Particle production at high energy. II. Accumulative impact and clustering in relativistic heavy-ion collisions

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Transverse energy dependence $dE_T/d\eta$ of O+Ag, S+Ag, and S+W collisions at 200 GeV/c are analyzed in a parameter-free phenomenological model of cascade and clustering based on $p+p$ and p+Ag collisions. The model uses an event generator which explicitly displays the impact parameter dependence of the colliding hadrons and incorporates basic features of multiparticle production in $p+p$ collisions. p+Ag data at 200 GeV/c are first analyzed with special attention to the time ordering of the cascading many-body processes using the space-time geometry and the impact parameter dependence of the colliding hadrons. We introduce a relaxation time parameter τ, the size of a time interval of the overlapping regions of space-time in the center-of-momentum frame of the colliding hadrons. Within a τ interval of relaxation, impacts of all collisions are accumulative. Only after this time has passed are pions allowed to be emitted from excited nuclear matter according to a set of rules for cascade. A value of $\tau\sim 0.1$ fm/c used for p+Ag data leads to a description of the gross features of the transverse energy dependence $dE_T/d\eta$ of O+Ag and S+Ag data of WA80 and S+W data in the forward region of HELIOS. [S0556-2813(97)00601-8]

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In the past decade various models have demonstrated the importance and usefulness of the concept of branching and cascading in relativistic heavy-ion collisions [1]. Broadly speaking, one type of approach is essentially statistical in nature. Very simple models of dynamics are used to elaborate certain universal features of multiparticle statistics. Specific formulations are then suggested in phenomenological diagnostics of real experimental data. It has often been stated that the bulk of salient features of experimental data are dictated by statistics and are independent of the details of dynamics [2]. Such models are, however, frequently too simple to satisfy the deep-rooted desire of a physicist to pinpoint the underlying dynamics of the physical world. Increasingly sophisticated formulations have been introduced in many statistical models in an attempt to take on the challenge to distinguish the unique features of the specific dynamics from the bulk of experimental data. On the other hand, a majority of approaches emphasizes the underlying dynamics of the multihadron systems. Many such models based on quantum chromodynamical (QCD) motivated formulations have continuously been improved. In such a dynamically oriented model, statistics is often treated as an unavoidable nuisance masking the underlying dynamics. Since rather lengthy Monte Carlo algorithms have to be constructed to simulate the complicated dynamics, statistical aspects are often reduced to the ''central-limit theorem.'' Features of the unique unstable system associated with each individual event in itself may often be overlooked. Given the possible existence of a quark-gluon plasma (QGP) to be one of the first priorities of current research in high-energy heavy-ion physics, it is important to recognize that such a system is a highly transit unstable system lasting for a very brief time within each event. Both a statistical and a dynamical consideration may be needed for a proper understanding of the nature of the possible QCD phase transition. Yet it remains a challenge both experimentally and theoretically to develop a set of unique diagnostic tools which distinguish unambiguously the differences between an unstable QGP and a hot hadron gas.

In order to obtain better insight into the characteristics of relativistic heavy-ion collisions (RHIC's) we would like to reexamine some basic concepts that enter many phenomenological studies. We would like to construct a model which is substantially statistical in nature and yet sufficiently realistic in the dynamics of the system. We notice that even with hadron collisions alone as the basic entities of internucleus processes, a sizable set of data can be interpreted [3]. Such a framework displays an explicit space-time evolution and can be readily coded numerically for Monte Carlo simulations. The need for simultaneously keeping track of many dynamically interacting entities then becomes obvious. In order to construct any self-consistent simulation of successive branching and cascades, a proper consideration of their time ordering also becomes a necessity. In the following we shall follow the language of particle and parton to focus on the multihadron dynamics. Energy-momentum propagation is therefore local in nature (in contrast to the strings). We further assume that all evolutions are the accumulation of binary processes. It is therefore crucial to use an efficient algorithm for an event generator with the basic binary collisions processes as the starting kernel of internuclear cascading processes. The ability to consider a large number of binary collisions successively enables us to study many-body effects systematically. As we shall discuss later on, it eventually leads us to evaluate quantitatively the concept of the impact and response of a nucleus system under collisions and introduce our own dynamical model for the more involved nucleus-nucleus (AB) collision systems.

In any Monte Carlo simulation of relativistic heavy-ion collisions, an event generator should always yield statistical predictions consistent with experimental data for simple systems. It should also possess the space-time characteristics of the colliding hadrons, since the geometry of the finite spatial extension of the constitutional hadrons is known to play an important role in heavy-ion collisions. When such a model is adapted to the internuclear cascading hadronic subprocesses, it can be used to probe interesting and nontrivial multihadronic dynamics. For instance, it may be used to evaluate the possibility of a cluster formation. It may also provide a useful background calculation for the next level of subhadronic interactions.

In order to keep the algorithm of our numerical simulation simple, we have treated individual hadrons as the basic entities for the propagation of energy and momentum and the binary collisions between hadrons as the kernel of interaction. Prior to any interaction, energy momentum is transferred along straight line trajectories of hadrons. During any binary collision, hadronic interactions are responsible for any abrupt change of momentum associated with the straight line trajectories, which essentially originate in a local space-time region. A more refined local structure would require the consideration of partons [4,5]. Still binary collisions and the time ordering of such collisions would then be of interest if the local interaction is a meaningful concept.

We present an analysis with particular emphasis on the space-time geometry of the internuclear hadronic distribution by using an impact-parameter-dependent event generator for hadron-hadron collisions. Its Monte Carlo simulation has given a consistent representation of the multiparticle production data of $p+p$ collisions (pp) for the range of laboratory momentum, $P \leqslant 250$ MeV/c [6].

Without altering any of the parameters used for the pp analysis, this same event generator is used for subhadronic pp collisions during the internuclear cascade of the proton + silver ($p+$Ag) systems. In order to take into account nonadditive effects due to multihadronic collisions, we shall find that it is necessary to introduce an additional parameter τ, the width of a time window. Within this window of space-time, the effects of all participating hadronic collisions are accumulative and the compound system is also assumed to be momentarily ''frozen'' in configuration space. After the ellipsis of such a time window, the accumulated ''stress'' is then allowed to relax collectively through hadronic emissions. Thus the emission processes present a clustering scenario in space-time when the world lines of incoming participating hadrons are very close to each other. Notice that the introduction of this ''time'' parameter does not alter our earlier phenomenological representation of $p+p$ collisions. In $p+p$ collisions, there are no other hadrons nearby [6], as the final state pp rescattering has already been included effectively in the phenomenological hh cross section. Once the value of this parameter τ is determined from a $p+$Ag collision, our model of accumulative impacts and clustering (AIC), can be applied to other more involved RHIC processes where more hadrons participate in an environment of multiple collisions. We shall demonstrate that without further adjustment of any parameter, this model can display many features of the transverse energy dependence of systems at 200 GeV/c.

While our model is an economic one to describe pp, pA, and AB systems simultaneously, it also brings attention to the need for evaluating collective responses for any spatially extended colliding objects under the impact of repeated internuclear subcollisions. Since such effects have not yet been fully addressed in other current phenomenological models, we shall explore this issue in a simple model. We shall keep the parametrization to a minimum by using only on-shell cross sections phenomenologically while ignoring the QGP structures of the strongly interacting hadronic matter.

We shall first review our geometrically oriented model for a pp collision to be adapted as a part of the kernel for hadron-hadron (hh) collisions during a typical internuclear cascading process [6]. Given a configuration with an impact parameter b between the center of mass (c.m.) of any two hadrons, we introduce a stopping power distribution which is stronger for central collisions than for peripheral ones. To construct this distribution, we start with the experimental total inelastic cross section $\sigma_{\rm in}(hh)$ at a given laboratory momentum q given by [7]

$$\sigma_{\rm in}(pp,q)=33.74+239.0q^{-4.33}-26.9q^{-1.21}+0.245\ln^2 q-1.59\ln q, \qquad (1)$$

$$\sigma_{\rm in}(p\pi,q)=-12.4+40.4q^{-0.28}-11.2q^{-1.67}-0.180\ln^2 q+5.21\ln q. \qquad (2)$$

We then assume that $\sigma_{\rm in}(hh)$ obeys geometrical scaling in terms of an eikonal function $\Omega(R)$ [8,9],

$$\sigma_{\rm in}(hh,q)=\int db^2(1-e^{-2\Omega})\equiv\int db^2\sigma_{\rm in}(hh,q,b), \qquad (3)$$

$$\sigma_{\rm tot}(hh,q)=2\int b^2(1-e^{-\Omega}),$$

with a Gaussian approximation given by Ref. [8] for the total cross section $\sigma_{\rm tot}$ and inelastic cross sections $\sigma_{\rm in}$ in relation to multiplicity fluctuations

$$1-e^{-\Omega}=Ae^{-(2A-A^2/2)R^2}, \quad A=0.68, \quad R=b/b_0(q), \qquad (4)$$

$$\sigma_{\rm in}(hh,q)\equiv\pi b_0^2 q,$$

to project out the b dependence of pp and $p\pi$ collisions. For the $\sigma_{\rm in}(\pi\pi)$ process which is not measured directly, a factorized expression is used as an approximation so that

$$\sigma_{\rm in}(\pi\pi,q)=\sigma_{\rm in}(p\pi,q)^2/\sigma_{\rm in}(pp,q). \qquad (5)$$

The above geometrical cross section stochastically dictates the occurrence of any collision. Given a collision occurring at a specific b, we further assume that the probability distribution of the energy loss of the colliding hadrons follows:

$$p(y)dy=(2-\alpha)(e^{y_{\rm max}}-1)^{\alpha-2}e^{y}(e^{y}-1)^{1-\alpha}dy, \quad 0\leqslant y\leqslant y_{\rm max}, \qquad (6)$$

where

$$\alpha=\alpha_0 e^{-\alpha_1 b}. \qquad (7)$$

Here, y is calculated in the center-of-momentum frame of the two colliding hadrons. $y_{\rm max}=\frac{1}{2}\ln\,[(E+|\vec{p}_L|)/(E-|\vec{p}_L|)]$ is the incident value of the rapidity of either incoming hadron. In this paper, the choice of $\alpha_0=1.4$ and $\alpha_1=0.51/\mathrm{fm}$ leads to a y distribution peaked toward the peripheral region. The result of a convolution in b is also consistent with the experimental leading particle spectrum [10]. Since Eq. (5) introduces the same impact parameter b for each colliding hadron, the energy loss of the opposing hadrons are positively correlated in their c.m. system.

Associated with this y distribution, the value of the transverse momentum $p_t=|\vec{p}_j|$ follows closely the experimental distribution of the inclusive measurements in $p+p\rightarrow\pi+X$ [3], and is given by

$$P(p_t)\sim e^{-4.1p_t^2} \quad (p_t\leqslant 0.81\ \mathrm{GeV}/c)$$
$$\sim 2.53e^{-4.4p_t}, \quad (0.81\ \mathrm{GeV}/c<p_t<2.4\ \mathrm{GeV}/c). \tag{8}$$

Given the final state momentum of the colliding hadrons, we now construct a statistical model for the stochastic emission of pions, ignoring the relatively smaller probability of kion and antinucleon production. Here an emitted pion is given a random charge assignment.[1] There exits, however, no general theoretical guideline, on the momentum distribution of the secondary particles when the impacts of collision originate from more than two axes. Historically, in dealing with binary collisions, the hydrodynamical-thermodynamical approaches of Fermi and Landau [11] realized that despite thermalization, secondary particles do not lose all the memory of the initial state. The directions of the Lorentz-contracted nuclear matter of the colliding systems also define the longitudinal axes of the secondary particles. In our situation the initial states may eventfully possess several colliding axes. It is therefore natural to allow each pion the possibility of carrying a rapidity value up to its kinematic limit $y_{j,\max}$ alone each of the j axis. We then assume that individually the direction specified by the index j is randomly chosen among all possible longitudinal directions (parallel to the momentum transfer of the colliding hadrons).

The probability distribution $f(y_\pi,j)$ of the rapidity y_π of the secondary pions is given in a universal form by

$$f_y(y_\pi,j)=C_j(2-\beta)(e^{\lambda y_{j,\max}}-1)^{\beta-2}e^{\lambda y_\pi}$$
$$\times(e^{\lambda y_\pi}-1)^{1-\beta}dy_\pi,$$

$$C_j=y_{j,\max}\Bigg/\sum_k y_{k,\max}\ , \quad y_\pi\leqslant y_{j,\max}\ , \quad j\leqslant j_{\max}, \tag{9}$$

with $j_{\max}=2$ for hadron-hadron (hh) processes. While the choice of a direction j is dictated by the relative strengths of the overall normalization factor P_j, the shape of the y_π distribution is controlled by the parameter β and λ. A choice of $\beta=2.1$ and $\lambda=-0.325$, give a rather flat y_π distribution. Together with the longitudinal momentum distribution, the associated transverse-momentum distribution $p_t=|\vec{p}_j|$ is given by

$$P(p_t)\sim e^{-6.2p_t} \quad (p_t\leqslant 0.81\ \mathrm{GeV}/c)$$
$$\sim 0.5326e^{-5.3p_t} \quad (0.81\ \mathrm{GeV}/c<p_t<2.4\ \mathrm{GeV}/c). \tag{10}$$

The above parametrization is typical of any longitudinal phase space model which does not use of light cone variables [3]. Since the distribution of each secondary pion depends on the energy momentum of a single parent, our model can be directly generalized to a RHIC processes where later on we shall allow more than two sources contributing their energy momentum to a common cluster.

We now turn our attention to pA systems. Our task is to construct a proper sequencing of the internuclear collisions. Given individual entities of collision such as extended objects, information on their rest mass, location of its center of mass, and effective range of interaction is not sufficient to construct a Lorentz-covariant algorithm for the ordering of collisions [12]. While we will address this question in detail at a later time, it is presently sufficient to notice that ordering becomes an important problem only for situations where internuclear collisions occur close to each other in space-time. In such circumstances, there is already the important question of the finiteness of the relaxation time (response time) of such transient multihadronic systems. In order to simplify the problem, we shall further assume that the entities of collisions are at the level of hadrons, and the hadronic cross section for the internuclear cascade is the same as that of the empirical on-shell ones.

In order to accommodate the possibility of a finite relaxation time, we shall now introduce a parameter τ, the size of a window in time, within which repeated impacts of collision will accumulate. Here τ is defined in the initial c.m. frame of the colliding constituent nucleon. This is the reference frame where all our bookkeeping of the dynamics is maintained at

[1]This requirement is technically intriguing, since true randomness requires independence between the secondary particles. To assure the overall neutrality, we assume that all charged secondaries are produced by neutral pairs which consist of a positive and negative pion only. Given the number of such pairs to be n_c, a Gaussian distribution is assumed for n_c, so that $\langle n_c\rangle$ is equal to the total number of secondary particles modulated by 3. In order to avoid such a Gaussian distribution to be either too broad or too narrow, we have further assumed that the variance of n_c is essentially $\langle n_c\rangle/3$. Different choices of this variance are related to charge fluctuation among individual events. Such information is generally not available phenomenologically. Our Monte Carlo simulation depends mildly on the specific value used for this variance. The effect of charge fluctuation can be compensated by adjustments of other parameters in order to achieve a reasonable representation of experimental data. The bulk of our conclusions is not sensitive to the specific choice given above.

all times. We note that after a binary collision, a participating hadron may soon be bombarded by another hadron. If the time lapse is small, no substantial evolution in the space-time configuration of the participating hadrons can occur during the interval between collisions. There always exists a competition between the accumulation of repeated impacts and the relaxation of an excited system to evolve in space-time. The precise definition of the time of collision is also subject to an intrinsic quantum mechanical uncertainty. With these considerations in mind, we have allowed for the possibility that within this time window τ of relaxation impacts on all energy-momentum transfers of successive subcollisions are accumulative. A compound cluster is first formed and the system decays collectively afterward [13,14].

Cluster formation is not a new concept for the investigation of aspects of the dynamics of strongly interacting systems. But its dynamics has seldom been successfully incorporated in any full fledged Monte Carlo algorithm. In our AIC model, the relaxation time is the window of time allowed for a cluster to absorb impacts. In the limit of a long relaxation time, a large amount of collisions would be accumulated, leading to a large invariant mass for a cluster. It would then correspond to an interacting tube scenario [15], where all the energy associated with all geometrically overlapping tubes will be added to a huge fire ball. This limiting scenario would be clearly different from those associated with an ensemble of wounded nucleons. (In other words, even though clusters receive their supply of energy and momentum from the hadrons directly, they do start to decay within a short time.) The relaxation time in the AIC model is more concerned with initial state configurations prior to hadronization instead of the formation of hadrons after the initial state interaction. Its emphasis is therefore different from the familiar concept of the ''formation time'' of hadrons. The dynamics of hadronization itself is beyond the scope of our simple approach.

For the cascade of a cluster we have adapted a statistical approach by assuming that after a cluster is formed, it remembers only the various impact axes of the participating hadrons. The cluster shall otherwise decay through the stochastic emission of pions. In our model, the underlying emission process is the same as that in the nucleon-nucleon (NN) system except that a cluster is allowed to emit pions along several longitudinal directions of rapidity [i.e., $j_{\max}>2$ in Eq. (9)]. Since the ensemble of collisions within a window is treated collectively, the detailed ordering of collisions within themselves is no longer a critical issue to be addressed. To simulate a real formation time of the pions, one could turn off the interaction of the on-shell secondary pions and let them travel ''collision free'' for a period of proper time. The present simulation, instead, has introduced a minor cutoff factor in the invariant mass and the four-momentum transfer to shorten the amount of CPU time needed for a typical run. Very soft pions are therefore not heavily involved in any individual re-scattering processes. Although our AIC Monte Carlo simulation allows this degree of freedom of pion formation time, this parameter has not yet been extensively dialed in conjunction with other degrees of freedom to look for potential interpretations of the data and to obtain a strong feeling toward the underlying physics.[2]

The AIC model presented here essentially assumes that all hadrons travel along classical straight trajectories both before and after any collision. Multihadron effects are significant only within the impact window τ when the hadrons meet. In order to treat the classical part of the space-time evolution, our simulation first traces each hadron through its future space-time trajectory. All potential pairwise ''instant of collisions'' are identified as the time of the minimum approach in the c.m. reference frame of the initial NN system. A comprehensive bookkeeping is kept to sort out all possible future ''instant of collisions,'' identify the ''first'' collision, and record all subsequent collisions within an allowed AIC window of time. Since the number of participating hadrons is large, our simulation for each collision is computationally intensive. In this paper, we have therefore restricted ourselves to the $p+$Ag, O+Ag, S+Ag, and S+W systems.

In a heavy-ion system, we assume that the incident nucleus takes the Woods-Saxon profile. During a RHIC collision, the constituent hadrons suffer repeated collisions which are either spacelike or timelike between each other. The ordering of the timelike collisions in fact will depend on the definition of the ''instant of collision.'' Typically the time difference between two potentially overlapping ''instants of collision'' is also very short in any reference of space-time representation. In order to proceed, we have adapted the following procedure to keep track of the collision dynamics of an N-hadron system.

(1) In the rest frame of a given hadron (say, hadron i), the ''instant of collision'' t'_{ij}, with another hadron j, is identified as the time when j reaches its minimum ''distance of approach'' b_{ij}. Given this impact parameter b_{ij} and its associated cross section, a stochastic decision determines whether a collision will occur at t'_{ij} assuming that the particle j is allowed to reach the distance b_{ij} without the interference of other collisions. The corresponding t_{ij} in the overall NN c.m. frame (i.e., the c.m. system between an initial target and projectile constituent nucleon) is recorded in a common table and time ordered after the scanning of the whole ensemble of collisions. We identify the two participating hadrons (say, X and Y) of the very next collision as the seeds of this step. With the pair of ''seed-hadrons,'' say, hadrons X,Y, all sub-

[2]In a typical scenario of a QCD model, a string is hadronized after a period of formation time. The energy and the momentum of the strings are associated with the end points and the kinks, and the body of the strings would not be subjected to rescattering directly. The energy distributed in the corresponding section of the string tension is not subject to collisions. In other scenarios, if strings are not completely transparent in the region between the kinks and the end points, time ordering of finitely extended objects may be relevant. To accommodate the possibility of a reduced effective cross section, we have also allowed for the reduction of the cross section for collisions of produced pions for a period of time after the ''instant of collision.'' Our present parametrization, however, prefers the use the hadronic cross section to determine the probability of pion production in the space-time region when pions are created. It is analogous to the situation of a small ''collision-free formation time.''

sequent collisions against X and Y within the window of response time τ are treated as follow-up secondary collisions of X and Y individually. We shall refer these hadrons as follow-up ''colliding partners'' to the seed hadrons.

(2) All collisions are treated as binary collisions according to the stopping power law of on-shell hadron-hadron collisions.[3] The piecewise straight line trajectories are constructed with the change in energy momentum assigned at the ''instant of collision'' of the seed hadrons. The loss of energy momentum of all the participating hadrons within the time window τ is first transferred to a common cluster. Collectively, the overall energy momentum is then converted to secondary pions. The energy-momentum assignment to the soft pions now follows the same prescription as before for that in the NN systems. We note, however, that there are in general more than two directions to choose.

(3) The newly created pions are also assumed to be uniformly distributed along the straight line between the center of mass of the overall cluster and point of interaction of the emitting hadron. The detailed dynamics on the formation of pions is not addressed.

(4) All the updating of the phase space trajectories is performed at a given time in the NN c.m. system. The emission process repeats itself until all the energy of the cluster is exhausted. At this point, the unbalanced momentum is evenly distributed to all the secondary particles to restore conservation of total momentum. A common momentum rescaling is finally used to restore conservation of the total energy also [6].

(5) With the newly scattered hadrons and the newly created secondaries, step (1) and step (2) are repeated for a new round of internuclear cascades. All of the newly produced pions are allowed to scatter with other existing hadrons, except with their seeding parents and the newly created pions themselves to avoid potential double counting in using on-shell cross sections.

A strong incentive for the need for an accumulated response can be appreciated through the existence of a ''loop of ordering'' of the collisions. In our calculation of step (1), we have identified the ''instant of collision'' of a particle X with all other hadrons $j=1,\dots,N$ in the rest frame of X. This definition sometimes runs into a logical loop when many particles are present. For example, after finding a particle Y being the next candidate to collide with X, we shift to the rest frame of Y and may find a particle Z, different from X, being the next candidate to encounter Y. This chain of ordering will complete a cycle, when a particle V is identified which takes particle X as its next candidate for collision. Our situation is a reflection of the infinite precision of the classical definition of the ''instant of collision'' and the lack of covariance of ''rigid body'' dynamics. The introduction of the accumulated time window τ lumps all the colliding partners into a single window, and the resultant dynamical evolution is not very sensitive to the details of the definition of the ''instant of collision.''

[3]To avoid an excessive CPU time occurring near the threshold and low momentum transfer, a cutoff of 2.15 GeV in the invariant mass and -0.4 GeV/c for the four-momentum transfer are set for any binary collision.

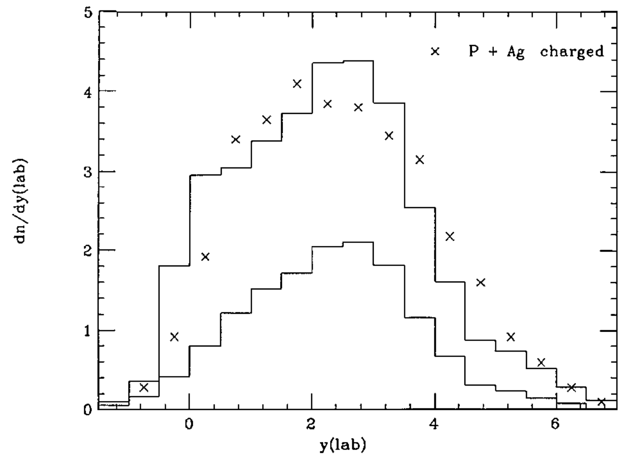

FIG. 1. Inclusive distributions of p + AG collision for charged particles at 200 GeV/c. Upper curve: dn_{ch}/dy. Lower curve: negatively charged particles dn_-/dy Data × from Ref. [25].

In Fig. 1, we have plotted dn_{ch}/dy and dn_-/dy for p +Ag collisions at 200 GeV/c for the value of $\tau=0.1$ fm/c. This choice leads to a $\langle n_{\mathrm{ch}}\rangle=17$. There is room for a somewhat different choice of τ, as other parameters can always be adjusted to restore a reasonable fit to the data. But our model does have difficulty generating enough secondary particles to fit the experimental data if the value of τ is taken to be too small. Given the fitting to the data as being acceptable, the above value of τ will be used for the more complicated analysis of the RHIC systems that follows.

In Fig. 2 we have used the above phenomenological formulation to calculate the transverse energy $dE_T/d\eta$ dependence for O+Ag and S+Ag collisions at 200 GeV/c using the minimum bias criterion of the WA80 experiment. In the forward region, the agreement between the S+Ag data and the Monte Carlo simulation is acceptable. In the backward region the Monte Carlo results are roughly 15% too high. Given the qualitative nature of our present phenomenological parametrization, we shall not pursue further improvement between our Monte Carlo simulations and the experimental

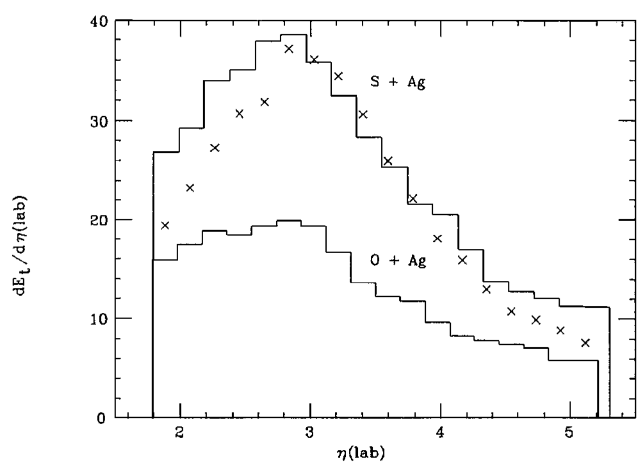

FIG. 2. Transverse energy $dE_t/d\eta$(lab) as a function of laboratory rapidity η_{lab}. Upper curve: S + Ag. Lower curve: O + Ag. The minimum bias criterion is the same as those used in the WA80 data to be compared. Data × for S + Ag from Ref. [26].

TABLE I. Peak and position of O + Ag and S + Ag collisions obtained from WA80 and Monte Carlo simulations for $dE_T/d\eta$ at 200 GeV/c in the central, intermediate, and peripheral regions.

Region	Peak	Position	Peak	Position
	WA80 O+Ag		MC O+Ag	
CEN	49.8	2.44	45.2	2.83
MID	30.0	2.57	27.8	2.64
PER	11.1	2.71	14.3	2.64
	WA80 S+Ag		MC S+Ag	
CEN	81.9	2.67	82.2	2.67
MID	55.0	2.78	53.2	2.67
PER	15.0	2.94	21.9	2.67

data until further studies. Table I shows a comparison of the peak values and the locations of $dE_T/d\eta$ with the O+Ag and S+Ag data of WA80 at 200 GeV using various criteria introduced by WA80 to label the center, middle, and peripheral collisions. The discrepancy is also $<15\%$.

In Fig. 3, we have calculated S+W collisions at 200 GeV/c. Since the system is larger and the Monte Carlo calculation demands a longer CPU time, it is not easy to obtain statistical information for the very rapid decreasing exponential tail of the high E_t region. Again in the forward region we observed better agreement between the Monte Carlo simulation and the experimental data. For the backward region and the full region, our Monte Carlo simulation is too high by roughly a factor of 2. Further tuning of the parametrization no doubt can improve the agreement. We shall leave it as a task for the future.

The AIC model we present here is a generalization of earlier models where the scattering between hadrons is confined to geometrically determined tubes [15,16]. Inside these encountering tubes all colliding hadrons possess cross sections which depend on their impact parameters and are smaller than the corresponding on-shell value at the same energy. If our τ value were taken to be zero (even with rescattering included), our model would underestimate the average number of secondary particles produced in pA and AB collisions. With a nonzero τ, the secondary pions being produced display substantial clustering and are more abundantly produced. A better agreement with the experimental data can be obtained. Thus, in our present model, it is necessary for the response time τ to be nonzero.

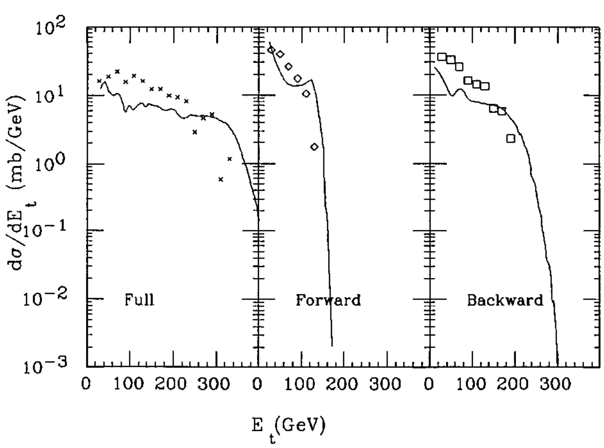

FIG. 3. Transverse energy $dE_T/d\eta_{\rm lab}$ as a function of laboratory rapidity $\eta_{\rm lab}$. The minimum bias criterion is the same as those used in the HELIOS data to be compared with data $\times$, $\Diamond$, and $\Box$ from Ref. [27].

In the NN c.m. system, the average spacing between the constituent hadrons is of the order 0.05 fm for the laboratory momentum of 200 GeV/c. $\tau=0.1$ fm/c allows two to three constituent hadrons to compound their energy losses into a central cluster before the pion emission begins. On the other hand, a typical cluster may contain a large number of secondary pions produced at an earlier time. In a typical pA collision with a large A, the dependence on the value of A in the projectile region is small. On the other hand, the rescattering effect is very strong in the target region and the A dependence is obvious. Our crude Monte Carlo model consistently leads to a somewhat higher value of E_t. Further refinement is clearly desirable.

Theoretically the value of τ is not easy to estimate, as the system under consideration is a unstable QCD system. Parton-parton interactions or string-string interactions should be considered. At the hadronic level, we have tried to take into account rescattering effects by ignoring the off-shell nature of the secondary pions and treating them as on-shell particles [17]. The secondary particles are created near the point of interaction along the longitudinal direction between the center of collision and the scattered hadron within the vicinity of the compound cluster. The detailed dynamics of the rearrangement of the compound cluster is therefore hidden in a black box and never addressed. Conservation of energy momentum is imposed at each intermediate step of the cluster cascade in our simulation. It should also be viewed as an approximation of the underlying dynamics also [6]. This is opposite to the other limiting scenario in which strings are treated as ''collision free'' entities before converting into pions.

Part of the merit of our model is the simplicity of the formulation. A detailed fine-tuning of the input parameters has not been performed for the more complicated heavy-ion systems. Considerable flexibility of our model still exists for a more realistic parametrization in the future. For example, more detailed considerations such as charge exchange interaction, factorization in $\pi\pi$ cross sections, transverse momentum p_t and impact parameter b dependence, production of the k mesons, and leading particle effects may also be incorporated. These and other fine-tuning should further improve the agreement between our model and the experimental data of the heavy-ion collision systems. The specific forms of the dependence of the rapidity and transverse momentum as in Eqs. (4)–(9) are adopted for their conveniences in numerical simulation. Since there are no intrinsic advantages in these forms, other reasonable parametrizations are clearly acceptable. None of these changes, however, will alter the rationale of our kinematic and dynamical treatments of the Monte Carlo simulation for the heavy-ion collision processes under consideration.

In a real sense, the goal of our research is not to create an ambitious model to explain all essential features of hadron- and nucleus-induced processes at relativistic energies, such the LUND and DPM models being developed over decades [4]. In order to demonstrate the central thesis of our approach, it is, nevertheless, necessary for us to use a comprehensive set of parametrizations for our Monte Carlo inputs and a reasonable representation of the system evolution in order to explore the kinematic and dynamics considerations of the interacting entities. Such considerations have forced us to be more critical in constructing our Monte Carlo simulation than most other statistical models. It also provided us with a quantitative tool to entangle the difficult issue of ''ordering'' multiple scatterings in a four-dimensional geometry of space-time. Since our Monte Carlo algorithm translates a rather intuitive physical picture to its associated computer simulation, it allows us to reevaluate the response of a typical localized system and introduce the concept of the accumulation of impacts and clustering. Thus the frequently cited issue of clustering in RHIC's can also be interpreted accordingly [14].

The space-time evolution of the many-body dynamics presented in this paper is essentially a classical one [18,19]. Quantum mechanical effects such as path interference are not incorporated. In this study, it is our intention to push the partonic localization concept to its limit so that better focus can be achieved on various techniques of numerical simulation in regions of densely populated hadronic matter. If the classical kernel of hadronic interaction is replaced by QCD parton or strings, questions of the time ordering of successive binary collisions discussed here remain an issue. Our assumptions on cluster formation and response may also be considered as an alternative phenomenological approach to the quark-gluon dynamics not being addressed in this study. The Monte Carlo simulations presented here could therefore be considered as one of the many complementary analyses to other models based on string dynamics.

In our phenomenological construction of the event generator, several important features of high energy processes have been ignored. One of the factors is local correlations of different kinds. Existing data indicate that the momentum and charge balance typically observes a compensation within one unit of rapidity [20]. In our representation, such correlations have been diluted to an overall global domain at the individual stage of interaction. For heavy-ion collisions, correlations between various produced hadrons also exist as a consequence of multilevels of internuclear cascade. Powerful phenomenological formations such as a wavelet analysis may lead to various correlation integrals for further illustration of the strong interaction dynamics illustrated by our Monte Carlo model as well [21].

Current extensive efforts exist on simulations of RHIC physics. Many of the Monte Carlo generators being developed can describe the available data (pp, pA, and AA) very well from low up to very high energies. It is therefore interesting to compare our AIC Monte Carlo generator explicitly with current generators. First the AIC generator is a hadronic-based generator, which is similar to ARC [22], and is therefore quite different from models that are QCD based such as FRITIOF [4], DPM [5], PCM [17], RQMD [23], and HIJING [24]. Second, the AIC generator is partially similar to HIJING in the use of the eikonal and stopping power formulations. But in the AIC generator, a collision is impacted on a whole hadron. Third, the AIC generator takes into account rescattering among the produced and scattered hadrons with no color degrees of freedom in a $(3+1)$-dimensional space. No color rope and resonance excitations are included. Fourth, the AIC generator considers a ''relaxation time'' for the formation of initial clusters. This possibility is not considered in most Monte Carlo generators. A separate consideration for the formation time of the secondarily produced pions is given in the vicinity of the AIC clusters. While RQMD and ARC are built for physics between AGS and SPS energies, HIJING and PCM for higher energies than that of SPS, the AIC generator has been selectively applied for both low and high energy regions.

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