Exclusive Electroproduction of $\pi^0$ Mesons

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Overview

- Physical motivations
- Brief experimental overview
- Backgrounds, corrections, and data exclusions
- Differential cross sections
Exciting the $\Delta$ in E01-002

- Kinematic variables
  $Q^2 = 6.3 \text{ GeV}^2; 7.4 \text{ GeV}^2$
  $W = \text{Elastic } \rightarrow 1.8 \text{ GeV}$
- Single photon exchange
- Full angular coverage in COM
Center of Mass Kinematics

\[ p, p', \gamma^*, \theta^*, \phi^*, \{\pi^0, \eta\} \]

\[ J = 0^- \]
Center of Mass Cross Section

- The cross section can be written in the center of mass:

\[
\frac{d\sigma}{dQ^2 dW d\Omega_{cm}} = \Gamma \frac{d\sigma_\nu}{d\Omega_{cm}}
\]

- The virtual photon flux factor \( \Gamma \) relates to kinematic quantities in center of mass:

\[
\Gamma = \frac{\alpha}{2\pi} \frac{E'}{E} \frac{W^2 - m_p^2}{2m_pQ^2} \frac{1}{1 - \epsilon}
\]

\[
\epsilon = \frac{1}{1 + 2\tan^2\left(\frac{\theta_e}{2}\right)\frac{|q|^2}{Q^2}}
\]

- In *virtual* photoproduction one may have:
  - virtual photons having "mass"
  - virtual photons having longitudinal polarization states
Virtual Photoproduction

Virtual photoproduction amplitude can be written

$$\mathcal{M}_{ph} = \epsilon_{\mu}^{\lambda} \langle h_f | J_{had}^{\mu} | h_i \rangle$$

$$\frac{d\sigma}{d\Omega_{cm}} = \sigma_T + \epsilon \sigma_L + \epsilon \sigma_{TT} \cos 2\phi^* + \sqrt{\frac{\epsilon (1 + \epsilon)}{2}} \sigma_{LT} \cos \phi^*$$

Current Decomposition

Current matrix element from virtual photoproduction amplitude can be decomposed

\[
\langle p' M | J^\mu_{had} | p \rangle = i \bar{u}_f (p'_p) \gamma_5 \left[ \gamma^\mu \not{q} B_1 + (p_p + p'_p)^\mu B_2 + p_p^\mu B_3 + q^\mu B_4 + \gamma^\mu B_5 
+ (p_p + p'_p)^\mu \not{q} B_6 + q^\mu \not{q} B_7 + p_p^\mu \not{q} B_8 \right] u_i(p_p)
\]

Scalar functions \( B_i \) can be expressed in terms of multipole expansions

\[
B_1 \propto \sum_{l \geq 0} \left[ (lM_{l+} + E_{l+}) P_{l+1}' + ((l + 1)M_{l-} + E_{l-}) P_{l-1}' \right]
\]

Quantum numbers \( l \) and \( \pm \) specify \( J = |l \pm \frac{1}{2}| \) in final state
Wave function of incident photon can be decomposed as vector spherical harmonics

$$Y_{\bar{I}LM} = \sum_{\nu} C(1\lambda, \bar{\nu} | LM) \hat{e}_\lambda Y_{\bar{\nu}}$$

Electric ($EL$) and Coulomb ($CL$) type radiation are made of parity even combinations and Magnetic ($ML$) is parity odd.

Since angular momentum is conserved one has $J = |l \pm \frac{1}{2}| = |L \pm \frac{1}{2}|$

Parity arguments can then give the following relations

- $EL, CL : |L - l| = 1$
- $ML : L = l$
The Atomic Analog

2s

1s

\[ \text{p} \quad \rightarrow \quad \text{p} \]

\( \Delta \quad \rightarrow \quad \text{N} \)
Resonance Production ($\Delta$)

Restriction to $\Delta$ decreases the number of independent functions to three.

Functions can be represented:

$$G^{\pm,0} = \frac{1}{2M} \langle \langle (\Delta), \lambda_{res} | e_{\mu}^{\pm,0} J_{had}^{\mu} | P, \lambda_p = \pm \frac{1}{2} \rangle$$
Multipole Definition

Considering only $\Delta$ production reduces the number of multipoles

\[
A_{\frac{1}{2}} \propto G^+ \\
A_{\frac{3}{2}} \propto G^- \\
S_{\frac{1}{2}} \propto G^0
\]

Also, these can be related (through $E_{i\pm}$ and $M_{i\pm}$) to $E2$ and $M1$:

\[
A_{\frac{1}{2}} = -\frac{1}{2}(M1 + 3E2) \\
A_{\frac{3}{2}} = \frac{\sqrt{3}}{2}(E2 - M1) \\
S_{\frac{1}{2}} = -C2
\]
Measurement and Prediction

Measured Quantities
- $E_{1+}$, $M_{1+}$ and $S_{1+}$ extracted for $\Delta$
- Above used to infer information about $\frac{E^2}{M_1}$

Predictions
- Perturbative QCD predicts that $\frac{E^2}{M_1} \rightarrow 1$ as $Q^2$ becomes large
- Constituent quark model predicts $M_1$ dominance because $\Delta$ transition is viewed as a simple spin flip excitation
Particle Selection

- Clean separation of $p$ and $\pi^+$ events
- Enough $\pi^+$ events for $\gamma^* p \rightarrow n\pi^+$
Baryon Resonances

- The $\Delta(1232)$ and $S_{11}$ resonances are clearly correlated with the $\pi^0$ and $\eta M_x^2$ peaks.
- The elastic events clearly come from lower $W$ with some overlap into a higher $W$ region due to pre or post radiation.
- The $\omega$ meson comes from the largest $W$ region for the experiment.
Exclusive Studies

- The $M_x^2$ peaks can be used to constrain the reaction and/or baryon resonance.

- The $M_x^2$ resolution for the $\pi^0$ allows detailed study of the reaction $^1H(e, e'p)\pi^0$.

- Exclusive cross sections and amplitudes will be compared to models and previous data.
Accidental Corrections

Use the beam structure away from coincidence proton peak

Extract angular distribution by above cut and subtract

Low momentum hadrons dominate beam structure
Elastic Radiative

Above example for $-1.0 \leq \cos \theta^* < -0.6$

For lowest $\cos \theta^*$ elastic radiative concentrated

Use same form for other $\cos \theta^*$ bins
Full Angular Coverage

- Uniform coverage in the center of mass angles
- All W plotted
- Elastic radiative cut removes bad data

\[ \phi^* = 0 \]
$W = 1.172 \text{ GeV} \; ; \; 30 \text{ MeV Bin} \; ; \; Q^2 = 6.3$
$W=1.202$ GeV ; $30$ MeV Bin ; $Q^2=6.3$
$W=1.232 \text{ GeV} \; ; \; 30 \text{ MeV Bin} \; ; \; Q^2=6.3$
$W=1.262 \text{ GeV}$ ; $30 \text{ MeV Bin}$ ; $Q^2=6.3$
$W=1.292 \text{ GeV} \; ; \; 30 \text{ MeV Bin} \; ; \; Q^2=6.3$
Beam energy of $5.5\, GeV$ with two $Q^2$ settings

- Measure the cross sections for $^1H(e, e'p)X$, $X = \{\pi^0, \eta, \omega\}$
- $X$ identified by missing mass, $M_x$
- $Q^2$ of $6.3$ and $7.7\, GeV$ for $\Delta$ resonance
- Varied proton arm angle and momentum to cover wide range of $\theta^*$ and $\phi^*$ bins for $W$ up to $2\, GeV$

Physics

- Showed angular distributions for low $Q^2$
- Distributions will be fit though it is not clear that the pure $\Delta$ multipoles will show
- Systematic uncertainties need to be brought under control