Proton electric polarizability

Pion cloud

Electric polarizability: proton between charged parallel plates
Electric polarizability: proton between charged parallel plates

Proton electric polarizability

\[ E \approx \frac{100 \text{ MeV}}{1 \text{ fm}} = 10^{23} \text{ volts} / \text{ m} \]
Theory for pion polarizability:
QCD expansion in powers of quark field operators

\[ L_{\text{QCD}}(p^4) = L^{\text{chiral-even}}(p^4) + L^{\text{chiral-odd}}(p^4) \]

Charged pion polarizability

\[ \alpha_\pi = -\beta_\pi = \frac{4\alpha}{m_\pi F_\pi^2} (L^r_9 - L^r_{10}) \]

\[ \pi^0 \rightarrow \gamma \gamma \]

Primex result:

\[ \Gamma(\pi^0 \rightarrow \gamma \gamma) = 7.80 \text{ eV} \pm 2.8\% \]
Compton Scattering and the E.M. polarizabilities

Either real or virtual $\pi^+$

$\vec{E} \approx 10^{23} \text{ volts/m}$

$\sim 100 \text{ MeV}$

$H = H_{\text{Born}}(e, \vec{\mu}) - 4\pi \left( \frac{1}{2} \alpha_{\text{EM}} \vec{E}^2 + \frac{1}{2} \beta_{\text{EM}} \vec{H}^2 \right)$

$10\%$
Crossing symmetry ($x \leftrightarrow t$):
Compton scattering $\gamma\gamma \rightarrow \pi^+\pi^-$

$\sim 100$ MeV
Primakoff process:
very low-$t$ photoproduction $\gamma A \rightarrow \pi^+ \pi^- A$

$$\sigma(\gamma \gamma \rightarrow \pi^+ \pi^-)$$

$$\frac{d^2 \sigma_{\text{Primakoff}}}{d\Omega dM} = \frac{2\alpha Z^2}{\pi^2} \frac{E_\gamma^4 \beta^2}{M} \frac{\sin^2 \theta}{Q^4} \left| F(Q^2) \right|^2 \left( 1 + P_\gamma \cos 2\varphi_{\pi\pi} \right) \sigma(\gamma \gamma \rightarrow \pi\pi)$$
Pion Polarizability Measurements

\[ \alpha_x - \beta_x \times 10^{-4} \text{ fm}^3 \]

- PLUTO (DESY)
- DM1 (DCI)
- PACHRA (LEBEDEV)
- DM2 (DCI)
- MAMI (MAINZ)
- SIGMA (SerpuKov)
- ChPT
- γγ → π⁺π⁻
- γ p→ nπ⁺γ
- π A→ π'γ A
- Fil'kov (DR)
- Gasser Pasquini (ChPT)

Theory Predictions
Sensitivity at ~20% level is typical for polarizability measurements at Mainz, Saskatoon, MIT-Bates, and Lund, where absolute cross sections were measured. At JLab we will be measuring relative cross sections.

\( \gamma \gamma \rightarrow \pi^+ \pi^- \)

\( \sigma_{\text{tot}} (|\cos(\theta_{\pi\pi}| < 0.6) \) (nb)

- \( \alpha - \beta = 13 \)
- \( \Delta \sigma \approx 20\% \)
- Prediction from ChPT and dispersion theory

\( \alpha - \beta = 5.7 \)

~ 200 events from Mark-II
Proposed Detector Setup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>12.0 GeV</td>
</tr>
<tr>
<td>Electron current</td>
<td>50 nA on 20 µm diamond</td>
</tr>
<tr>
<td>Coherent peak</td>
<td>5.5-6.0 GeV</td>
</tr>
<tr>
<td>Collimator</td>
<td>3.5 mm</td>
</tr>
<tr>
<td>Peak polarization</td>
<td>Coherent/incoherent 0.32</td>
</tr>
<tr>
<td>Target position</td>
<td>1 cm</td>
</tr>
<tr>
<td>Target</td>
<td>$^{116}$Sn, 5% RL</td>
</tr>
</tbody>
</table>
TRIGGER = FCAL, $E_{\text{th}} = 250$ MeV

Muon response in FCAL

$E_{\mu_1} + E_{\mu_2} = 5.5$ GeV

Pion response in FCAL

$E_{\pi_1} + E_{\pi_2} = 5.5$ GeV
1. Incoherent $\gamma A \rightarrow \pi^+ \pi^- X$

2. Coherent $\gamma A \rightarrow f_0(600)$

3. $\gamma A \rightarrow \rho^0 A$

4. $\gamma A \rightarrow e^+ e^- A$

5. $\gamma A \rightarrow \mu^+ \mu^- A$

**Backgrounds:** *PRIMEX can provide guidance on backgrounds.*

Calculations by T. Rodrigues

PRIMEX $\gamma \text{Pb} \rightarrow \pi^0$

Solid blue curve is $\pi^0$ nuclear incoherent.
Backgrounds: *PRIMEX can provide guidance on backgrounds.*

1. Incoherent $\gamma A \rightarrow \pi^+\pi^- X$

2. Coherent $\gamma A \rightarrow f_0(600)$

   Calculations by S. Gevorkyan, $\gamma p \rightarrow \pi^0\pi^0$ from RadPhi as a constraint

3. $\gamma A \rightarrow \rho^0 A$

4. $\gamma A \rightarrow e^+e^- A$

5. $\gamma A \rightarrow \mu^+\mu^- A$
Backgrounds

1. Incoherent $\gamma A \rightarrow \pi^+ \pi^- X$

2. Coherent $\gamma A \rightarrow f_0(600)$

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4. $\gamma A \rightarrow e^+ e^- A$

5. $\gamma A \rightarrow \mu^+ \mu^- A$

The nucleus acts as a filter for incoherent and coherent backgrounds. The nuclear effect will be even more pronounced for a $\pi \pi$ final state.
Backgrounds

1. Incoherent $\gamma A \rightarrow \pi^+ \pi^- X$

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Azimuthal distribution of $\pi^+$ in helicity frame $(1 + P_\gamma \cos 2\psi)$

5. $\gamma A \rightarrow \mu^+ \mu^- A$
Backgrounds

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0.995 $e^+e^-$ rejection at 99% $\pi^+\pi^-$ acceptance
Physics Backgrounds

1. Incoherent $\gamma A \rightarrow \pi^+ \pi^- X$

2. Coherent $\gamma A \rightarrow f_0(600)$

3. $\gamma A \rightarrow \rho^0 A$

4. $\gamma A \rightarrow e^+ e^- A$

5. $\gamma A \rightarrow \mu^+ \mu^- A$
Muon detector design

Concept:
Iron absorbers to initiate pion showers, followed by MWPC’s to detect muons and shower products

Design work is in progress:
Developing Geant3 and Geant4 simulations of this geometry

20 cm iron = $1\lambda_{\pi}$
Geant3 Simulations

1 GeV muon

1 GeV pion

Muon detectors

FCAL
Geant3 Simulations

2 GeV muon

2 GeV pion

Muon detectors

FCAL
Geant3 Simulations

3 GeV muon

3 GeV pion

Muon detectors

FCAL
Geant4 calculation of dE/dx in the MWPCs

\[ \pi^+ \quad \mu^+ \]

Energy deposition in MWPC gas

MWPC single layer efficiency = 98.5%
(for threshold=0.85keV)
Number of hits in all MWPCs (8 layers)

Pion showers tend to be absorbed in iron, not necessarily leading to many hits in MWPCs

Conclusion: may need more sampling layers
Particle ID Summary

- Can’t base particle ID on a single variable. Need to combine all sources of information about the event:
  
  i. Particle momenta
  
  ii. Energy in FCAL
  
  iii. # hits in muon chambers
  
  iv. track depths in muon chambers
  
  v. x,y distribution of hits in muon chambers

- Use Multi-Variate Analysis (MVA) to map the point in N-dimensional space to a probability value that can be used to classify the type of event.
MVA Classification Examples

Blue are $\pi^+$ events, red are $\mu^+$ events

Boosted Decision Tree
2GeV $\pi^+/\mu^+$

Neural Network
2GeV $\pi^+/\mu^+$
Multi-Variate Analysis for 2 GeV $\pi^+$ and $\mu^+$

$\mu$ rejection at 0.998, $\pi$ efficiency at 95%
Summary of the Muon System

- We conclude that a **muon system based on MWPCs and iron absorbers + FCAL** can deliver the $\pi/\mu/e$ separation required.

- Need to optimize the size of the detector, the number of detector planes, the total iron thickness, and *neural net/boosted decision tree* algorithms.

- Use MWPC’s operating in proportional mode: cheap, relatively easy to construct, high eff. for MIP.

- Channel estimate: assume cell spacing = 4 cm, four MWPC packages with $x, y$ planes, $2 \times 2 \text{ m}^2$, = 400 total cells.

- Electronics readout: borrow 25 FADC’ modules + ancillary electronics + crates. Need a relatively cheap preamp card on the MWPC’s.
The Road to $\sigma_{\gamma\gamma\rightarrow\pi\pi}$

1. Identify candidate events based on kinematic cuts
   a) $E_1 + E_2 = E_\gamma$
   b) $0.3 < W_{12} < 0.5$ GeV
   c) $\Theta_{12} < 0.6^\circ$
   d) $\pi\pi$ = event with no identified muon
   e) $\mu\mu$ = event with at least one identified muon

2. Subtract backgrounds from yields

   $N_{\pi\pi} = N_{\pi\pi-\text{candidate}} - f_{\text{bad-}\mu\mu(\pi\pi)}N_{\mu\mu} + f_{\text{bad-}\pi\pi(\mu\mu)}N_{\pi\pi} - f_{\text{bad-}\pi\mu(\pi\pi)}f_{\pi\rightarrow\mu\nu}N_{\pi\pi}$

   $N_{\mu\mu} = N_{\mu\mu-\text{candidate}} + f_{\text{bad-}\mu\mu(\pi\pi)}N_{\mu\mu} - f_{\text{bad-}\pi\pi(\mu\mu)}N_{\pi\pi} - f_{\text{bad-}\pi\mu(\mu\mu)}f_{\pi\rightarrow\mu\nu}N_{\pi\pi}$

   $f_{\pi\rightarrow\mu\nu} = \text{probability for pion decay} = 8\%$

   $f_{\text{bad-}\pi\pi(\mu\mu)} = \text{probability for } \pi\pi \text{ event to ID as } \mu\mu \text{ event} \sim 0.05$

   $f_{\text{bad-}\pi\mu(\pi\pi)} = \text{probability for } \pi\mu \text{ event to ID as } \pi\pi \text{ event} \sim 0.05$

   $f_{\text{bad-}\pi\mu(\mu\mu)} = \text{probability for } \pi\mu \text{ event to ID as } \mu\mu \text{ event} \sim 1$
The Road to $\sigma_{\gamma\gamma \to \pi \pi}$

3. Azimuthal fits to pion yields

$$N_{\pi\pi} = N_{\text{Primakoff}} \left(1 + P_\gamma \cos 2\phi_{\pi\pi}\right) + N_{\rho}$$

$$N_{\pi\pi} = N_{\rho} (1 + P_\gamma \cos 2\psi) + N_{\text{Primakoff}}$$

4. Form ratio with muon yields

$$\frac{N_{\text{Primakoff}}}{N_{\mu\mu}} = \left| \frac{F_{\text{strong}}(q^2)}{F_{EM}(q^2)} \right|^2 \frac{(FDC \cdot TOF)_{\pi\pi}}{(FDC \cdot TOF)_{\mu\mu}} \times \frac{\text{Trig}_{\pi\pi}}{\text{Trig}_{\mu\mu}} \times (1 - f_{\pi \to \mu\nu}) \frac{\text{CoulCorr}_{\pi\pi}}{\text{CoulCorr}_{\mu\mu}} \left[ \frac{\sigma_{\gamma\gamma \to \pi\pi}}{\sigma_{\gamma\gamma \to \mu\mu}} \right]$$

-4% 0% 0% -8% +1%
\[ \gamma + \gamma \rightarrow \pi^+ + \pi^- \]

\[ \sigma_{\text{tot}} (|\cos(\theta_{\pi\pi}| < 0.6) \text{ (nb)} \]

- \( \alpha_{\pi^-} - \beta_{\pi^-} = 13.0 \)
- \( \alpha_{\pi^-} - \beta_{\pi^-} = 5.7 \)
- \( \alpha_{\pi^-} - \beta_{\pi^-} = 0.0 \)

- MARK-II data
- proposed measurement
<table>
<thead>
<tr>
<th>Errors and correction factors</th>
<th>Correction factor</th>
<th>Uncertainty in correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall statistical error</td>
<td></td>
<td>0.6%</td>
</tr>
<tr>
<td>$\pi\pi$ inefficiency</td>
<td>5%</td>
<td>.5%</td>
</tr>
<tr>
<td>$\mu\mu$ contamination</td>
<td>2%</td>
<td>.5%</td>
</tr>
<tr>
<td>$\pi\mu$ identified as $\pi\pi$</td>
<td>0.4%</td>
<td>small</td>
</tr>
<tr>
<td>$\pi\mu$ identified as $\mu\mu$</td>
<td>0.8%</td>
<td>small</td>
</tr>
<tr>
<td>polarization</td>
<td>70%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Strong form factor</td>
<td>4%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Acceptance</td>
<td></td>
<td>0.5%</td>
</tr>
<tr>
<td>Trigger</td>
<td></td>
<td>0.5%</td>
</tr>
<tr>
<td>Coulomb correction</td>
<td>1%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Total error</td>
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<td>1.5%</td>
</tr>
<tr>
<td>Projected error in $\alpha-\beta$</td>
<td>$\pm 0.6 \times 10^{-4}$ fm$^3$</td>
<td></td>
</tr>
</tbody>
</table>
Summary

• The charged pion polarizability has special status among hadron polarizabilities; the predicted value comes directly from $L_{QCD}(p^4)$. The NLO corrections to $\alpha-\beta$ are small.

• The charged pion polarizability ranks as one of the most important tests of low-energy QCD unresolved by experiment. The experimental value for $\alpha-\beta$ is poorly known.

• We have proposed to measure the charged pion polarizability $\alpha-\beta$ by measurement of $\gamma\gamma \rightarrow \pi^+\pi^-$ cross sections in the threshold region.

• 20 days are requested for running, and 5 days for commissioning. The projected uncertainty in $\alpha-\beta$ is at the level of $\pm 0.6 \times 10^{-4}$ fm$^4$, equal to the PDG error on the proton electric polarizability.

• The experiment will utilize a muon counter/iron absorber system installed after FCAL, and a solid target installed near the upstream end of the GlueX magnet. The number of additional electronics channels, approx. 400.