18th Joint European Thermodynamics Conference
Belgrade, May 26–30, 2025

THERMAL NONEQUILIBRIUM AND QUARK-GLUON PLASMA

Johann Rafelski*, Cheng Tao Yang

Department of Physics, The University of Arizona, Tucson, Arizona 85721, USA
*JohannR@arizona.edu

ABSTRACT

The Universe folloqing on electroweak transformation at a temperature $T \simeq 125\,\text{GeV}$ was dominated during the folloqing $25\mu s$ by strongly interacting particles [1] quarks and gluons forming a new state of matter, the color deconfined Quark-Gluon Plasma (QGP) for $T > 150\,\text{MeV}$. In the laboratory environment QGP is formed in highly relativistic collisions of heaviest nuclei reaching $T \simeq 0.5\,\text{GeV}$; therefore thermalization of collision energy into thermal motion of a large number of newly created strongly interacting quarks and gluons is required for QGP state formation, a challenging frontier of ongoing research [2].

For the strong QCD force the thermal reaction rates in QGP have been studied in depth [1] as the lifespan of laboratory QGP $O(\infty/^{-\in\in}$ s) is of comparable magnitude. The expansion of the Universe is described by the Hubble parameter H which is many (*e.g.* 15-18) orders of magnitude slower [3] compared to microscopic reaction rates. Even so, we find that nonequilibrium of physical significance arises both, in the laboratory formed QGP environment, especially during transformation into normal matter gas phase, and in the primordial Universe.

The importance of any nonstationary condition in expanding QGP Universe is that this is the dynamic requirement for baryogenesis: We are searching for the origin of matter. To form matter we need ireversibilitiy among microscopic processes allowing emergence of newly formed baryons. In the study of nonstationary condition we distinguish between two possible nonequilibrium features inherent to QGP: i) The abundance (chemical) nonequilibrium and; ii) the momentum distribution (kinetic) nonequilibrium. The important difference between nonequilibrium and nonstationary condition is that latter requires time dependence, that is expansion of the Universe. I will describe both bottom quark flavor nonstationary condition which arises near to Universe hadronization [3], and Higgs particle dynamics in QGP across a large temperature range [4]. For the Higgs the two salient feature are that it practically does not scatter on low mass QGP particles and its decay channels into virtual gauge mesons are not reversible. The abundance of heavy particles in the Universe is shown in Fig. 1 as a function of Temperature T assuming equilibrium.

The laboratory environment is different [5] due to the rapid expansion-dilution of the high density QGP matter created in in laboratory ultra-relativistic nuclear collisions. Therefore, the laboratory situation allows to use the quark-flavor nonequilibrium to characterize the QGP properties [6], leading to the recognition of QGP as the new state of deconfined matter. To isolate the physical processes a detailed comparison of experimental results with theoretical models allowing for chemical non-equilibrium is required to achieve appropriate level of understanding of all physical mechanisms [7].

Keywords: Quark Deconfinement, Quark-Gluon Plasma, Higgs Particle, Baryogenesis,

Physics and Astronomy Classification Scheme: 05.70.Ln, 12.38.Mh, 14.65.-q, 14.80.Bn, 25.75.Nq, 98.80.Cq

REFERENCES

[1] J. Letessier and J. Rafelski, *Hadrons and Quark–Gluon Plasma*, Cambridge University Press, Cambridge, UK 2002.

[2] L. Ebner, B. Müller, A. Schäfer, L. Schmotzer, C. Seidl and X. Yao, *Entanglement Properties of SU(2) Gauge Theory*, [arXiv:2411.04550 [hep-lat]].

[3] J. Rafelski, J. Birrell, C. Grayson, A. Steinmetz and C. T. Yang, *Quarks to Cosmos: Particles and Plasma in Cosmological evolution*, Eur. Phys. J. ST (2025) in press, [arXiv:2409.19031 [hep-ph]].

[4] J. Rafelski and C. T. Yang, *Higgs in The Cosmos*, [arXiv:2503.03224 [hep-ph]].

[5] J. Rafelski, *Discovery of Quark-Gluon-Plasma: Strangeness Diaries*, Eur. Phys. J. ST **229**, no.1, 1-140 (2020) [arXiv:1911.00831 [hep-ph]].

[6] J. Rafelski and M. Petran, *QCD phase transition studied by means of hadron production*, Phys. Part. Nucl. **46**, no.5, 748-755 (2015) [arXiv:2212.13302 [hep-ph]].

[7] P. Koch, B. Müller and J. Rafelski, *From Strangeness Enhancement to Quark–Gluon Plasma Discovery*, Int. J. Mod. Phys. A **32**, no.31, 1730024 (2017) [arXiv:1708.08115 [nucl-th]].

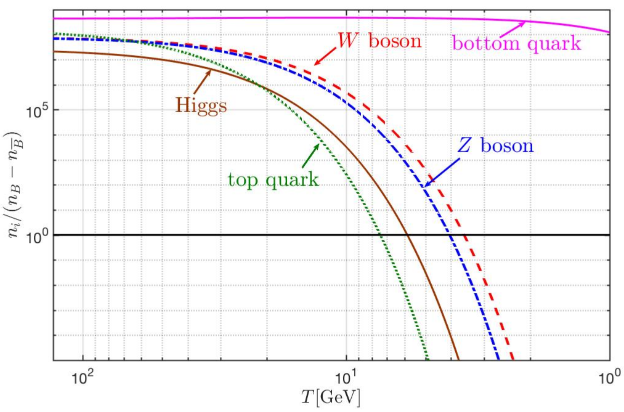

Figure 1: Thermal primordial QGP heavy particle abundances normalized by the net baryon abundance $n_B - \bar{n}_B$ as a function of Universe temperature T.