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Probing the early-time dynamics of relativistic heavy-ion collisions with electromagnetic radiation

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Abstract

Using 3 + 1D viscous relativistic fluid dynamics, we show that electromagnetic probes are sensitive to the initial conditions and to the out-of-equilibrium features of relativistic heavy-ion collisions. Within the same approach, we find that hadronic observables show a much lesser sensitivity to these aspects. We conclude that electromagnetic observables allow access to dynamical regions that are beyond the reach of soft hadronic probes.

Keywords: Electromagnetic radiation; Relativistic viscous hydrodynamics; Transport coefficients of strongly interacting media; Initial conditions of relativistic heavy-ion collisions

1. Introduction

Modern relativistic heavy ion colliders, such as the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), are capable of exciting strongly interacting matter to the point where its partonic degrees of freedom become available for experimental investigations. These degrees of freedom form a new state of matter: the Quark Gluon Plasma (QGP). Currently,

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relativistic viscous hydrodynamics provides a good description of the time evolution of the QGP and of the hadronic medium. Owing to their penetrating nature, electromagnetic (EM) probes are sensitive to the *entire* time evolution of the medium created by heavy ion collisions, which allows for a more stringent verification of the hydrodynamical behavior and also imposes more severe constraints on the parameters of the simulation approaches. In this study the sensitivity of EM observables to the initial conditions and to the shear relaxation time of viscous hydrodynamics is investigated.

2. Viscous hydrodynamics

We concentrate on conditions germane to RHIC. To describe the medium produced in nuclear collisions at such energies, we use MUSIC, a 3 + 1D hydrodynamical simulation [1]. The initial configurations are set by the optical Glauber model tuned to hadronic observables. The evolution of the energy–momentum tensor, $T^{\mu\nu}$, is governed by the conservation equation, $\partial_\mu T^{\mu\nu} = 0$. Note that $T^{\mu\nu} = \varepsilon u^\mu u^\nu - \Delta^{\mu\nu} P + \pi^{\mu\nu}$, with ε being the energy density, P the thermodynamic pressure, u^μ the fluid four-velocity, $\pi^{\mu\nu}$ the shear-stress tensor, and $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$ the projection operator onto the 3-space orthogonal to the velocity.

The dynamics of the shear-stress tensor are given by a version of Israel–Stewart (I–S) theory [2,3]:

$$\Delta^{\mu\nu}_{\alpha\beta} u^\lambda \partial_\lambda \pi^{\alpha\beta} + \frac{4}{3}\pi^{\mu\nu}\partial_\lambda u^\lambda = \left(\pi^{\mu\nu}_{\mathrm{NS}} - \pi^{\mu\nu}\right)/\tau_\pi \tag{1}$$

where the Navier–Stokes limit of the shear-stress tensor is $\pi^{\mu\nu}_{\mathrm{NS}} = 2\eta\,\sigma^{\mu\nu} = 2\eta\Delta^{\mu\nu}_{\alpha\beta}\partial^\alpha u^\beta$, with $\Delta^{\mu\nu}_{\alpha\beta} = (\Delta^\mu_\alpha \Delta^\nu_\beta + \Delta^\mu_\beta \Delta^\nu_\alpha)/2 - \Delta_{\alpha\beta}\Delta^{\mu\nu}/3$ being the double, symmetric, traceless projection operator. There are two coefficients, the shear viscosity η, also present in Navier–Stokes theory, and the shear relaxation time, τ_π, which only exists in Israel–Stewart theory. These are the only terms considered in this study. Furthermore, we assume the existence of an effective shear viscosity coefficient that is proportional to the entropy density: $\eta/s = 1/4\pi$. The relaxation time is assumed to be of the form $\tau_\pi = b_\pi[\frac{\eta}{\varepsilon+P}]$, and we will choose here $b_\pi = 3, 5$, and 10. Physically, τ_π governs the rate at which $\pi^{\mu\nu}$ evolves and relaxes towards the Navier–Stokes value. The coefficient b_π is constrained by causality to $b_\pi \geq 4/[3(1 - c_s^2)]$, where c_s is the velocity of sound [4].

To investigate the sensitivity of EM probes to the initial conditions of the medium, we start the fluid dynamic evolution in and out of equilibrium by introducing an initial $\pi^{\mu\nu}_0 = c \times 2\eta\sigma^{\mu\nu}$ where $c = 0, 2$, and $\sigma^{\mu\nu}$ is computed using initial flow $u^\mu_0 = (\cosh\eta_s, 0, 0, \sinh\eta_s)$, with the space–time rapidity given by $\eta_s = (1/2)\ln[(t + z)/(t - z)]$ where t is time and z is the longitudinal coordinate. A practical set of coordinates is hyperbolic space–time variables: $\tau = \sqrt{t^2 - z^2}$ and η_s; in these coordinates $u^\mu_0 = (1, 0, 0, 0)$.

3. Electromagnetic production rates and their viscous corrections

Viscous corrections to EM thermal production rates are introduced by including asymmetric corrections of the form $\delta n = C\, n(p)(1 \pm n(p)) p^\alpha p^\beta \pi_{\alpha\beta}/[2T^2(\varepsilon + P)]$ to the spherically-symmetric, thermal distribution functions $n(p)$ present in the rate calculations [5]. The constant C may be species-dependent [6]; here we shall set $C = 1$. With this formulation, thermal rates become dependent on the out-of-equilibrium hydro-evolution of $T^{\mu\nu}$. For dileptons, we use the quark–antiquark annihilation rate into dileptons at leading order (Born approximation) to describe the virtual photon emission of the QGP phase. In the hadronic sector, our rates are based