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The Compressed Baryonic Matter experiment at FAIR

Research Article

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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 high densities, and the search for the deconfinement and chiral phase transitions. The CBM detector is designed to measure both bulk observables with large acceptance and rare diagnostic probes such as charmed particles and vector mesons decaying into lepton pairs.

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1. Exploring the phase diagram of nuclear matter

Ordinary substances exist in different phases such as gas, liquid, and solid, depending on the temperature and pressure. A variation of these conditions may cause a transition from one phase to the other, and the boundaries between the different lines can be drawn in a diagram as function of temperature and pressure. These lines could meet at the triple point where several phases coexist. In general there is also a critical point where the distinct phase boundary between liquid and gas ends, and beyond which there is a continuous "crossover" between the two phases. The phase boundaries, the triple point and the critical point represent fundamental landmarks in the phase diagram of each substance.

Substantial experimental and theoretical efforts worldwide are devoted to explore the phase diagram of nuclear matter. A detailed review is given in the CBM Physics Book[1]. Up to date it is still open which of the structures discussed above may exist in dense and hot nuclear matter as it is created in heavy-ion collisions. On the other hand, the QCD phase diagram may be very complicated, in particular at large baryo-chemical potentials as illustrated in Figure 1 [2].

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[1] *CBM Progress Report 2010, http://www.gsi.de/documents/DOC-2011-Mar-235.html*

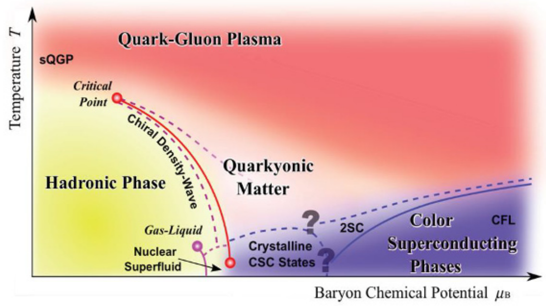


Figure 1. A sketch of a possible phase diagram of strongly interacting matter in the T-μ_b plane. Taken from [2].

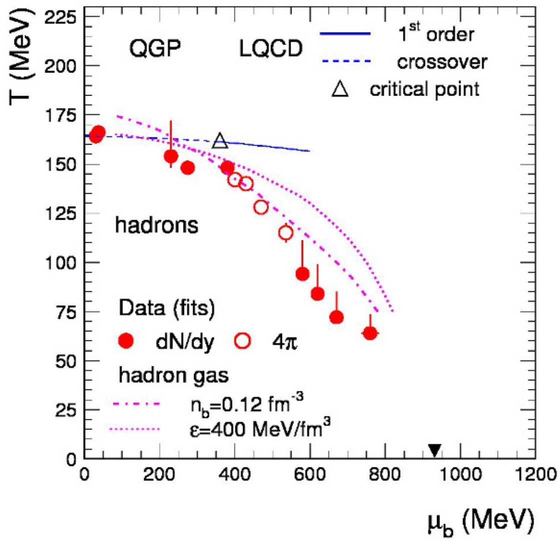


Figure 2. The phase diagram of hadronic and quark-gluon matter in the T-μ_b plane. The experimental values for the chemical freeze-out [3] are shown together with results of lattice QCD calculations [7].

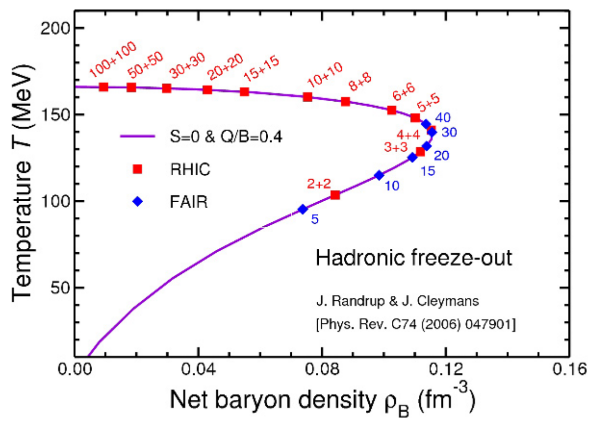


Figure 3. The hadronic freeze-out line in the plane temperature versus net-baryon density as obtained in the statistical model with the values of μ_B and T that have been extracted from the experimental data. The curve corresponds to Au+Au collisions. The symbols represent beam energies (in AGeV) at either RHIC (total energy in each beam), or FAIR (kinetic energy of the beam for a stationary target). The Figure is taken from [12].

Experimentally known are the freeze-out conditions, i.e. the temperature T and the baryon-chemical potential μ_B of the hadronic matter in the fireball at a time when the hadrons cease to interact. This information can be derived from the measured hadron multiplicities using a thermal model [3], the resulting data points for different beam energies are shown in Figure 2. A very interesting result of this analysis is the observation of a limiting temperature of $T = 164$ MeV which is reached above a collision energy of about $\sqrt{s_{NN}} \approx 10$ GeV. This value for the freeze-out temperature is close to the critical temperatures obtained by lattice QCD calculations for $\mu_B = 0$. The Wuppertal-Budapest collaboration finds a pseudo-critical temperature of $T_C = 147$ - 157 MeV for the chiral transition and $T_C = 165 \pm 6$ MeV for the strange quark number susceptibility [4]. The hotQCD collaboration reports a value of $T_C = 154 \pm 9$ MeV for the chiral transition [5]. At zero baryon-chemical potentials the nature of the transition has been found to be a crossover [6].

The onset of a limiting temperature coincides with structures in the excitation functions of hadronic observables [8]. It has been argued that these findings reflect the onset of deconfinement [9, 10] or the existence of a triple point [11]. It is worthwhile to note that the observed effects appear at beam energies where the highest net-baryon freeze-out densities are reached in central Pb+Pb collisions. This is illustrated in Figure 3 which depicts the chemical freeze-out line as function of temperature and net-baryon density as derived from a thermal model analysis of particle yields in heavy-ion collisions [12]. The numbers refer to either the total collision energy (from 2+2 to 100+100 A GeV), or to laboratory kinetic energies for fixed target experiments (from 5-40 A GeV). The calculations indicate, that beam energies between 30 and 40 A GeV (on fixed target), or total energies between $\sqrt{s}$=6 and 10 A GeV are best suited to create the highest net-baryon densities in the laboratory.

According to theoretical models, the structures in the QCD phase diagram - such as the critical point, the predicted first order phase transition between hadronic and partonic matter, and the chiral phase transition - are expected to exist at finite baryon-chemical potentials. The experimental discovery of these prominent landmarks of the QCD phase diagram would be a major breakthrough in our understanding of the properties of nuclear matter. Therefore, several experimental programs are planned to explore the QCD phase diagram at large baryon-chemical potentials. The STAR collaboration at RHIC has scanned the beam energies in order to search for the QCD critical endpoint [13]. First results have been reported for collision energies of $\sqrt{s_{NN}} = 39$, 11.5 and 7.7 GeV corresponding to baryon-chemical potentials ranging from 20 MeV to 400 MeV (see the contribution of A. Schmah). Earlier results from NA49 on the freeze-out temperatures and the kaon-to-pion ratios have been confirmed by STAR. A new and very intriguing result was the observation of a difference between anti-particle and particle elliptic flow at the lower energies. On the other hand, the constituent quark number scaling of the elliptic flow - which is regarded as a signature for flow generation in the partonic phase - holds separately for particles and antiparticles down to the lowest beam energy. This observation requires clarification by further investigations with better statistics and more particle/antiparticle species.

The search for the QCD critical point will be also continued at the CERN-SPS with the upgraded NA49 detector (NA61-SHINE) using light and medium size beams [14]. A new accelerator project devoted to the search for the first order deconfinement/chiral phase-transition and the corresponding phase coexistence has been launched at the Joint Institute for Nuclear Research (JINR) in Dubna [15]. It is planned to upgrade the existing NUCLOTRON facility with a booster and a heavy-ion collider in order to reach collision energies up to $\sqrt{s_{NN}} = 11$ GeV (see contribution of A. Sorin).

Due to luminosity limitations the above mentioned experiments are constrained to the investigation of bulk observables based on particles which are produced abundantly. This is quantified in Figure 4 which compares the experiments in terms of their beam energy range and the reaction rates. The Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt is designed for the detection of bulk and rare particles, and will benefit from the high-intensity heavy-ion beams provided by the FAIR accelerators. The CBM Experiment will provide the unique possibility to perform systematic and comprehensive measurements of diagnostic probes of the high-density fireball including charm, multi-strange hyperons, and lepton pairs.

2. Diagnostic probes of the high density fireball

Figure 5 depicts three snapshots of the evolution of a heavy-ion collision at FAIR energies, and illustrates the

Experiment	Energy range (Au/Pb beams)	Reaction rates Hz
STAR@RHIC BNL	$\sqrt{s_{NN}} = 7 – 200$ GeV	1 – 1000 (limitation by luminosity)
NA61@SPS CERN	$E_{kin} = 20 – 160$ A GeV $\sqrt{s_{NN}} = 6.4 – 17.4$ GeV	80 (limitation by detector)
MPD@NICA Dubna	$\sqrt{s_{NN}} = 4.0 – 11.0$ GeV	~1000 (design luminosity of 10^{27} $cm^{-2}s^{-1}$ for heavy ions)
CBM@FAIR Darmstadt	$E_{kin} = 2.0 – 35$ A GeV $\sqrt{s_{NN}} = 2.7 – 8.3$ GeV	$10^5 – 10^7$ (limitation by detector)

Figure 4. Beam energy range and reaction rates of experiments exploring the QCD phase diagram at large net-baryon densities.

time of production and eventual emission of various particle species. Particles containing charm quarks are expected to be created in the very first stage of the reaction. Then, D mesons and J/ψ mesons may serve as probes for the dense fireball and its degrees of freedom. Vector mesons like ω, ρ and ϕ mesons are produced continuously via $\pi\pi$ annihilation during the course of the reaction, and decay either again into mesons, or into a pair of leptons. However, as leptons are not affected by final-state interactions, the dileptonic decay offers the opportunity to look into the fireball. In particular, the short-lived ρ meson is a promising diagnostic probe of hot and dense nuclear matter. Due to their small hadronic cross sections, also multi-strange hyperons and ϕ mesons carry information on the dense phase of the collision, in particular via their collective flow. Finally, the bulk of the particles freezes out at densities below saturation density. Up to date, essentially these freeze-out probes have been measured in heavy-ion collisions at beam energies between 2 and 40 A GeV (on stationary target).

The experimental challenge is illustrated in Figure 6 where the notation "rare probes" is quantified in terms of the product of multiplicity times branching ratio. The points are calculated for central Au+Au collisions at 25 A GeV using either the HSD transport code [16] or the thermal model based on the corresponding temperature and baryon-chemical potential [17]. Mesons containing charm quarks are about 9 orders of magnitude less abundant than pions (except for the ψ' meson which is even more suppressed). The dilepton decay of vector mesons is suppressed by the square of the electromagnetic coupling constant $(1/137)^2$, resulting in a dilepton yield which is 6 orders of magnitude below the pion yield, similar to the multiplicity of multi-strange anti-hyperons.

The CBM experiment will enter a new era of nuclear matter research by measuring rare diagnostic probes never observed before at FAIR energies, and thus has a unique

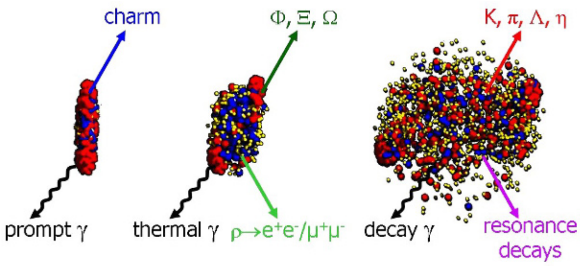


Figure 5. Sketch of the expansion phase of a U+U collision at a laboratory beam energy of 23 AGeV as calculated with the UrQMD model at different time steps: initial stage where the two Lorentz-contracted nuclei overlap (left), high density phase (middle), and final stage ("freeze-out") when all hadrons have been formed (right). Different particles are created in different stages of the collisions or escape from the interaction region at different times (see text). Almost 1000 charged particles are created in such a collision, most of them are pions.

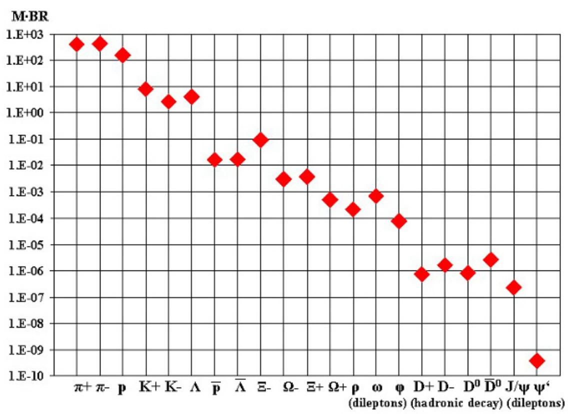


Figure 6. Particle multiplicities times branching ratio for central Au+Au collisions at 25 A GeV as calculated with the HSD transport code [16] and the statistical model [17]. For the vector mesons (ρ, ω, ϕ, J/ψ, ψ') the decay into lepton pairs was assumed, for D mesons the hadronic decay into kaons and pions.

discovery potential. In order to obtain a complete picture, a comprehensive set of observables will be measured in proton-proton, proton-nucleus, and nucleus-nucleus collisions over the full FAIR energy range. The CBM research program is focused on the following observables.

- **Open and hidden charm.** The transport properties of open charm mesons in dense matter – which depend on the interaction with the medium and, hence, on structure of the medium – can be studied via the yield, the elliptic flow and the momentum distributions of charmed particles. In a baryon-dominated medium these observables are expected to differ for D and $\bar{D}$ mesons. A global m_T-scaling of all mesons – in particular for strange and charmed particles – indicates in-medium modifications which may be related to the onset of chiral symmetry restoration. The crossing of the phase transition may be indicated by sudden changes of charm particle ratios such as the $\psi'/(J/\psi)$ ratio and the $(J/\psi)/D$ ratio when measured as function of beam energy. The elliptic flow of charmonium is a measure of the initial pressure of partonic nature.

- **Dileptons.** A precise measurement of the dilepton invariant mass spectrum up to about 1 GeV provides information on the in-medium properties of the vector meson spectral function as a signal of the chiral symmetry restoration in the hot and dense matter. At higher invariant masses the spectrum contains a substantial contribution from thermal dileptons from the early partonic phase. The different origin of the dileptons is also reflected in the inverse slope of their transverse momentum spectra. The experimental determination of dileptons emitted from the high-density phase of the collision requires the measurement (and subtraction) of contributions from very early nucleon-nucleon collision, from the dilute corona, and from freeze-out.

- **Hadron yields and phase-space distributions.** The excitation function (from 2 – 45 AGeV) of hadron yields and phase space distributions (including multi- strange hyperons) will provide information about the fireball dynamics and the nuclear matter equation-of-state over a wide range of baryon densities. A non-monotonic behavior of the inverse slope as function of beam energy would signal a change in the nuclear matter properties at a certain baryon density. The inverse-slope distribution as a function of particle mass is related to the particle freeze-out time, and, hence, may help to disentangle the early from the late collision stages.

- **Hypernuclei** Nuclei containing at least one hyperon in addition to nucleons, offer the fascinating perspective to explore the third, strange dimension of the chart of nuclei. Their investigation provides information on the hyperon-nucleon and even on the hyperon-hyperon interaction, which play an important role in neutron star models. In heavy-ion collisions at FAIR (even double-lambda) hypernuclei will be produced via coalescence of Λs with nucleons or light nuclei in the final state of the reaction.

- **Collective flow.** The strength of the elliptic flow v_2 measured as a function of transverse momentum for various particle species reflects the initial pressure of the system. The vanishing of directed flow at a certain beam energy would indicate a strong softening of the equation-of-state.

- **Fluctuations and correlations.** The presence of a phase coexistence region is expected to cause strong fluctuations from event to event in the charged particle number, baryon number, strangeness-to-pion ratio, average transverse momentum etc. Similar effects are predicted to occur in the vicinity of the QCD critical point.

3. The Compressed Baryonic Matter experiment at 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 and plasma physics[2]. A sketch of the facility is presented in Figure 7. The double-ring synchrotron (SIS100/SIS300) will deliver primary beams (protons up to 90 GeV, Uranium up to 35 AGeV, nuclei with Z/A = 0.5 up to 45 AGeV). High-intensity secondary beams of rare isotopes will be produced with the Superconducting Fragment Separator (SFRS), and can be accumulated, stored and analyzed with the Collector Ring (CR) and the New Experimental Storage Ring (NESR). The NUSTAR detectors will be used for experiments on the structure of unstable nuclei and on nuclear astrophysics. Intense beams of antiprotons will be accelerated and cooled in the High-Energy Storage Ring (HESR), and used for hadron physics experiments with the PANDA detector. Furthermore, there are experimental setups for Plasma Physics (PP) and Atomic Physics (AP). High energy nucleus-nucleus collisions will be investigated with the Compressed Baryonic Matter (CBM) detector. The construction of FAIR hast started in December 2011, first beams from SIS100 are expected in 2018.

The CBM experiment will study nuclear reactions by measuring bulk and rare particles including their phase-space distributions, correlations and fluctuations with unprecedented precision and statistics. The experimental tasks are manifold: identification of open charm via the displaced vertex in heavy-ion collisions at production threshold energies, identification of lepton pairs in a heavy-ion

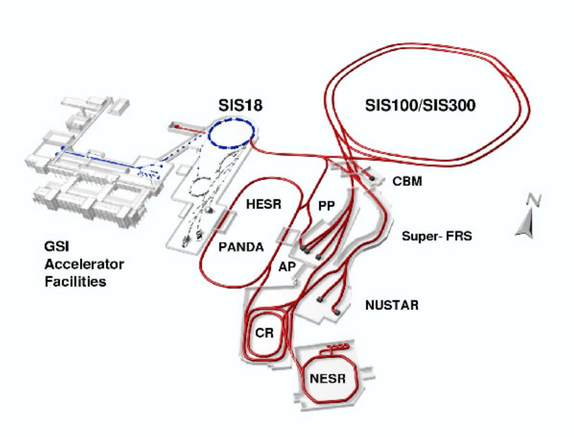


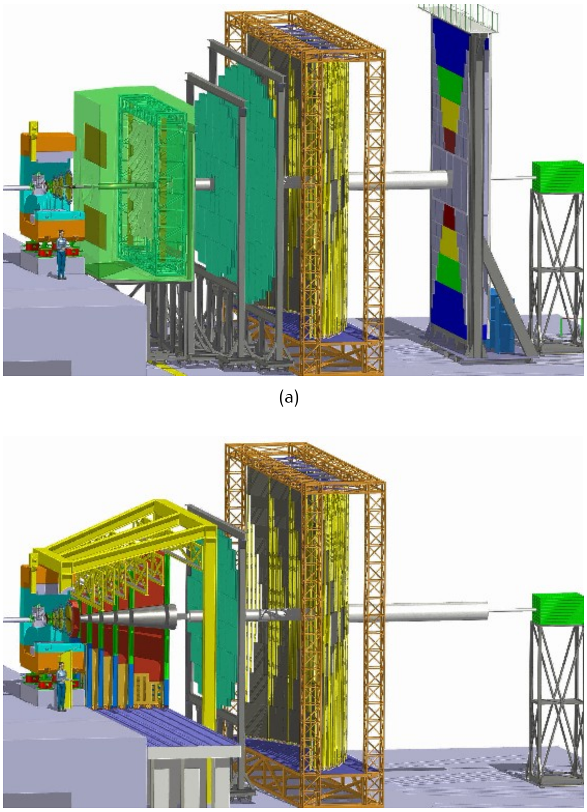
Figure 7. Layout the future Facility for Antiproton and Ion Research (FAIR)[2].

environment, online selection of rare events in nucleus-nucleus collisions with charged particle multiplicities of about 1000 per central event. Such measurements require fast and radiation hard detectors, fast and self-triggered read-out electronics, a high-speed data acquisition system, and online event selection based on full track reconstruction.

A schematic view of the proposed CBM experimental facility is shown in Figure 8. Inside a large aperture dipole magnet there is a Silicon Tracking and Vertexing System which consists of two parts: a Micro-Vertex Detector (MVD, 2 silicon pixel layers) and the Silicon Tracking System (STS, up to eight layers of silicon micro-strip detectors). The Silicon detector array has to provide the capabilities for track reconstruction, determination of primary and secondary vertices, and momentum determination. Particle identification will be performed by time-of-flight measured with a large area Resistive Plate Chamber (RPC) wall.

The panel a of Figure 8 depicts the setup with the Ring Imaging Cherenkov (RICH) detector for the identification of electrons from low-mass vector-meson decays. The Transition Radiation Detector (TRD) will provide charged particle tracking and the identification of high energy electrons and positrons. The Electromagnetic Calorimeter (ECAL) will be used for the identification of electrons and photons. The muon detection/hadron absorber system is shown in the panel b of Figure 8. It consists of 5 triple stations of highly granulated gaseous micro-pattern chambers (for example Gas-Electron Multiplier (GEM) detectors) sandwiched by iron plates with a total thickness equivalent to 13 absorption lengths. The status of detector R&D and recent results of detailed simulations are documented in CBM Progress Report 2010[1]. The measure-

[2] *FAIR Baseline Technical Report 2006, http://www.gsi.de/fair/reports/btr.html*



(a)

(b)

Figure 8. The CBM experimental facility with electron detectors RICH and TRD (panel a) and with the muon detection system (panel b).

ment of rare probes such as open charm or vector mesons decaying into lepton pairs requires efficient background suppression and very high interaction rates. In order to select events containing rare observables, the tracks of each collision have to be reconstructed and filtered online with respect to physical signatures. This concept represents a paradigm shift for data taking in high-energy physics experiments: CBM will run without hierarchical trigger system. The signals produced in the various detectors will be read out with individual time stamps, and the event reconstruction is performed by novel algorithms based on the 3 spatial coordinates and the time stamp of the hits ("4-dimensional tracking"). Self-triggered readout electronics, a high-speed data processing and acquisition system, fast algorithms, and, extremely radiation hard detectors are indispensable prerequisites for the experiment.

4. Acknowledgments

The design and development of the CBM experiment is performed by the CBM Collaboration which actually consists of more than 400 persons from 54 institutions and 15 countries. The CBM project is supported by the German Ministry of Education and Research, by the Hessian LOEWE initiative through the Helmholtz International Center for FAIR (HIC for FAIR), the Helmholtz Association, the EU I3Hadronphysics2 programme, and national funds of the CBM member institutions.

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