Precise measurement of the charged pion polarisability at COMPASS

Guskov Alexey
JINR, Dubna

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CERN experiment brings precision to a cornerstone of particle physics

11 Feb 2015

Geneva, 11 February 2015. In a paper published yesterday in the journal *Physical Review Letters*, the COMPASS experiment at CERN\(^1\) reports a key measurement on the strong interaction. The strong interaction binds quarks into protons and neutrons, and protons and neutrons into the nuclei of all the elements from which matter is built. Inside those nuclei, particles called pions made up of a quark and an antiquark mediate the interaction. Strong interaction theory makes a precise prediction on the polarisability of pions – the degree to which their shape can be stretched. This polarisability has baffled scientists since the 1980s, when the first measurements appeared to be at odds with the theory. Today’s result is in close agreement with theory.

“The theory of the strong interaction is one of the cornerstones of our understanding of nature at the level of the fundamental particles,” said Fabienne Kunne and Andrea Bressan, spokespersons of the COMPASS experiment, “so this result, in perfect agreement with the theory, is a very important one.”
Polarizabilities of a medium

\[ \mathbf{P} = \alpha \mathbf{E} \]

\[ \mathbf{\mu} = \beta \mathbf{H} \]

Electric

Magnetic
Hydrogen atom
- the simplest QED system

\[ \alpha_H = \frac{9}{2} a^3 \text{, where } a \text{ is the Bohr radius} \]
Polarizabilities of hadrons

**Compton amplitude:**

\[
A(\gamma X \rightarrow \gamma X) = \\
\left( -\frac{\alpha}{m} \delta_{o \pm} + \alpha_X \omega_1 \omega_2 \right) \hat{e}_1 \cdot \hat{e}_2 + \\
+ \beta_X \omega_1 \omega_2 (\hat{e}_1 \times \hat{q}_1) (\hat{e}_2 \times \hat{q}_2) + \ldots
\]

The electric and magnetic polarizabilities of a hadron are the quantities characterizing the rigidity of QCD system.

\[
H = \ldots - (\alpha_X E^2 + \beta_X H^2) / 2
\]

**PDG data:**

<table>
<thead>
<tr>
<th></th>
<th>$\alpha_X$, $10^{-4}$ fm$^3$</th>
<th>$\beta_X$, $10^{-4}$ fm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>12.0±0.6</td>
<td>1.9±0.6</td>
</tr>
<tr>
<td>$n$</td>
<td>12.5±1.7</td>
<td>2.7±1.8</td>
</tr>
</tbody>
</table>

$\pi, \ K^\pm$
Mass: Higgs boson vs. QCD

\[ 2.3 \text{ MeV} = 938 \text{ MeV} \]

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Since the constant of strong interactions $\alpha_s \sim 1$ at small energies, exact QCD formalism cannot make predictions with reasonable accuracy. Effective phenomenological models are needed.
Chiral perturbation theory

Mass of light quarks \((m_u, d)\) is much smaller than the typical scale \(M \approx 1\) GeV

\[ \mathcal{L}_{QCD} = \mathcal{L}^0 + \mathcal{L}_m \]

mass term - a small perturbation

Chiral symmetric term

\[ m_q/M, p/M - \text{small parameters in expansion} \]

Approximate chiral symmetry is in lagrangian but not in the mass spectrum of hadrons!

Pions are pseudo-Goldstone bosons in chiral theory.
The most of theoretical models are in agreement that $a_\pi - \beta_\pi \gg a_\pi + \beta_\pi \approx 0.2 \times 10^{-4} \text{fm}^3$. As for value $a_\pi - \beta_\pi$, predictions are quite different.
Experimental results for $\alpha_\pi$, $\beta_\pi$

At the moment experimental uncertainty for pion polarizabilities is too high. New experiments are needed!
Primakoff reactions

Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson

H. Primakoff

Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

January 2, 1951

It has now been well established experimentally that neutral \( \pi \)-mesons (\( \pi^0 \)) decay into two photons.\(^1\) Theoretically, this two-photon type of decay implies zero \( \pi^0 \) spin;\(^2\) in addition, the decay has been interpreted as proceeding through the mechanism of the creation and subsequent radiative recombination of a virtual proton anti-proton pair.\(^3\) Whatever the actual mechanism of the (two-photon) decay, its mere existence implies an effective interaction between the \( \pi^0 \) wave field, \( \varphi \), and the electromagnetic wave field, \( \mathbf{E}, \mathbf{H} \), representable in the form:

\[
\text{Interaction Energy Density} = \pi(h/\mu c)(\hbar c)^{-1} \varphi \mathbf{E} \cdot \mathbf{H}.
\]

Here \( \varphi \) has been assumed pseudoscalar, the factors \( h/\mu c \) and \( (\hbar c)^{-1} \) are introduced for dimensional reasons (\( \mu \approx \text{rest mass of } \pi^0 \)),

From Primakoff effect to Primakoff reactions

Coulomb field of a nucleus can be used as photon target
**Equivalent photons approach**

(Weizsaecker-Williams approximation)

Electromagnetic field of fast charged particle is similar to a field of flat electromagnetic wave

\[ \sigma_{x\gamma}(\omega, Q^2) \rightarrow \sigma_{x\gamma}(\omega, 0) \]

\[ d\sigma_{xZ} = \int n_\gamma(\omega) d\sigma_{x\gamma}(\omega) d\omega \]

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**Pion polarizabilities and Primakoff cross section**

\[
\frac{d\sigma}{ds \, dt \, dQ^2} = \frac{Z^2 \alpha}{\pi(s-m^2_\pi)} \cdot F^2_{\text{eff}}(Q^2) \cdot \frac{Q^2 - Q^2_{\text{min}}}{Q^4} \cdot \frac{d\sigma_{\pi \gamma}}{dt}
\]

\[Q_{\text{min}} = (s-m^2_\pi)/2E_{\text{beam}}\]

**Compton cross section:**

\[
\frac{d\sigma_{\pi \gamma}}{d\Omega_{cm}} = \frac{\alpha^2(s^2z^2_+ + m^4_\pi z^2_-)}{s(sz_+ + m^2_\pi z_-)^2} - \frac{\alpha m^3_\pi (s-m^2_\pi)^2}{4s^2(sz_+ + m^2_\pi z_-)} \cdot \mathcal{P}
\]

\[z_{\pm} = 1 \pm \cos \theta_{cm}\]

\[\mathcal{P} = z^2_-(\alpha_\pi - \beta_\pi) + \frac{s^2}{m^4_\pi}z^2_+(\alpha_\pi + \beta_\pi)\]

\[Q^2 \ll m^2_\pi\]

\[\sigma \sim Z^2\]

\[\alpha_\pi \text{ and } \beta_\pi \text{ can be extracted separately from the measurement of the differential cross section}\]
Polarizability effects

\[ \alpha_\pi + \beta_\pi \]

CM-system
\[ P_\pi = 190 \text{ GeV/c} \]
Simple case: $\alpha_\pi = -\beta_\pi$

$$R = \frac{\sigma}{\sigma_{p.l.}} \approx 1 - \frac{3}{2} \cdot \frac{x^2_\gamma}{1 - x_\gamma} \cdot \frac{m^3_{\pi}}{\alpha} \cdot \alpha_\pi$$

$x_\gamma$ - relative energy of emitted photon in Lab system
Pion polarizability and JINR
Retrospective review

Original proposal to measure pion polarizability via Primakoff reaction


The first observation of the Compton scattering off pion at SIGMA spectrometer

The first measurement of pion polarizabilities

Dubna group brought their experience to the COMPASS experiment
Measurement at the SIGMA setup
(Protvino, IHEP-JINR collaboration)

Beam: $\pi^-$, $P=40$ GeV/c
Target: C (0.25 $X_0$)
(also Be, Al, Fe, Cu, Pb)
Statistics: ~7 000 events
with $x_\gamma > 0.5$

SIGMA spectrometer

$Q^2 \times 10^2$, GeV$^2$/c$^2$
Under assumption $\alpha_{\pi} = -\beta_{\pi}$

$$a_{\pi} = -\beta_{\pi} = (6.8 \pm 1.4_{\text{stat}} \pm 1.2_{\text{syst}}) \times 10^{-4} \text{ fm}^3$$

$$a_{\pi} + \beta_{\pi} = (1.4 \pm 3.1_{\text{stat}} \pm 2.8_{\text{syst}}) \times 10^{-4} \text{ fm}^3$$

$$a_{\pi} = (7.8 \pm 2.8_{\text{stat}} \pm 1.8_{\text{syst}}) \times 10^{-4} \text{ fm}^3$$

1985

Z. Phys. C26 (1985) 495
The COMPASS experiment

COMPASS (COmmon Muon Proton Apparatus for Structure and Spectroscopy) is the fixed target experiment on the secondary beam of Super Proton Synchrotron at CERN.

The purpose of this experiment is the study of hadron structure and hadron spectroscopy with high intensity muon and hadron beams.

1996 - Proposal
2002-2011 - Physical data taking

11 countries, 28 institutions, ~240 physicists
COMPASS at CERN

\[ \pi^- + \gamma \rightarrow \begin{align*}
\pi^- + \gamma \\
\pi^- + \pi^0 \\
\pi^- + \pi^0 + \pi^0 \\
\pi^- + \pi^- + \pi^+ \\
\pi^- + \ldots
\end{align*} \]
CEDAR detectors for beam particle identification
Precise silicon detectors to measure small scattering angles
Magnetic spectrometer for pion momentum measurement
Electromagnetic calorimeter with good energy and spacial resolution for photon detection
Muon identification system
Main advantage of COMPASS

We can use **pion** and **muon** beams of the same momentum with the same setup configuration.

\[
\pi^- (A,Z) \rightarrow \pi^- (A,Z) \gamma \\
\mu^- (A,Z) \rightarrow \mu^- (A,Z) \gamma
\]

**Muon** is the point-like particle and corresponding cross section for muon is known with high precision. **So, muon data can be used as reference to control our systematics.**
Primakoff runs at COMPASS

- **Primakoff pilot run 2004**: ~1 week, ~10k events, 0.5X₀ Pb
- **Primakoff run 2009**: ~3 weeks, 63k events, 0.3X₀ Ni
- **Primakoff run 2012**: ~3 months, 200-400k events, 0.3X₀ Ni

πγ, Eγ/Ebeam > 0.4

**Topic of my present talk**
Pilot data taking in 2004

Pion radiative scattering was observed, some preliminary studies were performed

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Target: $C \rightarrow Pb \rightarrow Ni$

For high Z nuclei: we have better electromagnetic signal to nuclear background ratio but... we much stronger depends on calculation of numerous corrections
## Hadron and muon beams

<table>
<thead>
<tr>
<th></th>
<th>Hadron</th>
<th>Muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$, GeV/c</td>
<td>190</td>
<td>190</td>
</tr>
<tr>
<td>$dP/P$</td>
<td>1%</td>
<td>4%</td>
</tr>
<tr>
<td>$\sigma$ the target, cm</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Divergence, mrad</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Intensity, $10^7/9.6$ s spill</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Composition</td>
<td>$\pi^-$ 96%</td>
<td>$\mu^-$ 100%</td>
</tr>
<tr>
<td></td>
<td>$K^-$ 2.4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$p^-$ 0.8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\mu^-$ 1%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$e^-$ &lt;0.01%</td>
<td></td>
</tr>
</tbody>
</table>
CEDAR detectors

2 differential Cherenkov counters upstream the target

kaon rejection efficiency: ~95% for parallel beam
**Trigger**

**TRIGGER = (BC & ECAL2) !SW !BK1 !BK2**

<table>
<thead>
<tr>
<th>Trigger name</th>
<th>ECAL2 threshold, GeV</th>
<th>Scale factor</th>
<th>Rate, kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primakoff 1</td>
<td>~40</td>
<td>2</td>
<td>~20</td>
</tr>
<tr>
<td>Primakoff 2</td>
<td>~60</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

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Event selection

- **Primakoff**\textsubscript{1}, **Primakoff**\textsubscript{2} triggers
- 1 vertex with 1 outgoing negative track
- No other tracks*
- Beam track is parallel to the nominal beam axis
- Scattered track is not muon
- No activity in RPD
- Exactly 1 neutral cluster in ECAL\textsubscript{2} (E>2 GeV)*
- Beam particle is pion (CEDAR)
Kinematic cuts

**$p_T$-cut** to reject low $p_T$ region related with multiple scattering in the material

**Exclusivity cut** on the level ±15 GeV to reject events with missed particles in the final state
Kinematic cuts

\[ M_{\pi\gamma} < 3.5 \, m_\pi \] to avoid \( \rho \)-meson production and decay to \( \pi\pi^0 \)

\[ Q^2 < 1.5 \times 10^{-3} \, (GeV/c)^2 \] to reject \( \pi\gamma \) state production via strong interaction
**π⁰ background**

\[ \pi^- \text{Ni} \rightarrow \pi^- \text{Ni} \pi^0 \rightarrow \pi^- \text{Ni} \gamma\gamma \]

- single cluster in ECAL2
- 1γ lost

The same selection criteria were applied for this channel

Kaon decay \( K^- \rightarrow \pi^- \pi^0 \) out of the target is the reference process

Fraction of mis-reconstructed \( \pi^- \pi^0 \) events in \( \pi^- \gamma \) sample

Probability to mis-identify \( \pi^- \pi^0 \) state as \( \pi^- \gamma \)
Muon data

The same selection + muon beam momentum measurement
The measured $x_\gamma$ distributions
The result?

\[ \alpha_\pi = (1.4 \pm 0.6_{\text{stat}}) \times 10^{-4} \text{ fm}^3 \]

Not yet!

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Corrections

- Pion rescattering
- Radiative corrections (Compton vertex)
- Form factor of the Ni nucleus

- High Z effects (Zα = 0.2)
- Nuclear charge screening by atomic electrons
$\alpha_\pi = (2.0 \pm 0.6_{\text{stat}}) \times 10^{-4} \text{ fm}^3$
Systematic effects

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Estimated magnitude [10^{-4} 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>
<td>0.2</td>
</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>

$$\alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4} \text{ fm}^3$$
Ratio for muons

False polarizability for muon is consistent with zero within the error

\[ a_{false} = (0.5 \pm 0.5_{\text{stat}}) \times 10^{-4} \text{fm}^3 \]
The COMPASS result

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

Under assumption \( \alpha \pi = -\beta \pi \):

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

Protvino: \( a_\pi = -\beta \pi = (6.8 \pm 1.4_{\text{stat}} \pm 1.2_{\text{syst}}) \times 10^{-4} \text{ fm}^3 \), \( \chi \text{PT}: a_\pi \approx 2.8 \times 10^{-4} \text{ fm}^3 \)


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COMPASS preliminary result for pion polarizability is the most precise among dedicated measurements
Is $a_\pi$ really a constant in our kinematic range?


\[ t = (P_{0\pi} - P_\pi)^2 \]

\[ a_\pi(t) = a_{\pi \, ch} \chi(t) \]

\[ a_{\pi \, ch} = 5.8 \times 10^{-4} \text{ fm}^3 \]

$m_\sigma$ - parameter of the model

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Primakoff data collected in 2012 provide possibility:

- to reduce uncertainty of $a_\pi$ measurement to $\sim 0.4 \times 10^{-4} \text{ fm}^3$
- to measure $a_\pi + \beta_\pi$ with accuracy $\sim 0.04 \times 10^{-4} \text{ fm}^3$ ($\chi$PT: 0.16)
- to study dynamics of pion polarizabilities $a_\pi = a_\pi(s, t, \ldots)$
- to access quadrupole polarizabilities of pion $a_{\pi 2}$ and $\beta_{\pi 2}$

>200k of $\pi\nu$ events with $E_\gamma/E_{\text{beam}} > 0.4$
Kaon polarizabilities

Theoretical predictions:
$\chiPT$ prediction $O(p^4)$:
\[
\alpha_K + \beta_K = 0
\]
\[
\alpha_K = \alpha_\pi \times \frac{m_\pi F_\pi^2}{m_K F_K^2} \approx \frac{\alpha_\pi}{5} \approx 0.6 \times 10^{-4} \text{fm}^3
\]

Quark confinement model:
\[
\alpha_K + \beta_K = 1.0 \times 10^{-4} \text{fm}^3
\]
\[
\alpha_K = 2.3 \times 10^{-4} \text{fm}^3
\]

Experimental results:
\[
\alpha_K = (-4 \pm 11) \times 10^{-4} \text{fm}^3
\]
- from kaonic atoms spectra

At COMPASS:
• ~2.4% of kaons in hadron beam
• CEDARs for beam kaons identification

Polarization effects
$\sim m^3$

$\sigma_{Prim} \sim \frac{1}{m^2}$

1 $K\gamma$ event per 500 $\pi\gamma$
**$\alpha_{\pi}$ at JLab (proposal)**

Existing detector

**GlueX at Hall-D**

- Polarized photons of ~6 GeV
- $10^7$ tagged photons per second
- 0.6 mm $^{106}$Sn target
- 20 days of data taking
- Accuracy $0.3 \times 10^{-4}$ fm$^3$

**Main physical backgrounds:**
- pion pair production in strong interaction
- coherent $\rho^0$ production
- production of lepton pairs

Approved by JLab PAC

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Summary

The COMPASS experiment performed the most precise measurement of pion polarizability $a_\pi$ under assumption $a_\pi + \beta_\pi = 0$ basing on the data of 2009 year.

The result is:

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

This result is published in Physical Review Letters: **PRL 114 (2015) 06002**

Contribution of JINR group to this result is determinative at each stage from planning to data taking and analysis.

COMPASS Primakoff data of 2012 still are under analysis and new results for pion (and kaon) polarizabilities are expected.
Backup slides
Backup slides

Polarisability and Loop Contributions \( z = -1.0 \)

- \( \sigma/\sigma_{\text{Born}} \)
- \( \sqrt{s/m_{\pi}} \)
- Chiral loops, \( \alpha = 0.00 \)
- LEX \( \alpha = \beta = 2.00 \)
- LEX \( \alpha = \beta = 2.85 \)
- LEX + chiral loops
- DR [B. Pasquini]
- LEX(\( \alpha = 2 \)) + chiral loops
- LEX(\( \alpha = 0 \)) + chiral loops

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