The Fluid Nature of Quark-Gluon Plasma

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Abstract

Collisions of heavy nuclei at very high energies offer the exciting possibility of experimentally exploring the phase transformation from hadronic to partonic degrees of freedom which is predicted to occur at several times normal nuclear density and/or for temperatures in excess of ~ 170 MeV. Such a state, often referred to as a quark-gluon plasma, is thought to have been the dominant form of matter in the universe in the first few microseconds after the Big Bang. Data from the first five years of heavy ion collisions of Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC) clearly demonstrate that these very high temperatures and densities have been achieved. While there are strong suggestions of the role of quark degrees of freedom in determining the final-state distributions of the produced matter, there is also compelling evidence that the matter does *not* behave as a quasi-ideal state of free quarks and gluons. Rather, its behavior is that of a dense fluid with very low kinematic viscosity exhibiting strong hydrodynamic flow and nearly complete absorption of high momentum probes. The current status of the RHIC experimental studies is presented, with a special emphasis on the fluid properties of the created matter, which may in fact be the most perfect fluid ever studied in the laboratory.

Key words: perfect fluid, perfect liquid, quark-gluon plasma, QGP, RHIC, ultra-relativistic heavy ion collisions
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1. Introduction

Experiments at Brookhaven National Laboratory's Relativistic Heavy Ion Collider have achieved their goals of creating and characterizing a new state of matter, which has come to be known as the strongly-coupled Quark-Gluon Plasma (sQGP). The striking discoveries and their implications from the initial three years of RHIC operations were extensively detailed in "white papers" from the four experiments- BRAHMS[1], PHENIX[2], PHOBOS[3] and STAR[4] which, together with understanding developed in previous theoretical work[5], led to the announcement[6] of the "perfect liquid" behavior of the matter produced at RHIC.

Since that time, analysis of substantially larger data sets has provided additional experimental evidence in support of those statements. Perhaps more importantly, further discoveries have produced both new insights and new puzzles which demand more detailed experimental and theoretical investigation. Following a brief review, a sampling of these new experimental results and their implications will be presented. Due to length restrictions, the topics covered, while adhering closely to those presented at the conference, will be even more selective than the author's talk[7], to which the reader is referred for supporting material.

2. The Initial RHIC Discoveries

During the initial phase of RHIC operations it was quickly established that the relative abundances and spectra of the particles produced in Au+Au collisions at RHIC energies (initially $\sqrt{s_{NN}} = 130$ GeV in RHIC Run-1, followed by 200 GeV collisions in RHIC Run-2 in 2001-2) were consistent with emission from a thermally equilibrated source[8,9,10,11] with a chemical freeze-out temperature $T_0 \sim 170$ MeV and a low baryon chemical potential in a manner consistent with trends seen in lower energy collisions[12]. However, analysis of the yields as a function of the angle ϕ with respect to the reaction plane of the collision revealed the presence of strong "elliptic" flow[13] (Figure 1), parameterized in terms of the Fourier coefficient v_2 in the expansion

$$\frac{dn}{d\phi} \sim 1 + 2v_2(p_T)\cos 2\phi + \cdots \tag{1}$$

(here v_2 is also regarded as a function of the transverse momentum $p_T \equiv |\vec{p}|\sin\theta$ of the emitted particle). In contrast to behavior at lower energies, the strength of this angular modulation, and its systematic variation with the mass of the produced particles, was found for the first time to be consistent with the solutions of *ideal* (non-viscous) hydrodynamics. We will return to the importance of this observation in Section 3.4.

The discovery of "jet quenching" at RHIC[14]- a strong suppression in the production of high p_T particles in nuclear collisions relative to the expected yield based on p+p collisions, also stands in stark contrast to results at lower energy, where particle production at high transverse momentum is enhanced rather than suppressed in nucleus-nucleus collisions (Figure 1). Expressed in terms of the ratio $R_{AA}(p_T)$, defined as

$$R_{AA}(p_T) \equiv \frac{Yield\ \ in\ \ Au+Au\ \ events}{Scaled\ \ Yield\ \ in\ \ p+p\ \ events} \quad , \tag{2}$$

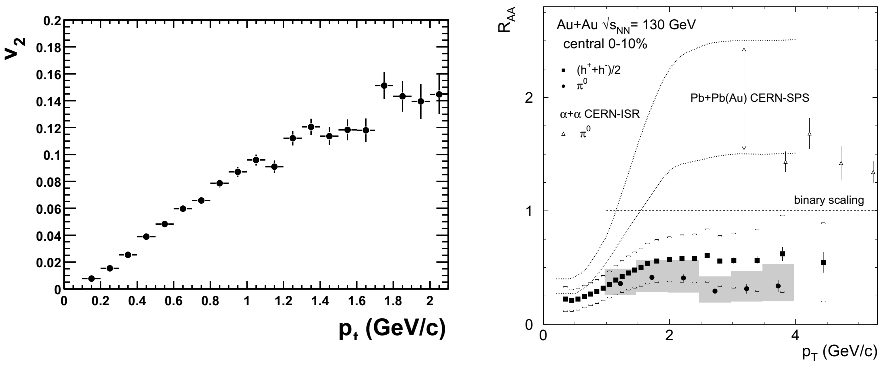

Fig. 1. The discovery in $\sqrt{s_{NN}} = 130\ GeV/c$ Au+Au collisions at RHIC of strong elliptic flow (left, [13]) and of jet quenching (right, [14]). Left: The flow strength parameter v_2 versus transverse momentum p_T for charged particles produced at mid-rapidity in minimum bias collisions. Right: The suppression factor R_{AA} versus p_T for π^0's (circles) and charged particles (squares) in central collisions, compared to lower energy results.

where the denominator consists of the p+p yield scaled, as per *perturbative* QCD (pQCD) by the equivalent parton+parton flux from a Au+Au collision, the suppression was found to be as large as a factor of 5 in the most central events at $\sqrt{s_{NN}} = 200$ GeV[15,16]. In a curious inversion, the realization[17] that detailed information on the opacity and other properties of a dense thermal QCD system could be obtained using the very deviations from pQCD expectations *absent interactions in a produced medium* spurred development and application of a sophisticated technology[18,19,20,21,22,23] making possible "tomographic" studies of the produced matter. The observed quenching was consistent with parton energy loss rates ~ 15 times higher than in cold nuclear matter[27], and demanded an initial matter density of order 100 times that of normal nuclear matter[24,25,26]. A striking observation in support of these estimates was the disappearance of the "away-side" jet partner in Au+Au collisions[29] (Figure 2), indicating that the matter density was essentially opaque to high-p_T partons and that the observed high transverse momentum "trigger" particles were dominated by surface emission.

Three other early key developments can only be briefly mentioned here:

- The interpretation of the jet-quenching results was bolstered by reliance on *in situ* measurement of baseline (p+p) and control (d+Au) data. Comparison of the p+p data to theoretical calculations established the quantitative reliability of pQCD calculations at RHIC energies[30]. The demonstration that suppression effects were absent in d+Au collisions[31,32,33,34] provided crucial evidence that the quenching observed in Au+Au collisions was due to parton propagation in a dense thermal environment, rather than to modifications of the nuclear wave function.

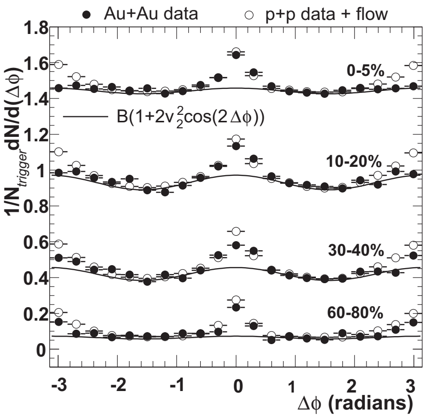

Fig. 2. Away-side jet disappearance: the angular distribution of high p_T (> 2 GeV/c) particles associated with a trigger particle $p_T^{trig} \in [4, 6]$ GeV/c measured in p+p (open circles) and Au+Au (filled circles) collisions as a function of centrality (expressed as the percentage of the total cross section). Taken from Ref. [29].

- While both thermal and hydrodynamic models worked with unprecedented accuracy to describe the final state distribution of particles at RHIC, the actual abundances were low compared to pre-RHIC expectations[35]. Both the low value of the charged-particle density[36] and its systematic variation with centrality and energy[37,40,38] were described quantitatively in a model incorporating gluon saturation in the initial nuclear wave-function[39]. Subsequent developments have shown the importance of this observation for establishing reliable initial conditions for hydrodynamic calculations at RHIC energies[41].
- The surprising observation that baryon and anti-baryon yields were comparable to those of mesons at intermediate (4-6 GeV/c) transverse momenta[42] was not understandable in terms of standard thermal production models with a chemical freeze-out condition. However, this so-called "baryon anomaly" found a natural explanation in recombination models[43,44,45,46,47], which in a sufficiently dense partonic medium will favor the creation of final-state hadrons via *coalescence* of lower-momentum quarks drawn from a thermal spectrum over the *fragmentation* of a higher-momentum parton to a hadron with lower momentum. The successes of this mechanism, which clearly requires partonic degrees of freedom in a dense medium, led the authors of Ref. [44] to note " . . . our scenario requires the assumption of a thermalized partonic phase characterized by an exponential momentum spectrum. Such a phase may be appropriately called a quark-gluon plasma."

3. More Recent Developments

The steady improvement in RHIC luminosity[1] and in experimental data-taking capabilities has led to an increase approaching three orders of magnitude in integrated luminosity over that of the initial (Run-1) discovery period. It is not possible to enumerate, much less fully explore, all of the results obtained from this cornucopia of data. (See Ref. [48] for a recent review.) Instead, focus will be applied to a very limited subset of topics most relevant to future investigations that seek to characterize the properties of the medium.

3.1. *Direct Photon Measurements*

While the absence of suppression effects observed in d+Au collisions also suggested that the pQCD scaling methodology was well-controlled, it obviously did not directly demonstrate that this was also the case for Au+Au collisions. High energy ($p_T >\sim 3$ GeV/c) direct photons, while experimentally very difficult to separate from the copious background from π^0 and η decays, do provide the desired calibration, since their production rate is proportional to the initial parton+parton flux and they interact only very weakly with medium. The measurement of R_{AA} for direct photons in Au+Au collisions[49], which requires tight control of experimental systematics over several orders of magnitude, clearly establishes the validity of the assumed scaling techniques.

The effort now turns to ever-increasing precision in measuring and normalizing the observed photon yield, in search of predicted $\sim 20\%$ effects due to the interplay of isospin, fragmentation, shadowing and energy loss[50,51]. An important experimental development is the first proof-of-principle results on gamma-hadron correlations[52,53], which are a necessary precursor to the long-desired goal of using direct photons as a calibrated tag to measure precisely jet energy loss in nuclear collisions[54].

3.2. *Detailed Investigations of Hydrodynamic Behavior*

The consistency of the RHIC experimental data on elliptic flow with calculations based on ideal hydrodynamics, together with the jet quenching results demonstrating the extraordinary density of the matter, resulted in the descriptor "perfect liquid", in analogy with usage of "perfect fluid" in general relativity to denote a fluid that is completely isotropic to co-moving observers[55] (thereby implying zero viscosity and perfect heat conductivity). A great deal of experimental and theoretical work is underway to determine the kinematic regime in which this description (approximately) applies, and to quantify the transport properties of the near-perfect medium. A highly restricted sample of these efforts is presented in this section.

3.2.1. *Scaling Behavior of Elliptic Flow*

As noted in Section 2, data from RHIC show that the detailed dependence of the elliptic flow parameter $v_2(p_T)$ on particle mass is consistent with calculations based on ideal

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[1] RHIC now routinely operates at more than 4 times its design luminosity of $2 \times 10^{26}\text{cm}^{-2}\text{s}^{-1}$ for Au+Au collisions.

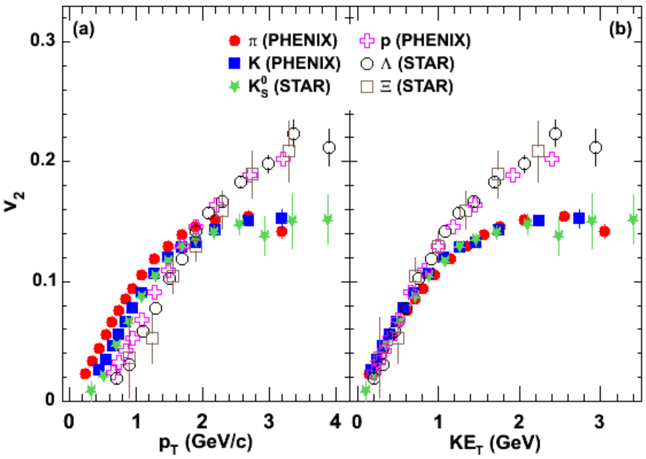

Fig. 3. The scaling[57] with transverse kinetic energy KE_T of PHENIX and STAR[58,59] data for the elliptic flow parameter $v_2(p_T)$ for various particles.

hydrodynamics. This observation has been considerably sharpened by the discovery of a family of exact scaling solutions to ideal hydrodynamics[56] which show a universal scaling behavior of the elliptic flow parameter v_2 upon a reduced kinematic variable. Near mid-rapidity, this variable reduces (approximately) to "transverse kinematic energy" K$E_T \equiv \sqrt{m^2 + p_T^2} - m$. Indeed, the mass-dependent structure in $v_2(p_T)$ does fall on such a scaling curve[57], as shown in Figure 3. While the scaling behavior appears limited to K$E_T <$ 1.0 GeV, note that a) more than 98% of the produced particles are in this domain and b) the larger values of KE_T correspond to a regime where hard scattering may already play a role, potentially explaining the observed deviations from hydrodynamic behavior (however, on this point see further discussion in Sections 3.4 and 3.5). With these mild caveats, the scaling behavior shown in Figure 3 is consistent with a key prediction of ideal (inviscid) hydrodynamics for bulk particle production at RHIC.

3.3. *Bounding Perfection*

Taken at face value, the good agreement between the experimental data and inviscid hydrodynamics supports Landau's observation[60] that the very conditions for the applicability of hydrodynamics to nuclear systems (a mean free path much smaller than the system size) necessarily lead to a negligible viscosity. One of the most fascinating developments in recent years has been the conjecture[61] that there may be a fundamental bound from below on the value of viscosity, that is, for any thermal fluid, the uncertainty principle requires a non-zero viscosity. More precisely, the conjecture states that the ratio of viscosity η to entropy density s must satisfy

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi} \quad . \tag{3}$$

Particularly intriguing is the origin of the bound. While the simple dependence on $\hbar$ implies it is a strictly quantum mechanical result, and while estimates based on uncertainty relations have been made[62,63], the first explicit derivation of a numerical value for the bound was obtained for a maximally supersymmetric Yang-Mills theory via the AdS/CFT correspondence[64]. By exploiting a duality between (string) quantum gravity in a higher-dimensional Anti de Sitter(AdS) spacetime and conformal field theory (CFT) on the boundary of AdS, strongly coupled problems in the field theory are mapped onto weakly coupled, and thus semi-classical, gravity calculations in the bulk. As a result, the entropy density in the field theory is dual to the entropy of extended black branes, and the viscosity is dual to graviton absorption by the brane. While the supersymmetric conformal field theory would appear to be far removed from non-conformal non-supersymmetric ordinary QCD, arguments have been made that for thermal QCD systems somewhat above the critical temperature may at least qualitatively be regarded as a conformal theory in which the only dimensionful quantity is the temperature[66,67].

3.4. *Approach to Perfection*

Given the (conjectured) existence of a bound on η/s, it is only natural to ask how closely does the QGP fluid produced at RHIC approach the bound. The most natural approach is not to separately extract η and s from the data, but instead to note that damping (of sound, flow, etc.), at temperature T and zero chemical potential is proportional to $\frac{\eta}{sT}$. This was the basis for a first schematic calculation[68] that was instrumental in developing the case for ideal fluid behavior at RHIC[69]. Since then, somewhat more sophisticated analyses coupled with greatly improved data sets have led to first attempts to determine the range of allowed values for η/s in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC. Estimates based on the magnitude of elliptic flow indicate $\eta/s = (1.1 \pm 0.2 \pm 1.2)\frac{1}{4\pi}$[70] and $\eta/s = (1.9 - 2.5)\frac{1}{4\pi}$[71] , an analysis of the damping of p_T fluctuations gives $\eta/s = (1.0 - 3.8)\frac{1}{4\pi}$[72], while a simultaneous analysis of the observed energy loss and flow of heavy quarks produces $\eta/s = (1.3 - 2.0)\frac{1}{4\pi}$[73]. These different methods provide consistent support for the conclusion that the produced matter is within a factor of 2-3 of the conjectured bound, that is, has a viscosity to entropy density ratio lower than any other known fluid. The above values are comparable to, although generally smaller than, the value $\eta/s \sim 0.5 \sim 6\ (\frac{1}{4\pi})$ obtained from a study of the breathing modes of a gas of cold trapped ^{6}Li atoms at the unitary limit[74], which exhibits a viscosity to entropy density ratio even lower than liquid helium near the lambda point[61].

3.5. *Reaction of the Medium*

While the jet energy loss phenomena would appear to be strictly in the domain of perturbative QCD, and therefore seemingly divorced from the bulk flow behavior at low transverse momenta, a fascinating connection between these effects has emerged in recent studies[75]. The disappearance of away-side jets shown in Figure 2 strongly suggests that the *directed* energy in a high momentum transfer parton scatter is absorbed by the *medium.* A sufficiently dense and strongly coupled medium, while thermalizing that energy, must nonetheless conserve momentum. One method for doing so is via the

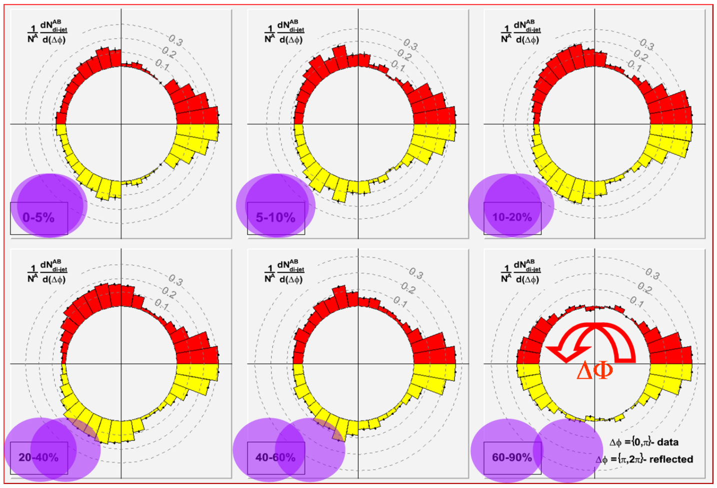

Fig. 4. A polar representation of the data from Ref. [78], showing the development of strongly modified away-side jet response as a function of centrality.

development of a shock or "Mach" cone[76,77], i.e., the transfer of the directed energy of an away-side jet into a collective excitation of lower momentum particles in the medium. Indeed, after carefully taking into account the modulation of the background due to elliptic flow, both published data[78,79] and more recent preliminary results[80,81,82] provide support for this hypothesis from an examination of the angular correlations of away-side particles in the range ~ 1 GeV/c $< \mathrm{p_T} <\sim 2$ GeV/c.

Further work, both experimental and theoretical, is required to determine if the clearly observed away-side jet distortions at low p_T are in fact Mach cones. Experimentally, more detailed analysis of both 2 and 3-particle correlations in more extensive data sets is underway. Theoretically, moving from a bulk description of hydrodynamic shock fronts to a more microscopic view of the energy-momentum transport is very challenging. Here too AdS/CFT methods have played a role, as the duality permits calculations at all length scales. While this approach suffers not only from the standard concern that the gauge theory studied in not QCD but also from the restriction to calculating wakes from infinitely massive quarks, it has nonetheless provided substantial insight into the energy flow and medium response[83].

3.6. *Puzzles from Quark Number Scaling*

The recent spectacular advances in our understanding of hot QCD have been driven by experimental discoveries, together with the subsequent development of detailed theoretical understanding. It is therefore appropriate to discuss briefly at least one area where such understanding remains elusive. A case in point is provided by the observed quark number scaling of elliptic flow[57,84]. Examination of the two branches of $v_2(\mathrm{KE_T})$ displayed in Figure 3 shows that the upper branch consists of baryons; the lower branch mesons. Upon further scaling of both $\mathrm{KE_T}$ and $v_2(\mathrm{KE_T})$ by n_q, the number of constituent quarks, the two branches merge into a universal scaling curve for elliptic flow (Figure 5). A critical test of this observation is the ϕ meson- although more massive than a nu-

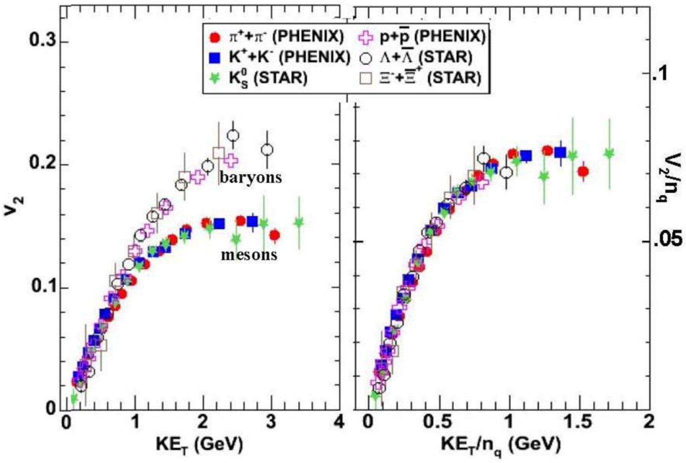

Fig. 5. The additional scaling of $v_2(\mathrm{K}E_T)$ with the number of constituent quarks n_q[57].

cleon, it follows the scaling curve for mesons, not baryons[85,86]. While it is tempting to conclude that the strict scaling according to constituent quark content provides incontrovertible evidence for the underlying role of quark degrees of freedom in establishing the elliptic flow, such a conclusion appears to be at odds with the observation of perfect fluidity. Quasi-particles with lifetimes comparable to the relatively long time over which hydrodynamic flow persists are incompatible with the very short mean free paths (and hence large widths and short lifetimes) implied by low viscosity[87]. This fact, already noted in the earliest calculation of viscosity via the AdS/CFT correspondence[65], has yet to be reconciled with the strong empirical evidence for quark number scaling of flow phenomena. Recent calculations[88] which indicate that the viscosity at RHIC may be even lower than the conjectured bound only sharpen the dichotomy.

4. Outlook

The RHIC experiments have conclusively demonstrated the feasibility, and indeed the desirability, of performing sensitive measurements of heavy ion phenomena in a collider environment. The discoveries made in the initial years of RHIC operation have initiated a paradigm shift in our understanding of deconfined QCD matter in the region of the transition temperature. In doing so they have also set the stage for the heavy ion program at the LHC, where Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV are planned following heavy ion commissioning in 2009. This unprecedented increase in center-of-mass energy will undoubtedly result in a new round of discoveries, to be made by the ALICE experiment[89], which is dedicated to the heavy ion program, together with the two large p+p collider detectors ATLAS[91] and CMS[90]. Questions of immediate interest are the fundamental properties of the QGP at the expected higher initial temperatures at the LHC- Will it remain strongly coupled? Will it exhibit ∼perfect flow? However, the RHIC experience has taught us that the very nature of the important questions changes in response to experimental data, and it would be wise to anticipate that the same will be true for heavy ion physics at LHC energies.

A compelling program of more detailed investigations at RHIC is already underway, based on a series of detector upgrades to PHENIX and STAR, together with ongoing and future substantial increases in RHIC luminosity. The unique properties of bulk, thermalized QCD matter at RHIC energies will be better quantified via increasingly differential measurements, such as associated particle production in direct photon events, jet tomography with respect to the reaction plane, and the suppression and flow patterns of both charmonium and open heavy flavor.

A particular strength of the RHIC facility is the wide range of collision energies, from the top energy of $\sqrt{s_{NN}} = 200$ GeV to values as low as a few GeV. This, together with the collider geometry which provides excellent control of acceptance systematics as the center-of-mass energy is varied, have stimulated interest in the search for the QCD critical point[92] at RHIC[93]. Especially intriguing in this regard is the possible connection[94] between physics in the region of the critical point and the minimal value of the viscosity to entropy density ratio. The simultaneous progress on multiple energy frontiers at RHIC, at the LHC and at GSI/FAIR[95] are certain to lead to new insights and a deeper understanding of the fluid nature of quark-gluon plasma.

References

[1] I. Arsene *et al.* [BRAHMS Collaboration], Nucl. Phys. A **757**, 1 (2005) [arXiv:nucl-ex/0410020].

[2] K. Adcox *et al.* [PHENIX Collaboration], Nucl. Phys. A **757**, 184 (2005) [arXiv:nucl-ex/0410003].

[3] B. B. Back *et al.* [PHOBOS Collaboration], Nucl. Phys. A **757**, 28 (2005) [arXiv:nucl-ex/0410022].

[4] J. Adams *et al.* [STAR Collaboration], Nucl. Phys. A **757**, 102 (2005) [arXiv:nucl-ex/0501009].

[5] D. Rischke and G. Levin, *Prepared for Workshop on New Discoveries at RHIC: The Current Case for the Strongly Interactive QGP, Brookhaven, Upton, New York, 14-15 May 2004*

[6] *"RHIC Scientists Serve Up 'Perfect' Liquid"*, `http://www.bnl.gov/bnlweb/pubaf/pr/PR_display.asp?prID=05-38` .

[7] *"Quark-Gluon Plasma: Experimental Overview"*, W.A. Zajc, presented at the International Nuclear Physics Conference; June 3-8, 2007; Tokyo, Japan; available as `http://inpc2007.riken.jp/P/P7-zajc.ppt` .

[8] P. Braun-Munzinger, D. Magestro, K. Redlich and J. Stachel, Phys. Lett. B **518**, 41 (2001) [arXiv:hep-ph/0105229].

[9] W. Florkowski, W. Broniowski and M. Michalec, Acta Phys. Polon. B **33**, 761 (2002) [arXiv:nucl-th/0106009].

[10] J. Cleymans, B. Kampfer, M. Kaneta, S. Wheaton and N. Xu, Phys. Rev. C **71**, 054901 (2005) [arXiv:hep-ph/0409071].

[11] J. Rafelski, J. Letessier and G. Torrieri, Phys. Rev. C **72**, 024905 (2005) [arXiv:nucl-th/0412072].

[12] A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A **772**, 167 (2006) [arXiv:nucl-th/0511071].

[13] K. H. Ackermann *et al.* [STAR Collaboration], Phys. Rev. Lett. **86**, 402 (2001) [arXiv:nucl-ex/0009011].

[14] K. Adcox *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **88**, 022301 (2002) [arXiv:nucl-ex/0109003].

[15] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **91**, 072301 (2003) [arXiv:nucl-ex/0304022].

[16] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **91**, 172302 (2003) [arXiv:nucl-ex/0305015].

[17] P. Levai, G. Papp, G. I. Fai, M. Gyulassy, G. G. Barnafoldi, I. Vitev and Y. Zhang, Nucl. Phys. A **698**, 631 (2002) [arXiv:nucl-th/0104035].

[18] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne and D. Schiff, Nucl. Phys. B **483**, 291 (1997) [arXiv:hep-ph/9607355].

[19] B. G. Zakharov, JETP Lett. **65**, 615 (1997) [arXiv:hep-ph/9704255].
[20] U. A. Wiedemann, Nucl. Phys. B **588**, 303 (2000) [arXiv:hep-ph/0005129].
[21] R. Baier, Y. L. Dokshitzer, A. H. Mueller and D. Schiff, JHEP **0109**, 033 (2001) [arXiv:hep-ph/0106347].
[22] M. Gyulassy, P. Levai and I. Vitev, Nucl. Phys. B **594**, 371 (2001) [arXiv:nucl-th/0006010].
[23] M. Gyulassy, P. Levai and I. Vitev, Phys. Rev. D **66**, 014005 (2002) [arXiv:nucl-th/0201078].
[24] M. Gyulassy, I. Vitev, X. N. Wang and P. Huovinen, Phys. Lett. B **526**, 301 (2002) [arXiv:nucl-th/0109063].
[25] M. Gyulassy, P. Levai and I. Vitev, Phys. Lett. B **538**, 282 (2002) [arXiv:nucl-th/0112071].
[26] C. A. Salgado and U. A. Wiedemann, Phys. Rev. Lett. **89**, 092303 (2002) [arXiv:hep-ph/0204221].
[27] E. Wang and X. N. Wang, Phys. Rev. Lett. **89**, 162301 (2002) [arXiv:hep-ph/0202105].
[28] D. Kharzeev and E. Levin, Phys. Lett. B **523**, 79 (2001) [arXiv:nucl-th/0108006].
[29] C. Adler *et al.* [STAR Collaboration], Phys. Rev. Lett. **90**, 082302 (2003) [arXiv:nucl-ex/0210033].
[30] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **91**, 241803 (2003) [arXiv:hep-ex/0304038].
[31] B. B. Back *et al.* [PHOBOS Collaboration], Phys. Rev. Lett. **91**, 072302 (2003) [arXiv:nucl-ex/0306025].
[32] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **91**, 072303 (2003) [arXiv:nucl-ex/0306021].
[33] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **91**, 072304 (2003) [arXiv:nucl-ex/0306024].
[34] I. Arsene *et al.* [BRAHMS Collaboration], Phys. Rev. Lett. **91**, 072305 (2003) [arXiv:nucl-ex/0307003].
[35] S. A. Bass *et al.*, Nucl. Phys. A **661**, 205 (1999) [arXiv:nucl-th/9907090].
[36] B. B. Back *et al.* [PHOBOS Collaboration], Phys. Rev. Lett. **85**, 3100 (2000) [arXiv:hep-ex/0007036].
[37] K. Adcox *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **86**, 3500 (2001) [arXiv:nucl-ex/0012008].
[38] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. C **71**, 034908 (2005) [Erratum-ibid. C **71**, 049901 (2005)] [arXiv:nucl-ex/0409015].
[39] D. Kharzeev, E. Levin and M. Nardi, Phys. Rev. C **71**, 054903 (2005) [arXiv:hep-ph/0111315].
[40] B. B. Back *et al.* [PHOBOS Collaboration], Phys. Rev. Lett. **88**, 022302 (2002) [arXiv:nucl-ex/0108009].
[41] T. Hirano and Y. Nara, Nucl. Phys. A **743**, 305 (2004) [arXiv:nucl-th/0404039].
[42] K. Adcox *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **88**, 242301 (2002) [arXiv:nucl-ex/0112006].
[43] R. C. Hwa and C. B. Yang, Phys. Rev. C **67**, 034902 (2003) [arXiv:nucl-th/0211010].
[44] R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, Phys. Rev. Lett. **90**, 202303 (2003) [arXiv:nucl-th/0301087].
[45] V. Greco, C. M. Ko and P. Levai, Phys. Rev. Lett. **90**, 202302 (2003) [arXiv:nucl-th/0301093].
[46] V. Greco, C. M. Ko and P. Levai, Phys. Rev. C **68**, 034904 (2003) [arXiv:nucl-th/0305024].
[47] R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, Phys. Rev. C **68**, 044902 (2003) [arXiv:nucl-th/0306027].
[48] B. Muller and J. L. Nagle, Ann. Rev. Nucl. Part. Sci. **56**, 93 (2006) [arXiv:nucl-th/0602029].
[49] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **94**, 232301 (2005) [arXiv:nucl-ex/0503003].
[50] S. Turbide, C. Gale, S. Jeon and G. D. Moore, Phys. Rev. C **72**, 014906 (2005) [arXiv:hep-ph/0502248].
[51] F. Arleo, JHEP **0609**, 015 (2006) [arXiv:hep-ph/0601075].
[52] J. Jin [PHENIX Collaboration], J. Phys. G **34**, S813 (2007) [arXiv:0705.0842 [nucl-ex]].
[53] S. Chattopadhyay [STAR Collaboration], Nucl. Phys. A **783** (2007) 591.
[54] X. N. Wang, Z. Huang and I. Sarcevic, Phys. Rev. Lett. **77**, 231 (1996) [arXiv:hep-ph/9605213].
[55] S. Weinberg, *Gravitation and Cosmology*, John Wiley and Sons, 1972.
[56] See references in M. Csanad, T. Csorgo, R. A. Lacey and B. Lorstad, arXiv:nucl-th/0605044.
[57] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **98**, 162301 (2007) [arXiv:nucl-ex/0608033].
[58] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **92**, 052302 (2004) [arXiv:nucl-ex/0306007].
[59] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **95**, 122301 (2005) [arXiv:nucl-ex/0504022].
[60] S. Z. Belenkij and L. D. Landau, Nuovo Cim. Suppl. **3S10**, 15 (1956) [Usp. Fiz. Nauk **56**, 309 (1955)].

[61] P. Kovtun, D. T. Son and A. O. Starinets, Phys. Rev. Lett. **94**, 111601 (2005) [arXiv:hep-th/0405231].
[62] P. Danielewicz and M. Gyulassy, Phys. Rev. D **31**, 53 (1985).
[63] T. Hirano and M. Gyulassy, Nucl. Phys. A **769**, 71 (2006) [arXiv:nucl-th/0506049].
[64] J. M. Maldacena, Adv. Theor. Math. Phys. **2**, 231 (1998) [Int. J. Theor. Phys. **38**, 1113 (1999)] [arXiv:hep-th/9711200].
[65] G. Policastro, D. T. Son and A. O. Starinets, Phys. Rev. Lett. **87**, 081601 (2001) [arXiv:hep-th/0104066].
[66] S. S. Gubser, Phys. Rev. D **74**, 126005 (2006) [arXiv:hep-th/0605182].
[67] H. Liu, K. Rajagopal and U. A. Wiedemann, JHEP **0703**, 066 (2007) [arXiv:hep-ph/0612168].
[68] D. Teaney, Phys. Rev. C **68**, 034913 (2003) [arXiv:nucl-th/0301099].
[69] E. Shuryak, Prog. Part. Nucl. Phys. **53**, 273 (2004) [arXiv:hep-ph/0312227].
[70] R. A. Lacey *et al.*, Phys. Rev. Lett. **98**, 092301 (2007) [arXiv:nucl-ex/0609025].
[71] H. J. Drescher, A. Dumitru, C. Gombeaud and J. Y. Ollitrault, Phys. Rev. C **76**, 024905 (2007) [arXiv:0704.3553 [nucl-th]].
[72] S. Gavin and M. Abdel-Aziz, Phys. Rev. Lett. **97**, 162302 (2006) [arXiv:nucl-th/0606061].
[73] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **98**, 172301 (2007) [arXiv:nucl-ex/0611018].
[74] T. Schäfer, arXiv:cond-mat/0701251v3 .
[75] E. Shuryak, Nucl. Phys. A **783**, 31 (2007) [arXiv:nucl-th/0609013].
[76] H. Stoecker, Nucl. Phys. A **750**, 121 (2005) [arXiv:nucl-th/0406018].
[77] J. Casalderrey-Solana, E. V. Shuryak and D. Teaney, J. Phys. Conf. Ser. **27**, 22 (2005) [Nucl. Phys. A **774**, 577 (2006)] [arXiv:hep-ph/0411315].
[78] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **97**, 052301 (2006) [arXiv:nucl-ex/0507004].
[79] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **98**, 232302 (2007) [arXiv:nucl-ex/0611019].
[80] M. J. Horner [STAR Collaboration], J. Phys. G **34**, S995 (2007) [arXiv:nucl-ex/0701069].
[81] J. G. Ulery [STAR Collaboration], arXiv:0704.0224 [nucl-ex].
[82] J. Jia [for the PHENIX Collaboration], arXiv:0705.3060 [nucl-ex].
[83] See S. S. Gubser and A. Yarom, arXiv:0709.1089 [hep-th], and references therein.
[84] J. Adams *et al.* [STAR Collaboration], Phys. Rev. C **72**, 014904 (2005) [arXiv:nucl-ex/0409033].
[85] S. Afanasiev *et al.* [PHENIX Collaboration], arXiv:nucl-ex/0703024.
[86] B. I. Abelev *et al.* [STAR Collaboration], arXiv:nucl-ex/0703033.
[87] The author would like to thank M. Csanád, T. Csörgő, B. Müller, J. Nagle, K. Rajagopal, T. Schäfer, and D. Son for useful discussions on many aspects of quasi-particles.
[88] H. Song and U. W. Heinz, arXiv:0709.0742 [nucl-th].
[89] F. Antinori [ALICE Collaboration], J. Phys. G **34**, S511 (2007) [arXiv:nucl-ex/0702013].
[90] R. R. Betts, J. Phys. G **34**, S519 (2007).
[91] P. Steinberg [ATLAS Collaboration], J. Phys. G **34**, S527 (2007) [arXiv:0705.0382 [nucl-ex]].
[92] M. A. Stephanov, K. Rajagopal and E. V. Shuryak, Phys. Rev. Lett. **81**, 4816 (1998) [arXiv:hep-ph/9806219].
[93] G. S. F. Stephans, J. Phys. G **32**, S447 (2006) [arXiv:nucl-ex/0607030].
[94] L. P. Csernai, J. I. Kapusta and L. D. McLerran, Phys. Rev. Lett. **97**, 152303 (2006) [arXiv:nucl-th/0604032].
[95] W. F. Henning, AIP Conf. Proc. **773**, 3 (2005).