Effective Field Theories for Heavy Quarkonium at Finite Temperature ◇

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Experiments at the past (SPS), present (RHIC) and future (LHC, FAIR) collider facilities are attempting to recreate an early condition of the universe known as the quark-gluon plasma, where quarks and gluons exist without being bound into hadrons. Present colliders explore the zero chemical potential region of the QCD phase diagram where lattice simulations indicate that a significant increase in the degrees of freedom happens above a certain critical temperature $T_c \approx 175$ MeV.

Heavy quarkonium dissociation has been proposed long time ago as a clear probe of the quark-gluon plasma formation in colliders through the measurement of the dilepton decay-rate signal. Since higher excited quarkonium states are more weakly bound than lower ones, the expectation is that, as the temperature increases, quarkonium will dissociate subsequently from the higher to the lower states providing also a dynamical probe of the quark-gluon plasma formation. In order to study quarkonium properties in a thermal bath at a temperature T, the quantity to be determined is the quarkonium potential V, which dictates, through the Schrödinger equation, the real-time evolution of the wave function of a $Q\bar{Q}$ pair in the medium. In QCD, V must come from a systematic expansion in $1/m$, the leading term being the static potential, and in the energy E. The potential will encode all contributions from scales larger than E and smaller than m. If the temperature lies in this range, the potential will depend on it, if the temperature is smaller than or of the same order as E, the potential will be temperature independent. The expansions in $1/m$ and E are best implemented in QCD by means of effective field theories (EFTs), very much in the same way as this has been done in order to describe quarkonium physics at zero temperature [1]. In the last couple of years, there has been a remarkable progress in constructing EFTs for quarkonium at finite temperature and in rigorously defining the quarkonium potential [2,3,4]. In [3], we have developed an EFT framework in real time and weak coupling for quarkonium at finite temperature. Quarkonium in a medium is characterized by different scales; the scales of the non-relativistic bound state: m, the heavy quark mass, mv, the typical inverse distance between Q and $\bar{Q}$ (v is the relative heavy-quark velocity), mv^2, the typical binding energy scale, and the thermodynamical scales: the temperature T, the inverse of the screening length of the chromoelectric interactions, i.e. the Debye mass m_D and lower scales. If these scales are hierarchically ordered, then we may expand physical observables in the ratio of the scales. Separating the contributions of the different scales at the Lagrangian level amounts to substituting QCD with a hierarchy of EFTs, which are equivalent to QCD order by order in the expansion parameters. At zero temperature, the EFTs that follow from QCD by integrating out the scales m and mv are called respectively non-relativistic QCD (NRQCD) and potential NRQCD (pNRQCD) [1].

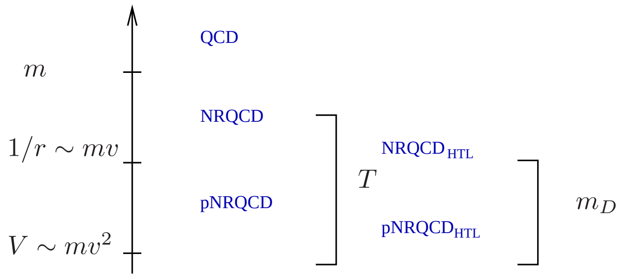

Fig. 1: Quarkonium at finite temperature: energy scales and EFTs.

We assume that the temperature is high enough that $T \gg gT \sim m_D$ holds but also that it is low enough for $T \ll m$ and $1/r \sim mv \gtrsim m_D$ to be satisfied, because for higher temperature the bound state ceases to exist. Under these conditions, different dynamical situation exist and we have studied them in [3]. If T is the next relevant scale after m, then integrating out T from NRQCD leads to an EFT that we may name $\text{NRQCD}_{\text{HTL}}$, because it contains the hard thermal loop (HTL) Lagrangian. Subsequently integrating out the scale mv from $\text{NRQCD}_{\text{HTL}}$ leads to a thermal version of pNRQCD that we may call $\text{pNRQCD}_{\text{HTL}}$. If the next relevant scale after m is mv, then integrating out mv from NRQCD leads to pNRQCD. If the temperature is larger than mv^2, then the temperature may be integrated out from pNRQCD leading to a new version of $\text{pNRQCD}_{\text{HTL}}$. The hierarchies of scales that lead to these different EFTs are schematically illustrated in Fig. 1. We also assume that $v \sim \alpha_s$, which is expected to be valid for tightly bound states: $\Upsilon(1S)$, J/ψ, ... In all these cases, the static $Q\bar{Q}$ potential acquires an imaginary part, which generates a finite thermal decay width of the quarkonium. We find that two mechanisms contribute to the thermal decay width: the imaginary part of the gluon self energy induced by the Landau-damping phenomenon, and the quark-antiquark color singlet to color octet thermal break up. Parametrically, the first mechanism dominates for temperatures such that the Debye mass m_D is larger than the binding energy, while the latter dominates for temperatures such that m_D is smaller than the binding energy. Since the thermal decay width becomes as large as the binding energy at a temperature at which color screening has not yet set in ($T \gg mv \gg m_D \gg mv^2$), it has been argued that quarkonium dissociation may be a consequence of the appearance of a thermal decay width rather than being due to the color screening of the real part of the potential. Further investigations and applications of these results are currently being carried on by our group.

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