Investigation of hadronic exit channels of the $\pi^- + C$ reaction at an incident momentum of 0.7 GeV/c

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QCD phase diagram studies

HADES objectives:

- Study hadronic matter at moderate temperature and high baryonic density.

A+A: 1-3A GeV
\[ \sqrt{s_{NN}} = 2-2.4 \text{ GeV} \]
(compl. to LHC, SPS, RHIC,...)

- Microscopic structure of baryon dominated matter
- Role of baryonic resonances (excited states of nucleons), hyperons

\[ \Delta(1232) \]
\[ N^*(1440) \]
\[ N^*(1520) \]
\[ N^*(1535) \]
Etc ...

The heavy ion context

In heavy-ion collisions at a few AGeV, pion dynamics crucial to describe the evolution of the collision:

- ✓ real pions copiously produced \((NN \rightarrow NN\pi, \pi + N \rightarrow N^*/\Delta)\)
- ✓ NN interaction driven by pion exchange

\[
\begin{array}{c}
N \quad N \\
\pi \\
N \quad N^*, \Delta
\end{array}
\]

- ✓ p+A or A+A at \(\sqrt{s_{NN}} < 2.6\) GeV \(\Delta(1232)\) region \(p_\pi = 250\) MeV/c well-known
- ✓ p+A or A+A at \(\sqrt{s_{NN}} > 2.6\) GeV, information on higher lying resonances needed: N(1520) region \(p_\pi \sim 700\) MeV/c has not been explored.

- 300\(<p<500\) MeV/c: few measurements \((\pi, \pi x)\) or \((\pi, \pi \pi x)\) (LAMPF, TRIUMF, KEK)
- \(p>500\) MeV/c: only total cross sections (Saturne-1, NIMROD, BNL) and differential elastic cross sections (KEK).

- ✓ p+A (SIS18 & SIS100) or A+A (SIS100)

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Exclusive hadronic channels in pim+C 0.69 GeV/c 3
$\pi^- + C \rightarrow e^+ e^- + X \at 0.685 \text{ GeV/c}$ consistent with quasi-free process: $\pi^- + p \rightarrow e^+ e^- + n$.

1\textsuperscript{st} investigation of the 2\textsuperscript{nd} resonance region with HADES:

- Our aim:
  - Investigate different hadronic exit channels in $\pi^- + ^{12}\text{C}$ reaction for 2\textsuperscript{nd} resonance region:
    - Information on pion-nucleus dynamics in the second resonance region (N1520).
      - study reaction mechanisms: quasi-elastic, rescattering, pion absorption, ...
      - Sensitive test INCL cascade and transport models (Smash, RQMD, GIBUU...).

- INCL is used in toolkits for the simulation of the passage of particles through matter (Geant).
- SMASH, rQMD & GIBUU are used for the description of heavy ion collisions.
- PLUTO event generator is also used for quasi-free simulations.
High Acceptance DiElectron Spectrometer (GSI, Darmstadt)

Experiments (2004-2014)

- **Hadronic matter studies**:
  - C+C 1 & 2 AGeV,
  - Ar+KCl 1.75 AGeV
  - Au+Au 1.25 AGeV
  - Ag+Ag 1.65 AGeV

- **Elementary reactions**:
  - p+ p 1.25, 2.2, 3.5 GeV,
  - d+p 1.25 GeV/nucléon
  - π⁻+CH₂/C 0.7 GeV/c

- **Cold matter**:
  - p+Nb 3.5 GeV,
  - π⁻+C/W 1.7 GeV/c

- **Acceptance**: Azimuthal angles 85% (6 sectors) polar angles: 18° - 85°
- **Detected particles**: e±, p, π±, K±
- **Tracking**: MDC
- **e± identification** with RICH, TOF/PreShower
- **p, π±, K± identification** TOF-Tracking
August 2014 commissioning experiment
Total ~15 days of measurements
Main run: momentum $p_{\pi} = 0.690$ GeV/c ($\sqrt{s}=1.49$ GeV)
Polyethylene ($\text{CH}_2$) and carbon targets
Secondary pion beam
Trigger on at least 2 charged particles.

- Data on carbon mainly used for subtraction of $\pi^- + \text{C}$ interactions in CH2 target to study $\pi^- + \text{p}$ reaction.
  [HADES collab., to be submitted]
- Large statistics for hadronic channels ($\pi^+, \pi^-, \text{p}$) on carbon target to be used for dedicated analysis.
Benchmark of models

Participant-spectator model: PLUTO

- $^{12}C = \text{participant off-shell proton} + \text{spectator on-shell 11B}$
- $\pi^-$ interact with an off-shell proton moving with momentum distribution in agreement with $(e, e'p)$ \(^{(1)}\)
- Further interaction of particles not taken into account
- Only elastic channels included (by choice).

IntraNuclear Cascade model: INCL

- $^{12}C = (\text{on-shell nucleons}) \text{ nucleon Fermi gas}$
- $\pi^- + p \text{ (moving and on-shell)} \rightarrow \pi^- + p + X$
- Further interaction of particles taken into account, depending on cross section
- Nuclear mean field is acting on products.
- inelastic channels are also included
- Only $\Delta(1232)$ resonance is included

SMASH & rQMD & GIBUU

- $^{12}C = (\text{on-shell nucleons}) \text{ nucleon Fermi gas}$
- $\pi^- + p \text{ moving and on-shell} \rightarrow \pi^- + p + X$
- Further interactions are taken into account
- inelastic channels are included
- All baryonic resonances included

- Pluto is a Monte Carlo simulation framework developed by the HADES collaboration for heavy ion and hadronic-physics reactions.
- Simulations processed in GEANT; comparison data with simulations in acceptance.

Particle identification is done using

\[ p = \beta \times m / \sqrt{1 - \beta^2} \]

Data normalisation (counts -> mb/unit) :

Using measurements on C and CH2 targets and known \( \pi^- + p \) elastic scattering cross-section, global systematic error = 4%.

statistical errors are negligible, point to point systematic errors (diff dist) : 5%
Main channels in $\pi^- + {}^{12}\text{C}$

- **Quasi-elastic and charge exchange:**
  - $\pi^- + p \rightarrow \pi^- + p$ quasi-elastic scattering $\sigma = 17.8$ mb (SAID)
  - $\pi^- + p \rightarrow \pi^0 + n$ charge exchange $\sigma = 10$ mb (SAID)

- **Inelastic (pion production)**
  - $\pi^- + p \rightarrow n + \pi^- + \pi^+ \sigma = 6.1$ mb
  - $\pi^- + p \rightarrow p + \pi^- + \pi^0 \sigma = 3.3$ mb (idem)
  - $\pi^- + n \rightarrow p + \pi^- + \pi^- \sigma = 0.4$ mb

- **Multi-step: rescattering** $\pi N \rightarrow \pi N$, $NN \rightarrow NN$

  - $\pi^- \rightarrow \Delta^0$ followed by $NN \rightarrow NN\pi$ kinematically suppressed
  - Two-pion production occurs mainly in the same step, via $\pi N \rightarrow \pi \pi N$

Main contribution from s-channel N* excitations, $N^* \rightarrow \pi \Delta$, $\sigma N$, $\rho N$
Selection of quasi-elastic channel

\[ p\pi^- \]

Selection of quasi-elastic channel:

- ** QE selection »**:
  - Momentum correlation + coplanarity condition:
    \[ 150^\circ < \Delta \phi < 210^\circ \]

- SMASH & rQMD overestimate \( p\pi^- \) channel.
- INCL: underestimates \( p\pi^- \) channel especially inelastic channel.
- GIBUU reproduces quite well \( p\pi^- \) total cross section with difference in yields (« QE » and inelastic).
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**pπ⁻: "quasi – elastic"**

\[
M_{\text{miss}} = M(\pi^- + ^{12}\text{C} \rightarrow \pi^- + p + X)
\]

- Data and transport models: missing mass close to \(^{11}\text{B}\) mass.
- Missing mass shifted in INCL.

Distributions are normalized to the surface in order to compare shapes.

- Ang. distrib. different from free \(\pi^- + p\) elastic scattering.
- INCL reproduces well pion angular distribution.
- PLUTO closer to free \(\pi^- + p\) data especially for high angles.
- Transport models have a too broad angular distribution.
**pπ⁻: Inelastic**

**Single step**

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

**Multi step**

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

\[ \pi^- + p \rightarrow \pi^0 + n \]
\[ \pi^0 + p \rightarrow p + \pi^- + \pi^+ \]

- No clear presence of \( \Delta^0 \) in data, some structure seen in GIBUU.
- GIBUU underestimates the yields.
- rQMD & SMASH in agreement with data, but overestimate yields.
- INCL & GIBUU underestimate yields. They favor multi step processes.
- $p\pi^+$ is necessarily an inelastic channel with two steps.
- Yields much lower than for $p\pi^-$ inelastic.
- Shifted missing mass w.r.t $p\pi^-$ inelastic.
- No clear sign of $\Delta^{++}$ in data.

\[ (a) \pi^- + p \rightarrow \pi^- + p \rightarrow n + \pi^- + \pi^+ \]

\[ (b) \pi^- + p \rightarrow \pi^0 + n \]

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

\[ (c) \pi^- + p \rightarrow \pi^0 + n + \pi^- \]

\[ \pi^0 + p \rightarrow n + \pi^+ \]
Two pion production (1)

\[ p\pi^-\pi^+ \]

(a) \[ \pi^- + p \rightarrow \pi^- + p \quad \pi^- + p \rightarrow n + \pi^- + \pi^+ \]

Elastic \( p\pi^- \) kinematics \( P_{cm} \sim 0.4 \) GeV/c

(b) \[ \pi^- + p \rightarrow \pi^0 + n \quad \pi^0 + p \rightarrow p + \pi^- + \pi^+ \]

(c) \[ \pi^- + p \rightarrow \pi^0 + p + \pi^- \quad \pi^0 + p \rightarrow n + \pi^+ \]

- SMASH and rQMD way too large yield, GIBUU small yield, very good description by INCL.

- In particular, too large contribution in rQMD of quasi elastic \( p\pi^- \) scattering in first step (a).

- \( \pi^- \) and \( \pi^+ \) play a symmetrical role. Dominance of (a) and (b).

- INCL++ does a good job
Two pion production (2)

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

Single step production:
\[ \pi^- + n \rightarrow p + \pi^- + \pi^- ; \text{recoiling } 11C \]
\[ \rightarrow \text{Minimum missing mass, max inv. mass} \]

Two step production:
\[ \pi^- + p \rightarrow \pi^- + n \rightarrow p + \pi^- + \pi^- \]
\[ \rightarrow \text{larger missing mass, lower inv. mass} \]

Elastic \( p\pi^- \) kinematics \( P_{cm} \sim 0.4 \text{ GeV/c} \)

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- Exclusive hadronic channels in pim+C 0.69 GeV/c
2-step processes with 2 $\pi$ production

$$\pi^- + p \rightarrow \pi^- + p$$

$$\pi^- + p \rightarrow \pi^- + \pi^0 + p$$

Overestimated by rQMD

2-step processes with 1 pion production

$\rightarrow \text{max inv. mass}$

(a) $$\pi^- + p \rightarrow p + \pi^-$$

$$p + p \rightarrow p + p$$

(b) $$\pi^- + p \rightarrow \pi^- + p$$

$$\pi^- + p \rightarrow \pi^- + p$$

not favored by data nor GIBUU nor INCL

Overestimated by rQMD and SMASH

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Exclusive hadronic channels in pim+C 0.69 GeV/c
Pion absorption investigation

- 3p channel needs 3 steps ($\pi^-$N or $\pi$ N rescattering step)
  Possibility of pion absorption: $\pi^- + p \rightarrow \pi^- + p$
  followed by
  (a) $\pi^- + p + p \rightarrow n + p$; $n + p \rightarrow n + p$
  or (b) $\pi^- + p \rightarrow \pi^0 + n$; $\pi^0 + p + p \rightarrow p + p$

Small $M_{inv}$ due to proton rescattering
$\pi^- + p \rightarrow p + \pi^-$
$p + p \rightarrow p + p$ overestimated by rQMD

Inv. mass very similar in the 3 channels, no sign of $\pi$ absorption?
Better investigation of pion absorption would need neutron reconstruction

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Exclusive hadronic channels in pim+C 0.69 GeV/c
## Cross sections

<table>
<thead>
<tr>
<th>$\pi^- + ^{12}\text{C} \rightarrow$ reaction 2-3 charged particles channels</th>
<th>$\sigma^{\text{acc}}_{\text{data}}$ [mb]</th>
<th>$\sigma^{\text{acc}}_{\text{SMASH}}$ [mb]</th>
<th>$\sigma^{\text{acc}}_{\text{rQMD}}$ [mb]</th>
<th>$\sigma^{\text{acc}}_{\text{GIBUU}}$ [mb]</th>
<th>$\sigma^{\text{acc}}_{\text{INCL}}$ [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\pi^-$ quasi-elastic</td>
<td>3.05749</td>
<td>12.6985</td>
<td>6.96586</td>
<td>3.44757</td>
<td>2.61393</td>
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<tr>
<td>$p\pi^-$ inelastic</td>
<td>3.35684</td>
<td>4.83481</td>
<td>7.45256</td>
<td>1.76097</td>
<td>2.15597</td>
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<tr>
<td>$\pi^-\pi^-$</td>
<td>0.229554</td>
<td>0.187058</td>
<td>0.438986</td>
<td>0.0529949</td>
<td>0.324116</td>
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<tr>
<td>$\pi^-\pi^+$</td>
<td>1.06115</td>
<td>2.17662</td>
<td>2.39893</td>
<td>0.459961</td>
<td>1.46397</td>
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<tr>
<td>$\pi^+\pi^+$</td>
<td>0.00207372</td>
<td>0.00755551</td>
<td>0.00636384</td>
<td>0.000245144</td>
<td>0.00305625</td>
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<tr>
<td>$p\pi^+$</td>
<td>0.320214</td>
<td>0.774002</td>
<td>1.12059</td>
<td>0.140976</td>
<td>0.300638</td>
</tr>
<tr>
<td>$pp$</td>
<td>1.8327</td>
<td>3.30951</td>
<td>6.35023</td>
<td>1.19376</td>
<td>1.06719</td>
</tr>
<tr>
<td>$p\pi^-\pi^+$</td>
<td>0.0463039</td>
<td>0.134989</td>
<td>0.202082</td>
<td>0.021943</td>
<td>0.0525704</td>
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<tr>
<td>$p\pi^-\pi^-$</td>
<td>0.0646787</td>
<td>0.0596407</td>
<td>0.16292</td>
<td>0.0228274</td>
<td>0.0536891</td>
</tr>
<tr>
<td>$p\pi^-\pi^-$</td>
<td>0.16887</td>
<td>0.617297</td>
<td>1.07159</td>
<td>0.192891</td>
<td>0.153924</td>
</tr>
<tr>
<td>$ppp$</td>
<td>0.047972</td>
<td>0.082285</td>
<td>0.300865</td>
<td>0.039017</td>
<td>0.0238212</td>
</tr>
</tbody>
</table>
Conclusion

- Study of different hadronic channels of $\pi^+{^{12}}C$ reaction @0.69 GeV/c measured with HADES

- Sensitive test of implementation of different processes: quasi-elastic, pion production, absorption in INCL++ and transport models (RQMD, SMASH, GIBUU)
  
  - Large dispersion of model predictions:
    1. INCL++ does a rather good job for channels with a detected pion in contrast to transport models.
    2. Improvements needed for transport models.

- Outlook:
  Access to Short Range Correlation Effects in Quasi-elastic process?
  Estimate total cross sections.
  Neutron reconstruction to test pion absorption.
Backup
Cross sections

\[ \sigma_{p+\pi^-\to p\pi^-} = 17.8 \text{ mb} \]
\[ \sigma_{p+\pi^-\to n\pi^0} = 10 \text{ mb} \]
\[ \sigma_{p+\pi^-\to n\pi^-\pi^+} = 6.21 \text{ mb} \]
\[ \sigma_{n+\pi^-\to n\pi^-} = 12.4 \text{ mb} \]
\[ \sigma_{n+\pi^-\to p\pi^-\pi^-} = 0.37 \text{ mb} \]