The Compressed Baryonic Matter Experiment at FAIR in Darmstadt

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I. 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 [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.

The aim of the nucleus-nucleus collision experiments is to explore the QCD phase diagram at high net baryon densities and moderate temperatures. This approach is complementary to the studies of matter at high temperatures and low net baryon densities performed at RHIC and LHC.

II. 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 [2]. 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 [3]. 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 [4]. The scientific progress in this exciting field, QCD at high baryon densities, is driven by new experimental data.

In order to study the dynamics of strongly interacting matter far from its ground state, laboratory experiments are performed with high-energy nucleus-nucleus collisions. The conditions inside the transiently existing fireball are reflected in the abundances and the phase-space distributions of the emitted hadrons. Important information on the early phase of the collision is provided by the quark flavor of the observed hadrons. In particular, hadrons containing strange or charm quarks are regarded as sensitive diagnostic probes of the collision dynamics. The hadrons are either observed directly or - in the case of short-lived resonances - are identified via their hadronic or leptonic decay products.

Lattice QCD calculations at vanishing baryon chemical potential and finite temperature predict the formation of a quark-gluon plasma above energy densities of about 1 GeV/fm^3 [5]. Such conditions may be created in central collisions between heavy nuclei already at bombarding energies of about 10 AGeV [6, 7]. Recent lattice QCD calculations at finite baryon chemical potential predict a critical endpoint of deconfinement phase transition at $\mu_B \approx 400$ MeV and T$\approx$160 MeV [8, 9].

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 [10–12]. The solid curve along the freeze-out points represents a calculation with a constant baryon density (baryons + antibaryons) of about $\rho_B = 0.75\ \rho_0$ [12]. The phase boundary between quark-gluon matter and hadronic and the location of the critical endpoint as shown in figure 1 is predicted by lattice QCD calculations [8, 9] which indicate that for values of μ_B larger than about 400 MeV the phase transition is first order, whereas for μ_B smaller than 400 MeV there is a smooth cross over from the hadronic to the partonic phase (dotted line). The search for the critical endpoint is a prime goal of the experiments.

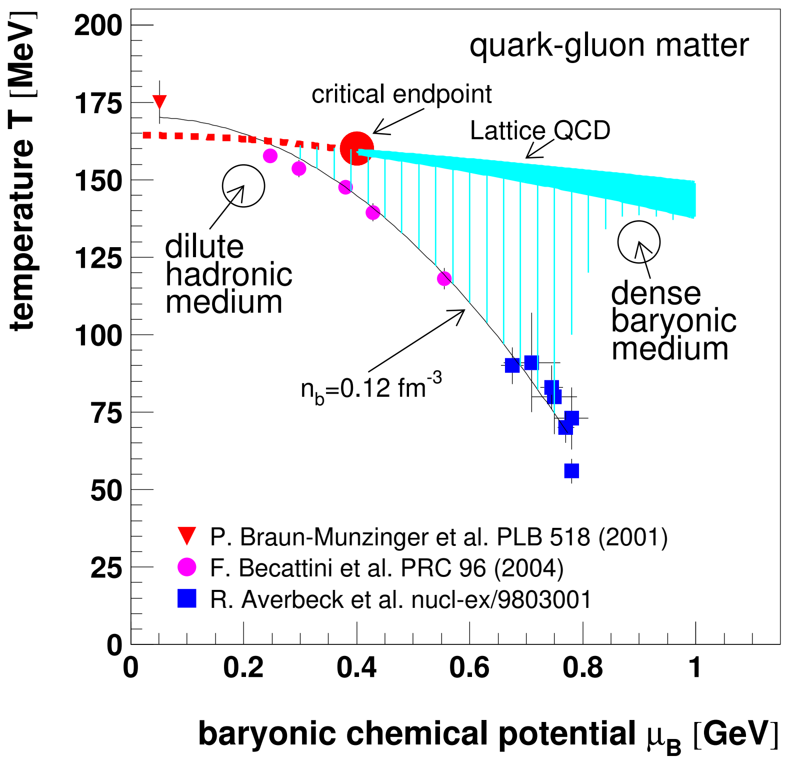

FIG. 1: The phase diagram of strongly interacting matter plotted as a function of temperature and baryon chemical potential. Full symbols: freeze-out points obtained with a statistical model analysis from particle ratios measured in heavy collisions [10–12]. The critical endpoint at $\mu_B \approx 400$ MeV is predicted by lattice QCD calculations [8, 9]. "Dilute hadronic medium": ρ_B=0.038 fm^{-3} $\approx 0.24\ \rho_0$. "Dense baryonic medium": ρ_B=1.0 fm^{-3} $\approx 6.2\ \rho_0$.

At ultra-relativistic beam energies provided by RHIC and the future LHC, partonic matter is expected to be produced at very high temperatures but at small baryon chemical potentials. Similar conditions prevailed in the early universe. The complementary situation exists in the core of a conventional neutron star: here the baryon density is very high and the temperature very low. In the laboratory, fireballs at high baryon densities and moderate temperatures are created at beam energies significantly below top SPS energies. This region of the QCD phase diagram - marked by the hatched area in figure 1- has not been studied experimentally in detail.

III. THE FUTURE NUCLEUS-NUCLEUS COLLISION RESEARCH PROGRAM

The proposed heavy-ion collision experiment at FAIR in Darmstadt will simultaneously measure observables which are sensitive to effects of high baryon densities and to phase transitions. In particular, we focus on the investigation of:

- short-lived vector mesons. Their spectral properties, the mass and the width, can be studied in the dense nuclear medium via their decay into lepton pairs. Since the leptons are very little affected 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.

- Charmonium production at beam energies close to the kinematical threshold. The J/ψ mesons will be measured via their decay into electron-positron pairs. The multiplicity of J/ψ mesons per participating nucleon as function of system size and beam energy is expected to be sensitive to the deconfinement phase transition.

- open charm, e.g. D-mesons. The effective masses of D-mesons - a bound state of a heavy charm quark and a light quark - are expected to be modified in dense matter similarly to those of kaons. Such a change would be reflected in the relative abundance of charmonium ($c\bar{c}$) and D-mesons.

- strange particles, in particular baryons (anti-baryons) which contain more than one strange (anti-strange) quark.

- macro-dynamical effects, like collective flow of nuclear matter during the expansion of the initially compressed system. Such probes provide constraints on the underlying equation of state which is of great significance e.g. for astrophysical problems. Moreover, the measurement of the flow of charmonium and multistrange hyperons will provide new information on the behavior of these rare probes in dense baryonic matter.

- characteristic event-by-event fluctuations near the critical point. The identification of a critical point would provide direct evidence for the existence and the character of a deconfinement phase transition in strongly interacting matter.

- search for exotica like pentaquarks, short-lived multi-strange objects, and precurser effects of a color super-conducting phase at highest baryon densities [13].

IV. THE CBM DETECTOR

The experimental task is to identify both hadrons and leptons and to detect rare probes in a heavy ion environment. The apparatus has to measure multiplicities and phase-space distributions of hyperons, light vector mesons, charmonium and open charm (including the identification of protons, pions and kaons) with a large acceptance. The challenge is to filter out those rare probes in Au+Au (or U+U) collisions at reaction rates of up to 10^7 events per second. The charged particle multiplicity is about 1000 per central event. Therefore, the experiment has to fulfill the following requirements: fast and radiation hard detectors, large acceptance, electron and hadron identification, high-resolution secondary vertex determination and a high speed trigger and data acquisition system. The CBM experimental setup consists of the following detector components (see figure 2):

- Dipole magnet for momentum determination and δ-ray deflection
- Radiation hard Silicon pixel/strip detectors for tracking and vertex determination
- Transition radiation detectors (TRD) for electron identification
- Ring imaging Cherenkov detector (RICH) for electron identification
- Resistive plate counters (RPC) for time of flight measurement
- Electromagnetic calorimeter for identification of electrons, photons and muons
- Diamond pixel detectors for TOF start signal

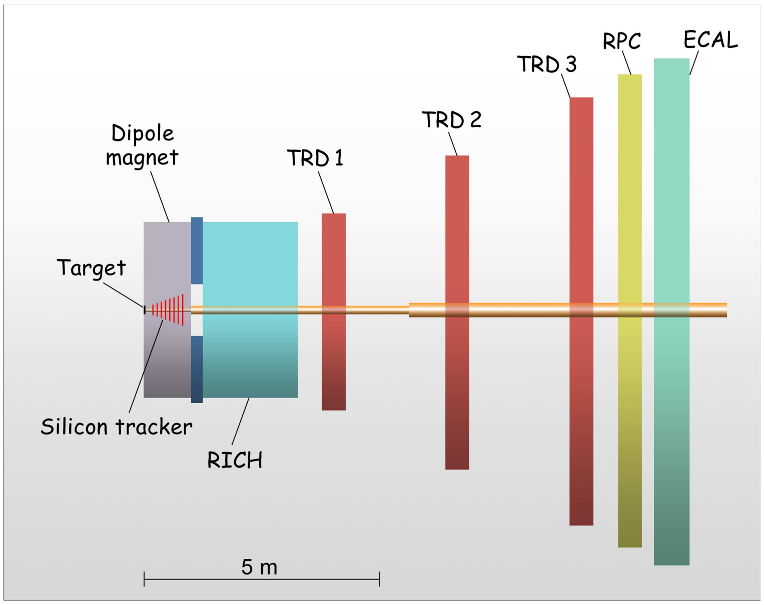

FIG. 2: *Sketch of the planned Compressed Baryonic Matter (CBM) experiment. The beam enters from the left hand side. The setup consists of a superconducting dipole magnet with a Silicon tracker System inside, a Rich Imaging Cherenkov detector (RICH) for electron identification, the three Transition Radiation Detectors (TRD), the Time-Of Flight (TOF) wall which is a Resistive Plate Chamber (RPC) and the electromagnetic Calorimeter (ECAL) (from left to right). The total length of the setup is approximately 12 m from target at the entrance of the dipole to the ECAL.*

The proposed experimental setup offers the possibility to determine particle multiplicities and phase-space distributions, the collision centrality and the reaction plane. The simultaneous measurement of electron-positron pairs and hadrons permits the study of cross correlations. This synergy effect opens a new perspective for the experimental investigation of nuclear matter under extreme conditions. Such systematic and detailed measurements include the variation of experimental conditions like beam energy and atomic number of the colliding nuclei and require a dedicated accelerator with high beam intensities, large duty cycle, excellent beam quality and high availability.

The CBM Collaboration, which actually consists of 39 institutions from 14 countries, has submitted a Technical Status report in January 2005 [14].

V. REFERENCES

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