The Compressed Baryonic Matter Experiment at FAIR

Peter Senger, July 2013

1. Exploring the phase diagram of nuclear matter

Substantial experimental and theoretical efforts worldwide are devoted to explore the phase diagram of strongly interacting matter. At top RHIC and LHC energies, the QCD phase diagram is studied at very high temperatures and very low net-baryon densities. These conditions presumably existed in the early universe about a microsecond after the big bang. For larger net-baryon densities and lower temperatures, it is expected that the QCD phase diagram exhibits a rich structure such as a critical point, a first order phase transition between hadronic and partonic or quarkyonic matter, and the chiral phase transition. The experimental discovery of these prominent landmarks of the QCD phase diagram would be a major breakthrough in our understanding of the properties of nuclear matter. Figure 1 illustrates the possible phases of nuclear matter and their boundaries in a diagram of temperature versus the baryon chemical potential.

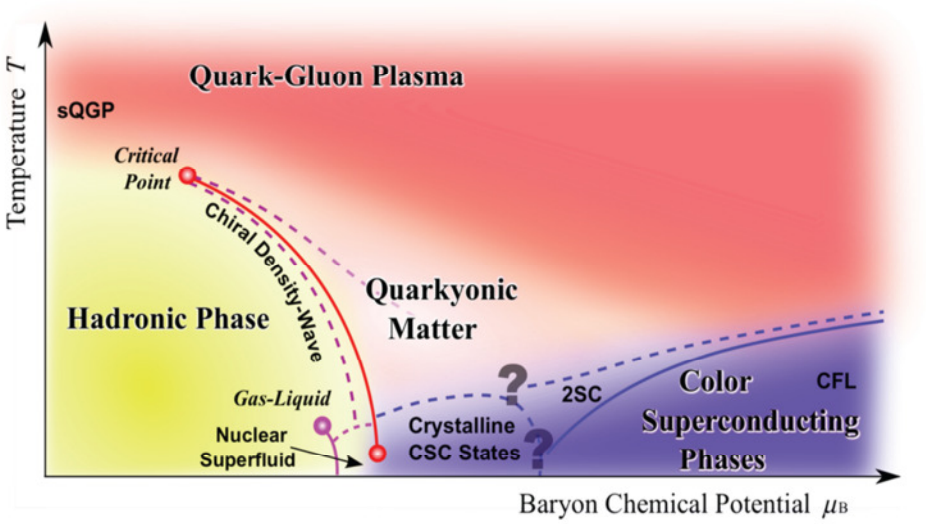

Figure 1: Sketch of the phase diagram for strongly-interacting matter (taken from [1]).

A dedicated heavy-ion experiment at FAIR opens the opportunity to shed light on fundamental questions:

- What is the origin of the mass of hadrons which determine the visible mass of the universe? The Higgs mechanism only explains the mass of the quarks which account for about 2 % of the proton or neutron masses. In hot and dense nuclear matter, as it is created in high-energy nucleus-nucleus collisions, the masses of the hadrons are expected to be modified. This phenomenon can be related to hadron mass generation.
- Why do we not observe individual quarks, the elementary building blocks of matter? At very high temperatures and densities the hadrons in fireball melt into a plasma of quarks and gluons. This phase transition is the only possibility to overcome the confinement of quarks in hadrons.

- What is the structure of compact stars? In heavy-ion collisions at FAIR energies baryon densities of up to 10 times nuclear matter density can be produced. Such densities are expected to exist in the core of neutron stars.
- 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? In heavy-ion collisions at FAIR energies, a large variety of hypernuclei are predicted to be created via coalescence of light fragments and hyperons, i.e. baryons which contain a strange quark.

2. Experiments on dense baryonic matter

Several experimental programs are devoted to the exploration of the QCD phase diagram at large baryon-chemical potentials. The STAR collaboration at RHIC scanned the beam energies in order to search for the QCD critical endpoint. However, due to a rapid decrease of luminosity with decreasing beam energy at RHIC, the data obtained by the STAR experiment at a collision energy of $\sqrt{s}$ = 7 GeV (corresponding to 30 A GeV on fixed target) suffer strongly from statistics. The measurements with the upgraded NA49 detector (NA61) at the CERN-SPS are also luminosity limited due to the use of a Time-Projection Chamber. In contrast, the CBM experiment is designed to perform systematic measurements with unprecedented precision and sensitivity. The beam energies and the corresponding reaction rates for various experiment are given in Table 1: STAR at RHIC, NA61 at CERN-SPS, MPD at the planned collider facility NICA at JINR Dubna, and CBM at FAIR.

Table 1: Beam energy ranges and reaction rates for running and future high-energy heavy-ion experiments exploring the QCD phase diagram in the region of high net-baryon densities.

Experiment	Au/Pb beam energies	Reaction rates in Hz
STAR@RHIC BNL	$\sqrt{s_{NN}}$ = 7 – 200 GeV	1– 800 (limitation by luminosity)
NA61@SPS CERN	E_{kin}= 20 – 160 A GeV $\sqrt{s_{NN}}$= 6.4 – 17.4 GeV	80 (limitation by detector)
MPD@NICA Dubna	$\sqrt{s_{NN}}$= 4.0 – 11.0 GeV	~1000 (L = 10^{27} $cm^{-2}s^{-1}$)
HADES@FAIR Darmstadt	E_{kin}= 1.5 A GeV (Au+Au) up to 8.0 A GeV (Ni+Ni)	$5\cdot10^{4}$ (limitation by detector)
CBM@FAIR Darmstadt	E_{kin}= 2.0 – 35 A GeV $\sqrt{s_{NN}}$= 2.7 – 8.3 GeV	10^5 – 10^7 (limitation by detector)

3. CBM physics cases and observables

The CBM research program is focused on the following physics cases:

The equation-of-state of matter at neutron star core densities.

In the laboratory, the highest net-baryon densities can be produced in nucleus-nucleus collisions at FAIR energies. The relevant measurements are:

- The excitation function of the collective flow of hadrons which is driven by the pressure created in the early fireball (SIS100/300).
- The excitation functions of multi-strange hyperons in Au+Au and C+C collisions at energies from 2 to 11 A GeV (SIS100). At subthreshold energies, Ξ and Ω hyperons are produced in sequential collisions involving kaons and Λ's, and, therefore, are sensitive to the density in the fireball.

Modifications of hadron properties in dense baryonic matter.

The generation of hadron masses is related to the spontaneous breaking of chiral symmetry. Chiral symmetry can be restored in dense baryonic matter, a process which will result in the modification of the hadron properties. The relevant measurements are:

- The in-medium mass distribution of vector mesons decaying in lepton pairs in heavy-ion collisions at different energies (2 – 45 A GeV), and for different collision systems. Leptons are penetrating probes carrying the information out of the dense fireball (SIS100/300).
- Yields and transverse mass distributions of charmed mesons in heavy-ion collisions as function of energy (SIS100/300).

Phase transitions from hadronic matter to quarkyonic or partonic matter at high net-baryon densities.

Already at SIS100 energies densities of up to 7 times ρ_0 are reached in central collisions between heavy-ions. Under these conditions the nucleons overlap, and theories predict a transition to a mixed phase of baryons and quarks. A discontinuity or sudden variation in the excitation functions of sensitive observables would be indicative of a transition. The relevant measurements are:

- The excitation function of yields, spectra, and collective flow of strange particles in heavy-ion collisions from 2-45 A GeV (SIS100/300).
- The excitation function of yields, spectra, and collective flow of charmed particles in heavy-ion collisions from 15-45 A GeV (SIS100/300).
- The excitation function of yields and spectra of lepton pairs in heavy-ion collisions from 2-45 A GeV (SIS100/300).
- Event-by-event fluctuations of conserved quantities like strangeness, baryons, and net-charge in heavy-ion collisions with high precision as function of beam energy from 2-45 A GeV (SIS100/300).

Hypernuclei, strange dibaryons and massive strange objects.

Theoretical models predict that single and double hypernuclei, strange dibaryons 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. The planned measurements include:

- The decay chains of single and double hypernuclei in heavy ion collisions at SIS100 energies.
- Search for strange matter in the form of strange dibaryons and heavy multi-strange short-lived objects. If these multi-strange particles decay into charged hadrons including hyperons they can be identified via their decay products.

Charm production mechanisms, charm propagation, and in-medium properties of charmed particles in (dense) nuclear matter.

The relevant measurements are:

- Cross sections and momentum spectra of open charm (D-mesons) in proton-nucleus collisions at SIS100/300 energies. In-medium properties of D mesons can be derived from the transparency ratio $T_A = (\sigma_{pA} \rightarrow DX)/(A \odot \sigma_{pN} \rightarrow DX)$ measured for different size target nuclei.
- Cross sections, momentum spectra, and collective flow of open charm (D-mesons) in nucleus-nucleus collisions at SIS300 energies.
- Cross sections, momentum spectra, and collective flow of charmonium (J/ψ) in proton-nucleus and nucleus-nucleus collisions at SIS100/300.

The intended measurements at SIS100 with HADES and CBM including the results of simulations and count rate estimates are described in the CBM Report 2012-01 [2]. A general review of the physics of compressed baryonic matter, the theoretical concepts, the available experimental results, and predictions for relevant observables in future heavy-ion collision experiments can be found the CBM Physics Book [3].

4. The Compressed Baryonic Matter (CBM) experiment

The CBM experimental strategy is to perform systematic measurements with unprecedented precision and sensitivity. The measurement of multi-strange hyperons, of hypernuclei, of particles with charm quarks and of vector mesons decaying into lepton pairs requires efficient background suppression and very high interaction rates. In order to select events containing those rare observables, the tracks of each collision have to be reconstructed and filtered online with respect to physical signatures. This concept represents a paradigm shift for data taking in high-energy physics experiments: CBM will run without hierarchical trigger system. Self-triggered read-out electronics, a high-speed data processing and acquisition system, fast algorithms, and, last but not least, radiation hard detectors are indispensable prerequisites for a successful operation of the experiment.

The CBM experiment comprises the following components: The core of the setup is a large-aperture superconducting dipole magnet hosting a Micro-Vertex Detector (MVD) and a Silicon Tracking System (STS) for the reconstruction of tracks, primary and secondary vertices, and particle momenta. Particle identification will be performed by time-of-flight measured with a large area Multi-gap Resistive Plate

Chamber (MRPC) wall. A Ring Imaging Cherenkov (RICH) detector will be used for the identification of electrons from low-mass vector-meson decays. A start version of the Transition Radiation Detector (TRD) consisting of 3 layers will serve as an intermediate tracker at SIS100. The full version of the TRD consisting of 9 layers will be used for the identification of high-energy electrons at SIS300. A start version of the muon chamber/hadron absorber system (MUCH) system (6-9 chambers) will be used for charmonium measurements at SIS100, the full MUCH system (18 chambers) is required for detecting muons from low-mass vector meson decays as well. A Projectile Spectator Detector (PSD) provides information on the collision centrality and the orientation of the reaction plane. The Electromagnetic Calorimeter (ECAL) will be used for the identification of photons. First level event selection will be performed online using a high-performance computer farm (GSI Green IT cube).

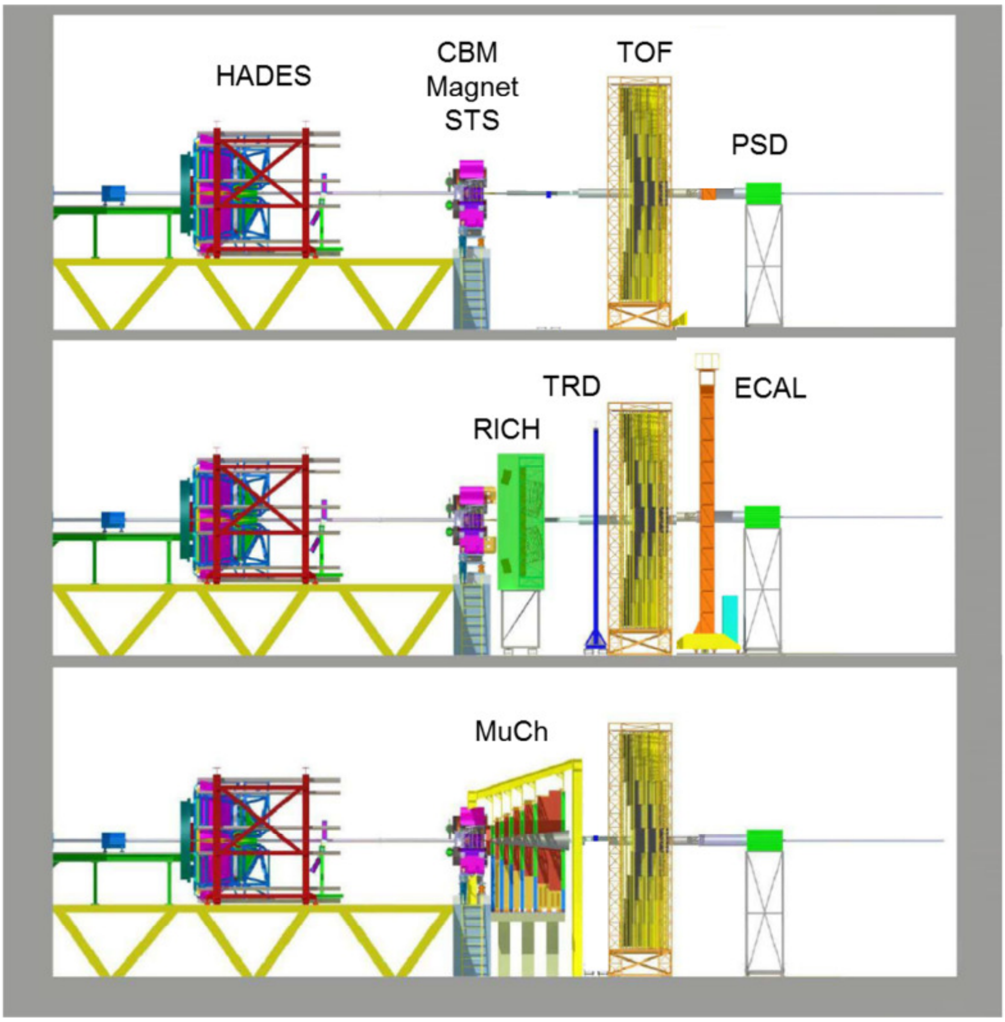

Figure 2: The CBM Modular Start Version. The HADES detector will be used to investigate small size collisions systems over the full SIS100 energy range, or Au+Au collisions up to about 4 A GeV. The CBM start version will be able to study the heaviest collision systems over the full SIS100/300 range. Upper panel: The superconducting dipole magnet hosting the Micro-Vertex Detector (MVD), the Silicon Tracking System (STS), the time-of flight wall (TOF), and the forward calorimeter for event characterization (PSD). This setup will be used to identify hadrons incl. multi-strange hyperons, charmed particles, and hypernuclei. Center panel: The RICH and the start version of the TRD are required to measure low mass electron-positron pairs, and the ECAL will identify photons. Lower panel: The start version of the MuCh will measure muon pairs, for example from charmonium decays.

The installation of the CBM start version components will start end of 2017. In addition, the HADES detector system will be installed, which covers large polar emissions angles, and, hence, complements the acceptance of CBM at low SIS100 energies. Measurements with HADES are limited to collision systems with moderate multiplicities, for example Au+Au up to 4 A GeV or Ni+Ni at 8 A GeV. The regulations for coexistence of the HADES and CBM detector systems in one cave are defined by a Memorandum of Understanding between the two collaborations.

5. Summary and conclusions

The mission of the CBM experiment is to explore the QCD phase diagram in the region of high net-baryon densities. The CBM research program includes the study of the equation-of-state of nuclear matter at neutron star densities, the search for the transition from hadronic to partonic or quarkyonic matter, the search for indications for chiral symmetry restoration in order to shed light on the origin of hadron masses, the search for hypernuclei and multi-strange massive objects, and the study of charm in dense matter. Most of the diagnostic probes of dense matter like lepton pairs, multi-strange hyperons and charm will be measured for the first time with the CBM experiment in the FAIR energy range. In conclusion, the CBM experiment has a unique discovery potential both at SIS100 and SIS300 energies.

The CBM experiment will be realized in stages according to the beam energies available. A substantial part of the CBM modular start version is funded via FAIR project funds, or by firm commitments of CBM partner institutions.

References

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