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The heavy-ion program at the upgraded Baryonic Matter@Nuclotron Experiment at NICA

P. Senger[a,b] for the BM@N Collaboration

a Facility for Antiproton and Ion Research
Planckstr. 1, Darmstadt, Germany

b National Research Nuclear University MEPhI,
Moscow, Russia

E-mail: p.senger@gsi.de

Abstract: In the coming years, the Nuclotron at JINR in Dubna will deliver gold beams with energies of up to 3.8A GeV and intensities of up to $2.5 \cdot 10^6$ ions/s. These beams are well suited for experiments devoted to the study of the properties of dense baryonic matter, such as the equation-of-state and new microscopic degrees-of-freedom which might emerge at neutron star core densities. The relevant observables in heavy-ion collisions at these energies include the yields and multi-differential distributions of (multi-) strange particles, the collective flow of identified particles, fluctuation of conserved quantities, and hypernuclei. In order to measure these observables in Au+Au collisions with rates of up to 50 kHz, the existing BM@N setup in the Nuclotron target hall will be upgraded with a highly granulated and fast hybrid tracking system, and a forward calorimeter for event plane determination. The BM@N physics program, the detector upgrades, and some results of physics performance studies will be presented.

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1. Introduction

Recent observations of gravitational waves emitted from mergers of compact stars [1], and first simultaneous measurements of radii and masses of neutron stars [2] opened new avenues for the exploration of the fundamental properties of dense nuclear matter, in particular the high-density equation-of-state (EOS), and the elementary degrees-of-freedom, which might emerge at high densities. Up to date, our knowledge on the high-density EOS of symmetric matter has been derived from heavy-ion collision experiments, i.e. from the collective flow of protons measured in central Au+Au collisions at beam energies from 2A to 10A GeV [3]. These data have been compared to results of microscopic transport models, and the extracted constraint of the EOS of symmetric nuclear matter is illustrated in figure 1 by the grey-hatched area as function of pressure and density on units of saturation density ρ_0 [4]. Because the interpretation of the direct flow data differs from the one of the elliptic flow, the result still is compatible both with a "hard" EOS (nuclear incompressibility K_{nm} = 300 MeV, red line) and with a "soft" EOS ((nuclear incompressibility K_{nm} = 210 MeV, blue line), and only excludes extreme values for K_{nm}. At densities between 1 and 2 times saturation density, the situation has been improved by detailed elliptic flow studies at GSI using Au+Au collisions from 0.4A – 1.5A GeV [5], and by the measurement of subthreshold kaon production in Au+Au collisions from 0.8A – 1.5A GeV [6,7,8]. Both data sets could be reproduced by transport model calculations assuming a soft EOS.
For pure neutron matter, the pressure shown in figure 1 further increases due to the breaking of the neutron-proton symmetry. This effect is described by the symmetry energy, which has been extracted at supra-saturation densities from the ratio of the elliptic flow of neutrons to protons measured in Au+Au collisions at 0.4A GeV at GSI [9].

Our knowledge on the EOS at neutron star core densities, i.e. up to 5 ρ_0, will be improved by future measurements of the collective flow of identified particles and of subthreshold particle production at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany, and at the Nuclotron-based Ion Collider fAcility" (NICA) in Dubna, Russia. In the near future, the Baryonic Matter @ Nuclotron (BM@N) fixed-target experiment will start to study Au+Au collisions at kinetic beam energies up to 4A GeV, in order to provide precise data on the collective flow and on multi-strange hyperon production, which both are sensitive probes of the high density EOS.

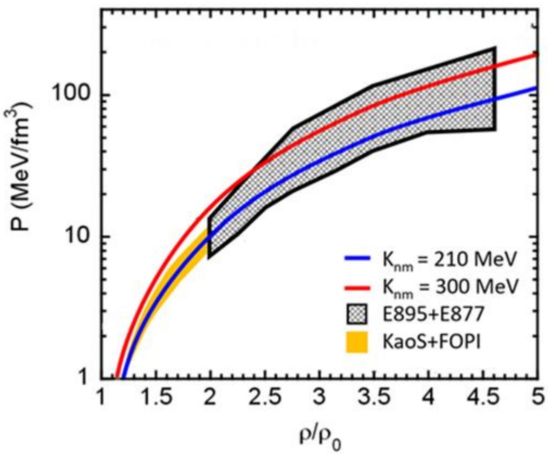

Fig. 1: Pressure as function of baryon density for symmetric nuclear matter. The grey hatched area is extracted from proton flow data taken at AGS [3,4]. Yellow area: constraint from fragment flow and kaon data taken at GSI [5-8]. Red line: hard EOS (K_{nm} = 300 MeV), blue line: Soft EOS (K_{nm} = 210 MeV).

Depending on the EOS, densities of more than 5 ρ_0 are expected to be reached in the core of massive neutron stars [10]. At those densities, various model calculations predict changes of the decrees-of-freedom, i.e. a transition from nucleons to quarks and gluons. Whether such a transition is continuous or of first order with a critical endpoint, is one of the most interesting questions of dense matter physics. For example, a soft crossover phase transition has been also proposed to happen in neutron stars within a quantum percolation model, which is able to explain 2 solar mass neutron stars [11]. Also at vanishing baryon-chemical potential, lattice Quantum Chromo Dynamics (QCD) calculations find a smooth crossover transition from the Quark-Gluon Plasma (QGP) to hadronic matter at a pseudo-critical temperature of about 155 MeV [12,13] as indicated by T_{pc} in the left panel of figure 2, and shown in the right panel of figure 2 as green and orange bands. In a recent lQCD calculation, an upper limit for the temperature of a hypothetical critical point of a chiral phase transition was found at T_c=132+3−6 MeV for a baryon-chemical potential of μ_B=0 [14,15]. The temperature T_{cep} of a critical endpoint at finite baryon-chemical potential μ_B and non-zero light quark masses will be even lower, as indicated by the red and blue lines. The right panel depicts results of various theoretical approaches including lattice QCD, Dyson-Schwinger Equations (DSE) and Functional Renormalization Group (FRG), describing the phase boundaries and the location of possible critical endpoints as function of temperature and baryon-chemical potential μ_B [16]. Moreover, freeze-out points extracted from measured particle yields by different statistical models are shown. For example, the FRG calculations, which are a QCD-based analytic continuation and pass lQCD benchmarks at vanishing μ_B, predict a chiral phase transition as illustrated by the black dashed line, ending in a critical endpoint at a temperature of T_{cep}=107 MeV and a baryon-chemical potential of μ_{cep}= 635 MeV. It is worthwhile to note that the FRG result for T_{cep} fits to the upper limit for T_c predicted by the lattice QCD calculation.

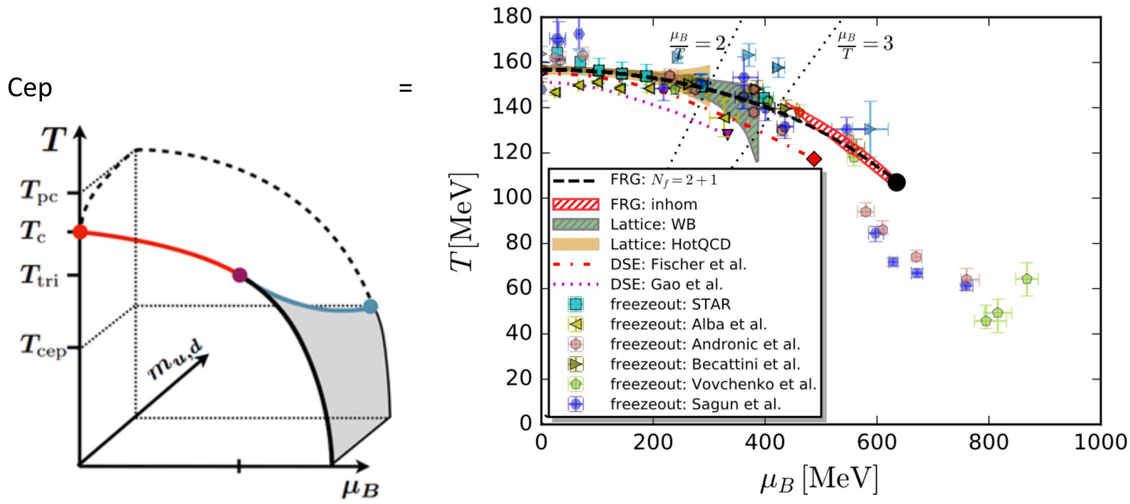

Fig. 2: Left: 3-dimensional phase diagram as function of temperature T, baryon-chemical potential μ_B and mass of the light quarks. The red dot corresponds to the upper temperature limit for the critical endpoint of a first-order chiral phase transition, which is T_c=132+3−6 MeV according to a recent lQCD calculation [14,15]. Right: Two-dimensional phase diagram for N_f = 2+1 flavor QCD in comparison to other theoretical approaches and phenomenological freeze-out data. For details see [16]. The FRG calculation predicts a critical endpoint of a 1st order chiral phase transition at T_{cep} = 107 MeV and μ_{cep} = 635 MeV.

In order to localize the beam energy, which is required to discover a possible first order chiral phase transition and its critical endpoint, μ_{cep} = 635 MeV has been correlated to a collision energy of $\sqrt{s_{cep}}$ = 3.7 GeV (= 5.4A GeV kinetic beam energy) via projection to the freeze out curve [16]. This energy is covered by the beam energy scan at RHIC, and will be covered by FAIR and NICA. However, according to fireball calculations [17,18], which are able to explain results of dilepton experiments [19,20], temperatures of 110 – 130 MeV can be already reached in heavy ion collisions at beam energies up to 4A GeV, which is covered by beams from the Nuclotron at JINR. According to the results illustrated in figure 2, Nuclotron energies should be sufficient to explore not only the onset of deconfinement and the mixed phase, but probably also the critical endpoint, if a first order phase transition exists at high net-baryon densities. The relevant observables sensitive to a first order phase transition will be discussed in the following.

2. The Baryonic Matter at Nuclotron (BM@N) experiment

At the Joint Institute for Nuclear Research (JINR), the existing Nuclotron presently is upgraded by new ion sources and a booster synchrotron in order to accelerate heavy-ion beams such as Au-nuclei up to kinetic energies of to 3.8A GeV. In the recent years, the Baryonic Matter at Nuclotron (BM@N) experiment has been installed in the Nuclotron target hall, where fixed target experiments can be performed. The BM@N setup comprises a normal conducting dipole magnet with a gap size of 96 cm, hosting 3 planes of 2-coordinate Silicon detectors with a strip pitch of 95/103 μm, and 6 tracking stations based on triple Gas-Electron-Multiplier (GEM) chambers covering half of the available acceptance. Downstream the GEM chambers, behind the magnet, 2 Cathode-Drift-Chambers (CDC) are located, which provide additional track information. Particle identification via time-of-flight measurement is performed by 3 stations equipped with Resistive-Plate-Chambers (RPCs). The collision centrality and the orientation of the reaction plane are derived from projectile spectator fragments, which are measured by a Zero-Degree-Calorimeter (ZDC) positioned at the end of the cave. This detector configuration was used for the measurement of lambda production in collisions of a 4A GeV C-beam with C, Al and Cu targets. Details on the experiment are described in [21]. A photo of the experiment is shown in figure 3.

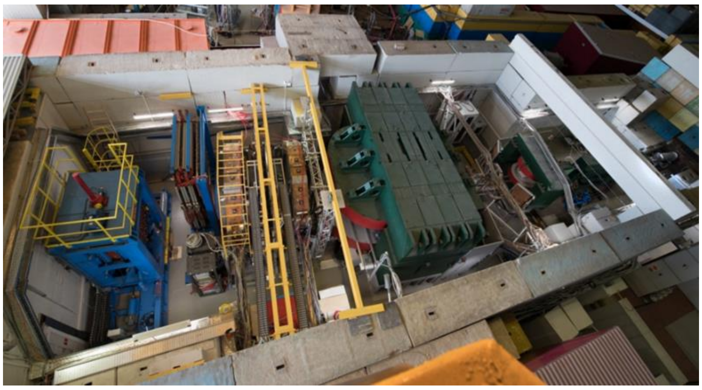

Fig. 3: Photo of the BM@N setup in the Nuclotron target hall at JINR (see text).

Figure 4 depicts a sketch of a slightly modified setup, which was optimized for measurements of short-range correlations (SRC). About 20% of the nucleons in a nucleus are strongly correlated via fluctuations, where two nucleons briefly are close together in coordinate space, with large opposite momenta but small c.m. momentum compared to the Fermi momentum. Short-range correlations probe both nucleonic and partonic degrees-of-freedom in nuclei. The SRC experiment at BM@N was performed in inverse kinematics with a 4A GeV/c C-beam bombarding a liquid hydrogen target. It was the first fully exclusive measurement in inverse kinematics probing the residual A-2 nuclear system, with identification of all products of the reaction ^{12}C + p $\rightarrow$ 2p + $_{10}{}^{4}Be$ + p (pp SRC), including momentum reconstruction. Details of the experiment, the data analysis, and the results have been published in Nature Physics [22].

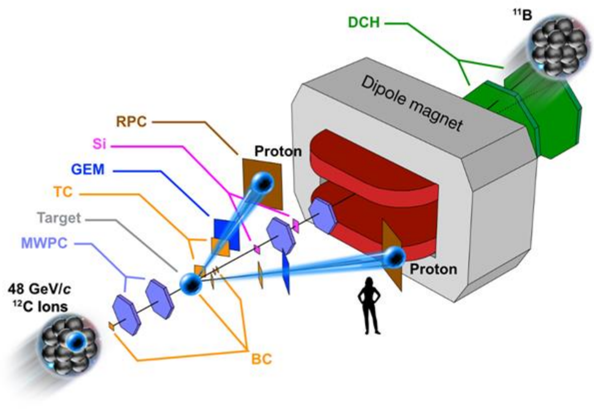

Fig. 4: Illustration of the SRC-configuration of the BM@N experiment [22].

While the present experiment configuration is well suited to study nuclear reactions with low multiplicities, the granularity of the detectors is too low in order to reconstruct tracks with high efficiency in heavy-ion collisions with high track density, such Au+Au collisions. In addition, the beam conditions have to be improved by closing the air gaps in the beam line from the Nuclotron to the experiment. In order to reduce the background radiation in the detectors, an evacuated target chamber and a downstream beam pipe in the BM@N setup will be implemented.

3. The physics program of the upgraded BM@N experiment

Model calculations predict that the reaction volume of a central Au+Au collision at top Nuclotron beam energy will be compressed to 4 -5 times saturation density [23]. Similar values are expected to prevail in the core of a neutron star. Both in heavy-ion collisions and in compact stellar objects, the density is governed by the EOS. As the matter composition in these two cases is different – neutron matter in the star and isospin symmetric matter in the heavy-ion collision - also the symmetry energy has to be measured in the laboratory, in order to contribute to our understanding of neutron stars. Therefore, laboratory experiments will provide important information on the EOS, complementary to astronomical observations of mass and radii of neutron stars. In addition, heavy-ion experiments will shed light on the role of hyperons in neutron stars, by investigating ΛN, ΛNN, and even ΛΛN interactions, either by measuring binding energies of hypernuclei or particle correlations. Finally, heavy-ion experiments are able to explore quark degrees-of-freedom of dense QCD matter, which are expected to emerge with increasing density. The relevant experimental observables to be studied at BM@N will be discussed in the next sections.

3.1. The high-density EOS

As mentioned above, an important observable of the EOS in heavy-ion collision is the elliptic flow of particles, as it is driven by the pressure gradient in the reaction volume. The elliptic flow of protons, deuterons, tritons, and ^{3}He has been measured by the FOPI collaboration in Au + Au collisions at beam energies from 0.4 to 1.5 A GeV, corresponding to matter densities of up to 2 ρ_0 [5]. The data could be reproduced by calculations with the isospin-dependent quantum molecular dynamics (IQMD) transport code, assuming a nuclear incompressibility of K_{nm} = 190 ± 30 MeV, which corresponds to a soft EOS for symmetric nuclear matter. At higher beam energies and densities, the data are scarce. In the Nuclotron beam energy range, the directed and elliptic flow has been measured at AGS in Au+Au collisions at 2A GeV and 4A GeV [4], but the interpretation of the date is not conclusive [5]. Meanwhile, elliptic flow data have also been taken around 3A GeV during the RHIC beam energy scan with the STAR fixed garget mode. This beam energy range, which corresponds to densities from 2 – 4 ρ_0, is particularly important, as the soft EOS at 2 ρ_0 should become stiffer towards 4 ρ_0, as required for the stability of the most massive neutron stars observed so far [24,25]. In order to determine as precise as possible the gradual change of the EOS with increasing density, the BM@N research program includes the measurement of the direct and elliptic flow of various particle species in steps of a few hundred MeV beam energy.

A complimentary diagnostic probe of the EOS of symmetric matter is subthreshold strangeness production in heavy-ion collisions. This method was pioneered by the KaoS collaboration at GSI, where the excitation function of K^+ meson production in Au + Au and C + C collisions at beam energies from 0.8 and 1.5 A GeV was measured [6]. At those energies, K^+ mesons are created by via sequential collisions involving pions and Delta resonances, because the direct production process $p+p \rightarrow K^+\Lambda p$ requires a proton energy of 1.58 GeV. The number of sequential collisions, and, hence, the resulting K^+ yield depends on the density, i.e. on the EOS. The nuclear compressibility is extracted from the measured data by comparison to results of relativistic transport calculations, which include information on the EOS, momentum-dependent interactions, and in-medium modifications of cross sections and masses. In order to reduce systematic uncertainties of data and model, and to correct for effects of Fermi momentum and short-range correlations, a light reference system like C+C has also been studied. It turned out, that the K^+ yield ratio measured in Au+Au over C+C as function of beam energy clearly supports a soft EOS with a nuclear incompressibility of $K_{nm}\approx$200 MeV [7,8].

In order to study the EOS at neutron star core densities, one has to increase the beam energy, and, hence, to study diagnostic probes with higher production thresholds. Obvious candidates are multi-strange (anti-) hyperons, like $\Xi^{\pm}$ and $\Omega^{\pm}$ hyperons, which have production thresholds in proton-proton collisions ranging from 3.7 to 12.7 GeV. Also these particles are produced in sequential strangeness-exchange collisions involving kaons, lambdas, sigma-hyperons, and, therefore, are sensitive to the density of the fireball [26,27]. As an example for future measurements at the BM@N experiment, preliminary results of calculations with the novel PHQMD transport code are presented in figure 5 [28]. The left panel depicts the hyperon yield ratio for a soft EOS (K_{nm}=240 MeV) over a hard EOS (K_{nm}=350 MeV), calculated for central Au+Au collisions at a beam energy of 4A GeV. The ratio increases with the threshold beam energy required to produce the respective hyperon. The left panel of figure 5 illustrates the hyperon yield ratios calculated for Au+Au over C+C collisions. As only 6 million events have been calculated for each system, only very few hyperons heavier than double-strange Xis were found in C+C calculations.

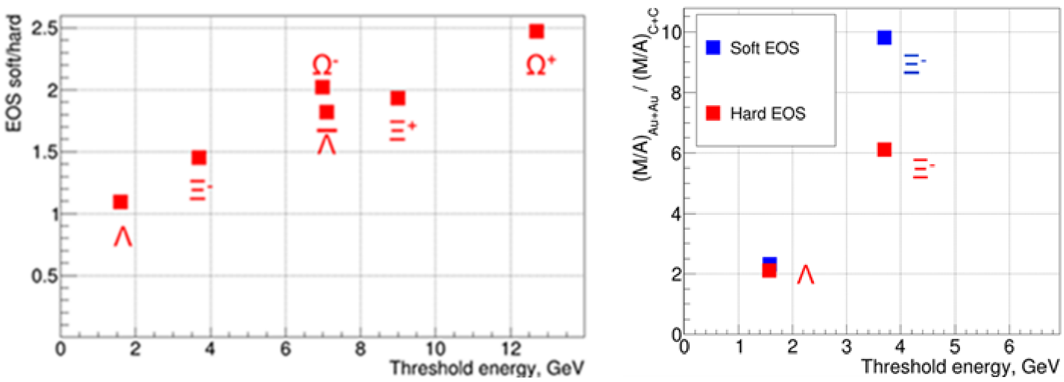

Fig.5: Left: Hyperon yield ratios for a soft over a hard EOS calculated for Au+Au collisions at a beam energy of 4A GeV with the PHQMD transport code [28] as function of production threshold in nucleon-nucleon collisions. Right: Hyperons yields per nucleon from Au+Au over C+C collisions for a soft and a hard EOS.

3.2 Hyperons in Dense Nuclear Matter

The role of hyperons in neutron stars is still an open issue. In nuclear matter in beta-equilibrium, the baryon chemical potential of neutrons μ_n increases with increasing density. At a certain density, μ_n exceeds the Λ hyperon chemical potential μ_Λ, and the neutron decays into a hyperon. This decay releases the Fermi pressure exerted by the neutrons, and results in a softening of the EOS. If this process occurs at densities, which are realized in neutron stars, it prevents the existence of massive neutron stars, which, however, have been observed. This "hyperon puzzle" can be resolved by the introduction of repulsive ΛN, ΛNN, and ΛΛN interactions, which would shift the condensation of Λ hyperons to rather high densities, which might not be realized in neutron stars [29]. One possibility, to experimentally prove this scenario in the laboratory, is to study hyperon-nucleon interactions, by measuring the lifetime and binding energy of hypernuclei. In heavy-ion collisions at Nuclotron beam energies, light hypernuclei are abundantly produced by coalescence of hyperons and light nuclei [30]. The research program of the BM@N experiment includes high-statistics measurements of light hypernuclei.

3.3 Searching for signatures of a chiral phase transition at large baryon-chemical potential

The search for traces of a chiral phase transition in dense nuclear matter in the laboratory poses a severe experimental challenge. The fireball created in energetic heavy-ion collisions is a highly dynamical, transient, inhomogeneous and microscopically small system. A phase transition has to occur within a few fm/c involving a major part of the reaction volume, in order to produce characteristic and measurable signatures. For example, within the PHQMD event generator, a crossover phase transition from hadronic matter to quark matter takes place if the energy density exceeds 0.5 GeV/fm^3, which is the case only briefly in the center of the reaction volume [28]. In QCD matter at very high temperatures and vanishing baryon-chemical potential, which is produced in heavy-ion collisions at ultra-relativistic energies, lattice QCD calculations also predict a crossover phase transition [12,13]. A promising observable for such a phase transition are multi-strange hyperons, which were found to be in chemical equilibrium in high-energy heavy-ion collisions. This observation was explained by multiple collisions occurring at the phase boundary, which drive the hyperons in equilibration, as the hyperon-nucleon scattering cross section is too small and the lifetime of the dense hadronic phase too short to equilibrate hyperons [32]. Also at heavy-ion collisions down to the beam energy of 30A GeV multi-strange hyperons still are found to be in chemical equilibrium [33]. In heavy-ion collisions at an energy of 1.76A GeV, however, the observed yield of Ξ^- hyperons exceeds the statistical model prediction by about a factor 24±9, while the other hadrons yields can be explained by one temperature and one baryon-chemical potential [34]. Most probably, the Ξ^- hyperons do not equilibrate at very low beam energies, because the matter is still in a hadronic phase. The BM@N research program includes the measurement of the excitation function of multi-strange hyperons in Au + Au collisions in order to explore the onset of equilibration of multi-strange hyperons at high net-baryon densities.

As discussed above and illustrated in figure 2, various models propose, that for large values of the baryon-chemical potential the crossover transition ends in a critical endpoint of a 1st order phase transition. Beyond the critical endpoint, towards even larger values of μ_B, a region of phase coexistence should follow, and finally the hadronic phase. These different regions of the phase diagram are expected to affect experimental observables in heavy-ion collision. For example, the phenomenon of "critical opalescence" - caused by particle density fluctuations near the critical endpoint - is predicted to cause fluctuations of the baryon number distribution in central heavy-ion collisions. The STAR collaboration measured precisely event-by-event the shape of the proton multiplicity distribution, and determined the higher order cumulants [35]. For the lowest collision energy of $\sqrt{s_{NN}}$ = 7.7 GeV, a non-monotonic variation in the ratio of the 4th to the 2nd cumulant C_4/C_2 (= $\kappa\sigma^2$) was observed. These measurements have to be continued towards lower collisions energies, in order to locate a possible maximum of the fluctuation, which might indicate a critical endpoint. The density fluctuations in the vicinity of the critical endpoint might also result in fluctuations of the yields of light nuclei, which are predicted to be observed as a peak in the yield ratios like $N_t \cdot N_p / N_d^2$ [36]. According to model calculations, the baryon density fluctuations should be even larger in the mixed phase due to spinodal decomposition, which leads to baryon clumping, and to anisotropic azimuthal angle distributions of baryons and light fragments [37,38]. If a 1^{st} order phase transition exists, the region of phase coexistence in the T-μ_B plane should be much larger than the spot of a critical endpoint, and, hence, easier to discover experimentally. The models that spinodal decomposition occurs at beam energies, which are covered by the CBM experiment at FAIR, and by the BMN experiment at NICA. The BM@N program includes the measurement of the excitation function of event-by-event fluctuation of the number distributions of protons and light fragments, together with their azimuthal angular distribution.

4. BM@N experiment upgrades

The physics program discussed above will be performed with Au+Au collisions at interaction rates up to 20 kHz. In order to handle the high rates and particle multiplicities, the tracking system has to be substantially upgraded. This includes the enlargement of the GEM tracker, from now 6 half stations to 7 full stations with fast readout. Moreover, the existing Silicon tracker will be replaced by 4 high-granulation tracking stations equipped with double-sided micro-strip silicon sensors. A new T0 detector system will be positioned around the target, in order to provide the start signal for the TOF measurements and the trigger signal for the data acquisition. Tracking downstream will be performed by 2 large by Cathode Strip Chambers, replacing the existing drift chambers (DCH). For particle identification via time-of-flight measurements, 3 walls of Resistive Plate Chambers (mRPC) with strip readout will be used. A new Zero Degree Calorimeter (ZDC) will be installed for determination of the collision centrality of the collision and the reaction plane. Finally, the experiment will be with an evacuated target chamber and a beam pipe. More information is given in [39]. The performance of the upgraded BM@N experimental setup has been studied in simulations of central Au+Au collisions at an energy of 4A GeV. The detector configuration was implemented in the transport code GEANT3, and 500 k events using the PHQMD code have been generated [40]. Figure 6 depicts the reconstructed invariant mass spectra for of Ξ^- hyperons (left panel) and of $_\Lambda{}^3H$ hypernuclei (right panel), indicating the decay channel, the signal/background ratio and the reconstruction efficiency.

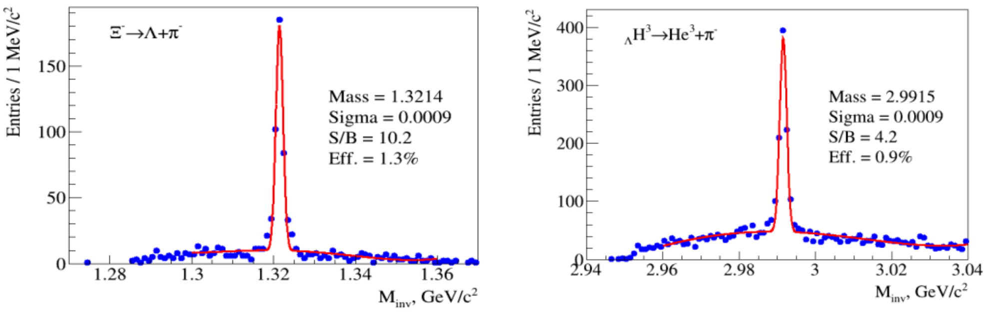

Fig. 6: Invariant mass spectra of Ξ^- hyperons (left) and of $_\Lambda{}^3H$ hypernuclei (right) reconstructed in central Au+Au collisions at an energy of 4A GeV, as simulated with the PHQMD code [40].

Conclusion

The proposed measurements planned at the BM@N experiment will address fundamental questions of nuclear and astrophysics: the high-density EOS, the role of hyperons in neutron stars, the existence and possible features of a chiral phase transition in dense QCD matter. These laboratory measurements will complement astronomical observations regarding the mass and radius of neutron stars, and from gravitational waves generated by neutron star mergers.

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