Studies of inclusive production of protons and charged pions and semi-exclusive channels in π^-+C collisions at 0.7 GeV/c with HADES

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Abstract. Pion beams are important tools to study features of baryonic resonances and pion-nucleus dynamics. In 2014 the HADES collaboration has performed an experiment using the π^-+C reaction at 0.7 GeV/c. This measurement provides a first insight into the π-nucleon dynamics in the energy range of the second resonance region ($\sqrt{s} \sim 1.5$ GeV). Measurements of protons and charged pions were provided in various inclusive and semi-exclusive exit channels (p$\pi^{\pm}$, pp, $\pi^+\pi^-$, p$\pi^+\pi^-$,...) and compared to predictions of the transport (SMASH, JAM2/RQMD.RMF, GIBUU) and the INCL++ cascade models. The results allow to test very selectively various reaction mechanisms like quasi-elastic, pion absorption or rescattering.

1 Introduction

Understanding pion-nucleus interaction is crucial to describe the evolution of the A+A and p+A collisions up to a few AGeV. In this energy range real pions are copiously produced. Their further elastic or inelastic interaction with nucleons, which proceed via excitation of baryon resonances, play an important role in thermalization processes of nuclear medium and in the particle production. In such processes the kinetic energy is dissipated in the nucleus and finally particles are produced. To properly describe such nuclear system dynamics these reactions need to be precisely constrained by experimental data.

So far, the region of the $\Delta(1232)$ resonance has been extensively studied by many experiments using pion beams at momenta around 300 MeV/c and various nuclear targets [1, 2]. However, at higher incident momenta, where heavier resonances are excited, the experimental information is very scarce [3, 4]. The pion beam facility at GSI/FAIR, covering a momentum range between 0.6 and 2 GeV/c offers a unique opportunity to enrich the data base for pion-nucleus reactions in the second resonance region ($\sqrt{s} \sim 1.5$ GeV) and above, which is important in the context of future studies using proton-nucleus and heavy-ion reactions at SIS100 energies. This energy range is also of interest for the next generation long-baseline neutrino experiments (Hyper-K, DUNE), where pion production, absorption and rescattering in nuclei constitute important ingredients of neutrino-energy reconstruction and generator uncertainties. To study such effects like CP violation or the neutrino mass hierarchy, the reduction of systematic errors, related to the modeling of the neutrino-nucleus interactions used to reconstruct the neutrino energy, is the key issue [5].

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The measurement of differential cross sections for various exit channel topologies delivers information on elastic and inelastic processes in the nucleus and allows to test selectively transport and hadronic cascade models used in GEANT4 for various applications.

2 HADES detector and pion beamline

The High Acceptance Di-Electron Spectrometer (HADES) [6], installed at GSI/FAIR in Darmstadt, was designed to measure di-electrons in the 1-3.5 AGeV energy range. It allows to study both hadron and rare di-lepton production in π/p+p, π/p+A and A+A collisions up to a few AGeV. It provides high acceptance ($18^\circ - 85^\circ$) in polar and almost full azimuthal angles. The HADES setup together with the secondary pion beam is a very unique apparatus in the world which allows the combined measurement of di-electrons and hadron production. The secondary pion beam was produced in reaction of ^{14}N on ^{9}Be target with an intensity on the HADES target of 3×10^5 pions/spill. The experiment has been performed with the carbon target consisting of 7 segments with total thickness of 2.52 cm and a diameter of 12 mm. The data acquisition trigger was defined by requiring the registration of at least two hits in the META (TOF or RPC) detectors and one hit in the START (T0) detector located in front of the target.

2.1 Analysis strategy

A goal of this analysis is to provide precise pion and proton emission spectra in various inclusive and semi-exclusive exit channels (p$\pi^{\pm}$, pp, $\pi^+\pi^-$, p$\pi^+\pi^-$,...). Such a database provides an extremely stringent test of available models which describe the pion-nucleus interaction.

The HADES data have been compared to a set of transport models GiBUU [7], SMASH [8], JAM2/RQMD.RMF [9] and the INCL++ cascade model [10]. INCL++ takes into account only the $\Delta(1232)$ resonance and elastic and inelastic reactions are treated using a parameterization of elementary cross sections [11]. The transport models include all known baryon resonances and particle production proceeds via their excitation and decay. In addition, the GiBUU model allows for a direct particle production, which is important at lower energies.

The data have been collected with the acquisition trigger which fired when at least two hits in the META detector were registered (M2). Such condition was required to study baryon resonance properties using two-pion or e^+e^- channels [12–14], which was a primary goal of this experiment. Since the M2 trigger introduces a significant bias on the inclusive spectra, a dedicated correction procedure is under development. In this article only the biased spectra are presented as an intermediate step of this analysis.

In order to have a realistic comparison of simulations to the data, generated events are processed via dedicated HADES-GEANT simulations, which include the detector response and the trigger M2 condition through the full reconstruction chain. The data and the models have been corrected for the detection inefficiency and the data have been normalized with the total integrated luminosity [12], providing cross sections inside the HADES acceptance.

2.2 Inclusive production of protons and charged pions

Figure 1 presents momentum distributions for protons and charged pions in comparison to GiBUU and INCL++ models. Even if the INCL++ predictions underestimate the data, information on the number of collisions (*nCol*) per event, available only in this model, was

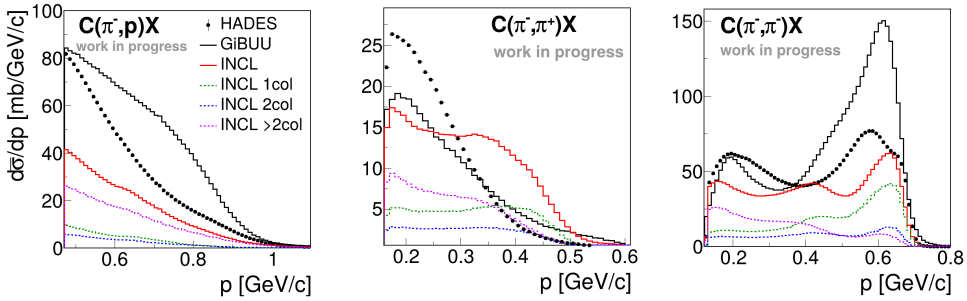

Figure 1. Momentum distributions for protons and charged pions, biased with the M2 trigger condition, in comparison to GiBUU (black line) and INCL++ (red line) models. The INCL++ spectrum was decomposed according to various number of collisions in the event, as specified in the legend.

used to follow the cascade evolution, rescatterings and secondary processes inside the carbon nucleus. As it can be visible in Fig. 1, the proton production is dominated by multi-step processes, with $nCol > 2$.

Positive pions are produced in a few collisions at momentum below ~ 0.35 GeV/c and at higher momenta mostly in a single $\pi^- + p \rightarrow \pi^+ + \pi^- + n$ reaction ($nCol = 1$). The two-pion process gives π^- with lower momentum, while at higher momenta $\pi^- + \mathrm{N} \rightarrow \pi^- + \mathrm{N}$ ractions contribute. In general neither GiBUU nor INCL++ properly describes the experimental distributions. The GiBUU model better reproduces the experimental spectrum of π^+ and the inelastic part ($0 - 0.4$ GeV/c) of the π^- spectrum.

2.3 Semi-exclusive two- and three-particle

Measurements of protons and charged pions were also provided in semi-exclusive channels like: $p\pi^{\pm}$, pp, $\pi^+\pi^-$, $p\pi^+\pi^-$ or $pp\pi^-$ [15, 16]. Momentum distributions of the pions and protons in the $\pi^- + \mathrm{C} \rightarrow p + \pi^-$+X, $\pi^- + \mathrm{C} \rightarrow p + \pi^- + \pi^-$+X and $\pi^- + \mathrm{C} \rightarrow p + p + \pi^-$+X processes were investigated and compared to the model predictions.

For $p\pi^-$ events, the two structures due to the inelastic and elastic first collisions are clearly visible in Fig. 2a), which displays the pion momentum in the center-of-mass of the $\pi^- + p$ reaction at 0.7 GeV/c. The quasi-elastic peak is better separated from the inelastic structure than in Fig. 1(right) because the laboratory pion momentum distribution is smeared due to the integration over angles. It is still broadened and shifted w.r.t. the value for the free πN elastic scattering (0.432 GeV/c), due to the nucleon potentials, Fermi motion and potentially also rescattering effects. The broad bump at lower momenta corresponds to pions produced in a $\pi\mathrm{N} \rightarrow \pi\pi\mathrm{N}$ reaction. The GiBUU model describes the data in a more reasonable way. The other models overestimate or underestimate the data with simultaneous quasi-elastic peak shift w.r.t. the data.

In addition to $\pi^- p$, also proton and pion momenta in the center-of-mass of the $\pi^- + p$ reaction were analyzed for $p\pi^-\pi^-$ and $pp\pi^-$ channels, respectively, to investigate inelastic and multi-step processes in more detail.

For the $p\pi^-\pi^-$ events, as shown in Fig. 2b), the proton momentum distribution in the $\pi^- + p$ center of mass is a broad structure, mainly due to inelastic two-pion processes. However a small peak is visible at $p^{CM} \sim 0.4$ GeV/c. This is due to the $\pi^- + p \rightarrow p + \pi^-$ reaction followed by the $\pi^- + n \rightarrow p + \pi^- + \pi^-$ process. This peak is too pronounced in the JAM2 model, which strongly overestimates the yield, while the other models give a better descrip-

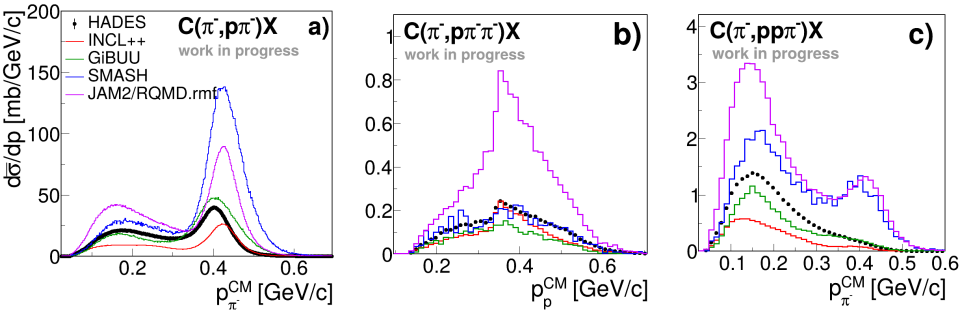

Figure 2. Center-of-mass momentum distributions calculated in the $\pi^- + p$ reference frame of a) negative pions for $\pi^- + \mathrm{C} \rightarrow p + \pi^- + \mathrm{X}$ reaction, b) protons for $\pi^- + \mathrm{C} \rightarrow p + \pi^- + \pi^- + \mathrm{X}$ reaction and c) negative pions for $\pi^- + \mathrm{C} \rightarrow p + p + \pi^- + \mathrm{X}$ reaction.

tion of this channel.

In the case of the $pp\pi^-$ channel, the three particles can be produced only in multi-step processes in at least two steps. Figure 2c) presents the $p_{\pi^-}^{CM}$ momentum distribution in comparison to the models. The peak at higher momenta predicted by the SMASH and JAM2 models, but missing in the data, correspond to the two-step elastic processes (e.g. $\pi^- + p \rightarrow \pi^- + p$, $p + p \rightarrow p + p$ or $\pi^- + p \rightarrow \pi^- + p$, $\pi^- + p \rightarrow \pi^- + p$). The peak at the lower momenta is due to the two-step inelastic processes (e.g. $\pi^- + p \rightarrow \pi^- + p$; $\pi^- + p \rightarrow p + \pi^- + \pi^0$).

The examples presented above demonstrate the sensitivity of the data to the details of the π^-+C reaction dynamics. Especially, studies of missing quantities, like momentum or energy, in the semi-exclusive channels are important for understanding of re-interactions of hadrons produced in neutrino-nucleus scattering with the residual nuclear medium, or final-state interactions (FSI).

The transport model predictions show an unexpectedly large dispersion, which points to the need for further development and tuning. These measurements provide new differential constraints on particle emission in π^-+C reactions above the $\Delta(1232)$ resonance region and constitute a stringent test of the reaction models.

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