Radiative Coupling of $a_2(1320)$ and $\pi_2(1670)$

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for the COMPASS collaboration

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Πάφος, Κύπρος
Why Radiative Couplings?

- Radiative coupling “map” wave functions of the involved particles (known transition matrix element)
  → Information of shape and inner structure of the meson resonances
- Related e.g. to $\pi \rho$ decay channels (vector meson dominance)
Outline

- Investigation of $\pi^-\gamma$ coupling through high-$E$ hadron scattering
  - Primakoff reactions
  - higher-order aspects
- The apparatus: COMPASS
- Partial-wave analysis for identification of resonance contributions
High-\(E\) Reactions: Momentum Transfer Regimes

- Small momentum transfer \(\Leftrightarrow\) large impact parameter in coordinate space
- At large distance: long-range \(EM\) potential dominates
- missing at this step:
  \(EM\) at higher order, finite size of nucleus, strong interaction
$EM$ at higher order

- corresponds to “multiple-photon exchange”, but e.g. for lead $Z \alpha \approx 0.6$
- main effect (at low $Q^2$): distortion of the wave function in the potential, calculable in Glauber (eikonal) approach
EM scattering becomes complex-valued, “Coulomb phase”
(∼ loops over resonance contributions)
no observable effect for elastic scattering on static (heavy-mass) target
Within the Glauber model

- also the charge extension (as modified potential) can be taken into account
- drawbacks: *e.g.* neglect of recoil, not QFT
at the same level, the (absorptive) nuclear potential can be taken into account → diffractive regime

exchange “particle” (Pomeron) ⇔ Fourier transform of potential
with a high-energy pion beam on nuclei, $\pi\gamma$ reactions become accessible

identification as a strong increase of cross-section at smallest $Q^2$, Primakoff effect
COmmon Muon and Proton Apparatus for Structure and Spectroscopy
CERN SPS: protons \( \sim 400 \text{ GeV} \) (5 – 10 sec spills)

- secondary \( \pi, K, \bar{\rho} \): up to \( 2 \cdot 10^7 / \text{s} \)
- tertiary muons: \( 4 \cdot 10^7 / \text{s} \)
  2002-04, 2006-07, 2010-11: spin structure of the nucleon
Fixed-target experiment

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

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


- 190GeV $\pi^-$ beam on nuclear targets (Ni, W)
- Silicon microstrip detectors for “vertexing”
- (digital) ECAL trigger
Principle of the measurement

- Trigger on multiplicity of charged forward tracks or on energy deposit in EM calorimeter
- Kaon component of the beam identified in Cerenkov detectors
- Free decay of beam $K^- \rightarrow \pi^- \pi^0$, $\pi^- \pi^0 \pi^0$ and $\pi^- \pi^- \pi^+$ allows for cross-section normalization
Access to $\pi + \gamma$ reactions via the Primakoff effect:

At smallest momentum transfers to the nucleus, high-energetic particles scatter predominantly off the electromagnetic field quanta ($\sim Z^2$)

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

analogously: 

$K^- + \gamma \rightarrow \ldots$
Primakoff technique: pion polarisability

- Charged pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{Ni}$: $E \sim 300$ kV/fm

- Bremsstrahlung emission
  - particle scatters off equivalent photons (Weizsäcker-Williams)
  - pion (or muon) Compton scattering

- Polarisability contribution
  - Compton cross-section typically diminished
  - Theory prediction: $\alpha_{\pi}^{\text{ChPT}} = 2.9 \pm 0.5 \cdot 10^{-4}$ fm$^3$
  - expected charge separation $\sim 10^{-5}$ fm $\cdot$ e
### Pion polarisability at COMPASS

<table>
<thead>
<tr>
<th>Source of Systematic Uncertainty</th>
<th>Estimated Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL = 68% [10^{-4} fm^3]</td>
<td>0.6</td>
</tr>
<tr>
<td>Tracking</td>
<td>0.3</td>
</tr>
<tr>
<td>Radiative corrections</td>
<td>0.4</td>
</tr>
<tr>
<td>Background subtraction in Q</td>
<td>0.2</td>
</tr>
<tr>
<td>Pion electron scattering</td>
<td>0.2</td>
</tr>
<tr>
<td>Quadratic Sum</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**COMPASS preliminary:**

\[
\alpha_\pi = 1.9 \pm 0.7_{\text{stat}} \pm 0.8_{\text{syst}} \times 10^{-4} \text{ fm}^3
\]
ΔQ_T \approx 12 \text{ MeV/c} \ (190 \text{ GeV/c beam} \rightarrow \text{requires few-μrad angular resolution})

- first diffractive minimum on Ni nucleus at Q \approx 190 \text{ MeV/c}
Coulomb-nuclear interference

Photon density squared form factor

- Calculation following a 2009 paper of G"oran F"aldt (Uppsala)
- Eikonal approximation: pions cross Coulomb and strong-interaction potentials
Access to $\pi + \gamma$ reactions via the Primakoff effect:

*At smallest momentum transfers* to the nucleus, high-energetic particles scatter predominantly off the electromagnetic field quanta ($\sim Z^2$)

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

*analogously: Kaon-induced reactions* $K^- + \gamma \rightarrow \cdots$
Three charged-pions final state

\[ \pi^- \text{Pb} \rightarrow \text{Pb} \pi^- \pi^- \pi^+ \]

- "Low \( t' \)":\n  \[ 10^{-3} \text{(GeV/c)}^2 < t' < 10^{-2} \text{(GeV/c)}^2 \]
  \( \sim 2000000 \) events

- "Primakoff region":\n  \[ t' < 10^{-3} \text{(GeV/c)}^2 \]
  \( \sim 1000000 \) events
First Measurement of $\pi\gamma \rightarrow 3\pi$ Absolute Cross-Section

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

$\sigma_\gamma$ [\mu b]

COMPASS 2004

$\pi^- \gamma \rightarrow \pi^- \pi^- \pi^+$

from $\pi^- \text{Pb} \rightarrow \pi^- \pi^- \pi^+ \text{Pb}$

- Fitted ChPT Intensity
- Leading Order ChPT Prediction

Full Systematic Error
Luminosity Uncertainty

Published in PRL 108 (2012) 192001
Higher-order effects

Chiral loops, e.g.
(N. Kaiser, NPA848 (2010) 198)
2004 Primakoff results on the resonances

\[ \pi^- \text{ Pb} \rightarrow \text{Pb} \, \pi^- \, \pi^- \, \pi^+ \]

- "Low \( t' \)": \( 10^{-3} \text{ (GeV/c)}^2 < t' < 10^{-2} \text{ (GeV/c)}^2 \) \( \sim 2000000 \) events
- "Primakoff region": \( t' < 10^{-3} \text{ (GeV/c)}^2 \) \( \sim 1000000 \) events
2004 Primakoff results on the resonances

\[ \pi^- \text{Pb} \rightarrow \text{Pb} \pi^- \pi^- \pi^+ \]

**COMPASS 2004**

\[ \pi \text{Pb} \rightarrow \pi \pi \pi^+ \text{Pb} \]

**PWA of**

\[ a1(1260), a2(1320) \]

**contributions**

in **t slices**

- **"Low \(t'\)"**: \(10^{-3} \text{ (GeV/c)}^2 < t' < 10^{-2} \text{ (GeV/c)}^2\) \(\sim 2000000 \text{ events}\)
- **"Primakoff region"**: \(t' < 10^{-3} \text{ (GeV/c)}^2\) \(\sim 1000000 \text{ events}\)
PWA: $a_1$, $a_2$ and $\Delta \Phi$ in separated $t'$ regions
Phase $a_2 - a_1$ in detail: $t'$ dependence

- Transition of $\pi \gamma$ to $\pi IP \rightarrow a_2$ production
- Work in progress
- Interference can be used to map details of resonances and production mechanisms
Primakoff production of $a_1(1260)$ vs. E272 result

No evidence for $a_1(1260) \rightarrow \pi\gamma$

M. Zielinski et al, Phys.Rev.Lett.vol.52, 14, 1195
Spin-exotic $1^{-+}$

No evidence for $\pi_1(1600)$ Primakoff production
Radiative Coupling of $a_2(1320)$ and $\pi_2(1670)$

\[ \Gamma_0(a_{2}(1320) \rightarrow \pi \gamma) \quad M2 \quad \Leftrightarrow \quad \text{meson w.f.'s: } \Gamma_{i \rightarrow f} \propto \left| \langle \psi_f | e^{-i \mathbf{q} \cdot \hat{r}} \quad \hat{e} \cdot \mathbf{p} | \psi_i \rangle \right|^2, \text{ VMD} \]

- normalization via beam kaon decays
- large Coulomb correction

\[ \Gamma_0(\pi_2(1670) \rightarrow \pi \gamma) \quad E2 \]
Coulomb and extended-charge correction


Effect on $a_2(1320)$ radiative width:

- form factor alone: +6.5%
- Coulomb correction alone: +26.0%
- combined: +22.2%
Radiative widths - experiment and theory

<table>
<thead>
<tr>
<th></th>
<th>(a_2(1320))</th>
<th>(\pi_2(1670))</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPASS preliminary</td>
<td>((358 \pm 6 \pm 42)) keV</td>
<td>((181 \pm 11 \pm 27)) keV \cdot \frac{0.56}{\text{BR}_{f_2\pi}}</td>
</tr>
<tr>
<td>COMPASS (F_{\text{eff}}^2 = j_1^2) prel.</td>
<td>((312 \pm 6)) keV</td>
<td>((151 \pm 9)) keV \cdot \frac{0.56}{\text{BR}_{f_2\pi}}</td>
</tr>
<tr>
<td>SELEX(^1)</td>
<td>((284 \pm 25 \pm 25)) keV</td>
<td></td>
</tr>
<tr>
<td>S. Cihangir et al.(^2)</td>
<td>((295 \pm 60)) keV</td>
<td></td>
</tr>
<tr>
<td>E. N. May et al.(^3)</td>
<td>((460 \pm 110)) keV</td>
<td></td>
</tr>
<tr>
<td>VMD model(^4)</td>
<td>((375 \pm 50)) keV</td>
<td></td>
</tr>
<tr>
<td>Relativ. Quark model(^5)</td>
<td>324 keV</td>
<td></td>
</tr>
<tr>
<td>Cov. Osc. Quark model(^6)</td>
<td>235 keV</td>
<td></td>
</tr>
<tr>
<td>Cov. Osc. Quark model(^7)</td>
<td>237 keV</td>
<td>335 keV / 521 keV</td>
</tr>
</tbody>
</table>

Summary and Outlook

- **Measurement of the pion polarisability at COMPASS**
  - Most precise experimental determination
  - Systematic control: $\mu \gamma \rightarrow \mu \gamma, \ K^- \rightarrow \pi^- \pi^0$

- **Chiral dynamics in $\pi \gamma \rightarrow \pi \pi \pi$ reactions**
  - Charged-channel $\pi \gamma \rightarrow \pi^- \pi^- \pi^+$ tree-level ChPT prediction confirmed,
  - Neutral-channel $\pi \gamma \rightarrow \pi^- \pi^0 \pi^0$ analysis ongoing

- **Radiative coupling of meson resonances**
  - Radiative width for $a_2(1320)$
    roughly in agreement with earlier experimental determinations
  - First measurement of the radiative width for $\pi_2(1320)$,
    order of magnitude as expected from theoretical models
  - no significant radiative coupling for $a_1(1260)$ or $\pi_1(1600)$

- **Future**
  - analysis of 2009 data for $\pi^- \pi^0 \pi^0$
  - investigation of Coulomb-nuclear interference
  - COMPASS 2012 run with high statistics for neutral channels:
    separate determination of $\alpha_\pi$ and $\beta_\pi$, quadrupole polarisabilities,
    measurement of $\alpha_K$