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Relativistic hydrodynamics in extreme conditions, without a semiclassical or a gradient expansion (SONATA 16, L. Tinti)

In the largest particle accelerators, like LHC at CERN and RHIC at Brookhaven, atomic nuclei collide at such high energy that the ordinary structure of matter collapses. Instead of protons and neutrons confined by the strong nuclear force (the strongest known thus far) in the very small volume of a nucleus, one has new state of matter, called quark-gluon plasma (QGP). In such extreme conditions ordinary matter “melts” in its constituent building blocks, quarks and gluons, partially shielding the strong nuclear force, as the electro-magnetic forces are partially shielded in an ordinary plasma. The newly formed system then explodes almost at the speed of light, until the density becomes low enough for protons and neutrons (and other more exotic unstable particles) to reform and exist separately from the high density continuous medium of the QGP.

The quark-gluon plasma is the system with the highest density ever achieved in an experiment, several orders of magnitude higher than the one in the center of the sun. In fact, it is the closest thing we have to the primordial matter at the very beginning of the universe. The exploding fireball of QGP obtained in particles accelerators has then been referred to as “the little bang”; that is, the miniature version of the expanding matter in the first stages of the big bang. Relativistic heavy-ion collision experiments therefore provide a unique window into an exotic state of matter, otherwise unreachable by direct or indirect measurements (like astrophysical observations). A state of matter that is, on the other hand, crucial to understanding the fundamental forces of nature, cosmology, and the very first steps of the evolution of the universe.

Relativistic hydrodynamics, as the name suggest, is the extension of hydrodynamics (the study of fluids), to include relativistic effects. In other words, to take into account Einstein’s relativity, when the fluid speed is fast enough that classical mechanics is no longer viable. Many systems show a fluid-like behavior in the right circumstances, and it seems that the QGP is not an exception. Relativistic hydrodynamics has been successfully used to describe the evolution of the QGP, which is still too complicated to to compute directly from standard model of particle physics. Relativistic hydrodynamics, however, should still be bound by the phenomenological assumptions made to derive it from a more fundamental microscopic background. More precisely one expects hydrodynamics to break down if the gradients are large (that is, a very turbulent expansion), if the system is far from local equilibrium (large pressure corrections with respect to the ideal case), and especially both. This is, in fact, what happens in heavy ion experiments. There is a lot of attention surrounding the unexpected reliability of the hydrodynamic evolution.

The best description we have of fundamental interactions is quantum field theory (QFT), second-order hydrodynamics can be extracted from it assuming the stress energy tensor can be as a second-order expansion in the gradients of the hydrodynamic degrees of freedom: density, pressure and fluid velocity. The pressure corrections are (at least) first-order in the gradients, therefore one expects hydrodynamics to be valid only for small gradients and small pressure corrections. The very same equations can be obtained, however, from the relativistic Boltzmann equation ,making use of the method of moments. Small gradients and small deviations from local equilibrium are not mandatory requirements in this approach, however the relativistic Boltzmann equation is a classical equation and the size of the system is much smaller than the ones in which quantum effects can be readily observed in experiments. In addition, it does not include the effects of the spin of particles. Recent results show that the QGPin periferal collisions is the most vorticous (hence turbolent) system ever observed, this induces a polarization on spinning particles, which is measured, and it would be important to describe the polarization-vorticity coupling in a dynamical way. Do the polarization degrees of freedom thermalize faster or slower than momenta? Do they change the effective viscosity of the fluid?

The relativistic Boltzmann equation is a limiting case of the evolution of the Wigner distribution (the quantum precursor of the classical distribution function), in particular it takes into account only the lowest terms in an expansion in the Plank constant, in other words the classical limit. In this project we aim to generalize the method of moments used in the classical case to the more rich structure of the quantum case, in order to extract hydrodynamics without requirements of laminar flow (small gradients, almost locally equilibrated) and without neglecting quantum effects, like the polarization of spinning particles.