CHEMICAL EQUILIBRATION IN THE PARTON CASCADE MODEL

K. Geiger

CERN TH-Division, CH-1211 Geneva 23, Switzerland

and

J. I. Kapusta

School of Physics and Asronomy, University of Minnesota, Minneapolis, MN 55455

Abstract

We respond to a recent Comment by D. Seibert on the question of chemical equilibration of quarks and gluons in ultra-relativistic heavy ion collisions.

PACS Indices: 12.38 Mh, 25.75.+r, 24.85.+p, 13.87.Fh

In a recent paper D. Seibert [1] commented on a work by Geiger and Kapusta [2] about chemical equilibration of quarks and gluons in ultra-relativistic heavy ion collisions within the Parton Cascade Model (PCM) [3] by questioning the results and suggesting that the PCM does not satisfy detailed balance. We would like to respond with the following remarks:

1. From Fig. 11 in [2], in which the effective temperatures of the various parton species are plotted as a function of time during the first 2.5 fm/c in the central region in $Au + Au$ collisions at RHIC energy, one can see that the gluons and quarks have rather different individual temperatures, determined by their ratio of energy density to entropy density, $T_a = (4/3)\varepsilon_a/s_a$, eq. (30), where $a = g, u, d, s, c$. The gluons

have clearly the highest temperature throughout and it coincides roughly with the temerature of the system as a whole (dotted line). The quarks have considerable smaller temperatures. In particular, the charm quark temperature T_c changes only very little between 0.25 fm/c and 2.5 fm/c, from about 290 MeV to 240 MeV (the gluon temperature changes during that time from 550 MeV down to 320 MeV!). In Fig. 12 the ratio of the corresponding number (energy) densities of quarks and gluons to the densities of an ideally equilibrated noninteracting parton gas at the same temperatures are shown in order to estimate the degree of chemical equilibration. Whereas the gluons densities achieve their chemical equilibrium value within about 2 fm/c, the quarks stay significantly below, the effect being the more prominent the heavier the quarks are. The curves in Fig. 12 were obtained from formula (32) with the individual(!) temperatures shown in Fig. 11. Therefore it is not surprising that the ratios in Fig. 12 are so small for charm quarks. This result implies that although there is significant charm production, the number of charm quarks is much too small when as compared to an equilibrated phase-space population of an ideal gas of charm quarks at T_c. Similarly, also the energy density generated by c-quarks alone is very small. Nevertheless, due to their heavy mass and their dilute phase space occupation, the once produced charm quarks will hardly annihilate again so that the overall charm yield comes out comparably large, even though the c-quarks are far from chemical equilibrium. We note that the species temperature defined by eq. 30) is a little different than the temperature as defined by the slope of the momentum distributions in Fig 4. Since the momentum distributions are not exactly exponential, there is some freedom in exactly how one defines the temperature, and this affects somewhat how close to chemical equilibrium the system appears to be.

2. The main point is that the gluons interact more strongly with each other than do the quarks. This means that the quarks will diffuse out of the central region (defined by eq. 15) faster than gluons. This diffusion is predominantly along the beam axis.

With the condition of eq. (15) the boundary of the central region moves with a speed of about 3/4 that of light, as measured in the CM frame. The lighter quarks, at least, move at nearly the speed of light, and if their random walk length is big then they will exit the central region as time goes on. In other words, the gluons tend more towards hydrodynamic flow while the quarks tend more towards free-streaming. Looseley speaking one is faced with the dynamical evolution of at least two 'fluids' (gluons and quarks) that superpose. This is the main reason for the behavior seen in Fig 12.

3. The kinetic equations as currently used in the parton cascade are written explicitly in such a way that detailed balance will be achieved in a static (nonexpanding) system, given sufficient time. As written on page 4915 of our paper, this was checked numerically in two ways: First, by increasing artificially the quark-quark-gluon coupling constant by a factor of ten. Second, by enclosing the colliding nuclei in a box and preventing the partons to escape the central collision region as they normally do in a realistic collision before they have a chance to chemically equilibrate. Both tests showed that then the quarks did achieve indeed chemical equilibrium. Therefore the concept of *detailed balance is correctly incorporated in the PCM.* The reason why it seems to be rather unlikely for the parton sytem to achieve a chemical equilibrium as a stable state of detailed balance - at least at RHIC energies - is the combination of the two effects, (i) the dominance of the gluon coupling, plus the large gluonic component in the initial nuclei, and (ii) the limited time available to the particles in the central region before streaming apart.

In conclusion, we state that one has to be careful when comparing the PCM calculations with e.g. the solutions of chemical rate equations in the Bjorken hydrodynamical model. The latter cannot account for the physics contained in points 1 and 3 above. This is typical of cascade-like calculations versus semi-analytical rate equations. We are aware that the PCM results are plagued by a number of uncertainties which have been repeatedly discussed in

preceding papers. The PCM is not to be misunderstood as a fine tuned 'event generator'. Rather than that its main purpose - at least at the current stage - is to approach in an explorative way the complicated many particle aspects of quark and gluon dynamics in heavy ion collisions. From a truly quantitative picture we are still far away.

REFERENCES

[1] D. Seibert, *Do Parton Cascade Model results approach chemical equilibrium?*, KSUCNR-005-94, also as nucl-th/9403005 on hep bulletin board.

[2] K. Geiger and J. I. Kapusta, Phys. Rev. D **47**, 4905 (1993).

[3] K. Geiger and B. Müller, Nucl. Phys. **B369**, 600 (1992); K. Geiger, Phys. Rev. D **47**, 133 (1993).