Does the Charm Flow at RHIC?

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Abstract

Recent PHENIX $Au + Au \rightarrow e^- + X$ data from open charm decay are shown to be consistent with two extreme opposite dynamical scenarios of ultra-relativistic nuclear reactions. Perturbative QCD \textit{without} final state interactions was previously shown to be consistent with the data. However, we show that the data are also consistent with zero mean free path hydrodynamics characterized by a common transverse flow velocity field. The surprising coincidence of both $D$ and $B$ hydrodynamic flow spectra with pQCD up to $p_T \approx 3$ and 5 GeV, respectively, suggests that heavy quarks \textit{may} be produced essentially at rest in the rapidly expanding gluon plasma. Possible implications and further tests of collective heavy quark dynamics are discussed. \textit{PACS numbers:} 12.38.Mh; 24.85.+p; 25.75.-q
I. INTRODUCTION

Heavy quark production in nuclear collisions \((A + A \rightarrow c(b) + X)\) is conventionally calculated via pQCD \([2, 3, 4, 5]\). Final state elastic scattering effects either at the partonic \([6]\) or the hadronic rescattering level \([7, 8]\) are not expected to be large distortions of the initial spectra because the cross sections involved are small. On the other hand, energy loss in dense matter via induced gluon radiation could possibly lead to a large suppression of the high \(p_T\) distribution relative to pQCD predictions \([9, 10, 11]\). It was this suppression that was thought to be essential to prevent the open charm “background” from swamping dilepton signatures of the sought after thermal plasma. However, more recent considerations suggest that the “dead cone” effect for heavy quarks \([12]\) may inhibit induced radiative energy loss. More quantitative calculations appear to support this assertion \([13]\). Therefore, it is not unreasonable to expect that heavy quark (and open charm hadron) production could be well approximated by conventional factorized pQCD even in central \(Au + Au\) collisions at RHIC. This would indicate that the produced medium is essentially transparent to heavy quarks, or equivalently, the heavy quark and subsequent D or B have mean free paths at least as large as nuclear dimensions. In this case, the charm and bottom quark yields are predicted to scale with atomic number \(A\) and impact parameter \(b\), simply according to the Glauber nuclear overlap density \(T_{AB}(b)\). The predicted distribution of heavy quarks, \(Q = c, b\), is then

\[
\frac{dN_Q^{AB(b)}}{dyd^2p_t} = T_{AB}(b) \frac{d\sigma_{PQCD}^Q}{dyd^2p_t}.
\]

For central 10\% \(Au + Au\) collisions \(T_{AuAu}(cent) = 22.6 \text{ mb}^{-1}\). Nuclear geometry therefore amplifies the \(p + p\) rate by the number of binary collisions \(N_{binary} \approx 905\). See ref. \([3]\) for an extensive survey of pQCD heavy quark production.

Experimentally, recent PHENIX data \([14]\) on “prompt” single electron production in central and “minimum bias” \(Au + Au\) collisions at \(\sqrt{s} = 130 \text{ AGeV}\) have tested the above pQCD predictions. Utilizing PYTHIA \([4]\) to take into account the \(c \rightarrow D, D^*\) fragmentation and subsequent open charm decays, the data were found to be in good agreement with the pQCD predictions within the errors quoted, revealing no indication of a medium effect. Furthermore the observed binary collision scaling of the yield with centrality shows no hint (within relatively large errors) of possible suppression due to gluon shadowing or saturation effects. It should be noted that nuclear modifications to the parton distribution functions
may only lead to a small effect on the charm cross section because the PHENIX acceptance spans both the conventional shadowing and anti-shadowing $x \sim 0.05 - 0.15$ range.

In this letter we point out however that the single electron spectra in the observed $p_T < 3$ GeV range may hide much more extreme dynamics. We show that the same observed $e^-$ spectra is reproduced by a thermal hydrodynamic model that is consistent with the lighter hadron transverse momentum distributions. In the $p_T < 2$ GeV range, striking collective flow signatures have been observed at RHIC for $\pi, K, p$ [15, 16, 17]. Hydrodynamic models of course assume that (at least for light quarks and gluons) the opacity of the produced quark-gluon plasma is high enough that local equilibrium is achieved early in the collision and maintained through hadronization. This extreme assumption, first proposed by Landau and Feinberg, has until recently consistently over-predicted collective flow effects in hadronic interactions.

The collective flow velocity field in hydrodynamics is predicted to lead to strong mass dependent distortions of the transverse momentum spectra [18, 19, 20] relative to pQCD predictions in Eqn. 1. In pQCD the spectral distribution in $A + B$ collisions is identical to that in $p + p$ up to the $T_{AB}$ geometrical scale factor. Recent detailed hydrodynamic calculations of collective flow patterns expected in $Au + Au$ at $\sqrt{s} = 130, 200$ AGeV using realistic QCD equations of state found remarkable good agreement with the radial flow and azimuthal asymmetries observed in the $\pi, K, p$ spectra [21, 22, 23]. This is in sharp contrast to lower energy data (SPS, AGS, SIS, Bevalac) where one fluid hydrodynamics always over-predicted collective flow and large dissipative non-equilibrium corrections to its predictions were necessary to reconcile theory with data. We note that phenomenological fits [24, 25] with adjustable parameters could reproduce SPS data, but these fits required fine tuning of initial conditions and are not consistent with more realistic one-fluid hydrodynamics results [24].

At RHIC the produced density and equilibration rates could be high enough that at least the light quarks and gluons may achieve local equilibrium and subsequent hydrodynamic collective flow. However, that local equilibrium could be achieved poses an entirely non-trivial problem for transport theory. Recent studies [27, 28, 29, 31] based on parton cascade dynamics indicate that the opacity needed to achieve local equilibrium must be at least an order of magnitude higher than pQCD estimates. We note that non-linear Yang-Mills dynamics [32] is too weak to account for the strong observed azimuthal collectivity.
observed out to several GeV. In contrast, the data are easily described if local equilibrium is simply assumed! Jet tomographic analysis of the high $p_T$ quenching pattern also suggests that the matter produced is indeed highly opaque [30].

The question then naturally arises whether in spite of the strong theoretical prejudice against heavy quark local equilibration in nuclear collisions, could the mechanisms that appear to effect such an equilibration in the light partons also coerce the heavy quarks “to go with the flow” [38]? We test this hypothesis by computing the transverse momentum spectra of open charm and bottom hadrons using the same transverse boosted Bjorken model that fits the light hadron $p_T$ spectra up to 2 GeV. The numerical results of realistic Bjorken boost invariant hydrodynamics at RHIC can be approximated via [24, 25]

$$\frac{dN_H}{dy d^2 p_\perp} = \frac{dN_H}{dy} \frac{m_\perp}{Z} \int_0^R \! r dr I_0 \left( \frac{p_\perp \sinh \rho_\perp(r)}{T_{f_0}} \right) K_1 \left( \frac{m_\perp \cosh \rho_\perp(r)}{T_{f_0}} \right)$$

(2)

where $T_{f_0}$ is the freeze-out temperature and $Z$ normalizes the transverse momentum integral. The radial Doppler boost rapidity is taken as

$$\rho_\perp(r) = \tanh^{-1}(\beta_T(r))$$

(3)

and

$$\beta_T(r) = \beta_{max} \left( \frac{r}{R} \right)$$

(4)

which assumes a linear boost profile.

In Fig.1, the resulting “Doppler shifted” transverse momentum distributions for $\pi$, $D$ and $B$ hadrons are compared to the pQCD event generator PYTHIA for 10% central $Au + Au$ collisions at $\sqrt{s} = 130$ AGeV. The PYTHIA parameters [33] for charm and bottom are taken from [1], where the values were tuned to lower energy FNAL charm data and ISR single electron data. The PYTHIA $\pi$ results use a K factor = 3.5, which agrees well with the UA1 parameterization scaled to $\sqrt{s} = 130$ GeV and scaled for the $\pi/h$ ratio, as calculated in [34].

For the hydrodynamic model calculation, we use a fixed temperature $T = 128$ MeV [35] and fit to the PHENIX $\pi, K, p$ transverse momentum distributions [37] to determine $\beta_{max} = 0.65$ for central collisions. These values are compatible with those previously derived [36]. The $\pi$ hydrodynamic calculation result is normalized to the PHENIX measured $dN/dy(\pi^+) = 276 \pm 3$ [37], and the $D$ and $B$ results are normalized to the PYTHIA pQCD integrated $dN/dy$ values. Different boost profiles are also allowed and should be considered, including full hydrodynamic model calculations.
FIG. 1: For 10% central $Au + Au$ collisions at $\sqrt{s} = 130$ AGeV we show the neutral pion $\pi^0$, $D$ meson, and $B$ meson transverse momentum distributions from a PYTHIA calculation and a thermal hydrodynamic model. A scaled UA1 parameterization for the $\pi$ production is also shown and is in good agreement with the PYTHIA calculation. Note that the PYTHIA calculation for $\pi$ and the UA1 parameterization are only shown for $p_T > 2$ GeV. For comparison, also shown are the PHENIX data for $\pi^+$ from 5% central collisions and $\pi^0$ from 10% central collisions for comparison.

Note that in the case of pions, there is a substantial difference between the unquenched PYTHIA pQCD prediction and the radial hydrodynamic flow results. Also shown in Fig. 1 are the PHENIX $\pi^+$ yields for 5% central $Au + Au$ collisions \cite{37} and the PHENIX $\pi^0$ yields for 10% central $Au + Au$ collisions \cite{34}. The data are well described by the hydrodynamic calculation up to $p_T \approx 2$ GeV, but still fall substantially below the PYTHIA and UA1 parameterization at higher $p_T$. However, remarkably the difference between these two extreme dynamics is much less for the heavy open charm and bottom hadrons. The two models agree quite well up to $p_T \approx 3$ and 5 GeV for $D$ and $B$ mesons respectively.
FIG. 2: The PHENIX 10% central $Au + Au$ at $\sqrt{s} = 130$ AGeV single electron invariant multiplicities as a function of transverse momentum. The dashed curves are the PYTHIA calculation for $D$ mesons, $B$ mesons and their combined resulting decay electrons. The solid curves are the results from the thermal hydrodynamic model.

In Fig. 2 we show the hydrodynamic model and PYTHIA pQCD calculations for $D$ mesons, $B$ mesons, and their resulting decay electron distributions for 10% central $Au + Au$ collisions at $\sqrt{s} = 130$ AGeV. Also shown are the PHENIX measured “prompt” single electron distribution [1]. Both the infinite mean free path pQCD PYTHIA prediction and the zero mean free path hydrodynamic flow prediction reproduce the electron data. This is the central observation of this letter.

We have also compared these calculations for “minimum bias” (0-92% central) $Au + Au$ collisions at $\sqrt{s} = 130$ AGeV as shown in Fig. 3. For the “minimum bias” data, PYTHIA pQCD is scaled by $T_{AA} = 6.2$ mb$^{-1}$ (or equivalently $N_{binary} = 246$). The hydrodynamic calculation uses temperature (T) and boost ($\beta_{max}$) values for discrete centrality bins and
FIG. 3: The PHENIX “minimum bias” (0-92% central) $Au + Au$ at $\sqrt{s} = 130$ AGeV single electron invariant multiplicities as a function of transverse momentum. The dashed curves are the PYTHIA calculation for $D$ mesons, $B$ mesons and their combined resulting decay electrons. The solid curves are the results from the thermal hydrodynamic model.

then takes a weighted average, using the number of binary collisions for each centrality class as the weight factor. Assuming a temperature $T = 128$ $MeV$ independent of centrality, we find reasonable agreement with the PHENIX $\pi, K, p$ spectra \[37\] with $\beta_{\text{max}} = 0.65, 0.65, 0.63, 0.55, 0.25$ for centralities 0-5%, 5-15%, 15-30%, 30-60%, 60-92%, respectively. Again, we find reasonable agreement between hydrodynamics, PYTHIA and the PHENIX experimental data.

It may be a coincidence at RHIC, but the fact is that the initial charm and bottom quarks from pQCD may be produced going with the flow of light quark and gluons. This means that even if the heavy quark would lose energy in a static plasma, they do not because they are essentially at rest in the comoving frame of the flowing plasma. The feedback of
positive energy gain from the comoving matter makes it impossible for the heavy quark in this momentum range to change its distribution appreciably. The single electron data are thus also consistent with the formation of a highly opaque fluid that sweeps even the heavy quarks along its strong currents.

If there exist interactions that maintain local thermal equilibrium, could they be strong enough to bring heavy quarks into chemical equilibrium as well? At lower SPS energies there is not sufficient time to “cook up the charm”, and chemical equilibrium calculations vastly over-predict the charm yield relative to pQCD \([39]\). However, at RHIC energies heavy quark chemistry may not be as far off as long as exact charm conservation is taken into account in the canonical formulation \([40]\). Recent estimates suggest that canonically suppressed charm is in fact too small by about an order of magnitude relative to pQCD and the PHENIX data \([41]\). However, charm and chemistry are exponentially sensitive to the freeze-out conditions \([39]\). More work is needed to test this most radical of possibilities.

The single electron data below \(p_T \approx 3 \text{ GeV}\) therefore provides strong motivation to look to other observables to help differentiate extreme dynamical scenarios. Certainly these models must be confronted with higher statistics single electron data and a full range of exclusive centrality bins. This data is expected in the near future from the PHENIX experiment in \(Au + Au\) at \(\sqrt{s} = 200\ AGeV\ \([42]\). Of course more precise data at higher \(p_T\) could differentiate such models since pQCD is only power law suppressed while hydrodynamics is always eventually exponentially suppressed. However, this does not rule out a role for hydrodynamics at the lower \(p_T\).

The smoking gun signature for hydrodynamic flow would be to observe elliptic flow for \(D\) (or \(B\)) mesons including of course \(J/\psi\). Unfortunately, the current statistical method used by PHENIX for measuring charm via single electrons requires the subtraction of a significant background from Dalitz decay and conversion electrons. This “background” makes extraction of \(v_2\) for heavy quarks challenging. Even a displaced vertex tag (from a future experimental upgrade) would only partially resolve this problem since the electrons direction is not well correlated with the \(D\) meson direction, thus blurring the orientation for measuring \(v_2\). It may prove that only a displaced vertex combined with a complete reconstruction via \(D \rightarrow \pi + K\) will suffice for such a measurement. Another possibility is that if the plasma is opaque enough to direct the \(J/\psi\) or its pre-cursor \(c\bar{c}\) into azimuthally asymmetric flow, then a \(v_2\) measurement of \(J/\psi\) could serve as the smoking gun. Note that in this case the \(J/\psi\)
may arise completely from a late stage “coalescence” [13]. This may be the easiest and most
direct way resolve whether the charm and bottom really flows or are simply bystanders that
coincidentally have the same azimuthally averaged transverse distribution as the plasma at
RHIC.

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