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Status and prospects of experiments with ultrarelativistic nuclear beams

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Summary. — Experiments with ultra-relativistic nuclear beams have been carried out since the early eighties, seeking a detailed understanding of Nuclear Matter at extreme temperatures and densities. In such conditions QCD predicts that quarks and gluons are no longer bound in hadrons, and form a so-called Quark-Gluon-Plasma (QGP), a state in which the Universe should have been a few microseconds after the Big Bang. This experimental programme has enjoyed enormous success, and the number of scientists involved has grown continuously through the years. In the meantime, while the experimental and theoretical tools to collect and understand the data were constantly improving, so has done the energy of the beams available for experiments. From the 1 GeV per nucleon pair of the Bevalac at Berkeley, accelerators have increased in energy to the AGS at BNL (few GeV) to the SPS at CERN (almost 20 GeV), to the Relativistic Heavy Ion Collider at BNL (200 GeV). Sometime during 2010 the LHC will bring in another major step, going to 5500 GeV. During these years an enormous path has been covered, and experimenters have learnt how to deal with events of unprecedented complexity, with first hundreds, then thousands of particles produced. The phase diagram of strongly interacting matter has been populated of measured points, and strategies have been developed to investigate the nature and dynamical evolution of the high-density system generated. Physicists are pursuing a new generation of experiments which will allow a quantum step in our understanding of the QGP but also a more detailed exploration of the phase diagram and in particular of the phase transition. In this paper, I will briefly review our present understanding of the physics with ultrarelativistic nuclear beams, and then outline the perspectives of the experiments for the coming years.

PACS 25.75.-q – Relativistic heavy-ion collisions.
PACS 12.38.Mh – Quark-gluon plasma.

1. – Introduction

This paper is not the appropriate place for a comprehensive review of the field, but several excellent review articles have been published recently [1-5] where more extensive discussion can be found of the subjects briefly mentioned here. At the moment, several facilities around the world provide ultrarelativistic nuclear beams: in collider mode RHIC at BNL, in the near future the LHC at CERN and in a more distant future NICA at JINR, and in fixed-target mode the CERN SPS, SIS at GSI and in the future SIS-100 and later SIS-300 at FAIR. The programme at RHIC has produced a very rich harvest of results and therefore the two large experiments (STAR and PHENIX) will upgrade their apparata and continue data taking with an increased luminosity. The two smaller experiments, PHOBOS and BRAHMS, have both completed their programme. RHIC will also perform an energy scan in search of threshold effects and critical phenomena linked to the phase transition. The fixed target programme at the CERN SPS has now lasted for more than two decades, with a peak of activity in the mid-nineties when Pb beams first became available, yet it is still lively, with the SHINE experiment to map the phase diagram looking for the critical point and several new proposals being considered. At GSI, a very lively programme is ongoing at SIS, with experiments such as HADES, Kaos and FOPI studying the equation of state of nuclear matter. In the future, the FAIR complex will provide beams of intensity two orders of magnitude larger than at the SPS, thus creating ideal conditions for the continuation of the mapping of the phase diagram in the region of high baryon densities. This is also the purpose of the proposed NICA Nuclear Collider, to be built at JINR in the coming years. Yet, the main source of new results in the field in the near future will certainly be the CERN Large Hadron Collider, which will start operating with proton beams in late 2009 and with nuclear beams in late 2010. The new machine will represent a 30-fold increase in center-of-mass energy as compared to RHIC, and will open not only a new regime of energy density and lifetime of the plasma but, even more importantly, make available a new set of probes to study its nature, from jets to heavy quarks. The LHC will open a completely new era in the study of strong interacting matter at high densities, and a huge effort has been devoted to preparing the experiments to fully exploit this opportunity: ALICE, the only experiment dedicated to heavy ions, has been optimized to cover comprehensively all relevant observables, while the two large multipurpose pp detectors, ATLAS and especially CMS, will exploit their excellent calorimetry and high-momentum lepton detection capability to study high-p_T probes of the QGP. Already the very first collisions of Pb beams at LHC will provide fundamental new insight in the field. Overall, about two thousand physicists are now active in experiments with ultrarelativistic nuclear beams. They come from all over the world, in part with a background in high-energy physics, in part with one in low-energy nuclear physics. The joining of these two communities, carrying each different methods both in detection techniques and in data analysis, is an asset which has enriched and dynamised this interdisciplinary field.

The method of colliding high-energy nuclei to heat and compress hadronic matter dates from the early eighties, but the path had been indicated already several years before. It was in 1975 that T. D. Lee had pronounced the famous sentence "it would be interesting to explore new phenomena by distributing a high amount of energy or high nuclear density over a relatively large volume", and the idea of deconfinement had been around for some time. Already in 1965 Hagedorn [6] had observed that the mass spectrum of hadronic states led naturally to the concept of a "limiting" or "critical" temperature beyond which the concept of hadron would cease to make sense. In 1973 the development of QCD as the theory describing strong interactions introduced the concept of asymptotic freedom [7,8]: at small distances quarks and gluons would be loosely interacting, or quasi-free. In 1975, N. Cabibbo and G. Parisi [9] proposed for the first time the existence of a "different phase of the vacuum in which quarks are not confined", and drew the first schematic diagram of hadronic matter with temperature and baryonic density as axes.

Two regions were defined: at low T and low baryonic density, ordinary hadrons, at high T, high μ_B a deconfined state: a new field of research was born! In the same year, J. C. Collins and M. J. Perry [10] developed the idea that matter under extreme density conditions, as in neutron star cores and in the early universe, is made of quarks instead of hadrons, which overlap and lose their identity. Their argument was based on the fact that quarks interact weakly when they are close together, and therefore at high densities could be described as a gas of free massless quarks. Finally, in 1980 [11] E. Shuryak introduced the term quark gluon plasma (QGP) to describe the state of nuclear matter in which quarks are deconfined, stressing the analogy between a classical plasma made by ionized atoms and the state made of coloured strongly interacting objects.

In a nucleus-nucleus collision the energy of the incoming projectiles is dissipated in the relatively large volume defined by the overlap region of the two colliding nuclei, thus creating the conditions for a phase transition to deconfined quark matter by heating. In case of heavy nuclei collisions, the QGP is expected to thermalize, expand and eventually cool down at the hadronization time. The lifetime of the QGP, $\tau_{\rm QGP}$, is expected to grow with the energy of the colliding nuclei up to $\tau_{\rm QGP} \geq 10\,{\rm fm/c}$ at LHC energies.

The study of the properties of high-energy nuclear collisions has allowed physicists to gather understanding of the properties of strongly interacting matter, and much more is expected to be learnt in the coming years, providing answers to questions such as:

What are the properties of matter at the highest temperatures and densities?

What is the QCD equation of state? How can we test it?

What are the dominant microscopic mechanisms of QCD non-equilibrium dynamics and thermalization?

How does hadronization proceed dynamically? How is it changed in dense QCD matter?

How can the QCD phase diagram be efficiently explored?

Clearly, a comparison of the experimental results with theory is not a trivial task. Since the transition to the deconfined phase is outside the limits of validity of the perturbative QCD, a number of different approaches has been developed to derive the equation of state and the transition temperature. Only at the LHC some aspects of the interactions will be accessible with perturbative methods. Effective Lagrangians have been extensively used, and also potential models, and even calculations based on the AdS/CFT correspondence have been providing a fresh look and new insight. Still, the most important and widely used are QCD calculations on a space-time lattice. They generally predict a phase transition to occur, and are able to determine its temperature. In fig. 1 results computed at vanishing chemical potential are reported, with two light and one heavier quarks, using different temporal extents ($N_\tau = 6$ and 8) and two different actions. The chemical potential is actually very low at midrapidity in A-A collisions at RHIC energies and should be close to zero at the LHC. In the left panel a quantity sensitive to the degrees of freedom that carry a net number of strange quarks and hence sensitive to deconfinement, the quark strange susceptibility χ_s

$$\frac{\chi_s}{T^2} = \frac{1}{VT^3}\frac{\partial^2 \ln Z}{\partial(\mu_s/T)^2}$$

(Z is the partition function, μ_s the s quark chemical potential and V is the volume of the fireball) is plotted as a function of the temperature T. This quantity changes rapidly in a temperature interval $185 < T < 195\,{\rm MeV}$. The horizontal line represents

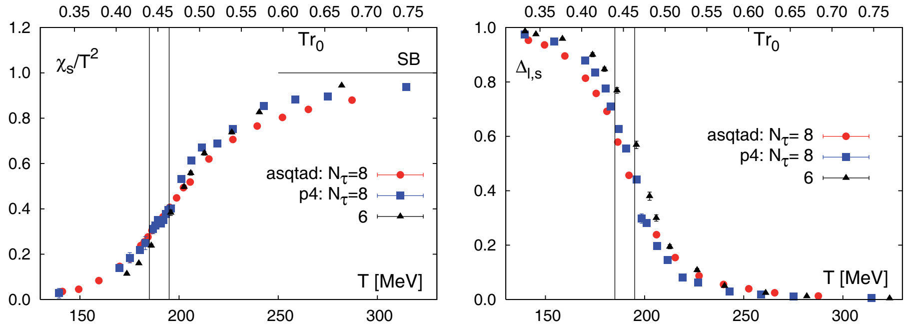

Fig. 1. – Left: susceptibility of quark s *vs.* temperature. Right: subtracted chiral condensate normalized to the corresponding zero value *vs.* temperature. The Sommer scale parameter has been fixed as $r_0 = 0.469\,\text{fm}$ from an analysis of the heavy-quark potential. The vertical bands correspond to an interval $185 < T < 195\,\text{MeV}$. Figures taken from [12].

the Stefann-Boltzmann limit for an ideal gas. In the right panel, the following order parameter (closely related to the chiral condensate) for chiral symmetry restoration

$$\Delta_{l,s}(T) = \frac{\langle\bar{\psi}\psi\rangle_{l,T} - \frac{m_l}{m_s}\langle\bar{\psi}\psi\rangle_{s,T}}{\langle\bar{\psi}\psi\rangle_{l,0} - \frac{m_l}{m_s}\langle\bar{\psi}\psi\rangle_{s,0}}\,,$$ where l stands for light quarks and s for strange

is plotted as a function of the temperature. These lattice QCD computations indicate that chiral symmetry restoration and phase transition occur at the same temperature. The critical energy density is expected to be $\epsilon_c = 0.7 \pm 0.2\,\text{GeV/fm}^3$ [3] and the transition at vanishing baryochemical potential should be a crossover, while at low temperature and high baryon density it is expected to be a first-order transition.

2. – Experimental results

The study of nucleus-nucleus collisions is a major experimental challenge. Thousands of particles are produced in each collision, and all of them are relevant to the thermodynamical description of the system formed. Moreover, the particles observed in the detectors are the result of the space-time evolution of the system, and have been influenced by the interactions occurred in the process. The goal of the experiments is to disentangle the effects of the subsequent phases of the system evolution from the initial hard scatterings to the time of last elastic collisions, called freezeout, throughout thermalization, expansion and hadronization. Last but not least, the initial conditions of the collision are not defined, since they change dramatically depending on the impact parameter, and therefore must be measured on an event-by-event basis for example by measuring the number of non-interacting nucleons (zero-degree energy flow). In practice, the measured quantity is the deviation of a nucleus-nucleus interaction from a simple incoherent superposition of nucleon-nucleon collisions: it is therefore essential to compare the experimental results with p-p and p-A data, possibly taken with the same apparatus and at the same energy. In this way the onset of collective phenomena and the role of nuclear effects can be detected. The main challenge in experimental heavy-ion physics is to single out a number of observables clearly linked to the formation of a deconfined phase. Since this is a topic in which perturbative QCD computations cannot be used,

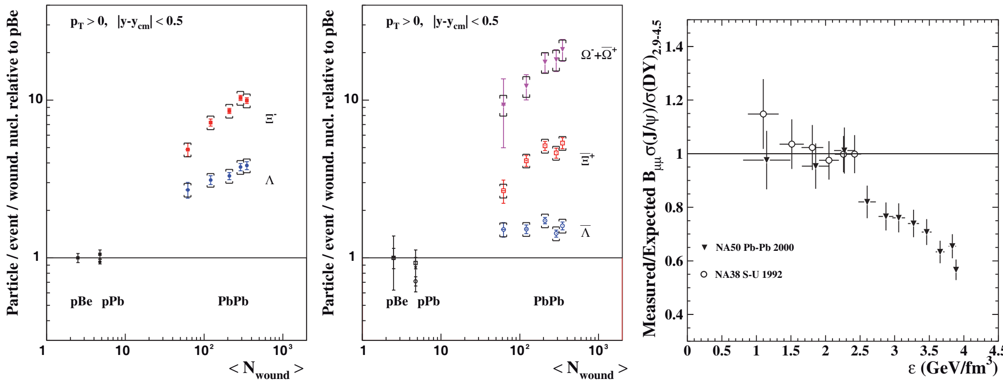

Fig. 2. – Left and centre: hyperon enhancements as a function of the number of wounded nucleons measured by NA57 experiment [15]. Right: (J/ψ/Drell-Yan) cross-sections divided by the normal nuclear absorption pattern as a function of the energy density, measured by NA50 experiment [16].

there were few clear predictions about QGP signatures when the SPS ion programme started in 1986. In particular there were predictions for strangeness enhancement [13] and J/ψ suppression [14], both of them actually observed at the SPS in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 17.3\,\text{GeV}$. These and the other results of the SPS programme cannot be easily explained in terms of conventional physics, however also the interpretation in terms of QGP is not compelling. In a QGP scenario the formation of $s\bar{s}$ quark pairs is competitive with that of $u\bar{u}$ and $d\bar{d}$ pairs because of the (partial) chiral symmetry restoration and because the production of s quarks is favored by the Pauli principle in an environment rich of light quarks. In fig. 2, left and central panels, the strange and multistrange hyperon enhancement as measured by the NA57 experiment is shown as a function of the number of wounded nucleons. The enhancement grows with the strangeness content and reaches a factor as high as 20 for the triply strange Ω.

The suppression of J/ψ production in nucleus-nucleus collisions due to color screening preventing the c and $\bar{c}$ quarks to form charmonia states was proposed by T. Matsui and H. Satz in 1986 [14]. The right panel of fig. 2 shows the J/ψ suppression as measured by the NA50 Collaboration [16]. The J/ψ yield, measured in its $\mu^+\mu^-$ decay channel, is normalized to the Drell-Yan process which can be used as a reference, being not sensitive to nuclear matter effects. The $(J/\psi/DY)$ ratio is then divided by the expected absorption in nuclear matter as observed in p-A collisions. This *normal* absorption is due to cold nuclear matter effects in contrast to the additional *anomalous* absorption observed in the hot nuclear matter formed in nucleus-nucleus collisions. The claim of having observed a new state of matter compatible with the QGP([1]) was largely based on these two experimental findings.

Presently the abundance of the hadron species, including the ones containing strangeness, is well described in terms of the thermodynamic grand-canonical ensemble (canonical ensemble for small particle numbers), assuming that hadronization occurs

([1]) `http://info.web.cern.ch/Press/PressReleases/Releases2000/PR01.00EQuarkGluonMatter.html`

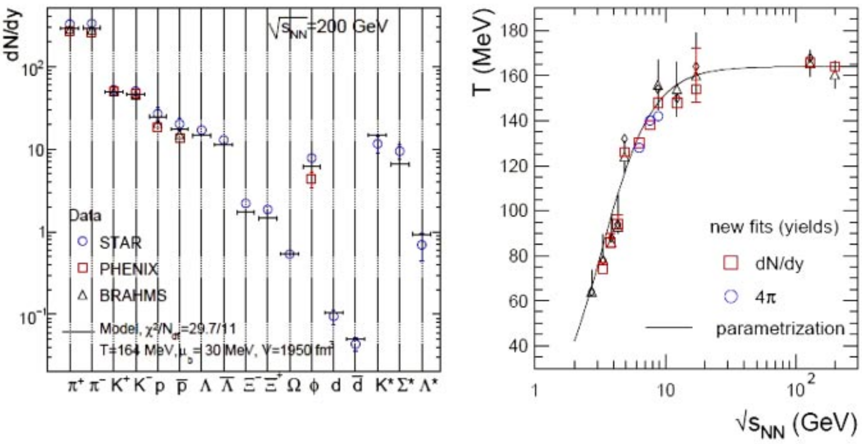

Fig. 3. – Left: experimental hadron yields and model calculations for the parameters of the best fit at 200 GeV compared with experimental data. Right: energy dependence of the temperature at chemical freeze-out. Figures taken from [17].

when the fireball reaches a specific equilibrium temperature and baryon chemical potential. In fig. 3, in the left panel, is shown one of the many plots comparing the model calculations with experimentally measured yields. The agreement is indeed remarkable for a model with only few parameters. The temperature measured in this way is the one at which the final particle composition is fixed, generally called Chemical Freezout Temperature. In the right panel of fig. 3 is shown the dependence of the chemical freezout temperature on the collision energy. A saturation effect is clearly evident, suggesting the temperature of the system has exceeded a limiting temperature through which it will go to the process of expansion-cooling. These results are interpreted assuming that the chemical freeze-out is caused by the quark gluon plasma and its transition to normal matter [2, 17].

The start of the RHIC operation in the year 2000, providing Au-Au and Cu-Cu collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ has opened a new era for Ultrarelativistic Nuclear Collisions. The new energy regime has offered a more abundant yield of *hard probes*, which are observables originating from hard scattering events that occur in the first stages of A-A collisions in binary nucleon-nucleon interactions. For these processes, *e.g.*, heavy flavor production and jets, pQCD predictions can be made. As a matter of fact, impressive results like jet suppression [18, 19] have been observed. The physics results of RHIC have led to hundreds of important publications and are impossible to summarize here in any detail. Still, three points are worth mentioning. First of all, the multiplicity measured at RHIC is considerably lower than expected, in fact lower than most of the predictions. This result has been interpreted as a manifestation of gluon saturation, a regime in which parton densities are maximal in the colliding systems. In other words, it is said that the two colliding nuclei behave as a Color Glass Condensate. Second, the matter produced at RHIC is opaque to hard probes, a feature often referred to as *jet quenching*. The effect is very striking both in inclusive high-p_T spectra and in two-particle azimuthal distributions. The first effect is shown in fig. 4 where the so-called nuclear modification factor R_{AA} is plotted *versus* transverse momentum for different hadron species and for photons. R_{AA} is the ration between the yield which one measures in AA collisions and

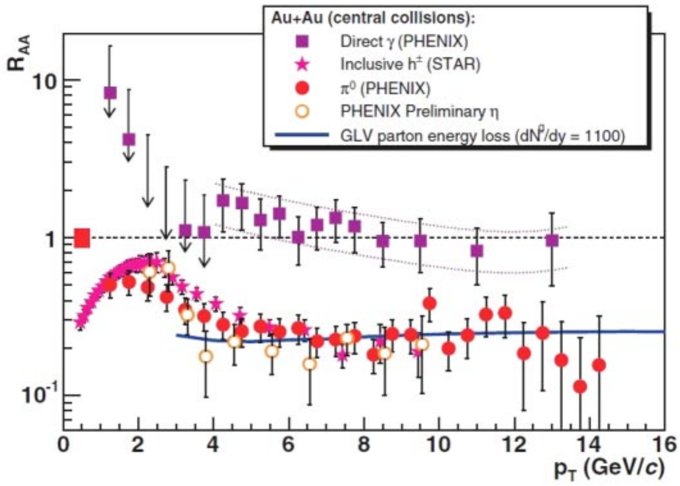

Fig. 4. – Nuclear modification factor R_{AA} for direct photons and hadrons in central Au + Au collisions at NN center-of-mass energy of 200 GeV. Data from the PHENIX experiment at RHIC [20].

the one computed from a superposition of pp collisions. Photons, which do not interact strongly, are little affected and exhibit an R_{AA} close to 1 as expected, while hadrons are strongly suppressed at high p_T, as they lose energy in the dense, strongly interacting medium.

The latter effect is shown in fig. 5, left panel. The suppression is not due to initial state effects, otherwise it should be present also in d-Au collisions. On the contrary, in d-Au collisions an enhancement of hadron production for $2 \leq p_T \leq 7\,\mathrm{GeV}/c$, compatible with the Cronin effect, is observed. In case of di-jets, the quenching of the away side jet is interpreted to be due to radiative and possibly collisional energy loss of the produced leading parton when crossing the hot nuclear matter before hadronization.

The third fundamental, and surprising, feature of the RHIC data is that the matter produced at RHIC shows strong collective motion and evidence for hydrodynamic behavior with very small viscosity. Moreover, there is evidence that flow builds up at the partonic level. The overlap region of two colliding nuclei is almond shaped, with the shortest axis along the impact parameter vector, which defines, together with the beam axis, the reaction plane. If the produced particles (or partons) interact with each other, the initial spatial anisotropy turns into a momentum anisotropy, which is called *elliptic flow*. In this way an azimuthal asymmetry in the produced particles can be observed. The azimuthal distribution can be written as

$$\frac{\mathrm{d}N}{d(\varphi - \Psi_{RP})} = \frac{N_0}{2\pi}\left[1 + 2v_1 \cos(\varphi - \Psi_{RP}) + 2v_2 \cos(\varphi - \Psi_{RP}) + \ldots\right],$$

where $v_1, v_2, \ldots$ are the Fourier coefficients and Ψ_{RP} is the reaction plane angle. The second coefficient (v_2) is non-zero when the number of particles emitted orthogonally with respect to the reaction plane is different from the number of particles emitted in the reaction plane. This is exactly what happens if the elliptic flow occurs. The measured elliptic flow at RHIC is strong and it can be interpreted quite successfully at the light of

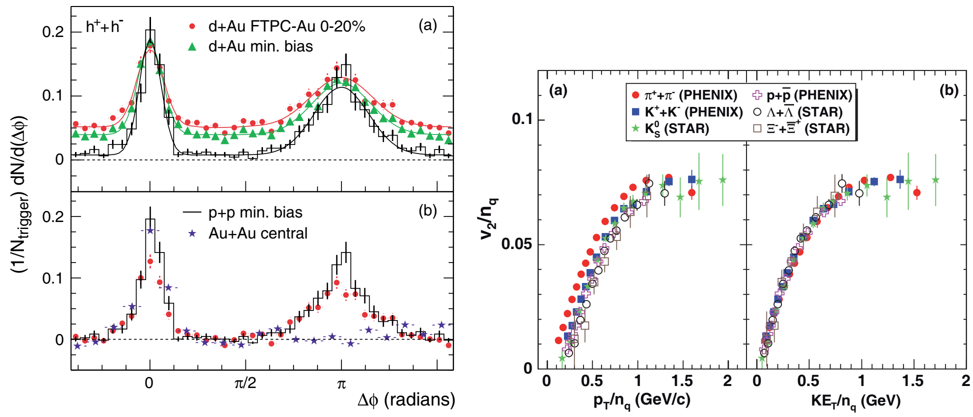

Fig. 5. – Left: two particle azimuthal distributions p-p and minimum bias and central d-Au collisions meaured by the STAR experiment. Curves are fits to the data (a). In (b) the comparison is done with central Au-Au collisions. The respective pedestals are subtracted [19]. Right: elliptic flow v_2 divided by the number of constituent quarks n_q as a function of p_T/n_q (a) and of the transverse kinetic energy divided by the number of constituent quarks KE_T/n_q (b) [21].

hydrodynamical models: what is produced at RHIC appears to be a strongly interacting ideal fluid (*strongly interacting QGP*—cf. [18] and references therein), characterized by an early thermalization ($\tau_{\mathrm{EQU}} \sim 0.6$–$1\,\mathrm{fm/c}$) and a vanishing viscosity. An interesting question is to know at what level collective behavior is established. In fig. 5, right panel (b), the elliptic flow divided by the number of constituent quarks as a function of the transverse kinetic energy ($KE_T = m_T - m$) also divided by the number of constituent quarks, is shown for different mesons and baryons. The observed quark number scaling indicates that the collective phenomena are at partonic level and the scaling variable, kinetic energy *vs.* transverse momentum should be useful to distinguish between different coalescence models [21]. Data from non-photonic electrons, originating from semileptonic decays of D and B mesons, show a large azimuthal anisotropy v_2 indicating a strong coupling with the medium and a substantial elliptic flow also for heavy flavors [22].

3. – The future

Thanks to the progress fueled by the results at the SPS and especially at RHIC, the physics of relativistic heavy ions is living a very exciting moment. Its development will follow two main lines of activity: the exploration of the QCD phase diagram in search for signs of the onset of the phase transition and the experimentation at the Large Hadron Collider.

The QCD phase diagram, as described by lattice QCD calculations, should exhibit a complex structure, similarly to what happens for water. The phase transition in the high-temperature, low baryon-density region explored by the collider experiments should be a smooth crossover, while at higher baryochemical potentials it should take the form of a sharper first-order transition. The point of transition between the two regimes is a *Critical Point* which could manifest itself in instabilities of the system, fluctuations and strong collective effects. Several experiments are now launching programs aimed at the systematic exploration of the Phase Diagram, to search both for the onset point for the features measured at high energies and for the critical phenomena associated to the critical point. RHIC itself will perform an energy scan, though at fairly low luminosity, while the SHINE experiment at the SPS will map by varying both the size and the energy of the system. The ultimate experiment in this field will be CBM at the future FAIR facility, which will exploit the extremely high luminosities provided by the new accelerator (two orders of magnitude above the SPS), to reach for hard processes in the lower energy regime where their cross-section is very low (for example, it will measure charm very close to the threshold for production). It is an extremely challenging experiment, but will allow a completely new understanding of Compressed Baryonic Matter.

The LHC should deliver its first p-p collisions in 2009 and a pilot Pb run in 2010 with a substantial step forward in energy with respect to RHIC ($\sqrt{s_{\mathrm{pp}}} = 14\,\mathrm{TeV}$ and $\sqrt{s_{\mathrm{NN}}} = 5.5\,\mathrm{TeV}$ for Pb-Pb collisions). Having gone through successful runs with cosmic rays already in 2008 and 2009 and likely through a long run with proton beams during 2010, the experiments at the LHC will be fully commissioned and ready to exploit the new conditions available at this unprecedented energy domain. A quite thorough revision of the available predictions for the LHC has been recently published [23] and the current estimates for the charged particle multiplicity ($1200 < \mathrm{d}N^{\mathrm{ch}}/\mathrm{d}\eta < 3500$) are consistently lower if compared to the estimates available when the LHC project started ($4000 < \mathrm{d}N^{\mathrm{ch}}/\mathrm{d}\eta < 8000$). As mentioned earlier the multiplicity measurement at RHIC was a surprise of great scientific interest, and the measurement at the LHC, which will be available shortly after the very first collisions, is eagerly awaited for. The first three minutes of data taking with lead beams will already give new insight on the saturation models and measure the energy density achieved. The temperature and energy density that are expected in Pb-Pb collisions at the LHC are largely exceeding the threshold for the onset of deconfinement and chiral symmetry restoration, determined by lattice QCD calculations. In this regime the deconfined matter should be closer to the Stefann-Boltzmann limit of a weakly interacting gas (see fig. 1) of quarks and gluons. The deconfined phase is expected to have a short thermalization time ($\tau_{\mathrm{EQU}} \sim 0.1\,\mathrm{fm}/c$) and a long lifetime ($\tau_{\mathrm{QGP}} > 10\,\mathrm{fm}/c$) fully justifying the thermodynamical approach used in several theoretical models. With just about one day of running particle composition, spectra of identified particles and flow patterns will be measured, giving a quantum step to our understanding of the behavior of deconfined matter. Finally, hard processes will be dominant at the LHC: charm and beauty cross-sections are expected to increase respectively by one and two orders of magnitude, leading to 115 (0.16) $c\bar{c}$ pairs in central Pb-Pb (p-p) collisions. For $b\bar{b}$ the figures are 4.6 and 0.007, respectively [24]. Also jets are expected to be copiously produced: $\sim 10^6$ for $E_T > 100\,\mathrm{GeV}$ at mid rapidity in one year of running ($10^6\,\mathrm{s}$) [25], while already $\sim 10^3$ will be collected in the ALICE acceptance in a short low-luminosity run. Hard probes will in general require longer runs and analysis, especially for beauty and process like photon-jet where errors are essentially dominated by statistics.

The ALICE experiment has been designed to measure all the known observables related to the QGP formation; a description of the ALICE apparatus can be found in [26]. This requirement explains the variety of particle identification techniques and the large number of different detectors implemented in this experiment. ALICE is equipped with a set of tracking detectors with hermetic azimuthal coverage in the central pseudorapidity region ($-0.9 < \eta < 0.9$) operating inside a relatively small solenoidal magnetic field ($B \leq 0.5\,\mathrm{T}$) which allows transverse momentum measurements down to $p_T \simeq 100\,\mathrm{MeV}/c$. These central detectors, thanks to their excellent tracking and particle identification capabilities will allow studies on soft processes on an event-by-event basis. They will also provide an access to several hard probes, like exclusive identification of charmed mesons in hadronic decay channels, inclusive detection of B mesons via semileptonic decay channels ($B \rightarrow e + X$), charmonium and bottomonium studies through two-body e^+e^- decays. A forward ($-2.4 < \eta < -4$) muon spectrometer will allow open beauty and quarkonia studies in the $\mu^+\mu^-$ channel in a different kinematic domain. It is important to note that direct measurement of charm production cross-section will be a natural reference for charmonia studies. Jet detection capabilities of the central detectors will be improved by the addition of an electromagnetic calorimeter, with a partial azimuthal acceptance (110°). The central barrel is completed, with a reduced azimuthal acceptance, by an array of ring imaging Cherenkov detectors for high-momentum particle identification and by a high-resolution electromagnetic calorimeter used as a photon spectrometer. The centrality of nuclear collisions is measured with a Zero Degree Calorimeter, which measures the number of spectators nucleons. The acceptance for charged multiplicity measurements is increased to $-3.4 < \eta < 5.1$ by a forward multiplicity detector. Recent and detailed presentations of the ALICE physics persepctives can be found in refs. [24,25] and [27].

The ATLAS and the CMS experiments will also study several aspects of heavy-ion collisions. As a difference with respect to ALICE, they are not designed to be minimum bias experiments so they will achieve their best performance in hard probes detection. Namely ATLAS [28] will excel in jet and photon measurements: it will reconstruct jets in a large kinematical domain ($E_T > 40\,\text{GeV}$ and $|\eta| < 5$) and will address multi-jet studies. CMS will have an excellent mass resolution for quarkonia studies in the $\mu^+\mu^-$ channel, allowing a good separation of the Υ family [29].

In conclusion, ultrarelativistic heavy-ion beams have been a very effective tool to explore the behavior of strongly interacting matter at high temperature and density. While our knowledge has grown enormously in the last two decades, a lot remains to be understood, and a rich programme of experiments is about to start. In particular, the LHC promises to be a fantastic discovery machine, and to reward the heavy-ion community preparing the experiments with a rich harvest of physics results. Already a short, low-luminosity pilot run would allow for fundamental new measurements, bringing new light into our understanding of strong interactions.

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