The fixed target experiment for studies of baryonic matter at the Nuclotron (BM@N)*

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Abstract. BM@N (Baryonic Matter at Nuclotron) is the first experiment to be realized at the accelerator complex of NICA-Nuclotron. The aim of the BM@N experiment is to study interactions of relativistic heavy-ion beams with fixed targets. The BM@N setup, results of Monte Carlo simulations and the BM@N experimental program are presented.

1 Introduction

Relativistic heavy-ion collisions provide an unique opportunity to study nuclear matter at extreme density and temperature. In the collision, nuclear matter is heated up and compressed for a very short period of time. At moderate temperatures, nucleons are excited to baryonic resonances which decay by the emission of mesons. At higher temperatures, also baryon-antibaryon pairs are created. This mixture of baryons, antibaryons and mesons, all strongly interacting particles, is denoted as hadronic matter, or baryonic matter if baryons dominate. If the energy density in the formed fireball is sufficiently large, the quark-gluon substructure of nucleons becomes visible. At even higher temperatures or densities hadrons melt, and the constituents, quarks and gluons, form a new phase, the Quark-Gluon Plasma (QGP). At these extreme conditions the following features (amongst others) can be studied: the equation of state (EoS) of strongly interacting matter at high temperatures and high net-baryon densities; the microscopic structure of strongly interacting matter in dependence on temperature and baryon density; the in-medium modifications of hadrons which might provide information on the onset of chiral symmetry restoration. Theoretical models, however, predict different characteristics of the created matter. New experimental data with high resolution and statistics are needed in order to disentangle different theoretical predictions [1].

2 Nuclotron heavy-ion physics program

The ratio of produced mesons to baryons in the fireball increases with the collision energy. A nucleus-nucleus collision at the Nuclotron with kinetic beam energy in the range from 1 to 4.5 GeV per nucleon produces a baryon dominated fireball contrary to higher energies at RHIC or SPS. According to the QGSM transport model calculations [2], at Nuclotron energies the nucleon densities in the collision zone of two gold nuclei exceed the saturation density by a factor of 3–4. At these densities nucleons start to overlap. It is expected that under such extreme conditions partial restoration of chiral symmetry might occur [3–7]. It will reveal in in-medium modification of hadrons, in particular, in collisional broadening and dropping mass of vector mesons decaying into di-leptons which are not much effected by final-state interactions.

The relevant degrees of freedom at Nuclotron energies are first of all nucleons and their excited states followed by light and strange mesons. Also the partonic degrees of freedom might show up in small space-time volumes and leave their traces in final hadronic observables. The focus of experimental studies will be on hadrons with strangeness, which are early produced in the collision and not present in the initial state of two colliding nuclei, as nucleons made up from light (u, d)-quarks. The measured production yields of light and strange mesons, as well as of hyperons and anti-hyperons are shown in fig. 1 as a function of the nucleon-nucleon collision energy in c.m.s. The Nuclotron beam energy range corresponds to $\sqrt{s_{NN}} = 2.3–3.5$ GeV. It is well suited for studies of strange mesons and multi-strange hyperons produced in nucleus-nucleus collisions close to the kinematic threshold. These studies and the measurements of collective flows of
hadrons provide insights on the EoS of strongly interacting matter.

Heavy-ion collisions are a rich source of strangeness, and the coalescence of lambda-hyperons with nucleons can produce a variety of light hyper-nuclei [6,7]. The study of the hyper-nuclei production is expected to provide new insights into the properties of the hyperon-nucleon and hyperon-hyperon interactions. Figure 2 presents the yields of hyper-nuclei as a function of the nucleon-nucleon collision energy in c.m.s. in Au+Au collisions, predicted by a thermal model [9]. The maximum in the hyper-nuclei production rate is predicted at $\sqrt{s_{NN}} \sim 4$–5 GeV, which is close to the Nuclotron energy range.

In sum, the research program on heavy-ion collisions at the Nuclotron [1,10] includes the following topics: investigation of the reaction dynamics and nuclear EoS, study of the in-medium properties of hadrons, production of (multi)-strange hyperons at the threshold and search for hyper-nuclei. In order to interpret experimental data from heavy-ion collisions and to provide a normalization for the measured A+A spectra, a study of elementary reactions (p + p, p + n(d)) is planned.

**3 Detector for studies of Baryonic Matter at Nuclotron (BM@N)**

BM@N (Baryonic Matter at Nuclotron) is the first experiment at the accelerator complex of NICA-Nuclotron. The schematic view of the NICA-Nuclotron complex and the position of the BM@N setup are presented in fig. 3. The sources of light and heavy ions, the beam Booster, Nuclotron accelerator and NICA collider are shown. The heavy-ion physics program of the NICA accelerator complex and the MPD experiment planned at the NICA collider are described in [11–14]. The aim of the BM@N experiment is to study interactions of relativistic heavy-ion beams with fixed targets [10]. The Nuclotron will provide a variety of beams from protons to gold ions with the kinetic energy of ions ranging from 1 to 6 GeV per nucleon. The maximum kinetic energy for ions with the ratio of the charge to the atomic weight ($Z/A$) of 1/2 is 6 GeV per nucleon. The maximum kinetic energy for gold ions

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**Fig. 1.** Yields of mesons and (anti-) hyperons as a function of the nucleon-nucleon collision energy in c.m.s. in Au+Au/Pb+Pb collisions, taken from [8]. The Nuclotron BM@N beam energy range corresponds to $\sqrt{s_{NN}} = 2.3$–3.5 GeV.

**Fig. 2.** Yields of hyper-nuclei as a function of the nucleon-nucleon collision energy in c.m.s. in Au+Au collisions, calculated with a thermal model [9]. The predicted yields of $^3$He and $^4$He nuclei are included for comparison. The Nuclotron BM@N energy range is specified.

**Fig. 3.** Schematic view of the NICA-Nuclotron complex and the existing position of the BM@N setup.
with the ratio of $Z/A \sim 1/3$ is 4.5 GeV per nucleon. The maximum kinetic energy of protons is 13 GeV. The existing beam line between the Nuclotron and the BM@N experiment is around 160 meter in length. It comprises 26 elements of magnetic optics: 8 dipole magnets and 18 quadruple lenses. An upgrade program of the beam line is foreseen to minimize the amount of scattering material on the way of heavy ions to the BM@N setup.

The planned intensity of the gold ion beam accelerated and accumulated in the Nuclotron and the Booster and transported to the BM@N experimental zone is up to $10^7$ ions per second. The gold ion beam is expected at the beginning of 2019. In the period before 2018 the following ions are foreseen to be accelerated: the polarized deuteron beam in 2016, the carbon, argon and krypton beams in 2017. In this period of operation the planned intensity of the beam interacting with the target inside the BM@N setup is $10^6$ ions per second. The proton-proton interactions will be studied after the Nuclotron upgrade planned in 2018 using the proton beam and the liquid hydrogen target. Beam types and intensities are specified in table 1.

Figure 4 shows the diagram of the interaction rates accepted by data acquisition systems of heavy-ion experiments running at different energies of colliding nuclei. The beam energy range in the BM@N experiment overlaps partially with that in the HADES experiment. The interaction rate of triggered non-peripheral central and intermediate collisions at the second stage of the BM@N experiment is expected to be around 50 kHz. It is limited by the capacity of the readout electronics and data acquisition system. The second stage of the experiment will be realized in 2020 and later.

A sketch of the proposed configuration of the setup of the experiment is shown in fig. 5. The experiment combines high-precision track measurements with time-of-flight information for particle identification and total energy measurements for the analysis of the collision centrality. The charged track momentum and multiplicity will be measured with the set of twelve planes of GEM (Gaseous Electron Multipliers) detectors with a two-coordinate readout located downstream of the target in the analyzing magnet and the drift/straw chambers (DCH, Straw) situated outside the magnetic field. The GEM detectors sustain high rates of particles and are operational in the strong magnetic field. The gap between the poles of the analyzing magnet is around 1 m. The magnetic field can be varied up to 1.2 T to get the optimal BM@N detector acceptance and momentum resolution for different processes and beam energies. The available drift chambers are suited for reconstruction of interactions of light and medium ion beams. The straw tube detectors will be constructed in addition to the drift chambers to increase the reconstruction efficiency of the outer tracker for

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### Table 1. Beam parameters and setup at different stages of the experiment.

| Year          | 2016 | 2017 spring | 2017 autumn | 2019 | 2020 and later |
|---------------|------|-------------|-------------|------|----------------|
| Beam          | d↑   | C, Ar       | Kr          | Au   | Au, p          |
| Maxim. intensity, Hz | 1M   | 1M          | 1M          | 1M   | 10M            |
| trigger rate, Hz | 10k  | 10k         | 20k         | 20k  | 20k            |
| Central tracker status | 6 GEM | 8 GEM | 10 GEM | 8 GEM | 8 GEMs or Si planes |
| Experim. techn. status | run  | run         | run         | physics | physics |
| techn. physics | stage 1 | stage 2 | physics | physics | physics |

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**Fig. 4.** Heavy-ion experiments: interaction rate and nucleon-nucleon collision energy in c.m.s. The BM@N range is superimposed on the plot taken from [15].

**Fig. 5.** Schematic view of the BM@N setup.
The BM@N setup behind the analyzing magnet in the first technical run in March 2015. The beam direction is from the right. Two big drift chambers, a movable platform with the zero degree calorimeter and elements of mRPC-1,2 time-of-flight detectors are installed.

Fig. 6.

The design parameters of the time-of-flight detectors based on multi-gap resistive plate chambers (mRPC-1,2) with a strip readout allow us to discriminate between hadrons (π, K, p) as well as light nuclei with the momentum up to few GeV/c produced in multiparticle events. The zero-degree calorimeter (ZDC) is designed for the analysis of the collision centrality by measuring the energy of forward-going particles. The T0 detector, partially covering the backward hemisphere around the target, is planned to trigger central heavy-ion collisions and provide a start time (T0) signal for the mRPC-1,2 detectors. An electro-magnetic calorimeter will be installed behind the mRPC-2 wall to study processes with electromagnetic probes (γ, e±) in the final state.

The first technical run of the BM@N detectors was performed with the deuteron and carbon beams in March 2015. The view of the BM@N setup in the run is presented in fig. 6. The experimental data from the drift chambers, time-of-flight detectors, zero-degree calorimeter, start time and trigger detectors were readout using the integrated data acquisition system. Meanwhile, the GEM detectors for the BM@N central tracker are being produced at the CERN workshop. The triple GEM detector with a size of 66 to 41 cm² at the final stage of the production is presented in fig. 7. The GEM detectors with a maximum size of 200 to 45 cm² are foreseen for the BM@N central tracker. Two GEM detectors, fixed around the beam pipe, comprise one full plane.

The minimal configuration of the central tracker in 2016 is based on 6 GEM detectors (half-planes) installed along the beam line. The central tracker will be extended step by step up to eight GEM planes of full size at the beginning of 2019. The factual realization depends on the production capacity of the CERN workshop. The first physics run is planned in autumn of 2017 with krypton beam. The full configuration of the central tracker assumes 12 GEM planes. The central tracker configurations at different stages of the experiment are specified in table 1. At the second stage of the BM@N experiment starting in 2020, four planes of two-coordinate silicon strip detectors could be installed instead of four GEM planes situated next to the target to improve the track reconstruction efficiency in Au+Au collisions. Presently, the detectors of this type are being developed for the CBM experiment [16]. The factual realization of the upgrade depends on the time schedule of the silicon tracker program at CBM.

4 BM@N simulations and feasibility study

Activities on the detector and beam line construction are complemented with intensive Monte Carlo simulation studies for the optimization of the detector setup. A special focus is set on the measurement of strange hyperons and hyper-nuclei in Au+Au collisions at the maximal kinetic beam energy of 4.5 AGeV. The simulation of Au+Au collisions is performed using the URQMD [17] and DCM-QGSM [18] models for heavy-ion collisions. The products of collisions are transported through the BM@N setup using the GEANT program and reconstructed using the track reconstruction algorithm for multi-particle events [19].

Figure 8 illustrates the distribution of primary protons generated in Au+Au collisions at the kinetic beam energy of 4.5 AGeV in the phase space of the transverse momentum and rapidity in the laboratory frame. The product of the geometrical acceptance and track reconstruction efficiency in 12 stations of the GEM tracker for primary protons for the same phase space is shown on the lower plot. Figure 9 presents the momentum resolution and the vertex impact parameter resolution of charged particles reconstructed in the GEM tracker. The results are presented for the magnetic field in the center of the magnet of 0.44 T. Figure 10 presents the distributions of the invariant mass of decay products of the Λ-hyperon, Ξ−-hyperon and hyper-triton 3H reconstructed with the GEM tracker.
Fig. 8. Upper plot: distribution of primary protons generated in Au+Au collisions at the kinetic beam energy of 4.5 AGeV in the phase space of the transverse momentum and rapidity in the laboratory frame. Lower plot: product of the geometrical acceptance and track reconstruction efficiency in 12 stations of the GEM tracker for primary protons as a function of the particle transverse momentum and rapidity.

Fig. 9. Momentum resolution (upper plot) and vertex impact parameter resolution (lower plot) of charged particles reconstructed in 12 stations of the GEM tracker shown as a function of the particle momentum.

Fig. 10. Distributions of the invariant mass of decay products of the $\Lambda$-hyperon, $\Xi^-$-hyperon and hyper-triton $^3\Lambda H$ reconstructed with 12 stations of the GEM tracker in simulated central Au+Au collisions at the kinetic beam energy of 4.5 AGeV.

in simulated central Au+Au collisions at the kinetic beam energy of 4.5 AGeV. The obtained results indicate that the proposed setup has a reasonable reconstruction capability for strange hyperons produced in high multiplicity central Au+Au collisions. The signal of the $\Lambda$-hyperon is reconstructed in 10k events of simulated central collisions. At least two $\Lambda$-hyperons are reconstructed in 30% of central events. The reconstructed signals of the $\Xi^-$-hyperon and hyper-triton $^3\Lambda H$ correspond to 0.9M and 2.6M of central collisions, respectively. Taking into account the signal reconstruction efficiency, the data acquisition capacity of 20 kHz of triggered central collisions and the duty factor of the Nuclotron beam of 0.5, the expected statistics of $\Xi^-$-hyperons and hyper-tritons $^3\Lambda H$ for a month of the BM@N operation are 7.5M and 8.5M, respectively. The expected statistics is sufficient to perform measurements of strange hyperon and hyper-nuclei production yields and ratios, transverse momentum spectra, rapidity and angular distributions. Studies of fluctuations of event properties and correlations between products of nucleus-nucleus interactions are also feasible.
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