The heavy-ion program of the future FAIR facility

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Abstract. The Compressed Baryonic Matter (CBM) experiment will be one of the major scientific pillars of the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt. The goal of the CBM research program is to explore the QCD phase diagram in the region of high baryon densities using high-energy nucleus-nucleus collisions. This includes the study of the equation-of-state of nuclear matter at neutron star core densities, and the search for the deconfinement and chiral phase transitions. The CBM detector is designed to measure rare diagnostic probes such as hadrons including multi-strange (anti-) hyperons, lepton pairs, and charmed particles with unprecedented precision and statistics. Most of these particles will be studied for the first time in the FAIR energy range. In order to achieve the required precision, the measurements will be performed at very high reaction rates of 1 to 10 MHz. This requires very fast and radiation-hard detectors, a novel data read-out and analysis concept based on free streaming front-end electronics, and a high-performance computing cluster for online event selection. The physics program and the status of the proposed CBM experiment will be discussed.

1. Introduction
Ordinary substances exist in different phases such as gas, liquid, and solid, depending on the temperature and pressure. A variation of these conditions may cause a transition from one phase to the other, and the boundaries between the different lines can be drawn in a diagram as function of temperature and pressure. These lines could meet at the triple point where several phases coexist. In general there is also a critical point where the distinct phase boundary between liquid and gas ends, and beyond which there is a continuous "crossover" between the two phases. The phase boundaries, the triple point and the critical point represent fundamental landmarks in the phase diagram of each substance.

Substantial experimental and theoretical efforts worldwide are devoted to explore the phase diagram of nuclear matter. In experiments at LHC and top RHIC energies, matter is produced at very high energy densities with equal numbers of particles and antiparticles, i.e. at almost zero baryon chemical potential. After hadronization, the fireball finally freezes out chemically at a temperature of 155 - 165 MeV [1]. This temperature coincides with the critical temperature predicted by Lattice QCD calculations for a chiral phase transition [2, 3] which is found to be a smooth crossover from partonic to hadronic matter [4]. Model calculations predict structures in the QCD phase diagram at large baryon chemical potentials, like a critical endpoint followed by a first order phase transition [5]. Moreover, new phases are predicted, such as quarkyonic matter which can be considered as a Fermi gas of free quarks, with all thermal and Fermi surface excitations permanently confined [6]. The experimental discovery of these landmarks and regions in the QCD phase diagram would be a major breakthrough in our understanding of the properties of strongly interacting matter at extreme conditions, with fundamental consequences.
for our knowledge on the structure of neutron stars, chiral symmetry restoration, and the origin of hadron masses. Figure 1 illustrates the conjectured phases of nuclear matter and their boundaries in a diagram of temperature versus baryon chemical potential [7].

![Figure 1. Sketch of the phase diagram for nuclear matter. Taken from [7].](image)

2. Heavy-ion experiments scanning the QCD phase diagram at high net-baryon densities

Explorative heavy-ion experiments at AGS in Brookhaven [8] and CERN-SPS [9] mainly measured abundantly produced hadrons. The NA61/SHINE experiment at CERN-SPS continues to scan the QCD phase diagram light and medium size beams [10]. The STAR collaboration at RHIC plans for a second beam energy scan to improve the statistical significance of the data taken in the first series of measurements [11]. In order to go down in collision energy and up in baryon-chemical potential, the STAR detector can be operated in a fixed target mode. At the Joint Institute for Nuclear Research (JINR) in Dubna, the collider facility NICA together with a multi-purpose detector is planned at JINR [12]. As an intermediate step, a fixed target experiment called "Baryonic Matter at Nuclotron" (BM@N) is being prepared at the Nuclotron to study heavy-ion collisions at gold-beam energies up to about 4.5 A GeV. The luminosity limitations of these existing and future facilities constrain the research programs to the investigation of bulk observables, and prevent high precision measurements of rare diagnostic probes. In contrast, the Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (FAIR) is designed to run at extremely high interaction rates (up to 10 MHz). This feature is the key requirement for the measurement of both bulk and rare probes with unprecedented precision. The rate capabilities of existing and planned heavy-ion experiments are plotted in figure 2 as function of beam energy. The combination of high-intensity beams with a high-rate detector system and sufficient beam time provides worldwide unique conditions for the study of nuclear matter at neutron star core densities.
3. The CBM Physics Program at SIS100

FAIR will provide heavy-ion beam energies from 2 - 11 (14) A GeV for Q = 0.4 A (0.5 A) nuclei with the SIS100 synchrotron. Already in central Au+Au collisions at 5 A GeV the nuclear fireball will be compressed - according to transport model and hydro calculations - to more than 6 times saturation density $\rho_0$, and at 10 A GeV even a density above 8 $\rho_0$ is reached as illustrated in figure 3 [13]. At such densities, the nucleons will start to melt and to dissolve into their constituents. The calculations predict that the dense fireball spends a relatively long time within the phase coexistence region or even beyond. Further indication, that a phase transition might occur at densities reached at SIS100 beam energies, comes from a non-local 3-flavor Nambu Jona-Lasinio model calculation of a neutron star, which predicts the development of a mixed phase of hadrons and quarks above densities of about 5 $\rho_0$, and the transition to
pure quark matter above $8 \rho_0$ [14]. The results of this calculation, which is able to reproduce a 2 solar mass neutron star, is depicted in figure 4.

![Figure 4. Particle population in a neutron star calculated with a Nambu Jona-Lasinio (n3NJL) model with repulsive vector interactions. The model is able to describe neutron stars with 2 solar masses and radii between 12 and 13 km [14].](image)

In conclusion, the beam energies available at SIS100 appear to be especially well suited for generating signals of the phase transition, and, therefore, offer the opportunity to address fundamental scientific questions:

- What is the equation of state of nuclear matter at neutron star densities, and what are the relevant degrees of freedom at these densities? Is there a phase transition from hadronic to quark-gluon matter, or a region of phase coexistence? Do exotic QCD phases like quarkyonic matter exist?
- To what extent are the properties of hadrons modified in dense baryonic matter? Are we able to find indications of chiral symmetry restoration?
- How far can we extend the chart of nuclei towards the third (strange) dimension by producing single and double hypernuclei? Does strange matter exist in the form of heavy multi-strange objects?
- What is the production mechanism of charm quarks at threshold beam energies, how does open and hidden charm propagate in cold and in hot nuclear matter?

The focus of the CBM experiment at FAIR is to study messengers from the dense fireball such as multiple strange hyperons, lepton pairs, and hadrons containing charm quarks in order to find answers to the questions raised above. A survey of the theoretical concepts and the experimental programs devoted to the exploration of the QCD phase diagram with focus on high baryon densities is given in the CBM Physics Book [15]. The CBM research program at SIS100 includes the physics cases and observables as discussed in the following.

3.1. The equation of state of nuclear matter at high baryon densities

According to transport models, multi-strange (anti-)hyperons are produced in sequential collisions involving kaons and $\Lambda$s, and, therefore, are sensitive to the density in the fireball. This sensitivity is expected to increase towards lower beam energies close to or even below the...
production threshold. SIS100 beam energies will be ideally suited to perform such experiments which require a systematic measurement of multi-(anti-)strange hyperons at different energies and for different colliding nuclei. The excitation functions of multi-strange hyperons ($\Xi^-(dss)$ and $\Omega^- (sss)$) and anti-hyperons ($\Xi^+(d\bar{s}s)$ and $\Omega^+ (\bar{s}s\bar{s})$) in A+A collisions with different A values at SIS100 beam energies are very promising observables which will shed light on the matter equation of state at neutron star core densities. Another promising observable is the collective flow of identified particles which is driven by the pressure gradient inside the fireball, and hence, is expected to be sensitive to the compressibility of nuclear matter. Up to now, only the proton flow excitation function has been measured at the AGS [8], and was used to extract the compressibility of nuclear matter [16].

3.2. Phase Transitions, phase coexistence, critical point
The experimental observation, that in ultra-relativistic heavy-ion collisions multi-strange hyperons including $\Omega^-$ and $\Omega^+$ are in chemical equilibrium as all the other produced particles, was taken as strong indication that the system had undergone a transition from a partonic phase to the hadronic final state, with the equilibration being driven by multi-body collisions in the high particle density regime near the phase boundary [17]. Agreement of the hyperon yield with thermal model calculations was found also at 40A GeV in Pb+Pb collisions at the SPS [18]. In Ar + KCl collisions at an energy of 1.76A GeV, however, the measured yield of $\Xi^+$ hyperons exceeds the thermal model prediction by about a factor of 20, indicating that $\Xi^+$ hyperons are far off chemical equilibrium [19]. High precision measurements of excitation functions of multi-strange hyperons in A+A collision at SIS100 energies will allow to study the degree of equilibration of the fireball, and, hence, open the possibility to find a signal for the onset of deconfinement in QCD matter at high net-baryon densities.

The slope of the dilepton invariant mass spectrum between 1 and about 2.5 GeV/$c^2$ reflects the average temperature of the fireball [20]. The precise measurement of the spectral slope as a function of beam energy opens the unique possibility to measure the caloric curve, which would be the first direct experimental signature for phase coexistence in high-density nuclear matter. This measurement would also provide indications for the onset of deconfinement and the location of the critical endpoint. Another direct experimental proof for a first order phase transition would be the discovery of phase coexistence by observing an enhanced production of composite particles or multi-particle correlations caused by the spinodal amplification of density fluctuations [21]. Higher moments of the net-baryon and the net-charge multiplicity distributions, which are related to the thermodynamical susceptibilities, have been measured by the STAR collaboration in order to search for the QCD critical point [22]. Most of these observables will be measured for the first time at SIS100 energies.

3.3. In-medium modifications of hadrons, onset of chiral symmetry restoration
Lepton pairs will be measured over a wide range of invariant masses covering low-mass vector mesons including their Dalitz decays and charmonium. The precise measurement of lepton pairs at low invariant masses will allow to analyze modifications of vector meson properties in dense baryonic matter. This observable is expected to be sensitive to chiral symmetry restoration [23]. The thermal radiation at intermediate invariant dilepton masses includes a broadened in-medium $\rho$ meson, radiation from the QGP, and dileptons from multi-pion annihilation. The latter contribution reflects $\rho - a_1$ chiral mixing, and, therefore, provides a direct link to chiral symmetry restoration.

3.4. Charm
With CBM at SIS100, charm production will be studied for the first time at beam energies close to production threshold. At these energies, the formation time of charmonium is small
compared to the lifetime of the reaction system. CBM is thus uniquely suited to study the interactions between fully formed $J/\psi$ and the dense medium with appropriate counting statistics and systematics. Systematic measurements of charmonium in p+A collisions with varying target mass number $A$ at proton energies up to 30 GeV will shed light on the charmonium interaction with cold nuclear matter and constitute an important baseline for measurements in heavy-ion collisions. Moreover, the simultaneous measurement of open charm will give access to the basically unknown charm production cross section at or near the kinematic threshold. According to a recent UrQMD calculation the subthreshold charm production in central Au+Au collision increased dramatically when considering secondary processes like $N^* \rightarrow \Lambda_c + D$ and $N^* \rightarrow N + J/\psi$ [24].

3.5. Hypernuclei and strange objects
Theoretical models predict that single and double hypernuclei, and heavy multi-strange short-lived objects are produced via coalescence in heavy-ion collisions with the maximum yield in the region of SIS100 energies [25, 26]. The discovery and investigation of new hypernuclei and of hypermatter will shed light on the hyperon-nucleon and hyperon-hyperon interactions which are essential ingredients for the nuclear equation-of-state at high densities and low temperatures [27]. According to a coupled transport-hydro-dynamics model, the high baryon densities created in heavy-ion collisions at FAIR energies favor the distillation of strangeness.

4. The Compressed Baryonic Matter (CBM) Experiment
The CBM detector is designed as a multi-purpose device which will be able to measure hadrons, electrons and muons in heavy-ion collisions over the full SIS100/SIS300 beam energy range. Therefore, no major adjustments have to be made to optimize the experiment for SIS100 beams, only some of the detectors and the DAQ system will be realized in phases (see below). In order to extract the dilepton signals, the physical and combinatorial background of lepton pairs has to be precisely determined, which is notoriously difficult. Measuring both electrons and muons will dramatically reduce the systematical error of the data, because the background sources of electrons and muons are completely different. In order to perform high-precision multi-differential measurements of rare probes the experiment should run at event rates of 100 kHz up to 10 MHz for several months per year. Because of the complicated decay topology of particles like $\Omega$ hyperons or $D$ mesons, no simple trigger signal can be generated, so the events have to be reconstructed and selected online by fast algorithms running on a high-performance computing farm. Therefore, the data readout chain is based on a free streaming frontend electronics which delivers time-stamped signals from each detector channel without event correlation. The reconstruction algorithms are tuned to run at high speed on modern many-core CPU architectures.

The detector system features a fixed target geometry accepting polar emission angles between 2.5 and 25 degrees in order to cover midrapidity for symmetric collision systems at beam energies between 2 and about 40 A GeV. The setup comprises the following components:

- A large aperture superconducting dipole magnet,
- a Silicon Tracking System (STS) based on double-sided silicon microstrip sensors arranged in 8 stations inside the magnetic field,
- a Micro Vertex Detector (MVD) consisting of 4 layers of silicon monolithic active pixel sensors,
- a time-of flight wall (TOF) based on multigap resistive plate chambers with low-resistivity glass for high-rate operation (up to 25 kHz/cm² with a time resolution of 50 ps),
- a Ring Imaging Cherenkov (RICH) detector for electron identification comprising a CO₂ radiator, glass-mirrors, and a photon detector based on multianode photomultipliers,
• a Transition Radiation Detector (TRD) for the identification of energetic electrons,
• a Muon chamber (MuCh) system for muon identification consisting of 5 triple stations of highly granulated gaseous micro-pattern chambers detectors sandwiched by iron plates with a total thickness equivalent to 13 absorption lengths,
• a forward hadron calorimeter (Projectile Spectator Detector) for event characterization,
• an Electromagnetic Calorimeter (ECAL) for event characterization,
• a First-Level-Event-Selection (FLES) system for online event reconstruction and selection.

The RICH detector and the Muon chamber (MuCh) system will be used alternatively. All detector systems are equipped with self-triggered read-out electronics. After data compression and conversion into optical signals, the data are delivered via about 1000 m long fibres to the FAIR high performance computing cluster (“Green-IT cube”) where the First Level Event Selection (FLES) will be performed. At high rate operation, a data volume of about 1 TByte will be delivered to the FLES, and about 1 GByte will finally be recorded.

The development of the experimental components is well in progress. The Technical Design Reports on the Superconducting Dipole Magnet, on the Silicon Tracking System, on the Ring Imaging Cherenkov Detectors, on the Projectile Spectator Detector, on the Time-of-Flight detector, and on the Muon Chamber system have been approved by FAIR. The TDRs on Data Acquisition and First Level Event Selection, on the Micro-Vertex-Detector, and on the Transition Radiation Detector will be submitted in 2017.

Until the start of FAIR, the nuclear matter research program at GSI will be pursued with the HADES experiment at SIS18. At the SIS100 accelerator, the HADES detector can be used to perform di-electron and hadron reference measurements in collision systems with moderate particle multiplicities, such as proton-proton, proton-nucleus and nucleus-nucleus collisions with light nuclei. A sketch of the CBM and HADES experimental setups is shown in figure 5.

**Figure 5.** The HADES detector (left) and the CBM experimental setup (right) with Ring Imaging Cherenkov detector in measuring position, and the muon detection system in parking position.
5. Summary
The Compressed Baryonic Matter (CBM) experiment will be one of the major scientific pillars of the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt. The goal of the CBM research program is to explore the QCD phase diagram in the region of high baryon densities using high-energy nucleus-nucleus collisions. This includes the study of the equation-of-state of nuclear matter at neutron star core densities, and the search for the deconfinement and chiral phase transitions. The CBM detector is designed to measure rare diagnostic probes such as multi-strange hyperons, charmed particles and vector mesons decaying into lepton pairs with unprecedented precision and statistics. Most of these particles will be studied for the first time in the FAIR energy range. In order to achieve the required precision, the measurements will be performed at reaction rates between 100 kHz and 10 MHz. This requires very fast and radiation hard detectors, and a novel data read-out and analysis concept based on free streaming front-end electronics and a high-performance computing cluster for online event selection. The use of the most modern detector and computer technology is the prerequisite for a large discovery potential of heavy-ion collision experiments at FAIR energies.

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