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Heavy-ion physics at the future colliders RHIC and LHC

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Abstract

By the end of this century, a new regime of very high energy density matter will be accessible in nucleus-nucleus collisions at the new colliders RHIC (Relativistic Heavy-Ion Collider) at BNL and LHC (Large Hadron Collider) at CERN. After a brief description of the main machine parameters, this contribution will summarize the improvements and changes expected for the physics of heavy-ion reactions at these colliders as well as the experimental program planned at RHIC and LHC.

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1 Introduction

The aim of high-energy heavy-ion physics is the study of strongly interacting matter at extreme energy densities. Statistical QCD predicts that, at sufficiently high density, there will be a transition from hadronic matter to a plasma of deconfined quarks and gluons — a transition which in the early universe took place in the inverse direction some 10^{-5} s after the Big Bang and which might play a role still today in the core of collapsing neutron stars. The study of the phase diagram of nuclear matter, utilizing methods and concepts from both nuclear and high-energy physics, constitutes a new and interdisciplinary approach in investigating matter and its interactions. It is of interest to explore and test QCD on its natural scale (Λ_{QCD}) and to address the fundamental questions of confinement and chiral-symmetry breaking. Moreover, it is of general relevance in understanding the dynamical nature of phase transitions involving elementary quantum fields, as the QCD phase transition is the only one accessible to laboratory experiments.

The study of ultra-relativistic heavy-ion collisions ($E/m \gg 1$) is a rather new, but rapidly evolving field. After the pioneering experiments at the BEVALAC and in DUBNA with relativistic heavy ions ($E/m \approx 1$), the first experiments started in 1986 with light ions ($A \approx 30$) almost simultaneously in Brookhaven with the AGS ($E_{beam} \approx 15$ GeV/nucleon) and at CERN with the SPS ($E_{beam} = 200$ GeV/nucleon). Really heavy ions ($A \approx 200$) are available in the AGS since the end of 1992 and will be so in the SPS by the end of 1994. When the colliders RHIC ($\sqrt{s} = 200$ GeV/n) and LHC ($\sqrt{s} = 5.5$ TeV/n) come into operation around the turn of the century, the available energy in the centre-of-mass will have increased by almost five orders of magnitude in less than 20 years. This unprecedented pace was made possible, of course, only by (re)using accelerators, and to a large extent even detectors, built over a much longer time scale for use in high-energy physics. The following sections will summarize the physics and experiments to come in the latest (and possible last) heavy-ion machines, the colliders RHIC and LHC.

2 RHIC and LHC: history and machine parameters

2.1 RHIC

The idea to build a dedicated collider machine for ultra-relativistic heavy-ion collisions preceded the first fixed-target experiments at BNL and CERN by several years. In its 1983 long-range plan, the Nuclear Science Advisory Committee recommended RHIC as the highest priority future project for Nuclear Physics in the US. A proposal and design report was submitted to DOE the following year. It then took six long years before the project was finally approved in 1990. In the meantime, physics signals and detector concepts were discussed and elaborated in a number of workshops [1]. Since 1992, the experimental program is essentially defined with two large detectors (STAR and PHENIX) and two smaller ones (PHOBOS and BRAHMS) in various stages of the approval process (originally there were 9 LoI's submitted after the first call for proposals in 1990).

RHIC, which uses the existing heavy-ion facilities at Brookhaven (Tandem, Booster and AGS) as injection chain, will be located in the existing 3.8 km tunnel of an earlier abandoned project (ISABELLE/CBA). Two independent rings with 3.45 T superconducting magnets will allow collisions between different nuclei (p-p, p-A, A-B), including protons, at a top energy of $250 \times (Z/A)$ GeV/n, i.e. up to a c.m.s energy of 500 GeV for p-p and 200 GeV/n for Au-Au. The current design luminosity is $2 \times 10^{26} [cm^{-2}s^{-1}]$ for Gold on Gold reactions and in excess of 10^{31} for p-p. For Au-Au, with a geometrical reaction cross section of ≈ 6 barn, the total interaction rate will be about 1000/s, out of which a few tens will be central collisions with the largest particle production and the

highest energy densities. Luminosity upgrades by up to an order of magnitude might be feasible and are under consideration.

At the time of writing this article, RHIC is expected to start operation in 1999. As a dedicated machine, it will run mostly with heavy ions (or protons for comparison data). There are six interaction regions available for experiments, out of which four have been assigned for the initial set of experiments mentioned above. In addition to heavy-ion physics, there are a number of experimental proposals to study p-p reactions with polarized beams at $\sqrt{s} = 500$ GeV.

2.2 LHC

The possibility to add a second machine, a hadron collider, on top of the LEP electron-positron collider at CERN, has been mentioned already in the mid 70's by Sir John Adams, then DG of CERN. When LEP was approved in 1981, the 27 km long tunnel was made sufficiently large to accommodate what is now known as the LHC. The idea to also use the LHC for heavy-ion collisions was first mentioned by C. Rubbia in the proceedings of the ECFA workshop on future colliders at La Thuile in 1987 [2]. It was however only during the preparation for the Aachen LHC workshop in 1990 [3], that the European heavy-ion community took up the challenge and discussed the potential physics program and detector concepts for nucleus-nucleus interactions at several TeV/nucleon.

Responding to a call for expressions of interest, three general-purpose pp detectors, three dedicated beauty experiments, and one heavy-ion detector were presented in 1992 [4]. Since then, the experimental program is taking shape, and so far two pp experiments (ATLAS, CMS) and the heavy-ion detector (ALICE) have been approved to proceed towards a technical proposal.

Also at CERN, the existing injector chain (Source, LINAC, PS, SPS), recently upgraded for the fixed-target Pb-program, will be used to inject into the LHC. In addition, the LEAR ring will accumulate and cool the beams to reach the highest luminosities. The 9 T superconducting magnets of the LHC will provide a maximum energy of $7 \times (Z/A)$ TeV, i.e. a c.m.s. energy of 14 TeV for p-p and 5.5 TeV/n for Pb-Pb. The design luminosity varies between $2 \times 10^{27} [cm^{-2}s^{-1}]$ for Pb-Pb (i.e. a factor of 10 above RHIC) and $> 10^{34}$ for p-p. The specific design of the magnets ('two-in-one') and the RF system allow only for symmetric beams (i.e. p-p or A-A), with the possible exception of nuclei with equal charge-to-mass ratio Z/A (e.g. d-Ca).

CERN hopes for approval of the LHC project in the course of this year (1994), and, depending on financing, LHC could start operation some time between 2002 and 2004. As a dedicated pp machine, it will run most of the time with protons at top energy. Heavy ions will however be an integral part of the initial experimental program, with typically a few weeks per year foreseen for nuclear beams; i.e. a sharing similar to the current fixed-target operations at the SPS or AGS.

3 Physics: from fixed-target to colliders

3.1 Initial conditions in nucleus-nucleus collisions

The primary aim for studying nucleus-nucleus collisions at very high energies is to understand the phase diagram (or equation of state) of strongly interacting matter — from nucleons to hadrons to partons — and the search for the quark-gluon plasma (QGP). The predictions of lattice QCD are rather firm in that a transition to the QGP should exist in the vicinity of a critical temperature T_c of ≈ 200 MeV (whether the transition is of first order, second order, or only 'rapid' is however still a matter of debate). However, whether

the QGP is actually *created* in heavy-ion collisions will depend on the dynamics of the reactions and in particular on the initial conditions of the system shortly after the collision. In order to reach the QGP, or even only to use macroscopic concepts (such as 'phase transition') and the language and variables of thermodynamics (such as 'temperature' or 'density'), three pre-conditions have to be met and experimentally verified:

- The system has to be *extended* and even 'big', i.e. its dimensions ought to be much larger than the typical scale of strong interactions ($\gg 1$ fm) and it should consist of many particles ($\gg 1$).
- In order to use thermodynamics, the system has to be in (or near) equilibrium, i.e. its *lifetime* has to be larger than the relaxation times ($\gg 1$ fm/c). Equilibrium can be reached and maintained throughout the expansion only in a sufficiently interacting system; therefore the number of collisions per particle has to be large.
- The *energy density* ϵ needed for QGP formation is predicted by QCD to be of the order of 1 - 3 GeV/fm³, equivalent to a temperature T_c of 150 - 200 MeV or a baryon density ρ_c of 5 to 10 times normal nuclear matter density.

Present results from the ongoing fixed-target program indicate that already with the light ions available now the initial conditions could indeed be favourable for QGP formation. In head-on central collisions, hundreds of particles are produced per unit of rapidity, the system expands to a size of the order of 1000 fm³, and initial energy densities are estimated to exceed 2 GeV/fm³. There are indications of 'thermodynamics' in the hadronic sector, i.e. strong rescattering and approach to equilibrium (e.g. particle abundances, shape of p_t spectra) and there are also a number of 'puzzles' which defy straightforward explanation, at least up to now (e.g. anti-hyperons, continuum lepton pairs). However, the expansion is extremely fast, with an estimated lifetime of only a few fm/c, which in addition is probably mostly spent in the cooler hadronic phase towards the end of the evolution.

While these results show that we are already now certainly *close* to the requirements listed above for QGP formation, they are by no means measured to be *sufficient*. In particular the energy density estimates are inversely proportional to the assumed 'formation time', i.e. the time needed to reach thermal equilibrium after the collision took place, and might well be smaller by a factor of the order of two. Also the lifetime of the system seems marginal, and even if a QGP is formed it might simply not live long enough for its signals to clearly stand out from the background created in later, hadronic phases of the evolution.

In order to improve on the initial conditions, or, if the QGP should be found in the current experiments with heavy projectiles, in order to explore QCD thermodynamics in different regions of the phase diagram, we have to go to higher energies. While the physics *subject* and to some extent the *observables* stay essentially the *same* from the AGS all the way to the LHC, the *object* under study will be very *different*. There are a number of *qualitative* and *quantitative* changes which will be summarized in the next three sections.

3.2 Qualitative changes

3.2.1 Baryon density

High energy density can be reached in nuclear collisions essentially along two different routes, either via 'compression' of the nuclei, i.e. increase of the net baryon density ρ as in a neutron star, or via 'heating', i.e. creation of a large number of hot (high p_t) particles (+ anti-particles) as in the early universe. In heavy-ion collisions, the incoming beam nucleons are decelerated in the course of the collision but will not be completely stopped

at very high energies. The phase space in rapidity y available for nucleons increases with $\ln\sqrt{s}$ from less than ± 2 units at the AGS to almost ± 9 units at the LHC. The phase space population after the collision will depend on the amount of 'stopping' (i.e. rapidity loss δy) suffered by the nucleons. Based on existing data, the average rapidity loss per nucleon is expected to be between $\delta y \approx 2$ and $\delta y \approx 3.5$ [5].

The highest baryon density will be reached at the energy where both target and projectile nucleons end up 'on top of each other' at midrapidity. This 'full stopping' regime could be in the energy range somewhere between AGS and SPS; its location should be known soon when baryon distributions with heavy projectiles will be available from both machines. RHIC might or might not have a baryon-free region at midrapidity, but LHC will certainly have zero net baryon density around $y_{cm} = 0$ and closely resemble the conditions prevailing in the early universe.

The physics properties of matter are predicted to be very different in the baryon-free and baryon-rich regions. While both are equally interesting, $\rho = 0$ has some practical advantages. It will eliminate one of the dynamically evolving parameters (the baryochemical potential) and therefore increase the predictive power of models (i.e. reduce the phase space for parameter tuning). It will also allow a more direct comparison with lattice QCD, the only means based on first principles to describe QCD in the non-perturbative regime, which to date can only make predictions for $\rho = 0$.

3.2.2 Energy density

The presence of a phase transition is seen in lattice QCD calculations by a rapid increase of the energy density at the critical temperature T_c . However, recent calculations indicate that the QGP deviates considerably from an ideal Stefan-Boltzmann behaviour around the transition temperature, as indicated by a sizeable difference in normalized energy density (ϵ/T^4) and pressure ($3P/T^4$) [6]. It seems likely that an 'ideal' quark-gluon plasma will exist at an energy density which is reachable, if at all, only at the LHC ($T/T_c > 1.5, \epsilon/\epsilon_c > 5$). The increase in energy density from SPS to LHC, about an order of magnitude (see below), would allow in an optimistic scenario to 'scan' across the interesting region above T_c and study the origin and nature of this effect (residual interactions, 'hadronic ghosts', ..), which is currently the subject of intense theoretical investigations.

3.2.3 Energy scale

In hadronic interactions at low energies ($\sqrt{s} < 50$ GeV), the average (minimum bias) particle production is dominated by soft, non-perturbative phenomena. The initial conditions and the dynamics in the pre-equilibrium phase, which should eventually lead to an equilibrated QGP, can therefore only be described phenomenologically and are subject to strong model dependence. At higher energies, semi-hard and hard QCD processes become more and more important ('minijets', $p_t > 2$, and jets, $p_t > 10$). While minijets are completely negligible at current fixed-target experiments, they are thought to contribute perhaps up to 50% of the total particle production at midrapidity at RHIC and more than 90% at LHC [7]. These semi-hard and hard processes can, at least in principle, be calculated in the well-tested framework of perturbative QCD. Both initial conditions as well as the early dynamics, and therefore important information such as initial energy density and formation time, are accessible to *calculations*; a vast improvement compared to the hand-waving and dimensional arguments needed at lower energies. While substantial numerical uncertainties are still present to date in parton cascade models, related to the

ill-defined boundary between 'soft' and 'hard', they are nevertheless expected to put the analysis and interpretation of nuclear collisions at the colliders on a much sounder basis.

3.3 Quantitative improvements

Besides being *different*, as mentioned in the previous paragraph, nuclear collisions at very high energies are also expected to provide a significantly *better* environment for QGP studies. Table 1 gives a summary of some of the relevant parameters for central Pb-Pb collisions at the SPS ($\sqrt{s} = 17$ GeV/n), RHIC ($\sqrt{s} = 200$ GeV/n), and LHC ($\sqrt{s} = 5.5$ TeV/n). The entries are based on a survey of a large amount of models and predictions, including some 'personal averaging'; therefore no original references are quoted. However, most of the numbers can be found in recent proceedings of the Quark-Matter conferences [8] or in [5, 9].

	dN/dy	$\epsilon[\text{GeV}/\text{fm}^3]$	$V_f[\text{fm}^3]$	$\tau_0[\text{fm}/c]$	$\tau_c[\text{fm}/c]$	τ_c/τ_0
SPS	500 - 800	1.7 - 2.7 1	$\approx 10^3$ 1	$\geq 1?$	$\leq 1?$ 1	1
RHIC	700 - 2000	2.3 - 6.8 2	$\approx 7 \times 10^3$ 7	$\leq 1?$	1.5 - 4 3	5
LHC	3000 - 8000	8.0 - 27 7	$\approx 2 \times 10^4$ 20	$\leq 0.2?$	4 - 11 7	≥ 30

Table 1: Comparison between SPS, RHIC and LHC predictions for central Pb-Pb collisions: dN/dy = charged particle multiplicity; ϵ = energy density (assuming $\tau_0 = 1$ in all cases); V_f = final volume at freeze-out; τ_0 = formation (thermalization) time; τ_c = time spend in QGP phase. For a number of these parameters, the average *relative increase* compared to the SPS is shown in a separate row (i.e. the SPS numbers are one by definition).

The charged particle multiplicity dN/dy will grow from about 500 at the SPS to perhaps up to 8000 at the LHC. The initial energy density, here calculated with a fixed formation time of $\tau_0 = 1$ fm/c (but see below), will grow proportionally by almost an order of magnitude to values much larger than the critical density ($\epsilon_c \approx 1 - 3$ GeV/fm³). The system expands to a final volume of more than 10.000 fm³, certainly huge by the standards of QCD. Because of the large particle and energy densities, collisions are more frequent and relaxation times will decrease. In particular the initial thermalization time (or 'formation time') τ_0 has been estimated in parton cascade models to be as small as a fraction of a fm/c [7], down by a factor of about five from the 'dimensional' estimate of 1 fm/c used currently at low energies. And, probably most important, the time spent in the QGP phase during the evolution (τ_c) could increase at LHC to up to 10 fm/c. This might seem to be still rather short, but it is not so much the absolute lifetime that is relevant but rather the ratio of lifetime to relaxation times, e.g. the ratio τ_c/τ_0 . With the lifetime growing and the relaxation times decreasing (the clock 'ticks faster' at high density) the net gain from SPS to LHC could be as much as a factor of 30. At LHC, the partonic phase should last for a significant, in some models even for a dominant, fraction of the overall lifetime until freeze-out. There will be more time available for the QGP to develop recognizable signals and less time for the hadronic phase to spoil them.

In summary, the system created in nuclear collisions at the colliders will be *hotter, bigger, and longer-lived*. The gain in all three variables is about an order of magnitude

when going from SPS to LHC, and still a factor of 3 - 5 when comparing RHIC with LHC. The gain is all the more significant as in current experiments we are neither far below nor far above the phase transition, and therefore already a factor two could make a big difference.

3.4 Differences in selected signals

The high c.m.s energy at the colliders will significantly increase the production cross-sections for a number of hard processes, which can serve as tools to probe the nature of the surrounding hadronic or partonic medium. The measurement of Υ production will give additional constraints on competing models describing the J/Ψ suppression, observed at current experiments, either in terms of deconfinement or hadronic interactions [10]. While Υ production rates at RHIC are marginal, they could be sufficient at the LHC but would require an optimized and large acceptance experiment. The J/Ψ is abundantly produced at both machines; however at the LHC a substantial fraction of the J/Ψ 's might come from bottom mesons, which decay long after freeze-out.

Jets will be frequently produced at both colliders. The energy loss of the fast quarks or gluons is directly proportional to the Debye screening scale and could therefore be different in a dense hadronic system and a QGP [11]. This 'jet quenching' effect could be observed as a striking difference in the shape of the p_t spectra for nucleus-nucleus and p-p collisions.

The high initial temperature associated with the high initial energy density will increase strongly the amount of thermal radiation (both in lepton pairs and direct photons) coming from a QGP. This radiation is difficult to discriminate from the background of hadronic decays, but at the colliders the signal-to-background ratio could be more favourable than at lower energies. If very high initial temperatures (> 500 MeV) should indeed be reached, even charm quark production might increase and serve as a signal in a way similar to the strangeness enhancement predicted in a QGP at lower temperatures.

One of the most promising new features at very high particle multiplicity is the possibility of measuring a large number of observables *event-by-event*: dN/dy , particle ratios (π , K, p, γ), p_t -spectra, and even size and lifetime of each 'fireball' via particle interferometry. This will allow a detailed study of correlations and non-statistical fluctuations which would be washed out when averaging over many events. Such fluctuations are, in general, associated with *critical phenomena* in the vicinity of a phase transition, and lead to local or global differences in the events, even for similar initial conditions.

4 Experiments at RHIC and LHC

The following is a very short summary of the main features of the approved experiments; a more detailed description can be found in the proceedings of the 1993 Quark Matter conference [8]. The statistical information added besides each experiment (I = number of participating Institutes, M = Members, P = Price) are for mid 1994 and only approximate.

4.1 RHIC

STAR (I = 30, M = 250, P = 65 M\$) : This experiment concentrates on hadronic probes, i.e. particle spectra and ratios, particle interferometry, and jets. Having a very large acceptance around midrapidity (2 units in y , full azimuth) and additional tracking chambers in the forward and backward hemispheres ($y = 2 - 4$), it will be able to do a detailed event-by-event analysis. It is housed in a large solenoid ($r = 2.3$, $l = 7$, $B = 0.5T$)

and employs a vertex detector, a large central TPC and additional forward/backward TPC's, an e.m. calorimeter and a large array of TOF counters.

PHENIX ($I = 45$, $M = 380$, $P = 70$ M\$) : PHENIX will measure both hadronic and e.m. signals, but concentrating on the later (i.e. dileptons, both electrons and muons, and photons). Its main components are an open axial field magnet, a two-arm lepton-photon spectrometer (with 1 steradian acceptance each) equipped with tracking chambers, a RICH and e.m. calorimeters, and a forward muon spectrometer. A part of one of the electron arms is in addition equipped with TOF counters for hadron identification.

PHOBOS ($I = 8$, $M = 40$, $P = 6$ M\$) : The physics goals of PHOBOS are to measure single particle spectra and correlations in particular at extremely low momenta ($15 < p_t < 600$ MeV/c). By the uncertainty principle, small momenta are associated with large length scales, and are therefore potentially very interesting in heavy-ion collisions. It has two very compact arms of silicon detectors for tracking, located in a 2 T dipole field on either side of the beam ($0 < \eta < 1.8$).

BRAHMS ($I = 6$, $M = 30$, $P = 6$ M\$) : This will be the only experiment which can access physics away from midrapidity. It will measure single inclusive hadron spectra both in the fragmentation region (up to $y = 4$) and around midrapidity with two movable spectrometer arms. In particular the forward arm, which has to cope with high momenta and particle densities, employs a large number of magnetic focusing elements, tracking chambers, and particle identification detectors (TOF, gas Cherenkov, and RICH counters).

4.2 LHC

ALICE ($I = 45$, $M = 300$, $P = 100$ MSF) : Being the only dedicated heavy-ion detector foreseen at the LHC, ALICE will be a general-purpose experiment, aiming at a comprehensive study of hadrons, electrons, and photons produced in the collision of heavy nuclei, up to the highest particle multiplicities anticipated at the LHC.

The central part of ALICE, which covers $(90 \pm 45)^\circ$ ($|\eta| < 0.9$) over the full azimuth, is embedded in a large magnet with a weak solenoidal field. The baseline design consists of a high-resolution inner tracking system, a cylindrical TPC, a particle identification array (TOF or RICH detectors), and a single-arm electromagnetic calorimeter. Possible upgrades under study include large acceptance electromagnetic calorimeters and a muon identification system. ALICE will trigger on central collisions with a Zero Degree Calorimeter and measure multiplicity distributions over a large fraction of the available phase space.

ATLAS, CMS ($I > 100$, $M > 1000$, $P = 400$ MSF, each) : The dedicated pp detectors at the LHC are optimized for physics differing by several orders of magnitude in event rate, multiplicity and p_t . Nevertheless, they are interested in and will take data with nuclear beams. In heavy-ion physics they aim at a small subset of high-mass, high- p_t phenomena, in particular high-mass dimuons (Υ production) and very high p_t jets. They are also well suited to measure some of the global parameters, in particular e.m. and hadronic E_t distributions.

5 Conclusions

The present exploratory program with light ions at CERN and Brookhaven has established the feasibility of high-energy ion-ion experiments with their abundant particle production. It has shown that high energy densities can indeed be obtained in these reactions and produced first hints for the onset of new, collective phenomena. The upcoming experiments with really heavy ions, both at BNL and CERN, should determine to what

extent we can actually get into a regime of thermodynamic behaviour. They should lead to baryon densities close to or even exceeding the ones in the core of neutron stars, and — if present estimates are correct — should have a chance to obtain more conclusive evidence for quark deconfinement.

The new generation of heavy-ion colliders with a centre-of-mass energy of 200 GeV/n (RHIC) or even 6 TeV/n (LHC) will bring us into the true high-energy heavy-ion regime; in particular the LHC will reach and even extend the energy range probed by cosmic-ray nucleus–nucleus collisions. Extrapolating from present results, all parameters relevant to the formation of the Quark–Gluon Plasma (QGP) will be more favourable: the energy density, the size and lifetime of the system, and the relaxation times should all improve by a large factor, at the LHC typically by an order of magnitude, compared to Pb-Pb collisions at the SPS. We should now get *average* energy densities well above the deconfinement threshold, and probe the QGP in its asymptotically free ‘ideal gas’ form. Unlike at lower energies, the central rapidity region will have nearly vanishing baryon number density, similar to the state of the early universe. It is possibly dominated in the early pre-equilibrium stage by a very dense system of semi-hard partons (‘mini-jets’), which would lead to rapid thermalization and even higher initial temperatures than in the conventional scenario.

Heavy-ion collisions at these new machines are therefore expected to provide a *very different*, and *significantly better*, environment for the study of strongly interacting matter than existing accelerators. The experimental program is taking shape and the community is looking forward to exploring the ‘wonderland’ which might open up in the years to come.

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