Pre-equilibrium dynamics and heavy-ion observables[☆]

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Abstract

To bracket the importance of the pre-equilibrium stage on relativistic heavy-ion collision observables, we compare simulations where it is modeled by either free-streaming partons or fluid dynamics. These cases implement the assumptions of extremely weak vs. extremely strong coupling in the initial collision stage. Accounting for flow generated in the pre-equilibrium stage, we study the sensitivity of radial, elliptic and triangular flow on the switching time when the hydrodynamic description becomes valid. Using the hybrid code iEBE-VISHNU [1] we perform a multi-parameter search, constrained by particle ratios, integrated elliptic and triangular charged hadron flow, the mean transverse momenta of pions, kaons and protons, and the second moment $\langle p_T^2 \rangle$ of the proton transverse momentum spectrum, to identify optimized values for the switching time τ_s from pre-equilibrium to hydrodynamics, the specific shear viscosity η/s , the normalization factor of the temperature-dependent specific bulk viscosity $(\zeta/s)(T)$, and the switching temperature T_{sw} from viscous hydrodynamics to the hadron cascade UrQMD. With the optimized parameters, we predict and compare with experiment the p_T -distributions of π , K , p , Λ , Ξ and Ω yields and their elliptic flow coefficients, focusing specifically on the mass-ordering of the elliptic flow for protons and Lambda hyperons which is incorrectly described by VISHNU without pre-equilibrium flow.

Keywords: collective flow, pre-equilibrium dynamics, quark-gluon plasma, viscosity, model-to-data comparison, parameter optimization, uncertainty quantification

1. Introduction

Relativistic viscous hydrodynamics has become the workhorse of dynamical modeling of ultra-relativistic heavy-ion collisions. However, hydrodynamics does not become valid until the medium has reached a certain degree of local momentum isotropization [2]. In an inhomogeneous system, collective flow (i.e. space-momentum correlations) begins, however, to develop already before hydrodynamics becomes valid. The hydrodynamic stage thus starts with a non-vanishing pre-equilibrium flow [3–7]. In [8] we therefore performed a systematic study of pre-equilibrium flow effects on heavy-ion collision observables. We here summarize the main results of this study and add a few recent results that go beyond the work reported in [8].

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2. The model

We assume longitudinal boost-invariance and model the approach towards local thermal equilibrium in a heavy-ion collision very simply [8] as a pre-equilibrium stage of noninteracting free-streaming massless partonic degrees of freedom, separated by a switching time τ_s from a strongly coupled quark-gluon plasma (QGP) stage in which frequent collisions isotropize the local momentum distribution sufficiently quickly that it can be described by viscous relativistic fluid dynamics. The variable switching time τ_s parametrizes the duration of the thermalization process. For massless degrees of freedom the evolution of the energy-momentum tensor during the free-streaming stage is independent of the initial transverse momentum distribution as long as it starts out locally azimuthally symmetric, and can be solved analytically [8].

At τ_s we Landau-match the analytically evolved pre-equilibrium energy-momentum tensor to viscous hydrodynamic form [8]. Space-momentum correlations established by the free-streaming dynamics in the pre-equilibrium stage manifest themselves as non-zero initial values for the hydrodynamic flow velocity profiles, giving rise to non-zero initial radial and anisotropic flows. Local momentum anisotropies resulting from the free-streaming evolution of a spatially inhomogeneous initial density profile generate nonzero initial values for the shear stress. Matching the traceless pre-equilibrium energy-momentum tensor of noninteracting massless degrees of freedom to a non-conformal, lattice QCD based equation of state [9] at τ_s generates a non-zero initial bulk viscous pressure field in the hydrodynamic fluid. All of these initial fields are then further evolved with the second-order viscous relativistic fluid dynamics code VISH2+1.

After hadronization of the QGP at a pseudocritical temperature $T_c \simeq 155$ MeV (determined by the equation of state [9]), the medium constituents are color neutral hadrons whose interactions are weaker than the gluon-mediated interactions in the earlier color-deconfined QGP, causing a rapid growth of their mean free paths and a subsequent breakdown of the fluid dynamic framework. We therefore switch from VISH2+1 to a microscopic description, using the hadron cascade code UrQMD, on an isothermal switching surface of temperature T_{sw} which we here consider as an unknown parameter to be optimized by comparison with experimental data.

Two additional important parameters affecting the evolution of collective flow and the p_T distributions of the finally emitted hadrons are the shear and bulk viscosities during the liquid QGP stage. For simplicity, we assume the QGP specific shear viscosity η/s to be a temperature-independent, adjustable constant. For the specific bulk viscosity ζ/s , which is expected to develop a strong peak due to critical scattering close to the quark-hadron phase transition, we adopt the temperature-dependent parametrization given in [10] (which features a peak at $T_{\text{peak}} = 180$ MeV), but consider its normalization as a freely tunable parameter. In practice, peak values of ζ/s exceeding 1 (corresponding to bulk viscosity normalization factors > 3) cause the (negative) bulk viscous pressure to become very large near T_{peak} , leading to negative total pressures and mechanical instability of the medium against cavitation. These physical instabilities also eventually render the hydrodynamic code numerically unstable.

3. Results

We found in [8] that an extended pre-equilibrium stage increases the final radial flow, leading to flatter p_T -spectra, while leaving the integrated charged hadron v_2 and v_3 almost unchanged unless τ_s significantly exceeds 2 fm/c. Bulk viscosity inhibits radial flow build-up, so the constraint from the measured p_T distributions causes a strong positive correlation between τ_s and the bulk viscosity normalization factor. The experimental charged hadron elliptic flow constraint anticorrelates bulk and shear viscosity; at low p_T , the bulk viscous correction δf_{bulk} at T_{sw} acts

as an effective positive chemical potential for massive hadrons [12], causing an anticorrelation between the bulk viscosity normalization factor and the chemical decoupling temperature T_{sw} .

Fig. 1. *Upper panel:* Likelihood distributions for each of the four fit parameters are shown on the diagonal, correlations between them in upper right triangle of plots, and 2-dimensional projections of the likelihood distributions for pairs of parameters (with dark red indicating the most likely regions) in the lower triangle of plots. *Lower panels:* p_T distributions for pions, kaons and protons (left), Λ , Ξ and Ω (middle), and the differential elliptic flows for π , K , p and Λ (right) from 400 hydrodynamic simulations with fluctuating initial conditions, each oversampled 400 times with UrQMD to obtain sufficient particle statistics. Solid lines: full VISHNU runs. Dashed lines: pure hydro runs with immediate freeze-out at T_{sw} , without subsequent hadronic rescattering using UrQMD. Experimental data from ALICE [11].

These tendencies are illustrated in the top panel of Fig. 1 for which we ran VISHNU simulations with smooth ensemble-averaged MC-Glauber initial conditions for 10-20% central Pb-Pb collisions at 2.76 A GeV for 1000 different quadruplets of the parameters listed in Table 1, calculated the experimental observables listed in the same table (chosen for their insensitivity to initial-state event-by-event fluctuations), determined the χ^2 for each quadruplet by comparing them with the experimental values, and then reconstructed the posterior likelihood distributions in the 4-dimensional parameter space using MCMC sampling [13]. For the set with the lowest χ^2 , listed in the lower left panel of Fig. 1, we then ran 400 event-by-event VISHNU simulations with fluctuating initial conditions, each oversampled 400 times in the UrQMD stage for suffi-

cient particle statistics, to predict the full transverse momentum distributions and their elliptic flows $v_2(p_T)$ for the specific hadron species shown in the bottom row of Fig. 1.

$\langle v_2^{\text{ch}} \rangle$ [14]	0.0782 ± 0.0019	parameter	best	mean	95% C.I.
$\langle v_3^{\text{ch}} \rangle$ [14]	0.0316 ± 0.0008	τ_s (fm/c)	2.233	1.889	1.187 - 2.591
$\langle p_T \rangle_{\pi^+}$ (GeV/c) [15]	0.542 ± 0.018	η/s	0.135	0.143	0.124 - 0.161
$\langle p_T \rangle_{K^+}$ (GeV/c) [15]	0.825 ± 0.028	T_{sw} (MeV)	133.4	134.0	128.5 - 151.1
$\langle p_T \rangle_p$ (GeV/c) [15]	1.311 ± 0.043	bulk norm.	3.998	3.277	N/A
$\langle p_T^2 \rangle_p$ (GeV ² /c ²) [15]	2.085 ± 0.070				
$(dN_{\pi^+}/dy)/(dN_{K^+}/dy)$ [15]	6.691 ± 0.670				
$(dN_{\pi^+}/dy)/(dN_p/dy)$ [15]	21.667 ± 2.292				
$(dN_{\pi^+}/dy)/(dN_{\Lambda}/dy)$ [15]	26.765 ± 3.639				

Table 1. *Left:* Measured values of nine hadronic observables from 2.76 A TeV 10–20% central Pb+Pb collisions used to constrain the model parameters listed on the right. $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ are truncated means calculated from the data tables for the transverse momentum distributions listed in [15]. *Right:* Best-fit parameters and 95% confidence intervals (C.I.) using the results from Markov Chain Monte Carlo sampling of the posterior parameter distribution shown in Fig. 1 (top).

To illustrate the effect of the microscopically simulated late hadronic rescattering stage on these observables we also added dashed lines illustrating their state at the end of the fluid stage at T_{sw} . Protons and Λ s experience a significant radial boost from UrQMD, pushing their yields and elliptic flows to larger transverse momenta. Since Λ s in UrQMD scatter with reduced cross sections relative to those of protons, this shift towards larger p_T is weaker for Λ s than for protons; as a result, the hydrodynamically predicted elliptic flow mass ordering between protons and Λ s at T_{sw} , clearly visible in the dashed lines in the lower right panel of Fig. 1 and also in the experimental data [11], is basically eliminated after hadronic rescattering, although not inverted as previously observed in the VISHNU model without pre-equilibrium dynamics [16]. A shorter lifetime of the hadronic rescattering stage could help to keep this from happening.

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