Precyzyjny pomiar polaryzowalności pionu

Andrzej Sandacz
Narodowe Centrum Badań Jądrowych, Warszawa

Konwersatorium IFD im. Jerzego Pniewskiego
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Electromagnetic polarisabilities of the pion

- Magnitude of polarisability of a composite system by an external electromagnetic field characterises the „rigidity“ of the system.

- $\pi$ meson, quark-antiquark system, lightest object bound by the strong force. Its rigidity reflects the strength of the binding force.

- Theory of strong interactions (ChPT) predicts the pion electric and magnetic polarisabilities with (present) uncertainties of $\approx 18\%$.

- Expected ‘deformation’ is about $2 \times 10^{-4}$ of the pion volume, tiny effect. Good control of experimental systematics needed.

- To produce such deformation the electric field of $10^{18} \text{ V/cm}$ needed.

- No trustworthy measurements of pion polarisabilities prior to COMPASS. No entry in „Review of Particle Physics“ yet.
Chiral perturbation theory in a nut-shell

- Chiral symmetry – symmetry of Lagrangian under which left- and right-handed Dirac fields (QCD quarks) transform independently
  
  • in QCD with mass-less quarks the chiral symmetry is *spontaneously* broken by a quark condensate $\langle \bar{q}_R^a q_L^b \rangle$ formed through nonperturbative action of QCD gluons, with mass-less pion identified as the Goldstone boson
  
  • due to non-vanishing and differing quark masses, in the real world the chiral symmetry is *explicitly* broken, and pions are not massless, they are pseudo-Goldstone bosons

- Chiral perturbative theory (ChPT) is low-energy expansion of QCD with the same symmetries as ‘mather’ theory, and hadrons as effective degrees of freedom

- Unknown coupling constants in ChPT Lagrangian are determined by fits to experimental data or derived from the underlying theory (QCD)

- ChPT provides a consistent description of low-energy hadronic physics:
  
  light-meson masses, decays, effective couplings, pion scattering lengths $a_0$ and $a_2$
  
  proton and neutron electric and magnetic polarisabilities etc,
COMPASS result makes ‘an event’ at CERN

- on February 11, 2015 in Physical Review Letters published COMPASS article „Measurement of Charged-Pion Polarizability”

- the same day the result announced at the CERN press release

  some citations from the press release
  
  • ” CERN experiment brings precision to a cornerstone of particle physic ”
  
  • ” […] a key measurements on the strong interaction”
  
  • ” This result is admirably complementary to the studies of fundamental interactions performed at the LHC and a testimony to the diversity and strength of CERN’s research program”, Rolf Heuer, Director General

- the first page in News of March 2015 issue of the CERN Courrier
Pion polarisabilities – definitions and access

2-loop ChPT prediction:

\[ \alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \times 10^{-4} \, \text{fm}^3 \]
\[ \alpha_\pi + \beta_\pi = (0.2 \pm 0.1) \times 10^{-4} \, \text{fm}^3 \]

CMS kinematic variables:

- \( s \): total energy squared
- \( \theta_{\text{cm}} \): scattering angle

Differential cross section for \( \pi \gamma \rightarrow \pi \gamma \) modified compared to point-like pion:

\[
\frac{d\sigma_{\pi\gamma}}{d\Omega_{\text{cm}}} = \frac{\alpha^2(s z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha m_\pi^2(s - m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)^2} \cdot \mathcal{P}
\]

\[
\mathcal{P} = z_+^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4}z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s}z_-^3(\alpha_2 - \beta_2)
\]

\[
z_\pm = 1 \pm \cos \theta_{\text{cm}} \quad \alpha = 1/137 \text{ fine structure constant}
\]
Effect of the pion polarisabilities on measured cross section

\[ \pi \gamma \rightarrow \pi \gamma \]

- Point-like pion
- ChPT 2-loop prediction
- Simulation assuming statistics collected in 2012

\[ s \text{ in units of } m_\pi^2 \]

- \( \sigma_{\text{tot}}(s) \) weak sensitivity to pion’s structure
- Up to 20% effect on backward \( \theta_{\text{CM}} \) scattering angles
Ways to access $\pi \gamma \rightarrow \pi \gamma$ scattering

\text{(A)} \quad \text{Primakoff process}

\text{(B)} \quad \text{radiative pion photoproduction}

\text{(C)} \quad \text{photon-photon fusion}

\begin{equation}
Q^2 = - (p^\mu_\pi + p^\mu_\gamma - p^\mu_{\text{beam}})^2
\end{equation}
GIS’06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006)
plots from Thiemo Nagel, PhD thesis, TUM 2012
Fil’kov analysis objected by Pasquini, Drechsel, Scherer, PR C81 (2010) 029802
Pion polarisability via Primakoff Compton scattering

- Charged pion traversing the nuclear electric field
  - typical field strength at
    \[ r = 5R_N; \quad E \sim 300 \text{ kV/fm} \]

- Bremsstrahlung emission
  - particle scatters off \textit{equivalent photons}
  - tiny momentum transfer
    \[ Q^2 \approx 10^{-5} \text{ GeV}^2/c^2 \]
  - pion/muon (quasi-)real Compton scattering

- Polarisability contribution
  - Compton cross-section typically diminished
  - expected charge separation
    \[ \sim 10^{-5} \text{ fm} \cdot e \]
Interplay of electromagnetic and strong interactions

\[ q_T = \left| \left( \vec{p}_\pi + \vec{p}_\gamma - \vec{p}_{\text{beam}} \right)_T \right| \]

G. Fäldt, Phys.Rev. C79, 014607
Pure Primakoff sample from $\mu^- \text{Ni} \rightarrow \mu^- \gamma \text{Ni}$

The graph shows the $q$ distribution with $q = |\vec{p}_\pi + \vec{p}_\gamma - \vec{p}_{\text{beam}}|$. The achieved resolution is 12 MeV/c, which is 10 times larger than the true peak structure.
\pi\text{-nucleus cross-section connection to } \pi\gamma\text{ cross section}

equivalent-photon approximation approach

\[ \pi (A,Z) \rightarrow X (A,Z) \]

\[ \frac{d\sigma^{EPA}}{dsdQ^2d\Phi_n} = \frac{Z^2\alpha}{\pi(s-m^2_\pi)} F^2(Q^2) \frac{Q^2 - Q_{\text{min}}^2}{Q^4} \frac{d\sigma_{\pi\gamma \rightarrow X}}{d\Phi_n} \]

nucleus electromagnetic form factor

phase-space element of final state X
fixed target experiment at the CERN SPS

~ 220 physicists from 24 institutions
- Located at CERN North Area M2 beam line
  - Possible beams: $\mu^+, \mu^-, \pi^+, \pi^-, K, p \rightarrow$ Several physics programs

- Programs with **muon beam**
  - Spin structure, gluon polarization
  - Flavour decomposition
  - Transversity
  - Transverse Momentum-dependent PDFs
    - p, d polarised target (L & T)
  - **COMPASS - II (2012 – 2017)**
    - DVCS and HEMP
    - Unpolarized SIDIS and TMDs

- Programs with **hadron beams**
  - Pion polarisability
  - Diffractive and Central production
  - Light meson spectroscopy
  - Baryon spectroscopy
    - small LH$_2$ or nuclear targets
  - **COMPASS - II (2012 – 2017)**
    - long LH$_2$ target
    - nuclear targets or polarised p target (T)

- Reconfigurable target region - versatile experimental setup!
M2 beam line schematics for ‘muon’ configuration

9.9 m long Be absorber (at B4): \textit{in} for muon beam, \textit{out} for hadron beam
Fixed-target experiment

- two-stage magnetic spectrometer
- high-precision, high-rate tracking, PID, calorimetry


- 190 GeV $\pi^-$ beam on $p$ and nuclear targets (C, Ni, W, Pb)
- Silicon microstrip detectors for “vertexing”
- recoil and (digital) ECAL triggers
5 cryogenic silicon micro-strip detector stations, with spacial resolution of 4 – 11 µm excellent for vertexing and precise determination of momentum transfer to the nucleus
CEDAR – to select beam pions (96.8%)

ChErenkov Differential counter with Achromatic Ring focus

Two CEDAR detectors located about 30 m upstream of the target

In 2009 Primakoff data taking both CEDARs set on kaons to attain the highest kaon suppression
Two dedicated Primakoff triggers: incoming beam particle AND energy deposit either > 60 or > 40 GeV in central part of ECAL2

Topology of event: just one outgoing negatively charged track
+ common vertex of beam and charged tracks within the target
+ just one ECAL2 energy cluster > 2 GeV not attributed to charged track

Outgoing pion with $p_T > 40$ MeV/c
to avoid region dominated by multiple scattering of pion in the target

Exclusivity selection: energy balance must be $|\Delta E| < 15$ GeV

Selection of photon exchange (Primakoff process): $Q^2 < 0.0015 \text{ (GeV/c)}^2$

Invariant mass $m_{\pi\gamma} < 3.5m_\pi \approx 0.49 \text{ GeV/c}^2$
to suppress background from $\rho^-(770)$ production with decay into $\pi^-\pi^0$
Vertex resolution and suppression of beam kaons (2.4%)

here and in the following slides all ‘Primakoff selections’ applied except those shown in a given plot

no PID of beam

no PID of beam kaons

kaons suppressed using CEDAR info.

decays of beam kaons: \( K^- \rightarrow \pi^- \pi^0 \rightarrow \pi^- \gamma \gamma \)

pion scattering angle vs. longitudinal position of the vertex

\( \theta_\pi \)-dependent cut on z to isolate interactions on Ni target (denoted by red lines)
Identifying $\pi \gamma \rightarrow \pi \gamma$ (or $\mu \gamma \rightarrow \mu \gamma$) reaction; selection of photon exchange

$Q^2 < 0.0015 \text{ (GeV/c)}^2$

$Q^2 = - (p^\mu_\pi + p^\mu_\gamma - p^\mu_{\text{beam}})^2$
Mass of the final $\pi\gamma$ (or $\mu\gamma$) system

$m_{\pi\gamma} < 3.5m_\pi \approx 0.49$ GeV/c²
to suppress background from $\rho^-(770)$ production
with decay into $\pi^-\pi^0 \rightarrow \pi^-\gamma\gamma$
Identifying $\pi\gamma \rightarrow \pi\gamma$ (or $\mu\gamma \rightarrow \mu\gamma$) reaction; exclusivity selection

$|\Delta E| < 15$ GeV

$\Delta E = E_{\pi} + E_{\gamma} - E_{\text{beam}}$

$\sigma \approx 3$ GeV, mainly from ECAL2

for selected range $Q^2 < 0.0015$ (GeV/c)$^2$

kinetic energy of Ni recoil $< 8$ keV, neglected for $\Delta E$
Extraction of the pion polarisability

- Assuming $\alpha_\pi = - \beta_\pi$, from the cross section for $\pi \gamma^{*} \to \pi \gamma$

\[
R_\pi = \left( \frac{d\sigma_{\pi\gamma}}{dx_\gamma} \right) / \left( \frac{d\sigma_{\pi\gamma}^0}{dx_\gamma} \right) = 1 - \frac{3 m_\pi^3}{2} \frac{x_\gamma^2}{\alpha \left( 1 - x_\gamma \right)} \alpha_\pi
\]

- Measured cross section
- Simulated cross section expected for $\alpha_\pi = 0$
- Fit to $R_\pi(x_\gamma) \rightarrow \alpha_\pi$

- Control systematics by
  - $\mu \gamma^{*}_{\text{Ni}} \to \mu \gamma$
  - $K^- \to \pi^- \pi^0 \to \pi^- \gamma \gamma$

$x_\gamma = E_\gamma / E_{\text{beam}}$
Photon energy spectra for pion and muon beams

≈ 63 000 Primakoff events \((x_\gamma > 0.4)\)
(Serpukhov ≈ 7 000 for \(x_\gamma > 0.5\))

\[x_\gamma = \frac{E_\gamma}{E_{\text{beam}}}\]

fraction \(f_{\pi^0}\) of \(\pi^0\) background from \(\pi^- \text{Ni} \rightarrow \pi^- \pi^0 X \rightarrow \pi^- \gamma \sqrt{X}\)
subtracted from the pion data

estimated from decays of beam kaons \(K^- \rightarrow \pi^- \pi^0 \leftrightarrow \pi^- \gamma \gamma\)

\(\pi^- \gamma \gamma\)
Pion polarisability – COMPASS result

\[ \alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4} \text{ fm}^3 \]

2-loop ChPT prediction \[ \alpha_\pi = 2.93 \times 10^{-4} \text{ fm}^3 \]
 expectation from ChPT confirmed within the uncertainties

control measurements of ‘false polarisability’
with muon beam

\[ \alpha_\mu = (0.5 \pm 0.5_{\text{stat}}) \times 10^{-4} \text{ fm}^3 \]
 no significant systematic bias
The new COMPASS result is in significant tension with the earlier measurements of the pion polarisability.

The expectation from ChPT is confirmed within the uncertainties.
Conclusions and outlook

- measurement of the pion polarisability via the Primakoff reaction \((2009\ data)\)
  \[ \alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4}\ \text{fm}^3 \]
  with assumption \(\alpha_\pi = -\beta_\pi\)

  - new precise experimental determination
  - control of systematics: \(\mu\gamma \rightarrow \mu\gamma\)
  - the expectation for ChPT confirmed within the uncertainties
  - the COMPASS results is in tension with the earlier measurements

- high statistics run 2012 (COMPASS-II) \((\approx 4\ times\ larger\ than\ in\ 2009)\)
  - separate determination of \(\alpha_\pi\) and \(\beta_\pi\)
  - measurement of quadrupole polarisabilities of \(\alpha_2\) and \(\beta_2\)
  - \(s\)-dependence of polarisabilities
  - first measurement of the kaon polarisability
Backup
Divergence of the hadron beam

beam divergence cut indicated in black
**Systematic uncertainties**

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Estimated magnitude $[10^{-4} \text{ fm}^3]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determination of tracking detector efficiency</td>
<td>0.5</td>
</tr>
<tr>
<td>Treatment of radiative corrections</td>
<td>0.3</td>
</tr>
<tr>
<td>Subtraction of $\pi^0$ background</td>
<td>0.2</td>
</tr>
<tr>
<td>Strong interaction background</td>
<td>0.2</td>
</tr>
<tr>
<td>Pion-electron elastic scattering</td>
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</tr>
<tr>
<td>Contribution of muons in the beam</td>
<td>0.05</td>
</tr>
<tr>
<td>Quadratic sum</td>
<td>0.7</td>
</tr>
</tbody>
</table>

**TABLE I.** Estimated systematic uncertainties at 68% confidence level.
Other Primakoff processes

\[ \pi^- + \gamma \rightarrow \begin{cases} 
\pi^- + \gamma \\
\pi^- + \pi^0 / \eta \\
\pi^- + \pi^0 + \pi^0 \\
\pi^- + \pi^- + \pi^+ \\
\pi^- + \pi^- + \pi^+ + \pi^- + \pi^+ \\
\pi^- + \ldots 
\end{cases} \]

analogously: *Kaon-induced reactions* \( K^- + \gamma \rightarrow \cdots \)

Measured absolute cross-section of \( \pi^- \gamma \rightarrow \pi^-\pi^-\pi^+ \)

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**COMPASS 2004**

\[ \pi^\gamma \rightarrow \pi^-\pi^+\pi^+ \]

from \( \pi \mathrm{Pb} \rightarrow \pi^-\pi^-\pi^+\mathrm{Pb} \)

- Fitted ChPT Intensity
- Leading Order ChPT Prediction

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