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Constraint on initial conditions from nonlinear causality

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Relativistic hydrodynamics has played a vital role in understanding the bulk and the transport properties of the deconfined nuclear matter, the quark gluon plasma, created in high-energy nuclear collision. It is often supposed that the local equilibrium is reached rapidly after the collisions and that the created matter starts to behave as a fluid with small viscous effects subsequently. It is, however, not at all trivial from which stage just after the collision the fluid picture can be applied to the system. In this study, we address this issue from a point of view of nonlinear causality.

In a recent study, necessary and sufficient conditions have been obtained for the system to be causal from the analysis of characteristic velocity of nonlinear relativistic dissipative hydrodynamic equations [1]. By analyzing numerical solutions of hydrodynamic equations from these conditions, it turned out that the causality is likely to be violated in the early stage [2]. This strongly suggests that the violation of causality occurs when the system is away from the local equilibrium.

In this study, we employ a one-dimensional expanding system [3], establish a relation between a degree of nonequilibrium and violation of causality and scrutinize whether solutions for given initial conditions obey causality. We find the inverse Reynolds number, which is a measure of nonequilibrium, is highly constrained from nonlinear causality. We also demonstrate how the solution violates or obeys the causality in a one-dimensional expanding system. We also obtain the minimum initial proper time allowed from the nonlinear causality and the observed transverse energy at RHIC and LHC. This sheds light on understanding the initial stages in high-energy nuclear collisions.

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[2] C. Plumberg *et al.*, Phys. Rev. C **105**, 061901 (2022).
[3] J.D. Bjorken, Phys. Rev. D **27**, 140 (1983).

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