

Λ hyperon reconstruction at the BM@N experiment and prospects for polarization studies

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Abstract. The BM@N detector at Nuclotron has collected data with different beams (C, Ar, Kr) on different targets. Results of the data analysis on Λ hyperon production in interactions of the 4 GeV kinetic energy carbon beam with C, Al, Cu targets are presented. Plans for future running of the experiment and physics analyses are described including expectations for the Λ hyperon polarization studies on the basis of the Monte Carlo simulated event sample.

1. BM@N Detector for Studies of Baryonic Matter at the Nuclotron

BM@N (Baryonic Matter at Nuclotron) is the first experiment operational at the Nuclotron/NICA accelerating complex. The purpose of the BM@N experiment is to study relativistic heavy ion beam interactions with fixed targets [1]. The Nuclotron will provide the experiment with beams of a variety of particles, from protons to gold ions, with a kinetic energy ranging from 1 to 6 GeV/nucleon. The maximum kinetic energy of ions with the charge to atomic weight ratio of 0.5 is 6 GeV/nucleon. The maximum kinetic energy of gold ions with Z/A of 0.4 is 4.5 GeV/nucleon, while the maximum kinetic energy for protons is 13 GeV. Recently the BM@N experiment collected data in beams of carbon, argon, and krypton ions. The planned intensity of the gold ion beam at BM@N is 10^6 ions/s. The acceleration of the gold ion beam is planned in 2021, after the Nuclotron upgrade. The beam energy of the BM@N experiment is in the intermediate range between experiments at the SIS-18 and NICA/FAIR facilities and partially overlaps the energy range of the HADES experiment. The acquisition rate of non-peripheral collisions, i.e., central or intermediate interactions is expected to range from 20 to 50 kHz at the second stage of the BM@N experiment in 2022 and later. The interaction rate is limited by the capacity of the data acquisition system and readout electronics.

2. First Results of the BM@N Runs

The technical runs with the BM@N detector were performed in the deuteron beam in December 2016 and in the carbon beam in March 2017. The kinetic energy was 4 GeV/nucleon for the deuteron beam and was varied from 3.5 to 4.5 GeV/nucleon for the carbon beam. The starting configuration of the central tracker was based on a forward silicon strip detector and a set of GEM detectors [2]. The experimental data from the central tracker, outer drift chambers, time-of-flight detectors, zero degree calorimeter and trigger detectors were read out using the integrated data acquisition system. The extended configuration of the BM@N set-up was realized



in the recent runs with the argon and krypton beams performed in March 2018. The set-up comprised GEM detectors with the size of $163 \times 45 \text{ cm}^2$, forward silicon strip detectors, full time-of-flight system, extended trigger system, hadron and electro-magnetic calorimeters. The collected data were used to check efficiencies of sub-detectors and develop algorithms for the event reconstruction and analysis. In particular, experimental data of minimum bias interactions of the beam with different targets were analyzed with the aim to reconstruct tracks, primary and secondary vertices using the central tracking detectors [3, 4, 5]. The reconstructed objects were used to select decays of Λ hyperons to p, π^- pairs. Since particle identification at this stage of the analysis was not used, all positive tracks were considered as protons and all negative as π^- . The invariant mass distributions of p and π^- are shown in Fig. 1 for reconstructed interactions of the carbon beam with the C and Al targets. In future, the background under the signal will be reduced by introducing additional silicon tracking detectors to improve the primary and decay vertex resolution.

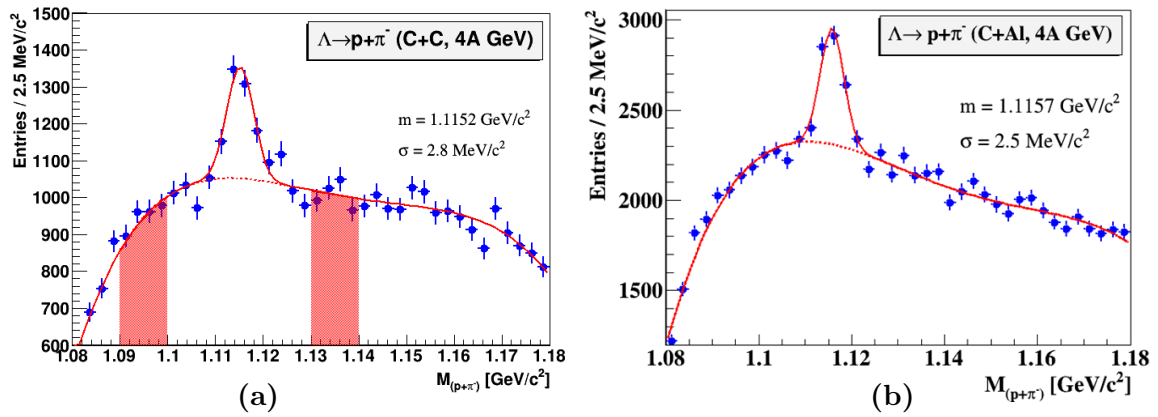


Figure 1. Invariant mass spectrum of proton and π^- pairs reconstructed in interactions of the 4 AGeV carbon beam with the C (a) and Al (b) targets. Shaded areas illustrate sidebands for the background estimation in Sect. 3.

The yields of Λ hyperons in minimum bias interactions of the 4 AGeV carbon beam with the C, Al, Cu targets were measured in the kinematic range on the Λ transverse momentum of $0.1 < p_T < 1.05 \text{ GeV}/c$ and the rapidity in c.m.s. of $0.03 < y^* < 0.93$. The y^* and p_T spectra of the Λ hyperon yields corrected for the detector acceptance and efficiency are presented in Fig. 2. The predictions of the DCM-QGSM [6] and URQMD models are shown for comparison. The measured spectra of the Λ hyperon yields in p_T are parameterized by the form: $1/p_T d^2N/dp_T dy \propto \exp(-(m_T - m_\Lambda)/T)$, where $m_T = \sqrt{(m_\Lambda^2 + p_T^2)}$ is the transverse mass, and the inverse slope parameter (temperature) T is a free parameter of the fit. The value of T extracted from the fit of the p_T spectra is about 100 MeV for C+C interactions rising up to 160 MeV for C+Cu interactions. The fit results are consistent within the uncertainties with the model predictions. The measured yields of the Λ hyperons in minimum bias C+C interactions are extrapolated into the full kinematical range using averaged predictions of the DCM-QGSM and URQMD models and compared in Fig. 3 with the results of other experiments [7, 8, 9].

3. A Monte Carlo Study of Lambda Hyperon Polarization

Reconstructed Λ hyperon decays to $p\pi^-$ pairs can be used to extract hyperon polarization from the angular distribution of the final state particles. The parity-preserving polarization of strange hyperons in hadronic interactions is transverse to scattering plane. It is large and sensitive to the strong interactions mechanisms. In the heavy-ion collisions this polarization can be diluted

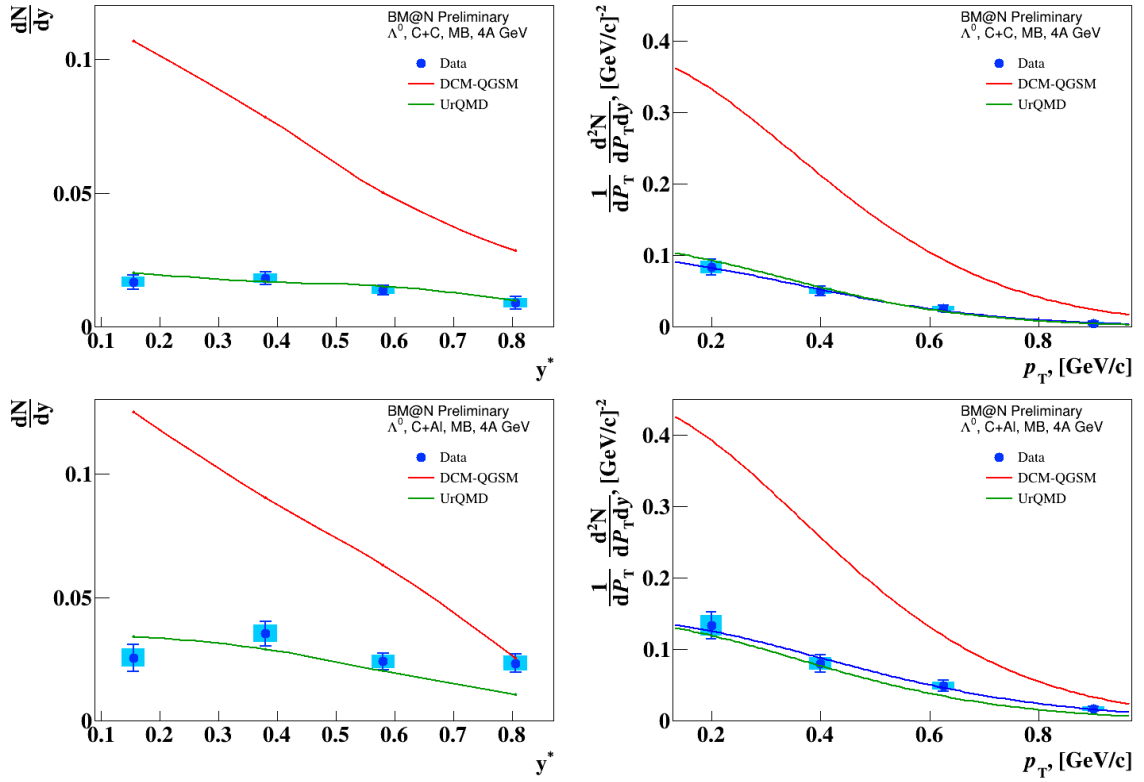


Figure 2. Yields of Λ hyperons in minimum bias C+C (upper row) and C+Al (lower row) interactions vs rapidity y^* in c.m.s. (left column) and transverse momentum p_T (right column). The predictions of the DCM-QGSM and UrQMD models are shown as lines.

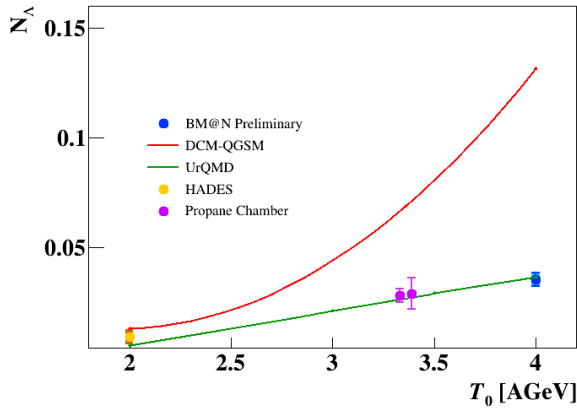


Figure 3. Energy dependence of Λ hyperon yields in C+C interactions measured in different experiments. The BM@N result is compared with the data taken from [7, 8, 9]. The predictions of the DCM-QGSM and UrQMD models are shown.

due to rescattering in the QCD medium, while the polarization transverse to reaction plane may emerge. It is sensitive to parity-odd characteristics of QCD medium (vorticity, hydrodynamic helicity) and to QCD anomalous transport.

To check the polarization extraction method and develop analysis procedures, an event sample of 500 thousand central Au+Au collisions (0-3.8 fm) with the beam kinetic energy of 4.5 GeV/nucleon ($\sqrt{s} = 3.5A$ GeV) was created using the DCM-QGSM event generator. Λ hyperon polarization was introduced according to the prescription described in [10]. In this approach, the polarization is measured with respect to the production plane of the Λ hyperon: $\vec{n} = \hat{p}_{beam} \times \vec{p}$, where \hat{p}_{beam} is aligned with the direction of the incoming beam and \vec{p} is the Λ momentum. In the Λ rest frame, the angle θ between the decay proton and the analyzing direction \vec{n} will follow

the probability distribution:

$$w(\cos \theta) = \frac{1}{2}(1 + \alpha P \cos \theta), \quad (1)$$

where $\alpha = 0.642$ is the decay asymmetry of the parity violating weak decay $\Lambda \rightarrow p + \pi^-$ and P is transverse Λ polarization.

The event generator output was used to produce two event samples: with and without polarization effects activated by switching on and off lambda anisotropical decay according to Expr. (1) during the particle transport through the detector set-up with the GEANT3 package.

After event reconstruction and selection of Λ candidates, a measured $\cos \theta$ -distribution was produced, where θ is defined in (1). In order to subtract the background contribution from the measured $\cos \theta$ -distribution, a so-called sideband approach was used. Its main idea is to subtract the distribution obtained for events well outside of the peak region of the Λ invariant mass distribuion (in sidebands - Fig. 1) dominated by the background $p\pi^-$ combinations from the one in the peak region (containing signal combinations). The subtraction was done in bins of $\cos \theta$ and the background contribution was evaluated from the polynomial fit of two sideband values and its integral in the peak region. One can see in Fig. 4 that the procedure produced a good description of the background contribution, i.e. the extracted from the data signal distribution is almost identical to the true one.

As can be seen in Fig. 4 (b) (filled circles), the reconstructed $\cos \theta$ -distribution can not be directly described by the expression (1) due to detector acceptance effects which distort the original linear dependence. In order to correct for detector effects, one can try to apply a simple approach based on the Monte Carlo simulation of the detector acceptance using events without the effect under study, i.e. with zero lambda polarization [11]. The “unpolarized” $\cos \theta$ -distribution is shown in Fig. 4 (b) (empty circles). By dividing the “polarized” distribution by the “unpolarized” one it is possible to observe the net effect due to polarization (Fig. 6).

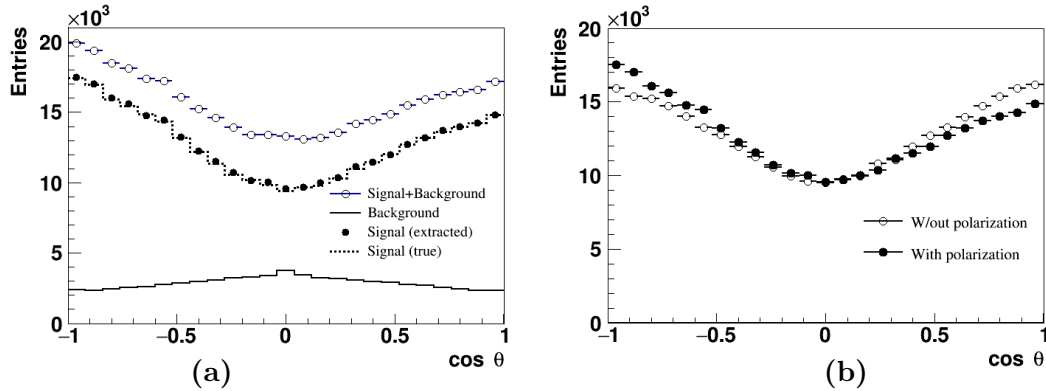


Figure 4. (a) $\cos \theta$ -distributions for $p\pi^-$ combinations from the peak region of the invariant mass distribution: empty circles - signal + background, solid line - estimated background, filled circles - extracted signal, dashed line - true signal; (b) background subtracted $\cos \theta$ -distributions with (filled circles) and without (empty circles) polarization effects taken into account.

4. Polarization extraction

Figure 5 shows the model predictions for lambda polarization as functions of its transverse momentum and Feynman variable $x = p_\Lambda/p_{beam}$. Polarization increases with transverse momentum and reaches a maximum for some intermediate values of the Feynman variable. One can see also some fraction of zero-polarization lambdas which are the secondary ones (mostly from Σ^0 decays) and which were forced to be unpolarized at this stage of the analysis.

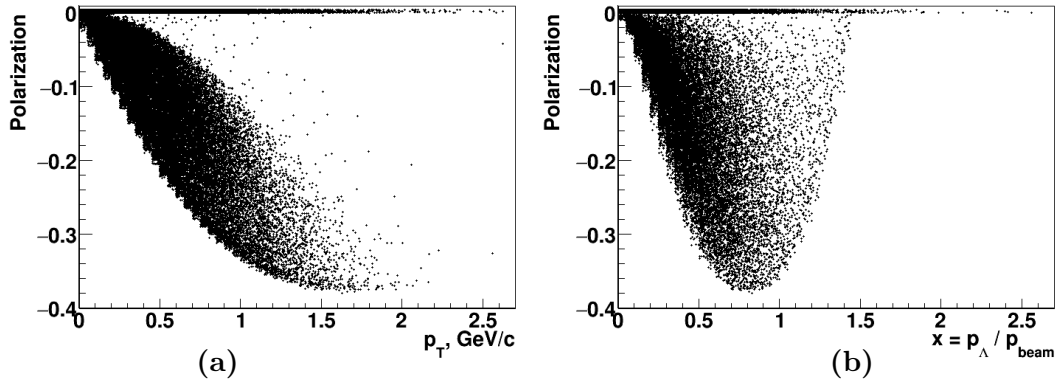


Figure 5. (a) lambda polarization vs p_T ; (b) vs x

The extracted polarization value in the full phase space covered by the detector can be seen in Fig. 6 (a) as the slope parameter of the fitted straight line. For comparison, in Fig. 6 (b) one can see the true polarization distribution obtained for selected Λ -hyperons. There is a reasonable agreement between the measured value (-0.1528) and the mean value of the true distribution (-0.1383). If the secondary lambda contribution is excluded the average polarization should be -0.182.

In order to check the sensitivity of the method in different regions of the phase space, two intervals of p_T ($p_T < 0.6$ and $p_T \geq 0.6$ GeV/c) were chosen. One can see from Fig. 7 that for these intervals the measured and true polarization values are quite close to each other as well, although there is a tendency to slightly overestimate the polarization value for the high-polarization region ($p_T \geq 0.6$ GeV/c). It can be attributed to the fact that in this domain the phase space covered by the detector becomes more different for polarized and unpolarized event samples, so the simple division of $\cos \theta$ -distributions does not completely removes the distortions, and the procedure should be modified to take into account this difference.

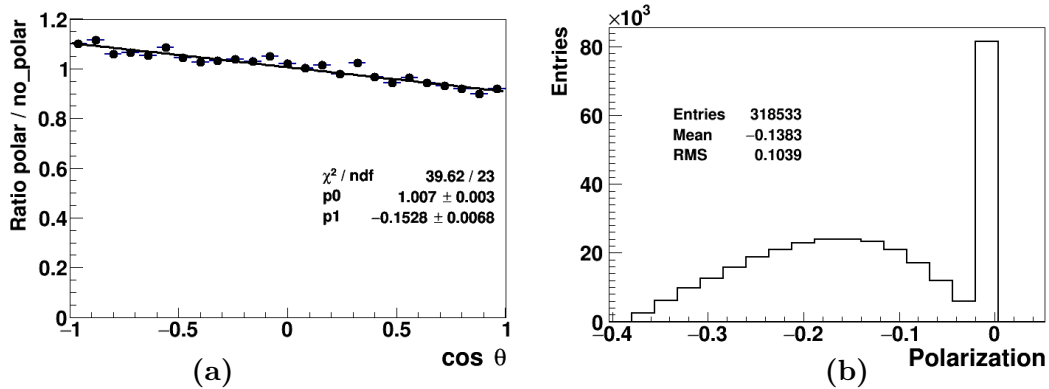


Figure 6. (a) reconstructed $\cos \theta$ -distribution corrected for detector acceptance fitted to the straight line; (b) true lambda polarization distribution for reconstructed events. Zero polarization corresponds to secondary lambdas.

5. Conclusions

Λ hyperon production in minimum bias C+A collisions at 4A GeV has been studied with the BM@N detector at the Nuclotron. Total Λ hyperon yields and yield dependencies on transverse momentum and rapidity have been obtained and compared with model predictions and results from other experiments.

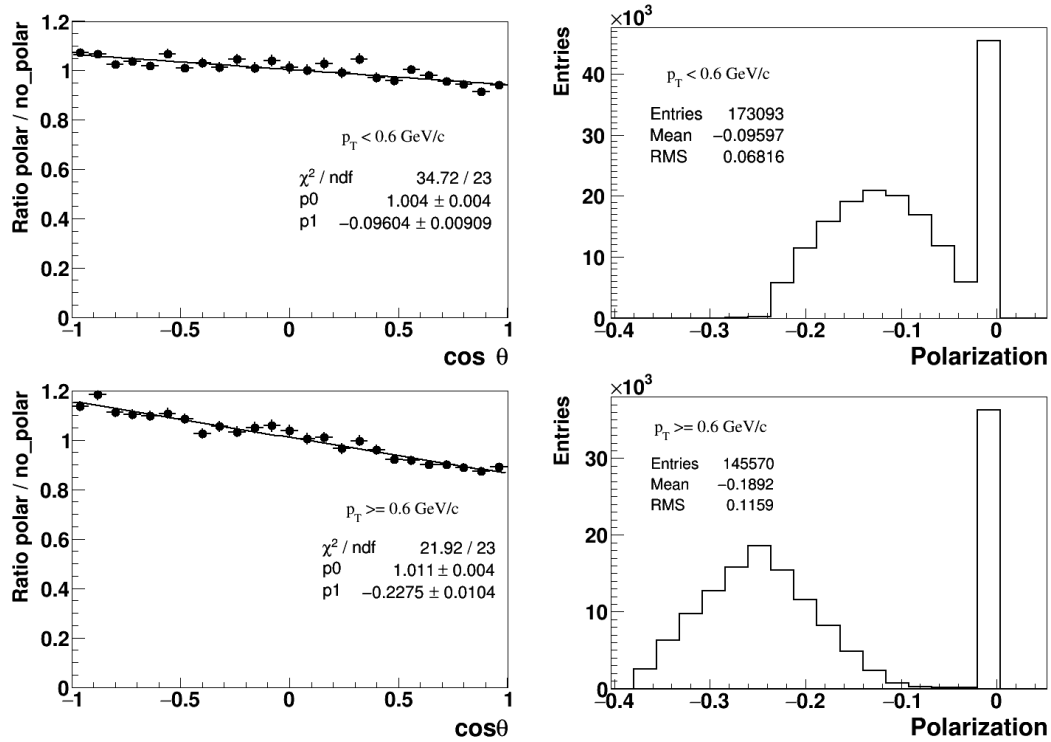


Figure 7. The same as in Fig. 6 for samples with $p_T < 0.6$ (upper row) and $p_T \geq 0.6$ GeV/c (lower row).

The analysis method and procedure for Λ polarization study have been developed and tested on simulated central Au+Au events at kinetic energy of 4.5A GeV in the BM@N detector. The obtained results demonstrate quite good sensitivity of the detector to polarization variables. As a continuation of the work, it is planned to apply the method to the experimental data.

Acknowledgments

This work is supported by the Russian Foundation for Basic Research (RFBR) under grant No. 18-02-40036 mega.

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