Partial Wave Analysis of HADES Data for Two-Pion Production in Pion-Nucleon Reactions

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Outline

1) Motivations for experiments with pion beams,
2) HADES detector,
3) Pion beam @ GSI,
4) Identification of $p\pi^-, n\pi^+\pi^-, p\pi^-\pi^0$ channels,
5) Results of PWA (BGa) - focus on $\rho$ meson production,
6) Summary and outlook.
Main advantages of pion beams:

→ **selectivity:** resonances can be excited at given mass by choosing the beam (pion) momentum, HADES starts with \( \sqrt{s} = (1.46-1.55) \text{ GeV} \) - second resonance region,

→ \( \pi^+ \pi^-, \pi^- \pi^0 \) **production:** off-shell coupling of \( \rho \) to resonance, \( \rho \rightarrow \pi \pi \) (~100%) „golden channel”,

→ **BR** of resonances in the \( \rho \)-N decay and two-pion production channels,

→ **dilepton channel** \( R \rightarrow N \ e^+e^- \), never measured in pion induced reactions.

Unique possibility to investigate em. resonance decays via **combined** Partial Wave Analysis of hadronic channels and Dalitz decays → **see also B. Ramstein talk**
\( \pi N \rightarrow \pi \pi N \) status

Most of data 1.3 < s < 2 GeV from

- Manley et. al PRD30 (1984) 904, 241214 bubble chamber events analysed in isobar PWA model
- Very scarce data base for pion-nucleon reactions
- Differential distributions are even more scarce (or missing)
- More recent data (CHAOS@ TRIUMF) do not help for \( \pi^+ \pi^- \) in 1.3 < s < 2 GeV region

Recent post-Bubble Chamber measurements:

- 349,611 events for \( \pi^- p \rightarrow \pi^0 \pi^0 n \) from CB@BNL at \( W = 1213 \) to 1527 MeV. [S. Prakhov et al Phys Rev C 69, 045202 (2004)]
- 20,000 events for \( \pi^+ p \rightarrow \pi^+ \pi^- n \) from TRIUMF CHAOS@TRIUMF at \( W = 1257 \) to 1302 MeV. [M. Kermani et al PRC 58, 3431 (98)]
- 40,000 events for \( \pi^0 p \rightarrow \pi^0 \pi^0 n \) from ITEP at \( W = 2060 \) MeV. [I. Alekseev et al Phys At Nucl 61, 174 (1998)]

Can provide much higher statistics!
Hades Detector
High Acceptance Di-Electron Spectrometer

- Beams from SIS18: protons (1-4 GeV), nuclei (1-2 AGeV), pions (0.4-2 GeV/c) – secondary beam
- Spectrometer with $\Delta M/M$ - 2% at $\rho/\omega$
- PID: TOF/tracking
- Electrons: RICH (hadron blind), TOF/Pre-Shower
- Momenta, angles: MDC+ magnetic field
- Full azimuthal, polar angles $18^\circ - 85^\circ$
- $e^+e^-$ pair acceptance $\sim 0.35$
Pion Beam @ GSI

- reaction $N+Be$, $8-10 \times 10^{10} N_2$ ions/spill (4s)
- secondary $\pi^-$ with $I \sim 2-3 \times 10^5$/$s$
- $p = 654, 686, 748, 787$ (+/- 1) MeV/$c$
- PE $(CH_2)_n$ and C targets

- pion momentum
  \[ \Delta p/p = 2.2\% \ (\sigma) \]
- ~50% acceptance of pion beam line
Identification of Channels

two-pion identification: $n\pi^+\pi^-$, $p\pi^-\pi^0$

→ elastic $\pi^-p$ used for normaliz.
→ event-by-event carbon subtraction: $\chi^2$ test
Elastic Scattering

SAID+EPECUR solution
I. Strakovsky
private communication

- syst. error of normaliz. ~2%,
- HADES data normalized to SAID in $\theta^{\text{CM}}$ : 60-110 deg

$\sqrt{s} = 1.47 \text{ GeV}$
$\sqrt{s} = 1.49 \text{ GeV}$
$\sqrt{s} = 1.52 \text{ GeV}$
$\sqrt{s} = 1.55 \text{ GeV}$

$\text{HADES more consistent with new EPECUR data: Phys. Rev. C 91, 025205 (2015)}$
Data: 2016-2018
130 datasets
solutions: A. Sarantsev

### 2π data included in fit

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Observable</th>
<th>W (GeV)</th>
<th>Formalism</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma p \to \pi^0\pi^0 p$</td>
<td>DCS, Tot</td>
<td>1.2-1.9</td>
<td>MAMI</td>
</tr>
<tr>
<td>$\gamma p \to \pi^0\pi^0 p$</td>
<td>E</td>
<td>1.2-1.9</td>
<td>MAMI</td>
</tr>
<tr>
<td>$\gamma p \to \pi^0\pi^0 p$</td>
<td>DCS,Tot</td>
<td>1.4-2.38</td>
<td>CB-ELSA</td>
</tr>
<tr>
<td>$\gamma p \to \pi^0\pi^0 p$</td>
<td>$P, H$</td>
<td>1.45-1.65</td>
<td>CB-ELSA</td>
</tr>
<tr>
<td>$\gamma p \to \pi^0\pi^0 p$</td>
<td>$T, P_x, P_y$</td>
<td>1.45-2.28</td>
<td>CB-ELSA</td>
</tr>
<tr>
<td>$\gamma p \to \pi^0\pi^0 p$</td>
<td>$P_x, P_{x}^{c}, P_{x}^{s}$ (4D)</td>
<td>1.45-1.8</td>
<td>CB-ELSA</td>
</tr>
<tr>
<td>$\gamma p \to \pi^0\pi^0 p$</td>
<td>$P_y, P_{y}^{c}, P_{y}^{s}$ (4D)</td>
<td>1.45-1.8</td>
<td>CB-ELSA</td>
</tr>
<tr>
<td>$\gamma p \to \pi^+\pi^- p$</td>
<td>DCS</td>
<td>1.7-2.3</td>
<td>CLAS</td>
</tr>
<tr>
<td>$\gamma p \to \pi^+\pi^- p$</td>
<td>$I^c, I^s$</td>
<td>1.74-2.08</td>
<td>CLAS</td>
</tr>
<tr>
<td>$\pi^- p \to \pi^0\pi^0 n$</td>
<td>DCS</td>
<td>1.29-1.55</td>
<td>Crystal Ball</td>
</tr>
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<td>$\pi^- p \to \pi^+\pi^- n$</td>
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</table>
1) carbon level in PE: multidimensional $\chi^2$ analysis:

- BLACK – PE
- RED1 – events from C target
- BLUE – $p\pi^-$ (simul.)
- RED2 – $p\pi^-\pi^0$ (simul.)
- MAGENTA (simul. sum)

2) event-by-event carbon subtraction:
matching C and PE by means of $\chi^2$:
- momenta of 3 particles
- angles of 3 particles: $\theta^{CM}$, GJ, helicity
Systematic Errors

Errors related to:
1) normalization ~ 2%,
2) normalization factor with/without Pion Tracker ~3-7%
3) precision of carbon level adjustment ~1%
4) event-by-event carbon subtraction ~ 2%
5) acceptance corrections derived from PWA  1.5-3%,
6) various PWA solutions (with fixed resonances masses, width and free 2-pion couplings vs all parameters free) ~ 2%

**total systematics (added in quadrature) ~ 8%**
PWA Results @ 654, 686, 748, 787 MeV/c
Separation into Final States - Example for 686 MeV/c

invariant mass $\pi^+\pi^-$

in the acceptance HADES distributions are distorted:

$\rightarrow$ extrapolation to 4PI

\[ \pi^-, \Delta | N | N \]
\[ p, \pi \rho \sigma \]

s-channel symbolic notation

$\rightarrow$ extrapolation to 4PI

in 4PI

\[ d\sigma/dM [mb/(GeV/c^2)] \]

$M_{\pi^+\pi^-}^{inv} [GeV/c^2]$
Decomposition into Final States - Example for 686 MeV/c

"subthreshold" – no peak in $\rho \rightarrow \pi^+ \pi^- \pi^0$ mass distributions

$M(n\pi)$

$M(\pi^+\pi^-)$

$M(p\pi^0)$

$M(\pi^0\pi^-)$

$n\pi^+\pi^-$

- $\Delta-\pi$ dominant,
- significant $N-\rho$ contribution, dominated by s-channels and N* (mainly D13)

$\rho\pi^-\pi^0$

- $\Delta-\pi$ rather small,
- $N-\rho$ dominant (s-channels, D13),
- no $N-\sigma$ (I=0)
Decomposition into Final States - Example for 686 MeV/c

- \( n\pi^+\pi^- \)
  - \( N-\rho \) component larger in \( p\pi^-\pi^0 \) channel,
  - \( \Delta-\pi \) and \( N-\rho \) have different signatures - connected to Dalitz plot (next slide)

- \( p\pi^-\pi^0 \)

\[ \cos \theta^{n-\pi^+}_{n\pi^-} \]
\[ \cos \theta^{p-\pi^0}_{p\pi^-} \]

\[ \Delta-\pi \]
\[ N-\rho \]
\[ N-\sigma \]
\[ s\text{-chan} \]
\[ N-\rho \text{ S11} \]
\[ N-\rho \text{ D13} \]
Dalitz Plots

HELICITY

\[ \cos \theta : \quad +1 \quad 0 \quad -1 \]

PWA

\( \Delta - \pi \)

\[ \rho \]

in acceptance

PWA

\( N - \rho \)
Decomposition into Final States - Example for 686 MeV/c

CM distributions

Anisotropic distributions
- higher partial waves involved in 2π production,
- in pπ dominance of ρ meson-main components:
  S11-flat and D13 anisotropic

\[ \cos \theta^\text{CM}_n (\pi^+\pi^-) \]

\[ \cos \theta^\text{CM}_p (\pi^-\pi^0) \]

\[ \cos \theta^\text{CM}_{\pi^-} (n\pi^+) \]

\[ \cos \theta^\text{CM}_{\pi^0} (p\pi^-) \]
Decomposition into Initial States - Example for 686 MeV/c

CM distributions

Acceptance corrected

\[
\cos \theta_{n}^{CM} (\pi^+ \pi^-)
\]

\[
\cos \theta_{\pi^-}^{CM} (n\pi^+)
\]

\[
\cos \theta_{p}^{CM} (\pi^- \pi^0)
\]

\[
\cos \theta_{\pi^0}^{CM} (p\pi^-)
\]

→ coherent sum of I=1/2 and I=3/2

Anisotropic distributions

- higher partial waves involved in 2π production,
- S11-flat and D13 anisotropic

\[1/2^+ \quad 3/2^- \quad 1/2^- \quad P11 \quad D13 \quad S11\]
Decomposition into Final States - Example for 686 MeV/c Gottfried-Jackson

acceptance corrected

\[ \cos \theta^n_{n \pi^-} \]

\[ \cos \theta^\pi^+_{\pi^+ \pi^-} \]

\[ \cos \theta^\pi^0_{\pi^0 \pi^-} \]

\[ \cos \theta^\pi^0_{\pi^0 \pi^-} \]

- useful to study 2-body scattering (one example above)
- large acceptance for GJ angles

\[ n\pi^+\pi^- \]

\[ p \]

\[ \pi^- \]

\[ \rho, \sigma \]

\[ \pi^+ \]

\[ t\text{-channel} \]

\[ \pi^- \]

\[ \rho, \sigma \]

\[ \pi^- \]

\[ \pi^+ \]
Decomposition into Initial States
Total Cross Sections

Crystal Ball
\( \pi^- p \rightarrow \pi^0 \pi^0 n \)

HADES
\( \pi^- p \rightarrow \pi^+ \pi^- n \)

HADES
\( \pi^- p \rightarrow \pi^- \pi^0 p \)

→ coherent sum of I=1/2 and I=3/2

\( N^* \) contributions (P11, D13, S11)
- dominance of I=1/2 but interferences with I=3/2 important
- D13 dominates in charged pion production
- P11 more important in neutral channel

P11

D13/P11

\( \text{D13/} \text{P11} \)
Decomposition into Final States
Total Cross Sections

\[ n\pi^+\pi^- \]

\[ p\pi^-\pi^0 \]

\[ \Delta-\pi \quad N-\rho \quad N-\sigma \]

world data:
D. M. Manley et al.

\[ D_{13} (1520) \text{ dominant contribution in } \rho \text{ production} \]
IMPORTANT FOR DILEPTON ANALYSIS:

D13(1520) coupling to $\rho$-$N$: 12$\pm$2 %
S11(1535): 3$\pm$0.5 %
P11(1440): 0.1$\pm$0.1 %

Total cross sec. $\rho$-$N$: 1.27 mb
(2.5 mb from Manley et al.)

Comparison to solutions: D. M. Manley et al.
1) **HADES & pion beam** is an unique tool to understand in details baryon - \( \rho \) couplings:

- significant off-shell contribution originating from N(1520)D13 shown by combined PWA,
- D13(1520) coupling to \( \rho - N \): 12\( \pm \)2 \%
- dominance of I=1/2 in 2\( \pi \) production in second resonance region.

2) Future measurement in 3’d resonance region with HADES are planned >2019
Thank You for Your Attention