The Fixed Target Experiment for Studies of Baryonic Matter at the Nuclotron (BM@N)

M. N. Kapishin (for BM@N collaboration)

Joint Institute for Nuclear Research, Dubna, Moscow oblast, 141980 Russia
e-mail: kapishin@sunse.jinr.ru

Received June 29, 2017

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

Keywords: relativistic heavy ion collisions, charged-particle spectroscopy, gas-filled counters, ionization chambers, calorimeters

DOI: 10.1134/S1063778817100027

1. INTRODUCTION

Collisions of relativistic heavy ions provide a unique opportunity to study nuclear matter of extreme densities and temperatures. In such collisions, nuclear matter is heated and compressed very quickly. At moderate temperatures, nucleons are excited into baryon resonances that decay with emission of mesons. Baryon-antibaryon pairs are generated at higher temperatures. The matter formed by these strongly interacting particles (baryons, antibaryons, and mesons) is termed hadronic or baryonic, if baryons dominate in it. If the density of the nuclear matter formed as a result of interaction is high enough, the nucleon quark-gluon substructure is manifested. At even higher temperatures or densities of the nuclear matter, quarks and gluons form a new phase: quark-gluon plasma (QGP). In such extreme conditions, the following properties of strongly interacting matter can be studied: parameters of the equation of state (EoS) of nuclear matter at high temperatures and net-baryon densities; microscopic structure of strongly interacting matter as a function of baryon temperature and density; and modification of hadron properties in nuclear medium, which can be an indication of restoration of the chiral symmetry. Theoretical models propose various possible scenarios to describe these features of strongly interacting matter. Therefore, new experimental data with high resolution and statistics are needed to verify the theoretical predictions [1].

2. THE NUCLotron HEAVY-ION PHYSICS PROGRAM

The ratio of meson yield to baryons produced in interaction increases with growth of collision energy. At the Nuclotron, baryons dominate in nucleus—nucleus collision products at the beam kinetic energy within the range from 1 to 4.5 GeV per nucleon, in contrast to collisions that occur at higher energies at the RHIC or SPS accelerators. According to the QGSM model calculations presented in [2], at Nuclotron energies, the nucleon density in the zone of collision of two gold nuclei is 3–4 times higher than the density of saturation. At such densities, nucleons start to overlap. In these extreme conditions, the signs of chiral symmetry restoration can be observed [3–7]. Changes in hadron properties become apparent in widening of the mass spectrum and decrease in mass of vector mesons—each of them decays into two leptons, which are not affected by final state interactions.

At Nuclotron energies, the properties of nucleons and their excited states are mostly displayed, as well as those of light and strange mesons. Parton degrees of freedom can also be manifested by the hadron final state dynamics. The experimental research is planned to focus on hadrons with strangeness produced in collision and not present in the initial state of two colliding nuclei, unlike the nucleons consisting of light (u and d) quarks. The measured yields of light and strange mesons, hyperons, and antihyperons are shown in Fig. 1 as a function of the energy of nucleon—nucleon collisions in the center of mass system (cms). The energy range of a beam of heavy ions at the Nuclotron corresponds to $\sqrt{s_{NN}} = 2.3–3.5$ GeV. These ener-
gies are sufficient to study strange mesons and multi-strange hyperons produced in nucleus-nuclear collisions close to the kinematic threshold.

Heavy ion collisions are an abundant source of strange hadrons, and fusion of $\Lambda$ hyperons with nucleons initiates formation of a variety of light hypernuclei [6, 7]. Studies of hypernucleus production processes are expected to provide insight into the properties of hyperon-nucleon and hyperon-hyperon interactions. In Fig. 2, the hypernucleus yields per event in dependence of the energy of nucleon-nucleon collisions in cms are presented (for example, Au + Au collisions), according to the thermal model predictions [9]. The maximum probability of hypernucleus production is predicted at energy of $\sqrt{s_{NN}} \approx 4–5$ GeV, which is close to the range of the Nuclotron energies.

In general, the program aimed at studies of heavy ion collisions at the Nuclotron [1, 10] includes the following issues: exploration of the reaction dynamics and the equation of state (EoS) of nuclear matter, study of hadron property modification in nuclear matter, production of (multi)strange hyperons in the vicinity of the threshold, and search for hypernuclei. The planned studies of particle reactions ($p + p, p + n(d)$) are aimed at interpretation of the experimental data obtained in heavy ion collisions and at providing normalization of the measured spectra obtained in interactions of nuclei.

3. BM@N DETECTOR FOR STUDIES OF BARYONIC MATTER AT THE NUCLotron

BM@N (Baryonic Matter at Nuclotron) is the first experiment at the NICA-Nuclotron accelerating complex. The layout of the NICA-Nuclotron complex with the BM@N setup is displayed in Fig. 3. The sources of light and heavy ions, beam Booster, Nuclotron accelerator, and NICA collider are shown.

The heavy-ion physics program of the NICA accelerating complex and MPD experiment planned at the NICA collider is described in [11–14]. The purpose of the BM@N experiment is to study relativistic heavy ion beam interactions with fixed targets [10]. The Nuclotron will provide the experiment with beams of a variety of particles, from protons to gold ions, with kinetic energy from 1 to 6 GeV per nucleon. The maximum kinetic energy of ions with the charge to atomic weight ratio $Z/A = 1/2$ is 6 GeV/nucleon. The maximum kinetic energy of gold ions with $Z/A \sim 1/3$ is 4.5 GeV/nucleon. The maximum kinetic energy of protons is 13 GeV. The length of the channel of beam transport from Nuclotron to the BM@N experiment is about 160 m. The channel comprises 26 magnetooptic...
components: 8 dipole magnets and 18 quadrupole lenses. An upgrade program is envisaged for the beam transport channel to minimize the amount of scattering matter in the path of heavy ions to BM@N.

The planned intensity of the gold ion beam accelerated and accumulated at the Nuclotron and Booster and transported to BN@M will total about 10^7 ions/s. The injection of gold ion beam is expected in 2019. It is planned to accelerate and transport beams of carbon, argon, and krypton into the BM@N experimental zone before 2018. By that time, the beam intensity at BM@N is planned to reach 10^6 ions/s. After the Nuclotron upgrade in 2018, proton-proton interactions will be studied using a proton beam and a target of fluid hydrogen. The types and intensities of the beams are compiled in Table 1.

In Fig. 4, the diagrams of data acquisition rates are presented for experiments with heavy ions at different energies of colliding nuclei in cms. The beam energy range in the BM@N experiment partially overlaps the energy range of the HADES experiment. The rate of registration of nonperipheral, i.e., central or intermediate, interactions is expected to reach 20 to 50 kHz at the second stage of the BM@N experiment. This parameter is limited by capacity of the data acquisition system and readout electronics. The second stage of the experiment will be implemented in 2020 and later.

The layout of the proposed BM@N configuration is shown in Fig. 5. The experiment combines high-precision measurement of track parameters with acquisition of time-of-flight information for particle identification and presumes measurement of the total energy by the ZDC calorimeter to analyze the collision centrality. The charged track momentum and multiplicity will be measured using a set of 12 planes of two-coordinate GEM (Gaseous Electron Multiplier) detectors mounted downstream of the target inside the analyzing magnet and drift/straw chambers (DCH, Straw) positioned outside the magnetic field. The GEM detectors are operational at high particle densities and in strong magnetic fields. The vertical gap between the poles of the analyzing magnet for detector installation is about 1 m. The magnetic field can vary up to a maximum value of 1.2 T, which makes it possible to optimize the BM@N geometrical efficiency (acceptance) and resolution on momentum for different processes and energies of the beam. The outer track system consists of large drift chambers that will

---

**Table 1. Parameters of the beam and setup at different stages of the experiment**

| Year          | 2016 | 2017     | 2017     | 2019  | 2020         |
|---------------|------|----------|----------|------|--------------|
|               |      | spring   | fall     |      |              |
| Beam          | d(↑) | 0.5M     | 0.5M     | Ar, Kr| Au           | Au, p          |
| Max. intensity, Hz | 5k   | 5k       | 5k       | 0.5M | 1M           | 10M            |
| Trigger rate, Hz |      |          |          | 10G  | 20–50k       | 12 GEM or     |
| Central tracker status | 6 GEM half-plane | 8 GEM half-plane | 10 GEM half-plane | 12 GEM full plane | 8 GEM or Si plane | Physics stage 1 |
| Exp. status   | Tech. run | Tech. run | Tech. run | Physics stage 1 | Physics stage 1 | Physics stage 2 |
be supplemented with Straw detectors to increase the efficiency of track measurement in Au + Au collisions. The time-of-flight detectors based on mRPC (multigap Resistive Plate Chambers) technologies with strip readout provide an opportunity to separate hadrons (π, K, p) and light nuclei with momentum up to several GeV/c, which are produced in multiparticle events. The ZDC (Zero Degree Calorimeter) detector is intended for detection of the collision impact parameter (centrality) by measuring the energy of fragment particles of the beam. Detector T0 partially overlapping the backward hemisphere positioned around the target is planned to measure the centrality of heavy ion collision and generate a trigger and starting signal (T0) for mRPC-1,2 detectors. The electromagnetic calorimeter will be mounted downstream of the drift/straw chambers and mRPC-2 detector for studying the processes with production of (γ, e+) in the final state.

The first technical run was carried out at the BM@N setup using deuteron and carbon beams in March 2015. The general view of the BM@N setup during the run is presented in Fig. 6. The experimental data from the drift chambers, time-of-flight detectors, ZDC calorimeter, and T0 and trigger detectors were read out using an integrated system of data acquisition. At the same time, production of GEM detectors was launched at CERN. A GEM detector of 66 × 41 cm² produced for the BM@N experiment at CERN is shown in Fig. 7. GEM detectors of maximum sizes of 200 × 45 cm² are envisaged for the central track system of BM@N. Two GEM planes having a half of this size in height will be installed around the beam to make one full plane. In 2016, the central tracker minimum configuration was based on six half-size GEM planes installed along the beam. By the beginning of 2019, the central tracker will be expanded to eight full-size GEM planes. The actual implementation of this program depends on the production capacities of CERN.

The central tracker full configuration presumes installation of 12 GEM planes. The central tracker configuration at different stages of the experiment is presented in Table 1. In 2020, at the second stage of the BM@N experiment, at least four planes of two-coordinate silicon strip detectors will be installed between the GEM detectors and the target to improve the track reconstruction in Au + Au nucleus colli-

**Fig. 4.** The rate of data registration and energy of nucleon-nucleon collision in cms in experiments with heavy ions. Data for BM@N are superimposed over the graph taken from [15].

**Fig. 5.** Layout of the BM@N setup.
Presently, the detectors of this type are developed for the CBM experiment [16]. The actual implementation of this BM@N upgrade depends on the timetable of the CBM silicon tracker program.

4. BM@N SIMULATION FOR FEASIBILITY STUDIES

Presently, active steps are taken on simulation of the BM@N setup by the Monte Carlo method. The simulation aimed at optimization of BM@N detectors is based on the generated Au + Au events. The simulation is focused on registration of strange hyperons and hypernuclei in central (0–3 fm) Au + Au collisions at the beam maximum kinetic energy of 4.5 GeV ($\sqrt{s_{NN}} = 3.46$ GeV). The interactions of Au + Au nuclei are generated using the URQMD [17] and DCM-QGSM [18] models describing collisions of heavy nuclei. The collision products are transported through the BM@N setup using the GEANT program and are reconstructed by applying the track reconstruction algorithm [19] for multiparticle events.

In Fig. 8, the distribution of primary protons generated in Au + Au collisions at the beam kinetic energy of 4.5 AGeV is shown in the phase space of transverse momentum and rapidity in the laboratory coordinate system. The efficiency of reconstruction of primary protons in the GEM tracker as a function of transverse momentum and rapidity is shown in Fig. 8 on the right.
In Fig. 9, resolutions of momentum and impact parameter are shown relative to the vertex of interaction of the charged particles reconstructed in the GEM tracker. These results are displayed for magnetic field $B$ at the center of the magnet.

In Fig. 10, the distributions of invariant mass of the decay products are presented, including $\Lambda$ hyperon, $\Xi^-$ hyperon, and $^3\Lambda$H hypertritium that are reconstructed in the GEM tracker in central collisions of Au + Au at the beam kinetic energy of $4.5\ A\ GeV$. The statistics of the simulated events are provided in the text.

In Fig. 9, resolutions of momentum and impact parameter are shown relative to the vertex of interaction of the charged particles reconstructed in the GEM tracker. These results are displayed for magnetic field $B = 0.44\ T$ at the center of the magnet.

In Fig. 10, the distributions of invariant mass of the decay products are presented, including $\Lambda$ hyperon, $\Xi^-$ hyperon, and $^3\Lambda$H hypertritium that are reconstructed in the GEM tracker in simulated central Au + Au collisions at the beam kinetic energy of $4.5\ A\ GeV$. The obtained results show that the proposed configuration provides the appropriate efficiency of reconstruction of strange hyperons produced in Au + Au central collisions with high multiplicity of reaction products. The reconstructed signal of $\Lambda$ hyperon corresponds to 10K central collisions. In 30% of central
collisions, at least two $\Lambda$ hyperons are reconstructed. The reconstructed signals of $\Xi^-$ hyperon and $^3_\Lambda$H hypertritium are obtained in 0.9M and 2.6M central collisions, respectively. Taking into consideration the signal reconstruction efficiency, data registration rate of 20 kHz for central collisions, and duty factor of 0.5 for the Nuclotron beam, the expected statistics for $\Xi^-$ hyperons and $^3_\Lambda$H hypertritium over a month of BM@N operation is 7.5M and 8.5M, respectively. Such event statistics are sufficient for measuring the strange hyperon/hypernucleus yield ratio, spectra of transverse momentum and rapidity, and angular distributions and for studies of a variety of correlations between interaction products.

REFERENCES
1. NICA White Paper. http://theor0.jinr.ru/twiki-cgi/view/NICA/NICAWhitePaper.
2. B. Friman, W. Nörenberg, and V. D. Toneev, Eur. Phys. J. A 3, 165 (1998).
3. R. Rapp and J. Wambach, Eur. Phys. J. A 6, 415 (1999).
4. G. E. Brown, Prog. Theor. Phys. 91, 85 (1987).
5. W. Cassing and E. L. Bratkovskaya, Phys. Rep. 308, 65 (1999).
6. J. Steinheimer et al., Prog. Part. Nucl. Phys. 62, 313317 (2009).
7. J. Steinheimer, K. Gudima, A. Botvina, I. Mishustin, M. Bleicher, and H. Stocker, Phys. Lett. B 714, 85 (2012).
8. C. Blume, J. Phys. G 31, S57 (2005).
9. A. Andronic et al., Phys. Lett. B 695, 203 (2011).
10. BMN Conceptual Design Report. http://nica.jinr.ru/-files/BMN/BMN_CDR.pdf.
11. G. Trubnikov, A. Kovalenko, V. Kekelidze, I. Meshkov, R. Lednicky, A. Sissakian, and A. Sorin, in Proceedings of the 35th International Conference on High Energy Physics ICHEP 2010, Paris, France, July 22–28, 2010, p. 523.
12. G. Trubnikov, N. Agapov, V. Kekelidze, A. Kovalenko, V. Matveev, I. Meshkov, R. Lednicky, and A. Sorin, in Proceedings of the 36th International Conference on High Energy Physics ICHEP 2012, Melbourne, Australia, July 4–11, 2012, p. 411.
13. V. Kekelidze, A. Kovalenko, R. Lednicky, V. Matveev, I. Meshkov, A. Sorin, and G. Trubnikov, in Proceedings of the 37th International Conference on High Energy Physics ICHEP 2014, Valencia, Spain, July 2–9, 2014.
14. V. Golovatyuk, V. Kekelidze, V. Kolesnikov, O. Rogachevsky, and A. Sorin, Eur. Phys. J. A 52, 212 (2016).
15. V. Friese, J. Phys.: Conf. Ser. 668, 012014 (2016); Talk at the SQM-2015 Conference, Dubna, Russia, July 6–11, 2015.
16. J. Heuser et al., GSI Report 2013-4. http://repository.gsi.de/record/54798.
17. URQMD Model. http://urqmd.org/.
18. A. S. Botvina et al., Phys. Rev. C 84, 064904 (2011).
19. I. Kisel, Nucl. Instrum. Methods Phys. Res. A 566, 85 (2006).

Translated by N. Semenova