The CBM experiment at FAIR

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Abstract. The study of high-energy nucleus-nucleus collisions will be one of the major activities at the future accelerator complex FAIR in Darmstadt. The goal of the research program is the exploration of the QCD phase diagram in the region of high baryon densities.

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

The future Facility for Antiproton and Ion Research (FAIR) in Darmstadt will provide unique research opportunities in the fields of nuclear, hadron, atomic and plasma physics \cite{1}. The accelerators will deliver primary beams (protons up to 90 GeV, Uranium up to 35 AGeV, nuclei with $Z/A = 0.5$ up to 45 AGeV) and secondary beams (rare isotopes and antiprotons) with high intensity and quality. The facility comprises a double-ring synchrotron, rings for accumulation, cooling and storage of primary and secondary beams, and dedicated detector arrangements. The research program includes the study of nuclei far from stability, hadron physics with antiproton beams, the study of compressed nuclear matter, the investigation of plasmas induced by ion and laser beams and atomic physics.

2. Exploring the QCD phase diagram with heavy-ion collisions

The exploration of the phase diagram of strongly interacting matter is a major field of modern high-energy physics. Of particular interest is the transition from hadrons to partonic degrees of freedom which is expected to occur at high temperatures or high baryon densities. These phases play an important role in the early universe and in the core of neutron stars \cite{2}. The discovery of this phase transition will shed light on fundamental but still puzzling aspects of Quantum Chromo Dynamics (QCD): confinement and chiral symmetry breaking. In particular, at high baryon densities one expects new phases of strongly interacting matter \cite{3}. The scientific progress in this exciting field, QCD at high baryon densities, is driven by new experimental data.

The aim of the planned Compressed Baryonic Matter (CBM) experiment at FAIR is to explore the QCD phase diagram at high net baryon densities and moderate temperatures in nucleus-nucleus collisions. This approach is complementary to the studies of matter at high temperatures and low net baryon densities performed at RHIC and LHC. Our current knowledge on the QCD phasediagram is illustrated in figure 1. The data points correspond to chemical freeze-out and result from a statistical analysis of particle ratios measured in Pb+Pb and Au+Au collisions at SIS, AGS, SPS and RHIC. The phase boundary between quark-gluon matter and hadronic and the location of the critical endpoint as shown in figure 1 is predicted by recent lattice QCD calculations which indicate that for values of $\mu_B$ larger than about 400 MeV the phase transition is first order, whereas for $\mu_B$ smaller than 400 MeV there is a smooth cross over from the hadronic to the partonic phase (dotted line).

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baryonic chemical potential $\mu_B$ [GeV]

Figure 1. The phase diagram of strongly interacting matter plotted as a function of temperature and baryon chemical potential. Full symbols: freeze-out points obtained with a statistical model analysis from particle ratios measured in heavy collisions [4, 5, 6]. The critical endpoint at $\mu_B \approx 400$ MeV is predicted by lattice QCD calculations [7, 8].

3. The experimental observables

The CBM research program includes the search for the deconfinement phase transition at high baryon densities, the study of chiral symmetry restoration in superdense baryonic matter, the search for the critical endpoint, and the study of the nuclear equation of state at high densities. The major challenge is to find diagnostic probes which are connected to chiral symmetry restoration and to the deconfinement phase transition. The observation of in-medium modifications of hadrons might be a signature for the onset of chiral symmetry restoration [9]. The in-medium spectral function of short-lived vector mesons can be measured directly via their decay into dilepton pairs. Since leptons are essentially unaffected by the passage through the high-density matter, they provide, as a penetrating probe, almost undistorted information on the conditions in the interior of the collision zone.

The anomalous suppression of charmonium due to screening effects in the Quark Gluon Plasma (QGP) was predicted to be an experimental signal of the QGP [10]. Particles containing heavy quarks like charm are produced in the early stage of the collision. At FAIR, open and hidden charm production will be studied at beam energies close to the kinematical threshold, and the production mechanisms of D and J/ψ mesons will be sensitive to the conditions inside the early fireball.

One of the early predictions for a QGP signal was the increased production of strangeness in the deconfined phase resulting in an enhanced yield of strange particles after hadronization [11]. This effect was expected to be even more pronounced for multistrange hyperons. Recently, data on the excitation function of strangeness production measured by NA49 have revived the discussion on the role of strangeness as a signature for a deconfinement phase transition [12].

Many signals for the the quark-gluon-plasma (QGP) have been proposed and are still under discussion, although the hope for finding a "smoking gun" has not yet become true. The
discovery of the critical endpoint of the deconfinement phase transition would be such a direct indication for the existence of a new phase. Theoretical investigations suggest that particle density fluctuations occur in the vicinity of the critical endpoint, which might be observed experimentally as nonstatistical event-by-event fluctuations of observables [13].

4. The experimental setup
The study of those very different observables calls for a modular setup and different running conditions. The measurement of J/ψ mesons via their electron-positron decay requires (i) high reaction rates of up to 10⁷ events/second to compensate for the low production cross sections at threshold, (ii) an online event selection to reduce the data flow down to an archiving rate of 25 kHz, and (iii) a detector system for electron identification and pion suppression (electron/pion ratio of 10⁻⁴ required). The detection of open charm (D mesons) via hadronic decays requires the measurement of displaced vertices with an accuracy of about 50 µm along the beam axis to suppress the combinatorial background of prompt pions and kaons. The measurement of low-mass vector mesons requires the rejection of close pairs (i.e. the detection of soft electrons) to reduce the combinatorial background caused by electrons/positrons from π⁰ Dalitz decays and gamma conversions. The study of observables event-by-event requires particle identification and a large acceptance which does not vary with beam energy.

In particular the charm measurements require unprecedented detector performances concerning rate capabilities and radiation hardness. The detector signals have to be processed by a high-speed data acquisition and an online event selection system. A sketch of the CBM detector is shown in figure 2.

The measurement of particle tracks and the determination of primary and secondary vertices will be performed with a Silicon Tracking System (STS). The current STS layout consists of minimum 7 layers (2 pixel and 5 strip) and is placed inside a magnetic dipole field which provides the bending power required for momentum determination with an accuracy of δp/p = 1 %. The STS has to fulfill the following requirements: material budget below 0.3% radiation length per layer to reduce multiple scattering, hit resolution of about 10 µm (for the pixel sensors) to achieve a vertex resolution of about 50 µm along the beam axis, radiation hardness up to a dose of 50 MRad corresponding to the dose accumulated in ten years of running, and read-out times of about 25 ns to accommodate reaction rates of 10 MHz.

The RICH detector is designed to provide identification of electrons and suppression of pions in the momentum range of electrons from low-mass vector-meson decays. The actual layout of the RICH detector consists of a radiator (3 gases under study: N₂, 40% He + 60 %CH₄, and 50% N₂ + 50 %CH₄, length 2.2 m), a mirror (3 mm Be covered with 0.5 mm glass, radius 4.5 m), and a photon detector composed of about 100,000 photomultiplier (PM) channels (6 mm diameter, quantum efficiency 20%). The glass window of the PMs is covered with wave-length shifter (WLS) films in order to increase the absorption of Cherenkov photons.

Three Transition Radiation Detector stations will serve for particle tracking and for the identification of high energy electrons and positrons (γ > 2000) which are used to reconstruct J/ψ mesons. According to simulations which are based on the experience obtained with the development of the TRD for ALICE and of the TRT for ATLAS, pion suppression factors of up to 200 (for momenta above 2 GeV/c) at an electron efficiency of better than 90% can be achieved.

The major technical challenge is to develop highly granular and fast gaseous detectors which can stand the high-rate environment of CBM in particular for the inner part of the detector planes covering forward emission angles. For example, at small forward angles and at a distance of 4 m from the target, we expect particle rates of more than 100 kHz/cm² for 10 MHz minimum bias Au+Au collisions at 25 AGeV. In a central collision, particle densities of about 0.05/cm² are reached. In order to keep the occupancy below 5% the size of a single cell should be
Figure 2. Sketch of the planned Compressed Baryonic Matter (CBM) experiment. The setup consists of a superconducting dipole magnet with a Silicon tracker System inside, a Rich Imaging Cherenkov detector (RICH), the three Transition Radiation Detectors (TRD), the Time-Of Flight (TOF) wall which is a Resistive Plate Chamber (RPC) and the electromagnetic Calorimeter (ECAL). The total length of the setup is approximately 12 m.

about 1 cm$^2$. Various prototypes of fast Multi Wire Proportional Chambers (MWPC) and Gas Electron Multipliers (GEM) have been tested with proton and pion beams up to intensities of 100 kHz/cm$^2$ and no major deterioration of the performance has been observed.

An array of Resistive Plate Chambers will be used for hadron identification via TOF measurements. The TOF wall is located about 10 m downstream of the target and covers an active area of about 120 m$^2$. The required time resolution is about 80 ps. For 10 MHz minimum bias Au+Au collisions the innermost part of the detector has to work at rates up to 20 kHz/cm$^2$. At small deflection angles the pad size is about 5 cm$^2$ corresponding to an occupancy of below 5% for central Au+Au collisions at 25 AGeV. With a small-size prototype a time resolution of about 90 ps has been achieved at a rate of 25 kHz/cm$^2$.

The electromagnetic calorimeter will be used to measure direct photons, neutral mesons decaying into photons, electrons and muons. Simulations and R&D have been started based on the shashlik type of detector modules as used in HERA-B, PHENIX and LHCb. Particular emphasis is put on a good energy resolution and a high pion suppression factor.

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