Strangeness Prospects with the CBM Experiment

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Abstract. The CBM experiment will study strongly interacting matter at high net-baryon densities with nuclear collisions up to 45A GeV beam energy at the future FAIR facility. With interaction rates unprecedented in heavy-ion collisions, CBM will give access also to extremely rare probes and thus to the early stage of the collisions, in search for the first-order phase transition from confined to deconfined matter and the QCD critical point. The CBM physics programme will be started with beams delivered by the SIS-100 synchrotron, providing energies from 2 to 11 GeV/nucleon for heavy nuclei, up to 14 GeV/nucleon for light nuclei, and 30 GeV for protons. The highest net baryon densities will be explored with ion beams up to 45 GeV/nucleon energy delivered by SIS-300 in a later stage of the FAIR project.

After several years of preparation, the CBM experiment now enters the realisation phase. In this article, we report on the current status of the system developments and the expected physics performance for strange and charmed observables, as well as on the roadmap towards the first data taking.

1. Introduction

In parallel to the investigation of strongly interacting matter at the highest energy densities achievable in the terrestrial laboratory as currently performed with the heavy-ion programme at the CERN-LHC, an increasing number of experimental projects address heavy-ion collisions at moderate energies, corresponding roughly to the beam energy range of BNL-AGS and CERN-SPS. Such collisions are expected to create matter at extreme net-baryon density but moderate temperature, as opposed to collisions at the LHC, where the temperature is highest, but the net-baryon density is almost vanishing. According to model predictions, the maximum net-baryon density at freeze-out is expected from nuclear collisions at about 30 GeV per nucleon [1], corresponding to a centre-of-momentum energy of $\sqrt{s_{NN}} \approx 8$ GeV.

Heavy-ion reactions in this energy range allow us to explore a region of the phase diagram of strongly interacting matter which has recently attracted renewed interest since it may bear a rich structure. Potential landmarks are the first-order phase transition from confined to deconfined matter, the restoration of chiral symmetry at high baryon densities, the critical point of QCD separating the region of first-order phase transition from the cross-over transition, and the transition to Quarkyonic matter. The physics of such "compressed baryonic matter" was repeatedly discussed in this conference series and elsewhere (see e.g., [2]); an extensive survey can be found in [3].

2. The CBM Experiment

The CBM ("Compressed Baryonic Matter") experiment will conduct a systematic research programme to study strongly interacting matter with external ion beams delivered from the FAIR accelerator complex currently under construction in Darmstadt. It will be operated in fixed-target mode with beam energies from $2A$ to $45A$ GeV and with a variety of projectile species ranging from protons up to heavy nuclei. CBM aims at a close-to-complete characterisation of the particles emitted from the final state of the collisions by measuring hadrons, electrons and muons in a large part of the forward rapidity hemisphere.

A key feature of the CBM design considerations is the capability to operate at very high interaction rates of up to 10^7 collisions per second – several orders of magnitude higher than any other existing or currently planned heavy-ion experiment. This high-rate capability will give CBM a unique discovery potential for extremely rare probes like multi-strange anti-hyperons, exotic hadronic states, or charm production near the kinematic threshold. It obviously puts severe requirements on detector design in terms of radiation hardness and read-out speed, as well as on data acquisition and online data processing.

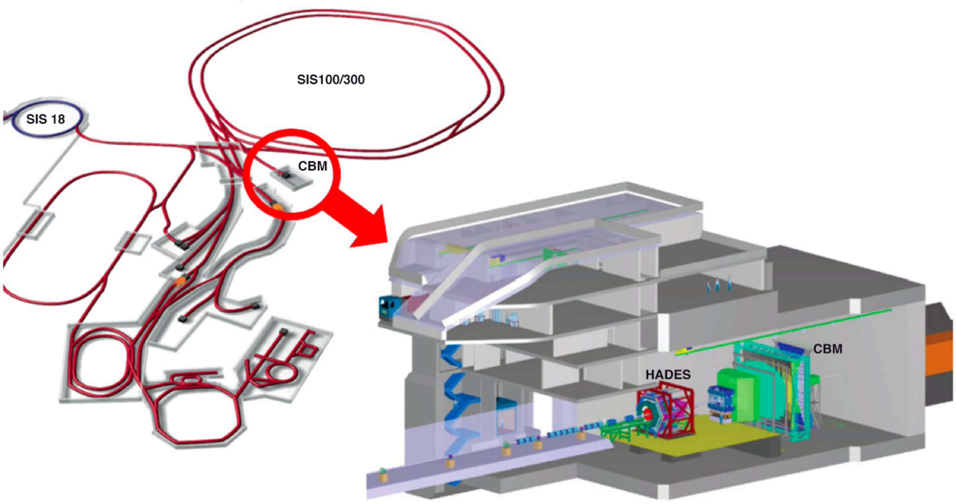

Figure 1. Left: The FAIR accelerator complex and the location of the CBM cave. Beams are extracted from the two synchrotron rings at the top. Right: layout of the CBM building and its underground hall.

CBM will be set up in an underground hall of the dimensions 37 m x 27 m x 17 m to which beams from the SIS-100 and SIS-300 synchrotrons will be extracted (Fig. 1). The experimental set-up is versatile in order to cope with the specific requirements of hadron, electron or muon measurements as well as with the different ranges of beam energy delivered by SIS-100 and SIS-300, respectively. Figure 2 shows a configuration for hadron and electron measurements, comprising the dipole magnet and the main tracker (STS), the RICH and TRD detectors for electron identification, the TOF detector for hadron identification, and the PSD calorimeter for event characterisation. The muon detection system, being installed on rails, will be interchangeable with the RICH detector.

The FAIR facility will be realised in different stages. The so-called Modular Start Version comprises the SIS-100 synchrotron with Au beams up to $11A$ GeV and proton beams up to 30 GeV, as well as the CBM experimental hall and the extraction beam line. In a later stage, the SIS-300 accelerator will enlarge the energy range to $35A$ GeV for Au, $45A$ GeV for symmetric nuclei, and 90 GeV for protons. The time line for this extension is not yet fixed. Thus, the first

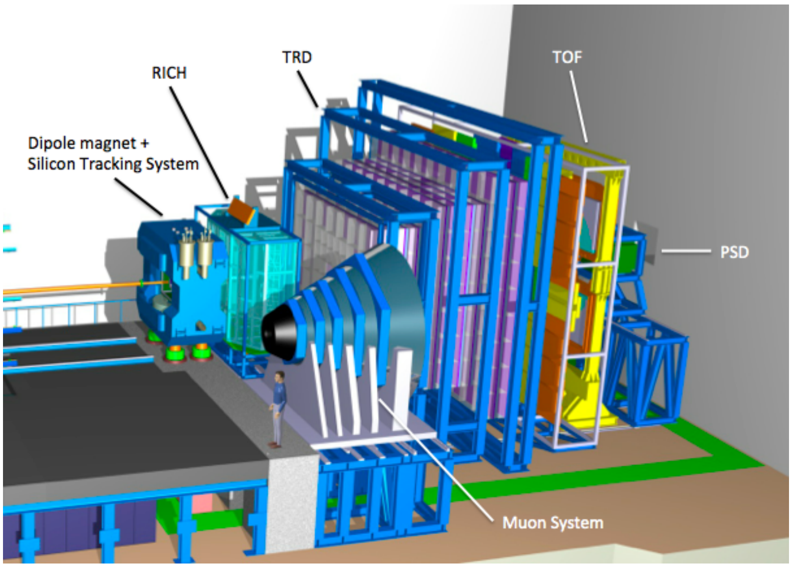

Figure 2. CBM experimental set-up for hadron and electron measurements. The beam enters the cave from the left side. The Silicon Tracking System is placed in the dipole magnet. Downstream are the RICH and TRD detectors, the TOF detector and the PSD calorimeter. The muon system is in its parking position; it can be moved into the acceptance on rails when the RICH detector is removed.

years of CBM operations will be restricted to beams from SIS-100, with which already a rich and unique research programme can be pursued. Some of the detectors systems (TRD, muon detector) come with a reduced start version for SIS-100, being optimised for the conditions in this beam energy range; others (STS, RICH, TOF, PSD) can be operated with beams from both accelerators.

3. Instrumentation

In the following, we give a brief overview for the detector systems relevant for strangeness and charm measurements. A recent review of all sub-systems can be found as shown in [4].

3.1. Silicon Tracking System

The core of the CBM setup is the silicon tracking system (STS) intended for the reconstruction of the trajectories of charged particles produced in the interaction and the measurement of their momenta. It is installed between the yokes of a superconducting dipole magnet [5], providing a field integral of 1 Tm and an aperture of 140 cm in vertical and 280 cm in horizontal direction.

The STS is realised as an array of eight tracking stations constructed from thin double-sided silicon micro-strip detectors. The roughly 1,200 sensors will be mounted on a light-weight carbon structure, the signals from the inner part being routed to the front-end electronics at the periphery of the station by ultra-thin cables. The aim is to keep the material budget below 1% radiation length per station. Figure 3 shows the conceptual design of the detector system and the current engineering model [6]. The development of the detector is advanced; production readiness is targeted for 2016.

Algorithms for track reconstruction is this system are already developed. They show a track finding efficiency of above 95% for tracks above 1 GeV momentum and a momentum resolution below 2% for the same track class.

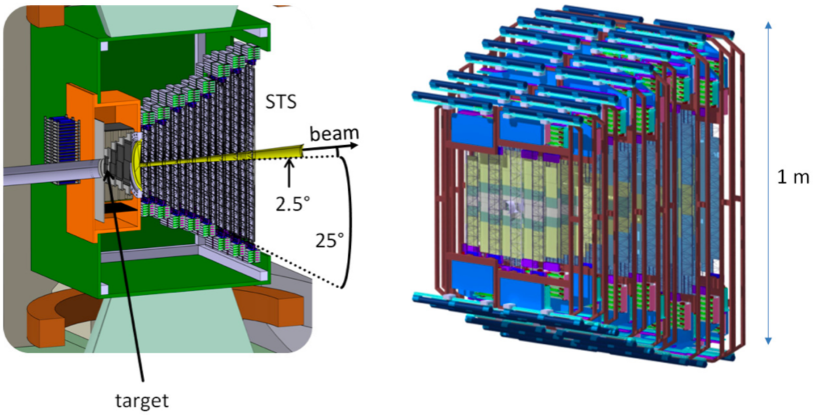

Figure 3. Left: conceptual design of the Silicon Tracking System, showing a cut through the detector in the dipole magnet. Right: engineering model of the STS, with the eight tracking stations to be mounted on the main support frame.

3.2. Micro-Vertex Detector

The MVD adds very high spatial resolution to the tracking in order to detect the decay products of short-lived particles like D mesons. The system will make use of Monolithic Active Pixel Sensors (MAPS), which combine excellent position resolution ($< 3\,\mu$m) with low material budget. However, the read-out speed of the current prototype MIMOSA-26 limits the interaction rate to about 10^5/s in runs where the MVD is operated. The sensors will be arranged on four stations in the target vacuum chamber [7]. The system under development arranges the sensors on both sides of a diamond carrier equipped with flex-print circuits. The material budget of such an assembly is below $0.5\%\,X_0$.

3.3. Time-of-Flight Detector

The identification of hadrons in CBM is achieved through the measurements of their time-of-flight. The TOF detector [8] is based on the technology of resistive plate chambers, providing a time resolution of about 60 ps. RPC modules will be assembled in a wall with an active area of about 120 m^2, the granularity being adapted to cope with the variation of hit rates, which range from 2 kHz/cm^2 at the periphery to 25 kHz/cm^2 in the inner sections. Prototypes were tested in various in-beam experiments, and production readiness will be achieved in 2016.

3.4. Projectile Spectator Detector

The Projectile Spectator (PSD) serves the determination of collision centrality and orientation of the event plane by the detection of the projectile spectator nucleons and fragments [9]. It is a fully compensating, modular lead-scintillator calorimeter with high and uniform energy resolution. The detector will be built from 44 individual modules, with 60 lead/scintillator layers, facing to the beam a surface of $20\,\mathrm{cm} \times 20\,\mathrm{cm}$. The read-out is realized by multi-anode photo detectors via wavelength shifting fibers. A similar device using the same technology is currently being installed at the NA61 experiment at the CERN-SPS.

3.5. Data acquisition and online data processing

At the maximum design interaction rate (10^7 events per second), the expected raw data flow from the front-end electronics (FEE) is about 1 TB/s, which has to be reduced by more than two

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orders of magnitude before archiving by online data selection. The high rates and complicated trigger patterns (e.g., open charm decays) forbid the use of conventional, latency-limited triggers; instead, the FEE will be self-triggered, i.e., autonomously streaming hit information with time stamps through the data acquisition chain (DAQ) to a first-level event selector, a dedicated computer farm where the association of hits to physical events, partial event reconstruction and event selection is performed. Several free-running read-out ASICs as well as DAQ components are under development, prototypes of which were already successfully operated in beam tests.

The online selection of signal events requires efficient and fast reconstruction algorithms [10]. The required speed is realised by applying massive parallelization to reconstruction algorithms and analysis tasks [11]. With the current software performance, we estimate the required size of the online computing farm to be of the order of 60,000 - 100,000 cores. This cluster will be hosted by the FAIR Tier-0 data centre currently under construction on the GSI campus. Prototypes of the computing architecture are being operated in Frankfurt (LOEWE-CSC), at GSI and at the FAIR-Russia Research Center.

4. Physics Reach

The physics capabilities of the CBM experiment are assessed by detailed simulations down to the raw data level, employing realistic detector geometries and response models which are constantly adapted to the developments in detector design and to the results of prototype tests in the laboratory and in beam. The performance figures shown in the following are the result of the full reconstruction software chain being applied to these simulated data.

Particles containing strange quarks continue to be important probes for hot and dense matter. Of particular interest for CBM are multi-strange anti-hyperons, since their production is strongly suppressed in a dense baryonic medium - a constraint which would be relaxed should deconfined matter be formed. This is demonstrated by calculations using the hadronic model HSD and its successor pHSD which includes both hadronic and partonic degrees of freedom. Figure 4 shows the predicted multiplicities for Ω^- and $\overline{\Omega}^+$ as function of beam energy for both models. While only small differences are seen for Ω^-, its anti-particle is enhanced by more than an order of magnitude in the CBM energy range if the creation of a QGP in the centre of the fireball is allowed. Still, the predicted multiplicities are extremely low; CBM with its high-rate capability will be the only experiment in this energy regime able to measure such particles.

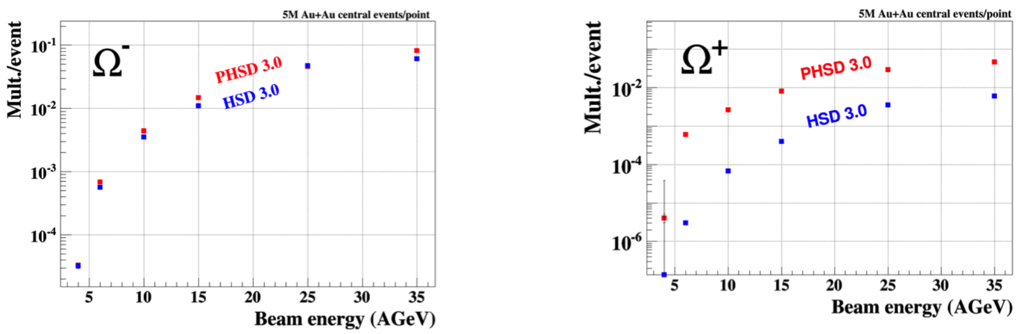

Figure 4. Multiplicity of (left) Ω^- and (right) $\overline{\Omega}^+$ in central Au+Au collisions as function of beam energy as predicted from the HSD and the pHSD model.

CBM will reconstruct anti-hyperons by the decay topology in the STS, using TOF identification of the daughter particles to further reduce the combinatorial background. The good position resolution of the STS detector results in an excellent signal-to-background ratio as demonstrated in Fig. 5. At 10A GeV and an interaction rate of 10^6/s, we expect to reconstruct about 10^5 $\overline{\Omega}^+$ per week of runtime in the 10% most central collisions, assuming the (lower) HSD multiplicity.

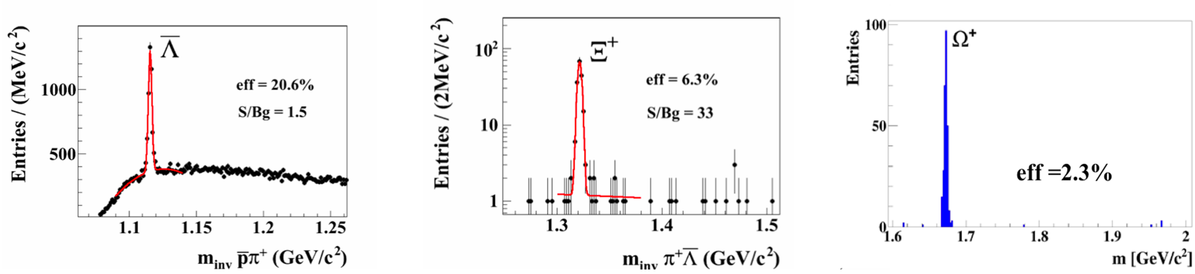

Figure 5. Reconstructed invariant-mass spectra for (left) $\overline{\Lambda}$, (centre) $\overline{\Xi}^+$ and (right) $\overline{\Omega}^+$ in central Au+Au collisions at 10A GeV. The input to the simulations was generated with UrQMD for $\overline{\Lambda}$ and $\overline{\Xi}^+$ and with pHSD for $\overline{\Omega}^+$.

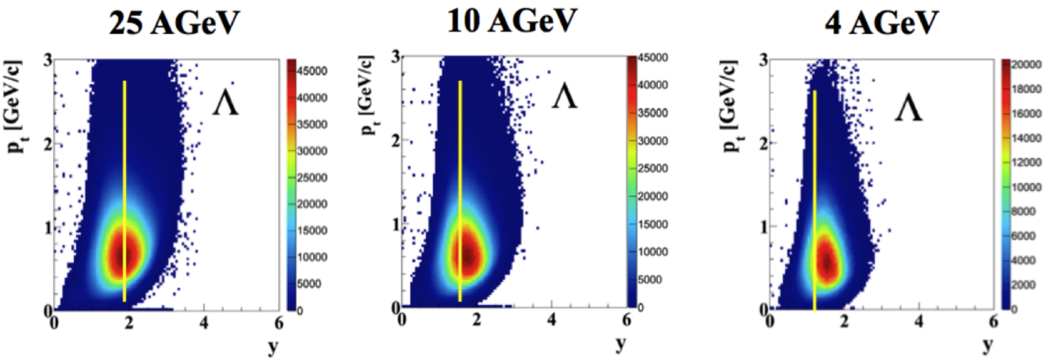

Figure 6. Phase-space coverage of CBM for Λ at three different energies in terms of rapidity and transverse momentum. Mid-rapidity is indicated by the vertical lines.

The phase-space coverage of the CBM setup for the reconstruction of hyperons is demonstrated in Fig. 6 for the Λ baryon at three different beam energies. At all of them, the acceptance covers the bulk production near mid-rapidity as well as a large part of the forward rapidity hemisphere. The acceptance figures for Ξ and Ω look similar.

The energy range of CBM is also particularly well suited for the study of hyper-nuclei and the search for exotic, meta-stable strange objects like di-baryons. In heavy-ion collisions, hyper-nuclei can be formed by the coalescence of Λ with nucleons or light nuclei in the final state of the reaction. Model calculations suggest that the maximum yield of hyper-nuclei is found in the SIS-100 energy domain [12]. The multiplicity of the $(\Xi^0\Lambda)_b$ bound state was calculated within a hybrid (microscopic transport + hydrodynamics) model to be about 10^{-2} in central collisions at 30A GeV [13] – well within reach for a high-rate experiment like CBM.

The detection principle - the weak-decay topology - is similar to that for hyperons. As examples for our performance studies, Fig. 7 shows the reconstructed invariant-mass spectra for He^3_Λ and for $(\Xi^0\Lambda)_b$ in central Au+Au collisions at 10A GeV. We again expect very good signal-to-background ratios and conclude that the CBM detector is capable to detect even exotic multi-strange objects, should they exist.

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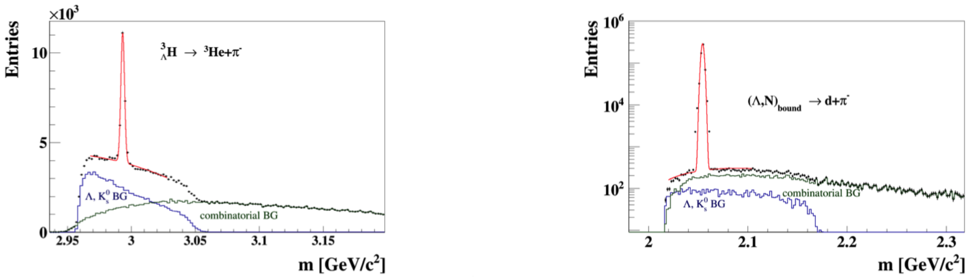

Figure 7. Reconstructed invariant-mass spectra for (left) He^3_Λ and (right) $(\Xi^0\Lambda)_b$ in central Au+Au collisions at $10A$ GeV. The blue line shows the correlated, the green line the uncorrelated background.

The study of charm production in heavy-ion collisions at moderate beam energies is both particularly interesting and challenging. Because of the very low charm cross section at these energies, CBM is again the only experiment which is sensitive to probes containing charm quarks. A systematic measurement of both open and hidden charm in nuclear collisions will only be possible with the SIS-300 accelerator. Already at SIS-100, however, precursor measurements are within reach; symmetric nuclei (e.g., Ni) can be accelerated up to $14A$ GeV, i.e., above the kinematic threshold for both D mesons and charmonium. At the top SIS-100 energy for Au+Au, a sub-threshold measurement of J/ψ might be feasible. Furthermore, the production and propagation of charm in cold nuclear matter can be investigated with p+A collisions up to 30 GeV. As an example of a feasibility study in this regards, Fig. 8 shows the sensitivity of CBM to charged D mesons in p+C collisions at 30 GeV. The crucial device here is the Micro-Vertex Detector, delivering a resolution for secondary vertices of about 60 μm along the beam, which is well sufficient to detect the open charm decay above the combinatorial background.

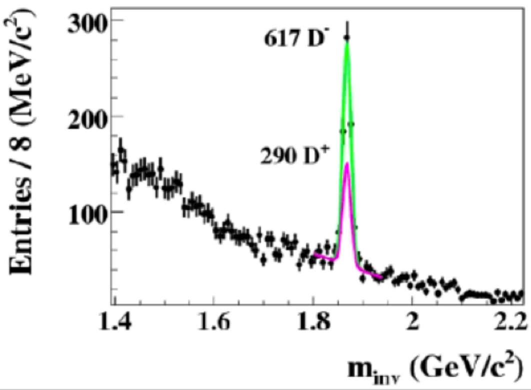

Figure 8. Reconstructed invariant-mass spectra for D^+ and D^- in p+C collisions at 30 GeV. The multiplicity of the D mesons was taken from the HSD model.

5. Status of preparations

The development of detector and technical systems for CBM is in an advanced stage [14] and will be largely completed by the end of 2016. For most of the systems, Technical Design Reports are already approved by FAIR or are under evaluation. Serial component production and the construction of the systems are planned to be completed by the end of 2019. Installation in the CBM cave and commissioning without beam will then follow in 2020.

Compared to the original planning, the current FAIR timeline is delayed by 2 – 3 years. First beams from SIS-100 into the CBM cave are not expected before 2022. In view of this delay, the CBM collaboration is investigating possibilities to install and commission parts of detector systems at other experimental facilities. Examples are the installation of a part of the TOF wall at the STAR experiment at RHIC or the co-operation of CBM with BM@N at NICA in the construction of the silicon detectors. Furthermore, CBM intends to install a reduced set-up at a beam line at the SIS-18 accelerator at GSI in order to test the interplay of systems and the full data chain including data processing in real-time. These activities have the objective to gain operational experience in order to minimize the start-up phase once beams from SIS-100 will become available. The first measurements of CBM will then comprise systematic and multi-differential measurements of multi-strange (anti-)hyperons and hyper-nuclei, a search for exotic strange objects and (not covered in this article) the measurement of di-lepton spectra in the energy range up to $11A$ GeV.

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