Measurements of charged pion and neutral pion polarizabilities at GlueX

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I. Charged and neutral pion polarizabilities
II. Overview of previous measurements
III. Update on the charged and neutral pion polarizability measurements at GlueX
I. Consider placing a hadron in a parallel plate capacitor at very high electric field

\[ E \approx \frac{0.1 GeV}{1 \text{ fm}} = 10^{23} \text{ volts/m} \]

Hadron surrounded by pion cloud

\[ \mathbf{p} = -\alpha \mathbf{E} \]
\[ \mathbf{\mu} = \beta \mathbf{H} \]

Electric polarizability \( \approx 10^{-4} \times \text{Volume} \)
Magnetic polarizability \( \approx 10^{-4} \times \text{Volume} \)

Small numbers because hadrons are “stiff”!

Polarizability measurements provide an important test of Chiral Perturbation Theory (ChPT), dispersion relation predictions, and QCD lattice calculations.
Pion polarizability has special importance because it tests fundamental symmetries, in particular chiral symmetry and its realization in QCD

**Charged pion polarizability**

**O(p⁴) prediction:** \[ \alpha_\pi = - \beta_\pi = \frac{4\alpha_{EM}}{m_\pi F_\pi^2} (L^r_9 - L^r_{10}) \approx \frac{F_A}{F_V} \]

where \( F_A \) and \( F_V \) are the weak FFs in \( \pi^+ \rightarrow e^+\nu\gamma \)

\[ \alpha_\pi = - \beta_\pi = 2.78 \pm 0.1 \times 10^{-4} e \text{ fm}^3 \]

**O(p⁶) prediction:** \[ \alpha_\pi - \beta_\pi = 5.7 \pm 1.0 \times 10^{-4} e \text{ fm}^3 \]

\[ \alpha_\pi + \beta_\pi = 0.16 \pm 0.1 \times 10^{-4} e \text{ fm}^3 \]

*O(p⁶) corrections are predicted to be small*
Neutral pion polarizability

NLO calculation: \( \alpha_{\pi^0} + \beta_{\pi^0} = 0 \)

\[ \alpha_{\pi^0} - \beta_{\pi^0} = -\frac{\alpha_{EM}}{48\pi^2 m_\pi F^2_\pi} \approx -1.1 \times 10^{-4} \text{ fm}^3 \]

NNLO calculation: \( \alpha_{\pi^0} + \beta_{\pi^0} = 1.15 \pm 0.30 \times 10^{-4} \text{ fm}^3 \)

\[ \alpha_{\pi^0} - \beta_{\pi^0} = -1.90 \pm 0.20 \times 10^{-4} \text{ fm}^3 \]

Neutral pion polarizability has never been reliably determined
Measuring hadron polarizabilities

Strong electric field is needed to polarize a hadron:

\[ E \approx 100 \text{MeV} \frac{1}{1\text{fm}} = 10^{23} \frac{V}{m} \]

Probe of choice is Compton scattering:

\[ \tilde{E} \approx 10^{23} \text{volts / m} \]

\[ H = H_{\text{Born}}(e, \vec{\mu}) - 4\pi \left( \frac{1}{2} \alpha \vec{E}^2 + \frac{1}{2} \beta \vec{H}^2 \right) \]

\[ \approx 10\% \]
II. Since a pion target doesn't exist, alternative methods must be used to determine pion polarizability

**Charged pion:**

i. Radiative pion photo-production: $\gamma p \rightarrow \gamma' \pi^+ n$

ii. Pion radiative scattering: $\pi^- A \rightarrow \gamma \pi^- A$

iii. $\pi^+ \pi^-$ production in two photon collisions: $\gamma \gamma \rightarrow \pi^+ \pi^-$

**Neutral pion:**

i. $\pi^0 \pi^0$ production in two photon collisions: $\gamma \gamma \rightarrow \pi^0 \pi^0$
i. Charged pion polarizability: radiative pion photoproduction

\[ \gamma p \rightarrow \gamma' \pi^+ n \text{ at Mainz A2} \]

Proton target

\[ d\sigma \propto d\sigma_{\text{Compton}} \]

sensitive to \( \alpha_\pi \) and \( \beta_\pi \)

\(~ 300 \text{ MeV}~\)
ii. Charged pion polarizability: pion radiative scattering

\[ \pi^- A \rightarrow \gamma \pi^- A \text{ at Compass} \]

\[ d\sigma \approx d\sigma_{Compton} \]

190 GeV \( \pi^- \) beam

Ni target

Sensitive to \( \alpha_\pi \) and \( \beta_\pi \)
iii. Charged and neutral pion polarizability: $\gamma\gamma \rightarrow \pi\pi$

$\gamma\gamma \rightarrow \pi^+\pi^-$ at Mark-II and Crystal Ball

$\sim 200$ MeV

敏感于 $\alpha_\pi - \beta_\pi$

$A_{\gamma\gamma \rightarrow \pi\pi} \rightarrow$ dispersion theory $\rightarrow A_{\text{Compton}}$
Published measurements of charged pion polarizability

COMPASS: $\pi^-Ni \rightarrow \pi^-\gamma Ni @ 160$ GeV

$\alpha_\pi - \beta_\pi = 4.0 \pm 1.2(stat) \pm 1.4(sys) \times 10^{-4} fm^3$
III. The charged pion polarizability (CPP) and neutral pion polarizability (NPP) experiments at GlueX

\[ \frac{d^2\sigma_{Prim}}{d\Omega dM_{\pi\pi}} = \frac{2\alpha Z^2 E_\gamma^2 \beta^2}{\pi^2 M_{\pi\pi}} \frac{\sin^2\theta}{Q^4} \left| F(Q^2) \right|^2 \left( 1 + P_\gamma \cos 2\phi_{\pi\pi} \right) \sigma(\gamma\gamma \rightarrow \pi\pi) \]

\( \text{208}^{\text{Pb}} \text{ target} \)

\( 6 \text{ GeV} \)

\( \pi \rightarrow \pi \)

sensitive to \( \alpha_\pi - \beta_\pi \)
Existing data for $\sigma(\gamma\gamma \rightarrow \pi^+\pi^-)$

![Graph showing the total cross section for $\gamma\gamma \rightarrow \pi^+\pi^-$ as a function of $W_{\pi\pi}$ (GeV). The data are from various experiments including MARK-II (SLAC), CELLO (DESY), and BELLE (KEKB). The graph highlights the contribution of the $f_2(1270)$ resonance.](image-url)
Existing data for $\sigma(\gamma\gamma \rightarrow \pi^0\pi^0)$

Threshold Region

Cross section (nb)

$W_{\pi\pi}$ (GeV)

$f_2(1270)$
The CPP and NPP experiments at JLab GlueX
The CPP and NPP experiments at JLab GlueX

208Pb → \vec{\gamma} → \pi^- \pi^+

New detector for \(\mu/\pi\) identification

- 5 cm lead
- 10 cm steel
- 15 cm steel
- 35 cm steel
- 6 x MWPCs, 60" x 60"

Target

\(\vec{\gamma}\)
The CPP and NPP experiments at JLab GlueX

The diagram shows a setup for detecting particles in the high field region of a solenoid, leading to a target of $^{208}\text{Pb}$. The emitted particles, $\pi^-$ and $\pi^+$, are tracked through a FDC and TOF system before being detected by a FCAL. A new detector is used for $\mu/\pi$ identification.
Eight MWPCs were built at UMass for the CPP measurement
Time-of-flight trigger for the CPP measurement

A trigger based on two charged tracks going into the forward time-of-flight (TOF) scintillator system was commissioned for CPP.
Update on the CPP and NPP experiments at GlueX

- A muon detector system was installed and commissioned for the experiment
- A trigger based on 2 charged tracks going into the forward time-of-flight scintillators was commissioned
- The Hall D photon tagger was reconfigured to provide a coherent photon peak at 6 GeV with 80% polarization
- A 5% RL lead target was installed 64 cm upstream of the nominal target position to give better acceptance at low $W_{\pi\pi}$
- The experiment started data taking June 9 and concluded on Aug. 18, taking the full allotment of 25 PAC awarded days
Reconstructed target vertex position observed during the run

Reconstructed Event Vertex Z

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Position of $^{208}Pb$ target
Invariant mass of $h^+h^-$ pairs observed during the run (no particle ID at this point)

Bethe-Heitler $\gamma A \to e^+e^- A$

$\rho^0 \to \pi^+\pi^-$
Summary

• Pion polarizability has special importance because it tests fundamental symmetries, specifically chiral symmetry and its realization in QCD

• The GlueX CPP and NPP experiments utilize a new technique for measuring pion polarizability: Primakoff photo-production of $\pi^+\pi^-$ and $\pi^0\pi^0$ pairs

• Data taking for the CPP and NPP experiments has been completed, and we look forward to physics results in the near future

Thank you!