Pre-equilibrium dynamics and heavy-ion observables

Ulrich Heinz and Jia Liu

Physics Department, The Ohio State University, Columbus, OH 43210, USA

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 eBE-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 $\tau_s$ from pre-equilibrium to hydrodynamics, the specific shear viscosity $\eta/s$, the normalization factor of the temperature-dependent specific bulk viscosity $\zeta(T)$, 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 $\pi$, $K$, $p$, $\Lambda$, $\Xi$ and $\Omega$ 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].

Work supported by the DOE, Office of Science, Office of Nuclear Physics under Award No. DE-SC0004286. Computing resources provided by the Ohio Supercomputer Center. Thanks to Chun Shen for fruitful discussions.
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 $\tau_s$ 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 $\tau_s$ 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 $\tau_s$ 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 $\tau_s$ 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 $T_c \approx 155$ 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 $\eta/s$ to be a temperature-independent, adjustable constant. For the specific bulk viscosity $\zeta/s$, 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 $\zeta/s$ exceeding 1 (corresponding to bulk viscosity normalization factors > 3) cause the (negative) bulk viscous pressure to become very large near $T_{\text{peak}}$, 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 $\tau_s$ 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 $\tau_s$ 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 $\delta f_{\text{bulk}}$ 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 $T_{sw}$.

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 $\chi^2$ 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 $\chi^2$, 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 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].
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 Markoff Chain Monte Carlo sampling of the posterior parameter distribution shown in Fig. 1 (top).

| Parameter | Best Mean | 95% C.I. |
|-----------|-----------|----------|
| \( \tau_s \) (fm/c) | 2.233 | 1.889 | 1.187 - 2.591 |
| \( \eta/s \) | 0.135 | 0.143 | 0.124 - 0.161 |
| \( T_{sw} \) (MeV) | 133.4 | 134.0 | 128.5 - 151.1 |
| Bulk norm. | 3.998 | 3.277 | N/A |

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 \( \Lambda \)s experience a significant radial boost from UrQMD, pushing their yields and elliptic flows to larger transverse momenta. Since \( \Lambda \)s in UrQMD scatter with reduced cross sections relative to those of protons, this shift towards larger \( p_T \) is weaker for \( \Lambda \)s than for protons; as a result, the hydrodynamically predicted elliptic flow mass ordering between protons and \( \Lambda \)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.

References

[1] C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass and U. Heinz, Comput. Phys. Commun. **199** (2016) 61.
[2] U. Heinz et al., Nucl. Phys. A, in press [arXiv:1509.05818 [nucl-th]].
[3] P. F. Kolb and R. Rapp, Phys. Rev. C 67 (2003) 044903; P. F. Kolb, PhD thesis, Universität Regensburg, 2002.
[4] W. Broniowski, W. Florkowski, M. Chojnacki and A. Kisiel, Phys. Rev. C 80 (2009) 034902.
[5] B. Schenke, P. Tribedy and R. Venugopalan, Phys. Rev. Lett. 108 (2012) 252301.
[6] W. van der Schee, P. Romatschke and S. Pratt, Phys. Rev. Lett. 111 (2013) 222302.
[7] P. Romatschke, Eur. Phys. J. C 75 (2015) 429.
[8] J. Liu, C. Shen and U. Heinz, Phys. Rev. C 91 (2015) 064906.
[9] A. Bazavov et al., HotQCD Collaboration, Phys. Rev. D 90 (2014) 094503.
[10] G. S. Demchen, T. Kodama, T. Koide and P. Mota, Phys. Rev. D 80 (2009) 064001.
[11] R. Preghenella [ALICE Collaboration], arXiv:1203.5904 [hep-ex]; B. B. Abelev et al. [ALICE Collaboration], JHEP 1506 (2015) 190; Phys. Rev. Lett. 111 (2013) 222301; Phys. Lett. B 728 (2013) 216.
[12] K. Dasling and T. Schäfer, Phys. Rev. C 85 (2012) 044909.
[13] C. Quammen, H. Canary, R. M. Taylor II, S. Pratt and J. Wyka https://github.com/MADAI/DistributionSampling/blob/master/doc/manual/
[14] G. Aad et al. [ATLAS Collaboration], JHEP 1311 (2013) 183.
[15] B. B. Abelev et al. [ALICE Collaboration], Phys. Rev. C 88 (2013) 044910; Phys. Rev. Lett. 111 (2013) 222301.
[16] X. Zhu, F. Meng, H. Song and Y. X. Liu, Phys. Rev. C 91 (2015) 034904.