

Production of Λ hyperons in 4.0A GeV and 4.5A GeV carbon-nucleus interactions at the Nuclotron



The BM@N collaboration

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ABSTRACT: The BM@N experiment (Baryonic Matter at the Nuclotron) is the first fixed-target experiment at the JINR NICA accelerator complex. In this work, data on the interactions of a carbon-ion beam with kinetic energies of 4.0A GeV and 4.5A GeV with C, Al, Cu, and Pb targets are used to measure transverse momentum spectra and rapidity distributions of Λ hyperon yields. The results are compared with the predictions of DCM-SMM, UrQMD, and PHSD transport models and with the Λ yield measurements in other experiments at similar collision energies.

KEYWORDS: Fixed Target Experiments, Heavy-Ion Collision, QCD, Quark Deconfinement

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1 Introduction

The study of collisions of relativistic nuclei provides a unique opportunity to explore nuclear matter under extreme conditions of high density and temperature. Theoretical models suggest that beam kinetic energies in the range of $5 - 20A$ GeV (corresponding to $\sqrt{s_{NN}} = 3.6 - 6.4$ GeV) are optimal for exploring the hadronization phase transition and the properties of dense baryonic matter [1].

The Nuclotron at the NICA accelerator complex provides a wide range of ion beams within the energy range of $\sqrt{s_{NN}} = 2.3 - 3.5$ GeV. These energies are sufficiently high for the production of strange mesons and (multi-) strange hyperons in nucleus-nucleus collisions close to the kinematical threshold. Measurements in this regime are therefore essential for understanding the mechanism of strangeness production and the dynamics of the dense hadronic matter [2, 3].

Λ hyperons, which contain a single strange quark, are important observables in this context. Their production near threshold is sensitive to multi-step processes, secondary interactions, and in-medium effects. Their transverse momentum spectrum and rapidity distribution provide insight into the degree of thermalization, the system dynamics and the underlying reaction mechanisms in heavy-ion collisions.

The production of Λ hyperons at low and intermediate energies has been studied by several experiments, such as FOPI (GSI) [4], HADES (GSI) [5], and STAR (RHIC) [6]. These experiments provided detailed information on Λ hyperon production in symmetric or almost symmetric systems such as Ni + Ni, Ar + KCl, and Au + Au. At higher energies, the collider experiments STAR (RHIC) and ALICE (LHC) have investigated hyperon production

primarily around midrapidity [7–10]. However, systematic measurements of Λ hyperon production in light-ion collisions on light and heavy nuclear targets at few-GeV energies in both the central and forward rapidity regions remain limited. In particular, asymmetric systems at near-threshold energies have not been extensively explored.

The BM@N experiment is the first fixed-target experiment operating at the NICA (JINR) accelerator complex, designed to investigate dense baryonic matter in heavy-ion collisions at Nuclotron energies. Thanks to its fixed-target configuration, the BM@N enables studies of both symmetric and asymmetric beam-target combinations over a broad rapidity range, including forward kinematics. At the moment the BM@N has collected data on collisions of carbon, argon, krypton, and xenon beams with different solid targets.

Results on the production of π^+ and K^+ mesons [11] and of protons, deuterons, and tritons [12] in argon-nucleus interactions were recently published.

This paper presents results on Λ hyperon production in carbon-nucleus interactions at the beam kinetic energies of 4.0A GeV and 4.5A GeV ($\sqrt{s_{NN}} = 3.32$ and 3.46 GeV). Transverse momentum and rapidity spectra are measured within BM@N acceptance, and Λ yields and production cross-sections are extracted and extrapolated to the full phase space. The results are compared with predictions of the DCM-SMM, UrQMD, and PHSD transport models, as well as with measurements from other experiments at similar collision energies.

The paper is organized as follows: section 2 outlines the BM@N experimental setup. Section 3 details the Monte Carlo simulations and trigger efficiency evaluation. Sections 4 – 6 cover the analysis methodology and the event selection procedure. Section 7 describes the procedure for the evaluation of the cross-sections, yields and estimation of the systematic uncertainties. The results and their comparison with models predictions and other experiments are summarized in section 8.

2 Experimental setup

The data used in this analysis were collected with a carbon beam with kinetic energies of 4.0A GeV and 4.5A GeV colliding with four different targets: C, Al, Cu, and Pb. The BM@N setup in the carbon-nucleus run is shown schematically in figure 1.

The BM@N spectrometer is a forward magnetic spectrometer, consisting of beam detectors, a central tracker system located inside a dipole analyzing magnet (0.61T) and outer detectors (not used in this analysis). Charged-particle tracking in this analysis was performed using the central tracking system consisting of one plane of a forward silicon tracking detector (ST) with double-sided readout and six two-coordinate GEM (Gaseous Electron Multiplier) stations composed of five GEM detectors of 66×41 cm² size and two GEM detectors of 163×45 cm² size [13].

The tracking stations were arranged such that the beam passed through their centers. Each successive GEM station was rotated by 180° around the vertical axis. This was done to ensure opposite electron drift direction in the successive stations in order to avoid a systematic shift of reconstructed tracks due to the Lorentz angle in the magnetic field. A technical description of the BM@N spectrometer is provided in [14, 15].

In the present analysis, information from the forward Si detector and GEM detectors [16, 17] was used to reconstruct tracks, as well as primary and secondary vertices. Since the

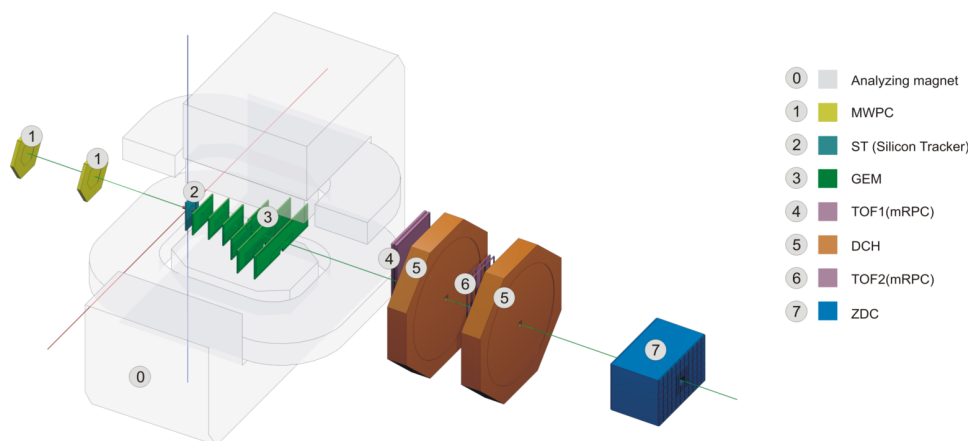


Figure 1. Scheme of the BM@N setup in the carbon beam run.

GEM tracker configuration was tuned to measure relatively high-momentum particles, the geometric acceptance for the relatively soft decay products of strange $V0$ (Λ , K_S^0) particles was rather low (a few percent). The acceptance covers mostly the forward rapidity region in the laboratory frame. The limited acceptance is accounted for in the analysis through detailed Monte Carlo simulations and bin-by-bin acceptance corrections, as described in section 5.

The minimum-bias trigger was based on the charged-particle multiplicity measured in the cylindrical Barrel Detector (BD), surrounding the target as shown in figure 2. The trigger condition required the hit multiplicity in the BD detector exceeds the threshold value, which was adjusted for the C, Al, Cu, and Pb targets. Additional beam-monitoring and timing information were provided by the beam counters (BC2), veto counter (VC), and T0 system (figure 2). The carbon beam intensity during data taking was of the order of a few 10^5 particles per spill, with a spill duration of 2.0 – 2.5 seconds. After quality selection, the analyzed data sample comprises approximately 13 million events at 4.0A GeV and 16 million events at 4.5A GeV.

3 Monte Carlo simulations

Monte Carlo event samples of C + A collisions were produced with the DCM-SMM event generator [18, 19]. The particle transport through the setup volume was simulated with the GEANT4 library [20] integrated into the BmnRoot software framework [21].

The GEM detector response in the magnetic field was simulated with the micro-simulation package Garfield++ [22]. The package provides a detailed description of the processes inside the GEM detector, including the drift and diffusion of released electrons in the electric and magnetic fields, as well as electron multiplication in the GEM foils. As a result, the output signal from the readout plane is well reproduced [13]. To speed up the simulation, the dependencies of the Lorentz shifts and the charge distributions on the readout planes were parameterized and used in the GEM digitization part of the BmnRoot package. The details of the detector alignment and Lorentz shift corrections are described in [23].

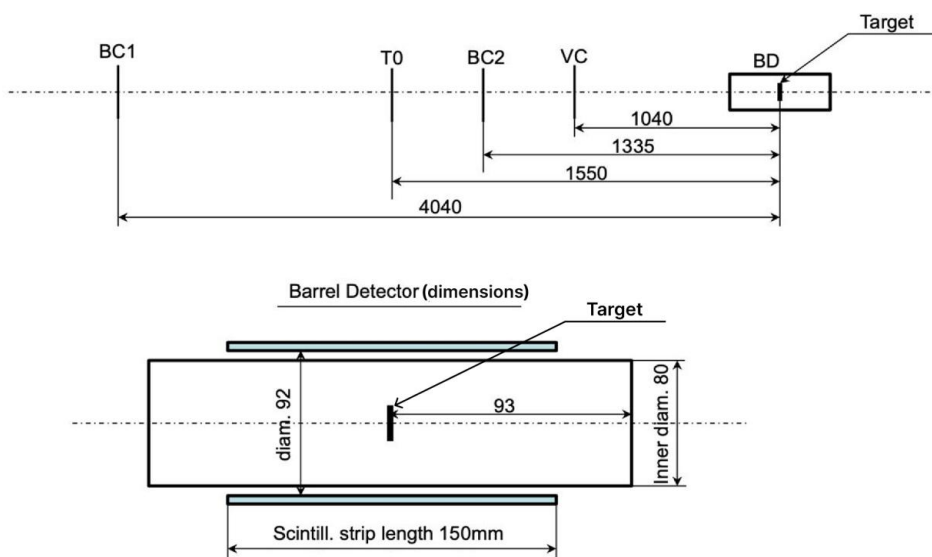


Figure 2. Schematic view of the beam counters, barrel detector, and target position. The target was installed in the center of the cylindrical barrel detector, on its axis. All dimensions are given in millimeters.

The trigger efficiency $\varepsilon_{\text{trig}}$ was evaluated with the DCM-SMM model simulated data. To reproduce the BD trigger response, the BD multiplicity distributions were constructed by combining simulated events containing Λ hyperons with δ -electron background events, which were identified as the main source of fake BD signals in C + A interactions. The BD trigger condition was applied to the Monte Carlo reconstructed events within the BM@N tracking system acceptance. The trigger efficiency is defined as a number of Λ events with passing BD criteria $N_{\Lambda}^{\text{rec}}(\text{BD} \geq n)$ to the total reconstructed number of Λ events N_{Λ}^{rec} :

$$\varepsilon_{\text{trig}} = \frac{N_{\Lambda}^{\text{rec}}(\text{BD} \geq n)}{N_{\Lambda}^{\text{rec}}}. \quad (3.1)$$

The calculated trigger efficiency ranges from $(80 \pm 2)\%$ for C + C to $(95 \pm 2)\%$ for minimum-bias C + Pb interactions.

The systematic uncertainties of $\varepsilon_{\text{trig}}$ include:

1. The contribution of the δ -electron background evaluated by varying the effective target thickness in the simulations between 0.5 and 1.0 of the nominal target thickness;
2. The spread of the trigger efficiency values due to variations of the rapidity y and transverse momentum p_T intervals of reconstructed Λ hyperons;
3. Variations of the trigger efficiency caused by reweighting the simulated track multiplicity distributions to match the experimental ones.

The trigger efficiency obtained in the simulation was cross-checked using data samples recorded with reduced trigger requirements. No significant dependence of the trigger efficiency

on the event multiplicity was observed within the studied range, indicating that the centrality bias of the trigger is negligible.

4 Event selection

Charged particle track reconstruction was based on the cellular automaton approach [24]. Events with Λ hyperon decay were selected by the candidate-driven approach, in which pairs of oppositely charged tracks form reconstructed secondary vertices.

Λ hyperons were identified via their dominant weak decay channel, $\Lambda \rightarrow p + \pi^-$. Particle identification was not used in this analysis. Therefore, all positive tracks were considered as protons, while negative ones were considered as π^- . Contamination from other particle species contributes to the combinatorial background and is accounted for by the invariant-mass background-subtraction procedure described below.

The track selection criteria were as follows:

- Each track was required to have hits in at least four of six GEM stations, where a hit is defined as a combination of two strip clusters on both readout sides (X and X' views) of each detector [13].
- The momentum range of the positive tracks is limited to $p_{\text{pos}} < 3.9(4.4) \text{ GeV}/c$ at 4.0 (4.5) A GeV carbon beam energy to suppress contributions from beam fragments.
- The momentum range of negative tracks is limited to $p_{\text{neg}} > 0.3 \text{ GeV}/c$.
- The distance of closest approach (DCA) between two tracks in the $X - Y$ plane at the vertex reconstructed Z coordinate is smaller than 1.0 cm.
- The distance between the primary and secondary vertices (decay path length - $path$) is required to be larger than 2.5 cm.

The signal from Λ hyperon decays is observed as a narrow peak in the invariant mass distribution of two oppositely charged tracks with the proton and pion mass hypothesis, as shown in figure 3 for a representative (y, p_T) interval.

The invariant mass distribution in each kinematic interval was modeled as the sum of a signal component and a combinatorial background contribution. The signal peak was described by a Gaussian function, $P(m, M_s, \sigma) \propto \exp(-0.5 \cdot ((m - M_s)/\sigma)^2)$, where m is the running invariant mass, M_s and σ are free fit parameters and denote the peak position and width, respectively. The background was parameterized by a threshold function multiplied by an exponential term:

$$f_{\text{bg}}(m) = N \cdot (m - M_0)^A \cdot \exp(-B \cdot (m - M_0)), \quad (4.1)$$

where N , A , and B are free parameters of the fit function and $M_0 = 1.078 \text{ GeV}$ is the kinematic threshold.

The peak region within $\pm 2.5\sigma$ around the Λ mass M_s was excluded from the background fit to avoid signal distortion. The Λ signal was then defined as the sum of the bin contents within the peak region after the background subtraction. The same signal-extraction procedure was consistently applied to Monte Carlo and experimental data.

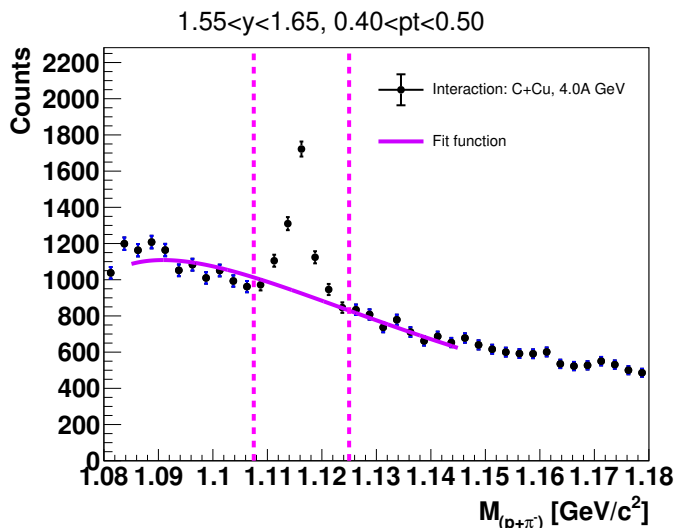


Figure 3. Invariant mass spectrum of (p, π^-) pairs reconstructed from Monte Carlo-generated events in the 4.0A GeV carbon beam with the Cu target (black points). The distribution corresponds to the kinematic region with rapidity $1.55 < y < 1.65$ and transverse momentum $0.4 < p_T < 0.5 \text{ GeV}/c$. The purple solid line represents the result of the background fit according to eq. (4.1) (see text for details). The magenta dashed vertical lines denote the mass window where the Λ signal is calculated as an excess of events with respect to the background fit.

5 Acceptance evaluation

The geometrical acceptance and reconstruction efficiency (referred to as detector acceptance thereafter) for Λ hyperons were evaluated using the DCM-SMM model data generated for the C beam at 4.0A GeV and 4.5A GeV energies and C, Al, Cu, and Pb targets. The simulated data were processed with the same reconstruction and analysis chain as the experimental data.

The kinematic range considered in the analysis ($1.2 < y < 2.1$ and $0.1 < p_T < 1.05 \text{ GeV}/c$) was divided into 8×8 cells in the (y, p_T) space [25]. In each cell, the signal was evaluated following the procedure described in section 4.

The detector acceptance value ω_{acc} was calculated as the ratio of the number of reconstructed Λ hyperons to the number of generated Λ in each (y, p_T) cell: $\omega_{\text{acc}} = N_{\text{rec}_{MC}}/N_{\text{gen}_{MC}}$.

The resulting acceptance maps for C + Cu interactions at 4.0A GeV and 4.5A GeV are shown in figure 4 as representative examples. The white areas indicate cells with negligible efficiencies. All cells with acceptance below 0.01 were excluded from the analysis. An extrapolation procedure was performed to obtain the number of expected Λ events for these low acceptance regions according to the model.

The extrapolation factor f_{extrap} at a given p_T was calculated as the ratio of the number of MC-generated Λ hyperons in all the cells along the p_T direction for a given rapidity interval to the number of reconstructed Λ hyperons with reconstruction efficiency $\omega_{\text{acc}_i} > 0.01$ in that rapidity interval.

The systematic uncertainty of the background subtraction and Λ signal extraction in the simulation was evaluated using a bootstrap sampling method [38]. This uncertainty contributes to the systematic uncertainty of the Λ acceptance. For each (y, p_T) cell, the

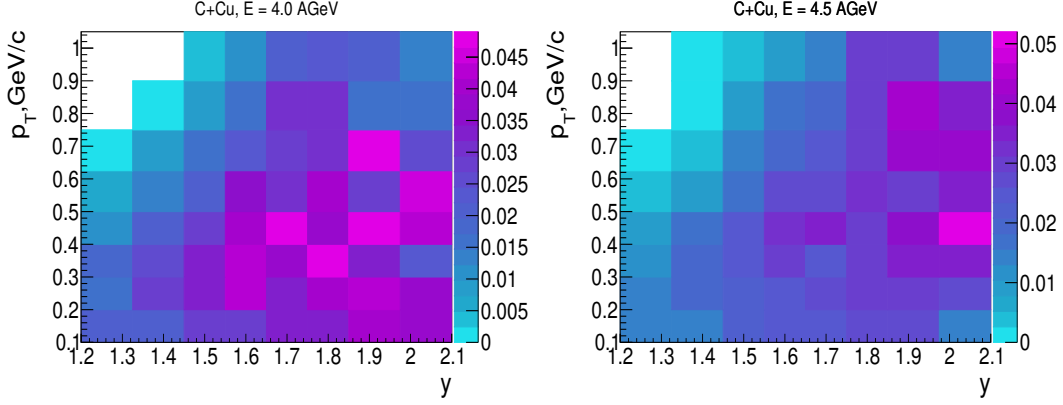


Figure 4. Detector acceptance for Λ emitted in given rapidity and transverse momentum intervals calculated for C + Cu interactions at the beam energy of 4.0A GeV (left) and 4.5A GeV (right).

invariant mass distribution was resampled 1000 times; each time, the signal value was calculated. The distribution of reconstructed yields was parameterized with a Gaussian function, and the σ of the fit was used as the systematic uncertainty of N_{recMC} evaluation. The full acceptance uncertainty includes both statistical and systematic contributions.

6 Data analysis

The number of (p, π^-) pairs reconstructed in each (y, p_T) cell was multiplied by the inverse acceptance value for this cell. The resulting invariant mass distributions of (p, π^-) pairs produced in interactions of a 4.5A GeV carbon beam with C, Al, Cu, and Pb targets are shown in figure 5.

The background part of these distributions was parameterized according to eq. (4.1) in the 1.085–1.145 GeV/c^2 mass region. The region of the Λ signal within the limits 1.1075–1.125 GeV/c^2 was excluded from the fit. The efficiency-corrected number of Λ hyperons was calculated as the sum of the bin contents within the mass-peak region after background subtraction. The uncertainty of the background evaluation was propagated to the Λ signal. The systematic uncertainty of the Λ signal in data was calculated using the same bootstrap sampling method applied previously to Monte Carlo data (see section 5).

7 Evaluation of Λ hyperon cross sections and yields

The inclusive cross section σ_Λ and yield Y_Λ of Λ hyperon production in C + C, C + Al, C + Cu, and C + Pb interactions were calculated in (y, p_T) intervals according to the following formulae:

$$\sigma_\Lambda(y) = \sum_{p_T} \left[\frac{N_\Lambda(y, p_T)}{\varepsilon_{\text{trig}} \cdot L} \right], \quad Y_\Lambda(y) = \frac{\sigma_\Lambda(y)}{\sigma_{\text{inel}}}, \quad (7.1)$$

$$\sigma_\Lambda(p_T) = \sum_y \left[\frac{N_\Lambda(y, p_T)}{\varepsilon_{\text{trig}} \cdot L} \right], \quad Y_\Lambda(p_T) = \frac{\sigma_\Lambda(p_T)}{\sigma_{\text{inel}}}, \quad (7.2)$$

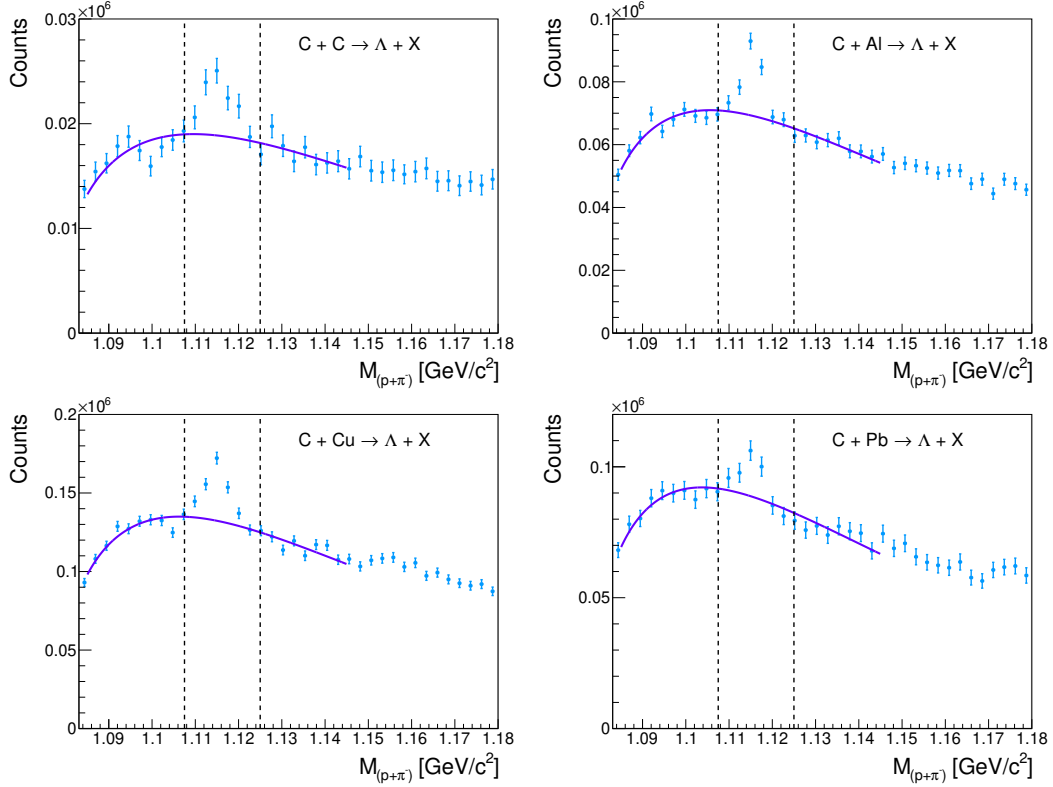


Figure 5. Invariant mass spectra of (p, π^-) pairs reconstructed in interactions of the 4.5A GeV carbon beam with C, Al, Cu, and Pb targets. The violet solid lines represent the result of the fit according to eq. (4.1). The vertical dashed lines show the mass window in which the Λ signal is calculated as the excess of the histogram relative to the background.

where L is the luminosity, N_Λ is the number of acceptance corrected Λ hyperons, $\varepsilon_{\text{trig}}$ is the trigger efficiency, and σ_{inel} is the inelastic C + A interaction cross section. The luminosity was evaluated according to the method presented in [11].

The inelastic cross section for C + C interactions was taken from the measurement published in [26]. The DCM-SMM model calculation is higher than the cross-section measurement by 8%. The inelastic cross sections for C + Al, C + Cu, and C + Pb interactions were calculated using the DCM-SMM model. The cross sections measured at various experiments have some scatter and can be parameterized by the formula [27–29].

$$\sigma_{\text{inel}} = \pi R_0^2 \left(A_P^{1/3} + A_T^{1/3} - b \right)^2, \quad (7.3)$$

with the parameters $R_0 = (1.46 \pm 0.01)$ fm, $b = (1.21 \pm 0.03)$ fm, at $\chi^2 = 3.5/NDF$, given in [26]. Deviations of model calculations from the cross-section parametrization provided by eq. (7.3) amount up to (10–12)%.

The values and uncertainties of σ_{inel} for C + C, C + Al, C + Cu, and C + Pb interactions, used to evaluate Λ hyperon yields, are presented in table 1.

The yields of Λ hyperons in minimum bias C + C, C + Al, C + Cu, and C + Pb interactions were measured in the kinematic range of the Λ hyperon transverse momentum

		C + C	C + Al	C + Cu	C + Pb
σ_{inel} , mb		830 ± 50 [26]	1250 ± 50 [26]	1790 ± 50 [26]	3075 ± 120 [26]
Extrapolation factor to 4π , average	4.0A GeV	2.49 ± 0.18	3.01 ± 0.13	4.00 ± 0.06	6.72 ± 0.44
	4.5A GeV	2.34 ± 0.08	2.88 ± 0.16	3.76 ± 0.15	6.24 ± 0.14
Λ cross section, extrapolated to 4π , mb	4.0A GeV	$47.3 \pm 5.8 \pm 8.3$	$121.0 \pm 15. \pm 31.$	$215. \pm 22. \pm 36.$	low statistics
	4.5A GeV	$52.5 \pm 9.7 \pm 11.6$	$91. \pm 11.3 \pm 31.3$	$249.0 \pm 36. \pm 40.$	$633. \pm 192. \pm 192.$
$Y_{\Lambda}/10^{-2}$	4.0A GeV	$2.3 \pm 0.3 \pm 0.5$	$3.2 \pm 0.4 \pm 0.8$	$3.0 \pm 0.3 \pm 0.5$	low statistics
	4.5A GeV	$2.7 \pm 0.5 \pm 0.6$	$2.5 \pm 0.3 \pm 0.7$	$3.7 \pm 0.4 \pm 0.6$	$3.3 \pm 0.1 \pm 0.1$
$Y_{\Lambda}^{4\pi}/10^{-2}$	4.0A GeV	$5.7 \pm 0.7 \pm 1.0$	$9.6 \pm 1.0 \pm 2.5$	$12.0 \pm 1.0 \pm 2.0$	low statistics
	4.5A GeV	$6.3 \pm 1.2 \pm 1.4$	$7.1 \pm 0.9 \pm 2.5$	$14.0 \pm 2.0 \pm 2.0$	$20.0 \pm 6.0 \pm 6.0$
Number of participants, model prediction					
N_{part} , DCM-SMM		9.0	13.4	23.0	50.5
N_{part} , UrQMD		7.2	11.4	19.3	50.0
N_{part} , PHSD		8.4	11.9	17.3	30.8
$Y_{\Lambda}^{4\pi}/N_{\text{part}}^{DCM-SMM}/10^{-3}$	4.0A GeV	$6.3 \pm 0.08 \pm 0.1$	$7.2 \pm 0.8 \pm 2.0$	$5.7 \pm 0.4 \pm 0.3$	low statistics
	4.5A GeV	$7.0 \pm 0.1 \pm 0.2$	$5.3 \pm 0.7 \pm 1.9$	$6.1 \pm 0.9 \pm 0.9$	$3.8 \pm 1.1 \pm 1.1$

Table 1. Λ hyperon production cross sections and yields at 4.0A GeV and 4.5A GeV in C + C, C + Al, C + Cu, and C + Pb interactions. The first uncertainty is statistical; the second one is systematic.

$0.1 < p_T < 1.05 \text{ GeV}/c$ and the Λ hyperon rapidity in the laboratory frame $1.2 < y < 2.1$ for 4.0A GeV and 4.5A GeV data.

The uncertainties of tracking reconstruction efficiency, luminosity, and trigger are taken into account as part of the uncertainty of the weighted event.

For each (y, p_T) interval, the uncertainty δY_{Λ} of the Λ yield includes several sources:

- statistical fluctuations of the signal in experimental and MC data — $\delta Y_{\Lambda}^{\text{stat}}(\text{data}, mc)$;
- systematic variations of the signal evaluated by the bootstrapping method for experimental and MC data — $\delta Y_{\Lambda}^{\text{syst}}(\text{data}, mc)$;
- systematic uncertainties originating from variations of the *path* and *dca* within 10% of the nominal value used in the analysis — $\delta Y_{\Lambda}^{\text{cuts}}(\text{data}, mc)$.

$$\delta Y_{\Lambda} = \sqrt{\left(\delta Y_{\Lambda}^{\text{stat}}(\text{data}, mc)\right)^2 + \left(\delta Y_{\Lambda}^{\text{syst}}(\text{data}, mc)\right)^2 + \left(\delta Y_{\Lambda}^{\text{cuts}}(\text{data}, mc)\right)^2} \quad (7.4)$$

The corresponding values are shown in tables 1, 2, and 3 of section 8.

8 Results

The production cross sections and yields of Λ hyperons, integrated luminosity, and extrapolation factors to the full phase space for C + C, C + Al, C + Cu, and C + Pb interactions are shown in table 1. The extrapolation factors were calculated by averaging the predictions of the DCM-SMM [18, 19] and UrQMD [30] models. In nucleus-nucleus collisions with different

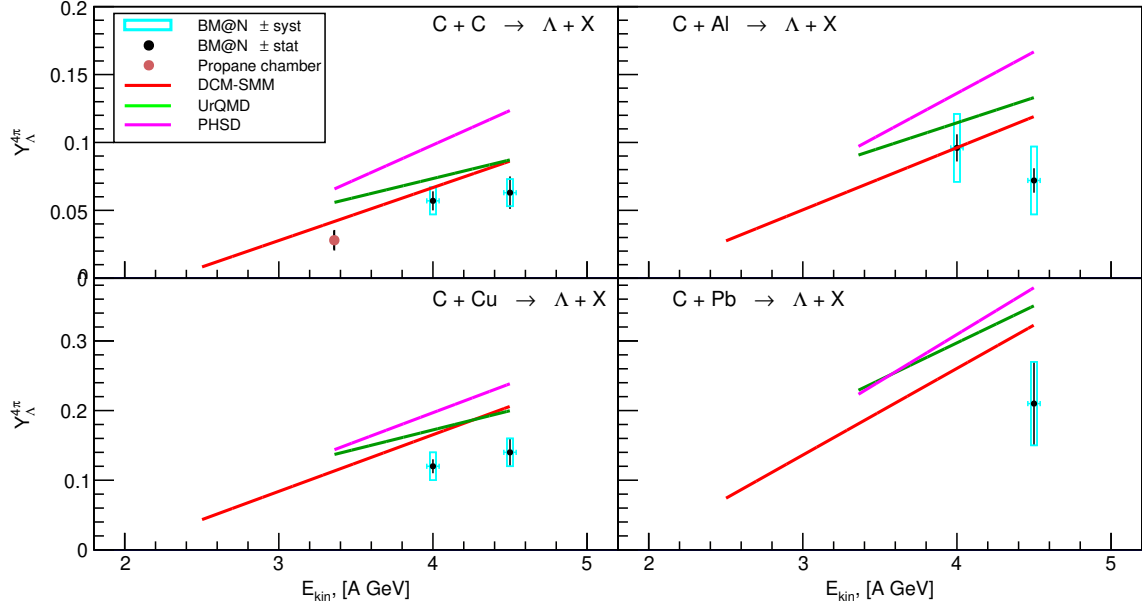


Figure 6. Energy dependence of Λ hyperon $Y_{\Lambda}^{4\pi}$ yields in C + C, C + Al, C + Cu, and C + Pb interactions. The result of the Propane Chamber experiment [32, 33] for C + C is shown for comparison. The error bars represent the statistical uncertainties; the blue boxes show the systematic uncertainties. The predictions of the DCM-SMM, UrQMD, and PHSD models are shown as colored lines.

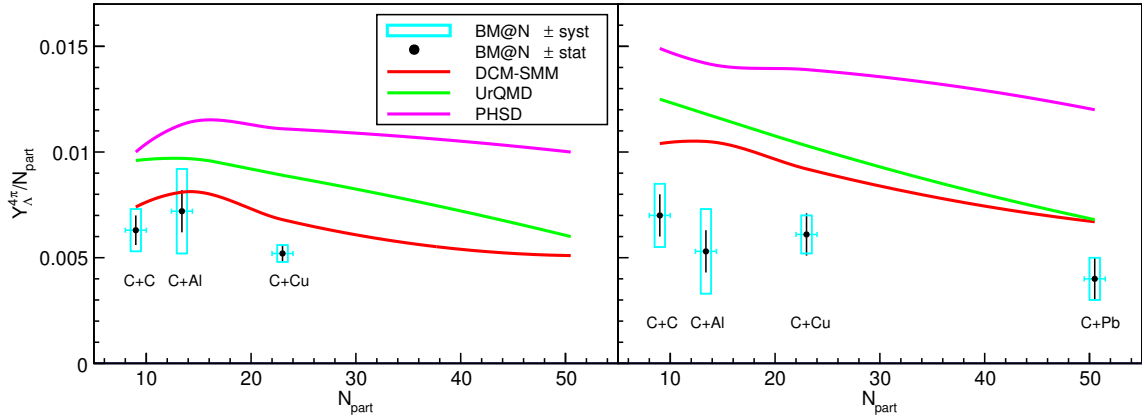


Figure 7. Ratios of the Λ hyperon yields to the number of nucleon participants measured by BM@N in minimum bias carbon-nucleus interactions at 4.0A GeV (left) and 4.5A GeV (right) compared with the model predictions.

atomic masses, the conventional quantity used in data analysis is the number of participants (N_{part}). The number of participants was calculated for C + C, C + Al, C + Cu, and C + Pb interactions on the basis of the DCM-SMM, UrQMD, and PHSD [31] models. The N_{part} values are the same for 4.0A GeV and 4.5A GeV. The yields of Λ hyperons normalized to N_{part} from the DCM-SMM are shown in table 1. The measured Λ yields (Y_{Λ}) within the BM@N acceptance were extrapolated to the full kinematic range ($Y_{\Lambda}^{4\pi}$).

		C + C	C + Al	C + Cu	C + Pb
$1.20 < y < 1.45$	4.0A GeV	$0.036 \pm 0.008 \pm 0.003$	$0.064 \pm 0.009 \pm 0.005$	$0.042 \pm 0.009 \pm 0.005$	low statistics
	4.5A GeV	$0.051 \pm 0.015 \pm 0.008$	$0.042 \pm 0.009 \pm 0.005$	$0.058 \pm 0.014 \pm 0.005$	$0.051 \pm 0.02 \pm 0.008$
$1.45 < y < 1.65$	4.0A GeV	$0.022 \pm 0.005 \pm 0.002$	$0.046 \pm 0.007 \pm 0.004$	$0.047 \pm 0.007 \pm 0.004$	low statistics
	4.5A GeV	$0.027 \pm 0.008 \pm 0.008$	$0.044 \pm 0.006 \pm 0.004$	$0.051 \pm 0.007 \pm 0.004$	$0.039 \pm 0.01 \pm 0.005$
$1.65 < y < 1.85$	4.0A GeV	$0.021 \pm 0.004 \pm 0.002$	$0.019 \pm 0.005 \pm 0.004$	$0.033 \pm 0.005 \pm 0.004$	low statistics
	4.5A GeV	$0.017 \pm 0.008 \pm 0.008$	$0.021 \pm 0.005 \pm 0.004$	$0.039 \pm 0.006 \pm 0.004$	$0.034 \pm 0.009 \pm 0.004$
$1.85 < y < 2.10$	4.0A GeV	$0.012 \pm 0.004 \pm 0.002$	$0.007 \pm 0.005 \pm 0.004$	$0.024 \pm 0.005 \pm 0.004$	low statistics
	4.5A GeV	$0.033 \pm 0.008 \pm 0.008$	$0.015 \pm 0.004 \pm 0.004$	$0.031 \pm 0.005 \pm 0.004$	$0.012 \pm 0.007 \pm 0.004$

Table 2. Λ hyperon yields as a function of rapidity for C + C, C + Al, C + Cu, and C + Pb interactions. The first uncertainty is statistical; the second one is systematic.

The $Y_{\Lambda}^{4\pi}$ yields as a function of the carbon beam kinetic energy (E_{kin}) are shown in figure 6. The result of the Propane Chamber experiment [32, 33] on the Λ yield in C + C interactions with a kinetic energy of 3.36A GeV is shown in figure 6 (top left) for comparison. The BM@N results are compared with the predictions of the DCM-SMM, UrQMD, and PHSD models. Models predict the increase of the Λ hyperon yield with increasing beam energy. All models predict higher yields than was measured and exceed the experimental data. The better agreement was achieved with the DCM-SMM model, while the PHSD model predicts considerably higher total Λ hyperon yield.

A comparison of the measured 4π extrapolated yields $Y_{\Lambda}^{4\pi}$ normalized to the number of participants N_{part} with the predictions of the DCM-SMM, UrQMD, and PHSD models for 4.0A GeV and 4.5A GeV carbon-nucleus interactions is shown in figure 7. The measured integral yields per participant show either independence of the number of participants or some decrease for heavier target nuclei as predicted by the theoretical models.

The rapidity distributions of Λ hyperons were measured in the transverse momentum range of $0.1 < p_T < 1.05$ GeV/c. The differential y rapidity spectra of Λ hyperons in the laboratory frame, corrected for the detector acceptance and efficiency, are presented in figure 8 and the corresponding numerical values are listed in table 2. The transformation of the y distribution from the laboratory system to the center-of-mass system is given by a shift $y_{CM} = y - 1.17(1.22)$ for 4.0 (4.5)A GeV.

The predictions of the DCM-SMM, UrQMD, and PHSD models are shown in figure 8 and figure 9 for comparison. The models describe the shape of the differential spectra in y and p_T in general. However, in most cases, they overestimate the measured Λ yields. The predictions of the DCM-SMM and UrQMD models are closer to experimental results than those of the PHSD model. The PHSD model predicts a stronger rapidity dependence of the Λ hyperon yield compared to the DCM-SMM and UrQMD models and provides worse agreement with BM@N data.

The transverse momentum spectra of Λ hyperons are presented in figure 9 and table 3. They were parameterized in the measured y range by the function:

$$\frac{1}{p_T} \cdot \frac{d^2 N}{dp_T dy} \propto \exp\left(-\frac{m_T - m_{\Lambda}}{T_0}\right), \quad (8.1)$$

		C + C	C + Al	C + Cu	C + Pb
$0.10 < p_T < 0.30$	4.0A GeV	$0.031 \pm 0.004 \pm 0.003$	$0.039 \pm 0.009 \pm 0.004$	$0.047 \pm 0.009 \pm 0.005$	low statistics
	4.5A GeV	$0.027 \pm 0.008 \pm 0.003$	$0.037 \pm 0.009 \pm 0.005$	$0.06 \pm 0.01 \pm 0.005$	$0.03 \pm 0.02 \pm 0.007$
$0.30 < p_T < 0.50$	4.0A GeV	$0.036 \pm 0.004 \pm 0.003$	$0.063 \pm 0.009 \pm 0.005$	$0.054 \pm 0.007 \pm 0.005$	low statistics
	4.5A GeV	$0.064 \pm 0.006 \pm 0.004$	$0.060 \pm 0.004 \pm 0.005$	$0.07 \pm 0.01 \pm 0.005$	$0.06 \pm 0.01 \pm 0.006$
$0.50 < p_T < 0.75$	4.0A GeV	$0.025 \pm 0.002 \pm 0.003$	$0.030 \pm 0.005 \pm 0.004$	$0.032 \pm 0.005 \pm 0.004$	low statistics
	4.5A GeV	$0.025 \pm 0.003 \pm 0.003$	$0.023 \pm 0.003 \pm 0.004$	$0.041 \pm 0.006 \pm 0.004$	$0.034 \pm 0.007 \pm 0.004$
$0.75 < p_T < 1.05$	4.0A GeV	$0.004 \pm 0.001 \pm 0.001$	$0.013 \pm 0.003 \pm 0.004$	$0.013 \pm 0.005 \pm 0.004$	low statistics
	4.5A GeV	$0.012 \pm 0.001 \pm 0.002$	$0.006 \pm 0.003 \pm 0.002$	$0.011 \pm 0.002 \pm 0.004$	$0.007 \pm 0.004 \pm 0.002$

Table 3. Λ hyperon yields as a function of transverse momentum for C + C, C + Al, C + Cu, and C + Pb interactions. The first uncertainty is statistical; the second one is systematic.

where $m_T = \sqrt{m_\Lambda^2 + p_T^2}$ is the transverse mass, the inverse slope parameter T_0 is a free parameter of the fit.

The inverse slope T_0 values resulting from the fit of the invariant p_T spectra are shown in table 4 for 4.0A GeV and 4.5A GeV carbon beam data, respectively. The calculated numbers show an increase in the T_0 inverse slope parameter with increasing target mass. Although statistical and systematic uncertainties do not allow a clear conclusion regarding the dependence of the spectral slopes on the system-size or energy.

The fully integrated 4π Λ yields (n_{CC}^Λ) in C + C collisions were compared with a calculation based on the parametrization of the total Λ hyperon yield n_{pp}^Λ in proton-proton ($p + p$) interactions [34, 35] and scaled to the C + C system by the number of participants and corrected for isospin effects.

The parametrization is based on the Lund String Model (LSM) [34] and expressed as:

$$n_{pp}^\Lambda = a(x - 1)^b x^{-c}, \quad (8.2)$$

where $x = s/s_0$ is the ratio of the center-of-mass energy squared s and the production threshold energy squared s_0 , and a , b , c are fit parameters [35].

Since C + C collisions include not only $p + p$ but also $p + n$ and $n + n$ interactions, and taking into account that the near-threshold Λ yields are about 25% lower in $n + n$ and $n + p$ compared to $p + p$ collisions [36], the following isospin correction factor was applied:

$$k_{\text{iso}} = f_{pp} \cdot \alpha + (f_{np} + f_{pn} + f_{nn}) \cdot \beta, \quad (8.3)$$

with $\alpha = 1.0$ for $p + p$ and $\beta = 0.75$ for $n + n$, $n + p$, and $p + n$ collisions. The fractions f_{ij} are determined by the composition of nucleons in the colliding carbon nuclei and targets (e.g. $f_{np} = f_{pn} = f_{pp} = f_{nn} = 0.25$ for $^{12}\text{C} + ^{12}\text{C}$ collisions).

The total yield $Y_\Lambda^{4\pi}$ for C + C was scaled as:

$$Y_\Lambda^{4\pi} = n_{pp}^\Lambda \cdot k_{\text{iso}} \cdot N_{\text{part}}, \quad (8.4)$$

where N_{part} is the number of participating nucleons, and k_{iso} is the isospin correction factor in eq. (8.3) for the 4π extrapolated Λ yields.

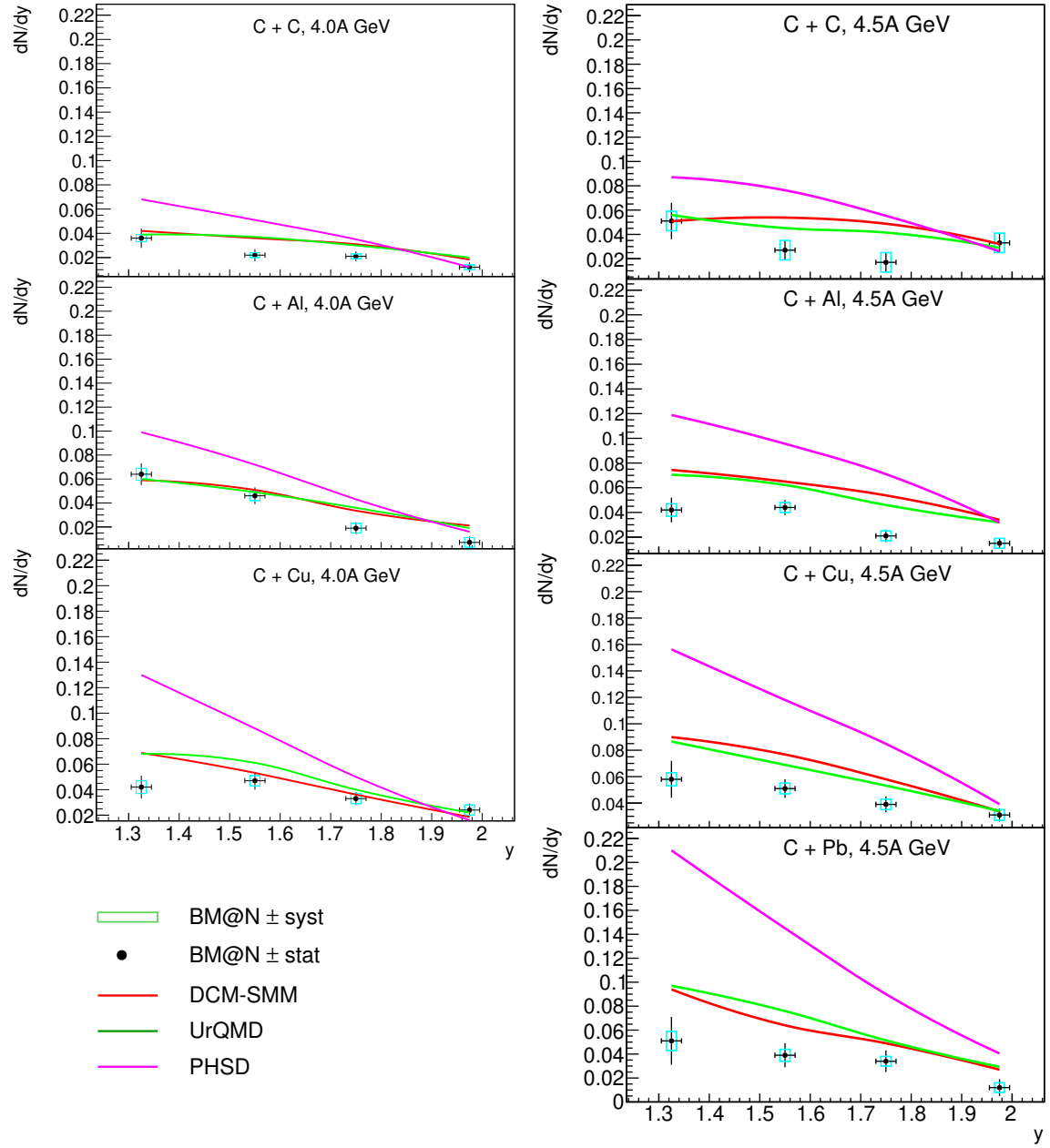


Figure 8. Rapidity distributions of Λ hyperons produced in C + C, C + Al, and C + Cu interactions at the carbon beam energy of 4.0A GeV (left column) and 4.5A GeV (right column).

		C + C	C + Al	C + Cu	C + Pb
Inverse slope T_0 , MeV	4.0A GeV	$89 \pm 9 \pm 17$	$99 \pm 10 \pm 16$	$108 \pm 11 \pm 14$	low statistics
	4.5A GeV	$107 \pm 17 \pm 17$	$86 \pm 8 \pm 17$	$91 \pm 8 \pm 15$	$99 \pm 17 \pm 20$

Table 4. The inverse slope parameters of the p_T spectra for C + C, C + Al, C + Cu, and C + Pb configurations at 4.0–4.5A GeV. The first value is statistical and the second one is systematic uncertainty.

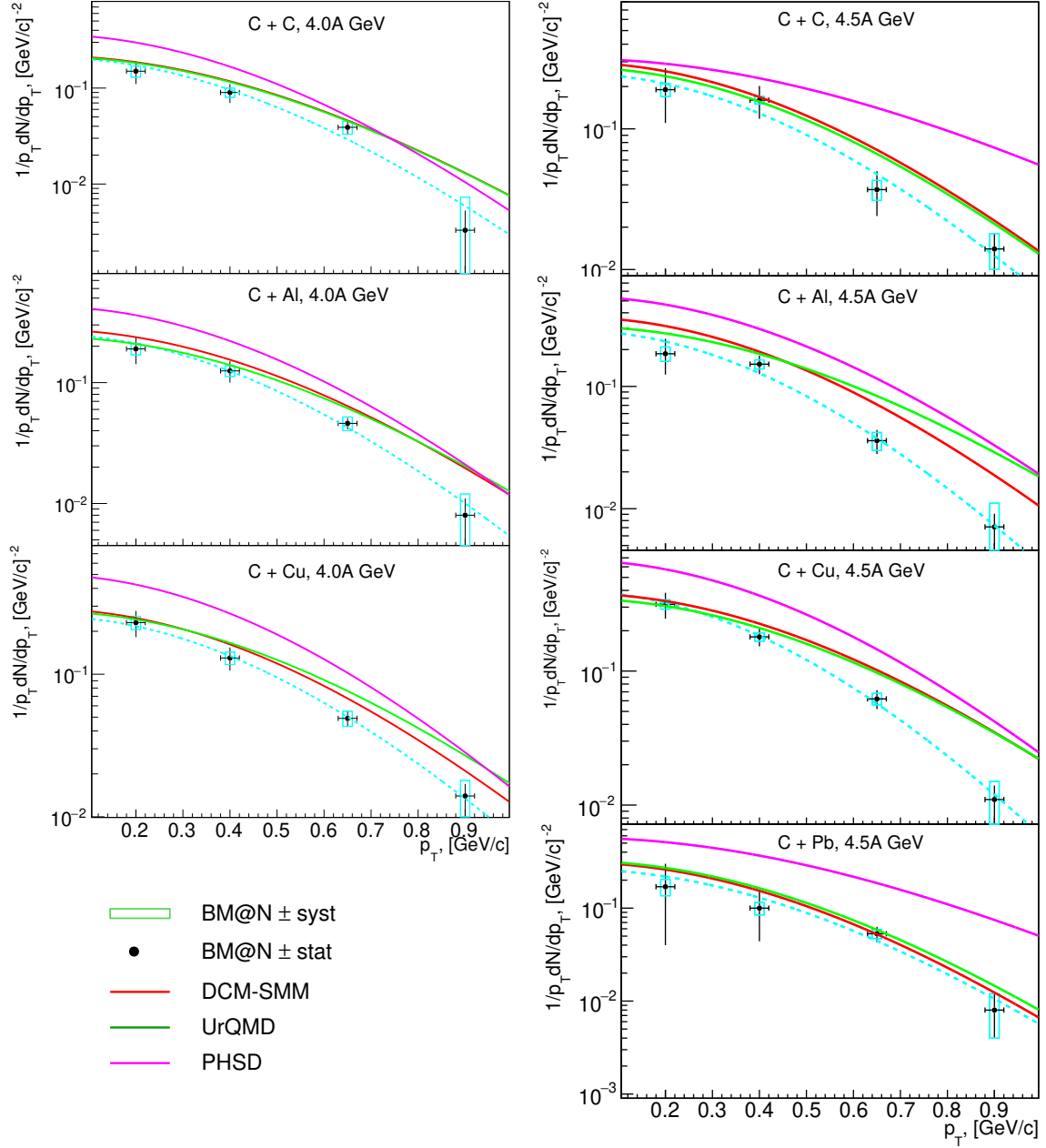


Figure 9. Transverse momentum distributions of Λ hyperons produced in interactions of the carbon beam with C + C, C + Al, and C + Cu targets at energies of 4.0A GeV (left plots) and 4.5A GeV (right plots). The blue lines represent the results of the parameterization described in the text.

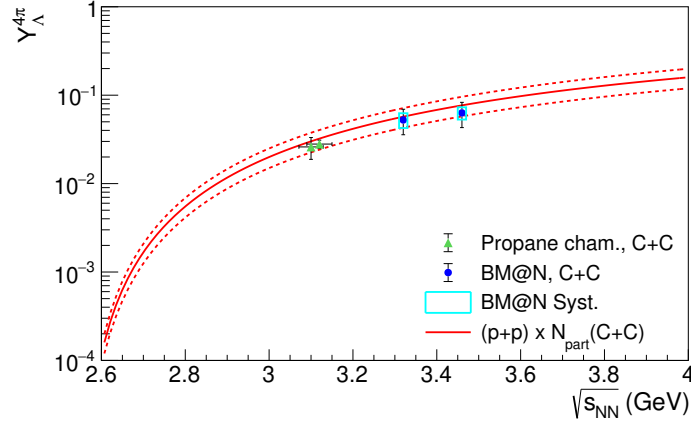


Figure 10. The integrated yield of Λ hyperons in $C + C$ collisions as a function of $\sqrt{s_{NN}}$. BM@N experimental data are compared with a parameterization based on pp collisions scaled to $N_{\text{part}} = 9$. Dashed red lines indicate the uncertainties in the predicted excitation function (about 25%).

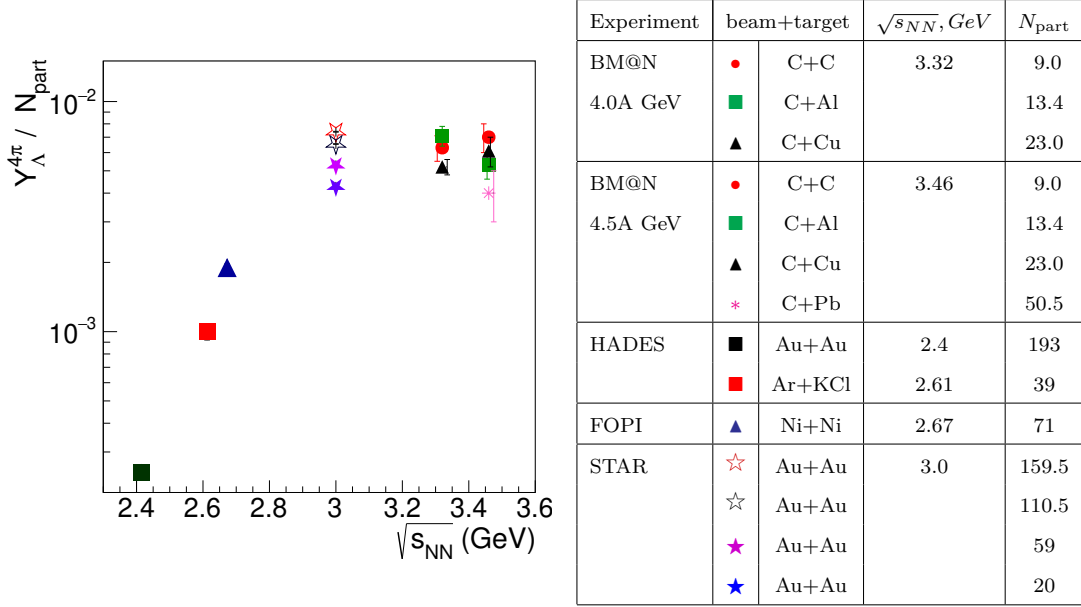


Figure 11. Integral Λ yields normalized to N_{part} as a function of collision energy $\sqrt{s_{NN}}$.

The BM@N results for Λ yields in $C + C$ collisions at 4.0A GeV and 4.5A GeV are in good agreement with the scaled $p + p$ parameterization model as shown in figure 10. The parameterization provides a reliable basis for estimating Λ hyperon production in carbon-carbon interactions. The agreement with the BM@N experimental data supports its applicability for light symmetric systems. In addition, it provides an independent cross-check of the number of participating nucleons N_{part} used in the scaling, which was taken from the DCM-SMM model and evaluated according to existing measurements from the Propane Chamber experiment.

The measured fully integrated 4π Λ yields were compared with the results from other heavy-ion experiments in figure 11. To allow for a direct comparison, all yields were normalized

to the corresponding average numbers of participating nucleons N_{part} , strongly depending on the colliding nuclei and collision centralities, see table in figure 11.

A comparison of the normalized Λ yields at lower energies, measured by the HADES collaboration in Au + Au at 1.23A GeV ($\sqrt{s_{NN}} = 2.4$ GeV) [37] and Ar + KCl at 1.76A GeV ($\sqrt{s_{NN}} = 2.61$ GeV) [5], as well as the FOPI result in Ni + Ni at 1.93A GeV ($\sqrt{s_{NN}} = 2.67$ GeV) [4], shows a smooth increase in the yield with rising collision energy. For $\sqrt{s_{NN}} = 3.0$ GeV, the integrated Λ yields and corresponding values of N_{part} for each centrality class were taken from the publication by the STAR collaboration [6].

The STAR results for relatively peripheral collisions with $N_{\text{part}} \simeq 20$ and $N_{\text{part}} \simeq 59$ are in agreement with the BM@N data points obtained at similar values of N_{part} . For more central Au + Au collisions, the STAR measurements show higher normalized Λ yields.

This comparison indicates that, after normalization by the number of participating nucleons, Λ production exhibits a smooth energy dependence across different collision systems within an overlapping N_{part} range.

9 Summary

The BM@N experiment, exploring the advantages of the fixed-target setup, studied Λ hyperon production in symmetric and asymmetric beam-target configurations. The data sets were collected with two kinetic energies of the carbon beam 4.0A GeV and 4.5A GeV, with one symmetric C + C and three asymmetric C + Al, C + Cu, and C + Pb layouts. These results are compared with the predictions of DCM-SMM, UrQMD, and PHSD models. For the C + C reaction, the Λ hyperon yield is also compared with the results of the Propane Chamber experiment obtained in C + C interactions at lower energy. The Λ hyperon production cross sections were evaluated to be $(47.3 \pm 5.8 \text{ mb})$ and $(52.5 \pm 9.7 \text{ mb})$ for C + C collisions at energies of 4.0A GeV and 4.5A GeV, respectively. These values are about twice as large as the results of the Propane Chamber experiment at 3.36A GeV ($24 \pm 6 \text{ mb}$), indicating a general rise in the production cross section with increasing collision energy. The cross sections and yields of Λ hyperons in C + C, C + Al, C + Cu, and C + Pb (only at 4.5A GeV) collisions are presented in table 1 for both beam energies, as well as in figure 6.

The BM@N results for Λ production in C + C collisions at 4.0A GeV and 4.5A GeV show good agreement with a proton-proton-based parameterization model scaled to the carbon-carbon system. The scaling takes into account the number of participants involved in the reaction, estimated by the DCM-SMM model, as well as the isospin effects.

The Λ yields from different experiments are scaled by the average number of participants, N_{part} , to allow a direct comparison between various colliding nuclear systems (figure 11). The results of this scaling are consistent with a general energy dependence for various collision systems measured over an overlapping N_{part} range.

There is an indication of an increase in the slope parameter T_0 , extracted from exponential fits to the transverse momentum spectra, with target mass. However, the statistical and systematic uncertainties do not allow a definitive conclusion regarding the system-size or the energy dependence of the spectral slopes. A more precise determination of these dependencies will require additional statistics to be collected in future BM@N runs.

The present BM@N results confirm the feasibility of high quality Λ hyperon production studies with different beam-target configurations at Nuclotron facility.

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Data Availability Statement. This article has no associated data or the data will not be deposited.

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