Precision Measurement of Electroproduction of $\pi^0$ Near Threshold

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and

Hall A collaboration
Background

Because the coupling between quarks in QCD increases at low energies, normal perturbation theory does not work at low energy.

There is a effective theory known as chiral perturbation theory (ChPT) that is expected to work well at low $Q^2$, low energy and momentum.

ChPT
Start with a Lagrangian embodying the underlying symmetries of QCD expressed in terms of the relevant degrees of freedom: the pion and nucleon. Scattering or production processes can be described in terms of small quantities $Q/M$, and $m_\pi/M$.

The detail of interaction are absorbed into parameters called Low Energy Constants (LEC’s), which obtained by measurement. Once LEC’s are determined, one can predict the evolution of cross section with $Q^2$ and $W$ (center of mass energy of the $\pi$-$N$ system).
The differential cross section for pion electro-production using an unpolarized electron beam can be written as

\[
\frac{d\sigma}{d\Omega_e d\Omega_{\pi}^cm dE'} = \Gamma \left\{ \frac{d\sigma_T}{d\Omega_{\pi}^cm} + \epsilon_L \frac{d\sigma_L}{d\Omega_{\pi}^cm} + [2\epsilon_L(1+\epsilon)]^{1/2} \frac{d\sigma_{LT}}{d\Omega_{\pi}^cm} \cos \phi + \epsilon \frac{d\sigma_{TT}}{d\Omega_{\pi}^cm} \cos 2\phi \right\}
\]

The transverse and longitudinal photon polarization parameters, $\epsilon$ and $\epsilon_L$, and the virtual flux factor, $\Gamma$ are defined as,

\[
\epsilon = \frac{1}{1 + 2q^2/Q^2 \tan^2 \frac{\theta_e}{2}},
\]

\[
\epsilon_L = \frac{Q^2}{\nu_{cm}^2} \epsilon,
\]

\[
\Gamma = \frac{\alpha E' k_{\gamma}}{2\pi^2 EQ^2(1-\epsilon)},
\]

\[
k_{\gamma} = \frac{W^2 - m^2}{2m},
\]

\[
\nu_{cm} = \frac{W^2 - m^2 - Q^2}{2W}.
\]
\[ \sigma_T = \left| E_{0^+} \right|^2 + \frac{1}{2} \left( \left| P_2 \right|^2 + \left| P_3 \right|^2 \right) + 2 \text{Re} \left( E_{0^+} P_1^* \right) \cos \theta^*_\pi + \left( \left| P_1 \right|^2 - \frac{1}{2} \left( \left| P_2 \right|^2 + \left| P_3 \right|^2 \right) \cos^2 \theta^*_\pi \right) \]

\[ \sigma_L = \left( \left| L_{0^+} \right|^2 + \left| P_5 \right|^2 \right) + 2 \text{Re} \left( L_{0^+} P_4^* \right) \cos \theta^*_\pi + \left( \left| P_4 \right|^2 - \left| P_5 \right|^2 \right) \cos^2 \theta^*_\pi \]

\[ \sigma_{TT} = \frac{1}{2} \left( \left| P_2 \right|^2 - \left| P_3 \right|^2 \right) \sin^2 \theta^*_\pi \]

\[ \sigma_{LT} = -\left( \left| L_{0^+} P_2^* + E_{0^+} P_5^* \right| \right) \sin \theta^*_\pi - \left( \left| P_1 P_5^* + P_4 P_2^* \right| \right) \sin \theta^*_\pi \cos \theta^*_\pi \]

S Waves: \( E_{0^+} \) and \( L_{0^+} \)

P waves: \( P_1, P_2, P_3, P_4, \) and \( P_5 \)
Previous experiments
\( \gamma^+ p \rightarrow \pi^0 + p \)

\( \gamma^+ p \rightarrow \pi^+ + n \rightarrow \pi^0 + p \)

\( Q^2 = 0 \) (Unitary Cusp)

\( \pi^0 \)-photo production on the proton

Explained by one loop corrections. Was a real triumph of ChPT.
LEC = 14.84 MeV\(^{-3}\) \( [O (p)^3] \),

Classic LET result is \(-2.3 \times 10^{-3}/m_\pi\). (Born terms)
Measured value is \(-1.3 \times 10^{-3}/m_\pi\)
π⁰-electro production on the proton

\[ \sigma_T(\theta_\pi^*) + \varepsilon_L \sigma_L(\theta_\pi^*) + \varepsilon_L \sigma_L(\theta_\pi^*) \]

\[ Q^2 = 0.10 \text{ (GeV/c)}^2 \]
\[ Q^2 = 0.05 \text{ (GeV/c)}^2 \]

Distler et al. PRL 80, 2294 (1998)

Merkel et al. PRL 88, 12301 (2002)

Fixes LEC’s
\[ a_3 = -0.92 \text{ and } a_4 = -0.99 \]

ChPT Bernard et al. NP A607, 379(1996)

Shows the quality of the fit to the data that determines LECs. ChPT prediction gets progressively worse away from threshold.
$\pi^0$-electro production on the proton

$Q^2=0.10 \text{ (GeV/c)}^2$
Distler PRL 80, 2294 (1998)

LEC’s
$a_3 = -0.92$ and $a_4 = -0.99$

$Q^2=0.05 \text{ (GeV/c)}^2$
Merkel et al. PRL 88, 1230 (2002)

ChPT

MAID

- Large deviations between ChPT and data
- Need data in a finer grid in $Q^2$
π⁰-electro production on the proton

Mainz data are from Distler PRL80 (1998) 2294 and Merkel PRL. 88 (2002)12301
AmPS NIKHEF data are from Welch PRL 69 (1992) 2761
π⁰-electro production on the proton $Q^2=0.05$

From MAMI recent experiment


By the cut in $\theta$ a large fraction of events was lost. In addition, the acceptance in $\theta$ was different for each kinematical setting. To overcome these two problems, a second, model-dependent method was used to separate the cross-sections. In this method, the phenomenological model MAID was used as parameterization of the cross-section. For each event, the differential cross-section was projected to the nominal kinematics at $\theta = 90^\circ$ by

$$
\sigma_{\text{model}}(\theta, \phi) = \frac{\sigma(\theta, \phi)_{\text{MAID}}(90^\circ, \phi)}{\text{MAID}(\theta, \phi)}.
$$

By this method, the statistical error could be reduced for the price of an additional model error.
The experiment

Extract structure functions $\sigma_T + \epsilon_L \sigma_L$, $\sigma_{TL}$ and $\sigma_{TT}$ and the asymmetry $A_{TL}$ from $p(e,e'p)\pi^0$ in a fine grid of $Q^2$ and $W$ from $Q^2 = 0.05 - 0.15$ in steps of 0.01 $(\text{GeV}/c)^2$ and from above threshold $(M+m_\pi)$ $\Delta W = 0 - 20$ MeV in steps of 1 - 2 MeV. This results will provide a test of chiral dynamics.
<table>
<thead>
<tr>
<th>W (MeV)</th>
<th>Above Threshold</th>
<th>Q2 (GeV/c)</th>
<th>$\theta_{cone}$ (Deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1075</td>
<td>1.7</td>
<td>-0.05</td>
<td>4.5</td>
</tr>
<tr>
<td>1076</td>
<td>2.7</td>
<td>-0.10</td>
<td>4.5</td>
</tr>
<tr>
<td>1095</td>
<td>22</td>
<td>-0.10</td>
<td>9</td>
</tr>
</tbody>
</table>

- $\theta_{cone} = 4.5^\circ$
- BigBite Solid Angle: ~100msr
- Vertical: +/- 18 deg
- Horizontal: +/- 5 deg

Diagram showing the scattering plane, reaction plane, and various angles and distances.
Coverage of bigbite at 1.2 GeV

Ellipses of constant $\Delta W$ ($W$ relative to $\pi$ threshold)
Target
- New 6 cm long, 1” diameter LH2 cell
- 200 µm 7075 Al Foil

Electron Beam
- $E = 1.194$ GeV
- 3-5 µA

Electron Beam Dump

HRS Electron Beam Snout

Luminosity
- $1 \times 10^{37}$ Hz/cm$^2$

Custom Helium Bags

Flange with special 0.003” Ti Exit Window

MWDC (6 Planes)

3 mm and 30 mm scintillator Arrays

BigBite
Special Flange with 0.003” Ti Window
E04-007: Custom 0.0035” thick polyurethane helium filled balloon
BigBite Arm

- BigBite Dipole Magnet
- Front and back MWDC chambers
- BigBite acceptance matches HRS Resolution $\Delta p/p = 1\%$
- Two large arrays of Scintillators. One 3 mm thick and the other 30 mm thick as trigger planes form coincident with LHRS and for PID.
- Helium bag in magnet gap and between MWDC chambers
E04-007: Installed In Hall A

- BigBite Spectrometer
  - Steel Shield Walls
  - 1 Tesla Dipole
  - Hadron Detector Package
E04-007: Calibration Data

For each production kinematics we took:

- Tantalum elastic - absolute beam energy- electron in HRS
- Proton elastic - electron in HRS, check cross section, proton in BigBite optics
- Carbon elastic and inelastic - check beam energy and cross section
- HRS Sieve slit data with hydrogen elastic
- BigBite Sieve Slit data with Quasi elastic from deuterium for optics
- Hydrogen data with collimated target cell
- Elastic recoil proton data with different currents in BigBite
- Production data with different beam currents (1-6 ua)
- Data with different wire chamber high voltage and threshold. First time used for protons.
- Electronic 1 KHz pulser in data stream to measure computer dead time correction
- Production data with widely varied prescale factors.
E04-007: $E - \Delta E$ from 30 mm and 3 mm paddles
$Q^2 = -0.058 \text{GeV}^2$

$Q^2 = -0.098 \text{GeV}^2$

$Q^2 = -0.147 \text{GeV}^2$

E plane scintillator Trigger
Cut on 30 ns peak - 30 ns background
Cut on W above Threshold

Pi0 Missing Mass For Different $Q^2$ Run
Peak is cut off by the cut on W
Pi0 Missing Mass For Different $W^2$
10 MeV W Bins
Pi0 Production Threshold = 1073 MeV
For Run 3622
$Q^2 = -0.147$ GeV$^2$
HRS Optics

Sieve: Run 4640 (New Database)
C12 elastic simulation
(from mceep)

C12 data

Run 4390
Time walk correction ($1/\sqrt{\text{adc}}$ vs tdc)
Beam energy determination

Analysis tool developed using previous data (G0 in Hall C) preliminary error < 0.1%

Miha Mihovilovic
(University of Ljubljana)
Asymmetry

\[ A_{LT}(\theta) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\sqrt{2}\epsilon(1-\epsilon) \sigma_{LT}(\theta)}{\sigma_T(\theta) + \epsilon \sigma_L(\theta) - \epsilon \sigma_{TT}(\theta)} \]

where \( \sigma^+ \) and \( \sigma^- \) are the differential cross-sections for \( \phi = 90^\circ \) with beam polarization parallel and antiparallel to the beam direction, respectively.

From MAMI recent experiment

Our accumulated charge will give us - stat. error from 20% to 5%
0.67 polarization, ave phi ~0.5

\[ Q^2 = 0.058 \text{ GeV}^2 \]
\[ E = 1.194 \text{ GeV} \]
Summary

The experiment is done
Data look good

Expect to finish analysis in 1 ½ year