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Heavy-Flavor Theory at “Hard and Electromagnetic Probes 2018"

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An overview is given of the theoretical developments on heavy quarks and quarkonia in heavy-ion collisions as reported at the “Hard and EM Probes 2018" conference. Specifically, we address progress in the understanding of heavy-flavor diffusion and its hadronization, quarkonium transport and the extraction of quarkonium melting temperatures, energy loss of heavy quarks at high momentum, and their rescattering in small colliding systems.

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†A footnote may follow.

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1. Introduction: Heavy Quarks and in-Medium QCD Force

Heavy quarks are hard-produced probes of ultrarelativistic heavy-ion collisions (URHICs), yet they provide a unique access to the soft properties of the QCD medium. The large mass of heavy quarks, $m_Q \gg \Lambda_{\rm QCD}, T_{\rm c}$, essentially limits their production to the primordial collisions of nucleons, and implies theoretical simplifications in the microscopic description of their transport and spectral properties. The production systematics of heavy quarkonia (charmonia and bottomonia) have long been suggested as a means to study the medium modifications of the fundamental QCD force. The in-medium QCD force governs the temperature dependence of the quarkonium binding energies and dissociation rates. On the one hand, these properties control the transport of quarkonia through the fireball and thus their finally observed yields and momentum spectra in URHICs. On the other hand, the in-medium binding energies and dissociation rates (widths) are encoded in their spectral and correlation functions, and as such allow for quantitative tests against lattice-QCD (lQCD) data. The increasing variety of measured quarkonia in URHICs is now enabling systematic studies of ground and excited states that are starting to narrow down their transport parameters in phenomenological applications (see Refs. [1, 2, 3] for recent reviews).

A basic building block in the microscopic description of in-medium quarkonia, especially their dissociation widths, is the interaction of the constituent heavy anti-/quarks with the surrounding quark-gluon plasma (QGP). Since the in-medium quarkonium binding energies are typically of the order of a few hundred MeV or less, their dissociation processes are directly related to the coupling of low-momentum heavy quarks to the medium. In particular, the zero-momentum limit of the thermal relaxation rate of heavy quarks, γ_Q, determines their spatial diffusion coefficient, $\mathscr{D}_s = T/(m_Q \gamma_Q(p=0))$, a fundamental transport parameter of QCD matter. This highlights the intimate connection between (chemical) quarkonium and (kinetic) heavy-quark (HQ) transport. A quantitative phenomenology of open heavy-flavor (HF) observables in URHICs requires, however, a good control over the 3-momentum dependence of the pertinent thermalization rates. A key issue here is the modelling of the medium constituents that the heavy quarks are interacting with – after all, this at the core of the idea to utilize heavy quarks and quarkonia as a probe of the medium. Limiting cases are a weakly interacting gas of quasiparticles vs. a strongly interacting system without explicit quasiparticles within the AdS/CFT correspondence. Current phenomenological extractions [4, 5] of the HQ *scattering* rate, Γ_Q (which for charm quarks is about an order of magnitude larger than the *thermalization* rate), yield values of 0.5 GeV or more; this implies that the thermal medium partons, with effective masses of order $m_q \sim T \sim \Gamma_q$, are no longer well-defined quasiparticles! On the other hand, heavy quarks (in particular bottom), with $m_Q \gg T$, can remain good quasiparticles, which is a central reason why they are excellent “Brownian probes" of the strongly interacting QGP liquid. These arguments continue to apply to hadronization processes, which should emerge continuously in the transition from the QGP into the hadronic liquid. To take advantage of the close connection between HF transport and QGP structure, a unified treatment of the interactions in the heavy and light sector is desirable.

The kinematics resulting from the HQ masses implies that the onset of radiative interactions is shifted to higher momenta, relative to light partons. For the latter the “transition" from elastic to radiative interactions is quite possibly in a regime where they are near-thermalized in URHICs; this is presumably not the case for charm and bottom quarks; therefore, they retain a memory of their interaction history and thus can serve as a “gauge" of the strength and type of their rescattering. Once radiation dominates, the quark mass dependence of energy loss can be studied.

In the following, we discuss (in a non-exhaustive manner) the theoretical developments reported at “Hard Probes ’18" in the context of the above considerations, organized into parts on HQ diffusion (Sec. 2) and hadronization (Sec. 3), quarkonium transport (Sec. 4), high-p_T energy loss (Sec. 5) and heavy flavor in small collision systems (Sec. 6), and conclude in Sec. 7.

2. Heavy-Quark Diffusion

The propagation of heavy quarks through QCD matter is a multi-scale problem [6]; while the hierarchies in kinematic variables can be reasonably well defined (*e.g.*, for momentum transfer in the diffusive regime, $Q^2 \sim T^2 \sim K_T^2 = (p_T^2/2m_Q)^2 \ll p_T^2 \ll m_Q^2$), the strong coupling of the QGP at moderate temperature renders the interactions intrinsically nonperturbative. There is mounting evidence that remnants of the confining force survive well above the pseudocritical temperature ($T_{\rm pc}$); they could well be at the origin of the QGP’s liquid-like properties at long wavelength, thereby providing a natural connection between the QGP’s strong-coupling behavior and hadronization.

The HF transport problem in URHICs can be decomposed into several components [4]: cold-nuclear-matter effects in HQ production, diffusion through a pre-equilibrium phase and the QGP, hadronization, hadronic diffusion, and the ambient bulk evolution. An estimate of the effects of the pre-equilibrium phase, based on turbulent chromodynamic fields, was presented in Ref. [7]; it was found that the pertinent HQ transport coefficients are comparable to, or even larger than the equilibrium values at the same energy density. A special feature of these coefficients, rooted in the largely longitudinally oriented chromo-electric fields, are rather pronounced rapidity dependences of the energy loss which may allow for experimental tests relative to the smoothly varying charged-particle densities figuring in the equilibrium description.

Updates of an AdS/CFT-based HQ diffusion calculation in the QGP were reported in Ref. [8]; the calculated B- and D-meson $R_{\rm AA}$’s, in comparison to LHC data, yield spatial diffusion coefficients in the range of $\mathscr{D}_s(2\pi T)$=1.2-1.7, somewhat smaller than most other calculations (at least in part due to neglecting recombination and the hadronic phase). In addition, a constant momentum diffusion coefficient, D_p, was clearly favored over a p-dependent one, implying that the thermalization rate falls off as $\gamma_Q \sim 1/E$, quite similar to QCD-based models [4].

The impact of the space-time evolution has been discussed in Ref. [9]; even within bulk evolutin models (here EPOS-2 vs. EPOS-3) that give a good description of light-hadron observables, significant uncertainty remains in the extraction of the HQ diffusion coefficient. For the concrete case at hand, the EPOS-3 framework tends to favor an increase of ∼30% of the $\mathscr{D}_s$ values in the Nantes energy-loss model (pQCD with running coupling and a rescaled Debye mass), bringing it, in fact, closer to values extracted by other groups, cf. Fig. 1. This increase is at least in part caused by viscosity effects in EPOS-3 which lead to a slower cooling than the ideal-hydro evolution used in EPOS-2 [9]. Also emphasized was the importance of controlled hadronization models, which for low- and intermediate-momentum observables should comply with the equilibrium limit in a locally thermalized medium. After all, hadronization is an interaction that should satisfy energy conservation and the central-limit theorem.

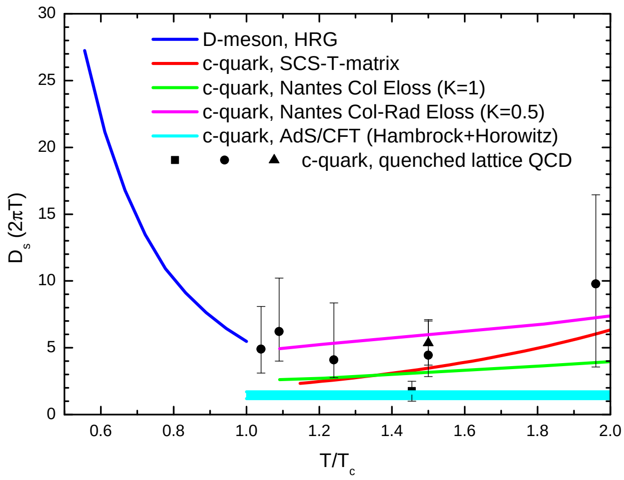

Figure 1: Spatial charm diffusion coefficient in the QGP ($T > T_c$) and hadronic matter ($T < T_c$) . Updated results from this conference (Nantes [9] and AdS/CFT [8]) are compared to recent T-matrix results ("Strong Coupling Scenario") [10], lQCD "data" [11, 12, 13] and a hadronic calculation [14]. Figure courtesy of M. He.

The developments reported at this meeting reiterate the need for broadly based, yet detailed model comparisons, as have been commenced in a first round in Refs. [4, 15]. They also corroborate that the (scaled) HF diffusion coefficient ($2\pi T \mathscr{D}_s$) in QCD matter reaches values below 5, with a putative minimum in the vicinity of the transition temperature, and increasing with temperature and 3-momentun reflecting the fundamental scale dependence of QCD.

3. Hadronization

The effects of charm-quark diffusion and hadronization through coalescence processes with light quarks from the comoving thermal medium are not easily disentangled from $R_{\rm AA}$ and v_2 observables, especially when limited to a single particle species (say, D-mesons). Thus, measurements of additional charm-hadron species are highly valuable to sort out the contributions of different mechanisms (likewise for bottom). An important benchmark are the production ratios in elementary pp collisions. To begin with, it turns out that, at the LHC, the non-strange D-meson ratios (such as D^+/D^0 or $D^{*,+}/D^0$) measured in pp [16] are compatible with predictions from the statistical hadronization model (SHM; including feeddown) [17]. This also holds for the D_s/D^0 ratio once a strangeness suppresion factor of $\gamma_s \simeq 0.5$ is introduced, consistent with the well-known strangeness suppression in the light-hadron sector. In AA collisions, the light D-meson ratios remain consistent with the SHM, at least at low p_T. In addition, as strangeness production approaches equilibrium, an enhancement of D_s production through recombination with chemically equilibrated strange quarks has been predicted [17, 18, 19], which appears to be realized at both RHIC [20] and the LHC [21, 22].

The challenge comes with the recently reported Λ_c production data. In particular, the STAR collaboration [20] measured a Λ_c/D^0 ratio in 10-80% Au-Au($\sqrt{s}$=200 GeV) collisions that is close to or even above one at relatively low $p_T \simeq 3$ GeV (which is comparable to the Λ_c mass implying that it represents a good fraction of the inclusive yield). As a consequence, the extracted Λ_c yields account for about half of the produced charm quarks. At the LHC, a first measurement of this ratio in Pb-Pb($\sqrt{s}$=5.02 TeV) collisions is also near one [23], although at a significantly higher average $p_T \simeq 7$ GeV. Attempts to describe these data within the resonance recombination model (which conserves 4-momentum and obeys the equilibrium limit) implemented on a hydrodynamic hypersurface have thus far failed [24]. Instantaneous coalescence models can get rather close to the data [25, 26] by utilizing nontrivial wavefunction effects in the hadronization process, allowing the Λ_c/D^0 ratio to exceed the equilibrium value by a large factor. This would imply that HQ hadronization proceeds rather far from equilibrium, with individual wavefunction effects for each hadron. It would be important to understand how this scenario can be reconciled with the light-hadron sector.

4. Quarkonium Transport

The (chemical-) equilibrium limit discussed in the previous section is a pivotal ingredient in description of quarkonium transport in URHICs [27]. This is highlighted in the pertinent rate equation for the time evolution of the number of quarkonia, $N_{\mathscr{Q}}$,

$$\frac{dN_{\mathscr{Q}}}{d\tau} = -\Gamma_{\mathscr{Q}}[N_{\mathscr{Q}} - N_{\mathscr{Q}}^{\rm eq}] \ , \tag{4.1}$$

where $\Gamma_{\mathscr{Q}}$ denotes the inelastic reaction rate which drives the quarkonium abundance towards it (temperature-dependent) equilibrium limit $N_{\mathscr{Q}}^{\rm eq}$ (as given, *e.g.*, by the SHM).

Since the individual HQ spectra are not necessarily thermalized throughout the fireball evolution in URHICs, corrections to the equilibrium limit in the regeneration of quarkonia (second term in Eq. (4.1)) need to be investigated. Pertinent progress has been reported in Ref. [28] where coupled Boltzmann equations for the diffusion of individual anti-/bottom quarks and inelastic bottomonium reactions have been solved. Detailed balance at fixed temperature has been verified leading to a near exponential approach to the equilibrium limit, $\mathscr{R}(\tau) = (1-\exp[\tau/\tau_b])$ [29], where the time scale is given by the thermal relaxation time, τ_b, of b-quarks. With bottomonium binding energies calculated from a vacuum Coulomb potential, a good description of the $\Upsilon(1S, 2S)$ data of CMS [30, 31] and STAR [32] can be achieved. A modest contribution from regeneration is found, similar to Ref. [29].

Bottomonium transport has also been studied within the AdS/CFT correspondence using a Coulomb potential and strong-coupling dissociation rates [33]. The latter turn out to over-suppress the $\Upsilon(1S)$ yield relative to CMS data. The agreement is much improved using smaller, perturbative-QCD (pQCD) rates, not inconsistent with a compilation of results from the Kent-State [34], Tsinghua [35] and TAMU [29] groups shown in Ref. [2].

A rate-equation approach using bottomonium binding energies from an in-medium complex Cornell potential, with additional break-up from gluo-dissociation, implemented into an ideal-hydro evolution, has been presented in Ref. [36]. Finite formation times of the Υ states, leading to a reduced suppression in the early phases, are found to be significant to obtain a fair description of the CMS data, leaving most of the inclusive $\Upsilon(1S)$ suppression due to feeddown contributions.

The significance of formation time effects in the transport of quarkonia in the early phases of the fireball – treated schematically in most existing approaches – calls for a more detailed investigation. Explicit quantum treatments of quarkonium transport, as discussed in Ref. [37], can more accurately address these effects, as well as the evolution leading up to the formation of the various bound states in the thermalized medium. It will be interesting to see whether quantum approaches, at both the single HQ and the quarkonium level, can be remapped into phenomenologically successful rate equation frameworks, and how large corrections to the current extraction of transport coefficients are.

In a slight generalization of the original idea of using the medium modifications of the $c\bar{c}$ binding into J/ψ as a probe of deconfinement, the ultimate goal remains to utilize the in-medium spectroscopy of quarkonium states, through their production systematics in URHICs, as a probe of the fundamental forces in QCD matter. The current combined phenomenology of quarkonium transport already puts significant constraints on the in-medium binding energies, $E_B^{\mathscr{Q}}(T)$, and dissociation rates, $\Gamma_{\mathscr{Q}}$, leading to a hierarchy in the bound state melting as (using the standard criterion $E_B^{\mathscr{Q}}(T_{\rm melt}) \simeq \Gamma_{\mathscr{Q}}(T_{\rm melt})$)

$$T_{\rm melt}[\psi(2S)] < T_0^{\rm SPS} \lesssim T_{\rm melt}[J/\psi, \Upsilon(2S)] \lesssim T_0^{\rm RHIC} < T_{\rm melt}[\Upsilon(1S)] \lesssim T_0^{\rm LHC} \; ; \qquad (4.2)$$

Here, $T_0^{\rm SPS}\simeq 240$ MeV, $T_0^{\rm RHIC}\simeq 350$ MeV and $T_0^{\rm LHC}\simeq 550$ MeV are initial temperatures as estimated, *e.g.*, from hydrodynamic simulations or electromagnetic radiation. Similar hierarchies are also found in lattice-QCD based extractions using non-relativistic QCD [38] or thermodynamic T-matrix approaches [10]. Clearly, the complexity of in-medium quarkonia renders them unsuitable as a thermometer; rather, with independent URHIC temperature information, their in-medium properties can be scrutinized, with the ultimate goal of determining the underlying interaction in QCD matter.

5. High-p_T Suppression

At high transverse momenta, HF particles provide a unique window on the characteristics of parton energy loss in the QGP. First, the transition from a collisional into a radiatively dominated regime can be studied (probably not possible in the light sector where the transition momentum is likely in the thermalized part of the spectrum); here, the factor of $\sim$3 difference in charm- and bottom-quark masses provides an extra leverage to identify this regime. Second, interference effects in gluon radiation can be scrutinized through the path length (L) dependence as discussed at this meeting in Ref. [39]: starting from an ansatz for the fractional energy loss, $\Delta E/E \sim \eta T^a L^b$ (with a p_T-dependent coefficient η), the observable $R_L \equiv (1-R_{XeXe})/(1-R_{PbPb}) \simeq (A_{Xe}/A_{Pb})^{b/3}$ has been proposed as direct measure of the power b. Pertinent model calculations [39] find a near linear dependence (b=1) for all flavors for $p_T\simeq$20 GeV; for light flavors, it quickly develops into a significant nonlinear dependence with increasing p_T, but more gradually for c and b quarks, and eventually recovering flavor independence at $p_T\simeq$100 GeV with $b\simeq$1.4. A very close-to-linear dependence for b quarks in the p_T=10-40 GeV range has also been found in the model comparisons conducted in Ref. [4], while for c quarks interference effects are somewhat more pronounced for $p_T>$10 GeV.

Furthermore, formation time effects arising from the finite virtuality in the production of c and b quarks can be studied at high p_T, where they are augmented by Lorentz-γ factors (similar to the case of quarkonia discussed above, where, however, the relevant timescale, given by the inverse binding energies, is (much) longer). This was discussed in Ref. [40]; in essence, the larger mass of the b quarks allows them to go on shell more quickly than c quarks, enabling an additional quenching of the bottom p_T-spectra in the 10-50 GeV range, not inconsistent with high-p_T suppression data.

6. Small Systems

Both heavy quarks and quarkonia can contribute to a better understanding of the mechanisms driving the apparent collectivity observed in small collision systems, *i.e.*, p/dA (and even high-multiplicty pp) collisions. In Ref. [41], it was reiterated that the modest modifications observed in the D-meson $R_{\rm AA}$ in pPb collisions [42] can be well described by baseline shadowing calculations, in fact better than in models where c-quark interactions in a QGP are evaluated, which tend to cause too much suppression toward higher p_T. However, the main problem is the large v_2, reaching up to 10% for D-mesons around $p_T \simeq 3.5$ GeV in high-multiplicity pPb collisions [43], which cannot be explained by "conventional" initial-state effects. It has been argued that the anisotropic escape effect, which is rather effective in generating light-hadron v_2 in small systems, is less effective for charm quarks [44], rendering them a better probe of medium collectivity. However, also in these calculations, using the AMPT transport model with 3 mb cross sections, large c-quark v_2 values cannot be obtained for pPb collisions.

7. Conclusions

The "Hard Probes 2018" meeting has demonstrated again the versatility and uniqueness of heavy-flavor hadrons to analyze key properties of QCD matter as produced in URHICs. Advances in understanding the different components in the modelling of low-momentum D-meson observables continue to narrow down the spatial diffusion coefficient of heavy quarks, a fundamental transport coefficient of the medium. The current range of extracted values, $\mathscr{D}_s(2\pi T)$=2-4, translates into a large scattering rates which imply that the medium's long-wavelength excitations do not support light-parton quasiparticles when approaching $T_{\rm pc}$ from above. This also offers a natural explanation why the hadronization region plays an important role in HF transport, and goes hand-in-hand with the observed changes in the hadrochemistry of HF hadrons in URHICs, relative to pp collisions, most notably the enhancements of D_s mesons and Λ_c baryons. For the latter, a satisfactory theoretical description remains challenging. Part of the resoultion of this puzzle might reside in their unexpectedly large production in pp. A reliable understanding of the HF hadrochemistry is also pivotal to transport descriptions of charmonium production via their (re-) generation, where chemical equilibrium represents the long-time limit; at finite times, (re-) generation is sensitive to the degree of the HQ thermalization. Going forward, the exploitation of these intricate connections promises for a tightly constrained framework of HF transport and hadronization, *i.e.*, kinetics and chemistry. The large HQ mass serves as a control parameter that can be utilized to check approximations and tested via comparisons of charm and bottom observables. It also provides a scale,

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$p_{\rm trans} \sim m_Q$, where the non-pertubatively dominated low-momentum diffusion physics transits into a perturbative regime dominated by energy loss via gluon radiation (with a possibly large coefficient). In the high-p_T regime, quark mass dependencies seem to survive into the 10's of GeV regime. Finally, modifications of HF particles in small systems remain intriguing. The lack of a noticable D-meson suppression observed at high p_T, together with their large v_2 signal, pose a challenge for explanations based on final-state effects. Clearly, much remains to be learned about what HF observables tell us about the QGP and its transition into hadrons.

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