

Heavy-Quark Probes of the Quark-Gluon Plasma at RHIC

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Thermalization and collective flow of charm (c) and bottom (b) quarks in ultra-relativistic heavy-ion collisions are evaluated based on elastic parton rescattering in an expanding quark-gluon plasma (QGP). We show that resonant interactions in a strongly interacting QGP (sQGP), as well as parton coalescence, can play an essential role in the interpretation of recent data from the Relativistic Heavy-Ion Collider (RHIC), and thus illuminate the nature of the sQGP and its hadronization. Our main assumption, motivated by recent findings in lattice Quantum Chromodynamics, is the existence of D - and B -meson states in the sQGP, providing resonant cross sections for heavy quarks. Pertinent drag and diffusion coefficients are implemented into a relativistic Langevin simulation to compute transverse-momentum spectra and azimuthal asymmetries (v_2) of b - and c -quarks in Au-Au collisions at RHIC. After hadronization into D - and B -mesons using quark coalescence and fragmentation, associated electron-decay spectra and v_2 are compared to recent RHIC data. Our results suggest a reevaluation of radiative and elastic quark energy-loss mechanisms in the sQGP.

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Introduction. Recent experimental findings at the Relativistic Heavy-Ion Collider (RHIC) have given intriguing evidence for the production of matter at unprecedented (energy-) densities with surprisingly large collectivity and opacity, as reflected by (approximately) hydrodynamic behavior at low transverse momentum (p_T) and a substantial suppression of particles with high p_T . This has led to the notion of a “strongly interacting Quark-Gluon Plasma” (sQGP), whose microscopic properties, however, remain under intense debate thus far.

Heavy quarks (HQs) are particularly valuable probes of the medium created in heavy-ion reactions, as one expects their production to be restricted to the primordial stages. Recent calculations of radiative gluon energy-loss of charm (c) quarks traversing a QGP in central Au-Au collisions at RHIC have found nuclear suppression factors $R_{AA} \simeq 0.3-0.4$ [1, 2], comparable to the observed suppression of light hadrons at high p_T , and in line with preliminary (non-photonic) single-electron (e^\pm) decay spectra [3, 4, 5]. The latter also exhibit a surprisingly large azimuthal asymmetry (v_2) [6, 7, 8] in semicentral Au-Au which cannot be reconciled with radiative energy loss, especially if c -quarks are hadronized into D -mesons via fragmentation. While the underlying transport coefficients [2] exceed their predicted values from perturbative Quantum Chromodynamics (pQCD) by at least a factor of ~ 5 [9], energy loss due to *elastic* scattering parametrically dominates toward low p_T (by a factor $1/\sqrt{\alpha_s}$ [10]). But elastic pQCD cross sections [11, 12] also have to be upscaled substantially to obtain c -quark v_2 and R_{AA} reminiscent to preliminary e^\pm data, as shown in a recent Langevin simulation for RHIC [10]. In addition, contributions of bottom (b) quarks [13, 14] will reduce the effects in the electron- R_{AA} and $-v_2$ at high p_T . Quark coalescence approaches suggest that an e^\pm - v_2 in excess

of 10% can only be obtained if [15] (i) light quarks impart their v_2 on D -mesons (see also Refs. [16, 17]), (ii) the c -quark v_2 is comparable to that of light quarks.

We are thus confronted with marked discrepancies between pQCD energy-loss calculations and semileptonic heavy-quark (HQ) observables at RHIC. The resolution of this issue is central to the understanding of HQ interactions in the QGP in particular, and to the interpretation of energy loss in general. HQ rescattering also has direct impact on other key observables such as heavy quarkonium production (facilitating regeneration) and dilepton spectra (where $c\bar{c}$ decays compete with thermal QGP radiation).

In this letter we investigate the HQ energy-loss problem by introducing resonant HQ interactions into a Langevin simulation of an expanding QGP. Our calculations implement a combined coalescence+fragmentation approach for hadronization, as well as bottom contributions, to allow for a quantitative evaluation of pertinent e^\pm -spectra (v_2 and R_{AA}) which is mandatory for a proper interpretation of recent RHIC data. Our main assumption of resonant D - and B -like states in the sQGP has been shown [18] to reduce HQ thermalization times by a factor of ~ 3 compared to pQCD scattering. Theoretical evidence for resonances in the sQGP derives from computations of heavy and light meson correlators within lattice QCD (lQCD) [19, 20], as well as applications of lQCD-based heavy-quark potentials within effective models [21, 22, 23, 24]. Except for the mass and width of these states, no further free parameters enter our description, with degeneracies based on chiral and HQ symmetry.

Heavy-Quark Interactions in the QGP. Following Ref. [18] our description of HQ interactions in the QGP focuses on elastic scattering, mediated by resonance ex-

citations on light antiquarks (\bar{q}) as well as (nonresonant) leading order pQCD processes dominated by t -channel gluon exchange. The latter correspond to Born diagrams [25] regularized by a gluon-screening mass $m_g=gT$ with a strong coupling constant, $\alpha_s=g^2/(4\pi)=0.4$. The key assumption [18] is that a QGP at moderate temperatures $T \leq 2T_c$ sustains strong correlations in the lowest-lying color-neutral D - and B -meson channels. Support for the relevance of such interactions stems from quenched IQCD computations of euclidean mesonic correlation functions, which, after transformation into the timelike regime, exhibit resonance structures for both (heavy) Q - \bar{Q} and (light) q - \bar{q} states [19, 20]. In addition, applications of IQCD-based Q - \bar{Q} potentials have revealed both bound [21, 22] and resonance states [23] with dissolution temperatures of $\sim 2T_c$, quite compatible with the disappearance of the peak structures in the IQCD spectral functions. Here, we do not attempt a microscopic description of these correlations but cast them into an effective lagrangian with \bar{q} - Q - Φ vertices ($\Phi=D, B$), at the price of 2 free parameters: the masses of the meson fields, fixed at $m_{D(B)}=2(5)$ GeV, *i.e.*, 0.5 GeV above the Q - \bar{q} threshold (with quark masses $m_{c(b)}=1.5(4.5)$ GeV, $m_{u,d}=0$), and their width, Γ , obtained from the one-loop Φ self-energy (which, in turn, dresses the Φ -propagator) with the pertinent coupling constant varied to cover a range suggested by effective quark models [26, 27], $\Gamma=0.4$ -0.75 GeV. The multiplicity of Φ states follows from chiral and HQ symmetries alone, implying degenerate $J^P=0^\pm$ and 1^\pm states. We emphasize again that, besides the mass and width of the Φ states, no other free parameters (or scale factors) are introduced.

The matrix elements for resonant and pQCD scattering are employed to calculate drag and diffusion coefficients of HQs in a Fokker-Planck approach [11]. Resonances reduce the thermalization times for both c - and b -quarks by a factor of ~ 3 compared to pQCD scattering alone [18].

Langevin Simulation. To evaluate thermalization and collective flow of HQs in Au-Au collisions we perform relativistic Langevin simulations [10] embedded into an expanding QGP fireball. In the local rest frame of the bulk matter, the change in position (\vec{x}) and momentum (\vec{p}) of c - and b -quarks during a time step δt is defined by

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

(E : HQ energy), where $\delta\vec{W}$ represents a random force which is distributed according to Gaussian noise [34],

$$P(\delta\vec{W}) \propto \exp \left[-\frac{\hat{B}_{jk} \delta W^j \delta W^k}{4\delta t} \right]. \quad (2)$$

The drag coefficient (inverse relaxation time), A , and the inverse of the diffusion-coefficient matrix,

$$B_{jk} = B_0(\delta^{jk} - \hat{p}^j \hat{p}^k) + B_1 \hat{p}^j \hat{p}^k, \quad (3)$$

are given by the microscopic model of Ref. [18], including p - and T -dependencies (the latter converts into a time dependence using the fireball model described below). The longitudinal diffusion coefficient is set in accordance with Einstein's dissipation-fluctuation relation to [10] $B_1=TEA$, to ensure the proper thermal equilibrium limit. The latter also requires care in the realization of the stochastic process in Eq. (1); we here use the so-called Hänggi-Klimontovich realization [34] which approaches a relativistic Maxwell distribution if the Einstein relation is satisfied (in the Ito realization, *e.g.*, an extra term has to be introduced in A [35]). Finally, the HQ momenta are Lorentz-boosted to the laboratory frame with the velocity of the bulk matter at the actual position of the quark, as determined by the fireball flow profile (see below).

The time evolution of Au-Au collisions is modeled by an isentropically expanding, isotropic QGP fireball with a total entropy fixed to reproduce measured particle multiplicities at hadro-chemical freezeout which we assume to coincide with the phase transition at $T_c=180$ MeV [28]. The temperature at each instant of time is extracted from an ideal QGP equation of state with an effective flavor degeneracy of $N_f=2.5$. Radial and elliptic flow of the bulk matter are parameterized to closely resemble the time-dependence found in hydrodynamical calculations [29], assuming a flow profile rising linearly with the radius. We focus on semicentral collisions at impact parameter $b=7$ fm, with an initial spatial eccentricity of 0.6 and a formation time of $\tau_0=0.33$ fm/c, translating into an initial temperature of $T_0=340$ MeV. The evolution is terminated at the end of the QGP-hadron gas mixed phase (constructed via standard entropy balance [28]) after about 5 fm/c, at which point the surface flow velocity and momentum anisotropy have reached $v_\perp=0.5c$ and $v_2=5.5\%$ (variations in τ_0 by a factor of two affect the c -quark v_2 and R_{AA} by 10-20% (less for the e^\pm spectra), while a reduction in the critical temperature to 170 MeV increases (decreases) v_2^c (R_{AA}) somewhat less. D -meson rescattering in the hadronic phase [30] is neglected).

To specify initial HQ p_T -distributions, $P_{\text{ini}}(p_T)$, and especially the relative magnitude of c - and b -quark spectra (essential for the evaluation of e^\pm spectra), we proceed as follows: we first use modified PYTHIA c -quark spectra with δ -function fragmentation to fit D and D^* spectra in d-Au collisions [31]. These spectra are decayed to single- e^\pm which saturate pertinent data from p - p and d-Au up to $p_T^e \simeq 3.5$ GeV [32, 33]. The missing yield at higher p_T is attributed to contributions from B -mesons, resulting in a cross section ratio of $\sigma_{b\bar{b}}/\sigma_{c\bar{c}} \simeq 5 \cdot 10^{-3}$ (which is slightly smaller than for pQCD predictions [13] and implies a crossing of c - and b -decay electrons at $p_T \simeq 5$ GeV, as compared to 4 GeV in pQCD).

Fig. 1 summarizes the output of the Langevin simulations for the HQ nuclear modification factor, $R_{AA}=P_{\text{fin}}(p_T)/P_{\text{ini}}(p_T)$ (P_{fin} : final p_T -distributions),

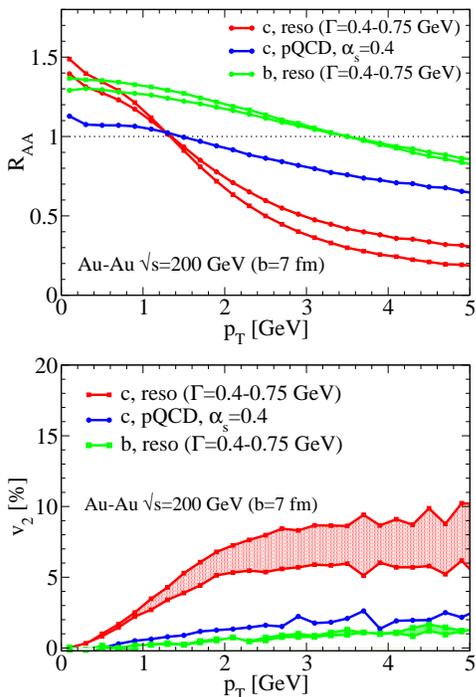


FIG. 1: Nuclear modification factor (upper panel) and elliptic flow (lower panel) of charm and bottom quarks in $b=7$ fm Au-Au($\sqrt{s}=200$ GeV) collisions based on elastic rescattering in the QGP. Red (green) and blue lines are for c - (b -) quarks with and without resonance rescattering, respectively, where the bands encompass resonance widths of $\Gamma=0.4-0.75$ GeV.

and elliptic flow, $v_2 = \langle (p_x^2 - p_y^2) / (p_x^2 + p_y^2) \rangle_{p_T}$ (evaluated at fixed p_T). For c -quarks and pQCD scattering only, our results are in fair agreement with those of Ref. [10] (recall that the Debye mass in our calculations is given by $m_g = gT$ while in Ref. [10] it was set to $m_g = 1.5T$ independent of α_s). However, both R_{AA} and v_2 exhibit substantial sensitivity to the inclusion of resonance contributions, increasing the effects of pQCD scattering by a factor of $\sim 3-5$. Also note the development of the plateau in $v_2(p_T > 3$ GeV) characteristic for incomplete thermalization of HQs in the bulk matter.

Hadronization and Single-Electron Spectra. Semileptonic single- e^\pm spectra are a valuable tool to investigate heavy-meson spectra in ultrarelativistic heavy-ion collisions, since their decay kinematics largely conserves the spectral properties of the parent particles [15, 36]. To compare our results to measured single- e^\pm in Au-Au collisions, the above HQ spectra have to be hadronized. To this end we employ the coalescence approach of Ref. [15] based on earlier constructed light-quark spectra [37]. Quark coalescence has recently enjoyed considerable success in describing, *e.g.*, the ‘‘partonic scaling’’ of elliptic flow and the large p/π ratio in Au-Au at RHIC [37, 38, 39], as well as flavor asymmetries in D -meson production in elementary hadronic collisions [40].

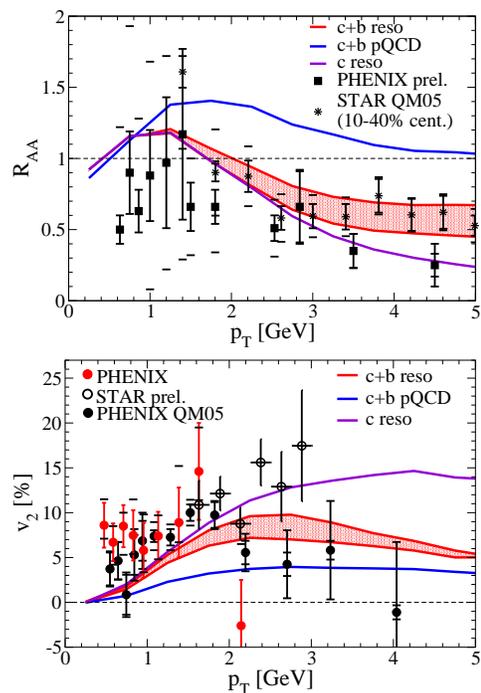


FIG. 2: R_{AA} (upper panel) and v_2 (lower panel) of semileptonic D - and B -meson decay-electrons in $b=7$ fm Au-Au($\sqrt{s}=200$ GeV) using HQ coalescence supplemented by fragmentation (line identification as in Fig 1). The data [4, 6, 7, 8] are for minimum bias collisions, the R_{AA} from STAR [5] for 10-40% central collisions.

Whereas at low p_T most of the HQs coalesce into D - and B -mesons, this is no longer the case at higher p_T where the phase space density of light quarks rapidly decreases. Therefore, to conserve HQ number in the B - and D -meson spectra, the remaining c - and b -quarks are hadronized using δ -function fragmentation. Finally, single- e^\pm p_T - and v_2 -spectra are computed via B - and D -meson 3-body decays, and compared to experiment in Fig. 2. We find that the effects of resonances are essential in improving the agreement with data, both in terms of lowering the R_{AA} and increasing v_2 . The B -meson contribution reflects itself by limiting R_{AA} and v_2 to values above 0.4 and below 10%, respectively, as well as the reduction of v_2 above $p_T \simeq 3$ GeV.

To better illustrate the effects of coalescence we plot in Fig. 3 calculations where *all* HQs are fragmented into D - and B -mesons. While R_{AA} is significantly reduced, most notably in the $p_T \simeq 1-2$ GeV region, v_2 also decreases reaching at most 6%, which is not favored by current data. It is, however, conceivable that modifications in the fraction of coalescence to fragmentation contributions, as well as improvements in our schematic (δ -function) treatment of fragmentation, will be necessary once more accurate experimental data become available. Additional corrections may also arise from a more precise determination of the b/c ratio and nuclear shadowing.

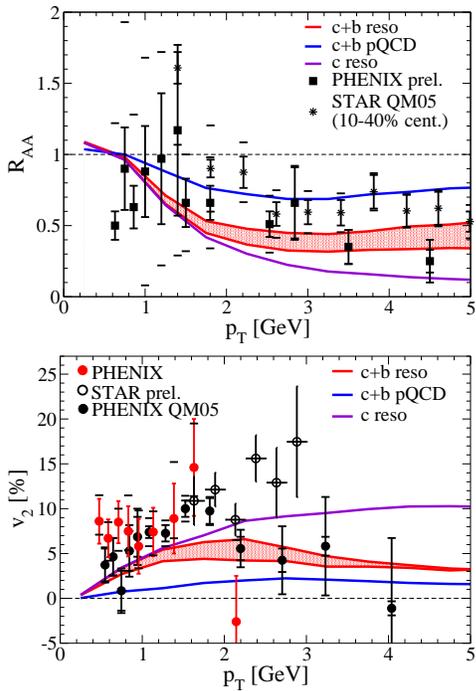


FIG. 3: Same as Fig. 2 but using HQ fragmentation only.

Conclusion. We have investigated thermalization and collective flow of c - and b -quarks within a relativistic Langevin approach employing elastic scattering in an expanding QGP fireball in semicentral Au-Au collisions at RHIC. Underlying drag and diffusion coefficients were evaluated assuming resonant D - and B -meson correlations in the sQGP, enhancing heavy-quark rescattering. Corresponding p_T -spectra and elliptic flow of c -quarks exhibit a large sensitivity to the resonance effects, lowering R_{AA} down to 0.2 and raising v_2 up to 10%, while the impact on b -quarks is small. Heavy-light quark coalescence in subsequent hadronization significantly amplifies the v_2 in single-electron decay spectra, but also increases their R_{AA} , especially in the $p_T \simeq 2$ GeV region. Bottom contributions dominate above 3.5 GeV reducing both suppression and elliptic flow. The combined effects of coalescence and resonant heavy-quark interactions are essential in generating a v_2^e of up to 10%, together with $R_{AA}^e \simeq 0.5$, supplying a viable explanation of current electron data at RHIC without introducing extra scale factors. Our analysis thus suggests that elastic rescattering of heavy quarks in the sQGP is an important component for the understanding of heavy-flavor and single-electron observables in heavy-ion reactions at collider energies. While induced gluon-radiation is expected to be the prevalent interaction with the medium at sufficiently high p_T [1, 2, 14], it may not be the dominant effect below $p_T \simeq 6$ GeV or so. A complete picture should clearly include *both* elastic and inelastic rescattering mechanisms.

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