QCD Thermodynamics and Fireball Evolution in URHICs

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Abstract

The fireball created in an ultrarelativistic heavy ion collision is the environment in which all processes providing clues about the possible formation of the quark-gluon plasma (QGP) happen. It is therefore crucial to understand the dynamics of this hot and dense system. We set up a model in which the fireball evolution is reconstructed between two stages, the freeze-out, which is accessible by hadronic observables, and the initial collision for which the overlap geometry can be calculated. Using the equation of state (EoS) provided by a quasiparticle model of the QGP, we are able to calculate thermodynamical properties in volume slices of constant proper time and determine the volume expansion self-consistently. The resulting evolution model can then be tested against other observables, such as dilepton yields.

1 Introduction

One of the most striking predictions of QCD at high temperatures is the formation of the quark-gluon plasma (QGP), a deconfined phase with quarks and gluons as degrees of freedom. Unfortunately, finding direct evidence for this phase or studying its properties is not an easy task. Ideally, one would like to study the behaviour of an observable sensitive to the formation of the QGP, such as the J/Ψ system or dilepton radiation. In reality, however, no static QGP system can be prepared in a heavy ion collision and all processes inside the resulting fireball are necessarily convoluted with its evolution dynamics. As this leaves two a priori unknown inputs into any model calculation, the modified reaction dynamics inside the system and the fireball evolution itself, a model which is able to describe just one (or a few) observables may not be sufficient to disentangle these two pieces and extract unambiguous information.

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The proper way to proceed seems therefore as follows: From the theoretical side, and especially from lattice calculations (see e.g. [1]), much is known about thermodynamical properties of the QGP in a static situation. Although there is no direct possibility to compare to experiment, this knowledge can be used under certain circumstances as an input for dynamical fireball models, which constitute the next important building block for modelling any specific process inside such a system. Here, experimental input is available in the form of bulk hadronic observables such as directed flow and total multiplicities which characterize the evolution endpoint. The third and final step is then the calculation of a given process within the arena prepared by the fireball evolution. In this way, fireball evolution and the process in question are tied to different observables and are readily disentangled.

In the following, we try to elaborate on the second building block, the dynamical fireball evolution in a simple framework and calculate as an application dilepton radiation from this fireball. This is more completely worked out in [2].

2 Model framework

We do not aim at the detailed description of the heavy-ion collision or its subsequent expansion on an event by event basis or by a hydrodynamical simulation. Instead we use a model of an expanding fireball which enables us to rapidly test different scenarios with different parameter sets in a systematic way, so as to gain insight into the time evolution of the strongly interacting system.

We assume that the physics of the fireball is the same inside each volume of given proper time $\tau$, thus averaging over spatial inhomogenities in density and temperature. The volume itself is taken to be an expanding cylinder, in which the volume elements move away from the center in order to generate the observed flow. There is no global Lorentz frame in which thermodynamics can be applied. As the fireball expands, volume elements away from the center are moving with large velocities and are subject to time dilatation when seen in the center of mass frame of the collision. In this frame, the fireball expands, at a given time, much more rapidly in the center than at the edges and does not resemble a cylinder any more. We assume a linear increase in rapidity when going from central volume elements to the fireball edge along the beam ($z$)-axis and the transverse axis. As the velocities along the $z$-axis are typically large (up to $c$) as compared to transverse motion (up to 0.55 $c$) for SPS and RHIC conditions, we make the simplifying assumption that the proper time
is in a one-to-one correspondence to the \( z \)-position of a given volume element, thus neglecting the time dilatation caused by transverse motion. The whole system is assumed to be in local thermal (though not necessarily chemical) equilibrium at all times.

Given this overall framework, the volume expansion of the fireball is governed by the longitudinal growth speed \( v_z \) and the transverse expansion speed \( v_\perp \) at a given proper time. These quantities can be determined at the freeze-out point and correspond to the observed amount of flow. However, flow is measured in the lab frame and needs to be translated into the growth of proper time volume.

Note that it is important to keep track of the velocity \( v_z \) at the fireball edge in this setup. If this quantity is simply assumed to be \( c \), the volume of given proper time does not grow like \( \tau c \) as one might naively expect (the c.m. frame volume does so, however), but is infinite right from the beginning.

We use a detailed analysis of the freeze-out conditions for central Pb-Pb collisions at 160 AGeV \[3\] to fix the endpoint of the evolution. The initial state is constrained using the overlap geometry of the colliding nuclei. The expansion between initial and freeze-out stages is then required to be in accordance with the EoS as determined from the quasiparticle model described in \[4\].

The volume expansion is parametrized by the following set of equations:

\[
v_\perp(\tau) = \int_0^\tau d\tau' c_\perp \frac{p(\tau')}{\epsilon(\tau')} \quad R(\tau) = R_0 + \int_0^\tau \int_0^{\tau''} d\tau' d\tau'' \frac{p(\tau'')}{\epsilon(\tau'')} c_\perp \tag{1}
\]

\[
v_z(t) = v_z^i + \int_0^t dt' c_z \frac{p(t')}{\epsilon(t')} \quad z(t) = z_0 + v_z^i \cdot t + \int_0^t \int_0^{t''} dt' dt'' c_z \frac{p(t'')}{\epsilon(t'')} \tag{2}
\]

Here, the acceleration was assumed to be proportional to the ratio of pressure \( p \) over energy density \( \epsilon \) with a proportionality constant \( c \). The free parameters \( c_\perp, c_z \), freeze-out proper time \( \tau_f \) and freeze-out c.m. time \( t_f \) can be fitted by requiring agreement with initial conditions \( R_0 \approx 4.5 \text{ fm} \) and \( v_\perp = 0 \) (overlap geometry) and final conditions \( R_f \approx 8.55 \text{ fm}, \; \tau_\perp = 0.5c, \; T_f = 100 \text{ MeV}, \; v_z = 0.9c \) (results from \[3\]). Assuming entropy conservation with an entropy per baryon of 26 for SPS conditions at 160 AGeV, the entropy density \( s \) at a given proper time can then be obtained by dividing the total entropy \( S_0 \) by the volume, \( s = S_0/V(\tau) \). With the help of the EoS, the temperature \( T(s) \), pressure \( p(s) \) and energy density \( \epsilon(s) \) can then be calculated. These are inserted into eqs.(1–2) in order to yield a self-consistent solution. Chemical
potentials for hadrons are introduced in order to agree with the experimentally observed particle abundancies. For the above conditions, a rise in the pion chemical potential $\mu_\pi$ up to 123 MeV towards freeze-out is necessary.

3 Results

The resulting volume expansion and temperature profile for SPS conditions at two different energies is shown in Fig. 1.

![Figure 1: Left panel: Volume of constant proper time at SPS 160 and 40 AGeV for central Pb-Pb collisions. Right panel: Corresponding temperature profile with entropy per baryon $s/\rho_B = 26$ (160 AGeV) and 13 (40 AGeV).](image)

The primary uncertainty is attached to the initial temperature, which appears rather large ($\sim 300$ MeV) for 160 AGeV collisions. Part of the difference in this value as compared to other approaches comes from the use of a more realistic equation of state, which even for the initial temperatures differs considerably from the EoS of an ideal gas. Moreover, it depends on the initial longitudinal expansion velocity. After a few fm/c evolution time, however, the system is not very sensitive to details of the initial conditions any more. Remarkably, even the 40 AGeV scenario shows some evolution above the critical temperature $T_C = 170$ MeV. This is unavoidable — for thermodynamical reasons the volume required for an initial temperature below $T_C$ would be by far too large to be found after the expansion within a sensible thermalization time of 1–2 fm/c. Note that there is no mixed phase present. This is again a consequence of the EoS which indicates a smooth crossover between the two phases. Close to the critical temperature there is a soft point in the EoS and its effect is included in the model.
As a test for the extracted fireball evolution scenarios, we consider dilepton emission. Once the thermal emission rate \( \frac{dN(T(\tau), M, \eta, p_T)}{d^4x d^4p} \) from a hot source is known, the experimentally measured rate can be calculated as

\[
\frac{d^2N}{dMd\eta} = \frac{2\pi M}{\Delta \eta} \int_0^{\tau_f} d\tau \int d\eta \, V(T(\tau), \eta) \int_0^\infty dp_T \, p_T \frac{dN(T(\tau), M, \eta, p_T)}{d^4x d^4p} \text{Acc.}
\]

(3)

Here ‘Acc’ refers to the acceptance characteristic of the detector. Using the thermal quasiparticle model \(^4\) for the QGP spectral function and and improved vector meson dominance model combined with chiral dynamics \(^5\) for the hadronic part, we insert the resulting rate into the fireball evolution shown above in order to compare to the CERES data \(^6\).

Figure 2: Left panel: Total dilepton yield for 30% central Pb-Au collisions at 160 AGeV (full), hadronic cocktail (dotted) and QGP contribution (dashed). Right panel: Contribution of the vector meson channels \(\rho\), \(\omega\) and \(\phi\).

The 160 AGeV scenario is shown in Fig. 2, the 40 AGeV scenario in Fig. 3. We calculate the full rate and also the contributions from different processes, namely the thermal rate from the QGP, the so-called cocktail contribution from Dalitz decays after freeze-out and the vector meson channels. In both scenarios we find good agreement with the data within errors. The driving force of the dilepton excess around 500 MeV invariant mass is the broadening of the \(\rho\)-meson due to finite baryon density. The QGP contribution is visible at invariant masses above 1 GeV in the 160 AGeV scenario and negligible for
Figure 3: Left panel: Total dilepton yield for 30% central Pb-Au collisions at 40 AGeV (full), hadronic cocktail (dotted) and QGP contribution (dashed). Right panel: Contribution of the vector meson channels $\rho$, $\omega$ and $\phi$.

40 AGeV. Note that we do not aim for a best fit. For example, in the invariant mass region around 200 MeV, our calculation overshoots the data. This could be easily cured by raising the freeze-out temperature which corresponds to a reduction of the hadronic rate. However, as we choose to fix the fireball evolution before with hadronic observables, this is not an option any more.

It is clearly an interesting and challenging task to also apply the fireball evolution model to other processes, e.g. direct photon emission or $J/\Psi$ and see whether further agreement can be found, giving support to the overall scenario. This is work currently in progress.

References

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