Nucleus-nucleus multiplicity distributions and quantum chromodynamics

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A model for nucleus-nucleus multiplicity distributions is proposed and its relations with hadron-proton and hadron-nucleus multiplicity distributions are explored and compared with the experimental data. The values of the parameters are the same for all these processes and owe their origin to the quantum chromodynamical gluon bremsstrahlung mechanism. Some other consequences of the model are also analyzed and compared with the available experimental data.

I. INTRODUCTION

Presently, there is much interest in ultrarelativistic nucleus-nucleus collisions, which are believed to produce a phase transition from ordinary confined matter to confined quark-gluon plasma (QGP). The detection of QGP will provide a new insight into the mechanism of quark confinement, the theory of quark-gluon forces, quantum chromodynamics (QCD). The ultrarelativistic nuclear collisions also reveal the nature of hadronic interactions at very short time and/or distance and throw fresh light on the role played by the internal structure of hadrons. Since colliding heavy ions are rather complicated systems, a good understanding of the colliding process can be obtained by analyzing it in terms of basic quark-gluon interaction processes and it can thus be utilized as a tool for relating the hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions at high energy. Recently we proposed[1] a model parametrizing the hadron-nucleus multiplicity distributions and derived some interesting consequences[2] involving some scaling laws obeyed by the average shower multiplicity. We further noticed that our model reproduces the available experimental features very well. The most important feature of our parameterization is that it relates the hadron-nucleus interactions to hadron-proton interactions and the values of the parameters remain unchanged from those derived by the QCD hypothesis[3] of "universal" hadronic multiplicities in electron-positron, lepton-proton, and hadron-proton collisions. Therefore, we rightly suspected that these parameters derive their origin in basic quark-gluon processes and this possibility was verified by evaluating the value of one of the parameters by using the gluon bremsstrahlung model[4] of Low and Nussinov in QCD where we have assumed that the gluons separated from breaking of colored strings give the particle multiplicity.

In this paper, our central motivation is to extend this model to nucleus-nucleus collisions so that we can have a consistent and related description of hadron-proton, hadron-nucleus, and nucleus-nucleus collisions which will amply demonstrate the role of basic QCD processes in relating these complicated production processes.

In QCD, the interaction mechanism between target and projectile nuclei can be described as follows. A projectile quark exchanges a gluon with a target quark and color forces thus manifest between them as well as other constituents because they try to restore the color singlet behavior. When two quarks separate, the color force builds up a field between them and as the energy in the color field increases, the color tubes break up into hadrons and quark-antiquark pairs are created. Different existing models such as the additive quark model (AQM),[5] dual parton model[6] (DPM), or color neutralization model (CNM)[7] differ mainly in their assumptions about the potential number of participant partons which can interact independently. In AQM, this number of participants is limited by the valence quarks and the reinteraction of the produced particles is governed by the "formation time." After a valence quark first interacts, a certain time must elapse before it can materialize into a jet of hadrons and this is called "formation time." In DPM or CNM the number of participant quarks is unlimited because these include sea quarks as well. However, the constraints imposed by the "formation time" concept are not obeyed here because the reinteractions of secondaries are neglected. By means of the present data on hadron-nucleus interactions one cannot decide firmly about the potential number of quarks but the data clearly suggest that more color strings between projectile and target are favored in hadron-nucleus than in hadron-proton collisions and the weak energy dependence of $R=\langle n_s\rangle_{hA}/\langle n_s\rangle_{hp}$ clearly favors a model which incorporates formation time concept. Thus we essentially consider a multiple collision model in which we describe the nucleon-nucleon interactions as having a valence quark of the incident nucleon suffering inelastic collisions with a valence quark of target nucleon. The quarks thus lose energy and momenta and produce hadrons in each quark-quark collision. However, all the collisions are independent and their effects should be incoherently superimposed. For the nucleus-nucleus collisions the model should adequately incorporate the basic quark-quark interactions, their number of inelastic collisions inside the nucleus as well as the partitioning of available energy for these collisions.

II. DESCRIPTION OF THE MODEL

Let us first examine the relations between hadron-proton and hadron-nucleus interactions in our model.

The essential difference is that more than one quark of the initial hadronic beam interacts in the nucleus and multiple collisions with quarks belonging to different nucleons or the same nucleus may occur. Similarly, the average number of constituent quarks N_q participating in the interaction increases as the size of the target increases. So using AQM, Shabelsky *et al.*[8] proposed that the hadron-nucleus charged particle multiplicity will in general be N_q times the hadron-proton multiplicity:

$$\langle n_s \rangle_{hA} = N_q \langle n_{\rm ch} \rangle_{hp} \ , \tag{1}$$

where N_q depends upon the number of valence quarks N_c in the hadron beam as

$$N_q = \frac{N_c \sigma_{qA}^{\rm in}}{\sigma_{hA}^{\rm in}} \ , \tag{2}$$

and $\sigma_{qA}^{\rm in}$ and $\sigma_{hA}^{\rm in}$ are the quark-nucleus and hadron-nucleus inelastic cross sections, respectively.

Meson multiplicity has also been predicted using the multichain model[9] (MCM) and the wounded nucleon model (WNM).[10] These models exploit essentially the superposition of nucleon-nucleon collisions by utilizing Glanber theory concepts. Thus inputs to these models are the inelastic proton-proton cross sections and the charged particle multiplicity for pp collisions $\langle n_{\rm ch} \rangle_{pp}$. The main difference between these two models can be written as follows: WNM uses a simple constant $\langle n_{\rm ch} \rangle_{pp}$ at a given energy whereas MCM calculates the multiplicity per chain including energy momentum conservation and energy degradation distribution functions using a fudge factor to account for cascading.

Caneschi and Schwimmer have proposed a different parametrization[11] as follows:

$$\langle n_s \rangle_{hA} = \bar{\nu} \langle n_{\rm ch} \rangle_{hp} \ , \tag{3}$$

where $\bar{\nu} = A\sigma_{hp}^{\rm in}/\sigma_{hA}^{\rm in}$, is the mean number of inelastically interacting nucleons. Alternatively, a new parameterization has been adopted by some authors[12] as follows:

$$\langle n_s \rangle_{hA} = \langle n(E) \rangle_{hp} [1 + \beta(\bar{\nu} - 1)] \ , \tag{4}$$

where the energy dependence of hadron-proton multiplicity is $\langle n(E) \rangle_{hp} = 2.5 E_{\rm lab}^{1/4} - 1.5$ and $\beta = 0.45$. Here $E_{\rm lab}$ is the laboratory beam energy in GeV and β may depend on the projectile hadron but seems to be a universal constant according to the experiment. Thome *et al.* have parametrized[13] the energy dependence of hadron-proton multiplicity distribution as follows:

$$\langle n_s \rangle_{hp} = a + b \ln s + c (\ln s)^2 \ , \tag{5}$$

where the values of the parameters are completely different for pp ($a = 1.17$, $b = 0.30$, $c = 0.13$) and πp ($a = 0.02$, $b = 1.07$, $c = 0.05$) interactions. Exploiting QCD hypothesis of universal hadronic multiplicity parametrizations[14] in e^+e^-, lepton-proton and hadron-proton collisions, we can propose[1,2] the following parameterization:

$$\langle n_{\rm ch} \rangle_{hp} = (a' + b' \ln\sqrt{s_a} + c' \ln^2\sqrt{s_a}) - \alpha \ , \tag{6}$$

where the values of the parameters are the same for pp and πp collisions and are given as $a' = 2.50$, $b' = 0.28$, and $c' = 0.53$, and α is the leading particle effect and is experimentally determined as 0.85. Here $\sqrt{s_a}$ is the available centre of mass energy in hN collision and is given as

$$\sqrt{s_a} = \sqrt{s} - m_B - m_T \ , \tag{7}$$

where $\sqrt{s}$ is the total c.m. energy, m_B is the mass of projectile hadron and m_T is the mass of the target hadron. We, therefore, propose[1,2] that the produced charged particles (mainly pions) in the hadron-nucleus interaction can be given by considering the multiple collision effect in the nucleus as follows:

$$\langle n_s \rangle_{hA} = N_q \left[a' + b' \ln \left[\frac{\sqrt{s_A}}{N_q} \right] + c' \ln^2 \left[\frac{\sqrt{s_A}}{N_q} \right] \right] - \alpha \ , \tag{8}$$

where the partitioning of energy is incorporated in the factor $\sqrt{s_A}/N_q$ and the total squared c.m. energy s_A can be related to s_a by invoking the coherent tube type of picture[15] as $s_A = \nu_q s_a$ with ν_q as the mean number of inelastic collisions of quarks with target nucleus $\nu_q = A\sigma_{qN}^{\rm in}/\sigma_{qA}^{\rm in}$. Here A is the atomic number of the target nucleus and quark-nucleus inelastic cross section $\sigma_{qA}^{\rm in}$ determined from $\sigma_{qN}^{\rm in}$ ($\simeq \frac{1}{3}\sigma_{NN}^{\rm in}$) by using Glauber's approximation. The unique values of the constants a', b', c' for all the processes hint at their origin from the basic constituent quark-gluon processes in QCD. Assuming that the gluons separated due to gluon bremsstrahlung by breaking of colored strings give the required multiplicity, we calculate the value of one parameter by using the model of Low and Nussinov and we find that the hadronic multiplicities in e^+e^- annihilation, deep inelastic lepto-production, and hadron-hadron collisions all display the same growth of multiplicity. Asymptotic $\ln^2 s$ behavior in this model is a reflection of the requirement that the produced quark (3) and antiquark ($\bar{3}$) energy are back to back in all these reactions. Thus we get[1] the coefficient of the $\ln^2 s$ term as $c' = 4C_F\alpha_s/\pi$ and $c' = 0.53$ leads to $\alpha_s = 0.31$ as the value of strong interaction coupling in the nonperturbative region.

The generalization of this picture to nucleus-nucleus collisions goes along the same lines and the problem we face here is to determine the effective number of wounded quarks in projectile and the target nuclei as well as the mean number of collisions suffered by each of them. Thus the extrapolation of Eq. (8) to the nucleus-nucleus case, can easily be done as follows:

$$\langle n_s \rangle_{AB} = N_q^{AB} \left[a' + b' \ln \left[\frac{\sqrt{s_{AB}}}{N_q^{AB}} \right] + c' \ln^2 \left[\frac{\sqrt{s_{AB}}}{N_q^{AB}} \right] \right] \ , \tag{9}$$

where $\sqrt{s_{AB}} = A(\nu_q^{AB} S_a)^{1/2}$ and the mean number of inelastic quark collisions ν_q^{AB} is given as follows:

$$\nu_q^{AB} = \nu_{qA}\nu_{qB} = \frac{A\sigma_{qN}^{\rm in}}{\sigma_{qA}^{\rm in}} \cdot \frac{B\sigma_{qN}^{\rm in}}{\sigma_{qB}^{\rm in}} \ . \tag{10}$$

Similarly, the mean number[16] of participant quarks N_q^{AB}

in the target and projectile nuclei is given by Glauber theory as follows:

$$N_q^{AB}=\frac{1}{2}\left[\frac{N_B\sigma_{qA}^{\rm in}}{\sigma_{AB}^{\rm in}}+\frac{N_A\sigma_{qB}^{\rm in}}{\sigma_{AB}^{\rm in}}\right], \quad (11)$$

and N_A and N_B are the number of valence quarks in nucleus A and B, respectively. Here we adopt the following parametrization for the nucleus-nucleus cross section:[17]

$$\sigma_{AB}^{\rm in}=\pi r^2\left[A^{1/3}+B^{1/3}-\frac{c}{A^{1/3}+B^{1/3}}\right]^2 \text{ fm}^2 \quad (12)$$

with

$$r=1.31\pm0.01 \text{ fm and } c=4.45\pm0.15 .$$

The expressions for ν_q^{AB} and N_q^{AB} reveal a symmetry in nuclei A and B. For A-A collisions, we get

$$N_q^{AA}=\frac{N_A\sigma_{qA}^{\rm in}}{\sigma_{AA}^{\rm in}} . \quad (13)$$

From this relation we find $N_q=N_c\sigma_{qA}^{\rm in}/\sigma_{pA}^{\rm in}$ and from Eq. (10), $\nu_q=A\sigma_{qN}^{\rm in}/\sigma_{qA}^{\rm in}$ for pA interactions. Thus the parametrization as given by Eq. (9) gives the most general relation relating nucleus-nucleus collisions to hadron-nucleus and hadron-proton collisions and the values of the parameters a',b',c' remain unaltered which shows the similarity in the role of basic quark processes in all these processes.

In a search for creating extreme conditions of temperature and density, greater emphasis is laid on the central or head-on collisions of two nuclei. In such a case, we assume that all the quarks of the beam nucleus are wounded and the resulting mean multiplicity can be obtained by setting $N_q^{AB}=3A$ in Eq. (9) and we get

$$\langle n_s\rangle_{AB}^{\rm central}=3A\left[a'+b'\ln\left[\frac{(\nu_q^{AB}S_a)^{1/2}}{3}\right]+c'\ln^2\left[\frac{(\nu_q^{AB}S_a)^{1/2}}{3}\right]\right] . \quad (14)$$

Similarly, we can define a quantity D_{AB} as the difference between nucleus-nucleus charged particle multiplicity from N_q^{AB} times proton-proton multiplicity per mean number of wounded quarks:

$$D_{AB}=\frac{\langle n_s\rangle_{AB}-N_q^{AB}(\langle n_{\rm ch}\rangle_{pp}+\alpha)}{N_q^{AB}} . \quad (15)$$

If we assume

$$\langle n_s\rangle_{AB}=N_q^{AB}(\langle n_{\rm ch}\rangle_{pp}+\alpha)$$

as suggested by Eq. (1) we find $D_{AB}=0$. Thus the nonvanishing value of D_{AB} demonstrates that the meson production in the nucleus-nucleus case is on the average inconsistent with the superposition of nucleon-nucleon collisions in the relativistic energy range. We can calculate the deviation D_{AB} from our model and we get

$$D_{AB}=A_1+B_1\ln\nu_q^{AB}+C_1\ln^2\nu_q^{AB} , \quad (16)$$

where

$$A_1=c'\ln^2A+\ln A(b'+2c'\ln\sqrt{S_a}) ,$$

$$B_1=\gamma[b'+2c'\ln(A\sqrt{S_a})] ,$$

$$C_1=c'\gamma^2=\frac{1}{2}-\frac{\ln N_q^{AB}}{\ln\nu_q^{AB}} .$$

From this follows an interesting property of scaling. We notice

$$\lim_{\sqrt{S_a}\to\infty}\frac{D_{AB}}{\ln\sqrt{S_a}}\simeq 2c'\ln\left[\frac{A(\nu_q^{AB})^{1/2}}{N_q^{AB}}\right] . \quad (17)$$

Thus we can infer that the quantity

$$\lim_{\sqrt{S_a}\to\infty}\frac{D_{AB}}{\ln\sqrt{S_a}\left[\ln\left[\frac{A(\nu_q^{AB})^{1/2}}{N_q^{AB}}\right]\right]}=2c' , \quad (18)$$

and thus scales and becomes independent of energy.

Using the Low and Nussinov gluon bremsstrahlung process in QCD, we get the expression for p_T distribution for pp collisions as follows:

$$\frac{dn}{dP_T}=\frac{4C_F\alpha_s}{\pi}\frac{1}{P_T}\ln\frac{\sqrt{S_a}}{m_T} , \quad (19)$$

where m_T is the transverse mass of emitted pions. Thus for nucleus-nucleus collisions, we can extrapolate this equation as

$$\frac{dn_{AB}}{dP_T}=\frac{4C_F\alpha_s}{\pi}\frac{N_q^{AB}}{P_T}\ln\left[\frac{(\nu_q^{AB}S_a)^{1/2}}{m_TN_q^{AB}}\right] . \quad (20)$$

So the variation of the mean multiplicity $\langle n_s\rangle_{AB}$ with P_T can be deduced by integrating this expression with respect to P_T and we finally get

$$\langle n_s\rangle_{AB}=\frac{4C_F\alpha_s}{\pi}N_q^{AB}\ln P_T\ln\left[\frac{(S_a\nu_q^{AB})^{1/2}}{P_TN_q^{AB}}\right]+C_0 , \quad (21)$$

where C_0 is a normalization constant.

III. RESULTS AND DISCUSSION

In Fig. 1, we have shown nucleus-nucleus multiplicities as a function of c.m. energy per nucleon. For comparison sake, we have also shown our theoretical results for pp, p-Em cases and the available experimental data for these processes. We have plotted the average multiplicity for O^{16}-Em, O^{16}-AgBr, O^{16}-Au, S^{32}-Au, and U^{235}-U^{235} interactions. We find that the recent experimental results[18] from the O^{16}-AgBr and S^{32}-Au agree well with our calculation. In Fig. 2, we have demonstrated the target mass number dependence of the average nucleus-nucleus multiplicity $\langle n_s\rangle_{AB}$ for different values of A and our results are well supported by the recent experimental data.[18] Our calculation indicates that $\langle n_s\rangle_{AB}$ increases as the target mass number B increases. Similarly as the beam mass number A increases, $\langle n_s\rangle_{AB}$ again increases.

In Fig. 3, we have shown the linear dependence of the quantity $D_{AB}/\ln\sqrt{S_a}$ on $\ln[A(\nu_q^{AB})^{1/2}/N_q^{AB}]$ as predict-

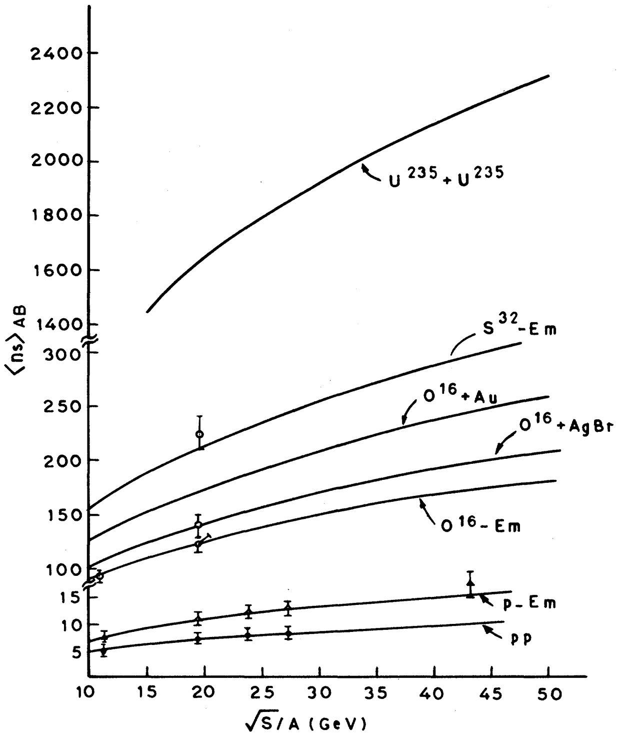

FIG. 1. Variation of average multiplicity $\langle n_s \rangle$ in the case of hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions with c.m. energy. Experimental data have been taken from Jain *et al.* (Ref. 18) for O^{16}-AgBr and Singh *et al.* (Ref. 18) for O^{16}-*Em* and S^{32}-*Em*.

ed by Eq. (17) and compared with the experimental data. We thus find that the curve obtained in this case retains its shape as we have found for hadron-nucleus interactions. This amply demonstrates the scaling behavior as shown in Eq. (17). In Fig. 4, we have displayed ν_q^{AB} dependence of the quantity D_{AB} for different beam and

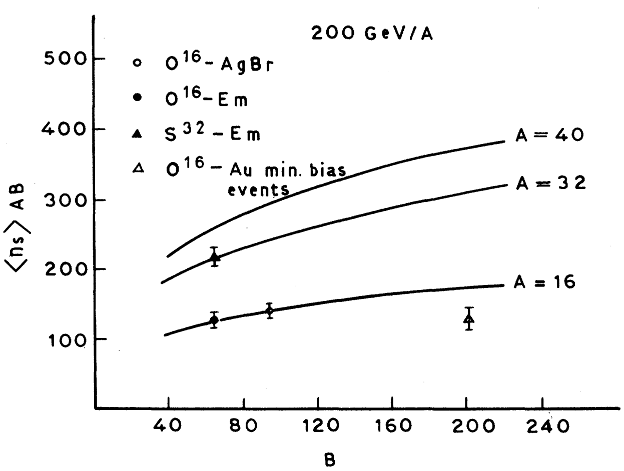

FIG. 2. Variation of $\langle n_s \rangle$ with target mass number B at 200 GeV/nucleon. Experimental data have been taken from Jain *et al.* (Ref. 18) for O^{16}-AgBr and Singh *et al.* (Ref. 18) for O^{16}-*Em* and S^{32}-*Em*, and Bamberger *et al.* (Ref. 18) for O^{16}-Au.

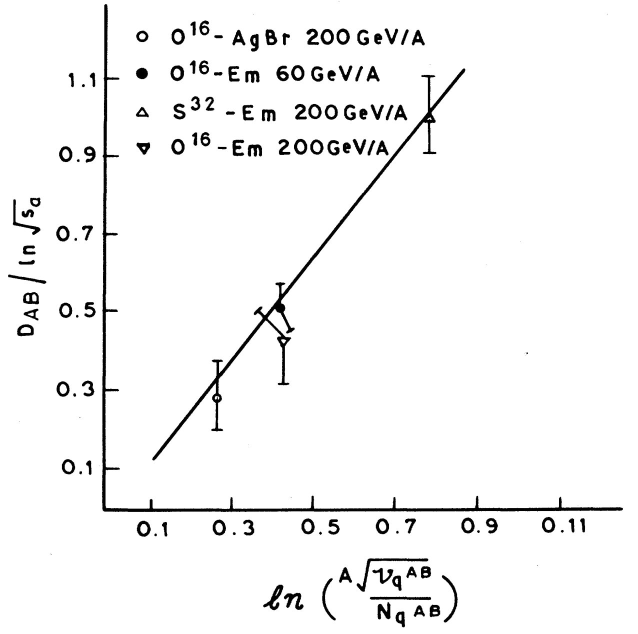

FIG. 3. Variation of $D_{AB}/\ln\sqrt{S_a}$ with $\ln[A(\nu_q^{AB})^{1/2}/N_q^{AB}]$. The solid line represents prediction of our model. Experimental data have been taken from Jain *et al.* (Ref. 18) and Singh *et al.* (Ref. 18).

target nuclei. This shows that D_{AB} barely changes by a small amount as ν_q^{AB} changes for the A-A type of nucleus-nucleus collisions. However, the variation in D_{AB} for the O^{16}-B collision (with $B > O^{16}$) shows a rapid decrease with increasing ν_q^{AB} while for A-AgBr (with AgBr$> A$), we get a rapid increase in the function D_{AB} as ν_q^{AB} increases. We again find that the available experimental data supports our claim.

In Fig. 5, we have shown the behavior of negative particle multiplicity as a function of transverse momentum P_T for α-α interactions. We find that the curve obtained from Eq. (21) agrees very well with the available experimental data. In Fig. 6, we have shown P_T dependence of

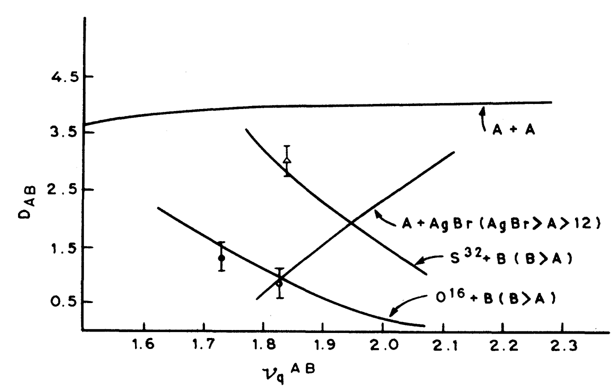

FIG. 4. Variation of D_{AB} with ν_q^{AB} for A-A, A-AgBr, O^{16}-B nucleus-nucleus interactions at energy 200 GeV/nucleon. Experimental data have been taken from Jain *et al.* (Ref. 18) and Singh *et al.* (Ref. 18).

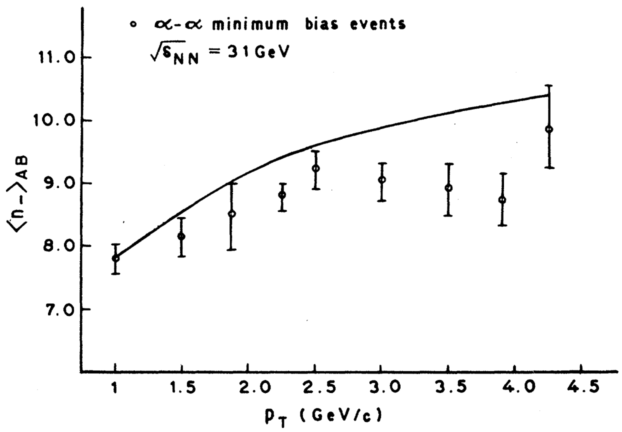

FIG. 5. Variation of mean negative charge particles multiplicity $\langle n_- \rangle$ in the case of α-α collision with P_T at $\sqrt{s_{NN}}=31$ GeV. Experimental data represent minimum bias events (Ref. 20).

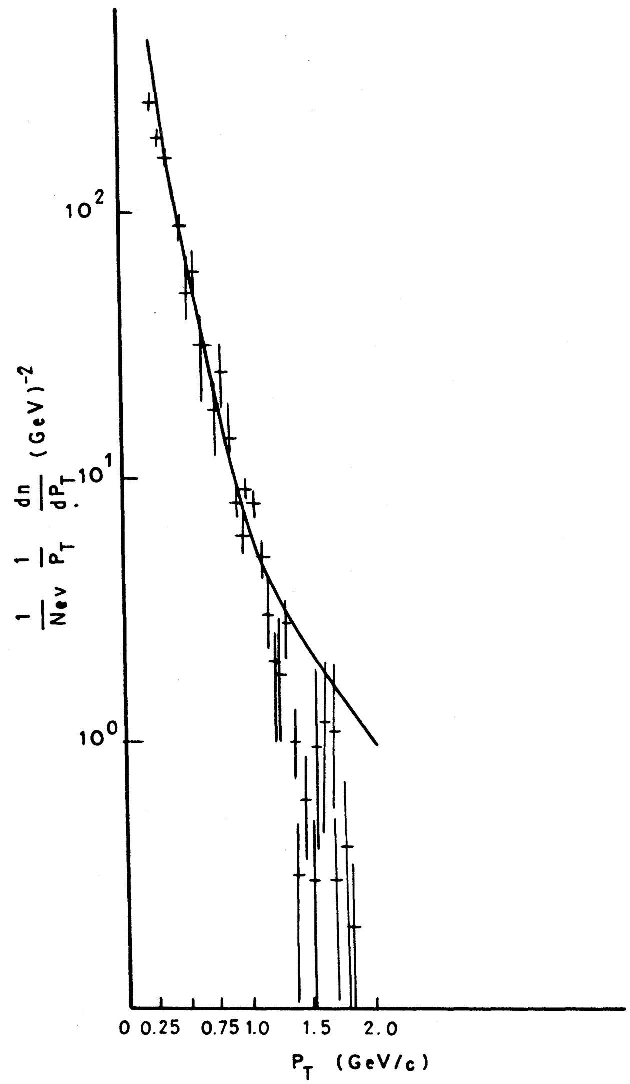

FIG. 6. Variation of $(1/N_{ev}P_T)dn/dP_T$ with P_T for O^{16}-Au collisions at 200 GeV/nucleon with number of events $N_{ev}=167$. Experimental results are taken from Bamberger *et al.* (Ref. 18).

the quantity dn/dP_T^2 as obtained from Eq. (20). We find that our result for O^{16}-Au reproduces well the main features of the recent experimental data of Bamberger *et al.*[18] These curves show the same features as found in hadron-nucleus collisions and hadron-hadron collisions. It is believed that Lund Monte Carlo model FRITIOF also fails to describe the transverse momentum distributions for central collisions although multiplicity distributions are reproduced well by the model.[19]

In Table I we have shown the comparison of our calculation for nucleus-nucleus collisions with the cosmic ray data. We find that the data lies within our calculated values for average multiplicity with and without the most central collisions (hard veto events). Similarly, in Table II, we have compared[10] the prediction of our model with those of the multichain model[20] (MCM) and coherent tube model[21] (CTM). Cosmic ray experimental data are also given for a comparison at these energies. However, no firm conclusions can be drawn from these comparisons because the experimental figures are not quite consistent with each other. For example, the collision of

TABLE I. Mean multiplicities in central collisions compared with cosmic ray data.

E (TeV/nucleon)	A	B	ν_q^{AB}	N_q^{AB}	$\langle n_s \rangle_{\text{cal}}$	$\langle n_s \rangle_{\text{cal}}^{\text{central}}$	$\langle n_s \rangle_{\text{expt.}}$
0.3	11	108	1.81	13.52	117.3	194	204
0.3	28	108	1.97	25.35	254.4	504	517
0.3	40	207	2.28	43.04	415.5	746	518
0.5	11	108	1.81	13.52	131.3	220	176
0.5	27	108	1.96	24.77	283.3	511	242
0.5	28	108	1.97	25.35	275.1	550	515
1.5	11	108	1.81	13.52	164.3	282	175
1.7	11	108	1.81	13.52	168.3	290	193
3	12	108	1.82	14.37	201.1	357	215
3.6	28	108	1.97	25.35	409.5	880	1050
100	12	40	1.60	9.59	257.1	658	600

TABLE II. Comparison with different models for cosmic ray data.

E (TeV/nucleon)	A	B	$\langle n_s \rangle_{\text{expt.}}$	$\langle n_s \rangle_{\text{MCM}}$	$\langle n_s \rangle_{\text{CTM}}$	$\langle n_s \rangle_{\text{our model}}$
0.3	11	108	204	200	155	194
0.3	28	108	517	420	345	504
0.5	11	108	174	235	174	220
0.5	27	108	242	500	381	511
0.5	28	108	515	510	389	550
1.5	6	108	175	200	160	152
1.7	11	108	193	350	228	290
3	12	108	215	450	282	357
3.6	28	108	1050	990		880
100	12	40	600	760		658

$A=11$, $B=108$ at 0.3 TeV/N energy produces more shower particles than the same collision at 1.5 TeV/N and 1.7 TeV/N. Similarly, the number of particles produced in collisions between $A=27$, $B=108$, and $A=28$, $B=108$ differ from each other by a factor larger than 2.

In conclusion, we have formulated a model which leads to a unified particle production mechanism for hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions in terms of "elementary" quark-gluon interactions. It has great predictive power and our detailed calculations for hadron-nucleus interactions compare quite well with available data. Although much detailed information has still to be obtained about the soft collision processes, it looks quite clear from the currently available experimental data that the main trends of observables like $\langle n_s \rangle$ are similar for hadron-hadron, hadron-nucleus, and nucleus-nucleus collision. We have drawn a line of similarity between these collisions and we have further made an attempt to correlate all these interactions in terms of basic QCD processes. However, much more experimental data are needed in order to verify the predictions made in this paper. We further believe that the scaling laws and other consequences derived for hadron-nucleus and nucleus-nucleus collisions and their simple relations with the proton-proton multiplicities as indicated in our model permit some optimism so that a better understanding in terms of QCD may emerge soon. We hope that in the near future more experimental support will be available for testing the space-time picture of the matter formation and evolution presented in this paper in ultrarelativistic nucleus-nucleus collisions.

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