D*-Meson as Quantitative Probe of Diffusion and Hadronization in Nuclear Collisions

Min He, Rainer J. Fries and Ralf Rapp

Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843-3366, U.S.A.

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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 $D_s = c s$ 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 $\sim 1.5$-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 $D_s$-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 $T_c \simeq 170$ 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 ($m_{c,b} \simeq 1.3, 4.5$ 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 $\sim m_q/T \simeq 5-20$ [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 non-perturbative 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 $p_t^e \simeq 5$ 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 [23]. It manifests itself as a $\sim 50\%$ increase of strange-to-light hadron ratios in central nucleus-nucleus (AA) relative to $pp$ collisions (e.g., in the $K/\pi$ 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 trans-
verse 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., $\phi$ and $\Omega^-$) 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 ($\eta/s$) [12], disentangling the former for hadronic and QGP phases would allow us to quantify the temperature dependence of $\eta/s$.

Let us start by describing our calculations of charm diffusion in medium. At the temperatures of interest in URHICs, $T \lesssim 400$ MeV, HQ kinetics can be approximated by Brownian motion, with a thermal relaxation rate $\Lambda(p, T)$ derived from a Fokker-Planck equation [8-10, 17, 21, 23]. The key input to calculate $\Lambda$ 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, 32] 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 $\sim 3-5$ 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 $\Lambda$-dependence, which allows us to scrutinize both diffusion and hadronization effects, especially in comparison to $D$ mesons.

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 [35] 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 ($T_{ch}\sim 110$ MeV) freezeout, respectively. The initial HQ distributions are taken from a PYTHIA tune to $c^\pm$ spectra in $pp$ and dAu collisions [17]. The Cronin effect in nuclear collisions is accounted for via a Gaussian transverse-momentum broadening with $\langle k_T^2\rangle = 0.6$ GeV$^2$, estimated from recent PHENIX $c^\pm$ 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 $\delta$-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 $P_{coal}(p) \sim \Delta \Gamma_{\text{res}} T_{\text{res}}^2(p)$, with the charm-quark reaction rate, $\Gamma_{\text{res}}(p)$ (as given by the heavy-light $T$ matrix), and a time duration $\Delta T_{\text{res}}$ characterizing one generation of $D$ and $D_s$ resonance formation [42]. With $\Gamma_{\text{res}}(0)=0.2$ GeV [43] and $\Delta T_{\text{res}}\approx 1$ 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 $\Gamma_{D,D_s}=0.2$ 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 $T_{fo}=110$ 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 [41], i.e., $D/s=c\simeq 82\%$ and $D_s/s=c\simeq 11\%$, 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 $p\bar{p}$ ($\sqrt{s}=1.96$ TeV) [15, 16] 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) [17], with an additional strangeness fugacity, $\gamma_s=0.85$ [20], for consistency with the hadronic equation of state in our hydro evolution [33]. Then, upon combining coalescence and fragmentation with the probabilities elaborated above, we obtain $D/s=c\simeq 75\%$ and $D_s/s=c\simeq 15\%$, or $D_s/D=0.20$, for Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV, hence obtaining an enhancement of the $D_s/D$ ratio of $\simeq 50\%$ 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, $R_{AA}(p_T)\equiv (dN^{AA}/d^3p_T)/(N_{coll}dN^{pp}/d^3p_T)$ ($N_{coll}$: 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 $\delta$-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).

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 $\simeq 4.5\%$, 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 hadroniza-
tion, 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 hadrodynamic 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 IQCD 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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