BM@N EXPERIMENT FOR STUDIES OF BARYONIC MATTER AT THE NUCLOTRON

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The first experiment at the accelerator complex of NICA-Nuclotron BM@N (Baryonic Matter at Nuclotron) is aimed to study interactions of relativistic heavy ion beams with fixed targets. Relativistic heavy ion collisions provide an unique opportunity to investigate the properties of nuclear matter at ultra-high densities and temperatures. The Nuclotron heavy ion beam energy range is well suited for studies of strange mesons and multi-strange hyperons which are produced in nucleus-nucleus collisions close to the kinematic threshold. Measurements will be carried out at the BM@N experimental setup, located at the extracted beam of the Nuclotron. The BM@N setup, status of the detector upgrade for data taking with the relativistic heavy ion beams and first results of the BM@N technical runs are presented.

Keywords: BM@N, relativistic heavy ion collisions, dense nuclear matter, hyperon production

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1. Physics possibilities at the Nuclotron

Collisions of relativistic heavy ions provide a unique opportunity to investigate properties of nuclear matter at extreme densities and temperatures. In such collisions, the nuclear matter is heated up and compressed for a very short period of time of about several fm/s. The kinetic energy range of the Nuclotron beams corresponds to 1 - 4.5 GeV per nucleon. At such energies, baryons form the majority of the products in a nucleus-nucleus collision, unlike collisions that occur at higher energies at RHIC or SPS accelerators. At the Nuclotron energies, the density of nucleons in a fireball created by two colliding Au nuclei is 3-4 times higher than the saturation density as it is predicted by the Quark Gluon String Model (QGSM) [1]. At such densities nucleons begin to overlap. At the Nuclotron the experimental interest is focused on hadrons with strangeness, which are produced in collisions and do not exist in the initial state of two colliding nuclei, in contrast to nucleons consisting of light u and d quarks. At the left plot of Fig.1 the measured yields of light and strange mesons, hyperons, and anti-hyperons are shown as a function of the energy per nucleon-nucleon collision in the center of mass system in Au+Au and Pb+Pb collisions. The energy range of heavy ion beams at the Nuclotron is $\sqrt{s_{NN}}$ = 2.3−3.5 GeV, these energies are high enough to study strange mesons and multi-strange hyperons produced in nucleus-nucleus collisions close to the kinematic threshold. Collisions of heavy ions are a rich source of strange hadrons that can bind with nucleons and initiate the formation of a variety of light hyper-nuclei. It is expected that studies of the processes of hyper-nucleus production will make it possible to understand the properties of the hyperon-nucleon and hyperon-hyperon interactions. At the right plot of Fig.1 the hyper-nucleus yields are presented as a function of the nucleon-nucleon collision energy in the center of mass system in Au+Au collisions. The maximum in the hyper-nuclei production rate predicted by the thermal model [2] is in the energy range $\sqrt{s_{NN}}$ = 4−5 GeV which is close to the Nuclotron heavy ion beam energies. The research program of the BM@N experiment is aimed to study heavy ion collisions at the Nuclotron including the following directions: investigation of the reaction dynamics and the equation of state of nuclear matter, production of strange and multi-strange hyperons close to the threshold and search for hyper-nuclei.

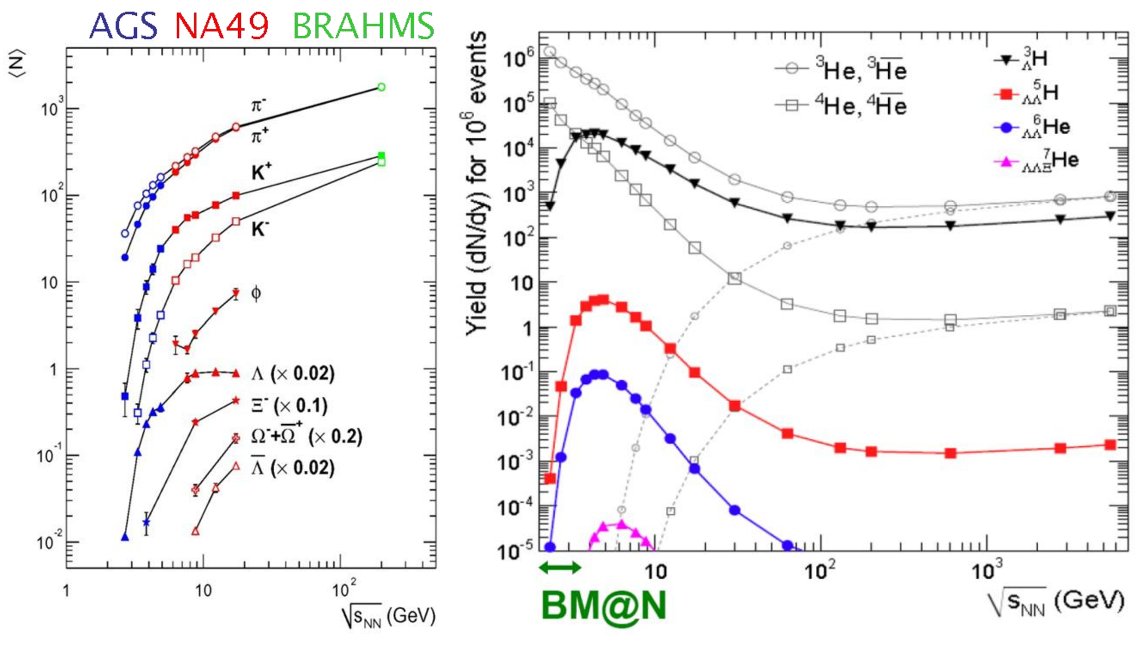

Figure 1. Left plot: Yields of mesons and (anti-)hyperons measured in different experiments as a function of the energy per nucleon-nucleon collision in c.m.s. for Au+Au and Pb+Pb collisions [3]. The Nuclotron beam energy range corresponds to $\sqrt{s_{NN}}$ = 2.3−3.5 GeV. Right plot: Yields of hyper-nuclei predicted by the thermal model in [2] as a function of the nucleon-nucleon collision energy in c.m.s. for Au+Au collisions. Predictions for the yields of 3He and 4He nuclei are presented for comparison. The Nuclotron BM@N energy range is specified

2. BM@N experiment

BM@N (Baryonic Matter at Nuclotron) is the first experiment put in operation at the Nuclotron/NICA accelerator complex. The goal of the BM@N experiment is to study interactions of the relativistic heavy ion beams with fixed targets [4,5]. The Nuclotron will provide the experiment with beams from protons up to Au ions, with a kinetic energy in the range from 1 to 6 GeV per nucleon.

The maximum beam kinetic energy for ions with the charge to atomic weight ratio of $\frac{1}{2}$ is 6 GeV per nucleon. The maximum kinetic energy of Au ions with $\frac{Z}{A}$ ratio equals to 0.4 is 4.5 GeV per nucleon, while the maximum kinetic energy for protons is 13 GeV. The first technical runs at the BM@N experimental setup were performed in 2016 with the deuteron beam and in 2017 with the carbon beam. After the heavy ion source "Krion" was launched, relativistic argon and krypton beams were accelerated and transported to the BM@N setup in 2018 for the first time. After the Nuclotron upgrade is finished, the acceleration of the Au ion beam is planned in 2021. For the second stage of the BM@N experiment (2022 and later) the expected maximum intensity of the Au ion beam is 10^6 ions per second. In Fig.2 the interaction rates are shown for different heavy ion experiments at different energies per nucleon-nucleon collision in the center of mass system. The beam energy of the BM@N 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 for central and intermediate interactions is expected to be from 20 to 50 kHz at the second stage of the BM@N experiment. The interaction rate is limited by the capacity of the data acquisition system and readout electronics.

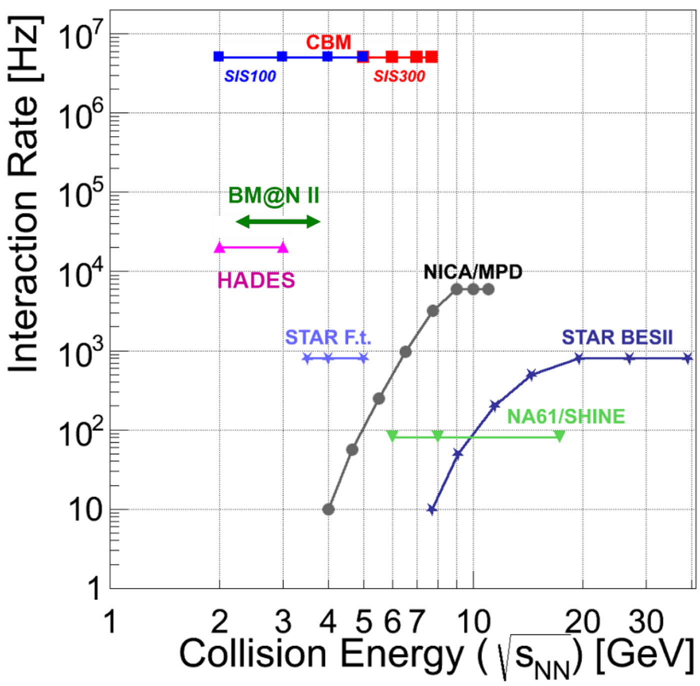

Figure 2. Interaction rate and energy per nucleon-nucleon collision in c.m.s. in experiments with heavy ions. The range for BM@N is superimposed

While the Nuclotron upgrade is being performed, work is underway to prepare the BM@N setup for data taking with the relativistic heavy ion beams. The requirements for detector subsystems are very high, as all physical measurements will be performed under conditions of high beam intensities in collisions with large multiplicity of charged particles. The scheme of the proposed BM@N configuration for heavy ion program is shown in Fig.3. The experiment combines high precision track measurements with time-of-flight information for particle identification. The magnetic field of the analyzing magnet can be varied up to 1 T to get the optimal detector acceptance and momentum resolution for different reactions and energies of the beam. The vertical gap between the poles of the analyzing magnet available for the detectors installation is about 1 m. A wide-aperture central tracking system is based on seven planes of triple Gas Electron Multipliers (GEM) [5]. Detectors of this kind are operational at high radiation loadings and in strong magnetic fields [6]. Central tracking system is located downstream the target inside the analyzing magnet. The momentum of charged particles — the products of interactions of the beam with the target — are measured by the curvature of their trajectories in a magnetic field. To eliminate a systematic shift of the reconstructed tracks in the magnetic field, GEM detectors are oriented in alternating order so that the electric field for the neighboring planes has opposite directions (see Fig.4 right). Double-sided silicon micro-strip detectors (FwdSi, STS) are installed between the target and the central tracking system to determine the interaction vertex with high accuracy and to improve the precision of track reconstruction, especially in the region of small particle momentum (see Fig.4 left and middle).

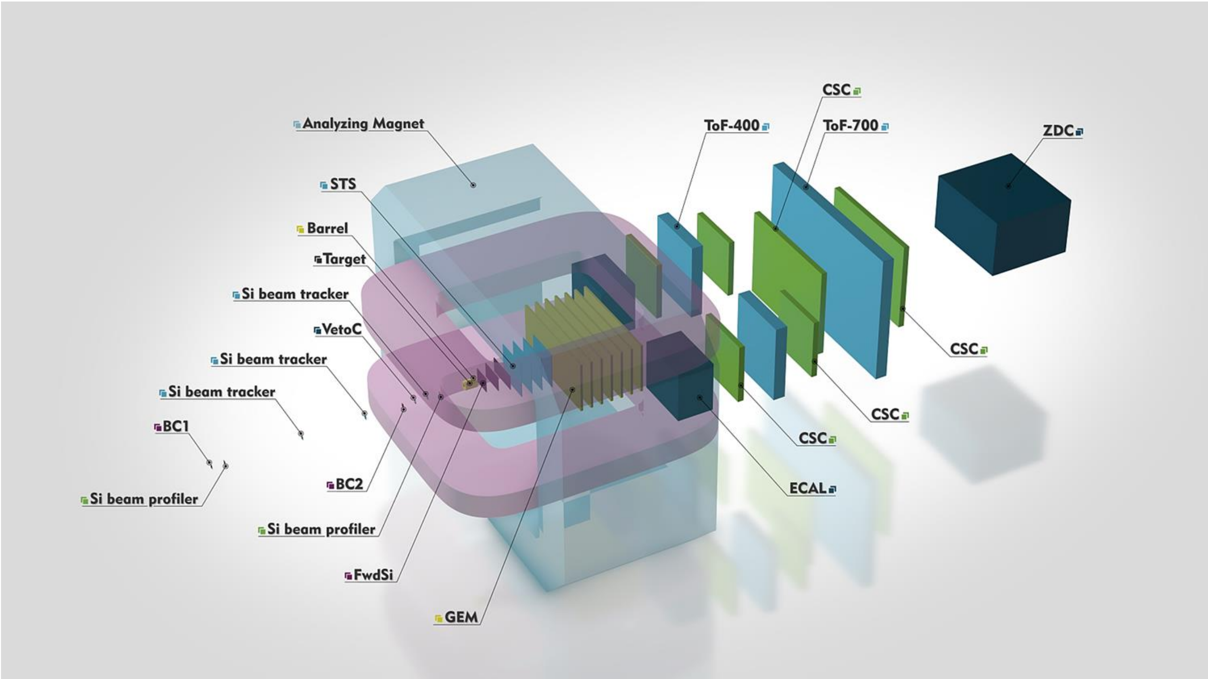

Figure 3. Schematic view of the BM@N setup for the heavy ion program (without vacuum beam pipe)

The outer tracking system consists of six planes of Cathode Strip Chambers (CSC). It is situated outside the magnetic field and is intended to precise parameters of tracks, obtained in GEM detectors inside the analyzing magnet, and thus to increase the efficiency of track reconstruction. Beside improvement of particles momentum identification, refined track in CSC is used to find corresponding hit in the ToF400 and ToF700 time-of-flight systems. The design parameters of the time-of-flight detectors based on a mRPC technology with a strip read-out allows one to perform separation between hadrons (π, K, p) as well as light nuclei with the momentum up to few GeV/c. The Zero Degree Calorimeter (ZDC) detector is foreseen for the analysis of the collision impact parameter by measuring the energy of the fragments of colliding particles. The Cherenkov modular quartz detector placed around the target and partially overlapping the backward hemisphere is planned to generate a trigger signal for the DAQ and a starting signal for the ToF400 and ToF700 detectors. A vacuum beam pipe will be integrated into the experimental setup to minimize the amount of scattering material on the way of heavy ions (it is not shown in Fig.3). Groups of trigger detectors and beam profile meters will be installed inside the beam pipe in vacuum boxes. The target will be installed inside the target station. The target station will allow changing three different types of targets for data taking and one empty target for background evaluation without breaking the vacuum.

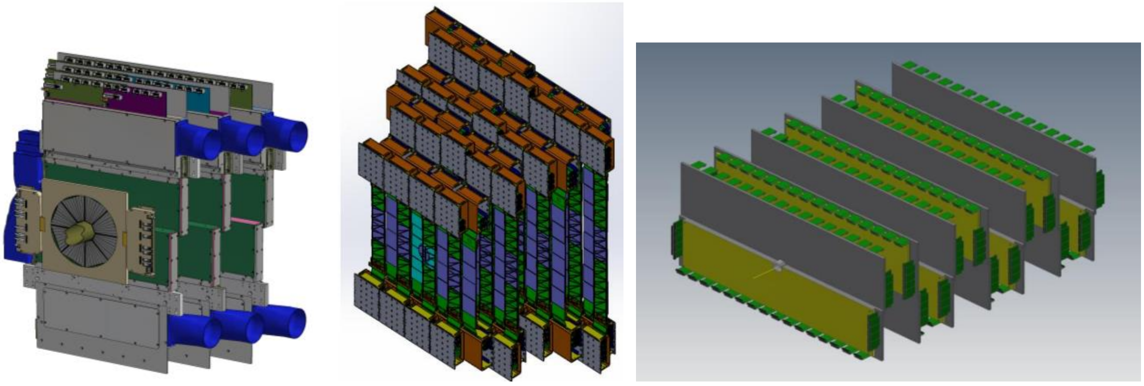

Figure 4. Design layout of the GEM central tracking system (right panel) and silicon micro-strip detectors – FwdSi (left panel) and STS (middle panel) integration into the BM@N setup

3. First results of the BM@N technical runs

Technical runs at the BM@N experimental setup were performed using the deuteron beam with the kinetic energy of 4 GeV per nucleon in December 2016 and the carbon beam with kinetic energy in the range of 3.5 - 4.5 GeV per nucleon in March 2017. The measurements were performed with a limited configuration of the central tracking system, which was based on one forward silicon strip detector and six planes of GEM detectors. 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 collected data were used to investigate the characteristics of the detector subsystems and read-out electronics, to test an integrated data acquisition system, and to develop the algorithms for data analysis and event reconstruction. 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 [5, 7]. The track reconstruction algorithm was based on the «cellular automaton» approach [8]. Since the GEM based central tracker configuration was set to measure relatively high-momentum beam particles, the geometrical acceptance for relatively soft decay products of strange V0 particles was rather low. The Monte Carlo simulation has shown that only $\sim$4% of Λ hyperons and $\sim$0.8% of K_s^0 could be reconstructed. Λ hyperons were reconstructed using their decay mode into p, $\pi-$ pairs [9]. Since particle identification at this stage of the analysis was not used, all positive tracks were considered as protons and all negative as $\pi-$. The invariant mass distributions of p and $\pi-$ are shown in Fig.5 for reconstructed interactions of the carbon beam with C, Al, Cu targets. In future experiments the background under the signal will be reduced by the integrating of the additional silicon tracking detectors to improve the primary and decay vertex resolution.

The extended configuration of the BM@N setup was implemented in the runs with the argon and krypton beams performed in February-March 2018. The setup contained six planes of 163 x 45 cm^2 GEM detectors, three planes of the forward silicon strip detectors FwdSi, full ToF400 and ToF700 systems, extended trigger system, ZDC and electro-magnetic calorimeter. The obtained experimental data are currently under analysis.

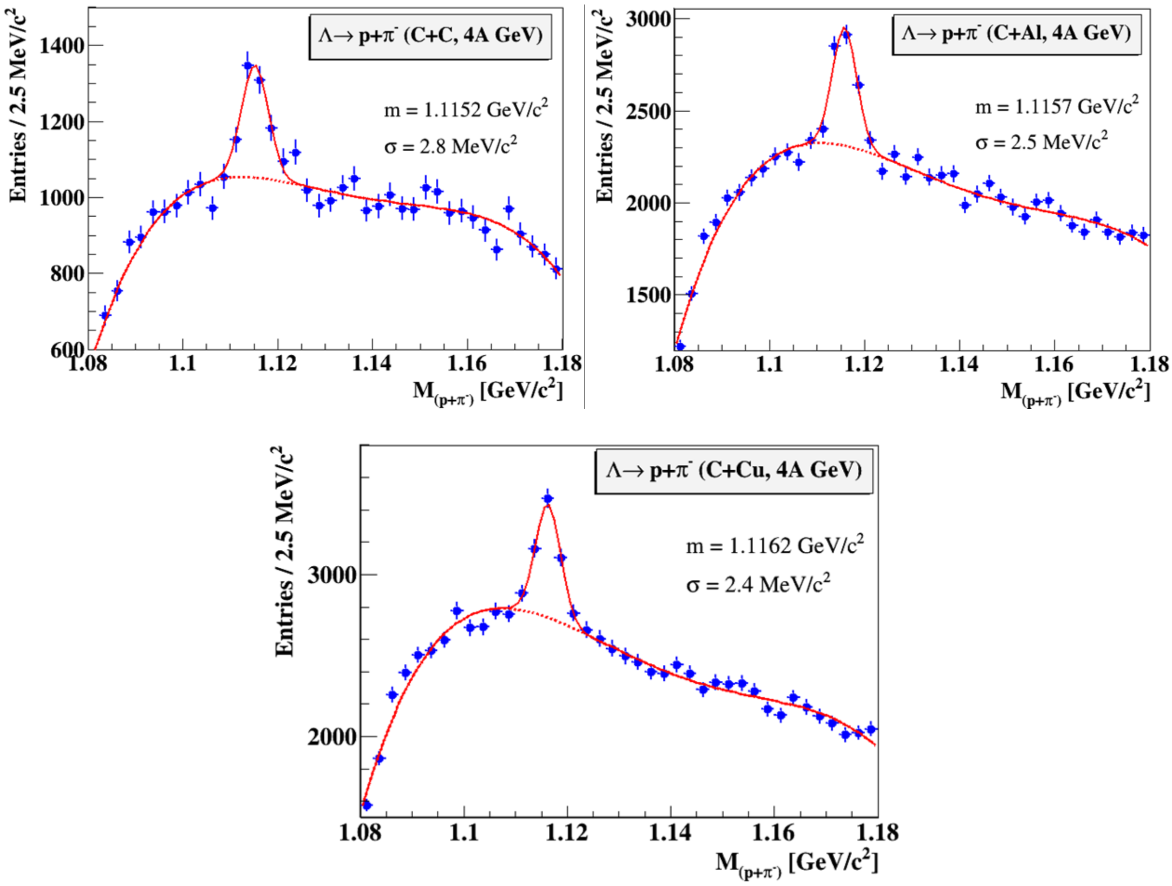

Figure 5. Invariant mass spectrum of proton and π− pairs reconstructed in interactions of the carbon beam with C,Al,Cu targets

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