Introduction

A considerable change in our ideas about the ultimate constituents of matter has occurred during the past few decades. One of the most intriguing and challenging tasks in physics is to establish a relationship between the macroscopic and the microscopic aspects of the World. A detailed, though still incomplete, theory of elementary particles and their fundamental interactions, called Standard Model, has been validated during the last two decades. Applying and extending the Standard Model to complex and dynamically evolving systems of finite sizes is the ultimate aim of ultra-relativistic heavy-ion physics. Ultra-relativistic heavy-ion collisions allow us to study the characteristics of the densest and the hottest form of matter that may be created in the laboratory and to address some fundamental questions relating to the state of matter at temperatures and energy densities which may be considered as "extreme" on the hadronic scale. The main aim of heavy-ion physicists is to study and understand how collective phenomena and macroscopic properties, involving many degrees of freedom, can be explained in terms of the microscopic laws of elementary particle physics.

The most striking feature of a collective bulk phenomenon predicted by the Standard Model is the occurrence of phase transition at the characteristic energy density. Standard Model predicts that the Universe evolved from an initial state of extreme energy density to its present state through rapid expansion and cooling, thereby undergoing a series of phase transitions. Within the framework of the Standard Model, the occurrence of phase transition involving elementary quantum fields is intrinsically connected to the breaking of the fundamental symmetries of nature and thus to the origin of mass. In general, intrinsic symmetries of the theory, which are valid at high energy densities, are broken below a certain critical energy density. Particle content and particle masses originate as a direct consequence of the symmetry breaking mechanism. In ultra-relativistic heavy-ion collisions, one expects to attain
energy densities which reach and exceed the critical energy density, $\varepsilon_c$. Thus, making the QCD phase transition the only one predicted by the Standard Model, that is, within reach of the laboratory experiments and in particular to answer the following questions:

- What is the limit of the ordinary hadronic matter?
- What are the conditions beyond which separate hadrons do not retain their identity?

However, in more precise and specific language, where one talks about the colored quarks and their confinement into colorless hadrons, the questions essentially are:

- What are the limits of confinement?
- Can the quarks be liberated from their hadronic prison?

It is interesting to mention that study of the properties of the de-confined matter is of immense importance, not only about the nature of matter but also about the evolution of the Universe.

To get a first idea of what the quark infrastructure of elementary particles implies for the behaviour of matter at extreme energy density, let us consider a very simple picture. If nucleons, with their intrinsic spatial extension, were both elementary and incompressible, then a state of close packing would constitute the high density limit of matter (Fig. 1a).

On the other hand, composite nucleons made up of point like quarks will start to overlap with increasing density, until eventually each quark finds within its immediate vicinity a considerable number of other quarks (Fig. 1b).

It has no way to identify which of these had been its partners in a specific nucleon in some previous state of lower density. Beyond a certain point, the concept of hadron thus loses its meaning; at extreme energy density, we are quite naturally led to a medium whose basic constituents are unbound quarks [1].
Introduction

Fig. 1. Strongly interacting matter: (a) at a density of closely packed nucleons and (b) as quark matter at much higher energy density.

Up to nuclear density, we have experimental information to guide our understanding of such matter. What happens beyond this? The high energy physics community is looking for an answer to this question. Even before the QCD got recognition as the fundamental theory of strong interactions, it had been argued that the basic properties of strongly interacting hadrons must lead to some form of critical behaviour at high temperature and/or energy density. Since a hadron has a finite size of $\sim 1 \text{ fm}^3$ (pions), there is a limit to the density and the temperature of a hadronic system beyond which hadrons start to superimpose [2].

The lattice QCD calculations have predicted that at a critical temperature around 170 MeV, corresponding to an energy density $\varepsilon_c \approx 1 \text{ GeV/fm}^3$, nuclear matter would undergo a phase transition to a de-confined state of quarks and gluons [3]. Consequently, chiral symmetry is partially restored and quark masses are reduced from their large effective values in hadronic matter to their small bare masses.

How to produce such a phase transition in the laboratory?

The phase transition may take place in ultra-relativistic heavy-ion collisions, where one expects to achieve energy densities, which may exceed the critical value $\varepsilon_c$, thus making possible transition to the de-confined state in laboratory experiments. Hence, the only way to achieve this is to collide two heavy nuclei at ultra-relativistic energies and study the resulting small and short lived droplets of hot and dense
medium. For such studies it is essential to have viable probes which can provide information about the formation of droplets in the early stages of nuclear collisions consisting of unbound quarks and gluons. Thus, one has to look for the signatures of color de-confinement.

The only laboratories providing sufficiently energetic nuclear beams are the Brookhaven National Laboratory (BNL), New York, USA and the European Organization for Nuclear Research (CERN), Geneva, Switzerland. Both began experimentation on heavy-ion physics in 1986 using the existing accelerators at that time. BNL had the Alternating Gradient Synchrotron (AGS), designed for 30 GeV/c proton beams, whereas CERN had the Super Proton Synchrotron (SPS) for 450 GeV/c protons. The injectors available at that time allowed only the acceleration of nuclei containing equal numbers of protons and neutrons \((A = 2Z)\), so that the beams were restricted to light ions \((A \leq 40)\). Both the laboratories have in the meantime built new injectors, allowing acceleration of arbitrary heavy nuclei in AGS and SPS [1]. From then onwards, energy of the ion beams has considerably increased, as evident from Table 1.

Table 1 Experimental facilities for high energy nuclear collisions along with beams and the center-of-mass energies.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Starting year</th>
<th>Type</th>
<th>Beam</th>
<th>(\sqrt{s}) (GeV/A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS - BNL</td>
<td>1986</td>
<td>Fixed target</td>
<td>(^{28}\text{Si})</td>
<td>5</td>
</tr>
<tr>
<td>SPS - CERN</td>
<td>1986</td>
<td>Fixed target</td>
<td>(^{16}\text{O},^{32}\text{S})</td>
<td>19</td>
</tr>
<tr>
<td>AGS - BNL</td>
<td>1992</td>
<td>Fixed target</td>
<td>(^{197}\text{Au})</td>
<td>5</td>
</tr>
<tr>
<td>SPS - CERN</td>
<td>1994</td>
<td>Fixed target</td>
<td>(^{208}\text{Pb})</td>
<td>17</td>
</tr>
<tr>
<td>RHIC - BNL</td>
<td>2000</td>
<td>Collider</td>
<td>(^{197}\text{Au})</td>
<td>200</td>
</tr>
<tr>
<td>LHC - CERN</td>
<td>2008</td>
<td>Collider</td>
<td>(^{208}\text{Pb})</td>
<td>5500</td>
</tr>
<tr>
<td>SIS 300 - FAIR</td>
<td>(\sim) 2014</td>
<td>Fixed Target</td>
<td>(^{232}\text{U})</td>
<td>(\sim) 7.5</td>
</tr>
</tbody>
</table>

Relativistic Heavy Ion Collider (RHIC), BNL is in operation since 2000 and the
Large Hadron Collider (LHC) has been commissioned and accelerating proton beams successfully. A new facility, FAIR SIS 300, for investigation of the behaviour of nuclear matter at low temperature and high energy density shall be constructed at the GSI, Dremstad, Germany. It will accelerate heavy-ion beams with energies up to 40 GeV/nucleon.

During the last two decades, the heavy-ion programmes involving fixed-target experiments at AGS and SPS and more recently the colliding beam experiments at RHIC have hinted towards the occurrence of phase transition. LHC will allow study of Pb-Pb collisions at the center-of-mass energy $\sqrt{s} = 5.5$ TeV per nucleon pair (approximately 20 times higher than the RHIC energy). LHC will be the next generation facility for the physics of the de-confined QCD matter and lead to a significant qualitative improvement with respect to the previous experiments. The SPS and RHIC experiments have answered the first set of questions, showing that there is a limit to confined matter. On the other hand, the twin tasks of the LHC heavy-ion programme are: (i) to address the remaining questions and (ii) to investigate the characteristics of the de-confined medium.
References:

