Snowmass LOI: Quarkonia and Exotic Hadrons in Relativistic Heavy Ion Collisions

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1 Quarkonia

Quarkonia production in nuclear collisions is sensitive to a range of fundamental QCD phenomena that are not completely understood, including modifications of the parton distribution functions in the colliding nuclei, energy loss in the hot/cold QCD medium, and late-stage interactions outside the nucleus. In the deconfined plasma phase produced in heavy ion collisions, quarkonium production experiences additional suppression due to the plasma screening effects, that include both screening of the real part of the potential and a dynamically generated thermal width of the heavy quark-antiquark pair. Recombination of uncorrelated heavy quark-antiquark pairs into quarkonium has also been shown to be a crucial production mechanism for charmonium, especially at higher collision energies, where more charm quarks can be produced in one collision. The mechanism by which the heavy quark-antiquark pair hadronizes into a color singlet is still not understood. With new theoretical developments and major experimental upgrades, the opportunity for significant progress in our understanding of quarkonia-in-medium is here.

New insights have been gained from recent theoretical developments based on the open quantum system formalism. In this formalism, quarkonium evolution inside the QGP is treated as an open system, embedded inside a thermal environment. After the environment is traced out, the time evolution of the system consisting of heavy quark-antiquark pairs can be written as a Lindblad equation in the weak coupling limit, which can further be cast as a stochastic Schrödinger equation. The stochastic interactions lead to decoherence of the quarkonium wavefunction, which results in the dissociation of the quarkonium state [1]. But at the same time, they may lead to formation of a different quarkonium state. For example, we start with $1S$ wavefunction, $|\psi(t=0)\rangle = |1S\rangle$. Wavefunction decoherence will lead to $|\langle 1S|\psi(t)\rangle|^2 < 1$, i.e., dissociation. At the same time, if the $2S$ state exists (the local temperature is below the melting temperature of the $2S$ state), we will also have $|\langle 2S|\psi(t)\rangle|^2 > 0$, i.e., formation of the $2S$ state from the dissociated $1S$ state. This type of recombination originates in a correlated heavy quark-antiquark pair, and is different from the originally proposed recombination, which comes from uncorrelated heavy quarks produced from different initial hard vertices. Phenomenological consequences of this correlated recombination were explored recently in Ref. [2]. It was found that due to correlated recombination, the ratio between the nuclear modification factors of $\chi_b(1P)$ and $\Upsilon(2S)$, $\frac{R_{AA}[\chi_b(1P)]}{R_{AA}[\Upsilon(2S)]}$, is about one third. This observable has a dramatic difference from previous studies without taking correlated recombination into account. For example, Ref. [3] predicts the ratio is slightly bigger than unity. Measurements of this ratio therefore offer powerful discrimination between models. Furthermore, we can learn how the QGP medium modifies the long-distance physics of the development of quarkonium wavefunction, which is parametrized by the long-distance matrix elements in the high energy community.

Measurements of the elliptic flow of bottomonia can also provide powerful discrimination between models. Calculations such as Refs. [4, 2] showed the v_2 of $\Upsilon(1S)$ in PbPb collisions is always positive as a function of p_T, while the recent calculation in Ref. [5] showed a negative v_2 at low p_T. Additionally, measurements of $\Upsilon(1S)$ flow in pPb collisions can provide constraints on the origin of v_2 observed in small systems [6, 7]. Current measurements of bottomonia v_2 have large statistical uncertainties, which limits the discrimination power of the data [8, 9].

Future data sets and detector upgrades at the LHC and RHIC can clarify many of these questions. The sPHENIX experiment, currently under construction at RHIC, will pursue precision measurements of the $\Upsilon(nS)$ states ($n = 1, 2, 3$) at a lower collision energy and plasma temperature than the LHC [10]. This will provide new constraints on models of color screening and transport in the QGP.

2 Exotic Hadrons

In recent years, dozens of new states have been discovered which contains pairs of heavy quarks, but are not predicted by any of the potential models that successfully describe the observed spectra of $c\bar{c}$ and $b\bar{b}$ bound states [11]. Multiple explanations for these unexpected resonances have been put forth, including tetra- and pentaquarks, hadronic molecules, and glueballs. It is unlikely that a single model will successfully explain all exotic states, given their widely varying attributes.

Embedding exotic hadrons in a QCD medium provides a new way to test their properties. In a relatively dilute medium, such as high multiplicity pp or pA collisions, exotic states can be disrupted by interacting with other particles produced in the event. The magnitude of such disruptions are expected to be closely related to the binding energy of the exotic state, and measurements can thereby discriminate between various models of exotic structure. Preliminary LHCb results on $X(3872)$ production as a function of multiplicity in pp collisions [12] are consistent with breakup calculations for a compact tetraquark state [13]. The production of other exotics states and the effects of a diffuse medium can be studied in similar ways in pp and pPb collisions with future high-statistics data sets.

Heavy ion collisions can provide a new source of exotic states through coalscence of deconfined quarks. Preliminary CMS results on $X(3872)$ production in PbPb showed the first evidence for exotic hadron production in heavy ion collisions [14]. Currently, there is disagreement between theoretical calculations of exotic production in heavy ion collisions: quark coalescence models [15] and the AMPT framework [16] give a larger yield for molecular $X(3872)$ than a compact tetraquark, while a recent transport calculation arrives at the opposite conclusion [17]. Additional data including the p_T-differential production yield of $X(3872)$, elliptic flow, and yields as a function of centrality are required to discriminate between these various models.

Another interesting measurement is the production of doubly heavy baryons and tetraquarks. A heavy quark-quark pair in the color antitriplet can also form a bound state inside the QGP. These states can also be formed via coalescence in heavy ion collisions, due to the large number of heavy quarks produced in one collision [18]. As such, they are extremely sensitive to QGP properties.

In addition to sampling high-statistics future data sets delivered by the LHC, the major LHC experiments are pursuing upgrades to enable these measurements:

- The ALICE detector is currently being upgraded with new vertex detectors and faster TPC readout, which will result in enhanced quarkonia capabilities and statistical precision [19, 20]. In the future, a proposed replacement for the ALICE detector will be able to measure quarkonia and exotic states down to low transverse momentum in heavy ion collisions [21].

- The ATLAS collaboration is pursuing upgraded triggering, tracking, and timing to take full advantage of expected HL-LHC luminosities [22, 23, 24]. The upgraded detector will enable enhanced high p_T reach in heavy ion collisions.

- The CMS collaboration is pursuing new silicon tracking and a precision timing detector that will allow for identification of pions, kaons, and protons, increasing the ability to suppress backgrounds and reconstruct the hadronic decays of exotic hadrons in nuclear collisions [25, 26].

- The LHCb collaboration is currently installing a completely new tracking system which will allow access to 30% or more central heavy ion collisions [27], a streaming DAQ to sample the full delivered LHC luminosity [28], and an upgraded fixed target system [29]. The unique ability to vary the target by changing the gas and high statistics will allow quarkonia and exotics to be studied in a range of nuclear environments. Further upgrades which will enable LHCb to operate in the full PbPb centrality range are being planned [30].

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