Cascade for Relativistic Nucleus Collisions

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A relativistic hadronic cascade is used to simulate collisions of Si on Au at 14.6 GeV/c per nucleon. When proper account is taken of resonances produced in elemental hadron-hadron collisions this cascade quantitatively describes most published E802 data from the BNL Alternating Gradient Synchrotron, including the problematic proton transverse mass distributions. No medium effects seem required to explain the apparent enhancement of strangeness production nor any other features of the data.

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We report on an attempt to construct a cascade for simulating heavy-ion collisions at energies of the BNL Alternating Gradient Synchrotron (AGS) and beyond. We believe a conscientious effort of this sort is required, paying close attention to empirical hadron-hadron scattering, if one is to extract from these collisions reliable signs of interesting collective behavior, in particular, of QCD plasma. Considerable work using thermal and hydrodynamic modeling [1] has identified possible signatures of plasma, but ultimately one is faced with the task of identifying their hadronic or non-QCD components. A modest beginning is made here with the presentation of the results obtained from a "purely" hadronic cascade at AGS energies. At the CERN Super Proton Synchrotron (SPS) and certainly at the BNL Relativistic Heavy Ion Collider, it may prove necessary to utilize the dual parton string models now in vogue [2]. The work closest in spirit to ours is that of Mattiello, Sorge, Stöcker, and Greiner [3], but as will become evident there are distinct differences in construction and results.

There can be only a pious hope that a strictly hadronic cascade will describe a relativistic ion collision. Lorentz dilation and finite formation times for hadrons produced in the nuclear medium prevent one from treating on-shell processes literally [4]. Thus an essential component in the dynamics is a prescription for the rescattering of produced hadrons. Conventionally one allows the leading hadrons to reinteract immediately, but delays the first interactions of produced particles. We argue that at least at AGS energies an alternative protocol might be based on the resonant structure of the final state. Examination of proton-proton collisions at laboratory energies of 12 and 24 GeV/c [5] shows that a majority of inelastic collisions yield final states containing one or more of the low-lying resonances, Δ, ρ, etc. The time delays associated with production from such transient particles, which possess lifetimes of the order of 1.5 fm/c or longer, may well take precedence over those arising from particle formation times. Specifically, in Si+Au collisions at 14.6 GeV/c per nucleon the average dilation factor for Δ's produced in initial nucleon-nucleon collisions is $\gamma_{\text{lab}} \approx 5$ and the average decay length, 7.5 fm, is a considerable portion of the Au diameter. It is of considerable importance in what follows that the Δ's in their passage through nuclear matter possess significantly higher momenta than would the nucleons they replace, since they combine the energy of the nucleon and one of the produced pions.

In this work we consider somewhat oversimplified but prototypical cascade models in which production is achieved either directly (DIR) or through the lowest-lying resonances (RES). Thus in the case of a channel with three produced pions we take

$$A:\ NN \to NN\pi\pi\pi \quad (\text{DIR}),$$

$$B:\ NN \to \Delta\Delta\pi \quad (\text{RES}).$$

At 14.6 GeV/c the number of pions produced ranges from $n_\pi = 1$ to 7 and for each channel a similar prescription is applied using ρ mesons as well as Δ's. In the case of model RES the inverse processes are also available. Adjusting the baryon resonance mass from, say, m_Δ to m_{N^*} has little effect, although a more complete description of both pp and ion-ion interactions would entail averaging over the mass and nature of the resonances. Indeed proton-proton interactions might well be characterized by final states of two excited baryons distributed over mass and lifetime. The operative distinction between models DIR and RES is the retention of mesons within the resonance during much of its passage through nuclear matter resulting in an overall increase in the average baryon-baryon collision energy during cascading.

Ensuing ΔN or $\Delta\Delta$ interactions are handled, aside from quantum-number partition, as if they were nucleon-nucleon interactions, and similarly meson-baryon interactions as if they were meson-nucleon interactions. The dependence of cross sections and pion multiplicity in NN collisions on the center-of-mass energy [6] is respected. Most other important processes, such as strangeness or antiparticle production, are accurately included but perturbative in their effects on the dynamics. All mesons produced directly in RES or DIR are still subject to formation times, which when kept within conventional limits only slightly influence the outcome. In the simulations, the two-body input parameters are adjusted so that *both* models reproduce relevant cross sections [7,8], as functions of energy, and the known transverse momentum (p_t) distributions [8]. The sampling of final-state longitudinal momenta is adjusted to give correct leading parti-

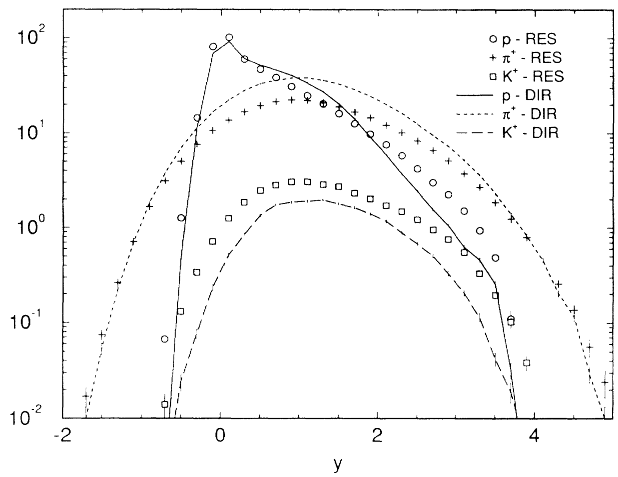

FIG. 1. Raw rapidity distributions from the cascade code ARC. Two features stand out. First, the severe reduction in π-meson numbers in RES. Second, higher baryon momenta and pion suppression in RES lead to enhanced projectile transparency.

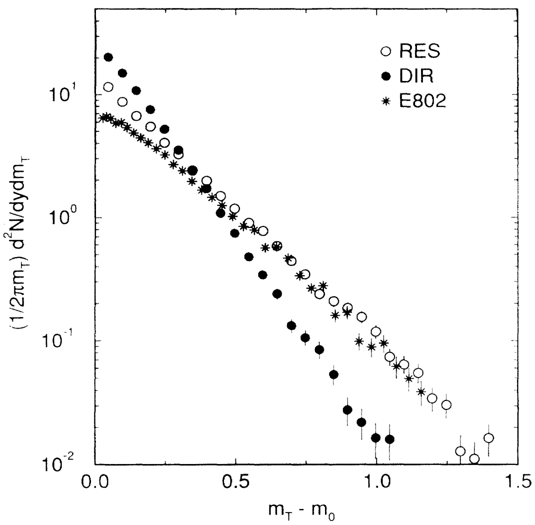

FIG. 2. Proton transverse mass distributions from direct and resonant production compared to E802 data for central rapidity $1.2<y<1.4$. Extrapolation of these distributions using $d^2N/dm_t^2dy \sim \exp(-m_t/T_i)$ leads to the dN/dy comparison seen in Table I. The agreement between RES and E802 is remarkable, especially when one notes [18] that the E802 data are expected to rise by (10–20)%. Neighboring experimental bins, i.e., for $y<1.2$ and $y>1.4$, do not show the suppression at the lowest m_t measured [18].

cle behavior at 12- and 24-GeV proton laboratory energy while transverse sampling is constrained to yield the p_t^2 distributions for $pp \rightarrow pX$ for the same energies [8] in the rapidity bins $0.0<y<0.5$, $0.5<y<1.0$, and $1.0<y<1.5$. Both leading particle behavior and the difference in π and p transverse momentum distributions are to a large extent built in by using resonances. With the average input transverse momentum for elastic or inelastic proton-proton collisions taken as $\langle p_t\rangle^{\mathrm{el}}=0.12$ GeV/c and $\langle p_t\rangle^{\mathrm{inel}}=0.55$ (0.50) GeV/c for RES (DIR), reasonable values for the observed p_t slopes obtain for pp, pBe, and pAu [9].

Before considering deeper justification for the physically more reasonable RES we compare calculations with the AGS experiment E802 [9]. Figure 1 displays the rapidity distributions from our Monte Carlo code ARC (a relativistic cascade) after approximating the E802 centrality cuts by the impact parameter constraint $b \leq 2$ fm. It is clear that less projectile stopping is obtained for RES. Figure 2 contains absolute comparisons between E802 and theoretical proton transverse mass distributions, while Table I shows rapidity distributions and inverse slope parameters T_i deduced with the E802 p_t extrapolation, i.e., using the assumed functional form $d^2N/dm_t^2dy=f_0\exp(-m_t/T_i)$. A more adequate representation of the actual Si+Au collisions emerges in RES. A significant achievement of this work, not seen in previous theoretical work, is the agreement between E802 and RES for the proton transverse mass slope (Fig. 2). This can be attributed in RES to the considerably higher energy of baryon collisions and to the severe reduction in meson numbers from DIR to RES.

We agree with Ref. [3] that there is probably no need to ascribe the strangeness production to plasma generation [10] nor to chiral symmetry restoration [11]. The absolute dN/dy for K^+ [RES (Table I)] and K^- are somewhat lower than seen in E802, but the uncertainties in both calculation and experiment preclude any strong conclusion being drawn at this stage. The total number of K^+'s produced per event provides a single quantitative estimate of strangeness production. Table I corresponds to a value of 6.6 for this number while an expected theoretical variation due to uncertainty in elementary cross section is perhaps 6 to 7. A rough extrapolation of E802 suggests a number near 7. If real, any discrepancy between theory and experiment should be even more marked in Au+Au collisions. Because of the higher momentum possessed by resonances, K^+ production is enhanced in secondary baryon-baryon collisions: For DIR some 50% of the production is from meson-baryon while for RES 70% is from baryon-baryon. Because of the generally low production energy only four K^+'s result in the nonresonant case. The K^-/K^+ ratio is close to 1/3 at production but is dropped to near 1/5 by K^- absorption, again in agreement with E802.

The Monte Carlo simulation ARC [12] is built around three basic components: a particle list, a collision list, and tables of both total and partial hadron-hadron cross sections over a broad range of energies. The code explicitly conserves energy, baryon charge, and flavor. Most relevant elastic and production processes from 0 to 450 GeV have been incorporated into our coding, often by ex-

TABLE I. Rapidity number densities and inverse slope parameters for p, π^+, and K^+. Centrality is defined theoretically by impact parameters $b \leq 2$ fm. Theoretical errors are not shown but for both the dN/dy's and T's are typically (3–5)% for pions and protons but 20% for K^+'s.

		dN/dy			T (MeV)		
	y	E802	RES	DIR	E802	RES	DIR
p	0.7	30.6 ± 0.5	38.4	46.6	···	0.162	0.116
	0.9	25.9 ± 0.3	30.8	41.2	···	0.177	0.125
	1.1	20.8 ± 0.2	24.9	34.1	···	0.194	0.132
	1.3	15.8 ± 0.1	20.4	27.8	0.215 ± 0.002	0.201	0.136
	1.5	12.1 ± 0.1	16.0	20.9	···	0.206	0.135
	1.7	8.8 ± 0.1	12.5	14.5	···	0.199	0.133
	1.9	6.7 ± 0.1	9.4	9.0	···	0.196	0.131
π^+	0.7	11.3 ± 2.0	13.3	23.0	···	0.160	0.126
	0.9	12.5 ± 0.9	15.0	24.5	···	0.160	0.131
	1.1	15.3 ± 0.7	15.8	26.3	···	0.164	0.132
	1.3	15.8 ± 0.5	16.1	27.7	0.162 ± 0.004	0.159	0.127
	1.5	14.5 ± 0.4	16.1	26.9	···	0.150	0.120
	1.7	14.0 ± 0.2	14.3	24.8	···	0.143	0.111
	1.9	12.9 ± 0.7	12.3	19.5	···	0.134	0.113
	2.1	9.0 ± 0.2	10.2	17.7	···	0.118	0.095
K^+	0.7	3.4 ± 0.6	2.4	1.5	···	0.160	0.138
	0.9	3.7 ± 0.3	2.9	1.8	···	0.159	0.133
	1.1	3.3 ± 0.2	3.0	1.9	···	0.156	0.136
	1.3	3.0 ± 0.1	2.7	1.9	0.203 ± 0.011	0.162	0.146
	1.5	2.6 ± 0.2	2.4	1.8	···	0.167	0.131

plicit parametrization, sometimes by the insertion of averaged energy-dependent partial cross sections. An important aspect of these two-body data is the constraint on transverse momentum, attributable to the soft QCD processes dominating the cross section. Propagation of particles between collisions is along straight Minkowskian trajectories. Apart from the initial start up of the cascade one need only search for the next occurring collision and limit the updating of the particle and collision lists appropriately. The particle list is very general in structure and may have partons and even strings cohabiting with the hadrons. In future development we intend to include hadron substructure and to generate plasma within the coding.

We will expand elsewhere on this issue of projectile transparency, important for predictions of the densities achieved in Au+Au collisions, but note that our preliminary results indicate appreciably less stopping than seen in relativistic quantum molecular dynamics (RQMD) [13,14], for both Si+Au and Au+Au. Published work by the E814 Collaboration [15] addresses this point directly. For Si+Pb at 14.6 GeV/nucleon E814 counts nucleons near beam rapidity falling into a narrow forward window. The number of E814 protons between $y=2.5$ and 3 is 1.94 ± 0.14 [15], in reasonable agreement with 1.5 in RES for $b < 2$ fm, not quite the correct centrality cut. One may conclude that the degree of transparency in RES is close to correct, but we will present detailed comparisons with E814 elsewhere, including proper experimental cuts.

Si+Au collisions have provided a testing ground for the relativistic scattering approach advocated here. Other experimental results exist: lighter projectiles on Au at the AGS [9,15], $p+A$ at the AGS [8] and Fermilab energies [16], and O+Pb at the SPS [17]. We have already checked that our preferred modeling is consistent with existing proton-nucleus data [8]. Patently, if ARC is capable of predicting the results of nucleus-nucleus collisions, no evidence for unusual or medium-dependent collective behavior can be claimed. Nevertheless quantitative success in describing the gross features of what one might call "thermal" regions of ion data lends confidence to extrapolation into as yet unexplored regions. Recent measurements by E802 [14] have considered proton spectra for p_t beyond 1 GeV/c. Our understanding of this highly nonequilibrium distribution derives from the two-body data, the precise fashion in which the dynamics determines the ratio of elastic to inelastic reactions and other features. The average p_t is a balance between the narrow two-body elastic $\langle p_t \rangle \sim 120$ MeV/c and the broader inelastic $\langle p_t \rangle \sim 500$ MeV/c, or more generally derives from the degree of nonelasticity of collisions. RES seems to get this admixture about right for $p_t \lesssim 1$ GeV/c and any deviations seen with its predictions for $p_t \gtrsim 1$ GeV/c would be of great interest. One might justifiably expect plasma or plasma percursors to require identification in both thermal and higher p_t regions.

Finally, one can question the implication of resonances in the final state of *NN* collisions. It is reasonable to expect the incoming nucleons, containing confined quarks and gluons, to be segmented into only a *few* excited chunks of material. As suggested earlier, a consistent model of high-energy nucleon-nucleon collisions might result from assuming their conversion into just two wave packets of baryon resonances with varying masses and widths. Given time the excited hadronic material would decay into on-shell particles, but in the nuclear medium the ratio of interaction to decay time fundamentally affects the dynamics. We intend to apply such a picture to a comprehensive study of proton-proton data and to the many-body problem.

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[1] See, for example, E. V. Shuryak, Nucl. Phys. **A525**, 3c (1991); M. Jacob, Nucl. Phys. **A498**, 1c (1989); G. Baym, Nucl. Phys. **A461**, 199c (1987), and references therein.

[2] B. Andersson, G. Gustafson, G. Ingelman, and T. Sjöstrand, Phys. Rep. **97**, 31 (1983); B. Andersson, G. Gustafson, and B. Nilsson-Almqvist, Nucl. Phys. **B281**, 289 (1987); T. Ludlam, A. Pfoh, and A. Shor, in "Proceedings of the RHIC Workshop I," 1985 (unpublished); K. Werner, Z. Phys. C **42**, 85 (1989).

[3] R. Mattiello, H. Sorge, H. Stöcker, and W. Greiner, Phys. Rev. Lett. **63**, 1459 (1989).

[4] L. Landau and I. Ya. Pomeranchuk, Dokl. Akad. Nauk SSSR **92**, 535 (1953); **92**, 735 (1953); J. Ranft, Phys. Rev. D **37**, 1842 (1988); J. D. Bjorken, Phys. Rev. D **27**, 140 (1983); A. Bialas, M. Bleszynski, and W. Czyz, Nucl. Phys. **B111**, 461 (1976).

[5] V. Blobel *et al.*, Nucl. Phys. **B111**, 397 (1976).

[6] J. Benecke *et al.*, Nucl. Phys. **B76**, 29 (1974); H. von Gersdorff, thesis, University of Minnesota, 1989 (unpublished).

[7] *Landolt-Boŕnstein: Numerical Data and Functional Relationships in Science and Technology*, edited by O. Madelung (Springer-Verlag, Berlin, 1988), Vol. 12, Pts. A and B.

[8] V. Blobel *et al.*, Nucl. Phys. **B69**, 454 (1974); H. J. Mück *et al.*, DESY Report No. DESY-F1-72/1, 1972 (unpublished); M. E. Law, J. Kasman, R. S. Panvini, W. H. Sims, and T. Ludlam, LBL Report No. LBL-80, 1972 (unpublished).

[9] E802 Collaboration, T. Abbott *et al.*, Phys. Rev. Lett. **64**, 847 (1990); **66**, 1567 (1991).

[10] J. Rafelski and B. Müller, Phys. Rev. Lett. **48**, 1066 (1982).

[11] C. M. Ko, Z. G. Wu, L. H. Xia, and G. E. Brown, in "Proceedings of the Workshop on Heavy-Ion Physics at the AGS," 1990, BNL Report No. BNL-44911 (unpublished), p. 361.

[12] Y. Pang, T. J. Schlagel, and S. H. Kahana (to be published).

[13] S. Chapman and M. Gyulassy, Phys. Rev. Lett. **67**, 1210 (1991).

[14] H. Sorge *et al.*, in "Proceedings of the Workshop on Heavy-Ion Physics at the AGS" [11], p. 344; A. von Keitz *et al.*, Phys. Lett. B **263**, 353 (1991).

[15] E814 Collaboration, J. Barrette *et al.*, Phys. Rev. Lett. **64**, 1219 (1990); E814 Collaboration, P. Braun-Munzinger, in Proceedings of Quark Matter '91 (to be published).

[16] W. Busza and A. S. Goldhaber, Phys. Lett. **139B**, 235 (1984); W. Busza and R. Ledoux, Annu. Rev. Nucl. Part. Sci. **38**, 119 (1988).

[17] NA35 Collaboration, A. Bamberger *et al.*, Phys. Lett. B **184**, 271 (1987); NA35 Collaboration, H. Ströbele *et al.*, Nucl. Phys. **A525**, 59c (1991); WA80 Collaboration, R. Albrecht *et al.*, Phys. Lett. B **199**, 297 (1987).

[18] E802 Collaboration, C. Chasman and O. Hansen (private communication).