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Review

Heavy-flavor production in heavy-ion collisions and implications for the properties of hot QCD matter

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ABSTRACT

Hadrons carrying open heavy flavor, i.e. single charm or bottom quarks, are among the key diagnostic tools available today for the hot and dense state of strongly interacting matter which is produced in collisions of heavy atomic nuclei at ultra-relativistic energies. First systematic heavy-flavor measurements in nucleus–nucleus collisions and the reference proton–proton system at Brookhaven National Laboratory's (BNL) Relativistic Heavy Ion Collider (RHIC) have led to tantalizing results. These studies are now continued and extended at RHIC and at CERN's Large Hadron Collider (LHC), where considerably higher collision energies are available. This review focuses on experimental results on open heavy-flavor observables at RHIC and the LHC published until July 2012. Yields of heavy-flavor hadrons and their decay products, their transverse momentum and rapidity distributions, as well as their azimuthal distributions with respect to the reaction plane in heavy-ion collisions are investigated. Various theoretical approaches are confronted with the data and implications for the properties of the hot and dense medium produced in ultra-relativistic heavy-ion collisions are discussed.

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1. Introduction

1.1. Strongly interacting matter in ultra-relativistic heavy-ion collisions

Quantum chromodynamics (QCD) is the underlying theory of the strong interaction [1]. At sufficiently high temperature, T, or baryo-chemical potential, μ_B, QCD inspired model calculations predict a phase transition of strongly interacting matter from a system of hadrons to a deconfined medium, dubbed a quark–gluon plasma (QGP), in which the relevant degrees of freedom are of partonic nature [2–4]. At zero baryo-chemical potential, corresponding to zero net baryon density, QCD calculations on a discretized space–time lattice [5–7] indicate that the phase transition is of the cross over type [8–10]. The critical temperature, T_C, is still not known precisely even for $\mu_B = 0$. Values in the range $150 < T_C < 190$ MeV, corresponding to an energy density in the vicinity of 1 GeV/fm^3, have been quoted [11,12]. However, even larger values in the range $180 < T_C < 200$ MeV cannot be excluded [13]. For nonzero baryo-chemical potential lattice QCD calculations become significantly more difficult. Some calculations predict that the phase transition remains of the cross over type for all values of μ_B. Several others indicate that towards higher μ_B the phase transition will eventually be of first order. Consequently, this would imply the existence of a critical point in the phase diagram of strongly interacting matter. At very high μ_B the presence of more exotic phases, e.g. color superconducting forms of strongly interacting matter, is expected [14–16]. A schematic QCD phase diagram is shown in Fig. 1.

Strongly interacting matter at extreme temperature and/or density is not only of fundamental interest in the context of mapping out the QCD phase diagram, but it is also of astrophysical relevance. The early universe is believed to have spent its first few microseconds after the big bang in the state of a quark–gluon plasma at high temperature and zero baryo-chemical potential. Hadronization took place when the universe expanded and cooled down below T_C. QGP matter at high density and moderate temperature might be present today inside of neutron stars [17], or it might be created briefly during the core collapse of a supernova explosion [18,19].

Collisions of heavy atomic nuclei at ultra-relativistic energies provide the unique opportunity to investigate experimentally the properties and the dynamics of hot and dense QCD matter in the laboratory, because only in such collisions the necessary temperature or density can be reached.

First "circumstantial evidence" for the production of a quark–gluon plasma was reported [20] from the fixed target heavy-ion program at the CERN Super Proton Synchrotron (SPS), where collisions of lead nuclei (Pb + Pb) were investigated at energies per nucleon–nucleon pair up to $\sqrt{s_{NN}} = 17.3$ GeV in the center of mass frame. Experiments with colliding gold nuclei (Au + Au) at $\sqrt{s_{NN}} = 200$ GeV at the dedicated BNL Relativistic Heavy Ion Collider (RHIC) have substantiated these findings and have led to a first quantitative characterization of the properties of the QGP [21–24], revealing some surprises. Here, only some of the most striking observations are briefly summarized.

The initially produced fireball has such a high temperature and density that the partons, i.e. quarks and gluons, equilibrate on a time scale of less than 1 fm/c. Large pressure gradients in the system lead to a hydrodynamic evolution of the fireball which subsequently expands, cools down, and undergoes hadronization. When the system is cold and dilute enough, the hadrons freeze out chemically and thermally and stream to the detectors. It is important to note that the geometrical shape of the initial equilibrated partonic fireball is asymmetric for collisions with non-zero impact parameter, exhibiting an almond-like shape averaged over many collisions. Consequently, the pressure gradients driving the expansion are asymmetric as well. Thus the initial spatial anisotropy is translated into an azimuthal anisotropy in momentum space of the produced hadrons. Originally, this anisotropy was quantified based on a Fourier expansion of the momentum distribution

$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_t d\phi dp_t dy}\sum_{n=0}^{\infty} 2v_n \cos[n(\phi - \Phi_R)] \tag{1}$$