Workshop on Future Physics @ COMPASS

Measurement of electric and magnetic $\pi$ and $K$ polarizability

@ COMPASS

Marialaura Colantoni on behalf of the COMPASS coll.
**Polarizability**

The polarizability (electric $\alpha$ and magnetic $\beta$) relates the average dipole (electric $\vec{p}$ and magnetic $\vec{\mu}$) moment to external electromagnetic field.

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

The *polarizability* is a quantity which characterizes a particle like its charge, radius, magnetic moment etc.
The pion polarizabilities can be described in the framework of the Chiral perturbation Theory ($\chi PT$) based on the chiral symmetry of QCD and Goldstone theorem.

Chiral dynamics describes:

- properties
- production
- decay amplitudes
- low-energy interactions of the Goldstone boson ($\pi, \eta, K$) among themselves and with $\gamma$'s.
Pion polarizabilities

The $\chi PT$ provide a rigorous way to determine $\alpha_\pi$, $\beta_\pi$ via the effective Chiral lagrangian using the coupling constants $L_9^r$, $L_{10}^r$ obtained in the radiative pion beta decay ($\pi^- \rightarrow e + \bar{\nu} + \gamma$):

$$\overline{\alpha}_\pi = \frac{4\alpha f}{m_\pi f_\pi^2} (L_9^r + L_{10}^r)$$

the numerical values are:

$$\overline{\alpha}_\pi = (2.4 \pm 0.5)10^{-4} \, fm^3$$

$$\overline{\beta}_\pi = (-2.1 \pm 0.5)10^{-4} \, fm^3$$

consistent with the chiral symmetry $(\overline{\alpha}_\pi + \overline{\beta}_\pi) = 0$.

Measurements of pion polarizability

Photon-Photon Collision:

- From the results of the MARK II group (1990)[1] with the reaction
  \[ \gamma + \gamma \rightarrow \pi^- + \pi^+ \]
  the value of
  \[ \alpha_\pi = (2.2 \pm 1.6_{stat+sys}) \times 10^{-4} \text{ fm}^3 \]
  was deduced [2].


Measurements of pion polarizability

Pion Photoproduction:

- A test made by the Lebedev group (1986) with the reaction 
  \[ \gamma + p \rightarrow \gamma + \pi^+ + n \] 
  showed feasibility.

High precision measurement made @ MAMI (A2 coll.). Data analysis is in progress.
Measurements of pion polarizability

We want to use

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

the Primakoff Reaction
The Primakoff reaction

For the reaction:

\[ \pi + Z \rightarrow \pi' + Z + \gamma \]

one measures the Primakoff cross section

\[
\frac{d^3\sigma}{dt\,d\omega\,d\cos\theta} = \frac{\alpha_f Z^2}{\pi \omega} \frac{t-t_0}{t^2} \frac{d\sigma_{\pi\gamma}(\omega,\theta)}{d\cos\theta} |F_A(t)|^2
\]

\( \omega \) photon energy in the antilab system

\( t = (p'_2 - p_2)^2 \)

\( t_0 = \left( \frac{m_\pi \omega}{p_{beam}} \right)^2 \)

\( \theta \) real photon scattering angle

\[
\frac{d\sigma_{\pi\gamma}(\omega,\theta)}{d\cos\theta} = \frac{2\pi \alpha_f^2}{m_\pi^2} \cdot \left( F_{\pi\gamma}^T h + \frac{m_\pi \omega^2}{\alpha_f} \cdot \frac{\alpha_\pi (1+\cos^2\theta)+\beta_\pi \cos\theta}{(1+\frac{\omega}{m_\pi} (1-\cos\theta))^3} \right)
\]

\( \alpha_\pi, \beta_\pi \) pion electric and magnetic polarizability
Measurement via Primakoff reaction

- The Serpukhov group (1985) with the Primakoff reaction

\[
\pi + Z \rightarrow \pi + \gamma + Z \text{ at } 40 \text{ GeV obtains:}
\]

\[\alpha_{\pi} = (6.8 \pm 1.4_{\text{stat}} \pm 1.2_{\text{sys}}) \times 10^{-4} \text{ fm}^3[1]\]

with the hypothesis \((\alpha_{\pi} + \beta_{\pi}) = 0\) and

\[\beta_{\pi} = (-7.1 \pm 2.8_{\text{stat}} \pm 1.8_{\text{sys}}) \times 10^{-4} \text{ fm}^3\]

\[(\alpha_{\pi} + \beta_{\pi}) = (1.4 \pm 3.1_{\text{stat}} \pm 2.5_{\text{sys}}) \times 10^{-4} \text{ fm}^3[2]\]


The goals

\[ p_{beam} = 190 \text{ GeV/c} \] to increase the ratio of the coulombian/nuclear cross section

Higher Z target \[ \rightarrow \sigma(Z^2) \]

Our goals:

- measure independently \((\alpha + \beta), \alpha, \beta\)
- enough statistics:
  - to get the statistical errors negligible versus the systematic ones
  - evaluate systematic error due to different cuts
  - more complete angular distribution
- higher energy \[ \rightarrow \text{smaller } t \rightarrow \text{to fit} \]

Compass acceptance

- \(\sigma(p_T) \approx 15 \text{ MeV/c} \) like in the Antipov experiment:

\[ N_{ev} \]
Trigger: \( \text{Hodoscope} \times \text{ECAL2} \)

\[ \pi^- \quad \gamma \]
Flow diagram of the simulation

POLARIS
the generator

↓

COMGEANT:
the simulation program based on Geant 3.21

↓

CORAL:
COmpass Reconstruction and Analysis Library.
The generator

- Target $^{208}$Pb
- Thickness $0.3 \times X_0 = 1.7 \, mm$
- $\bar{\alpha}_\pi = -\bar{\beta}_\pi = 6.8 \cdot 10^{-4} \, fm^3$

- $t < 850 \, MeV^2$
- $1.05 \cdot m^2_\pi < s_1 < 30 \cdot m^2_\pi$
- $E_\gamma > 90 \, GeV$
**Primakoff event reconstruction:** \( E_\gamma > 90\text{GeV} \)

Trasversal component of four-momentum transfer

\[
\sigma_{p_x} = \sigma_{p_y} = 13 \text{ MeV}/c \\
\sigma_{p_T} = 18\text{ MeV}/c
\]
The efficiency $= \frac{N_{\text{rec}}}{N_{\text{gen}}}$

Constant
efficiency vs $t$

![Graph showing efficiency vs $t_{MC}$ (GeV$^2$)]
Primakoff event reconstruction

Pair (\(\pi\gamma\)) total energy

The \(t\) variable

\[
E_{\text{tot}} = E_{\pi} + E_{\gamma} \quad [\text{GeV}]
\]

\[
t \quad [\text{MeV}^2]
\]
### Comparison with the Serpukhov data

<table>
<thead>
<tr>
<th></th>
<th>@ Serpukhov</th>
<th>@ COMPASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam momentum</td>
<td>40 GeV/c</td>
<td>190 GeV/c</td>
</tr>
<tr>
<td>beam intensity</td>
<td>10^6/spill</td>
<td>4 \times 10^7/spill</td>
</tr>
<tr>
<td>target</td>
<td>Z &lt; Fe</td>
<td>Pb</td>
</tr>
<tr>
<td>scattered pion</td>
<td>\sigma_\Theta \approx 0.12 mrad</td>
<td>\sigma_\Theta \approx 0.04 mrad</td>
</tr>
<tr>
<td></td>
<td>\sigma_p/p \approx 1%</td>
<td>\sigma_p/p \approx (0.3 \div 1)%</td>
</tr>
<tr>
<td>outgoing gamma</td>
<td>\sigma_\Theta \approx 0.15 mrad</td>
<td>\sigma_\Theta \approx 0.031 mrad</td>
</tr>
<tr>
<td></td>
<td>\sigma_E/E \approx 3.5%@ 27 GeV</td>
<td>\sigma_E/E \approx 2%@ 120 GeV</td>
</tr>
<tr>
<td>total flux</td>
<td>10^{11}</td>
<td>\approx 3 \times 10^{11}/day</td>
</tr>
<tr>
<td>primakoff events</td>
<td>6 \times 10^3</td>
<td>4 \times 10^5/day</td>
</tr>
</tbody>
</table>
Polarizabilities Statistics

With a $2 \cdot 10^7 \, \pi / s$, the spill structure is 5 sec beam every 16 sec, $3.2 \cdot 10^{11} \, \pi$ are expected per day.

The interaction probability $R = \sigma N_T = 5 \cdot 10^{-6}$ assuming:

- $\sigma = 0.5 \, mbarn$
- $N_T = 10^{22} \, cm^{-2}$

The global efficiency is estimated to be $\epsilon = 24\%$ due to:

- tracking efficiency 92%
- gamma detection 58%
- combined acceptance of COMPASS and SPS 60%
- analysis cut to reduce backgrounds 75%

$$3.2 \cdot 10^{11} \times 5 \cdot 10^{-6} \times 0.24 = 4 \cdot 10^5 \, Events/day$$
Summary & Outlook

Serpukhov:

$Z^2$ dependence

$$R = \frac{d\sigma}{d\omega}^{\text{(extended)}} \frac{d\sigma}{d\omega}^{\text{(pointlike)} \text{th}}$$
Compass:

- Different targets: $\rightarrow Z^2$ dependence in the cross section.
- Also interesting a comparison with a pointlike particle with the reaction: $\mu^- + Z \rightarrow \mu^- + Z + \gamma$
- Constant efficiency on $t$
- Statistics $10^3$ times better $\rightarrow$ overall resolution 3 times better

$$\delta \bar{\alpha}_\pi \approx 0.4 \cdot 10^{-4} \, fm^3 \left( \approx \sigma_{\text{theory}} \right)$$

- Polarizability measurements for $K^-$ are possible.
Kaon polarizability

The cross section scales down as $m^{-1} \rightarrow$ 3 times smaller compared to the $\pi$ one,

the polarizability goes as $\overline{\alpha}_h = \frac{4\alpha_f}{m_h F_h^2} (L_r^9 + L_r^{10}) \rightarrow \overline{\alpha}_K = \frac{\overline{\alpha}_\pi}{5.4}$

**Assume**

- $3 \times 10^5$ Kaon/sec @ 190 GeV/c
- $60 < \omega < 300$ MeV to avoid $K^*$ 1st excited state

overall resolution $\delta \overline{\alpha}_K = 0.6 \cdot 10^{-4} \text{ fm}^3$

$2 \cdot 10^4 \text{ events/day}$
\[ F_{3\pi} \text{ measurement} \]

\[ t = (p_1 - p_2)^2 \]
\[ s = (p_2 + p_3)^2 \]
\[ q_{\text{min}}^2 = \left( \frac{s - m_{\pi}}{2E} \right)^2 \]
\[ \pi^- + Z \rightarrow \pi^- + \pi^0 + Z \text{ useful to access } \gamma \rightarrow 3\pi \]

\[ F_{3\pi} \text{ allow to verify the low energy theorem: } \]
\[ F_{3\pi}(0) = \frac{F_{\pi}(0)}{ef^2} \]

\[ \frac{d\sigma}{dsdtdq^2} = \frac{Z^2 \alpha \sigma_f}{\pi} \left( \frac{q^2 - q_{\text{min}}^2}{q^4} \right) \frac{1}{s - m_{\pi}^2} \frac{d\sigma_{\gamma \pi \rightarrow \pi \pi}}{dt} \]

\[ \frac{d\sigma_{\gamma \pi \rightarrow \pi \pi}}{dt} = \frac{F_{3\pi}^2}{128\pi} \frac{1}{4} \left( s - 4m_{\pi}^2 \right) \sin^2 \theta \]

\[ F_{3\pi} = (12.9 \pm 0.9 \pm 0.5) \text{GeV}^{-3} \ [1] \quad F_{3\pi} = (9.7 \pm 0.2) \text{GeV}^{-3} \ [2] \]

**Expected \approx 5 \cdot 10^3 \text{ events/day vs } \approx \text{ 200 Serpukov events in total.}**


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Conclusions

Using **COMPASS** spectrometer one can measure:

- pion polarizabilities with an uncertainty of the same order of the theoretical one
- kaon polarizabilities for the 1\textsuperscript{st} time with the Primakoff reaction
- the chiral anomaly amplitude for the $\gamma \rightarrow 3\pi$

\[\text{Diagram:} F_{\pi} \rightarrow \gamma \rightarrow F_{3\pi} \quad \gamma \rightarrow \pi \rightarrow \pi \]