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Quark pair creation in color electric fields and effects of magnetic fields

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ABSTRACT

The time evolution of a system where a uniform and classical SU(3) color electric field and quantum fields of quarks interact with each other is studied focusing on non-perturbative pair creation and its back reaction. We characterize a color direction of an electric field in a gauge invariant way, and investigate its dependence. Momentum distributions of created quarks show plasma oscillation as well as quantum effects such as the Pauli blocking and interference. Pressure of the system is also calculated, and we show that pair creation moderates degree of anisotropy of pressure. Furthermore, enhancement of pair creation and induction of chiral charge under a color magnetic field which is parallel to an electric field are discussed.

1. Introduction

Study of non-perturbative pair creation from a classical electric field, which is known as the Schwinger mechanism [1], has a long history and wide range of applications (see Ref. [2] for a recent review). One of those applications can be found in studies of relativistic heavy-ion collisions, where the Schwinger mechanism has been used as a mechanism of matter formation from a color flux tube [3]. The color flux-tube model assumes that a strong color electric field is formed in a beam direction just after two nuclei collide and pass through each other [4,5]. Formation of longitudinal color electric fields is also predicted in the framework of color glass condensate [6,7]. Therefore, particle production due to the Schwinger mechanism attracts renewed interest [8–12].

Under these circumstances, getting an understanding of how an initial electric field and created particles evolve in time is of prime importance. To properly describe the time evolution, calculating vacuum persistence probability or pair creation probability, which were first derived by Schwinger, is not sufficient [13], and an electric field should be treated as a dynamical variable rather than a background field controlled by hand, i.e. back reaction should be taken into account. There have been considerable numbers of

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studies treating back reaction; the ones based on a kinetic theory [3,14,15] and the others on quantum field theory [13,16–19]. To our knowledge, however, field theoretical treatment of the back reaction problem under a *color* electric field has been lacking. Therefore, in this paper we investigate the pair creation of quarks under a color electric field incorporating back reaction.

In studies of physics under non-Abelian electromagnetic fields, SU(2) theory has been often used for simplicity. In the case of SU(3), however, a new feature arises: anisotropy in color space. It has been shown that an SU(3) color electric field has two independent directions and it is characterized by two gauge invariant parameters: one of them is determined by its field strength and the other is related with the color direction of the field [20,21]. More generally, an SU(N_c) color vector has (N_c-1)-independent directions in color space, and physical contents can generally depend on a color direction of an electric field [22]. In this paper, we deal with SU(3) color electric fields and examine the color direction dependence.

Not only new features which arise in non-Abelian fields, we also analyze phenomena whose essence is common to the Abelian case. Collective motion of created particles which couples to an electric field shows plasma oscillation. During this evolution, several phenomena are observed: suppression of pair creation or annihilation of the particles due to the Pauli blocking, damping of the electric field, and rapid oscillations in the momentum distribution of the created particles due to interference. We shall give an analysis of these phenomena to advance an understanding of physics in pair creation.

We take a uniform color electric field as an initial state. Pressure of this initial state is quite anisotropic: the longitudinal pressure is negative and the transverse pressure is positive. Therefore, if local thermalization is achieved starting from the flux-tube initial condition, isotropization of pressure should be needed during the time evolution. However, the full understanding of a thermalization process in heavy-ion collisions has not been obtained. In this paper, we examine the role of pair creation for the isotropization of pressure as a first step to understand a mechanism of thermalization in heavy-ion collisions.

One of remarkable differences of the color flux tube given by the color glass condensate from that in the original flux-tube model is the existence of a longitudinal color magnetic field in addition to an electric field [7]. It has been shown that a longitudinal magnetic field enhances pair creation of fermions and speeds up the decay of an electric field in the previous paper [13]. We extend it to the quark pair creation under a longitudinal color electric and magnetic field.

Furthermore, we study induction of chiral charge due to pair creation under a magnetic field. Since the chiral anomaly is a semi-classical effect where the quantum aspect of a gauge field is unnecessary, we can also apply our framework to study the chiral anomaly due to pair creation. The relation between pair creation and the chiral anomaly has been also studied in Refs. [24,25]. Emergence of a nonzero chirality in heavy-ion collisions attracts interest in the context of the chiral magnetic effect [23].

The remainder of this paper is organized as follows. In the next section, we shall explain the Abelianization of a color electromagnetic field, and introduce the parameter characterizing the color direction of the field. Although this formalism is essentially the same as that given in Ref. [26], we make the existence of color direction dependence clearer with the help of the method in Refs. [20,21]. In Section 3, we introduce a time-dependent particle picture to describe the time evolution of the system. Then, we shall show our numerical results in Section 4. Time evolution of momentum distribution functions of created quarks, color current density, electric field strength and pressure of the system are displayed and discussed. Color direction dependence of the results is also examined there. In Section 5, the effects of a longitudinal magnetic field, i.e. enhancement of pair creation and induction of chiral charge, are discussed.

2. General framework

Quark pair creation incorporated with back reaction is described by the following Lagrangian density

$$\mathcal{L} = \bar{\psi}\left(i\gamma^{\mu}D_{\mu}-m\right)\psi-\frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu}, \tag{1}$$

where ψ is a quark field and color indices $i(i=1,2,\ldots,N_c)$ are omitted. We assume for simplicity that each flavor has the same mass m, and flavor indices are also omitted. The number of flavor is set to be $N_f=3$ throughout this paper.