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Inclusive particle spectra at (56 and 130)*A* GeV

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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 $\sqrt{s}=17.2A$ GeV. The results compare well with these early measurements at RHIC.

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The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory was constructed with the explicit purpose of creating and analyzing 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 $\sqrt{s}\sim 200A$ GeV the contribution of such ''jets'' to the inclusive production of mesons is not large, perhaps less than 5% [1]. Nevertheless, sufficient thermal energy can possibly be pumped into a massive ion-ion system, via production of the less well-defined minijets [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 [3], is still the subject of debate. Truly macroscopic systems in which plasma might be realized do exist in nature, in the early universe [4], or inside neutron stars [5]. Although for a finite system the question of 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 discontinous 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 midrapidity 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 nonequilibrium finite system, and one reasonably expected to be highly sensitive to the increase in degrees of freedom accompanying parton deconfinement. The over-reaching 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 Collaboration [6] at RHIC. The highly successful, early running of the RHIC facility, albeit at lower than the ultimate energy and luminosity, together with this small efficient detector have already provided the heavy-ion community with interesting, perhaps even provocative results. PHOBOS lacks, for the moment, particle identification capability and momentum determination, and is thus initially limited to a measurement of the charged particle density in pseudorapidity $dN/d\eta$. We analyze the initial PHOBOS results theoretically with the hadronic cascade LUCIFER [7,8], adopting the position that this analysis simply presents an extrapolation from the earlier NA49 inclusive measurements [9] to the considerably higher energy RHIC experiments.

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 [10]. The instrument for the present exploration of the RHIC domain is the code LUCIFER, described in detail elsewhere [8] and available by downloading from a BNL theory site (URL http://bnlkah.phy.bnl.gov). 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. LUCIFER gave a good account of the two general particle production experiments at the SPS, those for S+U and for Pb+Pb [8,9,11]. 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, detailed below, of LUCIFER multiplicities to provide very close to quantitative agreement for the SPS h^- rapidity spectrum. In retrospect [8], the predictions for the latter spectrum were perhaps 15% high when compared with the latest NA49 h^- determination [12].

One possibility, exploited in our methodology, is that to some extent an ion-ion collision is described 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 the Pb+Pb collisions examined in NA49 [9]. 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 described as quark-gluon plasma.

Many simulations and/or cascades [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 rapid first stage, phase I, nucleons collide at high energy, but 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 $p_t \geqslant t_{AB}^{-1}$ could be introduced in this phase 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 AGS energies and for which soft energy loss is allowed and chronicled. This second cascade begins only after a meson formation time, τ_f, has passed. Using the entire space-time and energy-momentum history of phase I, a reinitialization is performed using an elementary hadron-hadron interaction model fixed by data [8,20,21] as a strict guide. Nucleons travel nearly 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 $q\bar{q}$ states with masses centered near 700 MeV and in the range $0.3-1.0$ GeV, and also generic baryons consisting of qqq excited states with rather light masses in the range $0.94-2.0$ GeV [8]. This same spectrum of hadrons is used to describe the known elementary baryon-baryon and meson-baryon collisions and the parameters of the model are 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 time structure which worked well at the lower $\sqrt{s} \sim 20A$ GeV SPS energy.

In phase II of the ion-ion interaction, the generic resonances decay into stable hadrons as well as colliding with each other. The tuning of LUCIFER multiplicities referred to above, to produce agreement with NA49 h^- data, was accomplished by a small change in the average number of mesons into which each generic resonance decays and thus a commensurate small reduction in the number of generic resonances resulting from phase I. This preserves the energy and medium independence of the elementary inputs.

The low mass of the generic hadrons guarantees that the transverse momentum acquired in any chain of interactions or decays will be relatively small, 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 [7,8] was a suggestion by Gottfried [22] that the particles produced in elementary two-body collisions within nuclear matter should exist for the purpose of reinteraction only after becoming sufficiently separated. Implementing such a constraint limits the density of interacting generic hadrons in phase II to nonoverlapping 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 $\sqrt{s} = 17.2A$ GeV then sets the constraint at all energies.

We refer readers to the above-mentioned Ref. [8] for more details of the simulation, its availability, the major physical assumptions, and the elementary hadron-hadron inputs: total nucleon-nucleon and meson-nucleon cross sections and the division into elastic, single diffractive, and nondiffractive production. In the earlier work the frame dependence of the model was studied in a worst case scenario, zero impact parameter Au+Au at 200A GeV, and demonstrated to have $\leqslant 10\%$ variation on $(dN/dy)_{y=0}^{\pi^-}$. In the equal velocity frame, where the present calculations are performed, errors are undoubtedly less.

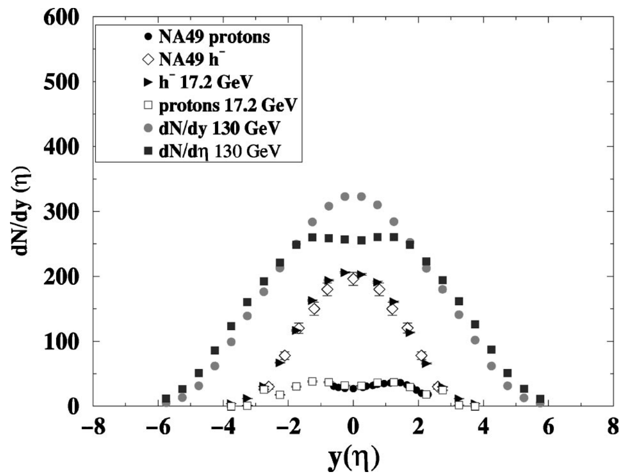

FIG. 1. Comparison between normalized LUCIFER and NA49 rapidity spectra for h^- and protons from Pb+Pb at 158A GeV per nucleon (lab). Also shown are rapidity and pseudorapidity distributions for π^- at $\sqrt{s} = 130A$ GeV. The latter should be increased by $\sim 4-5$ % to include K^- and are not corrected for a possible low p_t cut.

A concomitant problem in the search for quark-gluon "plasma" is to distinguish between such a state and simple medium dependence in a hadronic liquid. We neither impose any explicit collective effects of the nuclear environment, nor do we ascribe any departures between cascade predictions and measurements to the dependence of particle properties or interparticle forces on the conditions obtained during the nuclear collision [23,24].

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 [8] the meson formation time, τ_f, was determined from collisions of light ion systems, e.g., S+S, and employed in the massive Pb+Pb system. The assumed insensitivity of τ_f to mass number, collision energy, etc., is carried through to RHIC energies, $\tau_f \sim 0.6-0.8$ fm/c. It would be safer to recalibrate this sensitive parameter, essentially the only one in our model not determined from two body data, with similar measurements on the light nuclear systems at RHIC.

To facilitate comparison with the computations at $\sqrt{s} = 56-200\,A$ GeV, we present here LUCIFER results [8] for Pb+Pb at $E_p(\text{lab}) = 158A$ GeV. These appear in Fig. 1, compared to recent NA49 data [12]. As described above, the code was readjusted to give results close to the latest NA49 $(dN/dy)_{y=0}$ for negatively charged hadrons, these being π^-'s for the most part.

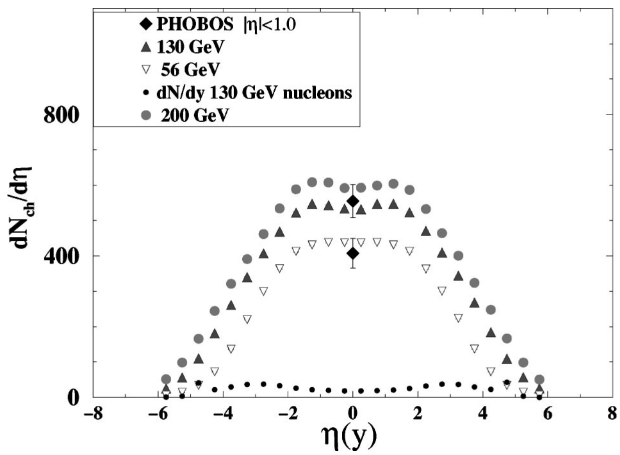

FIG. 2. Charged mesons for Au+Au at RHIC energies of $\sqrt{s}=56,130\,A$ GeV. Comparison with PHOBOS pseudorapidity averaged density measurements over the central two units of η. The LUCIFER spectrum for $\sqrt{s}=200A$ GeV is also shown. Small renormalizations can be expected for all results from a centrality definition more consistent with individual experimental setups. The total mesonic production at $\sqrt{s}=130A$ GeV in these simulations is some 6600 particles compared to near 2600 at $\sqrt{s}=17.2A$ GeV. The nucleon spectrum in this figure is for rapidity y.

The systems of the greatest physical interest involve the most massive ions in the most central collisions, where the greatest measured deviations from a simplified hadronic, medium independent picture, can be expected. The theoretical definition of centrality should take account of the complete experimental setup. However, for simplicity, centrality was here specified purely by theoretical collision geometry, initially selected as $b \leqslant 4$ fm to approximately reproduce the 6% PHOBOS cut [6]. Variations in multiplicities with impact parameter are not too severe but some error is attached to this choice.

LUCIFER simulations for $\sqrt{s}=56$, 130, and 200 A GeV are displayed in Fig. 2, and compared to the corresponding PHOBOS measurements [6]. The PHOBOS points represent an average over two central units of η. The minimum conclusion to be drawn from the cumulative evidence of Figs. 1 and 2 is surely that LUCIFER provides a satisfactory explanation of the PHOBOS charged meson density determinations, consistent with the normalization of the code to NA49 data. Additional information contained in Fig. 2 is the predicted shape of $dN/d\eta$ for the complete pseudorapidity range. The shape near central η yields some information on the degree of meson cascading. 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, in particular those which will be made at full energy, from the other RHIC detectors. Similar results can be calculated for the rapidity spectra of each meson species and for the baryons.

One interesting aspect of the calculations relates to the numbers of observed mesons resulting with and without phase II. With the second stage rescattering turned off, the final hadrons come from decays of generic resonances 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 number and transverse energy densities. Phase II begins only after a pause, dependent on τ_f and the relativistic factors γ for the secondary mesons. Thus, particles produced in phase II begin to materialize only when the interaction region has increased considerably in size. The multiplicity increase from phases I+II over phase I is about a factor 2.25 at $\sqrt{s}=130A$ GeV. This reasoning suggests that it is dangerous to directly relate the final measured $dN/d\eta$, in say PHOBOS, to an initially achieved E_T density and to infer on this basis that plasma was formed. The calculated increase in particle multiplicity from the SPS to RHIC, $\sim$2.5, is no sure indicator that plasma formation is more likely at high energy. Indeed, central $dN/d\eta$, which is a better measure of central densities during collisions, rises by a factor of only $\sim$1.5. On the other hand, an examination of Fig. 1 shows the calculated ratio of the central h^- rapidity densities grows by closer to a factor of 1.65 from the SPS to $\sqrt{s}=130$ GeV at RHIC.

The relatively low value of meson density found by PHOBOS may in itself be interpreted as a lack of unusual medium dependence, at least in the ''average'' 6% event. The expected increase in entropy due to a sudden release of additional parton degrees of freedom ought to show up as a sharp increase of central $dN/d\eta$ for mesons. Of course such an increase might yet be present in the neutral mesons and mitigating effects such as shadowing must be accounted for. Nevertheless, the PHOBOS $(dN/d\eta)_{\eta=0}$ cannot be considered unusually high. Surprises may still arise in the examination of more exclusive observables, for example in the very high p_t distributions.

One might now surmise that the anticipated QCD matter behavior will be at least harder to detect, and should be sought in rarer events. This conclusion is strengthened by viewing the hadronic cascade as a bridge between SPS and RHIC energies, with the $\sqrt{s}=17A$ GeV data calibrating the simulation, in which case the effect of theoretical uncertainties is minimized. Perhaps one must proceed to an order of magnitude higher centrality, e.g., $\leqslant$1%, or better still to identifying large multiplicity fluctuations in individual events, in order to unearth unusual behavior. A further conclusion 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 more elusive at RHIC. The reason is already evident in present calculations, although the J/ψ survival probability has not yet been estimated. The much larger number of mesons created in phase II of the LUCIFER simulation at higher energy may increase the suppression of J/ψ. The number of ''comovers'' is larger and the survival after purely hadronic interaction might be even less than at the SPS. Against this, one must however place the somewhat increased rate of production of J/ψ in phase II.

We have tried adjusting the dynamics of the simulation to test the stability of the extrapolation 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 elementary collision, and thus the total 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 may not be surprising to find the predictions of apparently widely different theoretical approaches to be alike [10].

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