

## Charm—a thermometer of the mixed phase\*

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### Abstract

A charmed quark experiences drag and diffusion in the quark-gluon plasma, as well as strong interaction with the plasma surface. Our simulations indicate that charmed quarks created in heavy ion collisions will be trapped in the mixed phase and will come to equilibrium in it. Their momentum distribution will thus reflect the temperature at the confinement phase transition.

Consider charm created in a high-energy nuclear collision. Some 99% of the charmed quarks created in hadronic collisions are *not* to be found in  $c\bar{c}$  bound states, but rather in the open charm continuum. Much like their bound counterparts, the unbound charmed quarks are created early, move through the interaction region slowly, and react strongly with their environment. They should contain as much information about the collision region as the  $J/\psi$ , although this information may be harder to extract.

Assuming invariance of the collision kinematics under longitudinal boosts [1], a space-time picture shows that a charmed quark, created near  $t = z = 0$  (the initial nucleus-nucleus collision), moves according to  $z = v_0 t$  which is exactly a longitudinal streamline of the fluid. Thus there is not much information to be gained from the quark's eventual longitudinal momentum; it is to the transverse momentum that we turn in order to learn about the quark's interaction with the surrounding matter.

The quark is created in the nascent plasma and, assuming it is not created too near the edge, sees this plasma cool to the mixed phase and beyond, to the hadron gas which dissociates soon after. The mixed phase lasts a long time, typically ten times as long as the pure plasma which precedes it. Our calculation thus concentrates on the charmed quark's interaction with the mixed phase [2]. We track the quark's diffusion through the initial plasma, its hadronization upon emerging into the hadron phase, its collisions (as a

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$D$  meson) with pions, and its possible reabsorption by a plasma droplet. For a given initial transverse momentum, we calculate the distribution of the final  $p_{\perp}$  of the  $D$  meson. (For details of the following see [3].)

Our simulation of the mixed phase is based on the cascade hydrodynamics code of Bertsch, Gong, and McLerran [4]. At proper time  $\tau = \tau_p$ , the uniform plasma breaks up into droplets of radius  $r_0 = 1.0$  or  $1.5$  fm (a parameter of which we have little knowledge). Each droplet has a mass equal to its volume times the Stefan-Boltzmann energy density at the transition temperature,  $M = (\frac{4}{3}\pi r_0^3) \times (\gamma T^{*4})$ , and its temperature is fixed at  $T^*$ . Each droplet then radiates pions as a black body. At each pion emission, the droplet shrinks (to conserve energy) and recoils (to conserve momentum). Similarly, a droplet absorbs any pion that comes close enough, with the concomitant growth and recoil. Pion-pion collisions are included in the simulation as well. The dominant motion of the droplet-pion mixture is a rarefaction due to the longitudinal expansion imposed by the initial conditions. This leads to the eventual evaporation of the droplets.

A charmed quark is created inside the plasma at  $\tau_0 < \tau_p$  and is allowed to diffuse according to a Langevin process [5],

$$\begin{aligned} \mathbf{x}(t + \epsilon) &= \mathbf{x}(t) + \frac{\mathbf{p}(t)}{E(t)}\epsilon \\ \mathbf{p}(t + \epsilon) &= \mathbf{p}(t) - \gamma(T)\mathbf{p}(t)\epsilon + \boldsymbol{\eta}(t)\sqrt{\epsilon} , \end{aligned}$$

where  $\boldsymbol{\eta}(t)$  is a Gaussian noise variable. The plasma cools as  $T = T_i(\tau_i/\tau)^{1/3}$  until it reaches  $T^*$ , whereupon it breaks into droplets. (We make sure the quark is *inside* a droplet.) The quark continues to diffuse. If the quark hits the surface of a droplet, it stretches a flux tube out into the vacuum. This flux tube has a tension  $\sigma = 0.16$  GeV<sup>2</sup> and a fission rate (per unit length)  $d\Gamma/d\ell = 0.5$  to  $2.5$  fm<sup>-2</sup>. (This is the range of values used in string-based event generator programs.) If the flux tube breaks in time, then the  $c$  quark finds itself to be a  $D$  meson outside the droplet; otherwise it is reflected back into the droplet.

If the quark indeed hadronizes, it is tracked as a  $D$  meson in the pion gas. If this  $D$  meson hits a droplet, it is absorbed: The light quark gets stripped off and the  $c$  quark proceeds back into the plasma.

Very often, a  $c$  quark coming to the surface of its droplet has insufficient energy to emerge as a meson. (It needs about 350 MeV.) In that case the quark is *trapped*. Unless it gains energy through diffusion or through droplet recoil, it will remain trapped until the droplet evaporates away much later.

Now to results. We show in Fig. 1 the mean  $p_{\perp}$  of a  $D$  meson as a function of the initial  $p_{\perp}$  of its parent  $c$  quark. Note the very weak dependence on the initial momentum. This feature, together with the width of the final-momentum distribution, indicates that the  $D$  meson is *thermalized*. The mean thermal  $p_{\perp}$  of a  $D$  meson at  $T^* = 150$  MeV is 820 MeV, and we attribute the higher  $\langle p_{\perp} \rangle$  shown in the figure to the flow of the droplet fluid.

In interpreting our results we distinguish between two populations of charmed quarks, those that emerge from flux-tube fission and then escape the system—*fragmentation mesons*—and those that are trapped within their original droplets until the latter evaporate—*breakup mesons*. As can be seen in Fig. 2, between 40% and 80% of the quarks are trapped until breakup. Fig. 3 shows that the breakup mesons are well thermalized while

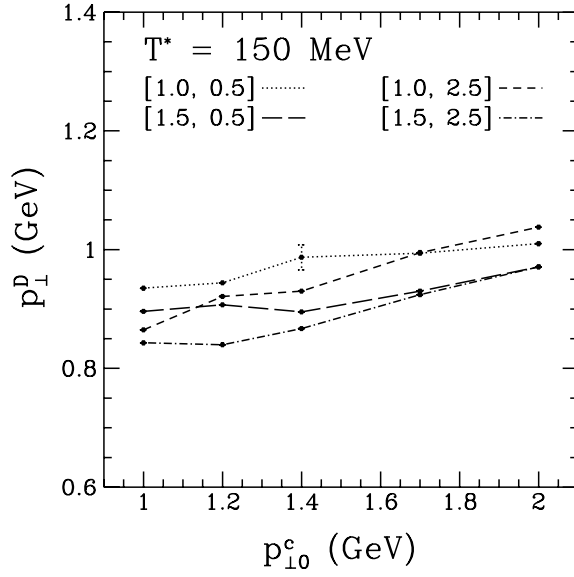


FIG. 1. RMS transverse momentum of  $D$  meson vs. initial transverse momentum of  $c$  quark, for transition temperature  $T^* = 150$  MeV. The four sets of points correspond to different values of  $r_0$  and  $d\Gamma/d\ell$  (in fm and  $\text{fm}^{-2}$ , respectively) as shown. A typical statistical error bar is shown.

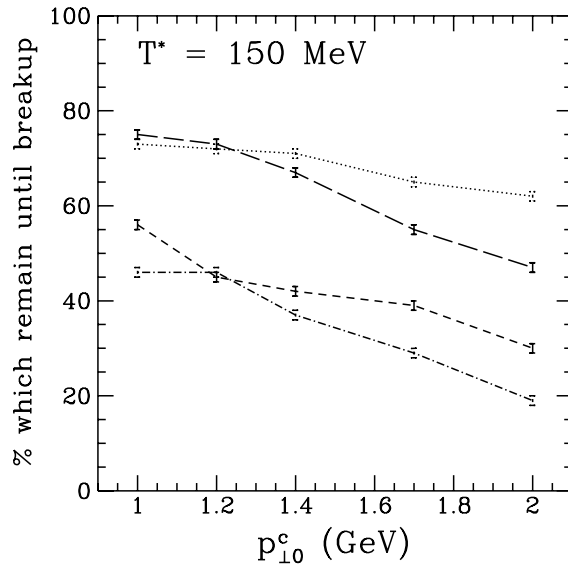


FIG. 2. The proportion of  $c$  quarks which are trapped inside their original droplets until their breakup. The four sets of points are for different values of  $r_0$  and  $d\Gamma/d\ell$  as in Fig. 1.

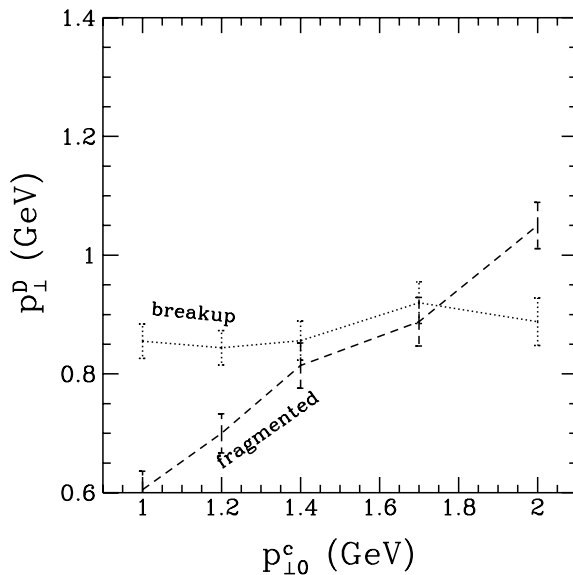


FIG. 3. Comparison of two populations of  $D$  mesons. The RMS  $p_{\perp}$  of  $D$  mesons is plotted against the initial  $p_{\perp}$  of the  $c$  quarks, for breakup mesons (dots) and for fragmentation mesons (dashes). Here  $T^* = 150$  MeV,  $r_0 = 1$  fm,  $d\Gamma/d\ell = 2.5$  fm $^{-2}$ .

the fragmentation mesons carry some memory of their quarks' initial momentum.

Finally, we compare results for two different transition temperatures. Fig. 4 shows a comparison of the predictions for  $T^*=150$  MeV with those for  $T^*=200$  MeV. The  $D$  transverse momentum shows a sensitivity to a temperature difference of 50 MeV which rises above the effects of the uncertainty in the two model parameters  $r_0$  and  $d\Gamma/d\ell$ .

To summarize our qualitative conclusions:

1. The mean  $p_{\perp}$  of a  $D$  meson is almost independent of the initial  $p_{\perp}$  of the parent  $c$  quark.
2. Many  $c$  quarks (40% – 80%) are trapped until the droplets evaporate, and come to equilibrium at the transition temperature.
3. Other  $D$  mesons come close to equilibrium in the plasma and in the pion gas, and in any case decouple shortly after the transition is complete.
4. Recapture by the droplets (which we haven't discussed) is an important effect, affecting the equilibration of 10% – 40% of the particles.

The distribution of  $D$  momenta is roughly thermal, but the mean momentum is above the thermal average because of transverse flow. Presumably the latter may be gauged by the momentum distributions of the lighter species. Everything considered, the  $p_{\perp}$  of the  $D$  mesons does provide a rough thermometer of the phase transition.

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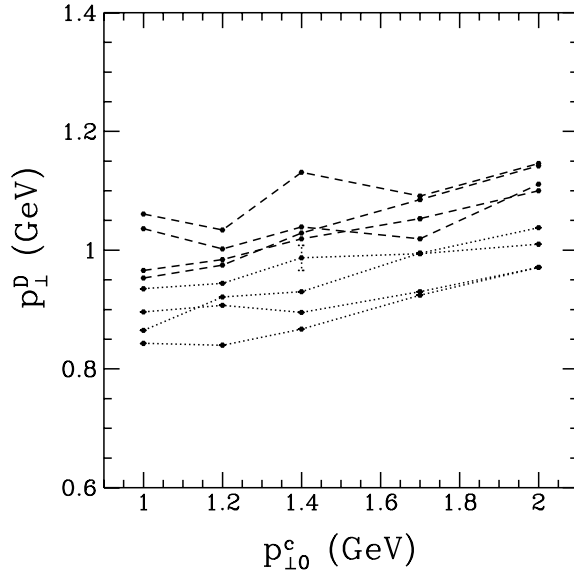


FIG. 4. Comparison of the mean  $D$  momentum for  $T^* = 150$  MeV (dots, same data as in Fig. 1) with that for  $T^* = 200$  MeV (dashes).

## REFERENCES

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