Inclusive Particle Spectra at RHIC

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A simulation is performed of the recently reported data from PHOBOS at energies of $\sqrt{s} = 56, 130$ A GeV using the relativistic heavy ion cascade LUCIFER which had previously given a good description of the NA49 inclusive spectra at $\sqrt{s} = 17.2$ A GeV. The results compare well with these early measurements at RHIC.

$25.75, 24.10.Lx, 25.70.Pq$

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory was constructed with the explicit purpose of creating and analysing a form of hadronic matter referred to as quark-gluon plasma. Certainly partons, when struck with sufficient energy, may acquire enough momentum to travel beyond the confines of their host hadron. In $p+p$ experiments at the RHIC energy of $\sqrt{s} \approx 200$ A GeV the contribution of such ‘jets’ to the inclusive production of mesons is not large, perhaps less than 5\%. Nevertheless, sufficient thermal energy can possibly be pumped into a massive ion-ion system, via generation of the less well defined mini-jets\textsuperscript{2} to free or create large numbers of partons in an ion-ion collision. The existence and precise nature of any ensuing phase change, from infinite hadronic to partonic matter\textsuperscript{1}, is still the subject of debate. Truly macroscopic systems in which plasma might be realised do exist in nature, in the early universe\textsuperscript{4} or in a neutron star\textsuperscript{5}. Although for a finite system the question whether an actual phase change occurs may be somewhat academic, one might still hope to identify a deconfined mode by sufficiently sharp rather than truly discontinuous changes in appropriate observables. For example, the transverse energy measured in an ion-ion collision can be used to define, in a model, the system temperature and the relationship to say the density, of the number of mid-rapidity pions as established by experiment. The hadron number density is a measure of the entropy created in the collision, a quantity definable even for a non-equilibrium finite system, and one reasonably expected to be highly sensitive to the increase in degrees of freedom accompanying parton deconfinement. The overreaching concern is, then, how to identify a meaningful variation in dependences between relevant observables.

Here, we address only the most recent and remarkably prompt measurements by the PHOBOS\textsuperscript{6} collaboration at RHIC. The highly successful, early running of the RHIC facility, albeit at lower than the ultimate energy and luminosity, together with this efficient small detector have already provided the heavy ion community with interesting, perhaps even provocative results. PHOBOS, lacking for the moment particle identification or momentum determination, is initially limited to a measurement of the charged particle density in pseudo-rapidity\textsuperscript{3}, together with this efficient small detector have already provided the heavy ion community with interesting, perhaps even provocative results. PHOBOS, lacking for the moment particle identification or momentum determination, is initially limited to a measurement of the charged particle density in pseudo-rapidity $dN/d\eta$. We analyse the PHOBOS results theoretically with the hadronic cascade LUCIFER\textsuperscript{8}, adopting the position that this analysis simply presents an extrapolation from the earlier NA49 inclusive measurements\textsuperscript{1} to the considerably higher energy RHIC determinations.

It seems appropriate to compare these initial observations at RHIC with simulations which assume no plasma is present. The purest such comparison would employ a model involving only hadronic degrees of freedom. A recent comparison does exist with the partonic code HIJING\textsuperscript{10}. The instrument for the present exploration of the RHIC domain is the code LUCIFER, described in detail elsewhere\textsuperscript{8} and available by downloading from a BNL theory home page. Suffice it to say that this simulation was prepared for use at relativistic energies attainable at RHIC and tested against the CERN SPS heavy-ion experiments. This purely hadronic simulation gave a good account of the two general particle production experiments at the SPS, those for $S+U$ and for $Pb+Pb$\textsuperscript{25,26}. Thus LUCIFER might be used as a standard against which to place the very interesting results from PHOBOS, a means for defining the ‘ordinary’ in proceeding from the SPS to RHIC. This can be accomplished by a slight tuning of LUCIFER multiplicities to provide very close to quantitative agreement for the SPS $h^-$ rapidity spectrum. In retrospect\textsuperscript{8}, the predictions for the latter spectrum were perhaps 10 − 15\% high when compared with the latest NA49 $h^-$ determination\textsuperscript{12}.

\textsuperscript{1}One possibility, exploited in our methodology, is that to some extent an ion-ion collision is describable by multiple interactions between excited hadrons only. In such a picture the constituent quarks are excited to states differing from those present in the lowest mass hadrons, but the glue holding them in place is still ‘sticky’. The quarks continue to act as if still confined within some hadron. This description was successful in say the Pb+Pb collisions examined in NA49\textsuperscript{1}.

\textsuperscript{2}It remains to be seen whether at the higher RHIC energies a large fraction of these quarks are free to roam over large spatial distances, and more importantly perhaps whether sufficient ‘free’ gluons are present to create the thermodynamic basis for hadronic material describable as quark-gluon plasma.

\textsuperscript{3}Many simulations and/or cascades\textsuperscript{8,10,13–19} have been constructed for relativistic heavy ion collisions. Some of
these are purely partonic cascades, some are hybrids of hadronic and partonic cascading. LUCIFER [8] is a hadronic cascade run sequentially through two stages. In the initial rapid phase I, at high energy, no energy loss is permitted for soft processes; however the complete collision histories are recorded. The time duration of phase I, $t_{AB}$, is essentially that which would be taken by the two colliding nuclei to pass freely through each other. Hard or partonic processes for which $p_t \geq t_{AB}$ could be introduced in this mode and consequent energy loss allowed for.

The second stage, phase II, is a conventional hadronic cascade at greatly reduced energy, similar to that applicable at the AGS and for which soft energy loss is allowed and chronicled. This second cascade begins only after a meson formation time, $\tau_f$, has passed. Using the entire space-time and energy-momentum history of phase I, a reinitialisation is performed using an elementary hadron-hadron model fixed by data as a strict guide. Nucleons travel along light-cones in phase I, but the number and type of collisions they suffer are instrumental in generating the produced mesons which take part in phase II. Participants in the second phase are treated as generic mesons, thought of as of $qq$ states with masses centered near 700 MeV and in the range $0.3 - 1.0$ GeV, and generic baryons consisting of $qqq$ excited states also with rather light masses, $0.94 - 2.0$ GeV. This same spectrum of hadrons is of course used to describe the known elementary baryon-baryon and meson-baryon collisions and the parameters of the model thereby determined. Ultimately, the cascade is exploited to derive predictions at the higher energy solely from knowledge of two body interactions and from a general structure which worked well at the lower $\sqrt{s} \sim 20$ $A$ GeV SPS level.

In phase II of the ion-ion interaction, the generic resonances decay into stable hadrons as well as colliding with each other. The low mass of the generic resonances guarantees that the transverse momentum acquired in any chain of interactions or decays will be relatively small, and hence one is modeling only soft processes. A deeper analysis might add parton production in phase I and cascading perturbatively. Also, and crucially, the sequential decay of the interacting generic hadrons into several mesons and baryons severely restricts the particle multiplicities and thus the amount of cascading during early stages of phase II. Previously included in our modeling was a suggestion by Gottfried that the particles produced in elementary two-body collisions not exist for the purpose of secondary interaction until they were sufficiently separated. Implementing such a constraint effectively limits the density of interacting generic hadrons in phase II to non-overlapping configurations. A very simple but accurate representation of this procedure results from just constraining the multiplicity at the end of phase I by this criterion, and in fact the calibration at the NA49 energy $\sqrt{s} = 17.2$ $A$ GeV then sets the constraint at all energies.

We refer readers to the above mentioned references for more details of the simulation, the major physical assumptions and measured elementary hadron-hadron inputs, and the availability of the code. The most important inputs from involve the total nucleon-nucleon and meson-nucleon cross-sections and of course the division into elastic, single diffractive(SD) and non-diffractive production(NSD). The multi-prong UA(5) data leading to multiplicity distributions for meson productions in the latter two categories are crucial.

A concomitant problem in the search for quark-gluon ‘plasma’ is to distinguish between such a state and simple medium dependence in a hadronic gas. We constrain the hadronic cascade by imposing no explicit collective effect of the inter-nuclear environment: however, one could still possibly ascribe any departure between cascade predictions and measurements to the A dependences of both particle properties and inter-particle forces on the conditions obtaining during the nuclear collision. For example, the apparently anomalous dilepton spectrum at the SPS is frequently attributed to medium dependent shifts in the masses of certain vector meson resonances [24]. Clearly also, particle-particle cross-sections might be influenced by the presence of a background medium. We have proceeded however, without introducing any medium dependence whatever.

At RHIC energies the time duration of phase I, $t_{AB} \sim d_{AB}/\gamma \sim d_{AB}/100$ with $d_{AB}$ being the combined size of the colliding nuclei, is an order of magnitude shorter than at the SPS. Moreover, phase II of the cascade at RHIC energies is a more serious matter. It occurs at higher energies, creates relatively more mesons and lasts for a longer time. At the SPS we determined the meson formation time, $\tau_f$, from collisions of light ion systems, e.g S+S, and we employed this same time, $\tau_f$, in the massive Pb+Pb system. Inherent in this procedure is the assumed insensitivity of $\tau_f$ to mass number, collision energy, etc. This assumption, equivalent to the one that hadron properties are independent of the nuclear medium, suggests that we must use the same $\tau_f$ at RHIC energies, i.e. $\tau_f \sim 0.6 - 0.8$ fm/c. It would be safer to recalibrate this sensitive parameter, essentially the only one in our modeling not determined from two body data, with similar measurements on the light nuclear systems at RHIC. The totality of mesons, particle and energy densities produced in the cascade are to an appreciable extent controlled by $\tau_f$, for obvious reasons. For the moment and to avoid the introduction of any other parameters, we employ the same $\tau_f$ at all energies.

To facilitate comparison with the computations at $\sqrt{s} = 56 - 200$ $A$ GeV, we present here LUCIFER results [8] for Pb+Pb at $E(lab) = 158$ $A$ GeV. These appear in Figure and are there compared to recent NA49 data [23]. As we described above the code was re-adjusted in this figure to give near the latest NA49 $dN/dy|_{p_T=0}$ for negatively charged hadrons, $\pi^-s$ for the most part.

In earlier work [8], we studied the relativistic invariance of the model, and demonstrated that for a worst case scenario, i.e. a zero impact parameter Au+Au collision at 200 $A$ GeV, frame dependence in the cascade, produced
by the action at a distance assumptions inherent in the theory, and as measured by the variation in $\frac{dN}{d\eta}$, was $\leq 10\%$, and virtually nonexistent at SPS energies. Calculations in the present work are performed in the equal velocity frame for which the errors are undoubtedly less.

We now exhibit typical meson production expected at RHIC in a purely hadronic simulation. Configurations of the greatest interest involve the most massive ions in the most central collisions. It is here that one might hope to see the greatest measured deviations from our simplified purely hadronic, medium independent picture. The centrality of a collision cannot of course, be defined in a purely theoretical context; one should account for the complete experimental set up. However, for simplicity, we specify centrality here by geometry and initially select $b \leq 4$ fm so as to approximately reproduce the 6% cut specified by PHOBOS. Variations in production levels with impact parameter are not too severe but some error attaches to the precise definition of centrality. We present results for the two energies $\sqrt{s} = 56, 130$ $A$ GeV reported by the PHOBOS Collaboration, as well as for the higher RHIC design energy of $\sqrt{s} = 200$ A GeV.

The simulation results obtained at SPS energies derived mainly from the above mentioned inputs: the two body energetics and the totality of nucleon-nucleon interactions in the course of an event. Although the time for phase I is considerably compressed at the higher RHIC energy, we expect much the same characteristics determine production levels as at the SPS.

The results of the LUCIFER simulations for $\sqrt{s} = 56, 130$ $A$ GeV are displayed in Figure 2, where they are compared to the corresponding PHOBOS measurements. One notes that the PHOBOS points represent an average over two central units of $\eta$. The minimum conclusion to be drawn from the cumulative evidence of Figure 2 and Figure 3 is surely that LUCIFER provides a satisfactory explanation of the PHOBOS central rapidity charged meson density determinations, consistent with the previous normalization of the code to NA49 data. Additional information contained in Figure 3 is the predicted energy dependence for the later full energy runs as well as the shape of $\frac{dN}{d\eta}$ for the complete pseudo-rapidity range. The precise shape of the spectrum for central $\eta$ yields some information on the degree of meson cascading. A narrower, less scalloped form suggests a higher degree of meson re-interaction after formation and/or of baryon-baryon interaction before. There is perhaps some indication that the theoretical energy dependence is too muted between 56 and 130 $A$ GeV, a point to watch in the as yet unreported results from the other RHIC detectors and as improvements surely are achieved with ongoing data taking. Similar results of course can be calculated for the rapidity ($y$) spectra of each meson species and for the baryons.

One interesting aspect of the calculations relates to the numbers of final, observed, mesons resulting with and without phase II. With the second stage rescattering turned off, all of the final hadrons are produced from decays of generic resonances that were produced in phase I. It is on the generic hadrons present after phase I that an effective multiplicity constraint is placed by normalizing to the SPS data. This initial multiplicity directly determines the important early particle and transverse energy densities. Phase II begins only after a pause, dependent on $\tau_f$ and the relativistic factors $\gamma$ for the secondary mesons. Particles produced in phase II begin to materialise only when the interaction region has increased considerably in size. The combined multiplicity increase from phases I+II over phase I with decays is about a factor 2.25 at $\sqrt{s} = 130$ $A$ GeV. This reasoning suggests that it is dangerous to tie the final measured $\frac{dN}{d\eta}$, in say PHOBOS, to an initially achieved $E_T$ density and on this basis to draw the inference that plasma was formed. Thus the calculated increase in particle multiplicity from the SPS to RHIC, $\sim 2.5$, is no sure indicator plasma formation is more likely at the higher energy. Indeed $\frac{dN}{d\eta}$, which is a better indicator of central densities during collisions, rises by less than a factor of 1.4. One caveat should be placed on the use of $\frac{dN}{d\eta}$ rather than $\frac{dN}{d\eta}$. An examination of Figure 1 shows the calculated ratio of the central rapidity densities grows by close to a factor of 1.6 from SPS energy to $\sqrt{s} = 130$ $A$ GeV at RHIC, perhaps a more hopeful circumstance.

The relatively low value of meson density found by PHOBOS is in itself interpretable as a lack of unusual medium dependence. The increase in entropy expected from the sudden release of additional parton degrees of freedom ought to show up as a sharp increase of central $\frac{dN}{d\eta}$ for mesons. Of course such an increase might yet be present in the neutral mesons, and mitigating effects like shadowing must be accounted for, but the PHOBOS $\frac{dN}{d\eta}|_{y=0}$ must still be considered not unusually high. Surprises may still arise in the examination of more exclusive observables, for example in the very high $p_t$ distributions.

One can now surmise that the anticipated QCD matter behaviour will be, at least, harder to detect and must be sought in rarer events. This conclusion is strengthened by viewing the hadronic cascade as a bridge between SPS and RHIC energies, with the $\sqrt{s} = 17$ $A$ GeV data calibrating the simulation. In this way the effects of artificialities necessarily present in this or any theoretical treatments of this complex problem are lessened. The PHOBOS data was collected for a centrality cut of 6%, reproduced theoretically by selecting $b \leq 4$ fm. Perhaps one must then proceed to an order of magnitude higher centrality, e. g. $\leq 1\%$, or better still to searching for large multiplicity fluctuations in order to unearth unusual behaviour. A further observation to be drawn from our simulations, which will be presented in more detail elsewhere, is that the hunt for plasma signatures in charmonium suppression is likely
to become increasingly difficult and the quarry to become more elusive at RHIC. The reason is already evident in present calculations, although the $J/\psi$ survival probability has not yet been estimated. The much larger number of mesons created in phase II of the LUCIFER simulation at higher energy will increase the suppression of $J/\psi$. The effective number of ‘comovers’ has been increased, and the survival after purely hadronic interaction will be even less.

We have tried adjusting the dynamics of the simulation to test the stability of the extension to higher energy: the inputs and the sharing of energy among generic resonances. Very little matters aside from the single overall normalization of produced particles at the SPS, with small changes in the latter leading to commensurate effects at RHIC. The broad features of the free multiplicity distributions, the energy lost per collision, and thus deposited in the ion-ion system, together with energy and momentum conservation seem to be the controlling elements.

Finally, since one could view the LUCIFER cascade as equivalent to a quark-gluon cascade in which the explicit role of color is neglected, it is not surprising to find the predictions of apparently widely different theoretical approaches to be alike.[10]

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FIG. 1. Comparison between normalised LUCIFER and NA49 $h^-$ rapidity spectra for and protons from Pb+Pb at 158 $A$ GeV per nucleon (Lab). Also shown are rapidity and pseudo-rapidity distributions for $\pi^-$ at $\sqrt{s} = 130 A$ GeV. The latter should be increased by $\sim 4 - 5\%$ to include $K^-$ and are not corrected for a possible low $p_t$ cut.
FIG. 2. Charged Mesons for Au+Au at RHIC energies of $\sqrt{s} = 56, 130 A$ GeV. Comparison with PHOBOS pseudorapidity averaged density measurements over the central two units of $\eta$. The LUCIFER spectrum for $\sqrt{s} = 200 A$ GeV is also shown. Small renormalisations can be expected for all results from a centrality definition more consistent with individual experimental setups. The total mesonic production at $\sqrt{s} = 130 A$ GeV in these simulations is some 6500 particles compared to near 2600 at $\sqrt{s} = 17.2 A$ GeV. The nucleon spectrum in this figure is for rapidity $y$. 

