Parton Cascade Description of Heavy-Ion Collisions at CERN?

K. Geiger

Physics Department
Brookhaven National Laboratory
Upton, N.Y. 11973, U.S.A.

There seems to be a general consensus now that a first glimpse of a QGP-like effect has become visible in the beautiful NA50 data on $J/\psi$ production and the ‘anomalous suppression’ phenomenon. On the other hand, it is still widely believed that the dynamics of heavy-ion collisions at CERN SPS energy is predominantly governed by soft, non-perturbative physics. This is ironic: after all, it is unlikely that a QGP could be formed if the underlying dynamics were essentially soft, rather than that it requires intense quark-gluon production with sufficient cascade-like reinteractions which drive the matter to large density and equilibrium. Therefore, I advocate in this contribution that for ultra-relativistic nucleus-nucleus collisions a description based on the pQCD interactions and cascade evolution of involved partons can and should be used, owing to the claim that short-range parton interactions play an important role at sufficiently high beam energies, including CERN energy $\sqrt{s} \approx 20$ A GeV. Here mini-jet production which liberates of quarks and gluons cannot be considered as an isolated rare phenomenon, but can occur quite copiously and may lead to complex multiple cascade-type processes.

1. INTRODUCTION

A QCD-based space-time model that allows to simulate nucleus-nucleus collisions (among other particle collisions), is now available\(^1\) as a computer simulation program called VNI \cite{1}. It is a pQCD parton cascade description \cite{2,3}, supplemented by a phenomenological hadronization model \cite{4}, with dynamically changing proportions of partons and hadrons, in which the evolution of a nuclear collision is traced from the first instant of overlap, via QCD parton-cascade development at the early stage, parton conversion into pre-hadronic color-singlet clusters and hadron production through the decays of the clusters, as well as the fragmentation of the beam remnants at late times. (I will in the following refer to the parton-cascade/cluster-hadronization model as PCM, and to its Monte Carlo implementation as VNI.) The PCM description has been used \cite{3} to provide very useful insight into the dynamics of the evolution of the matter at energies likely to be reached at BNL RHIC and CERN LHC. The experimental data for these will, however, come only in the next millennium.

Recently, D. Srivastava and myself have taken steps to investigate collisions at the CERN SPS and compare the model calculations with the increasing body of experimental data, thereby addressing the question: \emph{Can one really use the PCM picture already at the SPS energies ($\sqrt{s} \approx 17$–20 GeV/A)\(\textsuperscript{1}\)?} Recall that the parameters of the models were fixed by the experimental data for $pp$ ($p\bar{p}$) cross-sections over $\sqrt{s} = 10$–1800 GeV, and $e^+e^-$ annihilation \cite{3}. The nucleon-nucleon energy reached at SPS is well within this range. Indeed, as shown in \cite{3,4}, this approach does remarkably well in comparison to

\(\textsuperscript{1}\) The program VNI (pronounced Vinnie) is available from \url{http://rhic.phys.columbia.edu/rhic/vni}.
the gross particle production properties observed at CERN SPS. This came as a surprise, since no attempt was made to fine-tune the model to the data.

2. COMPARISON WITH CERN SPS DATA

In Figs. 1 and 2, I have plotted examples of the results of [5,6], for the relatively ‘light’ system $S + S$ and for the most ‘heavy’ system $Pb + Pb$. The first plot shows the rapidity distribution of negative hadrons in central collisions of sulfur nuclei, whereas the second plot shows the transverse mass spectra of negative hadrons in central lead-lead collisions. In comparison with the corresponding experimental data, it is evident that a decent description is obtained, and this without any adjustments of parameters. The analysis of [5] concluded:

(i) The simulations of heavy-ion collisions give a good overall description of the CERN SPS data on rapidity and transverse energy distributions, the multiplicity distributions, as well as a reasonable description of the transverse momentum distribution of hadrons. This success may be taken as a ‘post-hum’ justification of the applicability of a pQCD parton description even at CERN SPS energies.

(ii) Contrary to wide-spread belief, at CERN SPS energy the ‘hard’ (perturbative) parton production and parton cascading is an important element for particle production at central rapidities - at least in $Pb + Pb$ collisions. In effect it provides almost 50% of final particles around mid-rapidity. ‘Soft’ (non-perturbative) parton interactions on the other hand are found to be insignificant in their effect on final-state particle distributions.

3. IMPLICATIONS FOR $J/\psi$ SUPPRESSION

Let me now turn to the problem of the observed strong suppression of $J/\psi$ production in $Pb + Pb$ collisions, following a recent work [7] by B. Müller and myself. In particular, I would like to discuss briefly the $A$-dependence of the absorption of the $J/\psi$ by comoving produced hadronic matter. The key element in the following arguments is the fact
that, for most nuclear collision systems at the relatively low center-of-mass energy of the CERN-SPS experiments, perturbative mini-jet production is largely due to quark-quark scattering, because the typical value of Bjorken-$x$ probed is $\langle x \rangle \gtrsim 0.1$, where the gluon density is small. This implies that shadowing effects are negligible as explained in [7] and the critical momentum $p_{\text{crit}}$ where these effects turn on, lies below the perturbatively accessible range of momenta $p_\perp \geq 1$ GeV at the SPS energy, and may just begin to reach into it for the Pb + Pb system. If this is correct, then all mini-jet production involving momenta $p_\perp \geq 1$ GeV lies safely above $p_{\text{crit}}$. As immediate consequence, the density of comovers which can effectively interact and absorb the $J/\psi$ at the SPS grows like $A^{2/3}$, or $(A_1 A_2)^{1/3}$ in asymmetric collisions. This is a much stronger $A$-dependence than naively expected and embodied in most comover suppression models [8]. It also implies a stronger impact parameter or $E_T$-dependence of comover suppression than predicted by existing models.

Quantitative support for these speculations comes from recent calculations of secondary particle production in the parton cascade model, using VNI [1]. The calculations predict that the energy density $\epsilon$ produced by scattering partons (mini-jets) at central rapidity grows by a factor of more than 2 between $S+U$ and $Pb+Pb$, compatible with the scaling law $\epsilon \sim (A_1 A_2)^{1/3}$, but much faster than expected in the usual Glauber model approach which predicts $\epsilon \sim (A_1^{1/3} + A_2^{1/3})$, in which case $\epsilon$ increases only by 30%.

Figure 3. Time evolution of the energy density $\epsilon$ of the partonic matter in the central slice of the collision systems $S+U$ and $Pb+Pb$ at CERN-SPS beam energies of 200 $A$-GeV and 158 $A$-GeV [7].

Figure 4. Equation of state for two-flavor QCD [9], showing energy density $\epsilon$ and pressure $p$ as a function of temperature $T$ and corresponding energy densities with the location of the "melting" points of the $J/\psi$ and $\Upsilon$ states [10].

In $Pb+Pb$ collisions the initial partonic energy density $\epsilon$ is predicted to reach 5 GeV/fm$^3$ at times $\tau < 1$ fm/$c$ in the comoving reference frame (Fig. 3). For a thermalized gas of free gluons and three flavors of light quarks this corresponds to an initial temperature $T_i \approx 230$ MeV, clearly above the critical temperature $T_c \approx 150$ MeV predicted by lattice-QCD calculations [9] shown in Fig. 4. On the other hand, the parton density $\epsilon \approx 2$ GeV/fm$^3$ predicted for $S+U$ collisions (Fig. 3), just lies at the upper end of the transition region in the equation of state from lattice-QCD.

The temperature $T_D$ required for dissociation of the $J/\psi$ bound state due to color screening is known [10] to be higher than $T_c$, namely $T_D \approx 1.2 T_c = 180 - 200$ MeV. The parton cascade model results are therefore compatible with the experimental finding...
that there appears to exist no significant comover-induced suppression of $J/\psi$ in $S + U$ collisions, but a large and strongly impact parameter dependent effect is observed in Pb + Pb collisions.

It must be stressed that the model results do not contradict the experimental data collected at the SPS, as one might suspect, since it is usually claimed that those are fully consistent with the Glauber picture, in particular with the transverse energy production (Fig. 5) and the linear $E_\perp - E_{\text{veto}}$ relation (Fig. 6), both of which are in good agreement with the corresponding measured data [11].

ACKNOWLEDGEMENT
This work was supported in part by grant DE-AC02-76H00016 from the U.S. Department of Energy.

REFERENCES
1. K. Geiger, Comp. Phys. Comm. 104, 70 (1997), and references therein.
2. K. Geiger and B. Müller, Nucl. Phys. B369 (1992) 600.
3. K. Geiger, Phys. Rep. 258, 376 (1995).
4. J. Ellis and K. Geiger, Phys. Rev. D 54, 949 (1996); Phys. Rev. D 54, 1755 (1996).
5. K. Geiger and D. Srivastava, Phys. Rev. C56, 2718 (1997).
6. D. Srivastava and K. Geiger, [nucl-th/9708023].
7. K. Geiger and B. Müller, [nucl-th/9707048].
8. S. Gavin and R. Vogt, Nucl. Phys. A610, 442c (1996).
9. C. Bernard et al., Phys. Rev. D54, 4585 (1996).
10. F. Karsch and H. Satz, Z. Phys. C51, 209 (1991).
11. L. Ramello, these proceedings.