Collinear parton splitting for early thermalization and chemical equilibration in heavy-ion collisions

A. Monnai[*1] and B. Müller[*2,*3]

High-energy heavy-ion collisions at the BNL Relativistic Heavy Ion Collider (RHIC) and CERN Large Hadron Collider (LHC) are the gateway to the early universe, where quarks and gluons are deconfined from hadrons. The strong elliptic flow observed suggests that the system is thermally equilibrated within a very short time $\tau_{\rm th} = 0.5$-1 fm/c, at which point relativistic hydrodynamics becomes a valid description of the bulk medium. The mechanism that leads to the early equilibration, on the other hand, is still not well known. A theoretical explication of the formation of a QCD droplet is of high importance in collider physics.

In this work, we propose a phenomenological description of the local early equilibration based on collinear parton splitting and recombination[1)]. Equilibration of a heavy-ion system requires (i) thermalization, (ii) chemical equilibration, and (iii) isotropization since the colliding nuclei are described as the color glass condensate where gluons are saturated up to the typical momentum $p \simeq Q_s$[2)]. Collinear splitting introduces two low-momentum partons from a high-momentum incident parton. This is suitable for the description of the first two types of equilibration because the thermal distribution has a relatively large number of low-momentum partons. The processes we consider are (a) splitting of a gluon into two gluons, (b) gluon emission by quarks and (c) quark-antiquark pair production. Momentum fraction in a splitting is governed by the parton splitting functions[3)]. The rate of splitting in a dimensional analysis is given as $\Gamma \simeq \alpha_s^{1/2}(\hat{q}/p)^{1/2}$, where α_s is the QCD coupling and $\hat{q}$ is the transport coefficient for momentum diffusion. The recombination processes are introduced phenomenologically; hence, the equations of motion for the quark and the gluon phase-space distributions satisfy the second law of thermodynamics. The effects of elastic scattering, which creates off-shell partons, are encoded in the model via the Focker-Planck equation. The detailed expressions of the equations of motion can be found here[1)].

We perform numerical estimations with a non-expanding (1+1)-dimensional geometry to investigate the qualitative properties of the equilibration model. Figure 1 shows the gluon distribution of a pure gluon system before and after time-evolution. The effective degrees of freedom are included in the definition of the phase-space distribution. Here, the initial condition is a color-glass-like one where $f^g(p=0) \simeq 1/\alpha_s$ and $Q_s \simeq 2$ GeV. The system almost thermalizes at 0.8 fm/c when the initial time is 0.2 fm/c. Next, we consider the case when $N_f = 3$ and obtain the gluon and the quark distributions shown in Fig. 2. Here, the system approaches the thermalized state rather quickly, but the effective numbers of degrees of freedom remain far from those in equilibrium owing to the slowness of the quark chemical equilibration process. For the current parameter settings, the typical time required for chemical equilibration is estimated as $\tau_{\rm chem} \simeq 2$ fm/c. The results imply that collinear parton splitting and recombination play an important role in the early-time dynamics of heavy-ion collisions, and the quark-gluon plasma at the onset of hydrodynamic evolution can be gluon-rich.

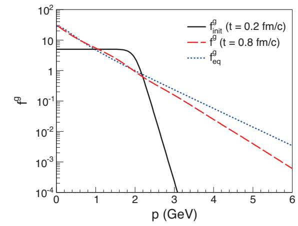

Fig. 1. Gluon distribution before and after the time-evolution compared with that in equilibrium.

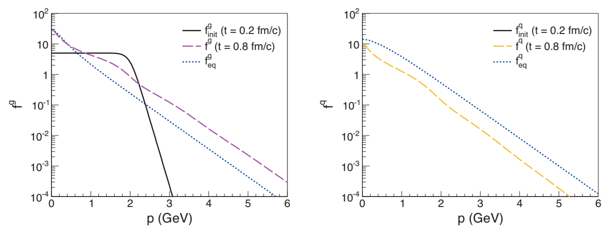

Fig. 2. (Left panel) Gluon and (right panel) quark distributions before and after the time-evolution compared with those in equilibrium.

Future prospects include improvement of the model parameters and development of a (3+1)-dimensional numerical model for quantitative description of isotropization in such QCD systems.

*1 RIKEN Nishina Center
*2 Physics Department, Duke University
*3 Brookhaven National Laboratory

References

1) A. Monnai and B. Müller: arXiv:1403.7310 [hep-ph].
2) L. D. McLerran and R. Venugopalan: Phys. Rev. D **49**, 2233 (1994); D **49**, 3352 (1994).
3) G. Altarelli and G. Parisi: Nucl. Phys. B **126**, 298 (1977).