Nuclear Science and Techniques (2023) 34:63
https://doi.org/10.1007/s41365-023-01213-3

RESEARCH HIGHLIGHT

Bottomonium suppression in heavy-ion collisions and the in-medium strong force

Ralf Rapp[1]

Received: 10 April 2023 / Revised: 11 April 2023 / Accepted: 11 April 2023 / Published online: 28 April 2023

A large suppression of various bottomonium states in ultra-relativistic heavy-ion collisions has been reported by the STAR collaboration at the Relativistic Heavy-Ion Collider. This observation is consistent with the formation of a quark-gluon plasma, but similar findings in more energetic collisions at the Large Hadron Collider suggest that a consistent picture requires additional mechanisms.

Bound states of a heavy quark (charm or bottom) and its antiquark, commonly referred to as quarkonia, have long been recognized as excellent probes of quark-gluon plasma (QGP) formation in high-energy collisions of atomic nuclei. In the vacuum, most quarkonium states are dominantly bound by a linearly rising potential (the so-called Cornell potential, see Fig. 1), as a direct manifestation of the confinement property of Quantum Chromodynamics (QCD). Thus, a suppression in the production of quarkonia in ultrarelativistic heavy-ion collisions, relative to that in elementary proton-proton (*pp*) collisions, has been among the earliest suggestions as a signature of QGP formation, signaling deconfinement through a Debye screening of the confining force [1]. However, it has been realized that a recombination of freely moving quarks and antiquarks in the QGP can lead to a significant "regeneration" of quarkonia [2–4], especially for charmonia. This effect has been confirmed by measurements at the Large Hadron Collider (LHC), where the suppression of the J/ψ was found to be markedly less than at lower collision energies [5, 6], despite the formation of a hotter medium at the LHC. On the other hand, for bottomonia, the regeneration contribution is expected to be subleading. Therefore, the production of bottomonia in heavy-ion collisions should give more direct insights into how deconfinement suppresses their yields.

On general grounds, one expects a "sequential suppression", with an onset and magnitude that is ordered by the binding energies (E_b) of the various bottomonia, i.e., excited states (such as $\Upsilon(2S)$ with $E_\mathrm{b} \simeq 0.54$ GeV and $\Upsilon(3S)$ with $E_\mathrm{b} \simeq 0.20$ GeV) should dissociate at lower temperatures than the ground-state $\Upsilon(1S)$ (with $E_\mathrm{b} \simeq 1.1$ GeV). In this way, the suppression pattern of bottomonia provides a powerful probe of the screening of the fundamental QCD force, in connection with the underlying dissociation processes, in the QGP. Smaller binding energies open more phase space for inelastic break-up reactions, accelerating the dissociation. The main experimental control parameters to vary the temperature of the fireball in heavy-ion reactions are the collision centrality and energy, where more peripheral or less energetic collisions of the incoming nuclei deposit less energy in the overlap zone and thus produce lower temperatures.

Groundbreaking results for the production of Υ mesons in 200 GeV Au-Au at the Relativistic Heavy-Ion Collider (RHIC) have recently been published by the STAR collaboration in Physical Review Letters [8]. As vector mesons, the Υ states can be rather cleanly measured through their decay into dileptons, *i.e.*, electron-positron or muon-antimuon pairs, $\Upsilon \to e^+e^-, \mu^+\mu^-$. The STAR collaboration took full advantage of their versatile detector systems to measure both channels and combine them in their analysis. That improved the statistics of these rather rare decay modes (with a branching ratio of typically 2%) and also provided an extra handle on assessing systematic uncertainties. In the high-multiplicity environment of heavy-ion collisions, high-precision data are not easily to come by, but routinely prove pivotal in promoting intriguing indications to robust insights into QCD matter properties.

The new data clearly establish a sequential bottomonium suppression pattern in Au-Au collisions, relative to *pp* collisions, that follows the hierarchy expected from the vacuum binding energies: a factor of ~ 2.5 for the ground-state $\Upsilon(1S)$

✉ Ralf Rapp
rapp@comp.tamu.edu

[1] Cyclotron Institute and Department of Physics and Astronomy, Texas A& M University, College Station, TX 77843-3366, USA

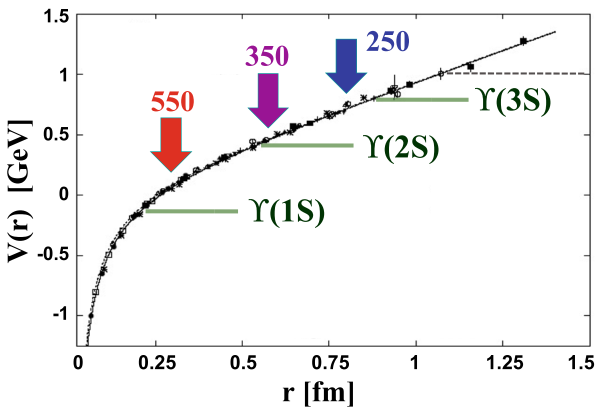

Fig. 1 (Color online) The QCD potential between a heavy quark and its antiquark in vacuum (black solid line, fit to lattice-QCD results [12, 13]) and the pertinent energy levels of ϒ states (green bars). The arrows schematically indicate the progression of the Debye screening of the potential in the QGP, at the approximate initial temperatures (in [MeV]) in heavy-ion collisions at the SPS (blue), RHIC (purple) and LHC (red), as inferred from quarkonium data and transport model calculations. Note that large dissociation rates lead to a strong suppression of the states even before they become unbound

and ∼ 4 for the first excited state, ϒ(2*S*), while for the ϒ(3*S*) yield only an upper limit could be established corresponding to a factor of 5 or more suppression (at a 95% confidence level). An important feature in interpreting these results are feeddown corrections, i.e., final-state decays where excited bottomonia end up in the ground state and thus contribute to the latter's observed yield. For the ϒ(1*S*) in *pp* collisions, feeddown makes up ca. 30% of its observed abundance. For the STAR measurement this implies that, with the excited states being largely suppressed, the medium-induced suppression of the ground state is actually rather moderate, i.e., the ϒ(1*S*) can still survive at the temperatures created in Au-Au collisions at RHIC, which are estimated to reach up to ∼ 350 MeV. This is more than two times larger than the crossover transition temperature into the QGP, $T_c \simeq 155$ MeV, as determined in numerical simulations of lattice-discretized QCD [9]. On the other hand, the strong but gradual suppression of the ϒ(2*S*) with increasing collision centrality of the Au-Au collisions suggests that its dissociation occurs in the vicinity of the early temperatures of the fireball evolution, i.e., ∼ 250–300 MeV. Finally, the near-complete suppression of the ϒ(3*S*), with no discernible signal even in peripheral collisions, indicates significantly lower dissociation temperatures, presumably close to T_c. These interpretations are corroborated by transport model calculations, e.g., a semi-classical approach [10] (which has an extensive track record also for charmonium observables) and an open-quantum system approach [11].

However, a comparison of the STAR results to LHC data is rather intriguing. Specifically, the centrality dependence of the ϒ(1*S*) suppression is found to agree with data from the CMS collaboration in 5.02 TeV Pb-Pb collisions [14]. Within a QGP suppression scenario this is somewhat unexpected: at the higher collision energy of the LHC, where the total-particle production is a factor of ∼ 2 larger than at RHIC, hotter fireballs are created, with estimated initial temperatures of $T_0 \simeq 550$–600 MeV [10]. There are several mechanisms to possibly resolve this puzzle. The first one is a larger regeneration contribution to the ϒ(1*S*), due to a larger production of bottom quarks, at the LHC. This feature is included in the transport model calculations, which, however tend to underpredict the ϒ(1*S*) data from STAR [8]. Another one is the "nuclear-absorption" effect, where the nascent bottomonium states, emerging out of a bottom-antibottom quark pair produced in a hard parton-parton collision, are dissociated by high-energy nucleons passing by from the incoming nuclei. STAR has previously measured ϒ production in d-Au collisions [15] and indeed found a ϒ(1*S*) suppression at a 20% level, albeit with a large uncertainty. A more systematic study that may be possible with the upcoming sPHENIX experiment might clarify this situation and help to develop the full potential of the STAR data as an important benchmark for determining the in-medium properties of quarkonia. At present, the indications are that substantial remnants of the confining force survive in the QGP (see Fig. 1) and are quite possibly responsible for its strongly-coupled properties [16].

References

1. T. Matsui, H. Satz, J/ψ Suppression by Quark-Gluon plasma formation. Phys. Lett. B **178**, 416–422 (1986). https://doi.org/10.1016/0370-2693(86)91404-8
2. P. Braun-Munzinger, J. Stachel, (Non)thermal aspects of charmonium production and a new look at J/ψ suppression. Phys. Lett. B **490**, 196–202 (2000). https://doi.org/10.1016/S0370-2693(00)00991-6
3. R.L. Thews, M. Schroedter, J. Rafelski, Enhanced J/ψ production in deconfined quark matter. Phys. Rev. C **63**, 054905 (2001). https://doi.org/10.1103/PhysRevC.63.054905
4. L. Grandchamp, R. Rapp, Thermal versus direct J/ψ production in ultrarelativistic heavy ion collisions. Phys. Lett. B **523**, 60–66 (2001). https://doi.org/10.1016/S0370-2693(01)01311-9
5. B. Alessandro et al., [NA50], A New measurement of J/psi suppression in Pb-Pb collisions at 158-GeV per nucleon. Eur. Phys. J. C **39**, 335–345 (2005). https://doi.org/10.1140/epjc/s2004-02107-9
6. J. Adam et al., [STAR], Measurement of inclusive J/ψ suppression in Au+Au collisions at $\sqrt{s_{NN}}$=200GeV through the dimuon channel at STAR. Phys. Lett. B **797**, 134917 (2019). https://doi.org/10.1016/j.physletb.2019.134917
7. S. Acharya *et al.* [ALICE], Measurements of inclusive J/ψ production at midrapidity and forward rapidity in Pb−Pb collisions at $\sqrt{s_{\rm NN}}$=5.02 TeV. https://doi.org/10.48550/arXiv.2303.13361
8. B. Aboona et al., [STAR], Observation of sequential ϒ suppression in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV with the STAR

experiment. Phys. Rev. Lett. **130**, 112301 (2023). https://doi.org/10.1103/PhysRevLett.130.112301

9. Y. Aoki, S. Borsanyi, S. Durr et al., The QCD transition temperature: results with physical masses in the continuum limit II. JHEP **06**, 088 (2009). https://doi.org/10.1088/1126-6708/2009/06/088
10. X. Du, M. He, R. Rapp, Color screening and regeneration of Bottomonia in high-energy Heavy-Ion Collisions. Phys. Rev. C **96**, 054901 (2017). https://doi.org/10.1103/PhysRevC.96.054901
11. N. Brambilla, M.A. Escobedo, A. Islam et al., Regeneration of bottomonia in an open quantum systems approach. https://doi.org/10.48550/arXiv.2302.11826
12. F. Karsch, E. Laermann, A. Peikert, Quark mass and flavor dependence of the QCD phase transition. Nucl. Phys. B **605**, 579–599 (2001). https://doi.org/10.1016/S0550-3213(01)00200-0
13. O. Kaczmarek, F. Zantow, Static quark anti-quark interactions at zero and finite temperature QCD. I. Heavy quark free energies, running coupling andquarkonium binding. Phys. Rev. D **71**, 114510 (2005). https://doi.org/10.1103/PhysRevD.71.114510
14. A.M. Sirunyan *et al.* [CMS], Measurement of nuclear modification factors of Υ(1S), Υ(2S), and Υ(3S) mesons in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Phys. Lett. B **790**, 270-293 (2019). https://doi.org/10.1016/j.physletb.2019.01.006
15. L. Adamczyk *et al.* [STAR], Suppression of Υ production in d+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Phys. Lett. B **735**, 127–137 (2014). [erratum: Phys. Lett. B **743**, 537-541 (2015)] https://doi.org/10.1016/j.physletb.2014.06.028
16. S.Y.F. Liu, R. Rapp, Spectral and transport properties of quark-gluon plasma in a nonperturbative approach. Eur. Phys. J. A **56**, 44 (2020). https://doi.org/10.1140/epja/s10050-020-00024-z