The Compressed Baryonic Matter experiment

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Abstract. The Compressed Baryonic Matter (CBM) experiment is a next-generation fixed target detector which will operate at the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt. The goal of this experiment is to explore the QCD phase diagram in the region of high net baryon densities using high-energy nucleus-nucleus collisions. Its research program includes the study of the equation-of-state of nuclear matter at high baryon densities, the search for the deconfinement and chiral phase transitions and the search for the QCD critical point. The CBM detector is designed to measure both bulk observables with a large acceptance and rare diagnostic probes such as charm particles, multi-strange hyperons, and low mass vector mesons in their di-leptonic decay. The physics program of CBM will be summarized, followed by an overview of the detector concept, a selection of the expected physics performance, and the status of preparation of the experiment.

1. Introduction

CBM is a fixed target experiment which will operate at the future FAIR facility (GSI, Darmstadt). This experiment seeks to study fundamental properties of the strong interaction and its underlying theory, the Quantum Chromo-Dynamics (QCD). Some of the most important features of the strong interaction are not quantitatively understood, like the phenomenon of color confinement in ordinary nuclear matter and the origin of most of the mass of light hadrons (thus, of most of the visible universe). In practice, CBM will study the properties of QCD matter at very high net baryon densities, in similar conditions as the ones presumably existing in the core of neutron stars.

Above a certain critical energy density, nuclear matter is believed to exist in a deconfined state of quarks and gluons. This is illustrated in Figure 1: such a state can be produced by heating and/or compressing nuclear matter. In accelerator laboratories, this is done by colliding heavy nuclei, thus creating a dense and hot fireball in the overlap region between the two nuclei. At the RHIC and the LHC colliders, collisions at ultra-relativistic energies lead to an extremely hot but almost net-baryon free fireball. According to lattice QCD, the phase transition from confined to deconfined matter at high temperatures and vanishing net baryon densities is a smooth cross-over, while at moderate temperatures but higher baryon densities a first-order phase transition may take place [1]. Exploring the latter region of the QCD phase diagram, poorly known theoretically and experimentally, is the object of a vast physics program at lower beam energies, which is currently carried out at SPS/CERN and RHIC/BNL and which will be continued later at NICA/JINR and FAIR. Possible indications of the onset of deconfinement have already been observed by NA49 (at the SPS), and confirmed recently by STAR (at the RHIC), at a beam energy of around 30 AGeV [2], which lies within the FAIR energy range.

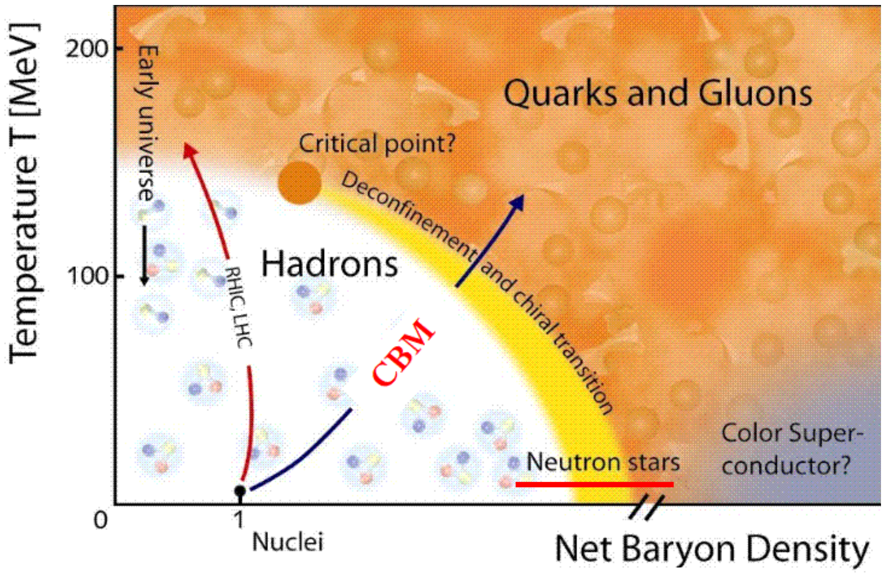

Figure 1. Sketch of the QCD phase diagram of nuclear matter as a function of temperature and net baryon density (see text).

The two different natures of the deconfinement phase transition in the high temperature and high density regions of the phase diagram suggest the existence of a QCD critical point (see Figure 1). The existence and location of this point are till today under debate since lattice QCD calculations have large systematic uncertainties at finite net baryon density [1]. This important feature of the QCD phase diagram thus motivates an experimental research program, which will be undertaken with CBM at FAIR.

The question of the hadron masses is supposedly related to the phenomenon of spontaneous breaking of chiral symmetry, a fundamental property of QCD (in the limit of vanishing quark masses). There are robust theoretical predictions that chiral symmetry is at least partially restored in dense matter [3], and that, among other effects, the in-medium masses of hadrons (containing light quarks) in dense baryonic matter can differ from their corresponding free masses. It is one of the most important goals of CBM to search for such in-medium effects.

An experimental evidence of the first-order phase transition, the QCD critical point and in-medium modifications of hadron masses in dense baryonic matter would be a breakthrough for understanding the properties of the strong interaction.

2. CBM physics program and observables

The FAIR facility will offer unique opportunities for the investigation of the QCD phase diagram at extreme net baryon densities, besides serving a variety of other research fields (hadron physics with anti-proton beams, nuclear structure physics with radioactive beams, and plasma physics with highly pulsed ion beams). For the nuclear collision program, two synchrotrons SIS100 and SIS300 (providing a magnetic rigidity of 100 and 300 Tm, respectively) will deliver fully stripped heavy ion beams up to uranium with extremely high intensities (of up to 2×10^9 ions per second) at beam energies from 2 AGeV to 10 AGeV, and from 15 AGeV to 35 AGeV, respectively. Lighter ions ($Z/A = 0.5$) will be accelerated up to 45 AGeV, while proton beams will be available up to 30 GeV and 90 GeV at SIS100 and SIS300, respectively.

The broad energy range provided by FAIR will allow producing nuclear matter at the maximal net baryon density achievable with heavy ion collisions [4, 5]. For example, according to various

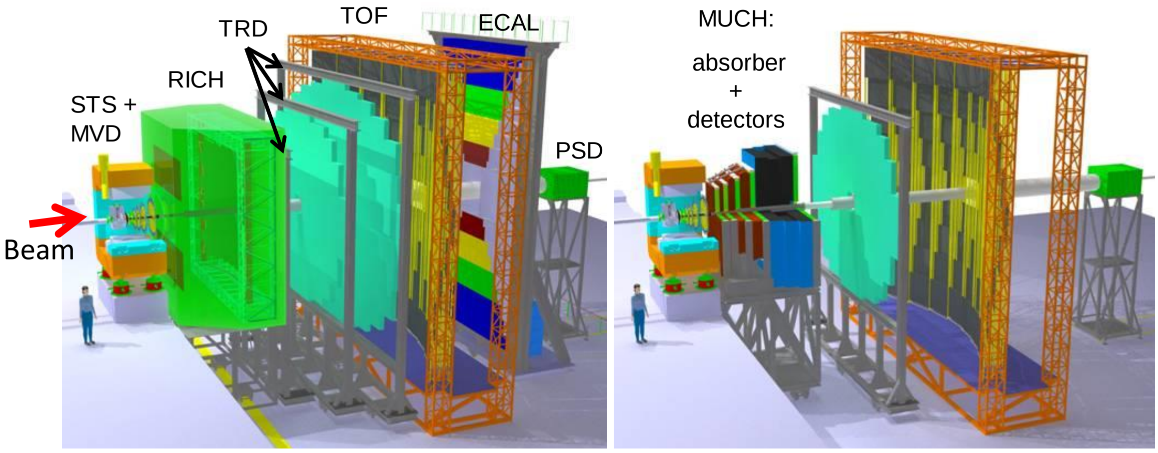

Figure 2. Layout of the CBM detector setup (see text). Two configurations are foreseen: one dedicated to the measurements of hadrons and electrons (left side), and another one optimized for detecting muons (right side).

transport models [5], the density reaches up to about twelve times the normal nuclear matter density in the core and at the early stage of central Au(20 AGeV)+Au collisions. Another important feature of this accelerator facility is that it will serve several (up to 5) experiments in parallel, allowing CBM operating with heavy ion beams up to 4 months per year. Both the unprecedented beam intensities and the high beam availability will allow CBM measuring rare probes, like charm hadrons and light vector mesons (in their di-leptonic decay), for the first time in the FAIR energy range. These rare probes also include multi-strange particles which are scarcely measured in heavy ion collisions at these energies.

CBM is designed to perform high statistics measurements of hadronic, leptonic and photonic probes with a large acceptance. Its physics program includes a large set of observables [5], among which: the yields and collective flow of strange and charm hadrons is expected to reflect the onset of deconfinement. The collective flow of hadrons (including strange and charm particles) is also expected to be sensitive to the equation-of-state of nuclear matter at the early stage of the reactions. Particle production at threshold energies (charm at SIS300 and possibly multi-strange particles at SIS100) is also expected to deliver important information about the equation-of-state of nuclear matter. In addition, event by event, non statistical, fluctuations of various quantities (particle yields and yield ratios) related to conserved quantum numbers (baryon, charge, and strangeness) would signal a QCD critical point. Finally, in-medium modifications of hadron masses, in particular of open charm hadrons [6] and light vector mesons, may provide valuable insight into the expected restoration of chiral symmetry in dense baryonic matter.

The experimental task of CBM is to measure all these observables in A+A, p+A and p+p collisions, as a function of collision energy and system size, with high precision and statistics, and to search for discontinuities in the aforementioned dependencies which would signal for example a first-order deconfinement phase transition. This vast physics program will be carried out by performing nuclear collisions at extremely high interaction rates.

3. CBM detector, experimental challenge and physics performance

Figure 2 shows a schematic view of the detector concept. Open charm and multi-strange hyperons will be measured through their weak decay into charged hadrons, while charmonium states and light vector mesons will be detected via their decay into both di-electrons and di-muons. The CBM detector setup thus features a flexible arrangement of particle identification detectors: one configuration is dedicated to the identification of hadrons and electrons, while another one is specialized in detecting muons. The second configuration includes absorbers which can efficiently absorb all particles except muons and is not compatible with the first one. In both configurations, the detector comprises a low mass Silicon Tracking System (STS) installed inside a superconducting dipole magnet, a Transition Radiation Detector (TRD) and a Time-Of-Flight (TOF) detector. In addition, a forward hadronic calorimeter, called Projectile Spectator Detector (PSD), will serve for event characterization (collision centrality and event plane determination). The electron and hadron configuration additionally comprises a high resolution Micro-Vertex Detector (MVD), located close to the target and in front of the STS, a Ring Imaging CHerenkov (RICH) and an Electromagnetic CALorimeter (ECAL). As for the muon configuration, these two last sub-detectors are replaced by a MUon CHamber (MUCH), which consists of absorber layers interlaced with tracking stations. The dimensions and positions of all detectors (except the PSD) are chosen such that for central A+A collisions at 25 AGeV and a magnetic dipole field of B = 1 T about 70% of the emitted charged particles are accepted (including mid-rapidity and forward rapidity particles, at low and high transverse momenta).

All detector components have been designed to operate at unprecedentedly high collision rates in order to perform high statistics and systematic measurements. For example, up to 10 MHz and on the order of 100 kHz collision rates are foreseen for J/Ψ and open charm measurements, respectively. This puts very strong constraints on the design of the detector components and readout electronics in terms of rate capability. Also, rare probes in A+A collisions at FAIR energies have multiplicities several order of magnitude lower than that of abundant particles (e.g. pions, protons and electrons). Measuring these rare probes thus calls for very efficient background rejection strategies, which rely on the detector capability for track reconstruction and particle identification.

The STS detector is meant to reconstruct the charged particles' trajectory inside a magnetic dipole field and to determine their momentum. It consists of 8 stations of thin and high resolution double-sided silicon strip sensors, stabilized by a low mass carbon support structure [7]. Detailed detector simulation studies, including in particular a realistic material budget with support structure and cables, demonstrated a high track reconstruction efficiency (of about 95%) and a good momentum resolution ($\Delta p/p$ on the order of 1%), over a large range (p from 0.1 GeV/c to 12 GeV/c). The tracking algorithm has also been proven to be sufficiently fast to deal with the high multiplicity per event in heavy ion reactions and the very high collision rates foreseen [8].

The MVD detector will serve to reconstruct the displaced decay vertex of open charm hadrons. This is crucial to reject the tremendous background which originates dominantly from the collision vertex. The setup will consist of 2 or 3 stations of thin and highly granular commercial CMOS silicon pixel sensors, placed inside a vacuum vessel. The stations are both stabilized and cooled by a low mass (diamond) support structure. Detector simulations, including a realistic material budget and CMOS typical performance, have demonstrated that the decay vertex of open charm hadrons can be reconstructed with a resolution typically below 100 μm [5].

Detailed simulation studies also demonstrated that the combined RICH and TRD detectors can be used to suppress pions mis-identified as electrons (by about a factor of 10^4), while keeping the electron reconstruction efficiency on the order of 50 %. The TOF detector, in combination with the STS providing particle momenta, aims at identifying hadrons. It features a time resolution of about 80 ps, and allows separating well protons and kaons up to about p=6 GeV/c. Pions and kaons can also be distinguished up to p=3.5 GeV/c. Above this range, the RICH detector can be used to further discriminate one another.

The extremely high particle flux expected through the detector (up to several 10^9 particles per second) calls for very high speed, free streaming data read-out, which is an unique feature compared with previous heavy ion experiments. The data will be transported to a large and high performance processor farm with about 60000 computing cores, where partial event

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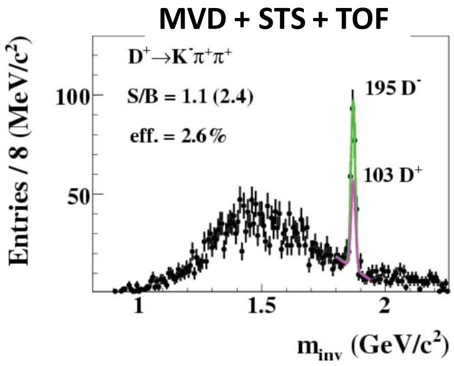

Figure 3. Invariant mass of π^+ π^+ K^- triplets surviving the selection procedure (including D$^+$ signals and background triplets) in central Au(25 AGeV)+Au collisions.

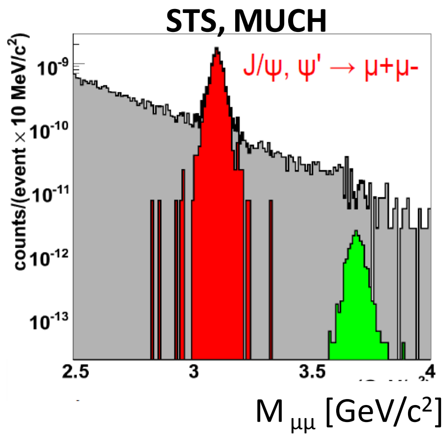

Figure 4. Invariant mass of μ^+ μ^- pairs surviving the selection procedure (including J/Ψ meson signals - red histogram, Ψ' meson signals - green histogram - and background pairs) in central Au(25 AGeV)+Au collisions.

reconstruction (tracking, vertexing, etc) and ultra fast on-line event selection will be performed 'on the fly'. This will allow selecting events which contain signal candidates (e.g. open charm displaced decay vertex, J/Ψ decay muons), making it possible to operate at the foreseen collision rates while keeping the event archiving rate at an acceptable level, on the order of 25 kHz.

Detailed detector simulations have been carried out, including realistic background generation and detector description. They demonstrate the detector performance for reconstructing the various probes foreseen by the experiment, including rare probes (see e.g. [9]). Examples of the expected performance are shown in Figures 3 and 4 in the case of central Au(25 AGeV)+Au collisions. As can be seen, the D$^+ \to \pi^+$ π^+ K^- signal can be extracted from the combinatorial background with high signal-to-background ratio and good reconstruction efficiency, thanks to the high vertexing precision of the MVD. Same conclusions are drawn for J/Ψ mesons, for which the 'muon' setup has been used in the simulations.

All detector components are at the stage of prototyping and are being tested on beam, and technical design reports are either submitted (see e.g. [7]) or in the process of submission. The construction phase of the FAIR accelerator is planned to end in 2017, when the experiment apparatus will be installed in the CBM cave. First measurements with nuclear collisions will start in 2019 at the SIS100 synchrotron, which will provide, for the first time, charm data in p+p and p+A collisions at about 30 GeV beam energy and below, and will open the investigation of very interesting strangeness physics in A+A collisions up to 10 AGeV.

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