PHYSICS at PHENIX, 15 years of discoveries

PHENIX and the quest for the quark–gluon plasma

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I review some of the remarkable contributions of PHENIX to the discovery and exploration of the perfectly liquid quark–gluon plasma at RHIC.

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1. Introduction

The PHENIX detector at RHIC was constructed to discover and explore the quark–gluon plasma [1], a new state of matter that was thought to be composed of individual, weakly interacting quarks and gluons. The two characteristic properties of this novel state were conjectured to be the screening of the long-range color force between quarks due to plasma effects, and the disappearance of the quark condensate that is responsible for the dynamically generated mass of light quarks in our normal world. PHENIX was designed to search for a collection of signatures that were expected to signal the transition from hadronic matter to the quark–gluon plasma, shown in Fig. 10 in Shoji Nagamiya’s article in this volume. Note that the three most characteristic phenomena associated today with the quark–gluon plasma and all discovered at RHIC—suppression of hadron emission at large transverse momentum (usually called jet quenching), strong angular anisotropy of hadron emission at low momentum (usually called elliptic flow), and enhancement of baryon relative to meson production at intermediate momenta (initially called the proton anomaly)—are all absent from this figure. That PHENIX, together with its sister collaboration STAR, succeeded in finding and exploring the quark–gluon plasma, although in many aspects the new state of matter turned out to differ substantially from expectations, is testimony both to the ingenuity of its design and to the cleverness of the scientific team that operated PHENIX and analyzed the data taken by the detector.

In order to illustrate the immense contributions of PHENIX to the discovery and exploration of the strongly coupled quark–gluon plasma, my article focuses on four topics, which are central to our current understanding of the nature of this new state of matter: Its properties of a nearly “perfect” liquid, which provides the most direct evidence of its strongly coupled nature; the novel process of hadronization by quark recombination from a bulk medium; the previously unknown phenomenon of jet quenching, which shows that quarks rapidly lose energy in the medium; and the sequential melting of the heavy quarkonium states, which is partly related to color screening in the QCD plasma. In doing so, I have done injustice to many other salient results from PHENIX, including evidence for the high temperature reached in the collision [2] (at least 300 MeV initially), for collective flow of direct
Fig. 1. Stages of a relativistic heavy-ion collision in the “standard model” currently in use. The central stage of core interest is the quark–gluon plasma phase, which can be described by viscous hydrodynamics.

photons [3] (still theoretically unexplained); measurements of low and intermediate mass dileptons [4]; as well as a great number of interesting results from d + Au collisions, such as the suppression of back-to-back hadron pairs at forward rapidity indicating parton shadowing in the Au nucleus at low $x$ [5] and from polarized p + p collisions with implications for, among other interesting aspects of QCD spin physics, the contribution of gluons to the proton spin [6].

2. Relativistic heavy-ion collisions and hot QCD matter

The quark–gluon plasma produced in nuclear collisions at RHIC [7] and LHC [8] is a new form of matter with unique properties [9]: It is relativistic, yet strongly coupled, it is a liquid that cools into a gas, it is a nearly “perfect” liquid with a shear viscosity near the quantum limit, and it thermalizes almost as fast as causality permits. Although we do not yet fully understand how this is possible, we have made progress towards developing a theoretical framework in which experimental data can be used to clarify those properties of hot QCD matter that cannot yet be reliably predicted from QCD.

Maybe the most important theoretical achievement in the past decade is that a “standard model” of the dynamics of a relativistic heavy-ion collision [10] has emerged (see Fig. 1). After a very brief period of equilibration—most likely less than 1 fm/c—the space-time evolution of the quark–gluon plasma can be described by relativistic viscous hydrodynamics with an exceptionally low shear viscosity. After cooling below $T_c$ the matter hadronizes. The subsequent expansion can be described by microscopic Boltzmann dynamics of a multi-component hadron gas until the gas becomes so dilute that all interactions cease and the hadron ensemble freezes out kinetically. The color glass condensate model of gluon saturation in the nuclear wave function at small $x$ has proven to be remarkably successful in predicting the initial energy and entropy deposition in the nuclear collision, and thus the initial conditions of the hydrodynamic evolution. This has made it possible to predict the bulk behavior over a wide range of collision energies and for a wide range of collision systems without arbitrary fit parameters. This remarkable achievement has been possible by the success of hydrodynamics during the dense phase of the collision where no microscopic transport approach could be reliable.

Lattice gauge theory has made impressive progress on the calculation of static thermodynamic properties of baryon symmetric QCD matter. The equation of state at $\mu_B = 0$ for physical quark masses is now known with a precision that far exceeds that required in viscous hydrodynamics calculations [11]. The quasi-critical temperature where susceptibilities related to chiral symmetry peak has been determined to lie at $T_c \approx 155$ MeV. The failure of resummed thermal perturbation theory [12] to describe temperatures below $\sim(1.5–2)T_c$ indicates that QCD matter in the range explored in
nuclear collisions at RHIC is highly nonperturbative and strongly coupled, making its description theoretically challenging and interesting.

There are many similarities between the evolution of the matter produced in a relativistic heavy-ion collision (the “little bang”) and the expansion of the matter-filled early universe (the “Big Bang”). In both expansions the initially imprinted quantum fluctuations propagate into macroscopic fluctuations in the final state via the acoustic and hydrodynamic response of the medium. In the Big Bang, the final temperature fluctuations probe the bulk dynamics; photons provide for penetrating probes, and light nuclei serve as chemical probes. In the little bang, the fluctuations in the final flow profile probe the expansion dynamics, photons and jets provide for the penetrating probes, and the various hadron species serve as the chemical probes. In each collision event the information that can be gathered from these probes is limited by the finite particle number; the advantage of the heavy-ion experiments is that data can be gathered from many millions or billions of collisions.

3. Probing QCD matter

It is worthwhile asking which intrinsic properties of the quark–gluon plasma we can hope to determine experimentally and from which observables. A non-exhaustive list includes [13]:

- The equation of state of the matter, given by relations among the components of the energy–momentum tensor $T_{\mu\nu}$ at equilibrium and their temperature dependence, is reflected in the spectra of emitted particles. As mentioned, lattice QCD is nowadays able to compute these quantities reliably.

- Transport coefficients of the quark–gluon plasma, especially the shear viscosity $\eta$, the coefficient $\hat{\eta}$ governing the transverse momentum diffusion of a fast parton (often called the jet quenching parameter), the coefficient of linear energy loss $\hat{\epsilon}$, and the diffusion coefficient $\kappa$ of a slow heavy quark, are related to the final-state flow pattern and to the energy loss of fast partons initiating jets. Lattice gauge theory presently cannot reliably calculate these dynamical quantities.

- The static color screening length $\lambda_D$ (the inverse Debye mass $m_D$) governs the dissolution of bound states of heavy quarks in the quark–gluon plasma. This static quantity can be reliably calculated on the lattice.

- The electromagnetic response function of the quark–gluon plasma is reflected in the emission of thermal photons and lepton pairs. This dynamical quantity is difficult to calculate on the lattice, but moderate progress has been made recently.

All but the last of these properties are microscopically related to correlation functions of the gluon field, implying that the associated experimental observables are mostly sensitive to the gluon structure of the quark–gluon plasma (QGP). On the other hand, much more is known theoretically from lattice simulations about the quark structure of hot QCD matter, because it is much easier to construct operators from quark fields that can be reliably calculated. Lattice calculations and heavy-ion experiments are thus to a certain degree complementary. The presence of jets in heavy-ion collisions at RHIC and LHC tells us that at high virtuality $Q^2$, the QGP is weakly coupled and has quasiparticle structure. The strong quenching of these jets indicates that the QGP becomes more strongly coupled at smaller virtuality scales, the quantitative aspects of this evolution being still unclear. On the other hand, the collective flow properties of the matter produced in the collisions, indicating liquid behavior, tell us that at thermal momentum scales the quark–gluon plasma is strongly coupled. The future heavy-ion physics will focus on answering the question, at which virtuality scale does the transition
between strong and weak coupling occur and does the quark–gluon plasma contain any partonic quasiparticles at the thermal scale?

4. The perfect liquid

Hydrodynamics is the effective theory of the transport of energy and momentum in matter on long distance and time scales. In order to be applicable to the description of the quark–gluon plasma created in relativistic heavy-ion collisions, which forms tiny, short-lived droplets of femtometer size, the hydrodynamic equations must be relativistic and include the effects of (shear) viscosity. The causal relativistic theory of a viscous fluid is based on the framework of the Müller–Israel–Stewart formulation of second-order hydrodynamics, which includes relaxation effects for the dissipative part \( \Pi^{\mu\nu} \) of the stress tensor \( T^{\mu\nu} \). Schematically, the equations have the form [14]

\[
\partial_\tau T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu + \Pi^{\mu\nu} \quad (1)
\]

\[
\tau \Pi(d\Pi^{\mu\nu}/d\tau) + \Pi^{\mu\nu} = \eta(\partial^\mu u^\nu + \partial^\nu u^\mu - \text{trace}). \quad (2)
\]

The quantity that most directly controls the behavior of the expanding fluid at high energies, even more so than its equation of state, is the ratio of the shear viscosity \( \eta \) to the entropy density \( s \). The quantity \( \eta/s \) is the relativistic generalization of the well known kinematic viscosity. In kinetic theory \( \eta \) is proportional to the mean free path of particles in the fluid, which is inversely proportional to the transport cross section. This places a unitarity limit on how small \( \eta \) can become under given conditions. An interesting consequence of this observation is that the quantity \( \eta/s \) has a lower bound of the order of 0.08 (in units of \( \hbar \)). The existence of such a bound was conjectured three decades ago [15], but it was quantitatively derived only recently using the technique of holographic gravity duals, the AdS/CFT duality [16]. It has been conjectured that \( \eta/s \geq (4\pi)^{-1} \) for any sensible quantum field theory [17].

The holographic bound is one aspect of a deep and fruitful relationship between the formation of black holes and thermalization in strongly coupled quantum field theories, which associates thermalization with the formation of an event horizon and maps viscous hydrodynamics onto the information absorbing dynamics of black hole horizons [18]. Although a gravity dual for QCD is still unknown, the AdS/CFT duality has made it possible to rigorously compute thermalization and the approach to hydrodynamic behavior in strongly coupled gauge theories with some similarity to QCD. This relationship has recently been employed to develop a schematic start-to-finish model of a relativistic heavy-ion collision that begins with the collision of two nuclei modeled as gravitational shock fronts to the dispersion of free streaming final-state hadrons [19].

The experimental handle for the determination of \( \eta/s \) is the azimuthal anisotropy of the flow of final-state particles in off-central heavy-ion collisions, where the nuclear overlap region is elongated in the direction perpendicular to the reaction plane. Hydrodynamics converts the anisotropy of the pressure gradient into a flow anisotropy, which sensitively depends on the value of \( \eta/s \). The average geometric shape of the overlap region in symmetric nuclear collisions is dominated by the elliptic eccentricity, resulting in an elliptic flow anisotropy characterized by the second Fourier coefficient \( v_2 \). Event-by-event fluctuations of the density distribution within the overlap region generate higher Fourier coefficients for the initial geometry and final flow, encoded in higher Fourier coefficients \( v_3, v_4, \) etc. Their measurement is analogous to the mapping of the amplitudes of multipoles in the thermal fluctuations of the cosmic background radiation.

The precise results of such an analysis of event-by-event fluctuations of the flow distribution are sensitive to the quantum fluctuations in the energy density of the colliding nuclei, in particular, to their
Density fluctuations in the transverse plane in a sample collision event. Left panel: fluctuations at the nucleonic scale. Right panel: fluctuations at the partonic scale.

Fourier components of collective flow, \( v_n(p_T) \), for Au + Au collisions at the top RHIC energy in comparison with a viscous hydrodynamics calculation [20].

Fluctuations on the partonic scale are of shorter range and more violent; they require a somewhat larger shear viscosity to be smoothed out over the course of the collision. The most complete study of this kind to date [20] starts from the quantum fluctuations of soft gluons in the colliding nuclei, evolves them for a brief period using classical Yang–Mills equations, and then inserts the fluctuating energy density distribution into viscous hydrodynamics. The calculated momentum-dependent anisotropies \( v_i(p_T) \) are then compared with the measured values. Figure 3 shows the comparison with the PHENIX data [21] for Au + Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV. The conclusion of this study is that the value of \( \eta/s \), averaged over the thermal history of the collision, at the top RHIC energy is 0.12, whereas the corresponding value for Pb + Pb collisions at LHC (\( \sqrt{s_{NN}} = 2.76 \) TeV) is 0.20. Each of these values has systematic uncertainties conservatively estimated as a factor of two. Figure 4, which compares these values with those of some macroscopic fluids, shows that the quark–gluon plasma at temperatures near \( T_c \) is a nearly “perfect” fluid, indeed.

5. Quark recombination

If the term quark–gluon plasma is to truly apply to the hot QCD matter created in heavy-ion collisions, it must contain excitations with the quantum numbers of quarks and gluons that are not confined into color singlet objects. One would then expect that hadrons are formed by recombination of quarks when the matter cools back down below \( T_c \). This was an underlying assumption of the
Fig. 4. Deduced average value of the ratio $\eta/s$ for heavy-ion collisions at RHIC and LHC in comparison with the values for some macroscopic fluids.

“quark-chemistry” models [22,23] that predicted a strongly enhanced production of hadrons containing multiple strange quarks as a characteristic signature of the formation of a quark–gluon plasma. While this enhancement—realized in the form of complete chemical equilibration of all hadrons containing $u$, $d$, and $s$ valence quarks—is clearly observed in Au + Au collisions at RHIC, its role as a quark–gluon plasma signature has been questioned on the basis of the fact that it is already present at the lower collision energies explored at the SPS and also occurs to a lesser degree in proton–nucleus collisions. Recent results from the beam energy scan at RHIC, which clearly indicate the presence of partonic collective behavior at the top SPS energy domain, and from p + Pb collisions at LHC and d + Au collisions at RHIC, which are indicative of collective flow, have lessened the power of these questioning arguments.

The quark recombination idea received a powerful boost early in the RHIC physics program from particle-identified spectra measured by PHENIX [24]. These showed a surprising enhancement in the ratio of protons to pions in the transverse momentum range $p_T = 1–3$ GeV/$c$. This became known as the “proton anomaly”. The data also showed an apparent deviation from the mass hierarchy of the elliptic flow $v_2(p_T)$ of identified hadrons in the same momentum range [25]. Hydrodynamics predicts that heavier hadrons should exhibit a smaller flow anisotropy at the same momentum $p_T$, but PHENIX data showed that the $v_2$ of protons and antiprotons exceeds that of pions for $p_T > 2$ GeV/$c$. Quark recombination explains both experimental findings. If the collective transverse flow is carried by quarks and these quarks recombine at the moment of hadronization, then protons carrying three valence quarks receive a larger transverse momentum boost from the collective expansion than pions, which contain only two valence quarks. The same argument applies of course to all baryons and mesons. The application of the sudden recombination model relies on the insight that valence quarks coalescing into a hadron with a few GeV/$c$ transverse momentum leave the quark–gluon plasma at nearly the speed of light and thus make a sudden transition from the dense matter into the surrounding vacuum.
Fig. 5. Proton-to-pion ratio and hyperon-to-kaon ratio in Au + Au collisions as a function of transverse momentum in comparison with two quark recombination models (from R. J. Fries [28]).

Calculations show that the mechanism of quark recombination from a thermal quark–gluon plasma [26,27] with the transverse flow generated by the expansion at RHIC exceeds the contribution to hadron formation by parton fragmentation for transverse momenta $p_T < 3–4 \text{ GeV}/c$, precisely the regime where the proton puzzle was observed. Using reasonable values for the expansion velocity when the cooling matter reaches $T_c$ leads to quantitative predictions for the transverse momentum dependence of the proton-to-pion ratio and the elliptic flow of protons and pions, which reproduce the essential features of the PHENIX data (see Figs. 5 and 6). A particularly interesting relationship is obtained for the elliptic flow spectrum of different hadron species containing $n$ valence quarks [29]: $v_2(p_t) \approx n v_2^q(p_T/n)$, which relates the elliptic flow spectrum of mesons ($n = 2$) to that of baryons ($n = 3$). At low transverse momenta, where mass effects are not negligible, it has been conjectured that the transverse momentum $p_T$ should be replaced by the transverse kinetic energy $m_T = \sqrt{p_T^2 + m^2}$. With this heuristic substitution, the valence quark scaling of elliptic flow seems to work over the entire range of available data [30] (see Fig. 6).
6. Jet quenching

Energetic partons, the precursors of jets, lose energy while traversing the quark–gluon plasma either by elastic collisions with the medium constituents or by gluon radiation. At high energies, radiation should dominate; collisional energy loss is expected to be important for intermediate energy partons and for heavy quarks. Each mechanism is encoded in a transport coefficient, $\hat{e}$ for collisional energy loss and $\hat{q}$ for radiative energy loss [31]:

$$\left(\frac{dE}{dx}\right)_{\text{coll}} = -C_2\hat{e}, \quad \left(\frac{dE}{dx}\right)_{\text{rad}} = -C_2\alpha_s\hat{q}L,$$

where $L$ denotes the path length traversed in matter and $C_2$ is the quadratic Casimir of the fast parton. The value of $\hat{q}$ is given by the transverse momentum broadening of a fast light parton per unit path length. The evolution of a jet in the medium, shown schematically in Fig. 5, is characterized by several scales: The initial virtuality $Q_\text{in}$ associated with the hard scattering process; the transverse scale at which the medium appears opaque, also called the saturation scale $Q_\text{s}$; and the transverse geometric extension of the jet, $r_\perp$. Those components of the jet, for which $r_\perp > Q_\text{s}^{-1}$, will be strongly modified by the medium. This means that the core of the jet will remain rather inert, except for an overall energy attenuation of the primary parton, but strong modifications are expected at larger angles and soft components of the jet characterized by a small value of the fragmentation variable $z \ll 1$. Figure 7 presents a schematic sketch of these features of jet modification. Because of its small acceptance, PHENIX has focused on measurements of the inclusive suppression of leading hadrons [33], encoded in the ratio $R_{AA}$, and two-particle correlation measurements. One particularly interesting measurement is that of the modification of the fragmentation function of a quark emitted opposite to a tag photon [34] (see Fig. 8).
Fig. 9. Nuclear suppression factor $R_{AA}$ for neutral pions emitted in Au + Au collisions at the top RHIC energy in comparison with theoretical calculations.

Fig. 10. Temperature-scaled jet quenching parameter $\hat{q}$ deduced from measurements of inclusive hadron suppression at RHIC and LHC.

The “jet quenching parameter” $\hat{q}$ can be determined by analyzing the inclusive suppression of leading hadrons in A + A collisions, compared with the binary-collision-scaled p + p data. The suppression factor $R_{AA}$ is of the order of 0.2 for neutral pions of transverse momenta in the range of 5–20 GeV/c in Au + Au at RHIC (see Fig. 9). The particle independence of the suppression factor, which is expected when the leading parton fragments outside the medium, is confirmed by PHENIX measurements of the suppression of $\eta$-mesons [35]. A systematic analysis of available data from RHIC and LHC was recently published by the JET Collaboration [32] (see Fig. 10). It suggests that the temperature-averaged value of $\hat{q}$ grows slightly less than linearly with the matter density between RHIC and LHC. This confirms the notion that the quark–gluon plasma formed at higher temperatures is somewhat less strongly coupled. A determination of the temperature dependence of $\hat{q}/T^3$ will require high-statistics jet quenching measurements at several energies, from somewhat below the top RHIC energy to the highest energies accessible at the LHC.

The RHIC and LHC jet quenching data have clearly ruled out speculations that the jet could be strongly coupled to the medium. The perturbative theory of jet evolution works, with appropriate
medium modifications, confirming that partons with energies of 10 GeV or more behave like quasi-particles in the quark–gluon plasma. The central remaining question is at which momentum scale partons become strongly coupled and lose their quasiparticle nature. This must be the case at thermal momenta (below 1 GeV) as evidenced by the “perfect” liquid behavior. Improved theoretical tools and precisely resolved jet measurements at RHIC will be needed to identify the transition scale between weak and strong coupling. This motivates the proposed sPHENIX upgrade of the PHENIX detector.

7. Quarkonium melting

Bound states of heavy quarks, especially quarkonia ($J/\psi$, $\psi'$, the $\Upsilon$ states), are sensitive to the distance at which the color force is screened in the quark–gluon plasma. Several mechanisms contribute to nuclear modification of the quarkonium yield (see Fig. 11). At sufficiently high temperatures the screening length becomes shorter than the size of the quarkonium radius and the $Q\bar{Q}$ bound state “melts”. Since the radii of the quarkonium states vary widely—from approximately 0.1 fm for the $\Upsilon$ ground state to almost 1 fm for $\psi'$—the sequential melting of these states could enable at least a semi-quantitative determination of the color screening length [36]. The static screening length, which is relevant for heavy quarks, can be calculated on the lattice. However, it has become well understood in recent years that static color screening is only part of the picture of quarkonium melting, and that quarkonium yields can not only be suppressed by the action of the medium, but also enhanced by recombination [37,38], if the density of heavy quarks and antiquarks is large enough. An important loss mechanism is ionization by absorption of thermal gluons. This mechanism gains in importance as the binding energy of a quarkonium state is lowered by color screening.

Recombination of a heavy $Q\bar{Q}$ pair can occur at or near hadronization, similar to the sudden recombination mechanism that is thought to be responsible for the valence quark scaling of the identified particle elliptic flow. The yield of quarkonia formed in this manner grows quadratically with the heavy-quark yield. Recombination of charm quark pairs into $J/\psi$ and $\psi'$ is thus expected to be much more frequent at LHC energies than at RHIC. This expectation is confirmed by a comparison of the centrality dependence of $J/\psi$ suppression observed by PHENIX in Au + Au at RHIC [39] and by ALICE in Pb + Pb at LHC [40] (see Fig. 12). The LHC data show less suppression in central collisions than the RHIC data, although the significantly hotter matter produced at LHC energy must surely be more effective in melting the $J/\psi$ state.
Fig. 12. Nuclear suppression factor $R_{AA}$ for $J/\psi$ as a function of collision centrality in $Au + Au$ at RHIC (red) and $Pb + Pb$ at LHC (blue). The fact that the charmonium ground state is less suppressed at LHC energy is clear evidence for a new production mechanism, most likely $c\bar{c}$ recombination.

8. Summary

The PHENIX detector has proved to be an extraordinarily powerful instrument for the quantitative exploration of hot QCD matter. The data gathered by it over more than a decade have helped to establish beyond reasonable doubt that hot QCD matter is a strongly coupled quark–gluon plasma with the characteristics of a near-perfect fluid. Among many discoveries made by the PHENIX Collaboration, the discovery of the novel phenomenon of jet quenching stands out, but many other measurements made by PHENIX have contributed to our present insight into the remarkable properties of the quark–gluon plasma.

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