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

Hendrik van Hees*, Vincenzo Greco† and Ralf Rapp*

*Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas 77843-3366, USA
†Laboratori Nazionali del Sud INFN, via S. Sofia 62, I-95123 Catania, Italy

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.

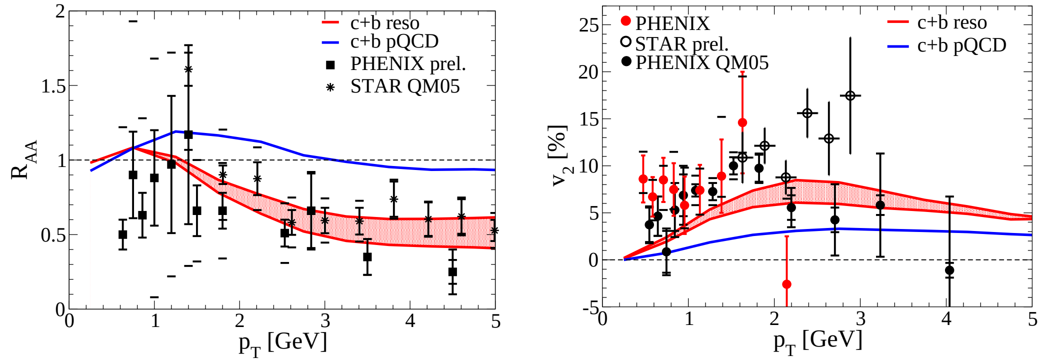

FIGURE 1. Nuclear modification factor, R_{AA} (left panel), and elliptic flow, v_2 (right panel), of semileptonic D- and B-meson decay electrons in b=7 fm, $\sqrt{s_{NN}} = 200$ GeV Au-Au collisions assuming different elastic HQ interactions in the QGP with subsequent coalescence, including the thermal 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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REFERENCES

1. S.S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **94**, 082301 (2005).
2. B. Jacak *et al.* [PHENIX Coll.], nucl-ex/0508036.
3. J. Bielcik *et al.* [STAR Coll.], nucl-ex/0511005.
4. S.S. Adler *et al.* [PHENIX Coll.], Phys. Rev. C **72**, 024901 (2005).
5. F. Laue *et al.* [STAR Coll.], J. Phys. G **31**, S27 (2005).
6. Y. Akiba *et al.* [PHENIX Coll.], nucl-ex/0510008.
7. V. Greco, C.M. Ko, R. Rapp, Phys. Lett. **B595**, 202 (2004).
8. D. Molnar, J. Phys. **G31**, S421 (2005).
9. B. Zhang, L.W. Chen, C.M. Ko, Phys. Rev. C **72**, 024906 (2005).
10. M. Djordjevic, M. Gyulassy, S. Wicks, Phys. Rev. Lett. **94**, 112301 (2005).
11. N. Armesto *et al.*, Phys. Rev. D **71**, 05027 (2005).
12. G.D. Moore, D. Teaney, Phys. Rev. C **71**, 064904 (2005).
13. S. Wicks, W. Horowitz, M. Djordjevic and M. Gyulassy, nucl-th/0512076.
14. H. van Hees, R. Rapp, Phys. Rev. C **71**, 034907 (2005).
15. H. van Hees, V. Greco, R. Rapp, nucl-th/0508055.
16. B.L. Combridge, Nucl. Phys. **B151**, 429 (1979).
17. B. Svetitsky, Phys. Rev. D **37**, 2484 (1988).
18. M. Asakawa, T Hatsuda, Phys. Rev. Lett. **92**, 012001 (2004); F. Karsch, E. Laermann, hep-lat/0305025; R. Morrin *et al*, PoS LAT2005 (2005) 176; E.V. Shuryak, I. Zahed, Phys. Rev. C **70**, 021901(R) (2004); C.Y. Wong, Phys. Rev. C **72**, 034906 (2005); M. Mannarelli, R. Rapp, Phys. Rev. C **72**, 064905 (2005); Á. Mócsy, P. Petretczky, hep-ph/0512156.
19. P.F. Kolb, J. Sollfrank, U. Heinz, Phys. Rev. C **62**, 054909 (2000).
20. J. Dunkel, P. Hänggi, Phys. Rev. E **71**, 016124 (2005).
21. J. Adams *et al* [STAR Collaboration], Phys. Rev. Lett. **94**, 062301 (2005); A. Tai *et al* [STAR Collaboration], J. Phys. G **30**, S809 (2004).
22. A.A.P. Suaide *et al* [STAR Collaboration], J. Phys. G **30**, S1179 (2004).
23. V. Greco, C.M. Ko, P. Levai, Phys. Rev. C **68**, 034904 (2003).