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Thermalization of the world's smallest fluids: Recent developments

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Abstract

The late Gerry Brown was not shy to tackle complex scientific problems that took time to play out but yielded in the end a deeper understanding of many-body phenomena. In this note, prepared for a memorial volume in his honor, we provide a perspective on a couple of outstanding scientific puzzles that have their origin in our understanding of the thermalization of matter in ultrarelativistic heavy ion collisions, and possibly, in high multiplicity proton–proton and proton–nucleus collisions.

Keywords: High parton densities; Quark–gluon plasma; Thermalization

1. Introduction

The successful comparison of hydrodynamical models to a wide range of data from heavy ion collisions suggests that the produced quark–gluon fluid is a viscous fluid with perhaps the lowest known viscosity to entropy density ratio (η/s) in nature. The low values of η/s, coupled with the fact that these hydrodynamical models employ an equation of state, appear to indicate that the matter is thermal, or at least nearly isotropic, with the ratio of the longitudinal pressure to the transverse pressure close to unity. Further, to reproduce key features of the data, it appears important that hydrodynamics be applicable at very early times of less than a Fermi after the collision.

There is some elasticity to the above conclusions, and it is conceivable that the hydrodynamic paradigm may be modified. Nevertheless, the phenomenology is sufficiently robust to approach seriously. From a theoretical perspective, at first glance, it seems astonishing that hydrodynamics

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is applicable at all to such small systems, and at such early times. Hydrodynamics is an excellent effective field theory of QCD, but for long wavelength modes and at late times [1]. In kinetic theory frameworks, the scattering rates of quarks and gluons have to be sufficiently strong to counter the rapid longitudinal expansion of the system. This appears challenging. From these elementary, and perhaps naive considerations, to paraphrase a quote by Wigner in another context, hydrodynamics is "unreasonably effective".

A weak link in hydrodynamic models is the statement that the system isotropizes/thermalizes at very early times. Most hydrodynamic models choose an initial time $\tau_i = 0.4$–0.6 fm. Nearly all these models ignore the pre-equilibrium dynamics prior to this time. The one model that does incorporate pre-equilibrium dynamics, the IP-Glasma model, does so imperfectly [2]. There is therefore a practical problem of how and when pre-equilibrium dynamics can be matched on to a hydrodynamic description. This of course is tied to resolving the more general conceptual problem of how thermalization occurs in QCD. The latter will be one of the two subjects of the discussion here.

Even if thermalization does occur in heavy ion collisions, as the hydrodynamic models suggest, there is the interesting question of whether this framework is applicable to smaller size systems. How and where does hydrodynamics break down? Does it apply to $\mathrm{p+A}$ and $\mathrm{p+p}$ collisions, as some interpretations of data (on long range rapidity correlations) in these collisions suggest? If it works for high multiplicities, at what multiplicities do we see an onset of hydrodynamic behavior? Are there alternative explanations for what is seen in the data? The interpretation of long range rapidity correlations in $\mathrm{p+p}$ and $\mathrm{p+A}$ collisions will be the other topic discussed here.

Both topics will be discussed within weak coupling frameworks here. It is a common misunderstanding that weak coupling implies weakly interacting. That is not the case for systems with high occupancy. It is a legitimate question to ask whether weak coupling is the right framework for heavy ion collisions – at RHIC and LHC, the coupling is not particularly weak. At one level, an answer is that this is the only framework we know how to compute in systematically and reliably. But this answer is also profoundly unsatisfying. A better answer is that weak coupling frameworks describe many non-trivial features of heavy ion collisions. It is however not a universal panacea, which disappoints some people, but that can't be helped – until some smart person solves QCD.

The lack of a satisfactory framework to address dynamical aspects of QCD in strong coupling is a powerful motivation for AdS/CFT duality inspired frameworks. The questions regarding the applicability of these methods to heavy ion collisions are well known, and I will not revisit them here. The next section will discuss the problem of thermalization in weak coupling. We will then discuss the recent results from $\mathrm{p+p}$ and $\mathrm{p+A}$ collisions on collimated long range rapidity correlations ("the ridge"). Since many of the issues discussed are open, and are the subject of much debate, conclusions may be premature. I will conclude instead with some personal reminiscences of Gerry Brown, whose early mentorship made it possible for me, however imperfectly, to tackle these issues.

2. A weak coupling treatment of the thermalization process in QCD

Multiparticle production at central rapidities is dominated by gluon configurations carrying small fractions x of the momenta of the colliding nuclei. Perturbative QCD (pQCD) predicts, and data from HERA confirm, that the occupancy of small x modes in a proton is large for fixed momentum transfer $\mathbf{Q}^2$. The occupancy saturates at $1/\alpha_S$ for any given $\mathbf{Q}^2 \gg \Lambda^2_{\mathrm{QCD}}$, for