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QCD Matter Physics at FAIR

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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 status of FAIR and the physics program of the proposed CBM experiment will be discussed.

Keywords: heavy-ion collisions, QCD phase diagram,

1. The future Facility for Antiproton and Ion Research (FAIR)

The future international Facility for Antiproton and Ion Research (FAIR) in Darmstadt will provide unique research opportunities in the fields of nuclear, hadron, atomic, plasma, and bio physics. In the FAIR start version, a synchrotron (SIS100) will deliver high-intensity primary beams (protons up to 29 GeV, Uranium up to 11 AGeV, nuclei with Z/A = 0.5 up to 15 AGeV). A Superconducting Fragment Separator will convert primary heavy-ion beams into secondary beams of rare isotopes. Their properties will be studied using the various experimental facilities of the NUSTAR collaboration. Intense secondary beams of antiprotons will be accelerated and cooled in the High-Energy Storage Ring (HESR), and will be used for hadron physics experiments with the PANDA detector. Furthermore, there will be a variety of setups to perform experiments in atomic, plasma, and bio physics, and in material science. High energy nucleus-nucleus collisions will be investigated with the Compressed Baryonic Matter (CBM) detector. FAIR will be financed by a joint international effort of so far ten member states. The Federal Republic of Germany together with the State of Hesse is the major contributor to the construction, the current nine international partners - Finland, France, India, Poland, Romania, Russia, Slovenia, Sweden and the United Kingdom - cover about 30% of the construction costs. The construction of the accelerator components is progressing, and civil construction has started. About 1350 reinforced concrete pillars (1.2 m diameter, 60 m long) have

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been drilled in order to carry the heavy buildings. The calls for tender on water management, excavation, and shell construction of the northern area have been released, and main civil construction works will start in summer 2017. Installation and commissioning of the experiments is planned during 2021-2024, and in 2025 FAIR will be fully operational.

2. Exploring the QCD matter at neutron star core densities

One of the scientific pillars of FAIR is the Compressed Baryonic Matter (CBM) experiment which is designed to study the properties of extreme states of strongly interacting matter as they are created in heavy-ion collisions at relativistic energies. 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 5 times saturation density ρ_0, and at 10 A GeV even a density above 8 ρ_0 is reached as illustrated in figure 1 [1]. At such densities, the nucleons will overlap, 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 ρ_0, and the transition to pure quark matter above 8 ρ_0 [2]. This calculation is able to reproduce a two-solar mass neutron star. 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:

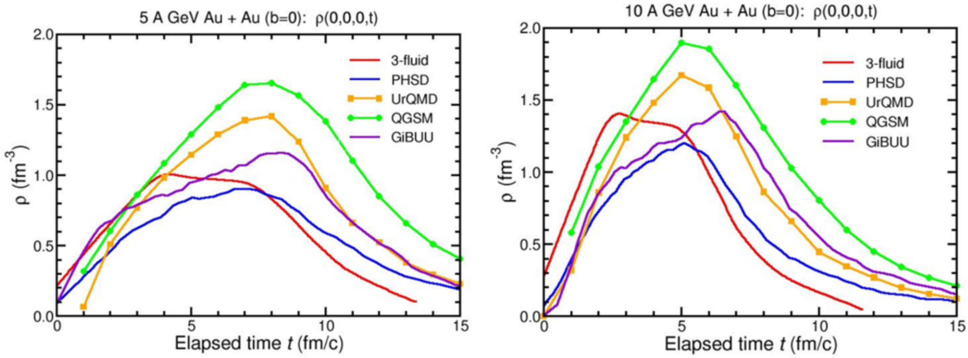

Fig. 1. Evolution of the central net baryon density $\rho(t)$ as a function of elapsed time as calculated by different transport models and by a 3-fluid hydrodynamics code for central Au+Au collision at 5 A GeV (left panel) and at 10 A GeV (right panel)[1].

- 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 CBM experiment at FAIR is designed to study observables related to the physics cases mentioned above.

- The equation-of-state can be studied by measuring (i) the collected flow of identified particles, which is generated by the density gradient of the early fireball, and (ii) by multi-strange hyperons, which are preferentially produced in the dense phase of the fireball via sequential collisions.
- A phase transition from hadronic to partonic matter is expected to cause the following effects: (i) multi-strange hyperons are driven into equilibrium at the phase boundary; (ii) in the case of a first-order phase transition, the excitation function of the fireball temperature measured by the invariant-mass spectra of lepton pairs should reflect a caloric curve. A possible critical point should produce event-by-event fluctuations of conserved quantities such as strangeness, charge, and baryon number.
- Modifications of hadron properties in dense baryonic matter and the onset of chiral symmetry restoration affect the invariant-mass spectra of di-leptons.
- The measurement of (double-Λ) hyper-nuclei will provide information on the hyperon-nucleon and hyperon-hyperon interaction which will shed light on the hyperon puzzle in neutron stars.

A more detailed discussion on the CBM physics cases and observables can be found in a recent review [3].

3. The Compressed Baryonic Matter (CBM) Experiment

The CBM detector is designed to identify hadrons, electrons and muons in heavy-ion collisions, and to measure multi-differential observables with unprecedented precision and statistics. This includes the study of rare diagnostic probes such as multi-strange (anti-) hyperons, (double-) Lambda-hypernuclei, charmed particles and vector mesons decaying into lepton pairs. Most of these particles will be studied for the first time in the FAIR energy range. In order to compensate for the low cross sections, the measurements will be performed at unrivalled reaction rates of up to 10 MHz (see figure 2). Because of the complicated decay topology of particles like Ω 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 free streaming frontend electronics that deliver time-stamped signals from each detector channel without event correlation. Based on the time and position information of the detector signals, first the tracks are reconstructed and from them the events by high-speed algorithms online, which are tuned to run on modern multi-core CPU architectures.

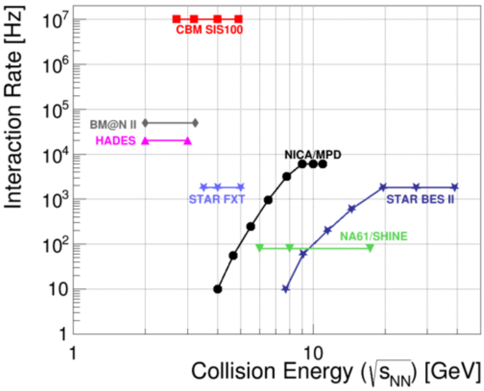

Fig. 2. Interaction rates achieved by existing and planned heavy-ion experiments as a function of beam energy. The NA61/SHINE experiment at CERN-SPS continues to scan the QCD phase diagram with light and medium size beams [4]. The STAR collaboration at RHIC plans for a second beam energy scan (STAR BES II) to improve the statistical significance of the data taken in the first series of measurements [5]. Moreover, 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 (MPD) is under construction [6]. As an intermediate step, a fixed target experiment called "Baryonic Matter at Nuclotron" (BM@N) is planned at JINR. HADES is a running experiment at GSI and will be also used at FAIR [7].

The CBM 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 CBM setup consists of the following components:

- A large aperture superconducting dipole magnet,
- 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/cm^2 with a time resolution of 50 ps),
- a Ring Imaging Cherenkov (RICH) detector for electron identification comprising a CO$_2$ 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,
- a First-Level-Event-Selection (FLES) system for online event reconstruction and selection.

A sketch of the CBM and HADES experimental setups is shown in figure 3. The HADES detector will 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.

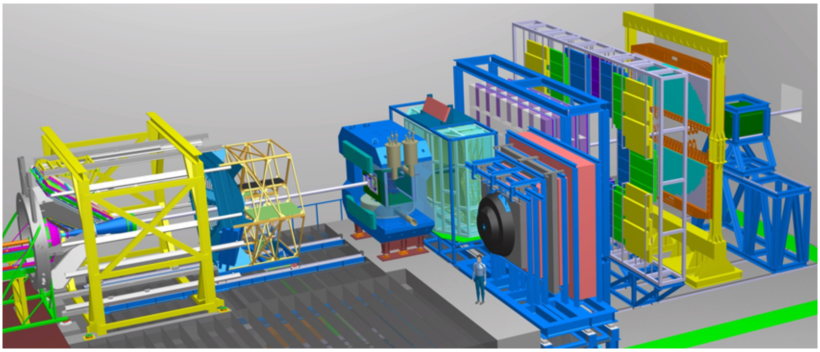

Fig. 3. The HADES detector (left) and the CBM experimental setup (right) with Ring Imaging Cherenkov detector in measuring position, and the muon detection system in parked position to the right.

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