$\mathbf{D_s}$-Meson as Quantitative Probe of Diffusion and Hadronization in Nuclear Collisions

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The modifications of D_s-meson spectra in ultrarelativistic heavy-ion collisions are identified as a quantitative probe of key properties of the hot nuclear medium. This is enabled by the unique valence-quark content of the D_s=$c\bar{s}$ which couples the well-known strangeness enhancement with the collective-flow pattern of primordially produced charm quarks. We employ a consistent strong-coupling treatment with hydrodynamic bulk evolution and nonperturbative T-matrix interactions for both heavy-quark diffusion and hadronization in the Quark-Gluon Plasma (QGP). A large enhancement of the D_s nuclear modification factor (R_{AA}) at RHIC is predicted, with a remarkable maximum of ∼1.5-1.8 at transverse momenta around 2 GeV/c. We show this to be a direct consequence of the strong coupling of the heavy quarks to the QGP and their hadronization via coalescence with strange quarks. We furthermore introduce the effects of diffusion in the hadronic phase and suggest that an increase of the D-meson elliptic flow compared to the D_s can disentangle the transport properties of hadronic and QGP liquids.

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The properties of nuclear matter at high temperatures and densities are under intense investigation. Numerical lattice simulations of Quantum Chromodynamics (QCD) predict the formation of a deconfined Quark-Gluon Plasma (QGP) at a transition temperature of $T_c \simeq 170\,\mathrm{MeV}$ [1, 2]. The QGP presumably filled the early universe during the first few microseconds of its existence. Ultra-relativistic heavy-ion collisions (URHICs) at BNL's Relativistic Heavy Ion Collider (RHIC) and at CERN's Large Hadron Collider (LHC) are aimed at producing the QGP and characterizing its properties. Thus far, the experimental results point to the creation of a color-opaque, strongly coupled and almost ideal liquid with initial temperatures well above T_c [3, 4]. However, this assessment remains qualitative at present [5, 6]. A quantification of the physical properties of the strongly-coupled QGP in terms of its microscopic interactions calls for novel probes and observables.

A special role in these efforts is played by heavy quarks (charm and bottom, Q=c,b). Their masses ($m_{c,b} \simeq 1.3, 4.5\,\mathrm{GeV}$) are significantly larger than the typical temperatures of a few hundred MeV reached at RHIC and LHC. Therefore, their production is essentially restricted to primordial nucleon-nucleon collisions [7], and their thermal relaxation during the subsequent evolution of the medium is delayed relative to light quarks by a factor of $\sim m_Q/T \approx$5-20 [8–12]. This renders the thermalization time of heavy quarks comparable to the typical lifetime of the QGP phase in URHICs, and thus makes them excellent probes. Current heavy-quark (HQ) observables, mostly in terms of pertinent semi-leptonic electron-decay ($e^\pm$) spectra [13–15], indicate a surprising degree of thermalization and collectivity, especially through a large elliptic flow [14, 15]. First data on D-meson spectra confirm this behavior [16].

The thermalization and collective flow imparted on heavy quarks by the ambient expanding QGP serves as a quantitative measure of their coupling to thermalized light quarks and gluons. Current experimental results call for an interaction strength that goes well beyond perturbative QCD (pQCD) with realistic strong coupling constants, $\alpha_s \simeq 0.3$ [17–24]. Calculations based on nonperturbative heavy-light quark interactions, followed by coalescence into D mesons [17, 20], describe the observed modifications of $e^\pm$ spectra reasonably well, up to transverse momenta of $p_t^e \simeq 5\,\mathrm{GeV}/c$. However, since the $e^\pm$ spectra are a superposition of charm and bottom contributions, an enhanced discrimination power is desirable. In this Letter we argue that accurate measurements of D_s mesons considerably improve our ability to constrain the interactions of heavy flavor in medium: by directly comparing D and D_s spectra and elliptic flow one can disentangle recombination effects in hadronization, as well as the charm coupling to the QGP and hadronic matter.

One of our key points here is to test the dual role of the resonant HQ interactions with light quarks – figuring into both diffusion and hadronization – by utilizing the well-established enhancement of strangeness production in URHICs. The latter is among the earliest suggested signatures of QGP formation [25]. It manifests itself as a ∼50% increase of strange-to-light hadron ratios in central nucleus-nucleus (AA) relative to pp collisions (e.g., in the K/π ratio) [26, 27], and can be understood as a strangeness equilibration within the statistical hadronization model [28]. Thus, if resonant HQ interactions and recombination with thermalized light quarks into D-mesons are key to explaining HQ observables, heavy quarks must also couple to the equilibrated strangeness content of the QGP. In contrast to earlier predictions of inclusive D_s yields in URHICs [29, 30], we here perform a full dynamical treatment of charm diffusion and hadronization over a large range in transverse momentum (p_T), encompassing thermal and kinetic regimes. Most notably, we predict the nuclear modification factor (R_{AA}) of the D_s to significantly exceed one, which would be the first of its kind for a meson at collider energies. The main, dynamical, information is, however, encoded in its p_T-dependence, which allows us to scrutinize both diffusion and hadronization effects, especially in comparison to D mesons.

The D_s and D observables encode yet another aspect which has not been evaluated in the HQ context to date: the role of the hadronic phase. Following the common, empirically supported notion that multistrange hadrons (e.g., ϕ and Ω^-) decouple close to the hadronization transition [31, 32], the same should apply to the D_s. Hence, after evaluating the effects of hadronic diffusion on the D-meson, a comparison of D and D_s observables enables a quantitative assessment of the hadronic transport coefficient. Since the HQ transport coefficient is believed to be closely related to the widely discussed viscosity-to-entropy ratio of QCD matter (η/s) [12], disentangling the former for hadronic and QGP phases would allow us to quantify the temperature dependence of η/s.

Let us start by describing our calculations of charm diffusion in medium. At the temperatures of interest in URHICs, $T \lesssim 400\,\mathrm{MeV}$, HQ kinetics can be approximated by Brownian motion, with a thermal relaxation rate $A(p,T)$ derived from a Fokker-Planck equation [8–10, 17, 20, 23]. The key input to calculate A are HQ scattering amplitudes; at low- and intermediate momenta, these are governed by elastic interactions of potential type. In the QGP, we employ thermodynamic T-matrix calculations [20, 33] with input potentials approximated by HQ internal energies computed in thermal lattice QCD (lQCD). The resulting T-matrices exhibit resonant states close to threshold in mesonic and diquark channels close to T_c. They accelerate thermal HQ relaxation by a factor of ~3-5 over leading-order pQCD [33]. In the hadronic phase, the thermal relaxation rate of D mesons is obtained [34] from elastic scattering amplitudes based on effective hadronic Lagrangians constrained by vacuum spectroscopy. Figure 1 summarizes our input for the spatial diffusion coefficient of charm in matter, defined by the Einstein relation as $\mathcal{D}_s = T/[m_{c,D}A(p=0,T)]$. Coming from high T we observe a steady decrease in the QGP (due to an increased interaction strength in the lQCD potentials), followed by an increase in hadronic matter. The calculations support a continuous evolution through the transition region, with a minimum of $\mathcal{D}_s \simeq (4-5)/2\pi T$ around T_c (translating into an estimate of $\eta/s \sim (2-4)/4\pi$). Also note that our results in the QGP are comparable to recent quenched lQCD estimates [35, 36], but far below the pQCD values.

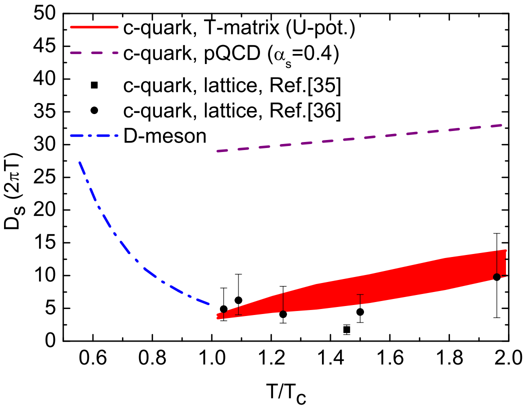

FIG. 1: (Color online) The spatial diffusion coefficients $\mathcal{D}_s$ (in units of the thermal wavelength, $1/(2\pi T)$) vs. temperature (in units of T_c) for charm quarks using T-matrix interactions in the QGP (red band) and D mesons using effective lagrangians in hadronic matter (blue solid line), compared to pQCD (purple dashed line) and quenched lQCD (data points) [35, 36].

The Brownian motion of charm is implemented into URHICs via relativistic Langevin simulations, with the space-time evolution of the medium approximated by boost-invariant ideal hydrodynamics. To this end we employ our recent tune [37] of the AZHYDRO code [38], optimized to describe bulk and multistrange hadron spectra and elliptic flow in Au-Au collisions RHIC. It utilizes a state-of-the-art lQCD equation of state [2, 39] with pseudo-critical deconfinement temperature of T_c=170 MeV, and a subsequent hadron-resonance-gas phase with chemical freezeout at T_{ch}=160 MeV to account for the observed hadron ratios. A compact initial spatial profile with pre-equilibrium flow permits a simultaneous fit of multistrange- and bulk-hadron data at chemical and thermal ($T_{\mathrm{fo}} \simeq 110\,\mathrm{MeV}$) freezeout, respectively. The initial HQ distributions are taken from a PYTHIA tune to $e^{\pm}$ spectra in pp and dAu collisions [17]. The Cronin effect in nuclear collisions is accounted for via a Gaussian transverse-momentum broadening with $\langle k_T^2 \rangle = 0.6\ \mathrm{GeV}^2$, estimated from recent PHENIX $e^{\pm}$ spectra in dAu [40].

After diffusion through the QGP charm-quark distributions are converted into charmed hadrons. We accomplish this by applying resonance recombination [41] with thermal light and strange quarks into D and D_s mesons on the hydro hypersurface at T_c [42]. Remaining c-quarks are treated with δ-function fragmentation (as used in the fits to pp data). For a reliable coalescence dynamics at low and intermediate p_T, it is crucial that the formulation of the resonance recombination model (RRM) via a Boltzmann equation [41] yields the long-time limit of thermal equilibrium. We have verified this in the present case with the full space-momentum correlations as given by the hydrodynamic flow field [42]. The coalescence probabilities are estimated via $P_{\mathrm{coal}}(p) \simeq \Delta\tau_{\mathrm{res}}\Gamma_c^{\mathrm{res}}(p)$, with the charm-quark reaction rate, $\Gamma_c^{\mathrm{res}}(p)$ (as given by the heavy-light T matrix), and a time duration $\Delta\tau_{\mathrm{res}}$ characterizing one generation of D and D_s resonance formation [42]. With $\Gamma_c^{\mathrm{res}}(0) \simeq 0.2\,\mathrm{GeV}$ [43] and $\Delta\tau_{\mathrm{res}} \approx 1\,\mathrm{fm}/c$, we assume a recombination probability of one at vanishing charm-quark momentum, decreasing thereafter as determined by the dynamics of the RRM expression [41]. The latter is evaluated with m_c=1.7 GeV, $m_{u,d}$=0.3 GeV, m_s=0.4 GeV and m_D=2.1 GeV, m_{D_s}=2.2 GeV with Γ_{D,D_s} = 0.2 GeV, approximately representing the in-medium values of the T-matrices [33] during the hadronization window. Since HQ resonant scattering is underlying both diffusion and hadronization interactions, there is, in principle, some overlap between the two (this does not apply to the non-resonant parts of the interactions). To characterize this uncertainty, we will study a scenario where diffusion interactions in the QGP are completely switched off for about 1 fm/c prior to T_c, corresponding to a temperature window of 180-170 MeV. The Langevin simulation resumes with hadronic diffusion of the combined coalescence+fragmentation distribution for D-mesons for $T<T_c$ until hydrodynamic freezeout at $T_{\rm fo}$=110 MeV, while the D_s-meson distribution is frozen at T_c.

It remains to determine absolute magnitude of the coalescence contribution to the D and D_s yields in AA collisions. In pp collisions we assume fragmentation only with hadronization fractions from recent PYTHIA simulations [44], i.e., D/c=82% and D_s/c=11%, including feed-down from excited states (here, $D{\equiv}D^+{+}D^0$). This gives D_s/D=0.134 in pp, in line with CDF data in $p\overline{p}$($\sqrt{s}$=1.96 TeV) [45, 46] and the value used in a recent PHENIX analysis [15]. Since our coalescence contribution is evaluated using thermalized light and strange quarks within RRM, the logical choice for the pertinent D_s/D ratio are thermal weights, which we adopt from the statistical hadronization model (including feeddown from excited states) [47], with an additional strangeness fugacity, γ_s=0.85 [26], for consistency with the hadronic equation of state in our hydro evolution [37]. Then, upon combining coalescence and fragmentation with the probabilities elaborated above, we obtain D/c=75% and D_s/c=15%, or D_s/D=0.20, for Au+Au collisions at $\sqrt{s_{\rm NN}}$=200 GeV, hence obtaining an enhancement of the D_s/D ratio of ∼50% over the value in pp.

Figure 2 summarizes our D and D_s meson spectra in semi-central Au+Au at RHIC relative to pp collisions in terms of the nuclear modification factor, $R_{AA}(p_T) = (dN^{AA}/dp_T)/(N_{\rm coll}dN^{pp}/dp_T)$ ($N_{\rm coll}$: number of binary NN collisions in AA), and elliptic-flow coefficient, $v_2(p_T)$ (the second harmonic of the azimuthal-angle dependence). Both the D and D_s R_{AA} (upper panel) exhibit a maximum around $p_T{\simeq}$2-3 GeV, induced by the transverse flow picked up from the expanding medium. Current STAR data are consistent with our D-meson result, but we predict the maximum to be more pronounced for the D_s (reaching beyond 1.5) due to c-quark coalescence with the enhanced strangeness in Au+Au. To further illustrate this effect, we also plot the result for c-quarks at the end of the QGP phase, which would directly represent D- and D_s-spectra if coalescence were absent and only δ-function fragmentation applied (as in pp). One clearly recognizes the important effect of coalescence, which only ceases above $p_T{\simeq}$5 GeV, where fragmentation takes over and the D, D_s and c-quark R_{AA} merge. While the c-quark spectra are not observable, the D and D_s ones are, so that their difference gives a quantitative measure of the coalescence effect. It turns out that hadronic diffusion does not significantly affect the D-meson R_{AA} (due to a compensation of a decreasing temperature and an increasing flow of the medium).

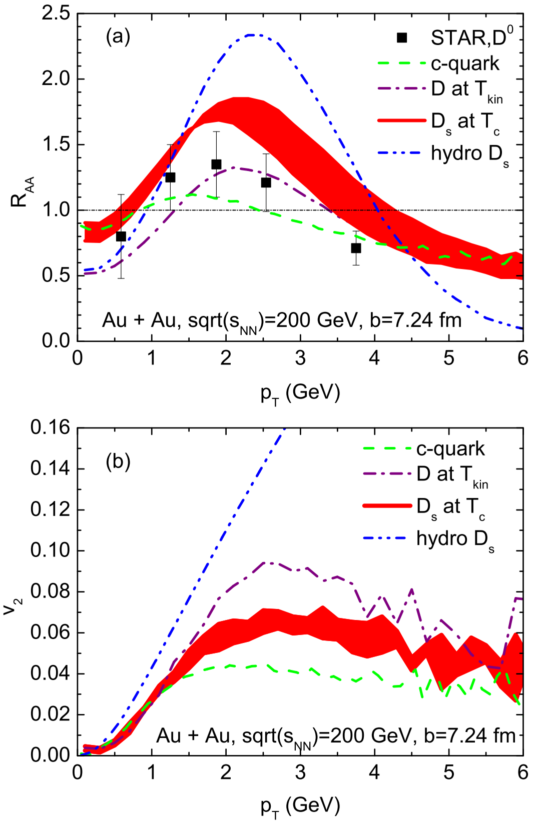

FIG. 2: (Color online) Our results for the nuclear modification factor (upper panel) and elliptic flow (lower panel) of D_s (red bands) and D mesons (green dash-dotted lines) in semi-central Au+Au collisions at RHIC. We also show the result for charm quarks at T_c (purple dashed lines), the equilibrium limit for D_s mesons in the hydrodynamic medium at T_c (blue dash-double-dotted line) and preliminary STAR data [16] for the D-meson $R_{\rm AA}$ in 0-80% Au+Au. In the upper panel, the red uncertainty band is governed by inclusion or omission of a Cronin effect in the initial charm spectra, while in the lower panel it is controlled by including or neglecting diffusion effects in the hadronization window.

The elliptic flow of particle spectra is known to be an excellent measure of the medium's collectivity due to hydrodynamic flow in non-central AA collisions (induced by the "almond-shaped" initial nuclear overlap zone). In our calculations, the diffusion in the QGP imparts an appreciable v_2 on the charm quarks of up to ∼4.5%, cf. lower panel in Fig. 2. Coalescence with thermal quarks amplifies this value by up to 50%, for both D and D_s mesons. However, while the D_s spectra freeze out after hadronization, the D coupling to the hadronic medium, which inherits the full elliptic flow from the QGP expansion [37], further augments v_2 by up to 30%. We therefore suggest the v_2-splitting between D and D_s, in the spirit of the early multistrange freezeout in the underlying hydro evolution, as a promising measure of the transport properties of the hadronic phase.

In summary, we have argued that measurements of D vs. D_s-meson R_{AA} and v_2 in URHICs provide powerful constraints on heavy-flavor diffusion and hadronization. We have made predictions for these observables employing a self-consistent framework where the concept of a strongly coupled QGP is implemented in both macro- and microscopic components of the calculation: a hydrodynamic medium evolution, quantitatively tuned to bulk- and multistrange-hadron observables, has been combined with nonperturbative charm-diffusion coefficients in the QGP which are compatible with currently available lQCD results. The diffusion of D mesons in the hadronic phase has been implemented for the first time, while D_s mesons are frozen out at T_c. A remarkable enhancement of the D_s-meson R_{AA} well above one emerges as a result of a strong charm-quark coupling to the QGP and subsequent recombination with equilibrated strange quarks. The latter can be directly tested by comparing D_s- and D-meson R_{AA}. The D meson picks up significant additional v_2 from the hadronic phase, which can be quantified by comparing to D_s-meson v_2 for which hadronic diffusion effects are absent. This picture should persist at LHC and can be directly carried over to the bottom sector using B and B_s mesons.

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