Eur. Phys. J. Spec. Top. (2021) 230:603–605
https://doi.org/10.1140/epjs/s11734-021-00018-y

THE EUROPEAN
PHYSICAL JOURNAL
SPECIAL TOPICS

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Editorial

Quark–Gluon plasma and heavy-ion phenomenology

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Received 10 February 2021 / Accepted 25 February 2021 / Published online 8 June 2021

Abstract Understanding the behaviour bulk matter governed by QCD elementary degrees of freedom and interaction, and studying how it turns into hadronic matter, offers challenging perspectives and touches fundamental issues in the study of QCD in its nonperturbative regime. This special issue of the European Journal of Physics: Special Topics entitled Quark–Gluon Plasma and heavy-ion phenomenology published a set of 7 papers aiming to put in perspective the important problems that are being addressed by the researchers in this area. The main motivation of this special issue is to learn the properties of the densest and hottest forms of QCD matter that one can produce in the laboratory.

Quark–Gluon plasma (QGP), the strongly interacting deconfined matter which existed only briefly in the early universe, a few microseconds after the Big Bang. The discovery and characterisation of the properties of QGP remains one of the best orchestrated international efforts in modern nuclear physics. This subject is presently actively studied at particle accelerators, where one collides heavy nuclei, moving at nearly the speed of light, to produce in the laboratory this hot and dense state of matter. The Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) are under way and future experiments are planned at Facility for Antiproton and Ion Research (FAIR) to study the collisions of heavy nuclei at relativistic energies. RHIC and LHC continue to generate a wealth of data which is being analysed to provide valuable information about the nature of the ephemeral matter thus created. This calls for a better theoretical understanding of particle properties of hot and dense deconfined matter, which reflect both static and dynamical properties of QGP.

The hot and dense matter produced in high energy heavy-ion collisions seeks theoretical tools from an interface of particle physics and high-energy nuclear physics. This requires the systematic use of QCD methods (both perturbative and nonperturbative) with a strong overlap from (i) finite temperature and density field theory, (ii) relativistic fluid dynamics, (iii) kinetic or transport theory, (iv) quantum collision theory, (v) statistical mechanics and thermodynamics and (vi) string theory.

The data accumulated over the years at BNL/RHIC and CERN/LHC have led to a truly impressive progress in our understanding of nucleus–nucleus collisions at high energy. There is clear evidence that at highest energy achieved so far, nuclear collisions deviate substantially from a naive picture based on mere superposition of independent nucleon–nucleon collisions; collective behaviour is seen. As the collision energy is tuned up the relevant degrees of freedom change, from nucleons to hadronic resonances and hadronic strings, and hints that quark degrees of freedom are playing a role have been obtained. However, while a coherent picture of collision dynamics is emerging, finding unambiguous signatures of QGP formation remains an open problem. Presumably confirmation of QGP production will not come from a unique signal, and evidences based on systematic and well focused observations will have to be accumulated. Indeed, several anomalies have been observed in the data. Among these are suppression of hadrons having large transverse momenta due to jet-quenching, suppression (and regeneration) of heavy quarkonia, elliptic (and higher order) flow, radiation of photons and dileptons.

Lattice results that the ideal gas limit are approached as temperature becomes large, but this approach is slow: typically, the energy density at $2T_c$ is about 85% of the Stefan-Boltzmann limit value. A main limitation of present lattice calculation is their inability to deal with finite chemical potential although a little progress has been made.

Collective flow of the final-state hadrons observed in ultra- relativistic heavy-ion collisions or even in smaller systems formed in high-multiplicity pp and $p/d/^3He$-nucleus collisions is one of the most important diagnostic tools to probe the initial state of the system and to shed light on the properties of the short-lived, strongly-interacting many-body state formed in these

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collisions. The evolution of initial state fluctuations leaves imprints on the power spectrum of flow coefficients. Therefore flow coefficients are a crucial probe of initial state fluctuations arising from the parton distributions of the colliding nuclei. One pedagogical review [1] is restricted to the issue of collectivity as seen in the large and small systems formed in the nucleus-nucleus, hadron-nucleus or hadron–hadron collisions at high energies. Another review [2] is restricted to the issue of initial fluctuations and power spectrum of flow anisotropies in relativistic heavy-ion collisions.

The production of J/ψ and Υ mesons in hadronic reactions occurs in part through production of higher excited $c\bar{c}$ (or $b\bar{b}$) states and their decay into quarkonia ground state. Since the lifetime of different subthreshold quarkonium states is much larger than the typical lifetime of the medium which may be produced in nucleus–nucleus collisions, their decay occurs almost completely outside the produced medium. This means that the produced medium can be probed not only by the ground state quarkonium but also by different excited quarkonium states. Since different quarkonium states have different sizes (binding energies), one expects that higher excited states will dissolve at lower temperature than the smaller and more tightly bound ground states. These facts may lead to a sequential suppression pattern in J/ψ and Υ yield in nucleus–nucleus collision as a function of the energy density. The behaviour of the heavy quarkonium states in hot strongly interacting matter was proposed as a test of its confining nature, since a sufficiently hot deconfined medium will dissolve any binding between the quark–antiquark pair. A mini-review [3] is restricted to the issue of Quarkonium propagation in QGP.

Hydrodynamic modelling of the strongly interacting medium, which successfully explains the particle spectra coming out of the medium after hadronization, indicates that the strongly interacting matter so produced achieves local thermal equilibrium within a proper time of few fermies after the collision. In the hydrodynamic evolution of the thermalized medium, transport coefficients play an important role. The evolution of the system towards equilibrium starting from an initial out of equilibrium state is determined by various transport coefficients which are important characteristics of any thermodynamic system. These transport coefficients encode the response of a thermodynamic system to external perturbations. A review [4] is included that discusses thermoelectric transport coefficients of hot and dense QCD matter.

In ultra-relativistic non-central heavy-ion collisions colliding nuclei carry a huge orbital angular momentum. Soon after the collision, a substantial portion of this orbital angular momentum gets deposited in the interaction zone which can further be transformed from initial purely orbital to the spin form. The latter can be displayed in the spin polarization of the emerging particles. A review [5] has discussed the progress made in formulation of the framework of hydrodynamics for spin polarized fluids and its applications to heavy ion collisions.

A captivating nature of non-central heavy ion collisions indicates that a very strong anisotropic magnetic field is generated in the direction perpendicular to the reaction plane, due to the relative motion of the ions themselves. The initial magnitude of this magnetic field can be very high at RHIC and LHC energies at the time of the collision and then it decreases very fast. Several novel phenomena like the chiral magnetic effect (CME) have been emerged subsequently as a result of taking the external magnetic field into consideration. In almost all of these studies two contrasting effects have attracted the main attention: magnetic catalysis (MC), which shows enhancement in the values of the quark condensate with increasing magnetic field (mostly at low temperature) and inverse magnetic catalysis (IMC), i.e., decreasing values of the condensate with increasing magnetic field (close to the transition temperature). Whereas the former is well explored and various studies have converged on its mechanism and theoretical basis, IMC appears as counterintuitive and some-what puzzling. The search for a complete theoretical understanding of the IMC effect is still ongoing and this gives us the proper platform to assess the current situation of the same through a mini-review [6].

Experiments performed at LHC and RHIC to explore the nuclear matter at high temperature have explored the corresponding region of the phase diagram extremely well. A renewed effort has started to perform experiments to explore the nuclear matter under high net-baryon density. This region of phase diagram could be explored by heavy ion collisions at relatively lower energy when overlap of interpenetrating nuclei create high net-baryon density. A medium with high net-baryon density is said to correspond to the core of neutron star which can be described using a deconfined state of quarks and gluons. Therefore, the theoretical basis and recent experimental efforts for studying the high density nuclear matter will be an important aspect. A mini-review [7] has covered this aspect.

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