D_{s} Meson as a Quantitative Probe of Diffusion and Hadronization in Nuclear Collisions

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Phys. Rev. Lett. **110**, 112301 — Published 11 March 2013

DOI: 10.1103/PhysRevLett.110.112301

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

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(Dated: January 24, 2013)

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. The unique valence-quark content of the $D_s{=}c\bar{s}$ couples the well-known strangeness enhancement with the collective-flow pattern of primordially produced charm quarks. This idea is illustrated utilizing 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 at RHIC is predicted, with a maximum of ∼1.5-1.8 at transverse momenta around 2 GeV/c. This is 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.

PACS numbers: 25.75.-q 25.75.Dw 25.75.Nq

Strongly interacting matter, as governed by Quantum Chromodynamics (QCD), is expected to exhibit a rich phase structure. Lattice-QCD (lQCD) computations predict the formation of a deconfined Quark-Gluon Plasma (QGP) at a pseudo-critical temperature of $T_{\rm pc}{\simeq}170\,$MeV [1, 2], which filled the early universe during the first few microseconds of its existence. Ultrarelativistic heavy-ion collisions (URHICs) at BNL's Relativistic Heavy Ion Collider (RHIC) and at CERN's Large Hadron Collider (LHC) aim at re-creating the QGP and studying its properties. The experimental results thus far suggest the QGP to be a color-opaque, strongly coupled and almost ideal liquid with initial temperatures well above $T_{\rm pc}$ [3, 4]. These rather qualitative assessments [5, 6] call for quantitative investigations of the strongly-coupled QGP in terms of its microscopic interactions which requires novel probes and observables.

A special role in these efforts is played by the heavy charm (c) and bottom (b) quarks. Their masses, $m_{c,b} \simeq 1.3, 4.5\,$GeV, are large compared to the temperatures of ∼1-3 $T_{\rm pc}$ reached at RHIC and LHC. Therefore, their production mostly occurs in 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 $\sim m_Q/T \approx$ 5-20 [8–12]. This renders their thermalization time comparable to the typical QGP lifetimes in URHICs, and thus makes them excellent probes. Current heavy-quark (HQ) observables [13–16] indicate a surprising degree of thermalization and collectivity, especially through large elliptic flow [14, 15].

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 require an interaction strength that goes well beyond perturbative QCD (pQCD) with realistic 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 observed semileptonic electron-decay ($e^\pm$) spectra reasonably well up to transverse momenta of $p_t^e \simeq 5\,$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 and the charm coupling to the QGP and hadronic matter.

Another key point here is to test the dual role of resonant HQ interactions with light quarks for 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]. It can be understood as strangeness equilibration within the statistical hadronization model [28]. Thus, if resonant HQ interactions and recombination with thermalized light quarks into D-mesons are important to explain HQ observables [17, 20], 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 encoded in its p_T-dependence, which allows us to scrutinize both diffusion and hadronization effects when compared to D mesons.

The D_s and D observables encode another aspect which has not been evaluated in the HQ context to date: the role of the hadronic phase. Following the 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. Recall that the D_s does not carry a light valence quark to easily form resonances in a hadronic matter. 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.

In the following we illustrate these ideas in a quantitative implementation of nonperturbative HQ diffusion in a hydrodynamic medium in URHICs. At the temperatures of interest, $T\lesssim 400$ 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], calculated using in-medium HQ scattering amplitudes. At low and intermediate momenta the latter 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 lQCD. The T-matrices develop threshold resonances in mesonic and diquark channels close to $T_{\rm pc}$. 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 $\mathcal{D}_s = T/[m_{c,D}A(p=0,T)]$ (verified to hold for HQ resonance interactions in [9]). Coming from high T, $\mathcal{D}_s$ decreases in the QGP (due to increasing 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 $T_{\rm pc}$ (translating into an estimated $\eta/s \sim (2-4)/4\pi$). Our results in the QGP are comparable to recent quenched lQCD estimates [35, 36], but far below the pQCD values.

The Brownian motion of charm is implemented into URHICs via relativistic Langevin simulations defined by

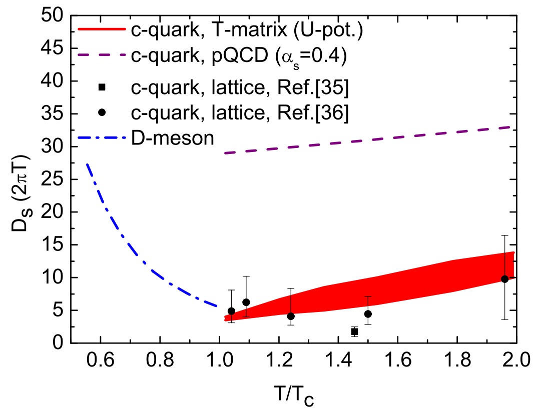

FIG. 1: (Color online) The spatial diffusion coefficients $\mathcal{D}_s$ (in units of the thermal wavelength, $1/(2\pi T)$) vs. temperature (in units of T_c) for charm quarks using T-matrix interactions in the QGP (red band) and D mesons using effective lagrangians in hadronic matter (blue solid line),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

"post-point" space-momentum updates [37, 38],

$$\delta\vec{x} = \frac{\vec{p}}{E}\,\delta t\ ,\ \ \delta\vec{p} = -A(p,T)\ \vec{p}\ \delta t + \delta\vec{W}(\vec{p}+\delta\vec{p},T) \quad (1)$$

where E is the HQ energy and $\delta\vec{W}$ a random force distributed according to a Gaussian noise; its width is determined by the momentum diffusion coefficient which is related to A via the Einstein relation. The space-time evolution of the medium is approximated by boost-invariant ideal hydrodynamics with a QGP above $T_{\rm pc}$ and a hot hadronic gas below. We employ our recent tune [39] of the AZHYDRO code [40], optimized to describe bulk and multistrange hadron spectra and elliptic flow in Au-Au collisions at RHIC. It utilizes a state-of-the-art lQCD equation of state [2, 41] with pseudo-critical deconfinement temperature of $T_{\rm pc}$=170 MeV (a possibly smaller $T_{\rm pc}^{\chi}$ for chiral restoration is not pertinent in the HQ context), and a subsequent hadron-resonance-gas phase with chemical freezeout at $T_{\rm ch}$=160 MeV to describe 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_{\rm fo}\simeq$110 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 approximated via a Gaussian transverse-momentum broadening with $\langle k_T^2\rangle = 0.6$ GeV^2 estimated from recent PHENIX $e^\pm$ spectra in d-Au [42].

After diffusion through the QGP charm-quark distributions are converted into charmed-hadron ones. This is realized through resonance recombination [43] with thermal light and strange quarks into D and D_s mesons on the hydro hypersurface at $T_{\rm pc}$ [38]. Remaining c-

quarks are treated with δ-function fragmentation (as in the fits to pp data). A reliable coalescence dynamics at low and intermediate p_T has to comply with the long-time limit of thermal equilibrium. The formulation of the resonance recombination model (RRM) via a Boltzmann equation [43] accomplishes this, including the full space-momentum correlations of the hydrodynamic flow field [38]. The coalescence probabilities are estimated via $P_{\rm coal}(p) \simeq \Delta\tau_{\rm res}\Gamma_c^{\rm res}(p)$, with the c-quark reaction rate, $\Gamma_c^{\rm res}(p)$, calculated from the heavy-light T matrix; the time duration $\Delta\tau_{\rm res}$ characterizes one generation of D and D_s resonance formation [38]. With $\Gamma_c^{\rm res}(0)\simeq 0.2\,$GeV [44] and $\Delta\tau_{\rm res}\approx 1\,{\rm fm}/c$, the recombination probability is approximated as one at zero c-quark momentum, decreasing thereafter as determined by the dynamics of the RRM expression [43]. 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 $\Gamma_{D,D_s} = 0.2\,$GeV, to represent the values from the in-medium T-matrices [33] during the hadronization window. Since HQ resonant scattering is underlying both diffusion and hadronization interactions, there is, in principle, an overlap between the two (not for 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 $1\,{\rm fm}/c$ prior to $T_{\rm pc}$, corresponding to a temperature window of 180-170 MeV. Note that there is a compensation between a larger hadronization window and a reduced diffusion effect, lending stability to the final results. The Langevin simulation resumes with hadronic diffusion of the combined coalescence+fragmentation distribution for D-mesons for $T<T_{\rm pc}$ until hydrodynamic freezeout at $T_{\rm fo}$=110 MeV, while the D_s-meson distribution is frozen at $T_{\rm pc}$.

It remains to determine the 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 [45], *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) [46, 47] (as also used in a recent PHENIX analysis [15]). Since our coalescence contribution is evaluated with thermalized light and strange quarks within RRM, the natural choice for the pertinent D_s/D ratio are thermal weights which we adopt from the statistical hadronization model (including feeddown) [48]. An additional strangeness fugacity, γ_s=0.85 [26], ensures consistency with the hadronic equation of state in our hydro evolution [39]. Upon combining coalescence and fragmentation with the probabilities elaborated above, we find D/c=75% and D_s/c=15%, or D_s/D=0.20, for $\sqrt{s_{\rm NN}}$=200 GeV Au+Au collisions, *i.e.*, the D_s/D ratio is enhanced by $\sim$50% over the pp value.

Figure 2 shows our D- and D_s-meson spectra in semi-central Au+Au collisions at RHIC relative to pp collisions in terms of the nuclear modification factor $R_{\rm AA}(p_T) = (dN^{\rm AA}/dp_T)/(N_{\rm coll}dN^{pp}/dp_T)$ ($N_{\rm coll}$: number of binary NN collisions in AA), and elliptic-flow coefficient $v_2(p_T)$ (the second harmonic of the azimuthal-angle dependence). Both D and D_s $R_{\rm AA}$ exhibit a maximum around $p_T\simeq$2-2.5 GeV, generated by the coupling to the transverse flow of 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 plot the result for c quarks at $T_{\rm pc}$ 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 im-

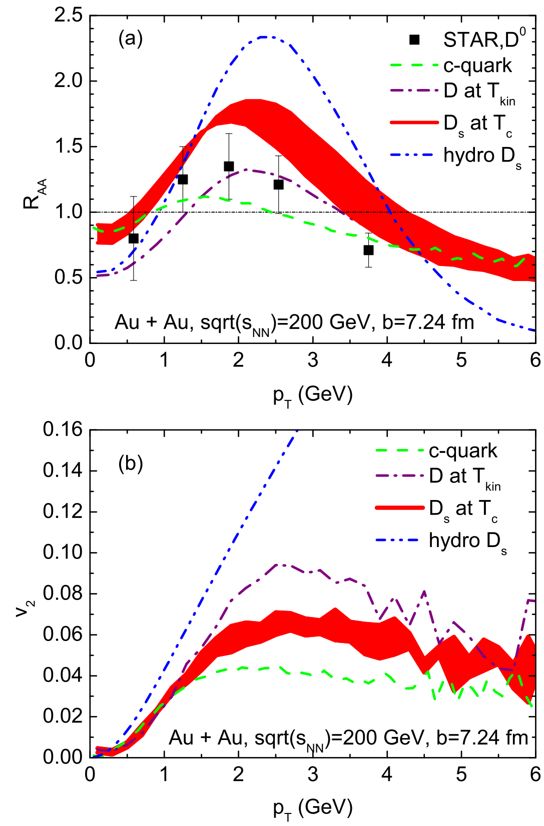

FIG. 2: (Color online) Our results for the nuclear modification factor (upper panel) and elliptic flow (lower panel) of D_s (red bands) and D mesons (purple dash-dotted lines) in semi-central Au+Au collisions at RHIC. We also show the result for charm quarks at $T_{\rm pc}$ (green dashed lines), the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

portant effect of coalescence; it ceases above $p_T \simeq 5$ GeV, where fragmentation takes over and the D, D_s and c-quark $R_{\rm AA}$ 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. We find that hadronic diffusion does not significantly affect the D-meson $R_{\rm AA}$ due to a compensation of decreasing temperature and increasing flow of the medium.

The elliptic flow of particle spectra is known to be an excellent measure of the medium's collectivity from hydrodynamic flow in non-central AA collisions, induced by the "almond-shaped" initial nuclear overlap zone. In our calculations, diffusion in the QGP imparts an appreciable v_2 on charm quarks of up to $\sim$4.5%, cf. lower panel in Fig. 2. Coalescence with thermal light and strange quarks amplifies this value by $\sim$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 carries the full elliptic flow built up by the QGP expansion [39], further augments v_2 by $\sim$30%. We therefore propose the v_2-splitting between D and D_s, in the spirit of early multistrange freezeout in the underlying hydro evolution, as a promising measure of the transport properties of the hadronic phase, essentially independent of the modeling of QGP diffusion and hadronization. Even if the D_s reinteracts in the hadronic phase, the v_2-splitting of D and D_s still provides a lower limit for the transport coefficient in the hadronic medium.

In summary, we have argued that measurements of D- vs. D_s-meson $R_{\rm AA}$ and v_2 in URHICs provide powerful constraints on heavy-flavor transport and hadronization. Our predictions for these observables employ a self-consistent framework where the concept of a strongly coupled QGP is implemented into both macro- and microscopic components of the calculation, by combining a hydrodynamic medium evolution (quantitatively tuned to bulk- and multistrange-hadron observables) with non-perturbative charm-diffusion coefficients in the QGP (compatible with current 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 $T_{\rm pc}$. A remarkable enhancement of the D_s-meson $R_{\rm AA}$ 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 the D_s- and D-meson $R_{\rm AA}$. The D-meson picks up significant additional v_2 from the hadronic phase, which can be quantified by comparing to the D_s-meson v_2 for which hadronic diffusion effects are suppressed. This picture persists at LHC and carries over to the bottom sector using B and B_s mesons.

Acknowledgments.— This work was supported by the U.S. National Science Foundation (NSF) through CAREER grant PHY-0847538 and grant PHY-0969394, by the A.-v.-Humboldt Foundation, and by the JET Collaboration and DOE grant DE-FG02-10ER41682. M.H. additionally acknowledges start-up support by NUST.

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