Available online at www.sciencedirect.com

SciVerse ScienceDirect

Nuclear Physics A 910–911 (2013) 114–122

NUCLEAR PHYSICS A

www.elsevier.com/locate/nuclphysa

Heavy Quarkonium in the Quark Gluon Plasma from Effective Field Theories and Potentials

A. Rothkopf

Institute for Theoretical Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

Abstract

The measurements of heavy quarkonium suppression at RHIC and LHC urge theory to develop intuitive as well as quantitative methods for the description of $Q\bar{Q}$ melting in the quark-gluon plasma. Here I will present a brief sketch on the effective field theory strategies underlying the definition of the heavy quark static potential and report on two recent advances in the extraction and interpretation of such a potential. On the one side, progress has been made in obtaining its values from lattice QCD, which promises to make possible investigating its real and imaginary part non-perturbatively. On the other side, the existence of an imaginary part emphasizes the dynamical nature of the melting process and invites us to make a direct connection to the framework of open quantum systems.

Keywords: heavy quarkonium, effective field theory, in-medium static potential, open quantum system

1. Introduction

The past decade has seen a golden age in the study of relativistic heavy-ion collisions. After the inauguration of the RHIC facility at the Brookhaven National Laboratory in 2000, experimental collaborations such as PHENIX and STAR were able to conclusively deduce the existence of a deconfined phase of strongly interacting matter. In collisions of gold nuclei at a center of mass energy per nucleon of $\sqrt{s_{NN}} = 200\,\text{GeV}$, the occurrence of e.g. elliptic flow [1, 2] and jet quenching [3, 4] provided unambiguous signals for the presence of a quark-gluon plasma (QGP).

Another candidate for a clean signal of deconfinement, introduced in the seminal work by Matsui and Satz [5], is the suppression of heavy quark bound states. Initially interest focussed on the melting of charmonium, the ground state of the $c\bar{c}$ vector channel. Even though the process of melting is amenable to analytic and numerical treatment as we will discuss later on and suppression of heavy quarkonium has been observed [6–9], it has become clear that the dynamics of $c\bar{c}$ in relativistic heavy ion collisions are quite complex. Cold nuclear matter effects (observed already in d + Au collisions) as well as final state effects (e.g. recombination and feed-down) lead to a competition between suppression and replenishment in the occupation of the ground state that is not necessarily related to the intrinsic stability, i.e. melting of the two-body system itself.

The response of bound states to the presence of a thermalized hot medium can be investigated more cleanly once bottom quarks are produced in adequate numbers in collisions. The necessary energies to do so are available at the Large Hadron Collider (LHC) at CERN, which recently commenced its first heavy ion runs, operating at a $\sqrt{s_{NN}} = 2.76\,\text{TeV}$. A dimuon spectrum showing clean signals for ground and two excited states in p + p and melting

---

Email address: `rothkopf@itp.unibe.ch` (A. Rothkopf)

http://dx.doi.org/10.1016/j.nuclphysa.2012.12.083

of the higher lying states in Pb + Pb collisions was published last year by the CMS collaboration [10]. Since $b\bar{b}$ is produced only in limited numbers in the hard processes in the initial phase of the collision, recombination is much less pronounced than for charmonium. Most importantly however, since the top quark is comparatively heavy, there will not be any appreciable feed down from $t\bar{t}$ bound states. This in turn should allow to establish a closer connection between bottomonium spectra and the idealized theoretical descriptions of heavy quarkonium melting.

Several strategies, varying in their degree of sophistication, have been developed to model the suppression of heavy quarkonia in relativistic heavy ion collisions (see e.g. [11–15]). In the following I will solely focus on the subset of the problem that is concerned with the melting of the bound state in an otherwise fully thermalized heat bath. As we will see, a dynamical description is possible within a non-relativistic framework based on effective field theories, which ultimately leads to a potential for a two-body wavefunction in a Schrödinger-type equation.

Past attempts to describe the stability of heavy quarkonium often relied on a static notion of a model potential and the bound states it can support. Since the early works of [16] the color singlet free energies $F^1(r)$ and subsequently the color singlet internal energies $U^1(r)$ or even linear combinations of both quantities were identified with the potential acting between a static Q and $\bar{Q}$ (see e.g. [17]). All of these quantities can be obtained from a suitable correlation function in lattice QCD, which is evaluated at a single imaginary time step $\tau = \beta$. Be aware that these purely real potentials are model choices, since there is no derivation available that connects quantities such as $F^1(r)$ to the real-time evolution of heavy quarkonium in a Schrödinger equation.

Even more interestingly, it has been shown in resummed perturbation theory that the potential in the QGP in general does not only contain a real part but in addition features an imaginary part [18, 19]. Hence the notion of a well defined bound state above the deconfinement temperature appears inapplicable and the question of stability and melting need to be formulated in a truly dynamical fashion.

We wish to show in the following how the Schrödinger equation for $Q\bar{Q}$ arises from a systematic coarse graining procedure, starting from QCD and how the values of the potential can be extracted non-perturbatively from lattice QCD. At last we will briefly touch upon our recent proposal on how to interpret such a, in general complex valued, potential as a manifestation of the open quantum systems nature of the heavy quark bound state.

2. The Effective Field Theory Strategy

A characteristic feature of heavy quarkonium is the presence of a wide separation of intrinsic scales. In the case of bottomonium e.g., the rest mass of the constituent heavy quarks $m_b \simeq 4.6\,\text{GeV}$ is significantly larger than both the dynamical scale of QCD, $\Lambda_{QCD} \sim 200\,\text{MeV}$ and the temperatures around the deconfinement phase transition $T_c \sim 200\,\text{MeV}$. This tells us that neither quantum fluctuations, nor thermal fluctuations are likely to excite a $Q\bar{Q}$ pair from the medium. If the velocity of the constituent quarks is also small, a hierarchy of scales emerges from hard to soft to ultra-soft, $m_Q \gg m_Q v \gg m_Q v^2$, along which appropriate effective field theory descriptions can be constructed [20–22]. The term appropriate means that we have to choose a set of relevant degrees of freedom at each energy scale and determine the most general action for these fields, which is compatible with the symmetries of the underlying field theory.

2.1. *NRQCD: Heavy Quarks as Pauli Spinor Fields*

The first reduction in complexity is achieved by treating explicitly only the physics of heavy quarks and the medium below the hard scale. The process of integrating out the higher energies from the underlying theory of QCD with its matrix valued gauge fields $A^\mu = A^\mu_a T^a$, light quarks of the medium q and the heavy quark field Q

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} F^{\mu\nu a} F_{\mu\nu a} + \sum_{l=1}^{N_f} \bar{q}^l \big(i\gamma^\mu(\partial_\mu + igA^\mu) - m_q^l \big) q^l + \bar{Q}\big(i\gamma^\mu(\partial_\mu + igA^\mu) - m_Q\big) Q, \tag{1}$$

leads us to the theory of NRQCD. The first step to take lies in identifying the degrees of freedom to use.

In case of the heavy quarks, pair production of Q and $\bar{Q}$ cannot persist below the threshold $2m_Q$. Hence it seems advantageous to use the upper ξ and lower components χ of the original Dirac four spinor $Q = (\xi,\chi)$. Fortunately the problem of separating upper and lower components can be treated systematically by use of the Foldy-Tani-Wouthuysen transformation, which amounts to a systematic expansion of the heavy quark part of the QCD action in a series involving terms of increasing powers of m_Q^{-1}. The first few terms in the effective Lagrangian read [21]: