Progress in Particle and Nuclear Physics 65 (2010) 209–266

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Charmonium and bottomonium in heavy-ion collisions

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ARTICLE INFO

Keywords:
Heavy quarkonia
Quark-Gluon Plasma
Nuclear matter
Ultrarelativistic heavy-ion collisions

ABSTRACT

We review the present status in the theoretical and phenomenological understanding of charmonium and bottomonium production in heavy-ion collisions. We start by recapitulating the basic notion of "anomalous quarkonium suppression" in heavy-ion collisions and its recent amendments involving regeneration reactions. We then survey in some detail concepts and ingredients needed for a comprehensive approach to utilize heavy quarkonia as a probe of hot and dense matter. The theoretical discussion encompasses recent lattice QCD computations of quarkonium properties in the Quark–Gluon Plasma, their interpretations using effective potential models, inelastic rate calculations and insights from analyses of electromagnetic plasmas. We illustrate the powerful techniques of thermodynamic Green functions (T-matrices) to provide a general framework for implementing microscopic properties of heavy quarkonia into a kinetic theory of suppression and regeneration reactions. The theoretical concepts are tested in applications to heavy-ion reactions at SPS, RHIC and LHC. We outline perspectives for future experiments on charmonium and bottomonium production in heavy-ion collisions over a large range of energies (FAIR, RHIC-II and LHC). These are expected to provide key insights into hadronic matter under extreme conditions using quarkonium observables.

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0146-6410/$ – see front matter
doi:10.1016/j.ppnp.2010.07.002

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1. Introduction

The properties of heavy quarkonium states (charmonium and bottomonium) in a hot and dense QCD[1] medium have been intensely studied for over 20 years now, both experimentally and theoretically. Current and upcoming heavy-ion collision experiments at the Relativistic Heavy-Ion Collider (RHIC, at Brookhaven National Laboratory (BNL) in New York), at the Large Hadron Collider (LHC, at the European Organization for Nuclear Research (CERN) in Geneva) and at the Facility for Antiproton and Ion Research (FAIR, at the Helmholtz Center for Heavy-Ion Research (GSI) in Darmstadt) put a large emphasis on heavy quarkonium programs in their campaigns. The interest in heavy quarkonia in medium is motivated by their unique role in the diagnostics of the highly excited medium created in ultrarelativistic heavy-ion collisions (URHICs). Early on, J/ψ suppression in URHICs was suggested as a signal of the formation of a Quark–Gluon Plasma (QGP) [1]. This idea was instrumental in triggering a corresponding experimental program at the CERN-SPS. The experimental results have been accompanied and pushed forward by a broad spectrum of theoretical work (see, e.g., Refs. [2–5] for various reviews). After many years of analysis and interpretation of the SPS data [6], with a first round of RHIC results completed and with new insights from the theoretical side (including thermal lattice QCD, effective models and phenomenology), it is timely to assess the current state of affairs to help facilitate the next stage of developments. In the remainder of this introduction we will give an initial view of the physics of quarkonia in a hot and dense medium, illustrating some of the difficulties in the interpretation of (charmonium) observables in URHICs at SPS and RHIC.

As a starting point, we collect in Tables 1 and 2 basic properties of the bound-state spectrum of a heavy quark ($Q = c$, b) and its antiquark ($\bar{Q}$) in the vacuum (note that the lifetime of the top quark is too short for developing a $t\bar{t}$ bound-state spectrum). These spectra can be well understood in terms of a potential-model approach, where the underlying potential is of the so-called Cornell-type [7],

$$V_{Q\bar{Q}}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r, \tag{1}$$

consisting of a (color-) Coulomb term dominant at small Q–$\bar{Q}$ separation, r, and a linearly rising ("confining") term at large r. The potential description is now understood as a low-energy effective theory of Quantum Chromodynamics (QCD) utilizing an expansion in the inverse heavy-quark mass ($1/m_Q$) [8,9]. Moreover, the pertinent vacuum potential has been computed in lattice QCD [10] and found to agree well with the phenomenological Cornell potential as deduced from applications to quarkonium spectroscopy.

The good understanding of the vacuum properties of heavy quarkonia in a relatively simple framework is one of the reasons why they are believed to be a good probe of medium effects. The latter can be roughly categorized into screening effects in the two-body potential and dissociation reactions with constituents of the heat bath. Since the heavy-quark mass is large compared to the typical temperatures realized in a heavy-ion reaction, a further practical benefit emerges: heavy-quark production is believed to be largely restricted to the earliest phase of the collision, i.e., in primordial "hard" (high-momentum transfer) collisions of the incoming nucleons. On the one hand, this implies a separation of the (hard) production process from the subsequent (soft) medium effects, and, on the other hand, it provides a baseline to determine the initial abundance prior to the formation of the medium. For total charm production, this picture is consistent with current experimental information [12,13] and also supported by theoretical estimates [14].

[1] Quantum Chromodynamics, the theory of the strong force and part of the Standard Model of elementary particle physics.