Hadron Spectroscopy & Primakoff Reactions at COMPASS

Jan Friedrich
TU München

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Investigation of the strong interaction where it is strong

- Formation of bound states of quarks and gluons
  → hadron spectroscopy
  COMPASS: high-statistics meson spectroscopy

- Hadron reactions at low relative momenta
  → manifestation of QCD by its symmetries
  COMPASS: pure pion-photon (Primakoff) reactions
Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- > 1 PByte/year
Physics goals: **Hadron spectroscopy**

- 190 GeV/$c$ secondary hadron beams
  - $h^-$ beam: 97% $\pi^-$, 2% $K^-$, 1% $\bar{p}$
  - $h^+$ beam: 75% $p$, 24% $\pi^+$, 1% $K^+$
- Various targets: $\ell H_2$, C, Ni, Cu, Pb, W
Spin-parity rules for bound $q\bar{q}'$ system
Spin-parity rules for bound $q\bar{q}'$ system

- Quark spins couple to total intrinsic spin $S = 0$ (singlet) or 1 (triplet)
- Relative orbital $\vec{L}$ and $\vec{S}$ couple to meson spin $\vec{J} = \vec{L} + \vec{S}$

![Diagram](image)
Spin-parity rules for bound $q\bar{q}'$ system

- Quark spins couple to total intrinsic spin $S = 0$ (singlet) or 1 (triplet)
- Relative orbital $\vec{L}$ and $\vec{S}$ couple to meson spin $\vec{J} = \vec{L} + \vec{S}$
- Parity $P = (-1)^{L+1}$
- Charge conjugation $C = (-1)^{L+S}$
- **Forbidden $J^{PC}$ combinations:** $0^{--}, 0^{+-}, 1^{-+}, 2^{++}, \ldots$
Mesons in the Constituent Quark Model

Spin-parity rules for bound $q\bar{q}'$ system

- Quark spins couple to total intrinsic spin $S = 0$ (singlet) or 1 (triplet)
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QCD allows for states beyond the CQM

- Hybrid $|q\bar{q}g\rangle$, Glueball $|gg\rangle$, Multi-quark states $|q^2\bar{q}^2\rangle$, ...
- Physical mesons: superposition of all allowed basis states
- “Exotic” mesons with $|q\bar{q}\rangle$-forbidden $J^{PC}$
Production of Hadrons in Diffractive Dissociation

- Soft scattering of beam hadron off nuclear target
  - Excitation into resonance $X$
  - $X$ decays into $n$-body final state
Production of Hadrons in Diffractive Dissociation

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Production of Hadrons in Diffractive Dissociation

- **Soft scattering** of beam hadron off nuclear target
  - Excitation into resonance $X$
  - $X$ decays into $n$-body final state

- At high energies **Pomeron exchange** dominates
- Use kinematic distribution of outgoing particles
  - Disentangle all resonances $X \rightarrow$ mass, width, $I^G J^{PC}$
  - **Method**: partial-wave analysis (PWA)
**Isobar model:** $X^-$ decay is chain of successive two-body decays

- Isobar with **spin** $S$ and bachelor $\pi^-$ have **relative orbital** $L$
  - $L$ and $S$ couple to **spin** $J$ of $X^-$
- **“Wave”:** unique combination of isobar and quantum numbers, specified by $J^{PC}M^\epsilon[\text{isobar}]L$
- **PWA:** disentangle waves using the **angular distributions** and interference
2004 Pilot Run: PWA of $\pi^-\pi^-\pi^+$ f.s. PRL 104 (2010) 241803

$\pi^-\pi^-\pi^+$ mass spectrum

![Mass Spectrum Graph](image-url)
2004 Pilot Run: PWA of $\pi^-\pi^-\pi^+$ f.s.

$\pi^-\pi^-\pi^+$ mass spectrum

$1^{++}0^+ [\rho\pi] S \ a_1(1260)$
2004 Pilot Run: PWA of $\pi^-\pi^-\pi^+$ f.s.  

$\pi^-\pi^-\pi^+$ mass spectrum

$1^{++}0^+[\rho\pi]S \ a_1(1260)$

$2^{++}1^+[\rho\pi]S \ a_2(1320)$
$\pi^-\pi^-\pi^+$ mass spectrum

$2^{-+}0^+[f_2\pi]S \pi_2(1670)$

$1^{++}0^+[\rho\pi]S a_1(1260)$

$2^{-+}0^+[f_2\pi]S \pi_2(1670)$

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2004 Pilot Run: PWA of $\pi^-\pi^-\pi^+$ f.s.

$\pi^-\pi^-\pi^+$ mass spectrum

$2^{-+}0^+[f_2\pi]S\ a_2(1670)$

$1^{++}0^+[\rho\pi]S\ a_1(1260)$

$2^{++}1^+[\rho\pi]S\ a_2(1320)$

$2^{-0}f_2\pi S$
Pb target

Data described by model consisting of 41 waves + incoherent isotropic background

- Isobars: $(\pi\pi)_S$, $f_0(980)$, $\rho(770)$, $f_2(1270)$, and $\rho_3(1690)$
2004 Pilot Run: PWA of $\pi^-\pi^-\pi^+$ f.s.  

**Spin-exotic $1^{-+}1^{+}[^{\rho\pi}]P$**

$1^{-+}1^{+}[^{\rho\pi}]P$

$1^{++}0^{+}[\rho\pi]S \quad a_1(1260)$

- Significant $1^{-+}$ amplitude
2004 Pilot Run: PWA of $\pi^-\pi^-\pi^+ \ f.s.$

Spin-exotic $1^{-+}1^+[\rho\pi]P$

$2^{-+}0^+[f_2\pi]\ S \ \pi_2(1670)$

$1^{-+}1^+[\rho\pi]P - 2^{-+}0^+[f_2\pi]\ S$

- Significant $1^{-+}$ amplitude
- $\pi_1(1600)$ BW + backgr.

$m = 1.660 \pm 10^{+0}_{-64}\ MeV/c$

$\Gamma = 269 \pm 21^{+42}_{-64}\ MeV$

Intensity: $(1.7 \pm 0.2^{+0.9}_{-0.1})\%$
2008 Data using H$_2$ Target

$\pi^-$ diffraction into $\pi^-\pi^-\pi^+$ final state

- **Spectrometer upgrade**: recoil proton detector, beam PID, calorimetry, tracking
- 190 GeV/c negative hadron beam: 97% $\pi^-$, 2% $K^-$, 1% $\bar{p}$
2008 Data using H$_2$ Target

$\pi^-$ diffraction into $\pi^-\pi^-\pi^+$ final state

- **Spectrometer upgrade**: recoil proton detector, beam PID, calorimetry, tracking
- 190 GeV/c negative hadron beam: 97% $\pi^-$, 2% $K^-$, 1% $\bar{p}$
- 200× 2004 statistics: $\approx 10^8$ events $\Rightarrow$ challenging analysis

$\pi^-\pi^-\pi^+$ mass distribution

Dalitz plot for $\pi_2(1670)$ region
Isospin partner to $\pi^- p \rightarrow \pi^- \pi^- \pi^+, p$

- Important consistency check
- Comparison with $\pi^- \pi^- \pi^+$: normalization to $a_2(1320)$

### Mass Distributions

**Left Panel:** $\pi^- \pi^0 \pi^0$ mass distribution

- $a_1(1320)$
- $a_1(1260)$
- $\pi_d(1670)$

**Right Panel:** $\pi^- \pi^+ \pi^-$ mass distribution

- $a_1(1260)$
- $a_2(1320)$
- $\pi_d(1670)$
Diffractive Dissociation into $\pi^- \pi^0 \pi^0$ Final State

Isospin partner to $\pi^- p \rightarrow \pi^- \pi^- \pi^+, p$

- Important consistency check
- Comparison with $\pi^- \pi^- \pi^+$: normalization to $a_2(1320)$
- Isospin symmetry: $I = 1$ isobar $\Rightarrow$ same intensity
  $I = 0$ isobar $\Rightarrow$ half intensity

$1^{++}[\rho\pi]S$: $a_1(1260)$

$2^{-+}[f_2\pi]S$: $\pi_2(1670)$
Production mechanism depends on $t$ region

- $0.1 < t < 1 \text{GeV}^2/c^2$ scattering on individual nucleons

![Graph showing the number of events vs. Momentum Transfer $t'$ (GeV$^2$/c$^2$) with $0.1 < t < 1 \text{GeV}^2/c^2$]
Production mechanism depends on $t$ region

- $0.1 < t < 1\text{GeV}^2/c^2$ scattering on individual nucleons
- For $t \lesssim 0.01\text{GeV}^2/c^2$: coherent scattering on Pb nucleus

$t < 0.1\text{GeV}^2/c^2$

COMPASS 2004
$\pi\text{Pb} \rightarrow \pi\pi\pi'\text{Pb}$

Number of Events

$10^5$
$10^4$
$10^3$
$10^2$

Momentum Transfer $t'$ (GeV$^2$/c$^2$)

$0$
$0.01$
$0.02$
$0.03$
$0.04$
$0.05$
$0.06$
$0.07$
$0.08$
$0.09$
$0.1$

$0.1$
$0.2$
$0.3$
$0.4$
$0.5$
$0.6$
$0.7$
$0.8$
$0.9$
$1$

$0.1 < t < 1\text{GeV}^2/c^2$

COMPASS 2004
$\pi\text{Pb} \rightarrow \pi\pi\pi'\text{Pb}$

Number of Events

$10^3$

$10^2$

Momentum Transfer $t'$ (GeV$^2$/c$^2$)
2004 Pilot Run: PWA of $\pi^-\pi^-\pi^+$ Final State at low $t$

Production mechanism depends on $t$ region

- $0.1 < t < 1\text{GeV}^2/c^2$ scattering on individual nucleons
- For $t \lesssim 0.01\text{GeV}^2/c^2$: coherent scattering on Pb nucleus
- For $t \lesssim 10^{-3}\text{GeV}^2/c^2$ Coulomb contribution

$t < 0.1\text{GeV}^2/c^2$

COMPASS 2004
$\pi^0\text{Pb} \rightarrow \pi\pi\pi^0\text{Pb}$

$t < 10^{-3}\text{GeV}^2/c^2$

COMPASS 2004
$\pi^-\text{Pb} \rightarrow \pi\pi\pi^-\text{Pb}$
Test of chiral perturbation theory (ChPT)

- $\gamma\pi^- \rightarrow \pi^-\pi^-\pi^+$ for $m_{3\pi} < 700\text{MeV}/c^2$
  - ChPT parameter-free prediction [N. Kaiser, JF, EPJ A36 (2008) 181]

- $\pi^-\pi^-\pi^+$ Primakoff production at $t < 10^{-3}\text{GeV}^2/c^2$ probes strong interaction at low energies $\sim 100$ MeV

- Use PWA to extract strength of ChPT amplitude as function of $m_{3\pi}$
2004 Pilot Run: PWA of $\pi^-\pi^-\pi^+$ Final State at low $t$

First measurement of $\gamma\pi^- \rightarrow \pi^-\pi^-\pi^+$ cross section

- **Absolute cross section** from beam flux measurement
  - Using $K^- \rightarrow \pi^-\pi^-\pi^+$ decays of beam $K^-$ (2.4%)

![Graph showing COMPASS 2004 $\pi Pb \rightarrow\pi \pi \pi^+ Pb$ with $t' < 0.001$ GeV$^2$/c$^2$. ChPT Intensity and ChPT Prediction with full systematic error and luminosity uncertainty.](preliminary)

- **Data** confirm leading order ChPT calculation
COMPASS – Analyzed Hadron Beam Channels

- $\pi^−\pi^−\pi^+ \text{ large } t \text{ on various targets Pb, p, Ni, W}$ F. Haas
- $\pi^−\pi^−\pi^+\pi^−\pi^+ \text{ all } t$, 2004 Pb S. Neubert
- $\pi^−\pi^−\pi^+ \text{ low } t$ S. Grabmüller
- $\pi^−K\bar{K}$ T. Schlüter
- $p\pi^−\pi^+, pK^−K^+$ baryon spectroscopy A. Austregesilo
- $p_s p_f \pi^−\pi^+\pi^−\pi^+$ J. Bernhard
- $K^−\pi^−\pi^+$ P. Jasinski
- $K\bar{K}\eta, K\bar{K}\pi^0$ K. Schoenning
- $\pi^−\pi^0\pi^0 \text{ large } t$ F. Nerling, S. Pflüger
- $\pi^−\eta(\eta) \text{ large } t$ S. Uhl, I. Uman, T. Schlüter
- $\pi\gamma$ Primakoff T. Nagel, J.F., A. Guskov
Access to $\pi + \gamma$ reactions via the Primakoff effect:

At small momentum transfer to the nucleus, high-energetic particles scatter predominantly off the el.mag. field quanta ($\sim Z^2$)
Access to $\pi + \gamma$ reactions via the Primakoff effect:

At small momentum transfer to the nucleus, high-energetic particles scatter predominantly off the el.mag. field quanta ($\sim Z^2$)

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

analogously: Kaon-induced reactions $K^- + \gamma \rightarrow \cdots$
Key idea: Use Coulomb field of (heavy) nuclei as "photon target" for hadronic reactions

[H. Primakoff, Phys. Rev. 81 (1951) 899]
Electric charge at rest
Electric charge moving
Electromagnetic field
Weizsäcker-Williams Method

further reading: J. D. Jackson chapt. 11.10, 15.4
Low-\(t\) production mechanisms

- Production via \textit{photon} and strong (pomeron) exchange
  - separable by different \(t\)–dependence
- e.g. resonance \(a_2(1320)\) is produced both ways
  - radiative width
  - phase between the photon and strong amplitudes
Compton scattering and polarisability

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

Leading deviation from pointlike particle ↔ e.m. polarisability

for \( \alpha_\pi - \beta_\pi \) [10^{-4} fm^3]: \( (\alpha_\pi \approx -\beta_\pi) \)

ChPT: 5.7±1.0

experiments: 4 — 14
Experiments
Polarisability effect (LO ChPT values)

loop effects not shown

- - - $\alpha_\pi = 3.00, \beta_\pi = -3.00$
Polarisability effect (NLO ChPT values)

\[ \theta = \cos^{-1} \left( \frac{-0.8}{1} \right) \]

\[ \frac{d\sigma}{d\Omega_{cm}} \text{ [\mu b]} \]

\[ s = 3m^2 \]

\[ s = 5m^2 \]

\[ s = 8m^2 \]

\[ s = 15m^2 \]

\[ \alpha_{\pi} = 3.00, \beta_{\pi} = -2.86 \]

loop effects not shown
Polarisability effect (wrong sign $\alpha_\pi + \beta_\pi$)

Loop effects not shown

$$d\sigma/d\Omega_{\text{cm}} \, [\mu b]$$

- $s=3m^2_\pi$
- $s=5m^2_\pi$
- $s=8m^2_\pi$
- $s=15m^2_\pi$

$E_\gamma < 20 \text{ GeV}$

$\alpha_\pi = 3.00, \beta_\pi = -3.14$
loop effects not shown

\[ \frac{d\sigma}{d\Omega_{cm}} \, [\mu b] \]

\( s=3m_\pi^2 \)
\( s=5m_\pi^2 \)
\( s=8m_\pi^2 \)
\( s=15m_\pi^2 \)

\(- - - \alpha_\pi = 6.10, \beta_\pi = -6.10\)

\( E_\gamma < 20 \text{ GeV} \)
Nov. 2004

- recorded statistics (eff. 3 days) competitive to Serpukhov
- setup not final → large estimated systematic error
Polarisability measurements at COMPASS

Nov. 2004
- recorded statistics (eff. 3 days) competitive to Serpukhov
- setup not final → large estimated systematic error

Nov. 2009
- major upgrade of calorimeter readout, new digital trigger
- fine tuning / offline corrections ongoing

New proposal
COMPASS-II proposal for a high-statistics Primakoff run
increase statistics by a factor $\geq 30$,
uncertainty on $\alpha_{\pi^-} - \beta_{\pi^-}$: $\pm 0.66$ (ChPT: 5.7)
First measurement of polarisability sum $\alpha_{\pi^+} + \beta_{\pi^-}$
expected uncertainty $\pm 0.025$ (ChPT: 0.16)
### Polarisability measurements at COMPASS

#### Nov. 2004
- recorded statistics (eff. 3 days) competitive to Serpukhov
- setup not final → large estimated systematic error

#### Nov. 2009
- major upgrade of calorimeter readout, new digital trigger
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#### ≥ 2012
- [http://wwwcompass.cern.ch](http://wwwcompass.cern.ch) → New proposal
- COMPASS-II proposal for a high-statistics Primakoff run
- increase statistics by a factor $> 30$, uncertainty on $\alpha_\pi - \beta_\pi$: $\pm 0.66$ (ChPT: 5.7)
- First measurement of polarisability sum $\alpha_\pi + \beta_\pi$
  - expected uncertainty $\pm 0.025$ (ChPT: 0.16)
COMPASS 2004: few days with 190 GeV hadron beam
  - Primakoff: calorimetry problems
  - diffractive: spin-exotic $\pi_1$ observation (PRL104)
  - still harvesting: chiral $\gamma\pi \rightarrow \pi^-\pi^-\pi^+$, radiative couplings ($a_2,...$), Pomeron/Photon interference

2008 and 2009 data with extended spectrometer
  - huge statistics on diffractive scattering (H, Pb, Ni)
  - central production with $p$ beam
  - Primakoff on Ni $\rightarrow$ pion polarisability result upcoming

Future Primakoff run
  - determine $\alpha_\pi$ and $\beta_\pi$ pion polarisabilities independently, first value for forward polarisability $\alpha_\pi + \beta_\pi$
  - first experimental value for the Kaon polarisability
Kinematics of the Primakoff Compton Reaction

Cross section small, a-b significant

Cross section large, polarisability effect small

\( \sqrt{s}/m_{\pi} \)

\( \cos \theta_{CM} \)

\( \frac{d\sigma}{d\sqrt{s} \, dc\cos\theta_{CM}} \)
Estimated errors on 20,000 Primakoff events

\[ \frac{d\sigma}{d\Omega_{\text{cm}}} \] [\mu b]

\[ s=3m_{\pi}^2 \]
\[ s=5m_{\pi}^2 \]
\[ s=8m_{\pi}^2 \]
\[ s=15m_{\pi}^2 \]

\[ \alpha_{\pi} = 3.00, \beta_{\pi} = -3.00 \]
Estimated errors on 500,000 Primakoff events

\[ \frac{d\sigma}{d\Omega_{\text{cm}}} \text{ [\(\mu b\)]} \]

\[ \cos \theta_{\text{cm}} \]

\[ s=3m_{\pi}^2, s=5m_{\pi}^2, s=8m_{\pi}^2, s=15m_{\pi}^2 \]

\[ E_\gamma < 20 \text{ GeV} \]

\[ \alpha_\pi = 3.00, \beta_\pi = -3.00 \]
Primakoff measurements: principle and goals

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

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

\(\pi / K\) on Ni with \(Q^2 < 10^{-3}\) GeV\(^2/c^2\) dominated by \(\gamma\)-exchange \(\leftrightarrow \sum p_T \approx 0\)

\[\pi / K + \gamma \rightarrow \begin{cases} 
\pi / K + \gamma & \rightarrow \text{polarisabilities} \\
\pi / K + \pi^0/\eta & \rightarrow \text{chiral anomaly} \\
\pi / K + \pi^0/\eta + \pi^0/\eta & \rightarrow \text{chiral tree & loops} \\
\pi / K + n \cdot [\pi / K]^\pm & \rightarrow \text{radiative couplings, exotics}
\end{cases}\]
Primakoff Compton: retrieving polarisabilities

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

\[
\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2 (s^2 z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha m_\pi^3 (s - m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)}. P
\]

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

- leading (non-pointlike) order: \( \alpha_\pi - \beta_\pi \)
  \[ \rightarrow \text{suppression of large } E_{\gamma}^{lab} \]

- next ("s-dependent") order: \( \alpha_\pi + \beta_\pi \) and