Reference measurements for indirect dark matter searches with p+C collisions at the NA61/SHINE experiment

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Abstract

NA61/SHINE is a large-acceptance fixed-target experiment located at the CERN SPS, which studies final hadronic states in interactions of various particles and nuclei. It is unique in terms of providing data on a variety of collision systems at different collision energies. This allows for wide deuteron, antiproton and antideuteron production cross-section studies. The latter are currently considered a possible dark matter interaction signal with exceptionally small background. The measurements on carbon targets are important to reduce systematic experimental effects due to experiment-internal antideuteron production, as the most abundant element in the path of an incoming particle for the AMS-02 experiment is carbon. This manuscript will focus on analysis of NA61/SHINE data on p+C thin target collisions in the context of light (anti)nuclei production. A preliminary analysis of experimental data and the particle identification method as well as current deuteron and antideuteron yields will be described.

1 Introduction

The NA61/SHINE physics program pursues many topics in different areas of physics. The core focus is on the Strong Interaction program with a scan of the collision system size and collision energy two-dimensional space. Additionally, cosmic ray and neutrino reference measurements are conducted.

The first results on $\pi^{\pm}$ and $K^{\pm}$ spectra produced in p+C interactions at 31GeV/c were already published by NA61/SHINE [2,3] in 2011 and 2012. After an additional run in 2009, which took an eight times larger dataset, results on pion, kaon, and proton as well as K^0_S spectra in p+C interactions at 31GeV/c were published [4].

The latter data set can be used to support indirect dark matter signal searches. Investigating the flux of antiparticles in cosmic-rays is especially interesting because antiparticles do not have sizable astrophysical sources (see Fig.1). An important source of background antideuterons for cosmic searches comes from interactions of p and $\bar{p}$ with the interstellar medium [5]. p+C measurements are important to reduce systematic experimental effects due to experiment-internal antideuteron production, as the most abundant element in the path of an incoming particle for the AMS-02 experiment is carbon.

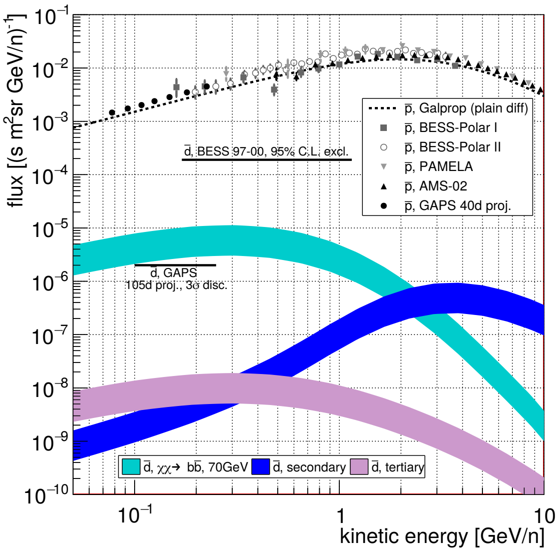

Figure 1: The predicted antideuteron flux corresponding to Dark Matter parameters indicated by AMS-02 antiproton signal as well as the predicted secondary and tertiary astrophysical antideuteron flux. Figure taken from Ref. [6]

2 Analysis method

Reconstruction and calibration algorithms applied to the 2009 data are summarized in Ref. [2]. They resulted in good data quality suitable for the analysis (see e.g. Ref. [8]). The procedure was repeated recently for the p+C data set with the newest version of the reconstruction software and updated calibration parameters. Measurements of the specific energy loss dE/dx of charged particles by ionization in the TPC gas are used for their identification. The dE/dx of a particle is calculated as the 50% truncated mean of the charges of the clusters (points) on the track traversing the TPCs. The calibrated dE/dx distributions as a function of particle momentum for positively and negatively charged particles are presented in Fig. 2. The Bethe-Bloch parametrization of the mean energy loss, scaled to the experimental data, is shown by the curves for positrons (electrons), pions, kaons, (anti)protons, and (anti)deuterons. The typical achieved dE/dx resolution is about 4%.

In this analysis, a simplified approach to identify particles is used. Namely, a 2σ wide band around the Bethe-Bloch curves will serve as the classification border together with a cut-off for low dE/dx particles. The latter is used to distinguish the particles of interest from electrons and positrons. All particles within the band will be identified as the corresponding particle type. For the antideuterons and antiprotons, which suffer from low statistics, the same band as deuterons and protons, respectively, are used.

2.1 Data driven correction

To establish the contribution of deuterons produced in secondary processes, a specific analysis procedure has been developed. The contributions of particles produced in events with the main vertex z coordinate before and after the target center are compared. The probability of deuteron production in the coalescence of primary particles is uniform along the target length. The additional contributions from the monotonously growing probability of secondary processes should be excluded.

To compensate for differences in detector acceptance using events with the main vertex z coordinate before and after the target center, an acceptance map was used. 5 M deuterons in

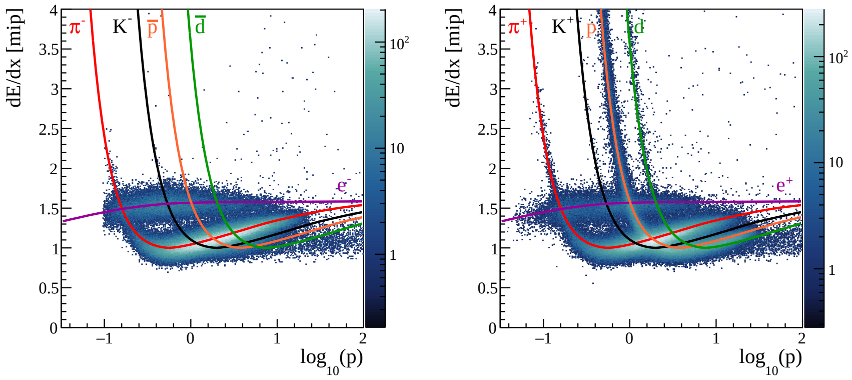

Figure 2: Specific energy loss dE/dx in the TPCs for negatively (left) and positively (right) charged particles as a function of momentum. Curves show the Bethe-Bloch parameterizations of the mean dE/dx calculated for different particle species. In the case of electrons and positrons, which reach the Fermi plateau, the mean dE/dx is parameterized by a constant.

flat phase-space (y, p_T and ϕ) were simulated and reconstructed to determine the detector efficiencies for the two cases. Next, only bins common for the two versions – before and after target center, were used. The common acceptance map was used to obtain $\langle d \rangle$.

2.2 Monte-Carlo correction

(Anti)deuteron production can be described within the coalescence model [9], which states that any (anti)proton and (anti)neutron within the sphere of radius p_0 in momentum space will coalesce to produce an (anti)deuteron. In order to simulate deuteron production in a collision, a coalescence afterburner was introduced and applied for events generated with Epos1.99 model (version CRMC 1.5.3) [10, 11]. Two particles coalesce if the following condition is met in the center of mass frame of reference:

$$|\vec{k}_1 - \vec{k}_2| < 2p_0, \tag{1}$$

where

$$p_0 = \frac{A}{1 + \exp B - \ln(T/C)}, \tag{2}$$

with T being collision energy in GeV, $A = 89.6$, $B = 6.6$ and $C = 0.73$ for deuterons as described in Ref. [12].

The simulation allows for generating a correction factor for the detector acceptance due to geometry and reconstruction effects.

2.3 Calculating the cross section

NA61/SHINE has already calculated and published the p+C interaction trigger probability and resulting "trigger" cross-section value:

$$\sigma_{\text{trig}} = 305.7 \pm 2.7(\text{stat}) \pm 1.0(\text{det})\ \text{mb}, \tag{3}$$

with (stat) being statistical and (det) systematic uncertainty. Using the latter it is possible to calculate the deuteron production cross-section with its statistical uncertainty from the following formula:

$$\sigma_d = \frac{\sigma_{\text{trig}}}{f_{\text{prod}}(1-\epsilon)} \left(\frac{n_d^I}{N_{\text{trig}}^{\text{I}}} - \epsilon \frac{n_d^R}{N_{\text{trig}}^{\text{R}}} \right), \tag{4}$$

where N^{I} and N^{R} are the numbers of events with the target inserted and removed, respectively, n_d^{I} and n_d^{R} number of deuterons produced with target inserted and removed, respectively. $\epsilon = 0.123 \pm 0.004$ is the ratio of the interaction probabilities for operation with the target removed and inserted, and $f_{\text{prod}} = 0.993$ is the fraction of production events.

Applying this method allows calculating the deuteron production cross-section in p+C collisions. Applying similar methods in order to calculate yields of $\bar{p}$ and $\bar{d}$ in the case of the p+C dataset does not give a satisfactory number of entries. This causes statistical uncertainties to be significantly above 10% and prevents meaningful inference. In the case of $\bar{p}$, the total multiplicity obtained with the simplified dE/dx method was 27, which results in a statistical uncertainty of about 20%. In the case of $\bar{d}$ there were 9 candidates, resulting in a statistical uncertainty of ≈30%. In order to reduce the statistical uncertainties below 10% the amount of data would have to be increased fourfold in the case of $\bar{p}$ and twelve-fold in case of $\bar{d}$.

3 Conclusion

This work presents a performance study of the deuteron production cross-section measurements in p+C collisions with the NA61/SHINE experiment. An overview of cuts on events and tracks as well as a description of the simplified dE/dx method was given. Details of the coalescence model together with a description of a Monte-Carlo-based correction for detector geometry were presented. Using this method it will only be possible to obtain results on d yields and production cross-section. For $\bar{p}$ and $\bar{d}$, the event statistics were too low and would have to be significantly increased in order to obtain meaningful results. This might become possible in further data-taking campaigns. NA61/SHINE provides a source of valuable information on many collision systems, which may be utilized for reference measurements in indirect dark matter searches.

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