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Quark scattering off quarks and hadrons

A.V. Friesen, Yu.L. Kalinovsky, V.D. Toneev

Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia

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Abstract

The in-medium elastic scattering $qq \to qq, q\bar{q} \to q\bar{q}$ and $\bar{q}\bar{q} \to \bar{q}\bar{q}$ is calculated within the two-flavor Polyakov-loop-extended Nambu–Jona-Lasinio model. The integral and differential quark–quark scattering, its energy and temperature dependence are considered and their flavor dependence is emphasized. The comparison with results of other approaches is presented. The consideration is implemented to the case of quark–pion scattering characterizing the interaction between quarks and hadrons in a kinetic multiphase treatment, and the first estimate of the quark–pion cross sections is given. A possible application of the obtained results to heavy ion collisions is shortly discussed.

Keywords: Quark–gluon plasma; Quark; Hadron; Scattering; Cross section

1. Introduction

To describe high-energy nuclear physics, the knowledge of the in-medium behavior of quasi-particles such as quarks, gluons, mesons and baryons including their antiparticles is crucial. The quantum chromodynamics (QCD) seems to be the best tool to proceed to this study. Nevertheless, it is well known that the direct implementation of the QCD Lagrangian is not feasible in this state except for some particular cases. In order to avoid the QCD difficulties, some effective models were developed.

In this respect, the low-energy particle sector is well described by effective chiral theories of QCD, the Nambu and Jona-Lasinio (NJL) model [1]. The advantage of this model is that it can be studied in the entire temperature range. The NJL model also offers a simple intuitive view of chiral symmetry breakdown and restoration via the realization of the quark–antiquark pairing similar to the BCS theory of superconductivity. However, a simple point-like interaction form of the model does not ensure its renomalizability, and a cutoff scale Λ must be introduced in

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the theory. The impossibility to treat the confinement–deconfinement phase transition and the absence of gluons are other important defects of the NJL model.

To eliminate partially these defects, it has recently been proposed to couple the quarks to a Polyakov loop [2,3] as a mechanism that could simulate the confinement, even if the model does not consider the color degrees of freedom as done in QCD. This realized approach is called the Polyakov–Nambu–Jona-Lasinio model (PNJL) [4–8]. Some recent results show that this approach, exhibiting a smooth crossover at zero baryon density and a first-order phase transition at a large baryon chemical potential, provides some advantages [4,7]. In particular, the extended model allows one to correctly reproduce lattice data of QCD thermodynamics [5,9] as well as to improve the NJL model at low temperature due to the suppression of the contribution of colored states. In addition, the PNJL model is more efficient for describing the restoration of the chiral symmetry by a rapid decrease in the effective masses of the quarks [9]. Nevertheless, the phase structure and its dependence on thermodynamic variables is still an open problem and raises some interesting questions including chiral symmetry restoration, color superconductivity, and charged pion condensation phenomena. In particular, it has been found that if the isospin chemical potential μ_I in a charge neutral quark matter is lower than the critical value required for the realization of the pion condensation, pions do not condense and, therefore, even above the critical temperature a bound state with the pion quantum numbers can be formed [10].

At high temperatures ($T > 300$ MeV) it is supposed that the PNJL description is reliable up to a temperature of approximately $2.5T_c$. For still higher temperatures the transverse gluons, ignored in the PNJL treatment, are expected to be non-negligible [11]. The strong interaction in such a nonperturbative regime of the deconfinement phase is taken into account through an effective temperature-dependent mass for the gluons with a Polyakov-loop background, leaving open the possibility that lighter quasiparticles propagate in the medium [12–14].

Allowability of quark–gluon degrees of freedom along with hadronic ones means that the model for heavy-ion collisions should be multiphase in nature and include possible phase transitions between different phases. Generally, this complicated situation can be described in terms of hydrodynamics or kinetics which have their own advantages and disadvantages. The use of kinetics for the quark–gluon phase needs knowledge of in-medium cross sections for its constituents. In A MultiPhase Transport (AMPT) model [15] this phase is described in terms of the parton cascade with the partonic elastic cross sections estimated within the perturbative QCD (pQCD). The effect of the surrounding matter was roughly included by introducing the effective Debye mass.

The microscopic quark dynamics is studied in a more elaborated way in the Parton Hadron String Dynamics (PHSD) model [16–18] where the plasma evolution is solved by a Kadanoff–Baym type equation. Here the potentials between the plasma constituents are chosen in such a way that the model equation of state is consistent with lattice calculations. The cross sections are derived from the spacelike part of the interaction and are employed for the scattering interactions among the plasma constituents. In this model, gluons as well as quarks acquire a large mass when approaching the phase transition. Therefore, the prehadrons which are created in the phase transition are rather heavy. Another model which allows for these studies is a gluonic cascade realized in the Boltzmann Approach to Multi Parton Scattering (BAMPS) [19]. The gluon emission and interaction during the expansion stage of the QGP move the system towards equilibrium. A parton cascade approach with a pQCD inspired cross section was applied also at the RHIC energy to study scaling properties of the elliptic flow [20] and 'chemical' composition of the quark–gluon plasma [21].