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Investigation of hadronic exit channels of the $\pi^- +^{12} C$ reaction at an incident momentum of 0.7 GeV/*c*

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Differential distributions obtained for different exit channel topologies ($p\pi^-$, $p\pi^-\pi^-$ and $p\pi^-\pi^+$) for the $\pi^- + C$ reaction are reported. The data have been collected with the High Acceptance Dielectron Spectrometer (HADES) setup, using the GSI pion beam at an incident pion momentum of 0.69 GeV/c. Pion and proton spectra are compared to theoretical predictions of the INCL++ cascade, and of SMASH, RQMD.RMF transport models and PLUTO. Large dispersion is found between model predictions.

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1. Introduction

The pion-nucleus reaction is an important source of information about hadronic matter. For pion momenta below 2 GeV/c, it provides a unique tool to access the behavior of baryon resonances in the nuclear medium. Pion-nucleus dynamics is also a crucial ingredient for the description of heavy-ion reactions up to a few AGeV and therefore needs to be understood in detail in the context of dense baryonic matter studies. For incident energies below 2 AGeV, the $\Delta(1232)$ resonance plays a major role. The latter has been the subject of many experimental studies using pion-nucleus reactions [1, 2], which provided realistic inputs for the theoretical models. The situation is very different at higher energies, where data are very scarce. For example, the second resonance region corresponding to the excitation of the N(1440), N(1520) and N(1535) is almost unexplored, although it plays an important role for proton-nucleus or nucleus-nucleus reactions at incident energies of a few AGeV, which will be studied in the near future at SIS18 or SIS100. Detailed measurements of proton and pion spectra in pion-nucleus reactions in the second resonance region are needed to validate the theoretical predictions. In particular, the study of exclusive channels allows for a selective test of rescattering and absorption processes in different isospin configurations. More generally, such data are also needed to validate and test selectively transport models or hadronic cascades used in GEANT4 for various applications involving pion detection. In this work, we focus on the analysis of the proton and pion spectra in different final states ($p\pi^-$, $p\pi^+$, $p\pi^-\pi^-$ and $p\pi^-\pi^+$) measured in the $\pi^- + C$ reaction at an incident pion momentum of 0.69 GeV/c.

2. Pion beam experiment with HADES spectrometer

The measurements were performed in August 2014 at the Helmholtzzentrum f*ü*r Schwerionenenforschung (GSI) in Darmstadt using the SIS-18 accelerator which provided a secondary pion beam at an incident momentum of 0.69 GeV/c [4]. Charged hadrons (p, π^-, π^+) were reconstructed using the High-Acceptance Di-Electron Spectrometer (HADES) [5]. Both carbon and polyethylene (CH2) targets were used for subtraction of $\pi^- + C$ interactions in CH_2 target to study free $\pi^- + p$ collisions [6]. In this work, we present a dedicated analysis using the large available statistics for hadronic channels (π^-, π^+ and p) production in the $\pi^- + C$ reaction. To normalize the data measured on the CH_2 and carbon targets, the analysis of the $\pi^- + p$ elastic scattering is used, as described in [6].

3. Simulations

The experimental results are compared to predictions of the INCL++ (Intranuclear Cascade model) [7], SMASH [8, 9], RQMD.RMF [10]. In these models, the carbon target is described as a nucleon Fermi gas where all nucleons are on-shell, and the pion-nucleus reaction proceeds via a sequence of binary collisions. While in transport models all baryon resonances are included, only $\Delta(1232)$ resonance is taken into account in INCL++ through reactions of the type: $\pi N \longleftrightarrow \Delta(1232)$ or $NN \longleftrightarrow N\Delta(1232)$ and no higher lying baryon resonances are included. Also, in INCL++, multi-pion production is treated using parameterizations of elementary cross sections and following phase space distributions [11], while in transport models, it arises via decay of meson or baryon resonances. We are using also PLUTO [12], a Monte Carlo simulation framework developed by the HADES collaboration for heavy ion and hadronic-physics reactions, for the comparison to the quasi-elastic process. In PLUTO, the incident pion interacts with the carbon target described as an off-shell participant proton moving with a momentum distribution which follows an effective spectral function taken from (e,e'p) results [13], and an on-shell spectator nucleus (^{11}B). Only well defined quasi-free channels can be included and no further interactions are taken into account.

In order to have a realistic comparison of simulations to the data, simulated events are processed via dedicated GEANT simulations (with implemented HADES geometry) and reconstruction chain, which simulates the detector response.

4. Main channels

The interaction of the pion in the nucleus target can occur in either a single step where all the final state particles are emitted, or in a multi-step process, where the pions and/or the nucleons from the final state rescatter on other nucleons. This first step can be :

(1) One pion channel (elastic or charge exchange)

- Quasi-elastic :
  - $\pi^- + p \to \pi^- + p$ (σ = 17.8 mb) [14]
  - $\pi^- + n \to \pi^- + n$ (σ = 12 mb) [14]
- Charge exchange : $\pi^- + p \to \pi^0 + n$ (σ = 10 mb) [14]

(2) Pion production channels (inelastic) :

- $\pi^- + p \to \pi^- + \pi^+ + n$ (σ = 6.1 mb) [6]
- $\pi^- + p \to \pi^- + \pi^0 + p$ (σ = 3.3 mb) [6]
- $\pi^- + n \to \pi^- + \pi^- + p$ (σ = 0.4 mb) [14]

The indicated cross sections correspond to the free process. The multi-step process consists of the different possible combinations of these single steps, with also possible NN rescattering as $NN \to NN$. It has to be noted that $\pi + N \to \pi + N$ followed by $NN \to NN\pi$ is kinematically suppressed, which means that two-pion production will occur mainly in a single step as shown above in (2).

5. Analysis

5.1 Quasi-elastic pπ^-

Quasi-elastic scattering (QE) is a process where the incident particle interacts with only one nucleon called the participant particle, while keeping the other nucleons as spectators. To select the quasi-elastic channel, as a first step, events with one proton and one π^- were selected. The π^- and p momentum correlation is shown in Fig. 1. For comparison, calculations for the free process $\pi^- + p \to \pi^- + p$ have been drawn (black line). A graphical cut is applied on the momentum correlation of the π^- and proton in the laboratory frame as shown in Fig. 1 (right red line). Another

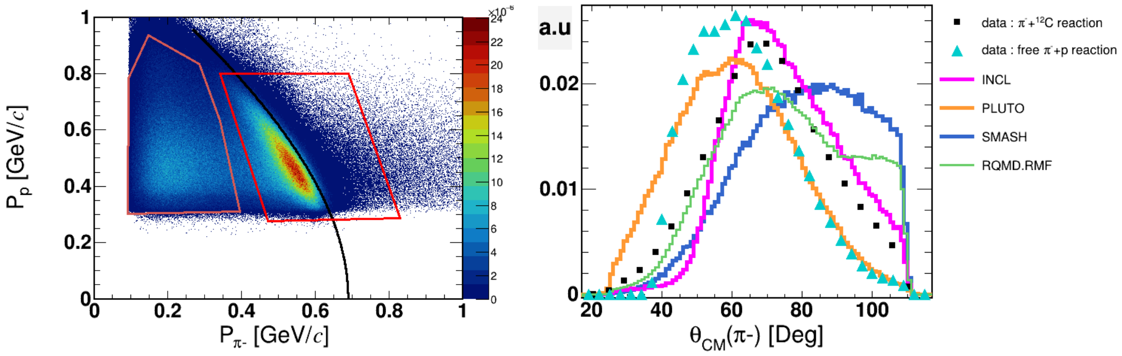

Figure 1: Right: Momentum correlation between the detected protons and negative pions showing two well separated contributions (inelastic on the left and QE on the right). The black line corresponds to the momentum correlation for the free binary reaction $p + \pi^- \to p + \pi^-$. The red lines shows the selections used for quasi-elastic and inelastic $p\pi^-$ events. Left : Angular distribution of the π^- from quasi-elastic events. The distribution is shown in the center-of-mass frame of a $\pi^- + p$ reaction with a proton at rest.

cut reflects the coplanarity condition ($150° < \Delta\phi < 210°$ where $\Delta\phi$ is the difference between the π^- and the proton azimuthal angles) is enforced.
The angular distribution of detected pions after the quasi-elastic (QE) cuts, in the center of mass frame of a $\pi^- + p$ reaction with a proton at rest, is shown in Fig.1, where all spectra are normalized to the surface in order to compare the shapes. To make a relevant comparison with the data, QE cuts are also applied to the simulations. The data measured on the carbon target give a shifted distribution w.r.t data measured on free proton (cyan triangles in Fig.1). PLUTO describes a distribution close to the free proton scattering. Both transport models SMASH and RQMD.RMF predicts very broad distributions of pion angles, while INCL gives the closest description of our data.

5.2 Inelastic pπ^- & pπ^+

Another graphical cut is applied on the momentum correlation of the π^- and proton in the laboratory frame to select inelastic pπ^- events as shown in Fig.1 (left red line). Such events correspond to exit channels with two pions, which can be produced either in a single step as :

(1) $\pi^- + p \to \pi^- + \pi^0 + p$ or $\pi^- + n \to \pi^- + \pi^- + p$

or in multiple steps as :

(2) $\pi^- + p \to \pi^- + p$ followed by $\pi^- + p \to \pi^- + \pi^+ + n$

(3) $\pi^- + p \to \pi^0 + n$ followed by $\pi^0 + p \to \pi^- + \pi^+ + p$

The $p\pi^+$ channel can be produced by the same processes as listed above with a difference in the first process (single step) that must be followed by charge exchange as follows:

(4) $\pi^- + p \to \pi^- + \pi^0 + p$ followed by $\pi^0 + p \to \pi^+ + n$.

One way to see this difference is to study the missing mass (MM) in the reaction $\pi^- + C \to \pi + p + X$ and invariant mass spectra of detected particles (Figs. 2 & 3). It can be observed that in the case of pπ^- the missing mass (invariant mass) extends to lower (respectively higher) values,

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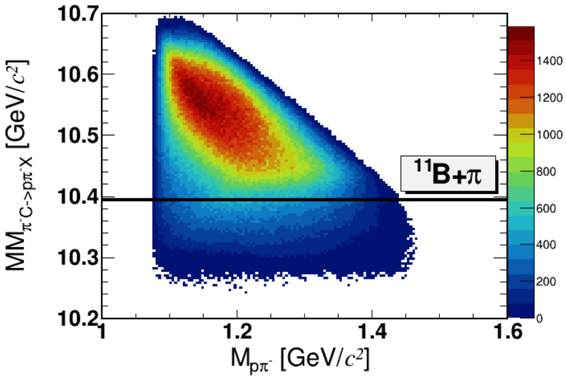

Figure 2: Analysis of the $\pi^- + C \longrightarrow \pi^- + p + X$ reaction after selection of inelastic events: missing mass as a function of invariant mass.

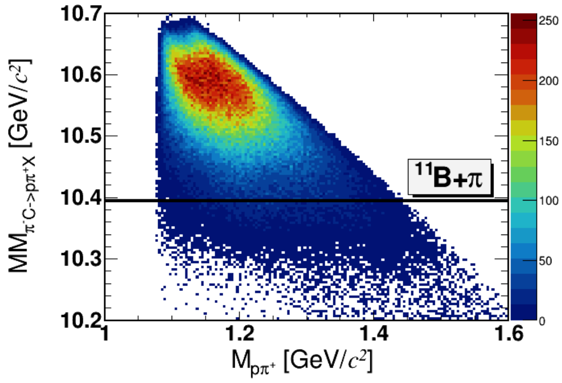

Figure 3: Analysis of the $\pi^+ + p$ in $\pi^- + C \longrightarrow \pi^+ + p + X$ reaction: missing mass as a function of invariant mass.

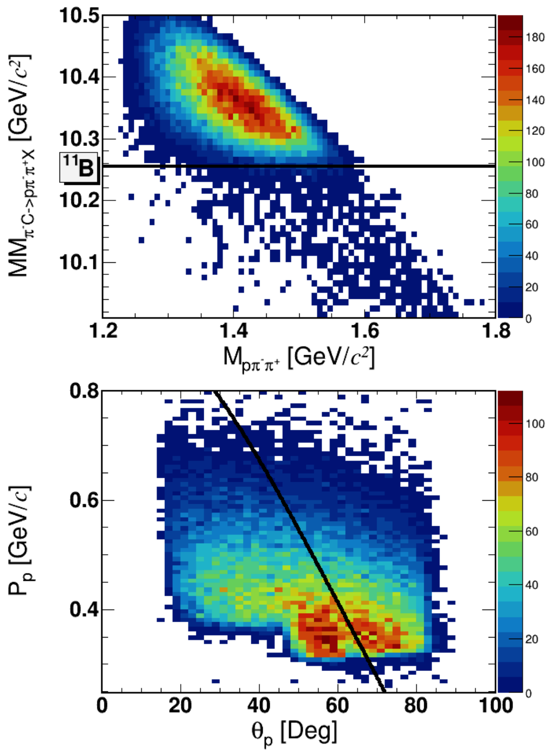

Figure 4: Analysis of the $\pi^- + C \longrightarrow \pi^- + \pi^+ + p + X$ reaction. Top: missing mass as a function of invariant mass. Bottom: momentum as a function of angle of proton.

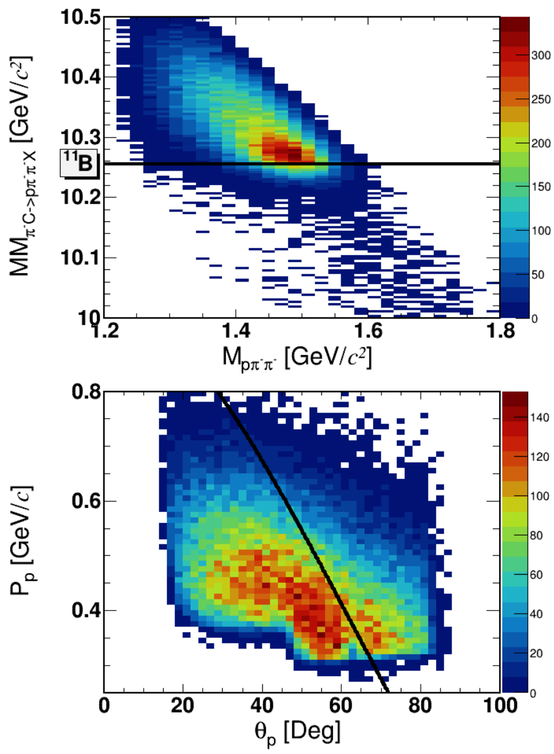

Figure 5: Analysis of the $\pi^- + C \longrightarrow \pi^- + \pi^- + p + X$ reaction. Top: missing mass as a function of invariant mass. Bottom: momentum as a function of angle of proton.

which can be expected due to the contribution of single step two pion production. In addition, the yields of $p\pi^+$ channel are much lower than for $p\pi^-$ inelastic, which is consistent with the fact that this channel requires specific multi-step processes.

5.3 Two pion production : $p\pi^-\pi^+$ & $p\pi^-\pi^-$

For a more detailed description, we have studied, on the one hand, the $p\pi^-\pi^+$ channel which is produced by the same multi-step processes as listed above for $p\pi^+$ emission and, on the other hand, the $p\pi^-\pi^-$ channel, which can be produced by $\pi^- + n \rightarrow \pi^- + \pi^- + p$ either in a single step or preceded by a quasi-elastic step. This difference is seen very clearly by comparing the correlation between missing mass and invariant masses for both event categories (top rows of Fig. 4 and Fig.5), which is peaked at much lower missing mass and higher invariant mass values for $p\pi^-\pi^-$ than for $p\pi^+\pi^-$ events. In addition, as shown in the bottom rows of Figs. 4 and 5, the contribution of events from a first quasi-elastic step with a correlation between the proton momentum and angle close to the free kinematics curve is much larger in the case of $p\pi^+\pi^-$ events.

6. Conclusion

We measured the production of different exclusive channels of $\pi^- +^{12} C$ reaction ($p\pi^-$, $p\pi^+$, $p\pi^-\pi^-$ and $p\pi^-\pi^+$) with the HADES spectrometer at incident pion momentum of 0.7 GeV/c. The aim is to use the collected statistics to test different theoretical predictions as INCL cascade, SMASH and RQMD.RMF transport models. A large dispersion between models is seen in describing the exclusive hadronic processes inside the nucleus. A first comparison is represented for the QE pπ^- channel where the INCL cascade model shows a better description than the transport models. The selective test of various hadronic processes in data is obtained by studying for different exit channels physical variables as the invariant mass and the missing mass, or the kinematics of the detected particles. These distributions allow to get sensitivity to the contribution of various processes (single and multiple steps) and can be compared to the models in order to test the rescatterings effects in target.

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