Charged pion polarizabilities measurement at the COMPASS experiment

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Matter in external fields

\[ \vec{P} = \alpha_\pi \times \vec{E} \]

\[ \vec{\mu} = \beta_\pi \times \vec{H} \]

Electrical and magnetic polarizabilities of a medium

Saturday, July 17, 2010
Hydrogen atom - the simplest QED system

$$\alpha_H = \frac{9}{2}a^3$$, where $a$ is the Bohr radius
Pion - the “atom” of QCD

\[ T(\pi^-\gamma \rightarrow \pi^-\gamma) = \left(-\frac{\alpha}{m_\pi} + \alpha_\pi \omega_1 \omega_2\right) \cdot \hat{e}_1 \hat{e}_2 + \beta_\pi \omega_1 \omega_2 (\hat{e}_1 \times \hat{q}_1) \cdot (\hat{e}_2 \times \hat{q}_2) + \ldots \]

Diagrams of Compton scattering on point-like pion

1) \[ \mathbf{k}_1 \quad \mathbf{P}_1 \quad \mathbf{P}_2 \]

2) \[ \mathbf{k}_2 \quad \mathbf{P}_2 \]

3) \[ \mathbf{k}_1 \quad \mathbf{P}_1 \]

4) Corrections related to pion internal structure

In nonrelativistic approximation the hamiltonian of pion interaction with external electromagnetic field (Compton scattering) corresponding to the 4th diagram can be represented as:

\[ H = -\frac{1}{2} \left( \alpha_\pi E^2 + \beta_\pi H^2 \right) \]

The electric and magnetic polarizabilities of pion are the quantities characterizing the rigidity of complex QCD system.
Theoretical predictions for pion polarizabilities

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>$[10^{-4} fm^3]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi$PT</td>
<td>$\alpha_\pi - \beta_\pi$</td>
<td>5.7 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>$\alpha_\pi + \beta_\pi$</td>
<td>0.16</td>
</tr>
<tr>
<td>NJL</td>
<td>$\alpha_\pi - \beta_\pi$</td>
<td>9.8</td>
</tr>
<tr>
<td>QCM</td>
<td>$\alpha_\pi - \beta_\pi$</td>
<td>7.05</td>
</tr>
<tr>
<td></td>
<td>$\alpha_\pi + \beta_\pi$</td>
<td>0.23</td>
</tr>
<tr>
<td>QCD sum rules</td>
<td>$\alpha_\pi - \beta_\pi$</td>
<td>11.2 ± 1.0</td>
</tr>
<tr>
<td>Dispersion sum rules</td>
<td>$\alpha_\pi - \beta_\pi$</td>
<td>13.60 ± 2.15</td>
</tr>
<tr>
<td></td>
<td>$\alpha_\pi + \beta_\pi$</td>
<td>0.166 ± 0.024</td>
</tr>
</tbody>
</table>

Different theoretical models predict quite different values of pion polarizabilities. An experimental measurement provides a stringent test of theoretical approaches.
Compton scattering on pion? How we can observe it?

- Radiative scattering of pion on nuclear target with hard photon emission (Primakoff scattering)
- Radiative pion photoproduction
- $\pi^+\pi^-$ pair production in $e^+e^-$ collision

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# Experimental results for $\alpha_\pi$ and $\beta_\pi$

<table>
<thead>
<tr>
<th>Data</th>
<th>Reaction</th>
<th>Parameter</th>
<th>$[10^{-4} fm^3]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serpukhov ($\alpha_\pi + \beta_\pi = 0$)</td>
<td>$\pi Z \rightarrow \pi Z \gamma$</td>
<td>$\alpha_\pi$</td>
<td>6.8±1.4±1.2</td>
</tr>
<tr>
<td>Serpukhov ($\alpha_\pi + \beta_\pi \neq 0$)</td>
<td>$\alpha_\pi + \beta_\pi$</td>
<td>1.4±3.1±2.8</td>
<td></td>
</tr>
<tr>
<td>Lebedev</td>
<td>$\gamma N \rightarrow \gamma N \pi$</td>
<td>$\alpha_\pi$</td>
<td>20±12</td>
</tr>
<tr>
<td>Mami A2</td>
<td>$\gamma p \rightarrow \gamma \pi^+ n$</td>
<td>$\alpha_\pi - \beta_\pi$</td>
<td>11.6±1.5±3.0±0.5</td>
</tr>
<tr>
<td>PLUTO</td>
<td>$\gamma \gamma \rightarrow \pi^+ \pi^-$</td>
<td>$\alpha_\pi$</td>
<td>19.1±4.8±5.7</td>
</tr>
<tr>
<td>DM1</td>
<td>$\gamma \gamma \rightarrow \pi^+ \pi^-$</td>
<td>$\alpha_\pi$</td>
<td>17.2±4.6</td>
</tr>
<tr>
<td>DM2</td>
<td>$\gamma \gamma \rightarrow \pi^+ \pi^-$</td>
<td>$\alpha_\pi$</td>
<td>26.3±7.4</td>
</tr>
<tr>
<td>Mark II</td>
<td>$\gamma \gamma \rightarrow \pi^+ \pi^-$</td>
<td>$\alpha_\pi$</td>
<td>2.2±1.6</td>
</tr>
<tr>
<td>Global fit: MARK II, VENUS, ALEPH, TPC/2$\gamma$, CELLO, BELLE (L. Fil’kov, V. Kashevarov)</td>
<td>$\gamma \gamma \rightarrow \pi^+ \pi^-$</td>
<td>$\alpha_\pi - \beta_\pi$</td>
<td>13.0±2.6±1.9</td>
</tr>
<tr>
<td>Global fit: MARK II, Crystal ball (A. Kaloshin, V. Serebryakov)</td>
<td>$\gamma \gamma \rightarrow \pi^+ \pi^-$</td>
<td>$\alpha_\pi - \beta_\pi$</td>
<td>5.25±0.95</td>
</tr>
</tbody>
</table>

For $\alpha_\pi + \beta_\pi = 0$
For extraction of pion polarizabilities we compare the measured differential cross section of Primakoff reaction and the theoretically predicted cross section for point like pion.
How the polarizabilities can be extracted?

For measurement of $\alpha_\pi$ and $\beta_\pi$ under approximation $\alpha_\pi + \beta_\pi = 0$ we compare differential cross section

$$\frac{d\sigma}{d\omega}, \text{ where } \omega = \frac{E_\gamma}{E_{beam}}$$

measured and theoretically predicted for point like pion

$$R = \frac{\sigma_{\text{measured}}(\omega)}{\sigma_{\text{point-like}}(\omega)} = \frac{N_{\text{measured}}(\omega)}{N_{\text{point-like}}(\omega)}$$

$$R \approx 1 - \frac{3}{2} \cdot \frac{\omega^2}{1 - \omega} \cdot \frac{m_\pi^3}{\alpha} \cdot \alpha_\pi$$

1: $\alpha_\pi = 2 \times 10^{-4} \text{ fm}^3$
2: $\alpha_\pi = 5 \times 10^{-4} \text{ fm}^3$
3: $\alpha_\pi = 8 \times 10^{-4} \text{ fm}^3$
Cross section (pion at rest)

\[
\frac{d^3 \sigma}{dQ d \omega_1 d(\cos \theta)} = \frac{2 \alpha^3 Z^2}{m_\pi^2 \omega_1 m_\gamma^2} \times \frac{Q^2 - Q_{\text{min}}^2}{Q^4} |F_A(Q^2)|^2 \times \\
x \left( F_{\pi \gamma}^P + \frac{m_\pi \omega_1^2}{\alpha} \cdot \frac{\alpha_\pi (1 + \cos^2 \theta) + 2 \beta_\pi \cos \theta}{(1 + \omega_1 m_\pi (1 - \cos \theta))^3} \right)
\]

\[\alpha_\pi - \beta_\pi = 5.7 \times 10^{-4} \text{ fm}^3\]
\[\alpha_\pi + \beta_\pi = 0 \times 10^{-4} \text{ fm}^3\]

\[\alpha_\pi - \beta_\pi = 5.7 \times 10^{-4} \text{ fm}^3\]
\[\alpha_\pi + \beta_\pi = 0.16 \times 10^{-4} \text{ fm}^3\]
Pion polarizabilities are important parameters of hot hadron matter near the critical point where the chiral symmetry restoration, phase transition and deconfinement of quarks take place.
Pion polarizabilities and calorimetry at LHC

For pion momenta above \( \sim 1 \) GeV, radiation losses dominate over ionization. For precise simulation of calorimeter response (cluster shape) at such energies detailed knowledge about pion bremsstrahlung and pion polarizabilities is needed.

\[
\begin{align*}
E_c \pi (Z) & \sim \frac{1}{Z} \\
E_c \pi (Cu) & \approx 600 \text{ GeV}
\end{align*}
\]
# COMPASS Experiment

The fixed target experiment on SPS at CERN

## MUON PROGRAM

- $\Delta G/G$
- Structure functions
- Exclusive production of vector mesons
- $\Lambda$-physics
- Transversity
- GPD

## HADRON PROGRAM

- Pion and kaon polarizabilities
- Chiral anomaly
- Charm baryons
- Glueballs and exotic mesons
- Diffractive production
- Drell-Yan

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1996 - COMPASS proposal
1999 - 2001 - construction and installation
2001 - technical run
October-November 2004 - pilot hadron run
2008 - hadron run
2009 - hadron run
Self-test with muon beam

At COMPASS we have possibility to use pion and muon beams with the same momentum and the same configuration of the setup.

Since muon is the point-like particle, the measured differential Primakoff cross section should exactly correspond to theoretically predicted one.

So the statistics collected with muon beam can be used for study of systematic effects.
COMPASS pilot hadron run 2004

About 10 days of data taking (pilot run)
Integrated beam flux is $10^{11}$ pions

**TARGETS:**
- main
  - Pb 3 mm
  - Pb 1.6 mm
  - Pb 2 + 1 mm
  - C 23.5 mm
  - Cu 3.55 mm
  - Empty target

**Beam:**
- secondaries beam from SPS
  - $\pi^-$ (190 GeV)
  - $\mu^-$ (190 GeV)

**Trigger:**
- >100 GeV in electromagnetic calorimeter

Beam counter
Veto system
Target
Silicon stations
HCAL1
Primakoff hodoscope
Pion
Photon
ECAL2
HCAL2
Background processes and corrections

**Primakoff**

\( \pi \rightarrow \pi \gamma \) (Born)

\( \pi \rightarrow \pi \gamma \) diffractive

**Correction to Compton vertex**
**Vacuum polarization**
**Nuclear charge screening**
**Multiple photon exchange**
**Electromagnetic form factor of nucleus**

\( e \rightarrow e \gamma \)
\( \mu \rightarrow \mu \gamma \)
\( K \rightarrow K \gamma \)
\( p \rightarrow p \gamma \)

\( \pi \rightarrow \rho \rightarrow \pi^- \pi^0 \)
\( K \rightarrow \pi^- \pi^0 \)
\( \pi \rightarrow \pi^- \pi^0 \) Primakoff
\( \pi \rightarrow \pi^- \pi^0 \) diffractive

\( K \rightarrow K^*(892) \rightarrow K^- \pi^0 \)
\( K \rightarrow K_2^*(1430) \rightarrow K^- \pi^0 \)

Too many processes correspond to X- and 1 cluster in the calorimeter the final state!

<table>
<thead>
<tr>
<th>Particle</th>
<th>Fraction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^- )</td>
<td>93.5</td>
</tr>
<tr>
<td>( K^- )</td>
<td>3</td>
</tr>
<tr>
<td>( \mu^- )</td>
<td>3</td>
</tr>
<tr>
<td>( p^- )</td>
<td>0.5</td>
</tr>
<tr>
<td>( e^- )</td>
<td>~0.1</td>
</tr>
</tbody>
</table>

Hadron beam
Event selection

- $\pi + \gamma$ in the final state
- No other clusters in ECAL2 with $E > 7$ GeV
- Primary vertex near the nominal target position
- Invariant mass $M_{\pi\gamma} < 3.75 M_\pi$
- $| E_\gamma + P_\pi - P_{\text{beam}} | < 25$ GeV
- $P_t > 45$ MeV/c
- $0.5 < \omega < 0.9$
- $Q < 2 \times 10^{-3} \text{ (GeV/c)}^2$

The same selection criteria for pion and muon events
Q2 distribution for $\pi\gamma$ and $\mu\gamma$ exclusive events
Primakoff scattering on different nuclear targets

$Q^2$-distribution for different target materials

Z-dependency of the Primakoff cross section

Strong dependence of Primakoff signal ($Q=0$) to diffractive background ($Q>>0.01$) ratio on the target material

Good agreement with $Z^2$-dependency for the Primakoff cross section in the wide Z range
COMPASS hadron run 2009

Main changes:

<table>
<thead>
<tr>
<th></th>
<th>Run 2004</th>
<th>Run 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main target</td>
<td>Pb (0.5 $X_0$)</td>
<td>Ni (0.3 $X_0$)</td>
</tr>
<tr>
<td>Total beam flux, $10^{11}$</td>
<td>$1$ ($\pi$), $0.7$ ($\mu$)</td>
<td>$3$ ($\pi$), $1.3$ ($\mu$)</td>
</tr>
<tr>
<td>Main trigger condition</td>
<td>$E_\gamma &gt; 90$ GeV</td>
<td>$E_\gamma &gt; 65$ GeV</td>
</tr>
</tbody>
</table>

New target $\rightarrow$ smaller radiative corrections, better resolution for $Q^2$

New digital calorimeter trigger: only the central part of electromagnetic calorimeter was included into the trigger $\rightarrow$ lower trigger threshold, identical performance during operation with pion and muon beams.
COMPASS hadron run 2009: other changes

- CEDAR for beam kaons identification
- Electron converter for electron background suppression
- Beam momentum measurement for muon beam
- Extended identification of secondary particles
- Better performance of electromagnetic calorimeter
- Cluster timing for better pile up rejection
- Stable conditions of data taking

Covered in 2009

Background from $\rho$-meson decay from $\omega = 0.4$

MC simulation

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New opportunities

* Precise measurement of $\alpha_\pi$ and $\beta_\pi$
* $\alpha_\pi(\omega)$, $\alpha_\pi(M)$ - the first measurement
* Estimation of quadrupole polarizabilities $\alpha_{2\pi}$ and $\beta_{2\pi}$
* First observation of Primakoff scattering with kaons and first estimation of kaon polarizabilities

New data taking for Primakoff physics is proposed to be performed in 2012 (see the COMPASS-II proposal at wwwcompass.cern.ch for details)

<table>
<thead>
<tr>
<th>Days</th>
<th>$\pi$ beam, days</th>
<th>$\mu$ beam, days</th>
<th>Flux $\pi, 10^{11}$</th>
<th>Flux $\mu, 10^{11}$</th>
<th>$\alpha_\pi - \beta_\pi$ $\sigma_{tot}$</th>
<th>$\alpha_\pi + \beta_\pi$ $\sigma_{tot}$</th>
<th>$\alpha_{2} - \beta_{2}$ $\sigma_{tot}$</th>
<th>ChPT prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>90</td>
<td>30</td>
<td>59</td>
<td>12</td>
<td>$\pm0.27$</td>
<td>fixed</td>
<td>fixed</td>
<td>5.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\pm0.26$</td>
<td>$\pm0.016$</td>
<td>fixed</td>
<td></td>
</tr>
</tbody>
</table>
Summary

During the pilot hadron run 2004 the possibility to measure pion polarizabilities at COMPASS was tested. The obtained experience was used for the preparation for the new data taking in 2009.

In 2009 new data taking for Primakoff study was performed. Setup improvements made since 2004 and stable conditions of data taking permit to expect that pion polarizabilities can be extracted with high precision from the data collected in 2009.

χPT physics and hadron polarizability measurement remain one of the most important points of future COMPASS physical program.