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Review

Effective QCD and transport description of dilepton and photon production in heavy-ion collisions and elementary processes

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ABSTRACT

In this review we address the dynamics of relativistic heavy-ion reactions and in particular the information obtained from electromagnetic probes that stem from the partonic and hadronic phases. The out-of-equilibrium description of strongly interacting relativistic fields is based on the theory of Kadanoff and Baym. For the modeling of the partonic phase we introduce an effective dynamical quasiparticle model (DQPM) for QCD *in equilibrium*. In the DQPM, the widths and masses of the dynamical quasiparticles are controlled by transport coefficients that can be compared to the corresponding quantities from lattice QCD. The resulting off-shell transport approach is denoted by Parton–Hadron–String Dynamics (PHSD) and includes covariant dynamical transition rates for hadronization and keeps track of the hadronic interactions in the final phase. It is shown that the PHSD captures the bulk dynamics of heavy-ion collisions from lower SPS to LHC energies and thus provides a solid basis for the evaluation of the electromagnetic emissivity, which is calculated on the basis of the same dynamical parton propagators that are employed for the dynamical evolution of the partonic system. The production of *direct* photons in elementary processes and heavy-ion reactions is discussed and the present status of the photon v_2 "puzzle" – a large elliptic flow v_2 of the *direct* photons experimentally observed in heavy-ion collisions – is addressed for nucleus–nucleus reactions at RHIC and LHC energies. The role of hadronic and partonic sources for the photon spectra and the flow coefficients v_2 and v_3 is considered as well as the possibility to subtract the QGP signal from the experimental observables. Furthermore, the production of e^+e^- or $\mu^+\mu^-$ pairs in elementary processes and A + A reactions is addressed. The calculations within the PHSD from SIS to LHC energies show an increase of the low mass dilepton yield essentially due to the in-medium modification of the ρ-meson and at the lowest energy also due to a multiple regeneration of Δ-resonances. Furthermore, pronounced traces of the partonic degrees-of-freedom are found in the intermediate dilepton mass regime ($1.2\text{ GeV} < M < 3\text{ GeV}$) at relativistic energies, which will also shed light on the nature of the very early degrees-of-freedom in nucleus–nucleus collisions.

Contents

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1. Introduction

Present experiments at the Relativistic Heavy-Ion Collider (RHIC) or the Large Hadron Collider (LHC) have reached for short time scales the conditions met in the first micro-seconds in the evolution of the universe after the 'Big Bang'. The 'Big Bang' scenario implies that on these time scales the entire state has emerged from a partonic system of quarks, antiquarks and gluons – a quark–gluon plasma (QGP) – to color neutral hadronic matter consisting of interacting hadronic states (and resonances) in which the partonic degrees-of-freedom are confined. The nature of confinement and the dynamics of this phase transition is still an outstanding question of today's physics. Early concepts of the QGP were guided by the idea of a weakly interacting system of massless partons which might be described by perturbative QCD (pQCD). However, experimental observations at RHIC and LHC indicated that the new medium created in ultra-relativistic heavy-ion collisions is interacting more strongly than hadronic matter. It is presently widely accepted that this medium is an almost perfect liquid of partons as suggested experimentally from the strong radial expansion and the scaling of the elliptic flow $v_2(p_T)$ of mesons and baryons with the number of constituent quarks and antiquarks. While the last years have been devoted to explore the collective and transport properties of this partonic medium, the present focus lies on the electromagnetic emissivity of the new type of matter, i.e. its emission of *direct* photons or dilepton pairs. Since the system is initially far from equilibrium and no clear evidence has been achieved so far that an early equilibration at times of the order of 0.5–1.0 fm/c is achieved, microscopic studies based on non-equilibrium dynamics are mandatory.

Non-equilibrium many-body theory or transport theory has become a major topic of research in nuclear physics, in cosmological particle physics as well as condensed matter physics. The multidisciplinary aspect arises due to a common interest to understand the various relaxation phenomena of quantum dissipative systems. Important questions in nuclear