Thermalization and Flow of Heavy Quarks in the Quark-Gluon Plasma

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Abstract. Elastic scattering of charm (c) and bottom (b) quarks via D- and B-meson resonance states in an expanding, strongly interacting quark-gluon plasma is investigated. Drag and diffusion coefficients are calculated from an effective model based on chiral symmetry and heavy-quark effective theory, and utilized in a relativistic Langevin simulation to obtain transverse-momentum spectra and elliptic flow (v_2) of c- and b-quarks. The hadronization to D- and B-mesons is described by coalescence and fragmentation, and the resulting decay-electron spectra are compared to recent RHIC data.

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Introduction. Recent experimental results at the Relativistic Heavy-Ion Collider (RHIC) have given convincing evidence for the creation of dense partonic matter with large collectivity and opacity. A key challenge in the description of this strongly interacting quark-gluon plasma (sQGP) is the understanding of the microscopic reaction mechanisms, leading to its approximate behavior as a nearly perfect fluid.

Heavy quarks (HQs) are valuable probes for the properties of the dense matter produced in heavy-ion reactions, since they are expected to be created in the early stages of the collision. Recent measurements of the transverse-momentum (p_T) spectra of non-photonic single electrons ($e^{\pm}$) at RHIC, attributed to the decay of D- and B-mesons, show a surprisingly small nuclear modification factor, R_{AA}^e [1, 2, 3], and large elliptic flow, v_2^e [4, 5, 6]. To explain these findings, especially the large $v_2^{(e)}$, quark-coalescence models [7, 8, 9] require that charm quarks are in approximate thermal equilibrium with light partons. A large degree of c-quark thermalization is, however, not supported by approaches based on perturbative Quantum Chromodynamics (pQCD), e.g., using radiative energy-loss [10, 11]. While at lower p_T elastic scattering processes parametrically dominate the energy loss ($\sim 1/\sqrt{\alpha_s}$) [12], a c-quark R_{AA} compatible with the observed R_{AA}^e can only be obtained with unrealistically large values of the strong coupling constant [12]. Also the combined effects of elastic and radiative energy loss may not explain the experimental findings [13].

In this talk we introduce D- and B-meson like resonance states in the sQGP [14] mediating elastic rescattering for heavy quarks. Employing pertinent drag and diffusion coefficients within a Fokker-Planck approach [17], we calculate HQ distributions in a flowing thermal QGP to simulate semi-central Au-Au collisions at RHIC [15]. Hadronization to D- and B-mesons is described by a combined quark-coalescence and fragmentation model, and subsequent semileptonic decay electron spectra are compared to recent data.

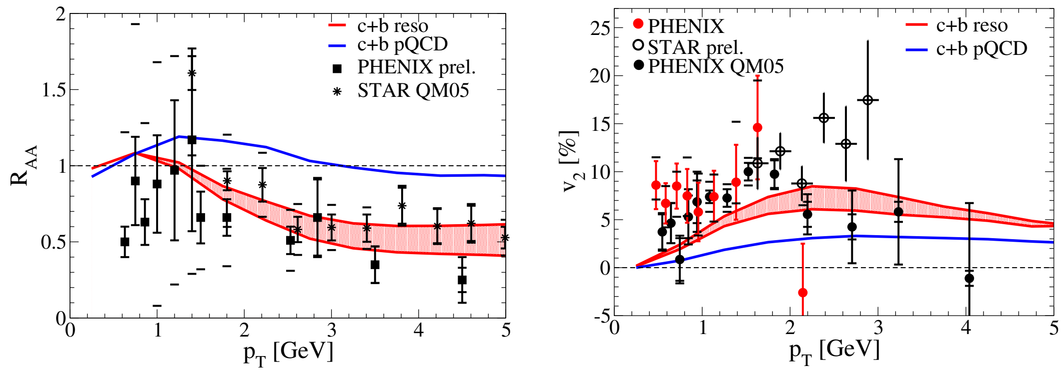

FIGURE 1. Nuclear modification factor, R_{AA} (left panel), and elliptic flow, v_2 (right panel), of semileptonic D- and B-meson decay electrons in b=7 fm, $\sqrt{s_{NN}} = 200$ GeV Au-Au collisions assuming different elastic HQ interactions in the QGP with subsequent coalescence, including the thermal weight factor described in the text, and fragmentation hadronization, compared to PHENIX and STAR data [1, 2, 5, 6].

Heavy-quark rescattering in the QGP. Lattice QCD (lQCD) computations of hadronic correlators and lQCD-based effective models suggest that mesonic resonance/bound states survive in the QGP up to temperatures of $\sim 2T_c$ in the light- and heavy-quark sector [18]. We here assume that the lowest pseudoscalar D- and B-meson states persist above the heavy-light quark threshold [14]. Chiral and HQ symmetry imply the degeneracy with scalar, vector and axial-vector states. Pertinent resonant Q-$\bar{q}$ cross sections are supplemented with leading-order pQCD processes [16], using $\alpha_s = g^2/(4\pi) = 0.4$. The evaluation of drag and diffusion coefficients within a Fokker-Planck model [17] results in HQ thermalization times which are lower by a factor ~ 3 compared to pQCD scattering [15].

These coefficients are used in a relativistic Langevin simulation [12] for the rescattering of HQs in an isentropically expanding QGP fireball corresponding to $b = 7$ fm Au-Au collisions at RHIC. The expansion parameters are determined to resemble the time evolution of radial and elliptic flow in hydrodynamic models [19], with an ideal QGP equation of state with 2.5 flavors and a formation time of $1/3$ fm/c (initial temperature $T_0 = 340$ MeV). The proper thermal equilibrium limit in the Langevin process is implemented via the Hänggi-Klimontovich realization [20], with longitudinal diffusion coefficient $B_1 = TEA$ [12] (Einstein's dissipation-fluctuation relation).

The initial HQ-p_T-distributions and the relative magnitude of c- and b-quark spectra are determined by fitting experimental D and D^* spectra in d-Au collisions [21]. The corresponding $e^{\pm}$ spectra saturate data from p-p and d-Au for $p_T^e \lesssim 3.5$ GeV [21, 22] with the missing yield at higher p_T attributed to B-meson decays, leading to a cross-section ratio of $\sigma_{b\bar{b}}/\sigma_{c\bar{c}} = 4.9 \cdot 10^{-3}$ and a crossing of D- and B-decay electrons at $p_T \simeq 5$ GeV.

Hadronization and single-electron observables. The c- and b-quark spectra from the Langevin simulation are used in the coalescence model of Ref. [7] with light-quark distributions from [23]. Here we take into account the thermal weight factor for the production of D^* mesons relative to D mesons, $(m_{D^*}/m_D)^{3/2}\exp[-(m_{D^*} - m_D)/T]$, as described in [7]. This leads to a reduced fraction of c-quarks which hadronize to D^* mesons via coalescence, compared to our analysis in [15]. To conserve c- and b-

number unpaired HQs are hadronized via δ-function fragmentation. Finally, the single-$e^{\pm}$ are obtained from D- and B-meson three-body decays. Fig. 1 shows that resonance scattering leads to a substantial increase in v_2^e and decrease in R_{AA}^e, as compared to pQCD rescattering alone. Coalescence further amplifies v_2^e but also increases R_{AA}^e. The B-meson contributions reduce the effects for $p_T \gtrsim 3$ GeV.

Note that the nonperturbative resonance formation mechanism employed in this work importantly resides on a finite (equilibrium) abundance of (anti-) quarks, while perturbative calculations [11, 10] typically assume a maximum of color charges entirely residing in gluons.

Conclusions. Assuming the survival of D- and B-meson resonances in the sQGP, we have evaluated c- and b-quark spectra in an expanding fireball at RHIC within a relativistic Langevin simulation. The elastic resonance rescattering of c-quarks leads to an R_{AA} down to 0.2 and v_2 up to 10%, while b-quarks are less affected. The HQs were hadronized in a combined quark-coalescence and fragmentation model followed by semileptonic D- and B-meson decay. The resulting R_{AA}^e and v_2^e are in reasonable agreement with recent RHIC data, suggesting that HQ-interactions via resonances may play an important role in the understanding of the microscopic properties of the sQGP, especially the rapid thermalization of heavy quarks.

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