Double polarization experiments in meson photoproduction at Jefferson Lab
Outline

- Introduction and formalism
- Experimental tools
- Selected results
- Summary
Masses, widths, and coupling constants not well known for many resonances
Most models predict more resonance states than observed

Mass($\pi$) = 396 MeV

From the Experiment to Theory

Experiment
- cross section, spin observables

Amplitude analysis
- → multipole amplitudes
- → PWA

Theory
- LQCD, quark models, QCD sum rules, ...

Reaction Theory
- dynamical frameworks

(single) $d\sigma/d\Omega, \Sigma, P, T$
(beam-target) $E, F, G, H,$
(beam-recoil) $C_x, C_z, O_x, O_z,$
(target-recoil) $L_x, L_z, T_x, T_z,$
Polarization observables in pseudoscalar meson production

4 Complex amplitudes: 16 real polarization observables.

Complete measurement from 8 carefully chosen observables.

\( \pi N \) has large cross section but in KY recoil is self-analysing

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Transversity representation</th>
<th>Experiment required</th>
<th>Type</th>
</tr>
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<tr>
<td>( d\sigma/dt )</td>
<td>( b_1^2 + b_2^2 + b_3^2 + b_4^2 )</td>
<td>( { -; -; - } )</td>
<td>( S )</td>
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<tr>
<td>( \Sigma d\sigma/dt )</td>
<td>( b_1^2 + b_2^2 - b_3^2 - b_4^2 )</td>
<td>( { L(\pm \frac{1}{2}\pi), 0; -; - } )</td>
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<td>( T d\sigma/dt )</td>
<td>( b_1^2 - b_2^2 - b_3^2 + b_4^2 )</td>
<td>( { -; y; - } )</td>
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<tr>
<td>( P d\sigma/dt )</td>
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<td>( C d\sigma/dt )</td>
<td>( 2 \text{Im}(b_1 b_3^* + b_2 b_4^*) )</td>
<td>( { L(\pm \frac{1}{2}\pi); z; - } )</td>
<td>( BT )</td>
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<tr>
<td>( H d\sigma/dt )</td>
<td>( -2 \text{Re}(b_1 b_3^* - b_2 b_4^*) )</td>
<td>( { L(\pm \frac{1}{2}\pi); x; - } )</td>
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<td>( E_0 d\sigma/dt )</td>
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\( O_x d\sigma/dt \) | \( -2 \text{Re}(b_1 b_4^* - b_2 b_3^*) \) | \( \{ L(\pm \frac{1}{2}\pi); -; x' \} \) | \( BR \) |
| \( O_y d\sigma/dt \) | \( -2 \text{Im}(b_1 b_4^* + b_2 b_3^*) \) | \( \{ L(\pm \frac{1}{2}\pi); -; z' \} \) | |
| \( C_z d\sigma/dt \) | \( 2 \text{Im}(b_1 b_4^* - b_2 b_3^*) \) | \( \{ C; -; x' \} \) | |
| \( C_y d\sigma/dt \) | \( -2 \text{Re}(b_1 b_4^* + b_2 b_3^*) \) | \( \{ C; -; z' \} \) | |
| \( T_x d\sigma/dt \) | \( 2 \text{Re}(b_1 b_2^* - b_3 b_4^*) \) | \( \{ -; x; x' \} \) | \( TR \) |
| \( T_y d\sigma/dt \) | \( 2 \text{Im}(b_1 b_2^* - b_3 b_4^*) \) | \( \{ -; x; z' \} \) | |
| \( L_x d\sigma/dt \) | \( 2 \text{Im}(b_1 b_2^* + b_3 b_4^*) \) | \( \{ -; z; x' \} \) | |
| \( L_y d\sigma/dt \) | \( 2 \text{Re}(b_1 b_2^* + b_3 b_4^*) \) | \( \{ -; z; z' \} \) | |


Jefferson Lab

E. Pasyuk

SPIN2014

Beijing, October 20-24, 2014
Spin dependent cross section

\[d\sigma^{B.T,R}(\vec{p}_y, \vec{p}_T, \vec{p}_R) = \frac{1}{2} \{d\sigma_0[1 - P_L^y P_T^y P_R^y \cos(2\phi_y)] \]

\[+ \Sigma[-P_L^y \cos(2\phi_y) + P_T^y P_R^y] \]

\[+ T[P_T^y - P_L^y P_R^y \cos(2\phi_y)] \]

\[+ P[P_R^y - P_L^y P_T^y \cos(2\phi_y)] \]

\[+ E[-P_c^y P_T^z + P_L^y P_T^x P_R^y \sin(2\phi_y)] \]

\[+ F[P_c^y P_T^x + P_L^y P_T^x P_R^y \sin(2\phi_y)] \]

\[+ H[P_T^y \sin(2\phi_y)] \]

\[+ C_x[P_c^y P_R^x - P_L^y P_T^x P_R^x \sin(2\phi_y)] \]

\[+ C_y[P_c^y P_R^y + P_L^y P_T^y P_R^y \sin(2\phi_y)] \]

\[+ O_x[P_L^y P_T^y \sin(2\phi_y)] \]

\[+ O_z[P_c^y P_R^z \sin(2\phi_y) - P_L^y P_T^z P_R^z \sin(2\phi_y)] \]

\[+ L_x[P_T^x P_R^x + P_L^y P_T^x P_R^x \cos(2\phi_y)] \]

\[+ L_y[P_T^x P_R^y - P_L^y P_T^x P_R^y \cos(2\phi_y)] \]

\[+ T_x[P_T^x P_R^x + P_L^y P_T^x P_R^x \cos(2\phi_y)] \]

\[+ T_y[P_T^y P_R^y - P_L^y P_T^y P_R^y \cos(2\phi_y)] \]

\[+ T_z[P_T^y P_R^z - P_L^y P_T^y P_R^z \cos(2\phi_y)] \]

Single spin observables

Beam-Target

Beam-Recoil

Target-Recoil

Experiments

<table>
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<tr>
<th>Beam</th>
<th>Target</th>
<th>Recoil</th>
<th>Target + Recoil</th>
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<tr>
<td></td>
<td>x</td>
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<td>z</td>
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<td>unpolarized</td>
<td>$d\sigma_0$</td>
<td>$T$</td>
<td>$P$</td>
</tr>
<tr>
<td>$P_L \gamma \sin(2\varphi_\gamma)$</td>
<td>$H$</td>
<td>$G$</td>
<td>$O_{x'}$</td>
</tr>
<tr>
<td>$P_L \gamma \cos(2\varphi_\gamma)$</td>
<td>$\Sigma$</td>
<td>$-P$</td>
<td>$-T$</td>
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<tr>
<td>circular $P_c \gamma$</td>
<td>$d\sigma_0$</td>
<td>$F$</td>
<td>$-E$</td>
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- Every observable can be measured in at least two different experiments.
- They are not all independent. There are relations between the known as Fierz identities.
CEBAF Large Acceptance Spectrometer 1997-2012

Torus magnet
6 superconducting coils

Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

Drift chambers
35,000 cells

Gas Cherenkov counters
e/π separation, 256 PMTs

Time-of-flight counters
plastic scintillators, 684 photomultipliers

target + start counter
Polarized photon beam

Circular polarization from 100% polarized electron beam

Circularly polarized beam produced by longitudinally polarized electrons

Linearily polarized photons: coherent bremsstrahlung on oriented diamond crystal

Data for PERP 1.3GeV Calculation

Polarization corresponding to calc (Peaking at > 90%)
**The FroST target and its components:**
A: Primary heat exchanger
B: 1 K heat shield
C: Holding coil
D: 20 K heat shield
E: Outer vacuum can (Rohacell extension)
F: CH2 target
G: Carbon target
H: Butanol target
J: Target insert
K: Mixing chamber
L: Microwave waveguide
M: Kapton coldseal

**Performance Specs:**
Base Temp: 28 mK w/o beam, 30 mK with
Cooling Power: 800 µW @ 50 mK, 10 mW @ 100 mK, and 60 mW @ 300 mK
Polarization: +82%, -90%
l/e Relaxation Time: 2800 hours (+Pol), 1600 hours (-Pol)
Roughly 1% polarization loss per day.
HDice polarized target

- Polarized at very high magnetic field and very low temperature
- Transferred to in-beam cryostat
- Spin can be moved between H and D with RF transitions
- All material can be polarized with small background

(X. Wei, Parallel VII S10)
What we measure with CLAS

- $\gamma p \rightarrow \pi^0 p, \pi^+ n$
- $\gamma p \rightarrow \eta p$
- $\gamma p \rightarrow \eta' p$
- $\gamma p \rightarrow K Y (K^+ \Lambda, K^+ \Sigma^0, K^0 \Sigma^+)$
- $\gamma p \rightarrow \pi^+ \pi^- p \omega p, \rho p, \phi p$
- ....

- $\gamma n \rightarrow \pi^- p$
- $\gamma n \rightarrow \pi^+ \pi^- n$
- $\gamma n \rightarrow \Sigma^- K^+, \Lambda K^0$
- ......
### CLAS Experiments: $g1c$, $g11$

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<th>Target + Recoil</th>
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<tr>
<td>$x$</td>
<td>$y$</td>
<td>$z$</td>
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</tbody>
</table>

| Unpolarized     | $d\sigma_0$ | $T$    | $P$             | $T_{x'}$ | $L_{x'}$ | $\Sigma$ | $T_{z'}$ | $L_{z'}$ |
| $P_L^{\gamma} \sin(2\phi_{\gamma})$ | $H$ | $G$ | $O_{x'}$ | $O_{z'}$ | $C_{z'}$ | $E$ | $F$ | $-C_x$ |
| $P_L^{\gamma} \cos(2\phi_{\gamma})$ | $\Sigma$ | $-P$ | $-T$ | $-L_{x'}$ | $T_{z'}$ | $-d\sigma_0$ | $L_{x'}$ | $-T_{x'}$ |
| Circular $P_c^{\gamma}$ | $d\sigma_0$ | $F$ | $-E$ | $C_{x'}$ | $C_{z'}$ | $-O_{z'}$ | $G$ | $-H$ | $O_{x'}$ |

- Unpolarized target
- $g1c$ – circularly polarized beam
- $g11$ – unpolarized beam, high statistics
<table>
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<th></th>
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<td>$-E$</td>
<td>$C_{x'}$</td>
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- **linearly polarized beam**
### CLAS Experiments: g9a

#### Table

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<td>$z$</td>
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| unpolarized   | $d\sigma_0$ | $T$ | $P$ | $T_x'$ | $L_x'$ | $\Sigma$ | $T_z'$ | $L_z'$ |
| $P_L\gamma\sin(2\phi_L)$ | $H$ | $G$ | $O_{x'}$ | $O_{z'}$ | $C_{z'}$ | $E$ | $F$ | $-C_{x'}$ |
| $P_L\gamma\cos(2\phi_L)$ | $\Sigma$ | $-P$ | $-T$ | $-L_{x'}$ | $T_{z'}$ | $-d\sigma_0$ | $L_{x'}$ | $-T_{x'}$ |
| circular $P_c\gamma$ | $d\sigma_0$ | $F$ | $-E$ | $C_{x'}$ | $C_{z'}$ | $-O_{z'}$ | $G$ | $-H$ | $O_{x'}$ |

- Longitudinally polarized target
### CLAS Experiments: g9b

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<td>Oₓ’</td>
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**.transversely polarized target**
g10 unpolarized beam, unpolarized deuterium target

g13 circularly and linearly polarized beam on unpolarized deuterium target

g14 circularly and linearly polarized beam on longitudinally polarized HD target  (A. Sandorfi, Parallel VI S6)
Single pion production

\[ \gamma p \rightarrow \pi^+ n \]
T for $\gamma p \rightarrow n \pi^+$ $E_\gamma = 675$ to 1075 MeV

courtesy M. Dugger, ASU
T for $\gamma p \rightarrow n \pi^+$ $E_\gamma = 1125$ to $1525$ MeV

courtesy M. Dugger, ASU
T for $\gamma p \rightarrow n\pi^+$ $E_\gamma = 1575$ to $1975$ MeV

courtesy M. Dugger, ASU
F for $\gamma p \rightarrow n\pi^+$ ($E_\gamma = 675$ to $1075$ MeV)

courtesy M. Dugger, ASU
$F$ for $\gamma p \rightarrow n \pi^+ \ E_\gamma = 675$ to 1075 MeV

courtesy M. Dugger, ASU
F for $\gamma p \rightarrow n \pi^+ \ E_\gamma = 1575 - 1975$ MeV
E for $\gamma p \rightarrow p \eta$

$E(\cos_{cm}^\eta)$

- $1500 < W < 1550$ MeV
- $1550 < W < 1600$ MeV
- $1600 < W < 1650$ MeV
- $1650 < W < 1700$ MeV
- $1700 < W < 1750$ MeV
- $1750 < W < 1800$ MeV
- $1800 < W < 1850$ MeV
- $1850 < W < 1900$ MeV
- $1900 < W < 1950$ MeV
- $1950 < W < 2000$ MeV
- $2000 < W < 2050$ MeV
- $2050 < W < 2100$ MeV

- Juelich 2014
- ANL-Osaka 2013
- SAID 2012
- BnGa 2012
- Juelich 2014 (fit)
- BnGa 2014 (fit)

courtesy I. Senderovich, ASU
Kaon production

\[ \gamma p \rightarrow K^+ \Lambda , \ K^+ \Sigma^0 \]
What is this Bump?

SAPHIR data (1998) triggered discussion on “missing” $D_{13}$: $D_{13}(1890)$, $P_{11}(1840)$, $D_{13}(1900)$... lots of other interpretations

CLAS got into the game
First CLAS measurements ($g_{1c}$): $d\sigma/d\Omega$, $P$, $C_x$, $C_z$
Confirmed bump around 1.9 GeV
g11 cross sections and $P$

data: CLAS g11
fit: BoGa
Polarization transfer $C_x$, $C_z$

without $N(1900)\ 3/2^+$

with $N(1900)\ 3/2^+$

Major revision of the baryon table to large extent driven by new photoproducton data, particularly CLAS data.

- Them “bump” origin seems to be settled being attributed to N(1900) 3/2+
- Other new states still require more confirmation

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Energy dependence: $\Sigma$

$\gamma + p \rightarrow K^+ \Lambda$

$\gamma + p \rightarrow K^+ \Sigma$

courtesy D. Ireland, UGlasgow
Energy dependence: $O_x$

$$\gamma + p \rightarrow K^+ \Lambda$$

$W (\text{GeV})$

$$\gamma + p \rightarrow K^+ \Sigma$$

$W (\text{GeV})$

courtesy D. Ireland, UGlasgow
Energy dependence: $O_z$

$\gamma + p \rightarrow K^+ \Lambda$

$\gamma + p \rightarrow K^+ \Sigma$

courtesy D. Ireland, UGlasgow
Energy dependence: $T$

$\gamma + p \rightarrow K^+ \Lambda$

$\gamma + p \rightarrow K^+ \Sigma$

courtesy D. Ireland, UGlasgow
Two pion production

\[ \gamma p \rightarrow p \pi^+ \pi^- \]
Spin dependent cross section for $\gamma p \rightarrow p \pi^+ \pi^-$

The differential cross section for $\gamma p \rightarrow p\pi^+\pi^-$

(without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{dx_i} = \sigma_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot \left( \vec{l}^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot \right) \right\}$$

$$+ \delta_L \left[ \sin 2\beta \left( \vec{l}^s + \vec{\Lambda}_i \cdot \vec{P}^s \right) + \cos 2\beta \left( \vec{l}^c + \vec{\Lambda}_i \cdot \vec{P}^c \right) \right] \right\}$$

- $\sigma_0$: The unpolarized cross section
- $\beta$: The angle between the direction of polarization and the x-axis
- $x_i$: The kinematic variables
- $\delta_\odot, \delta_L$: The degree of polarizaton of the photon beam $\Rightarrow \delta_\odot, \delta_L$
- $\vec{\Lambda}_i$: The polarization of the initial nucleon $\Rightarrow (\Lambda_x, \Lambda_y, \Lambda_z)$
- $\vec{l}^\odot, \vec{l}^s, \vec{l}^c$: The observable arising from use of polarized photons $\Rightarrow \vec{l}^\odot, \vec{l}^s, \vec{l}^c$
- $\vec{P}$: The polarization observable $\Rightarrow (P_x, P_y, P_z)$, $(P_x^\odot, P_y^\odot, P_z^\odot)$, $(P_x^s, P_y^s, P_z^s)$, $(P_x^c, P_y^c, P_z^c)$
$I_s$ for $p \pi^+ \pi^-$

$W \in [1.716; 1.770] \text{GeV}$

Data of unprecedented statistical quality

$$I = I_0 \{ (1 + \vec{\lambda}_i \cdot \vec{P}) + \delta_\odot (I^\odot + \vec{\lambda}_i \cdot \vec{P}^\odot)$$
$$+ \delta_l \{ \sin 2\beta (I^s + \vec{\lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\lambda}_i \cdot \vec{P}^c) \} \}$$

Charles Hanretty (FSU), g8b
Priyashree Roy (FSU), CLAS g9b (FROST)
Data of unprecedented statistical quality

\[ l = l_0 \left\{ (1 + \vec{\lambda}_i \cdot \vec{P}) + \delta_\odot (l^\odot + \vec{\lambda}_i \cdot \vec{P}^\odot) \right. \\
+ \left. \delta_\parallel \left[ \sin 2\beta \left( l^s + \vec{\lambda}_i \cdot \vec{P}^s \right) + \cos 2\beta \left( l^c + \vec{\lambda}_i \cdot \vec{P}^c \right) \right] \right\} \]
$P_z$ for $p \pi^+ \pi^-$

\[
l = l_0 \left\{ (1 + \vec{\lambda}_i \cdot \vec{P}) + \delta_\odot (l_\odot + \vec{\lambda}_i \cdot \vec{P}_\odot) + \delta_I \left[ \sin 2\beta (l^s + \vec{\lambda}_i \cdot \vec{P}^s) + \cos 2\beta (l^c + \vec{\lambda}_i \cdot \vec{P}^c) \right] \right\}
\]

Data of unprecedented statistical quality

Sungkyun Park (FSU), under collaboration review
$P_z^\circ$ for $p\pi^+\pi^-$

$\phi_{\pi^+}^*$

Data of unprecedented statistical quality

\begin{align*}
I &= I_0 \left\{ \left( 1 + \vec{\Lambda}_i \cdot \vec{P}\right) + \delta_\circ \left( I^\circ + \vec{\Lambda}_i \cdot \vec{P}^\circ \right) \\
&\quad + \delta_I \left[ \sin 2\beta \left( I^s + \vec{\Lambda}_i \cdot \vec{P}^s \right) + \\
&\quad \cos 2\beta \left( I^c + \vec{\Lambda}_i \cdot \vec{P}^c \right) \right] \right\}
\end{align*}

Fix and Arenhooewel

W. Roberts (FSU)

CLAS Data (g9a)
Polarization measurements in photoproduction proved themselves to be a critical piece for understanding of the nucleon resonance spectrum.

More interesting data are on the way for strange and non-strange meson production both on proton and deuteron targets.

High level analysis tools are in great demand.