta (I_c + \vec{\Lambda}_i \cdot \vec{P}_c) \right] \right\}
\]

- \( \sigma_0 \): The unpolarized cross section
- \( \beta \): The angle between the direction of polarization and the x-axis
- \( \delta_\odot, I \): The degree of polarization of the photon beam \( \Rightarrow \delta_\odot, \text{and} \delta_l \)
- \( \vec{\Lambda}_i \): The polarization of the initial nucleon \( \Rightarrow (\Lambda_x, \Lambda_y, \Lambda_z) \)
- \( I_\odot, I_s, I_c \): The observable arising from use of polarized photons \( \Rightarrow I_\odot, I_s, I_c \)
- \( \vec{P} \): The polarization observable \( \Rightarrow (P_x, P_y, P_z) \)
The concept of physics for my dissertation

The 3-particle final state for $\gamma p \rightarrow p \pi \pi$

The center of mass system

The $\pi^- \pi^+$ final state requires 5 independent invariables.

$$\gamma p \rightarrow N^* \rightarrow \hat{p} \rho \rightarrow \hat{p} \pi^+ \pi^-$$

$\phi, \theta_{cm}, k, m_{\rho \pi^+}$, and $m_{\pi^+ \pi^-}$

The differential cross section for $\gamma p \rightarrow p \pi^+ \pi^-$ (without measuring the polarization of the recoiling nucleon)

$$\frac{d \sigma}{d x_1} = \sigma_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I_\odot + \vec{\Lambda}_i \cdot \vec{P}_\odot) + \delta_I \left[ \sin 2\beta (I_s + \vec{\Lambda}_i \cdot \vec{P}_s) + \cos 2\beta (I_c + \vec{\Lambda}_i \cdot \vec{P}_c) \right] \right\}$$

- $\sigma_0$: The unpolarized cross section
- $\beta$: The angle between the direction of polarization and the x-axis
- $\delta_\odot, I$: The degree of polarizatton of the photon beam $\Rightarrow \delta_\odot$, and $\delta_I$
- $\vec{\Lambda}_i$: The polarization of the initial nucleon $\Rightarrow (\Lambda_x, \Lambda_y, \Lambda_z)$
- $I_\odot, I_s, I_c$: The observable arising from use of polarized photons $\Rightarrow I_\odot, I_s, I_c$
- $\vec{P}$: The polarization observable $\Rightarrow (P_x, P_y, P_z) (P_x, P_y, P_z) (P_x, P_y, P_z)$

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Measurement of the Helicity Difference using CLAS
The concept of physics for my dissertation

The 3-particle final state for $\gamma p \rightarrow p\pi\pi$

The center of mass system

The $\pi^-\pi^+$ final state requires 5 independent invariables:

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$\phi, \theta_{cm}, k, m_{p\pi^+},$ and $m_{\pi^+\pi^-}$

The differential cross section for $\gamma p \rightarrow p\pi^+\pi^-$ (without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{dx_i} = \sigma_0 \left\{ (1 + \vec{\Lambda}_j \cdot \vec{P}) + \delta \circ (I \circ + \vec{\Lambda}_i \cdot \vec{P} \circ) + \delta I [\sin 2\beta (I^s + \vec{\Lambda}_j \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c)] \right\}$$

- $\sigma_0$: The unpolarized cross section
- $\beta$: The angle between the direction of polarization and the x-axis
- $\delta \circ, I$: The degree of polarization of the photon beam $\Rightarrow \delta \circ$ and $\delta I$
- $\vec{\Lambda}_i$: The polarization of the initial nucleon $\Rightarrow (\Lambda_x, \Lambda_y, \Lambda_z)$
- $I \circ, I^s, I^c$: The observable arising from use of polarized photons $\Rightarrow I \circ, I^s, I^c$
- $\vec{P}$: The polarization observable $\Rightarrow (P_x, P_y, P_z) (P_x \circ, P_y \circ, P_z \circ) (P_s, P_s, P_s)$

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Measurement of the Helicity Difference using CLAS
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The 3-particle final state for $\gamma p \rightarrow p\pi\pi$

The $\pi^-\pi^+$ final state requires 5 independent invariables.

$\gamma p \rightarrow N^* \rightarrow \hat{p}\rho \rightarrow \hat{p}\pi^+\pi^-$

$\phi, \theta_{cm}, k, m_{\pi^+},$ and $m_{\pi^+\pi^-}$

The differential cross section for $\gamma p \rightarrow p\pi^+\pi^-$ (without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{dxd_i} = \sigma_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) + \delta_I \left[ \sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c) \right] \right\}$$

- $\sigma_0$: The unpolarized cross section
- $\beta$: The angle between the direction of polarization and the x-axis
- $\delta_\odot, \delta_I$: The degree of polarizaton of the photon beam $\Rightarrow \delta_\odot, \text{ and } \delta_I$
- $\vec{\Lambda}_i$: The polarization of the initial nucleon $\Rightarrow (\Lambda_x, \Lambda_y, \Lambda_z)$
- $I^\odot, I^s, I^c$: The observable arising from use of polarized photons $\Rightarrow I^\odot, I^s, I^c$
- $\vec{P}$: The polarization observable $\Rightarrow (P_x, P_y, P_z) (P^\odot_x, P^\odot_y, P^\odot_z) (P^s_x, P^s_y, P^s_z) (P^c_x, P^c_y, P^c_z)$

15 observables
The concept of physics for my dissertation

The 3-particle final state for $\gamma p \rightarrow p\pi\pi$

The center of mass system

The combination of the beam and the target for my dissertation
- The circularly-polarized beam $\rightarrow \delta \odot$
- The longitudinally-polarized target $\rightarrow \Lambda_z$

The differential cross section for $\gamma p \rightarrow p\pi^+\pi^-$ (without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{dx_i} = \sigma_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta \odot \left( I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot \right) + \delta_I \left[ \sin 2\beta \left( I^s + \vec{\Lambda}_i \cdot \vec{P}^s \right) + \cos 2\beta \left( I^c + \vec{\Lambda}_i \cdot \vec{P}^c \right) \right] \right\}$$

- $\sigma_0$: The unpolarized cross section
- $\beta$: The angle between the direction of polarization and the x-axis
- $\delta \odot, \delta_I$: The degree of polarizaton of the photon beam $\Rightarrow \delta \odot$, and $\delta_I$
- $\vec{\Lambda}_i$: The polarization of the initial nucleon $\Rightarrow (\Lambda_x, \Lambda_y, \Lambda_z)$
- $I^\odot, I^s, I^c$: The observable arising from use of polarized photons $\Rightarrow I^\odot, I^s, I^c$
- $\vec{P}$: The polarization observable $\Rightarrow (P_x, P_y, P_z) (P_x^\odot, P_y^\odot, P_z^\odot) (P_x^s, P_y^s, P_z^s) (P_x^c, P_y^c, P_z^c)$

15 observables
The 3-particle final state for $\gamma p \rightarrow p\pi\pi$

The combination of the beam and the target for my dissertation
- The circularly-polarized beam $\rightarrow \delta \odot$
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The differential cross section for $\gamma p \rightarrow p\pi^+\pi^-$ (without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{dx_i} = \sigma_0 \left\{ \left(1 + \Lambda_z \cdot P_z\right) + \delta \odot \left( I \odot + \Lambda_z \cdot P_z \odot \right) \right\}$$

- $\sigma_0$: The unpolarized cross section
- $\beta$: The angle between the direction of polarization and the x-axis
- $\delta \odot$: The degree of circular polarization of the photon beam
- $\Lambda_i$: The polarization of the initial nucleon $\Rightarrow (0, 0, \Lambda_z)$
- $I \odot$: The photon polarization asymmetry
- $P$: The polarization observable $\Rightarrow (0, 0, P_z \odot)$
The main goal for my dissertation is to measure $P_z^\odot$.

- In the combination of circularly-polarized beam on a longitudinally-polarized target

$$\frac{d\sigma}{dx_i} = \sigma_0 \{ (1 + \Lambda_z \cdot P_z) + \delta^\odot (I^\odot + \Lambda_z \cdot P_z^\odot) \}$$

- Flipping the polarization of the beam

$\rightarrow$ and $\leftarrow$ indicate circular polarization of the beam

$\Rightarrow$ and $\Leftarrow$ indicate longitudinal target polarization parallel or anti-parallel to the beam

$$\left(\rightarrow\Rightarrow - \leftarrow\Rightarrow \right) := \frac{d\sigma(\rightarrow\Rightarrow)}{dx_i} - \frac{d\sigma(\leftarrow\Rightarrow)}{dx_i} = 2 \cdot \sigma_0 \{ \delta^\odot (I^\odot + \Lambda_z \cdot P_z^\odot) \}$$

$$\left(\leftarrow\Leftarrow - \rightarrow\Leftarrow \right) := \frac{d\sigma(\leftarrow\Leftarrow)}{dx_i} - \frac{d\sigma(\rightarrow\Leftarrow)}{dx_i} = 2 \cdot \sigma_0 \{ \delta^\odot (-I^\odot + \Lambda_z \cdot P_z^\odot) \}$$

- Flipping the polarization of the beam and the target polarization together

$$\left(\rightarrow\Rightarrow - \leftarrow\Rightarrow \right) + \left(\leftarrow\Leftarrow - \rightarrow\Leftarrow \right) := \frac{d\sigma_{3/2}}{dx_i} - \frac{d\sigma_{1/2}}{dx_i} = 4 \cdot \sigma_0 \cdot \delta^\odot \cdot (\Lambda_z \cdot P_z^\odot)$$
Outline

1. Introduction
   - Problems in Hadron Spectroscopy
   - Motivation for this work

2. The concept of physics for my dissertation

3. FROST Experiment
   - Experimental Setup
   - The FROST Data
   - Summary
The continuous electron beam accelerator facility (CEBAF) can deliver a continuous electron beam up to 6 GeV.
CEBAF Large Acceptance Spectrometer (CLAS)

- **Torus magnet**: 6 superconducting coils
- **Electromagnetic calorimeters**: Lead/scintillator, 1296 photomultipliers
- **Target + start counter**
- **Drift chambers**: argon/CO₂ gas, 35,000 cells
- **Time-of-flight counters**: plastic scintillators, 684 photomultipliers
- **Gas Cherenkov counters**
The Frozen-Spin Target (FROST)

The magnets in the FROST experiment

1. The longitudinal holding magnet. (About 0.5 T)
2. The transverse holding magnet. (Next experiment)
   - Charles Hanretty
3. The polarizing magnet. (5 Tesla internal solenoid)

- Polarized Butanol ($C_4H_9OH$) ($L = 5.0 \text{ cm}, \phi = 1.5 \text{ cm}$) $\sim 5 \text{ g}$
- Carbon ($^{12}C$) ($L = 0.15 \text{ cm}$) (6 cm from CLAS center)
- Polyethylene ($CH_2$) ($L = 0.35 \text{ cm}$) (16 cm from CLAS center)

$L$: The length and $\phi$: The diameter

Evan McClellan (from the CEU poster)
The Frozen-Spin Target (FROST)

How to polarize the FROST?

(a) The longitudinal holding magnet. (About 0.5 T)
(b) The transverse holding magnet. (Next experiment)
(c) The polarizing magnet. (5 Tesla internal solenoid)
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Polarizing mode
- Microwave ON
- 5T magnet ON
- Temperature 0.5 K
- Photon beam OFF
The Frozen-Spin Target (FROST)

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The Frozen-Spin Target (FROST)

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How to polarize the FROST?

The magnets in the FROST experiment

(a) The longitudinal holding magnet. (About 0.5 T)
(b) The transverse holding magnet. (Next experiment)
(c) The polarizing magnet. (5 Tesla internal solenoid)

Frozen spin mode

* Microwave OFF
* 5T magnet OFF
* 0.5T magnet ON
* Temperature $\sim 0.05$ K
* Photon beam ON
The Frozen-Spin Target (FROST) - polarizing mode
The tagging system at CLAS

JLAB Hall B bremsstrahlung photon tagger

- Circular polarized photon beam
- Longitudinally polarized electron beam
- The amorphous radiator (poly-crystalline graphite)
- Linearly polarized photon beam
- Unpolarized electron beam
- The oriented diamod radiator

**PARA** photon polarization plane is parallel to the floor.

**PERP** photon polarization plane is perpendicular to the floor.

$E_\gamma = 20$-95% of $E_0$

$E_\gamma$ up to $\sim 5.5$ GeV

$E_\gamma = E_0 - E_e$

- $E_\gamma$: The energy of the emitted photon
- $E_0$: The energy of the incident electron
- $E_e$: The energy of the outgoing electron
The FROST Data

The FROST run period: Nov. 3, 2007 - Feb. 12, 2008
Data set: 35 TBytes

Production Data

Beam current: 15 nA
Torus current: 1920 A
Target:
- Longitudinal polarized target
- Average target polarization $\sim 80\%$

Photon beam:
- Circularly and linearly polarized photon beam
  0.5 - 2.4 GeV
- Electron beam polarization $\sim 85\%$

10.5 Billion events
Calibration

ST calibration

TOF calibration

DC calibration

EC calibration

Introduction
The concept of physics for my dissertation
FROST Experiment
Summary

ST calibration

TOF calibration

DC calibration

EC calibration

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Measurement of the Helicity Difference using CLAS
DC calibration

How to find the fitted DOCA and drift time?

DOCA means the distance of closest approached of the charged particle to the sense wire

The quasi-hexagonal pattern with six field wires surrounding one sense wire.

$90\% \text{argon} - 10\% \text{CO}_2 \text{gasmixture}$
DC calibration

How to find the fitted DOCA and drift time?

DOCA means the distance of closest approached of the charged particle to the sense wire

Inside these cells a traversing charged particle ionizes the gas
DC calibration

How to find the fitted DOCA and drift time?

DOCA means the distance of closest approached of the charged particle to the sense wire

find the fitted DOCA and drift time.
DC calibration

How to find the fitted DOCA and drift time?

DOCA means the distance of closest approached of the charged particle to the sense wire

find the fitted DOCA and drift time.
How to find the fitted DOCA and drift time?

DOCA means the distance of closest approached of the charged particle to the sense wire.
How to find the fitted DOCA and drift time?

DOCA means the distance of closest approached of the charged particle to the sense wire
DC calibration

How to find the fitted DOCA and drift time?

DOCA means the distance of closest approached of the charged particle to the sense wire.

1. Find the fitted DOCA and drift time.
2. Find the drift velocity function using fitting.
3. Find the calculated DOCA using the velocity and the time.

The residual = calculated DOCA - fitted DOCA
DC calibration

How to find the fitted DOCA and drift time?

DOCA means the distance of closest approached of the charged particle to the sense wire.

- Find the fitted DOCA and drift time.
- Find the drift velocity function using fitting.
- Find the calculated DOCA using the velocity and the time.
- The residual = calculated DOCA - fitted DOCA.

The residual = calculated DOCA - fitted DOCA.
Monitoring

The monitoring page has three kinds of plots.

(1) The plot for checking that the system is working properly.
The monitoring page has three kinds of plots.

(2) The plot for useful information on some basic particle properties
Monitoring

The monitoring page has three kinds of plots.

(3) The plot for checking the quality of the existing calibration.
The analysis for my dissertation

The combination of differential cross sections for the measurement of $P_z^\odot$

\[
(\rightarrow\rightarrow - \leftarrow\leftarrow) + (\leftarrow\leftarrow - \rightarrow\rightarrow) := \frac{d\sigma_3/2}{dx_i} - \frac{d\sigma_1/2}{dx_i} = 4 \cdot \sigma_0 \cdot \delta_\odot \cdot (\Lambda_z \cdot P_z^\odot)
\]

Targets for the FROST experiment → $C_4H_9OH$, $^{12}C$, and $CH_2$

\[
P_z^\odot \propto \left\{ \left( \frac{d\sigma_3/2(H,C,O)}{dx_i} - \frac{d\sigma_3/2(C,O)}{dx_i} - \frac{d\sigma_3/2(H,unpolarized)}{dx_i} \right) \right. \\
\left. \quad - \left( \frac{d\sigma_1/2(H,C,O)}{dx_i} - \frac{d\sigma_1/2(C,O)}{dx_i} - \frac{d\sigma_1/2(H,unpolarized)}{dx_i} \right) \right\}
\]

\[
P_z^\odot \propto \left\{ \frac{d\sigma_3/2(H,polarized)}{dx_i} - \frac{d\sigma_1/2(H,polarized)}{dx_i} \right\}
\]

$P_z^\odot \propto \left( N^+ - N^- \right)$

$N^+$: The positive photon helicity ($\rightarrow\rightarrow + \leftarrow\leftarrow$)
$N^-$: The negative photon helicity ($\leftarrow\leftarrow + \rightarrow\rightarrow$)
Sample analysis $\gamma p \rightarrow \pi^+ n$

Particle identification $\rightarrow m = \frac{p}{v}$

* measured charged-particle momenta (from DC)
* The flight time from the target to the respective TOF counters.

\[ pion \] (mass $\sim 135 \text{ MeV} / c^2$)
\[ kaon \] (mass $\sim 498 \text{ MeV} / c^2$)
\[ proton \] (mass $\sim 940 \text{ MeV} / c^2$)
\[ deuteron \] (mass $\sim 1876 \text{ MeV} / c^2$)

\[ \text{Neutron 0.94 GeV} \]
\[ \text{Miss. Mass (GeV)} \]

\[ \text{Entries: 289415} \]

\[ \gamma p \rightarrow \pi^+ X \text{ (for target)} \]

\[ \text{Neutron 0.94 GeV} \]
\[ \text{Miss. Mass (GeV)} \]

\[ \text{Entries: 78242} \]

\[ \gamma p \rightarrow \pi^+ X \text{ (for C, CH2)} \]
Sample analysis $\gamma p \rightarrow \pi^+ n$

Helicity asymmetry for $\gamma p \rightarrow \pi^+ n$

$$E_{\text{raw}} = \frac{N^+ - N^-}{N^+ + N^-}$$

($N^+$ is positive photon helicity, $N^-$ is negative photon helicity)

hel.asym.$(\gamma p \rightarrow \pi^+ n)$

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Measurement of the Helicity Difference using CLAS
The goal of my dissertation is to determine the helicity difference in the reaction, $\gamma p \rightarrow p\pi^+\pi^-$. The FROST experiment has already taken the data. The data is in the process of the calibration.

My current contribution in the FROST experiment is

* I reconstruct the data.
* I undertake the part of the DC calibration.
* I manage and update the monitoring web.
Quantum numbers in Schrödinger’s three-dimensional model

Orbitals - regions in space where electrons are most likely to be found

The principal quantum number \( (n = 1, 2, 3, 4 \ldots) \)

- This number describes the **SIZE** of the orbital.
- This number has a dependence on the distance between the electron and the nucleus.

The angular quantum number \( (l = 0, 1, 2 \ldots n-1) \)

- This number describes the **SHAPE** of the orbital.
- This number gives the orbital angular momentum through the relation \( L^2 = \hbar^2 (l + 1) \).

The magnetic quantum number \( (m_l = -l,-l+1, ..., 0 ... ,l-1, 1) \)

- This number describes an orbital’s **ORIENTATION** in space.
- This number is the eigenvalue, \( L_z = m_l \hbar \).
- This is the projection of the orbital angular momentum along a specified axis.

The spin quantum number \( (m_s = -1/2 \text{ or } +1/2) \)

- This number describes the **SPIN** in which an electron spins
- This number is the eigenvalue, \( L_z = m_l \hbar \).
- This is the projection of the orbital angular momentum along a specified axis.
Quantum numbers in Schrödinger’s three-dimensional model

- The principal quantum number \((n = 1, 2, 3, 4 \ldots)\)
- The angular quantum number \((l = 0, 1, 2 \ldots n-1)\)
- The magnetic quantum number \((m_l = -l, -l+1, \ldots, 0 \ldots ,l-1, 1)\)

### Graphical Representation of Allowable Combinations of Quantum Numbers

<table>
<thead>
<tr>
<th>Shell (n)</th>
<th>Subshell (l)</th>
<th>Subshell Notation</th>
<th>Orientation (m)</th>
<th>Number of Orbitals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1s</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>2s</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2p</td>
<td>-1 0 +1</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>3s</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3p</td>
<td>-1 0 +1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3d</td>
<td>-2 -1 0 +1  +2</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>4s</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>4p</td>
<td>-1 0 +1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4d</td>
<td>-2 -1 0 +1  +2</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4f</td>
<td>-3 -2 -1 0 +1 +2+3</td>
<td>7</td>
</tr>
</tbody>
</table>
The main goal for my dissertation is to measure $P_z^\circ$. In the combination of circularly-polarized beam on a longitudinally-polarized target

$$
\frac{\text{d} \sigma}{\text{d} x_i} = \sigma_0 \left\{ (1 + \Lambda_z \cdot P_z) + \delta \circ (I \circ + \Lambda_z \cdot P_z^\circ) \right\}
$$

Flipping the polarization of the beam

$$
(\rightarrow\rightarrow - \leftarrow\leftarrow) := \frac{\text{d} \sigma(\rightarrow\rightarrow)}{\text{d} x_i} - \frac{\text{d} \sigma(\leftarrow\leftarrow)}{\text{d} x_i} = 2 \cdot \sigma_0 \left\{ \delta \circ (I \circ + \Lambda_z \cdot P_z^\circ) \right\}
$$

Flipping the polarization of the beam and the target polarization together

$$
(\rightarrow\rightarrow - \leftarrow\leftarrow) + (\leftarrow\leftarrow - \rightarrow\leftarrow) := \frac{\text{d} \sigma^{3/2}}{\text{d} x_i} - \frac{\text{d} \sigma^{1/2}}{\text{d} x_i} = 4 \cdot \sigma_0 \cdot \delta \circ (\Lambda_z \cdot P_z^\circ)
$$
The Frozen-Spin Target (FROST)

How to polarize the spin

1. Use **brute force** to polarize free electrons in the target material.
2. Use **microwaves** to “transfer” this polarization to nuclei.

Dilution factor of butanol \((C_4H_9OH)\)

\[
f = \frac{9+1}{(6 \times 4+1 \times 9+8 \times 1+1 \times 1)+(6 \times 4+8 \times 1)} = \frac{10}{74} = 0.135
\]

\[
\begin{pmatrix}
^1H & ^{12}C & ^{16}O
\end{pmatrix}
\]
How do we make the low temperature?

**Refrigeration below 4.2 K – Evaporative Cooling**

In absence of a heater, liquid will absorb heat from surrounding and temperature will drop.

**3^He/4^He Dilution Refrigeration**

The specific heat of a $^3$He atom is higher in the lower, dilute phase than in the upper, concentrated phase.

$$C_d > C_c$$

$^3$He will absorb energy when it dissolves into the dilute phase.
How do we make the low temperature?

Practical Dilution Refrigeration

Horizontal Dilution Refrigerator for Frozen Spin Target
Bremsstrahlung is electromagnetic radiation produced by the deceleration of a charged particle, such as an electron, when deflected by another charged particle, such as an atomic nucleus.

The term is also used to refer to the process of producing the radiation.

Bremsstrahlung has a continuous spectrum.
Sample analysis $\gamma p \rightarrow \pi^+ n$

Helicity asymmetry for $\gamma p \rightarrow \pi^+ n$

$$E_{\text{raw}} = \frac{N^+ - N^-}{N^+ + N^-}$$

($N^+$ is positive photon helicity, $N^-$ is negative photon helicity)

hel. asym.($\gamma p \rightarrow \pi^+ n$)

Sungkyun Park
Measurement of the Helicity Difference using CLAS