Nonperturbative heavy-quark diffusion in the quark-gluon plasma

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Heavy quarks (charm and bottom) are valuable probes of the hot and dense matter produced in ultrarelativistic heavy-ion collisions: they are produced in initial hard nucleon-nucleon collisions and subsequently interact with the medium consisting of light quarks and gluons. Data on light hadron spectra in 200 AGeV Au-Au collisions at the Relativistic Heavy-Ion Collider (RHIC) have shown that the produced partonic medium can be described by ideal hydrodynamics, suggestive for a strongly interacting quark-gluon plasma (sQGP) [1,2]: after the collision the medium appears to equilibrate rapidly building up pressure which is associated with the observed collective flow of hadrons. Heavy quarks, due to their large mass, $m_Q \gg T_c$ ($T_c \approx 180$ MeV: critical temperature), are particularly sensitive to the microscopic interaction mechanisms underlying the apparent rapid thermalization. At RHIC the measurement of transverse-momentum (p_t) spectra and elliptic flow, v_2, of non-photonic electrons [3,4] - originating from the decay of open-charm (D) and –bottom mesons (B) - have lead to the conclusion that heavy quarks interact surprisingly strongly with the medium, largely inheriting its collective-flow pattern via the corresponding drag within the medium. These observations indicate large momentum-diffusion coefficients which can not be accounted for in perturbative QCD (pQCD).

We have investigated the drag-diffusion processes of heavy quarks in the QGP via relativistic Langevin simulations of a Fokker-Planck equation with transport coefficients calculated from a non-perturbative evaluation of elastic heavy-quark (HQ) scatterings in the QGP [5]. We have employed static quark anti-quark potentials extracted from heavy-quark free energies computed in lattice-QCD (lQCD) within a Brueckner many-body calculation, defined by a coupled set of Bethe-Salpeter (BS) and Dyson equations. The four-dimensional BS equation has been reduced to a three-dimensional Lippmann-Schwinger (LS) equation using the Thompson scheme. The interaction kernel, K, is identified with the static lQCD-based potential and supplemented with a relativistic Breit (current-current) correction for finite quark velocities. The uncertainty due to different input potentials from lattice QCD is at the 40% level (here we use a parameterization of a quenched calculation [6]). The LS equation has been partial-wave expanded and solved numerically in S- and P-wave channels. All color channels (singlet and octet for quark-antiquark, as well as antitriplet and sextet for quark-quark) are included. The resulting finite-temperature T-matrices exhibit resonance states close to the quark-antiquark threshold in the attractive color-singlet (meson) and -antitriplet (diquark) channels up to temperatures of ~1.5 T_c. Compared to our earlier introduced effective resonance model [7], the interactions in the present approach are generated dynamically without free parameters.

The heavy-light quark T-matrices are utilized to compute drag and diffusion coefficients within a Fokker-Planck equation. The nonperturbative HQ interactions with light anti-/quarks from the medium are supplemented with elastic scattering off gluons in leading-order pQCD using a strong coupling constant, $\alpha_s = g^2/(4\pi) = 0.4$, and a Debye-screening mass, $\mu = gT$. The drag coefficients, γ (related to the pertinent thermal relaxation time via $\tau^{\text{eq}} = 1/\gamma$), reach up to $\gamma = 1/(7\text{fm}/c)$ for c-quarks at low momenta close to T_c. This is comparable to the effective resonance model of Ref. [7] but a factor of ~4 larger than elastic pQCD scattering alone. The “melting” of the resonance states toward higher temperatures leads to drag coefficients decreasing with increasing temperature, which is opposite to both pQCD and the effective resonance model [7].

HQ diffusion in semi-/central 200 AGeV Au-Au collisions has been simulated using a Langevin process in an elliptic fireball model [8]. The temperature evolution is determined by an ideal gas QGP equation of state assuming isentropic expansion, and the flow field has been adjusted to results of hydrodynamical models [9]. In particular, the elliptic flow for semicentral collisions is parameterized with confocal elliptic isobar surfaces within the fireball, with a bulk elliptic flow of 5.5% to reproduce the empirical hadron elliptic flow consistent with quark coalescence models [10]. The final HQ distributions of the Langevin simulation are hadronized into D- and B-mesons at T_c in a combined coalescence/fragmentation scheme [8]. We emphasize that the microscopically calculated resonance correlations in the meson and diquark channels of the T-matrix close to T_c naturally merge into a coalescence description of hadronization [11].

Semileptonic decays of the D- and B-meson spectra provide single-electron ($e^{\pm}$) spectra which are compared to STAR [3] and PHENIX [4] data in Fig. 1. The agreement with experiment is rather remarkable in view of the essentially parameter-free calculation of the HQ-scattering rates (the uncertainty of the lQCD-based potentials amounts to ~30% at the level of observables). The increase of the HQ drag and momentum-diffusion coefficients with decreasing temperatures seems to be supported by the data since the at high-p_t suppression of heavy quarks (i.e. R_{AA}<1) occurs mostly early in the fireball evolution, while the anisotropy of the flow, v_2, builds up in the later stages.

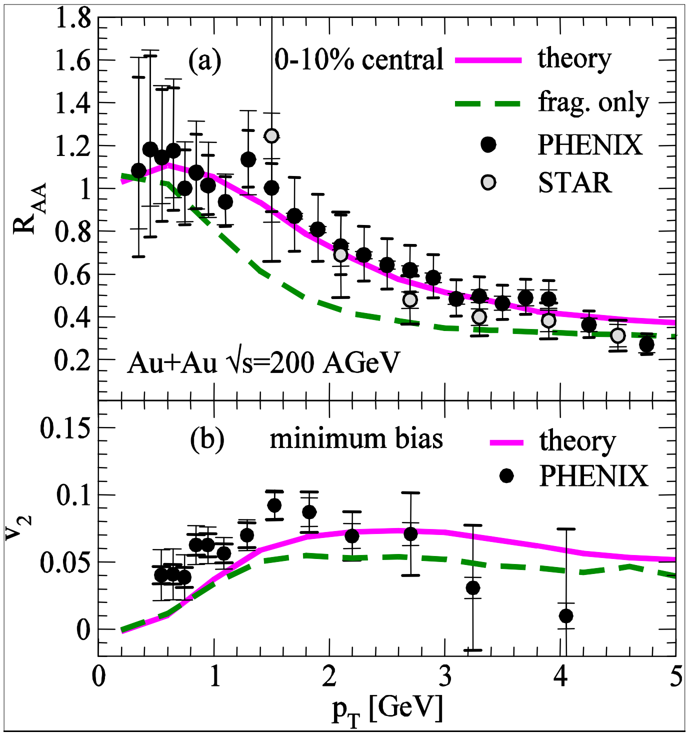

Figure 1. Upper panel: nuclear modification factor, R_{AA}, of single electrons in central 200 AGeV Au-Au collisions. The solid line represents the result of our HQ-diffusion model based on nonperturbative elastic scattering of charm and bottom quarks with light anti-/quarks evaluated using the in-medium T-matrix [5]. The dashed line shows the result when only (δ-function) fragmentation is taken into account for the hadronization process. Lower panel: elliptic flow coefficient, v_2, within the same model applied to semi-central (b=7 fm) 200 AGeV Au-Au collisions. The data in both panels are taken from Refs. [3,4].

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