

The Compressed Baryonic Matter Experiment

The mission of the Compressed Baryonic Matter (CBM) experiment at the Future Facility for Antiproton and Ion Research (FAIR) in Darmstadt/Germany is to explore the phase diagram of nuclear matter in order to find answers to the fundamental questions raised above. The experimental challenge is to measure and to identify the most of the particles which are produced in a high-energetic collision between two atomic nuclei. Their abundancy, momentum, mass and composition reflect the temperature and density of the fireball. Promising diagnostic probes are instable particles which contain heavy strange or charm quarks, or particles which decay already in the dense phase of the fireball in electron-positron or muon pairs. Another important observable is the expansion of matter after the collision – the so called collective flow of particles. Similar to the expansion of the universe, which reflects the conditions shortly after the big bang, the flow of particles provides information on the matter in the early fireball. Fluctuations of certain particle numbers may indicate the presence of a critical point or phase coexistence. The discovery of new double hypernuclei will shed light on the interaction between strange baryons which are supposed to play an important role in the core of neutron stars. Figure 5 depicts the central collision of two gold nuclei at FAIR beam energies according to a simulation.

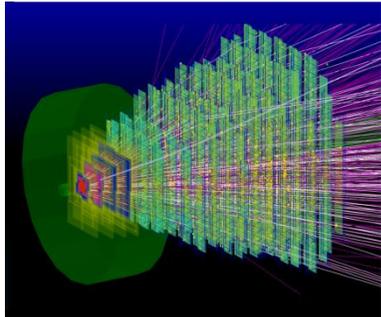


Figure 5: Simulation of a central collision of two gold nuclei at a beam energy of 8 GeV per nucleon. The CBM experiment will be able to measure, reconstruct and analyze up to 10 million collisions per second.

Most of these observables will be studied for the first time in the FAIR energy range. However, many of the particles which serve as diagnostic probes of dense nuclear matter are produced very rarely, some of them only once in one million collisions. Therefore, the experimental challenge is to measure as much collisions as possible in a short time. The CBM experiment is designed to record and to analyze up to 10 million events per second, which will provide unprecedented statistics and precision. This requires very fast and radiation hard detectors, a novel data read-out and analysis concept including free streaming front-end electronics, and a high performance computing cluster for online event selection. The unrivalled rate capability of the CBM experiment is illustrated in figure 6 which shows the interaction rates of existing and planned heavy-ion experiments in the beam energy range where the highest matter densities are expected.

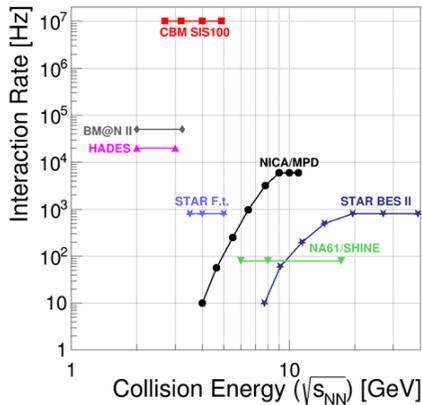
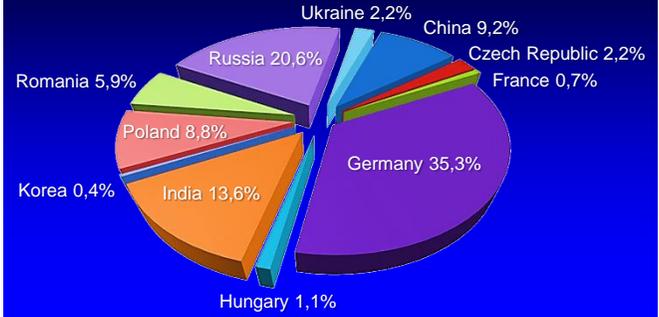


Figure 6: Interaction rates achieved by existing and planned heavy-ion experiments as a function of center-of-mass energy. At SIS 100 beam energies, nuclear matter densities like those in the core of neutron stars can be reached.

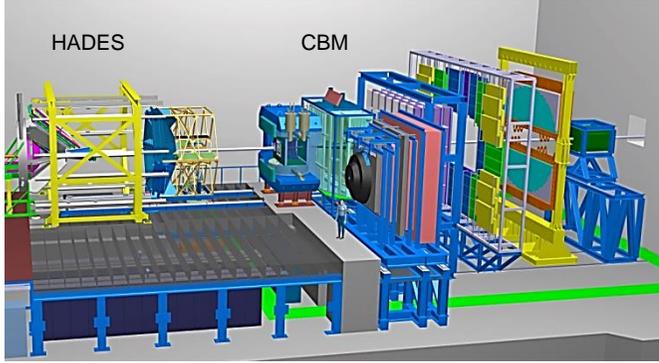
In conclusion, the unique combination of an accelerator which delivers a high-intensity heavy-ion beam with a modern high-rate experiment based on innovative detector and computer technology offers optimal conditions for a research program with substantial discovery potential for fundamental properties of nuclear matter.

The experiment is realized by the CBM collaboration which consists of more than 460 scientists from 54 institutions and 11 countries.



29th CBM Collaboration Meeting, 20-24 March 2017, GSI

Compressed Baryonic Matter Experiment at FAIR



<http://www.fair-center.eu/for-users/experiments/cbm.html>



Collisions between heavy atomic nuclei at very high energies offer the unique opportunity to produce and study extremely hot and dense matter in the laboratory. At the highest bombarding energies available, as provided by the Relativistic Heavy Ion Collider at BNL in USA or by the Large Hadron Collider at CERN in Switzerland, a mixture of matter and anti-matter is produced which is more than hundred-thousand times hotter than the core of our sun. Such conditions presumably existed in the early universe about a microsecond after the big bang. At lower bombarding energies, as available at the SPS at CERN and at the future Facility for Antiproton and Ion Research (FAIR) at Darmstadt, the colliding nuclei are compressed to extreme high densities, similar to matter densities which are expected to exist in the core of a neutron star.

Neutron stars are the most compact objects known so far. They have masses between 1.2 and 2 solar masses and a radius of only 10 – 20 km. In the core of a neutron star the density is so high, that nucleons, the building blocks of atomic nuclei, are expected to melt, and their constituents, the quarks and gluons, form a new state of elementary matter. This situation is illustrated in figure 1, which depicts two model calculations of the possible structure of a neutron star.

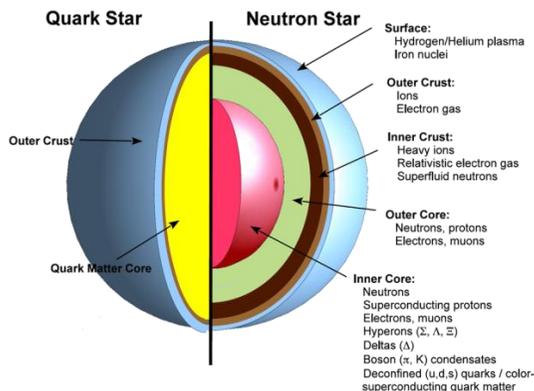


Figure 1: Schematic structure of a neutron star (right part). The degrees of freedom in the inner core are still unknown. Theoretically possible are also strange quark stars, which consist of up, down, and strange quarks (left part).

In the laboratory, hot and dense nuclear and quark matter can be created only for extremely short times during a collision between heavy nuclei at very high bombarding energies.

A simulated snapshot of such an event is shown in figure 2 for two colliding gold nuclei at a beam energy of 10 GeV/nucleon as it will be provided by the FAIR accelerators. In the hot and dense phase of the collision various particles and antiparticles are produced and emitted, which can be measured and serve as diagnostic probes of the conditions inside the fireball. The temperatures and densities of the fireball produced in a heavy-ion collision at FAIR energies are similar to those created in the center of a neutron star merger, i.e. in a collision of two neutron stars.

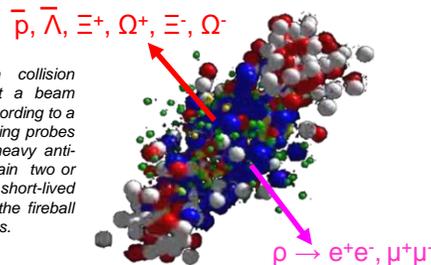


Figure 2: Snapshot of a collision between two gold nuclei at a beam energy of 10 GeV/nucleon according to a simulation. Particular interesting probes of the fireball matter are heavy anti-particles, particles which contain two or three strange quarks, and short-lived particles which decay inside the fireball into pairs of electrons or muons.

Model calculations of heavy-ion collisions predict, that the density in the center of the fireball exceeds 8 times the density of an atomic nucleus, which is already 300 million tons per cm³. At such densities, the nucleons are expected to fuse and form large bags of quarks. The calculations show that the dense fireball spends a comparatively long time within the phase coexistence region at energies around 5A GeV and goes beyond this region with increasing beam energy. Figure 3 depicts the density in the center of the fireball as a function of time as predicted by five different model calculations for central Au+Au collisions at a beam energy of 10 A GeV. Note that $\rho=1 \text{ fm}^{-3}$ corresponds to about 7 times the density of an atomic nucleus.

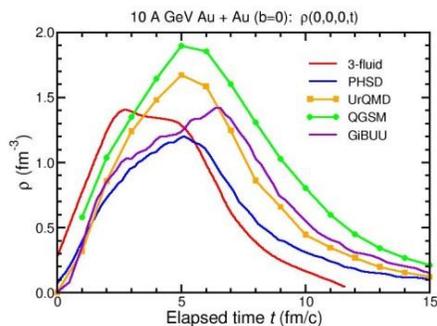


Figure 3: Density as a function of time reached in the center of the fireball for central Au+Au collisions at 10 A GeV as calculated by transport models and a hydro model.

Like ordinary substances, nuclear matter is expected to 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 phases can be drawn in a diagram as function of temperature and pressure. Figure 4 depicts the conjectured phases of nuclear matter as function of temperature and baryon density, and indicates the conditions in the early universe, in neutron star cores and in neutron star mergers.

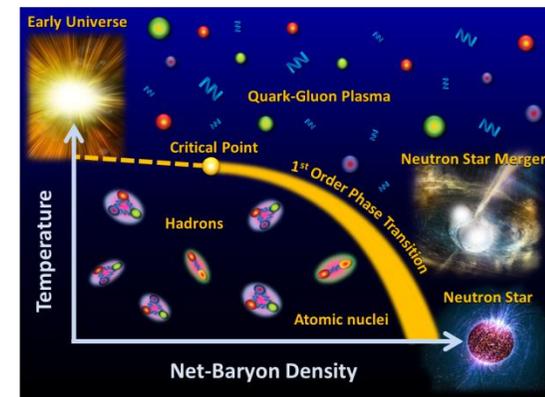


Figure 4: Sketch of the phase diagram of strongly interacting matter as function of temperature and baryon density.

The phase diagram may exhibit a rich structure such as a critical point, a first order phase transition between the world of hadrons and the Quark Gluon Plasma, and the chiral phase transition. The experimental discovery of these prominent landmarks of the phase diagram would be a major scientific major breakthrough, which would shed light on the following fundamental questions:

- What is the equation of state of nuclear matter at neutron star densities, and what are the relevant degrees of freedom at these densities?
- Is there a 1st order phase transition from nuclear to quark-gluon matter, together with a region of phase coexistence? Do exotic phases like quarkyonic matter exist?
- Why is the mass of protons and neutrons, the building blocks of atomic nuclei, about 50 times larger than the mass of the sum of their elementary constituents?
- How far can we extend the chart of nuclei towards the third (strange) dimension by producing nuclei which contain one or even two strange baryons, so called single or double hypernuclei? Does strange matter exist in the form of heavy multi-strange objects?