The Compressed Baryonic Matter experiment at FAIR

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Abstract.
The CBM experiment will investigate highly compressed baryonic matter created in A+A collisions at the new FAIR research center. With a beam energy range up to 11 AGeV for the heaviest nuclei at the SIS 100 accelerator, CBM will investigate the QCD phase diagram in the intermediate range, i.e. at moderate temperatures but high net-baryon densities. This intermediate range of the QCD phase diagram is of particular interest, because a first order phase transition ending in a critical point and possibly new high-density phases of strongly interacting matter are expected. In this range of the QCD phase diagram only exploratory measurements have been performed so far. CBM, as a next generation, high-luminosity experiment, will substantially improve our knowledge of matter created in this region of the QCD phase diagram and characterize its properties by measuring rare probes such as multi-strange hyperons, dileptons or charm, but also with event-by-event fluctuations of conserved quantities, and collective flow of identified particles. The experimental preparations with special focus on hadronic observables and strangeness is presented in terms of detector development, feasibility studies and fast track reconstruction. Preparations are progressing well such that CBM will be ready with FAIR start. As quite some detectors are ready before, they will be used as upgrades or extensions of already running experiments allowing for a rich physics program prior to FAIR start.

1 Mapping the high density region of the QCD phase diagram with CBM

Heavy ion experiments at relativistic energies are *the* experimental tool in order to map the conjectured QCD phase diagram, see figure 1 (left), which is of fundamental interest for understanding the strong interaction and strongly interacting matter in particular in the non-perturbative regime. In dependence on the collision energy strongly interacting matter of varying temperature and baryon chemical potential is created. The exploration of matter at high temperatures but low baryon chemical potential in heavy-ion collisions at the highest energies at RHIC and LHC [1, 3] reveals insight into the characteristics of the quark-gluon plasma and the phase transition to hadronic matter. Experimental results can be compared to lattice QCD calculations at $\mu_B = 0$ which predict a crossover from partonic to hadronic matter at temperatures around 160 MeV [4] in accordance to experimental findings. According to lattice QCD, the phase transition is driven by the energy density and occurs at a critical density on the order of 1 GeV/fm^3. At large baryon densities the QCD phase diagram is uncharted territory as lattice calculations are not applicable, and as only few experimental measurements mainly of bulk

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probes are available from former AGS experiments. However, this region of the phase diagram is predicted to have rich structures like e.g. new exotic phases as the quarkyonic matter [5] or a first order phase transition and a critical point, see e.g. [6]. The experimental discovery of such structures and the characterization of dense baryonic matter would be a major milestone in our understanding of strongly interacting matter and has triggered a number of experimental campaigns worldwide.

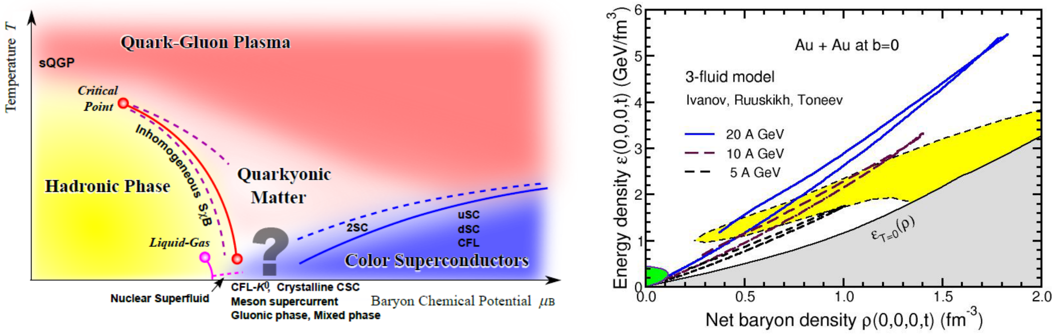

Figure 1. Left: Conjectured QCD phase diagram [2]. Right: Energy density versus baryon density in the central cell of Au+Au collisions at various energies from a 3-fluid model [7].

At FAIR the SIS 100 accelerator will offer heavy-ion beams with energies up to 11 AGeV for Au ions at intensities up to 10^9 ions/s. Light ions and protons will be available at respectively higher energies. Heavy ion collisions in this energy range create matter at energy densities that reach beyond the critical density of about 1 GeV/fm^3. In parallel to the energy density also the baryon density increases in those collisions and can reach up to 10 times normal nuclear matter density in the center of central Au+Au collisions [8], see fig. 1 (right). The CBM experiment is being prepared in order to characterize the dense baryonic matter created in heavy-ion collisions at FAIR by measuring a wide variety of observables including rare probes such as multistrange particles, charm (if the energy is sufficient) and dileptons.

2 Probes of strongly interacting matter at high baryon densities

Unfortunately, to all our knowledge there is no simple key measurement that will reveal the phase structure of dense baryonic matter. The experimental strategy thus relies on systematic measurements of a set of promising observables in dependence on collision energy and system size. In the following, some of the promising observables and their connection to the open physics questions will be discussed briefly, for more details see [9].

Strangeness production

Particles containing strange quarks are important probes of the matter created in heavy-ion collisions. The strange quark plays a special role in investigations that are connected to the question whether the created matter reaches equilibrium. Strange quarks are newly produced quark flavours, however they are still light enough to be produced thermally, i.e. in secondary collisions of produced particles. Whether or not strangeness is in thermal equilibrium may be seen in the yields and phase space distributions of multi-strange particles, in particular the Ω baryon [10]. New HADES measurements show on the other hand [11] that multi-strange particle production may happen through more complicated reaction mechanisms, which may be connected to the equation-of-state at high baryon densities. CBM therefore plans to measure yields, phase space distributions, flow and fluctuations of strange particles including multi-strange baryons and the ϕ-meson in dependence on energy and system-size.

Directed and elliptic flow

The collective flow of hadrons is driven by geometrical anisotropies of the heavy-ion collision and (resulting) pressure gradients. Theoretical calculations compared to experimental results can connect the experimental findings with the equation-of-state of dense matter and in-medium properties of hadrons. However, so far no consistent measurements of in particular also flow of strange hadrons is available in dependence on energy. The various pieces of experimental observations that are available already show very interesting behaviour, and with CBM measurements the aim is to bring all of this together to a consistent picture. For example, measurements from the STAR experiment show an increasing difference in particle and antiparticle flow the lower the collision energy becomes [12]. Measurements from AGS show that Λ and K^0 flow have opposite signs [13] and measurements of kaon flow from FOPI and KAOS [14, 15] reveal a strong dependence on in-medium potentials.

Existence of exotic strange objects

Thermal model calculations predict a maximum of the production of single and double hypernuclei close to top SIS 100 beam energies [16]. This maximum is reached due to a counterplay of increasing hyperon production and decreasing production of light nuclei with higher beam energy. As a result, CBM should have a major discovery potential for the production of light double-Λ hypernuclei. Such measurements would be a breakthrough in hypernuclei physics and substantially improve the knowledge in $\Lambda - \Lambda$ and $\Lambda - N$ interactions. More speculative is even the connection to remnants of dense, chirally restored matter which also should result in the production of more exotic strange objects [17].

Charm production

Charm production at threshold can be investigated with proton beams at SIS 100. Interestingly, in Ref. [18] the authors predict subthreshold charm production in Au+Au collisions at SIS 100 energies. As the CBM experiment is being prepared also for the measurement of open charm and J/ψ, charmed hadrons will be measurable if being produced with the predicted multiplicity. If measured, this signal would open up a new door for the understanding of charm production in dense baryonic matter and for the understanding of the important role of excited baryons in this process.

Event-by-event fluctuations

Event-by-event fluctuations of conserved quantities such as baryon number, electric charge or strangeness can be directly related to thermodynamic susceptibilities and thus provide an ideal tool to investigate the predicted existence of phase transitions, the order of phase transitions or the existence of mixed phases. Event-by-event fluctuations are thus one of the experimental measurements that can rather directly be compared to lattice QCD calculations [19]. Measurements of event-by-event fluctuations have been performed in order to search for the critical point or signs of a first order phase transition, however, always have to fight with the many experimental artefacts that can mimic fluctuations. Currently, the most interesting and promising measurements are an energy scan of net-proton fluctuations from the STAR experiment [20] combined with preliminary results from the HADES experiment [21]. The results clearly call for high-precision measurements at energies in between in order to search for a possible peak in this fluctuation measurement.

Dileptons

Dileptons emitted in heavy-ion collisions offer the unique property of giving insight into the early phase of the created matter. Due to their penetrating nature and the large variety of processes in which they are created, they provide information on the early temperature of the fireball, in-medium properties of vector mesons, lifetime of the fireball, baryon density due to coupling to baryonic resonances and possibly chiral symmetry restauration. In CBM, particular emphasis will be put on measuring dilepton rates in the mass range beyond 1 GeV/c^2 as this allows to directly access the fireball temperature [22] and a contribution from ρ-a_1 chiral mixing [23]. Figure 2 highlights the discovery potential connected to this measurement.

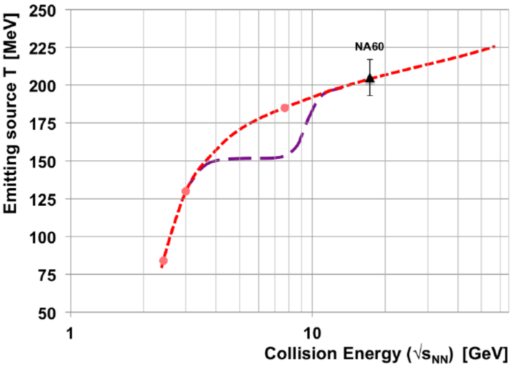

Figure 2. Model calculation (dashed red curve) of the excitation function of the fireball temperature measured with dileptons and speculated shape (violet) with a first order phase transition in the SIS 100 energy range [24].

3 The CBM experiment - challenges and experimental status

CBM aims at systematic measurements of the above introduced observables in order to access their excitation functions and their dependence on centrality and system size. For efficient measurements also of the rare probes, running at highest possible interaction rates is a must for CBM. Figure 3 (left) compares the maximum interaction rates for different experiments in dependence on center of mass energy for Au+Au collisions. The anticipated maximum interaction rates of 10 MHz for CBM outrange all other experiments and open up new and exciting possibilities, however, they come with a challenge: The whole detector, see figure 3 (right), has to be radiation hard and fast, and has to cope with very high particle fluxes due to the fixed target geometry.

In addition to this, the online systems will be as important and challenging as the CBM detector itself [25]. CBM will not employ hardware triggers for event selection but will collect free streaming triggerless data. Each detector hit is sent with a time stamp to a high performance computing farm in the GSI GreenIT cube. A high speed first level event selection (FLES) system [26] will deliver online event reconstruction and selection including secondary vertex finding in real-time [27]. Only this effort will allow to filter out the rare events with, e.g., weakly decaying multi-strange hyperons. In order to cope with the high rates and time-stamped data format, the track reconstruction routines will add time as a fourth dimension in order to disentangle the different events [28]. Reconstructed tracks are then clustered in groups representing the original events (figure 4).

The detector setup of CBM ensures a large acceptance for all interesting observables for the full SIS 100 energy range, and detailed feasibility studies are being performed in order to evaluate the performance, see e.g. [29, 30]. One benchmark observable is the capability to measure Ω-baryons. Assuming one week beamtime each, 1 MHz interaction rate and 10% central Au+Au collisions, CBM

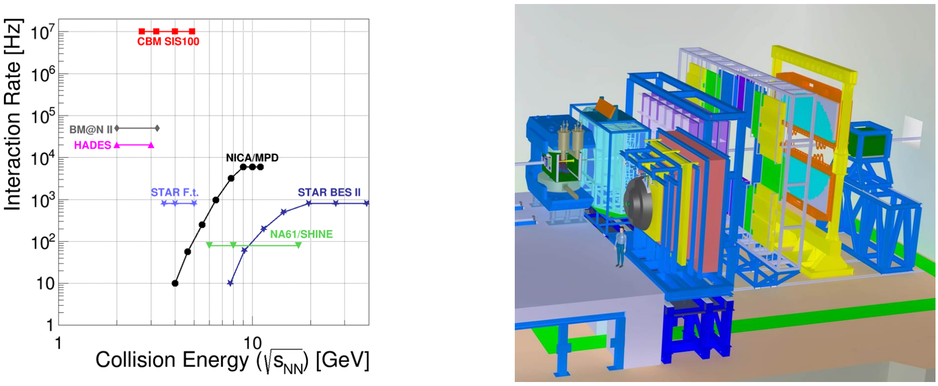

Figure 3. Left: Interaction rates achieved by existing and planned heavy-ion experiments as a function of center-of-mass energy [9]. "STAR F.t." denotes the fixed-target operation of STAR. Right: Setup of the CBM experiment at SIS 100. The beam is entering from left, the sequence of the detectors is: tracking system consisting of silicon pixel (MVD) and micro-strip detectors (STS) in the superconducting dipole magnet, RICH detector, some layers of TRD, TOF, ECAL and a calorimeter for event caracterization (PSD). The muon detector (MuCh) is shown here in the parking position.

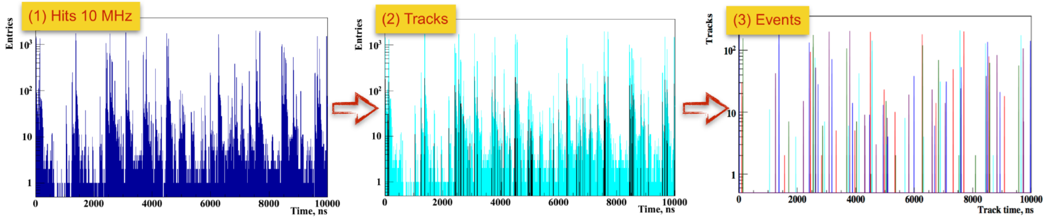

Figure 4. Part of a time-slice with 100 minimum bias Au+Au collisions at 25 AGeV beam energy [28]. Left: time distribution of hits in the selected time-slice. Middle: reconstructed tracks (black) within the time distribution of hits. Right: reconstructed tracks clustered into event groups.

expects to measure 10^6 Ω at 6 AGeV and 10^7 Ω at 10 AGeV beam energy - far enough in order to evaluate yield and phase space distributions. Most notably this performance will allow to reconstruct the elliptic flow of the Ω. Within a week beamtime at 10 AGeV beam energy and running minimum bias collisions with 250 kHz interaction rate only, the Ω flow will be reconstructed with approximately (10-20)% statistical errors at medium p_t [31]. According to new software developments, the high performance silicon tracking system will allow even for Σ^+ and Σ^- baryon reconstruction through their decay topology and a missing mass hypothesis. 4π efficiencies of (1-3)% are expected. This may even allow to address physics questions related to the symmetry energy. Assuming the predicted production rates in Ref. [16] ${}^{5}_{\Lambda\Lambda}H$ double hypernuclei can be discovered in 10^{12} central Au+Au collisions at 10 AGeV beam energy.

The current FAIR schedule foresees the full modularized start version to be operational in 2025, with first detector installations and commisioning as well as first beams 2021-2024. CBM will be the first day experiment of SIS 100 due to its position right behind SIS 100. CBM will be ready until then, even more, several detector components will be ready substantially earlier in time. Therefore, CBM detector components will be installed prior to the usage at FAIR in existing heavy-ion experiments at other laboratories. This so called *FAIR phase 0* program has many benefits: CBM detector components will substantially improve the detector performance of other heavy-ion experiments and increase their physics output. Furthermore, CBM detectors and their readout chain will be thoroughly tested and calibrated, being fully operational and well understood for the start of CBM at FAIR. In this context several projects are pursued: Four STS stations will improve the tracking of the BM@N experiment in Dubna, 10% of the TOF detector modules will substantially improve the forward particle identification in STAR during beam energy scan II, and 40% of the RICH MAPMTs can be used to upgrade the HADES RICH detector for new beamtimes at SIS 18. This replacement of the old photondetector will improve the efficiency of dilepton reconstruction for close pairs of about a factor 5. Within the next heavy-ion HADES beamtime at SIS 18 we expect a breakthrough in dilepton physics at low beam energies, i.e. the possibility to measure dielectron signal pairs with masses beyond 1 GeV/c^2. Besides the use of CBM detectors in other heavy-ion experiments a proposal for a miniCBM experiment at SIS 18 during FAIR phase 0 has been accepted. MiniCBM will use detector prototypes of all CBM components in order to test and establish the self-triggered readout, data transfer to FLES, time-based event building and the online analysis. A succesful operation of miniCBM will substantially reduce commissioning and setup time at SIS 100.

4 Summary

The CBM experiment at FAIR is part of a world-wide endeavour to experimentally map the QCD phase diagram and characterize strongly interacting matter in dependence on temperature and baryon density. The CBM experiment will be unique for the exploration at high-net baryon densities because CBM will operate at interaction rates several orders of magnitude higher than anywhere else. CBM will thus be able to explore matter at high baryon densities with systematic high-precision measurements of rare observables like multistrange particles, dileptons and charm. This offers the chance to resolve many open fundamental physics questions related to baryon-dense matter such as for the nuclear matter equation of state, phase transitions and possible new phases or in-medium modifications of hadrons. CBM thus has a substantially discovery potential. The CBM detector development is well advanced, and several of the detector components can even be used in other heavy-ion experiments prior to FAIR start, substantially enhancing their physics potential.

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