Studies of π^--^{12}C reactions at 0.7GeV/c with the HADES spectrometer

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Abstract. The HADES collaboration has recently studied the $\pi^- + $ C reaction at 0.685 GeV/c, using the GSI pion beam. This provides a first insight in the pion-nucleus dynamics in the energy range above the Δ(1232) resonance, which has been very poorly studied and is relevant for the study of heavy-ion collisions in the few GeV range. Measurements of $\pi^{\pm}$, p, d and t were provided in various exit channels (inclusive, pπ^-, pπ^+, pp, $\pi^+\pi^-$, p$\pi^-\pi^+\ldots$,) and compared to predictions of the INCL++ cascade and of transport models (SMASH, RQMD.RMF, GIBUU). The results allow to test selectively the capacity of such models to describe the various mechanisms (quasi-elastic, multipion production, rescatterings and pion absoprtion). The sensitivity of the data measured in the quasi-elastic channel to short range correlations is also investigated.

1 Introduction

Pion-nucleus dynamics plays a crucial role in heavy-ion collisions up to a few AGeV. In this energy range, pions are copiously produced via inelastic nucleon-nucleon collisions and further interact with nucleons, leading to baryon resonance excitation, which regenerate the pions via their decay. Such processes, which are instrumental in the way kinetic energy is dissipated in the nucleus and finally particles are produced need to be precisely constrained by experimental data. The region of the Δ(1232) resonance has been the subject of many experimental studies using pion-nucleus reactions [1, 2] with pion beam momenta around 300 MeV/c, but the experimental information for pion-nucleus reactions at higher incident momenta, where higher lying resonances are excited is extremely scarce. The pion beam at GSI, covering a momentum range between 0.6 and 2 GeV/c offers a unique opportunity to improve the data base for pion-nucleus reactions in the second resonance region ($\sqrt{s} \sim 1.5$ GeV) and above, which will be relevant for future baryon-rich matter studies using proton-nucleus reactions at the highest SIS18 energies or heavy-ion reactions at SIS100 energies. The measurement of differential cross sections for various exit channels is expected to bring constraints on elastic and inelastic scattering processes in the nucleus, which are essential to understand the evolution of heavy-ion reactions and thermalization processes in the context of baryon-rich matter studies. In addition, such data are needed to validate and test selectively transport models or hadronic cascades used in GEANT4 for various applications involving pion detection.

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2 HADES pion beam experiments

The main objective of the HADES pion beam experiment realized in August 2014 was the study of electromagnetic baryon time-like form factors in the reaction $\pi^-p \to ne^+e^-$using polyethylene and carbon targets [5, 6]. A primary ^{14}N beam impinging a beryllium target was used to produce pions. The secondary pion beam at a central momentum of 0.685 GeV/c and a dispersion of about 1.7% (rms) was selected after a 33m long beam line consisting of 2 dipoles and 9 quadrupoles [3]. The average pion beam flux incident on the HADES target was of the order of 2×10^5 pions/s. The present analysis uses pion and proton spectra measured in the $\pi^- + C$ reaction at 0.685 GeV/c. Particle momenta are deduced from the particle trajectories in the toroidal magnetic field, using position information provided by the Mini Drift Chambers (MDC) [4]. For pion and proton identification, the correlation between momentum, time-of-flight and energy loss in the MDC is used and the normalization is based on the analysis of the $\pi^- + p$ elastic scattering, as described in [7].

3 Main channels

Considering the energy of the incident pion, the first πN collision can be either a quasi-elastic or charge exchange πN scattering or an inelastic reaction of the type π N $\to \pi\pi$ N. After the first collisions, further elastic or inelastic reactions might occur, depending on the energy of the products of the primary collision. However, secondary inelastic nucleon-nucleon reactions are highly suppressed, so that two-pion production occurs mainly in the same collision, either as a first step, or after a primary quasi-elastic collision. The mean free path of pions, which is of the order of 2.5 fm at 0.685 GeV/c strongly decreases as a function of decreasing energy. Pions scattered elastically at forward angles are therefore expected to be much less affected by secondary collisions than those produced in a primary inelastic collision. As a rather small number of collisions is expected, these data allow for a detailed test of rescattering processes in hadronic models. We used three transport models GiBUU [9], SMASH [10, 11], RQMD.RMF [12] as well as the INCL++ cascade model [8]. INCL++ takes into account only the first baryon resonance ($\Delta(1232)$) and treats elastic and inelastic reactions using a parameterization of elementary cross sections [13], while in transport models, all known baryon resonances are included and pion production proceeds via their excitation and decay. 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 Data analysis of various exit channels

Different final states (pπ^-, pπ^+, p$\pi^-\pi^-$, p$\pi^-\pi^+$ and pp π^-) were analyzed, where the label indicates the particles which should at least be detected. Various distributions were compared to the predictions of models. Events in the pπ^- channel are clearly due to two distinct reaction types, with either an elastic or inelastic first collision, which can be easily identified by the two structures in the distribution of the pion momentum in the center-of-mass of the π^-+ p reaction at 0.685 GeV/c (Fig. 1). The quasi-elastic peak is broadened and shifted w.r.t. the value for the free π N elastic scattering (0.432 GeV/c), indicated as an arrow in the figure, due to the combined effect of nucleon potentials and Fermi motion, while the broad bump at lower momenta corresponds to pions produced in a π N $\to \pi\pi$ N reaction.

To select the quasi-elastic channel, we chose events with one proton and one π^- and applied kinematical selections (correlation between pion and proton momenta and coplanarity condition as described in [14]). A good description of the pion angular distribution

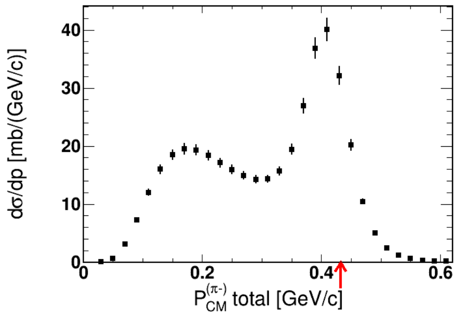

Figure 1. π^- momentum distribution in the center-of mass of the π^-+ p reaction at 0.685 GeV/c for the π^-p events. The red arrow indicates the value corresponding to the free π^-p elastic scattering.

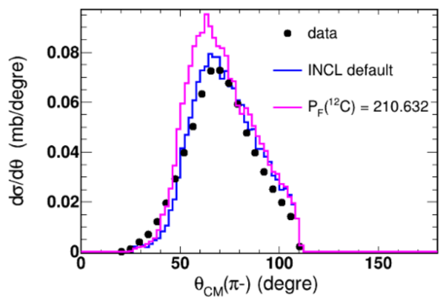

Figure 2. Pion angle distribution measured for the π^-p quasi-elastic events (black dots) compared to INCL++ simulations using the Fermi momentum value p_F= 270 MeV/c (blue), as in the standard option and p_F=211 MeV/c (magenta).

in the center-of-mass of the π^-+ p reaction at 0.685 GeV/c is obtained by the INCL++ model, as shown in Fig. 2, while the other models are less sucessful. The yields and shapes of the distributions measured for the quasi-elastic channel are quite sensitive to the nucleon momentum distribution in the carbon nucleus. This is due to the combined effect of acceptance cuts, potential and Pauli blocking. In the standard INCL++ option, the Fermi momentum value is p_F= 270 MeV/c. We tested the effect of using the value p_F = 211 MeV/c, as measured by the electron scattering measurements. The standard option seems to give a better result, in particular, concerning the yields (Fig. 2). The role of secondary elastic and inelastic collisions can also be quantified using the INCL++ model. According to this model, pions with momenta larger than 600 MeV/c are mostly produced by a pure quasi-elastic process. This opens the possibility to study Short Range Correlations (SRC) by investigating the missing momentum $\overrightarrow{p_{miss}} = \overrightarrow{p_{\rm inc}} - \overrightarrow{p_\pi} - \overrightarrow{p_{\rm p}}$, where $\overrightarrow{p_{\rm inc}}$, $\overrightarrow{p_\pi}$ and $\overrightarrow{p_{\rm p}}$, are the momenta of the incident pion, the detected π^- and the detected proton, respectively. The recent version of the INCL++ model gives a good decsription of the high momentum tail of the p_{miss} distribution. The effect of SRC is found to be very small, which is probably due to the fact that mostly the surface of the carbon nucleus is probed in the quasi-elastic π^- + C reaction.

In addition to pπ^-, other channels (pπ^+, p$\pi^+\pi^-$, p$\pi^-\pi^-$, ppπ^-, pp and ppp) were analyzed to investigate inelastic and mutistep processes. In particular, the missing mass distributions carry useful information on the way energy is dissipated in the carbon nucleus. As shown in Fig. 3 Left, the distribution for the p$\pi^-\pi^-$process is peaked at a value close to the ^{11}B mass, which is expected in the case of a single step collision of the type π^-n $\rightarrow$ p$\pi^-\pi^-$, but it presents also a long tail, pointing to further rescatterings. In the case of the p$\pi^+\pi^-$ channel, the three particles can not be produced in a single quasi-free π^-p or π^-n collision, and at least one additional nucleon needs to participate to the reaction. This is consistent with the missing mass which appears shifted towards higher values w.r.t. the p$\pi^-\pi^-$ case (Fig. 3 middle). For ppπ^- events, at least two collisions are needed. In the case of a π^-p elastic scattering followed either by a second π^-p or pp scattering, most of the energy available in the reaction is carried by the three detected particles. The rising slope of the missing mass distribution measured for the ppπ^- events, which is close to the ^{10}B mass, reflects such contributions. However, most of the yield is found at higher missing masses, hence corresponding to a larger number of collisions or to inelastic processes, where the second

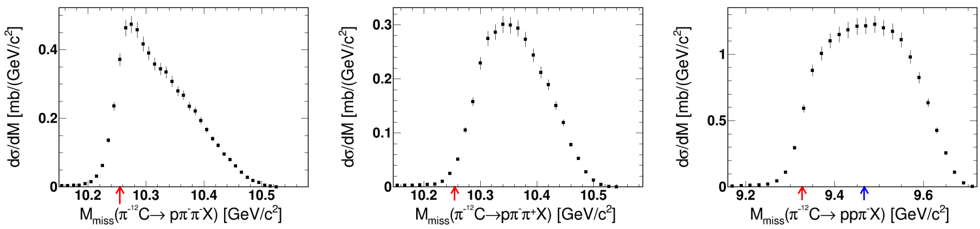

Figure 3. Distribution of the missing mass of the π^- + C→ p $\pi^-\pi^-$+X (left), π^- + C→ p $\pi^+\pi^-$+X (middle) and π^- + C→ p p π^-+X reactionss (right). The red arrow indicates the mass of the ^{11}B for the left and middle pictures and the mass of the ^{10}B in the right picture. The blue arrow in the right picture shows the threshold for two-pion emission.

pion is either undetected or absorbed. These examples demonstrate the sensitivity of the data to the detailed dynamics of the π^- + C reaction. The transport model predictions show an unexpected large dispersion, which points to the need for futher adjustments.

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