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Particle production in high energy nucleus-nucleus
collisions in a dual Monte-Carlo multi-chain
fragmentation model

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Abstract

A dual Monte-Carlo multi-chain fragmentation model for particle production in high energy nucleus-nucleus collisions is presented. Average multiplicities and rapidity distributions for average and for central collisions are compared to results from alternative calculations and to cosmic ray data.

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1. Introduction

High energy collisions of heavy ions offer the exciting possibility to discover experimentally a new state of matter, the quark gluon plasma /1-5/. In order to understand, which signatures of heavy ion collisions are useful to identify effects due to the formation of a quark-gluon plasma, we should however understand also the characteristics of such collisions within conventional models of low $p_{\perp}$ particle production. Presumably such conventional events will be the background against which the effects of the quark gluon plasma have to be found.

There are several models, which are highly successful in describing data on hadron-nucleus interactions. These models have also been extended to nucleus-nucleus collisions.

Examples are:

- (i) the dual multi-chain parton fragmentation model /6,7/
- (ii) the additive quark model /8,9/
- (iii) the gluon exchange model of Brodsky et al. /10,11/.

Here we follow the general philosophy of the dual multi-chain fragmentation model as formulated by Capella, Pajares and Rammallo /6/. Different from Ref. /6/ however, we formulate the model as a Monte-Carlo generator of exclusive events similar to our formulation of the dual multi-chain fragmentation model in the case of hadron-hadron collisions /12,13,14/ and hadron-nucleus collisions /12,15/. The generation of Monte-Carlo events in this model proceeds in two steps. In a first step a multi-chain event is generated. In the second step all chains fragment into stable hadrons according to a Monte-Carlo chain decay fragmentation model /16/. In this approach energy momentum and additive quantum numbers are conserved exactly.

In Section 2 we describe the dual multi-chain model. In Section 3 we describe the threshold behaviour of the model and the kinematical approximations needed to formulate the model at limited collision energies. In Section 4 we compare the results of our Monte-Carlo multi-chain fragmentation model with data from cosmic ray interactions and with predictions from alternative models. The results are summarized in Section 5.

2. The multi-chain model for nucleus-nucleus collisions

In order to construct a Monte-Carlo model for nucleus-nucleus collisions we use the dual multi-chain model of Capella et al. /6,7/. In this model the interaction between two nucleons starts with the separation of their valence quarks into two colored systems (a quark and a diquark), which subsequently recombine and evolve into multiparticle chains. In Ref. /7/ the model was discussed neglecting the difference between valence and sea quarks. This might be a good approximation for α - α collisions.

Describing a nucleus-nucleus scattering process in such a model, one starts selecting the total number n of inelastic collisions taking place during the interaction and the numbers $n_A(n_B)$ of inelastically interacting nucleons of nucleus $A(B)$. We sample n , n_A and n_B according to the cross section $\sigma_{AB}^{n_A, n_B, n}$ given in Ref. /6/, see also the Appendix. n , n_A and n_B are related by $n \geq n_A$ and $n \geq n_B$.

From the knowledge of n , n_A , n_B we can construct all our chains. Each interaction gives rise to two chains. We get altogether $2n$ chains. There are $n_A(n_B)$ valence quarks and diquarks in nucleus $A(B)$.

The chains are in the case $n_A \leq n_B$:

- (i) valence-valence chains: We have n_A chains of the type $q_A^V - (qq)_B^V$ and n_A chains of the type $(qq)_A^V - q_B^V$.
- (ii) valence-sea chains: We have $n_B - n_A$ chains of the type $\bar{q}_A^S - q_B^V$ and $n_B - n_A$ chains of the type $q_A^S - (qq)_B^V$. Altogether there are $2n_A + 2(n_B - n_A) = 2n_B$ chains, in which valence constituents are present.

Since the total number of collisions n may be larger than n_B we have to construct finally

- (iii) sea-sea chains: There are $n - n_B$ chains of the type $\bar{q}_A^S - q_B^S$ and $n - n_B$ chains of the type $q_A^S - \bar{q}_B^S$.
 $q^S, \bar{q}^S, q^V$ and $(qq)^V$ stand for sea quarks, sea antiquarks, valence quarks and valence diquarks.

In Fig. 1 we give an example for the chain structure of a nucleus-nucleus scattering process with $n = 5$, $n_A = 2$ and $n_B = 3$.

In order to determine the energies or invariant masses of the chains we need the x-fractions of their constituents. Since we want to realise energy-momentum conservation for the whole nucleus-nucleus collision we have to normalize all x-fractions of each interacting nucleon to 1. That means we obtain the x-values of the valence quark q^V and k sea quarks q^S and k sea antiquarks $\bar{q}^S$ of the considered nucleon from a multiquark fragmentation function

$$F(x_{\bar{q}}^V, x_{q\bar{q}}^V, x_{q_1}^S, x_{\bar{q}_1}^S, \dots, x_{q_k}^S, x_{\bar{q}_k}^S) \cdot \mathcal{J}(1 - x_{\bar{q}\bar{q}}^V - x_{q\bar{q}}^V - \sum_{i=1}^k (x_{q_i}^S + x_{\bar{q}_i}^S)). \quad (1)$$

Indeed we use a more simple factorized distribution in order to sample the x-fractions:

$$d(x_{\bar{q}}^V) \cdot \prod_{i=1}^k (d(x_{q_i}^S) \cdot d(x_{\bar{q}_i}^S)) \cdot \mathcal{J}(x_{\bar{q}\bar{q}}^V - (1 - x_{q\bar{q}}^V - \sum_{i=1}^k (x_{q_i}^S + x_{\bar{q}_i}^S))). \quad (2)$$

with

$$d(x_{\bar{q}}^V) \sim \frac{(1-x)^2}{\sqrt{x}} \quad (3)$$

and

$$d(x_{q_i}^S) = d(x_{\bar{q}_i}^S) \sim \frac{(1-x)^6}{x} \quad (4)$$

The hadronization of the chains is handled for each chain separately on the basis of a Monte-Carlo chain decay fragmentation model /16/ going into the centre of mass system of the considered chain as described for our hadron-hadron model /12,13/ or for our hadron-nucleus model /12,15/.

After a Lorentz boost of all hadronized chains back into the laboratory frame of the nucleus-nucleus collision we obtain a complete final hadronic state conserving exactly energy-momentum and all additive quantum numbers. The conservation of these quantities is guaranteed, because our Monte-Carlo chain decay model conserves energy-momentum and additive quantum numbers during the hadronization process of each chain.

Finally we consider the decay of hadron resonances into stable final hadrons using the Monte-Carlo code DECAY /17/.

3. Threshold behaviour of the model

The numbers n , n_A , n_B sampled according to (A1) are nearly energy independent. Therefore, we get at low energies many chains, which might have invariant masses below the kinematical minimum corresponding to the quantum numbers of the chain considered. Using exact kinematics such chains are not allowed in our Monte-Carlo model. In order to avoid kinematical problems arising from these light chains we have to introduce some kinematical cuts and approximations concerning the x-fractions of the parton constituents building up the chains. Our corrections are done in two steps:

- (1) Starting from the numbers n , n_A , n_B sampled according to (A1) we select the x-fractions of all sea quarks and sea antiquarks only in the range $x_0 \leq x \leq 1$ with $x_0 = 0.2 \text{ GeV}/(\sqrt{s}/2)$. $\sqrt{s}$ is the centre of mass energy of a nucleon-nucleon collision. Thus we guarantee that our invariant chain masses built up only from sea quarks are larger than $0.2 \text{ GeV}/c^2$. This corresponds to the threshold for the creation of pions with some transverse momentum. Furthermore we require that for the valence quarks and diquarks a minimum x-fraction is available $x_q^V + x_{\bar{q}}^V > x_{min}^V$ with $x_{min}^V = 3 \text{ GeV}/(\sqrt{s}/2)$. If this would be violated, we decrease the originally sampled number of sea quarks present in nucleus A : $n_{sea} = n - n_A$ by decreasing the number of collisions n , and if necessary also n_B , correspondingly.
- (2) The hadronization of the chains on the basis of the Monte-Carlo chain decay model is only possible, if their invariant masses are large enough to create two or more hadrons. We proceed in our model in the following way:
  - (i) For invariant chain masses $m_{ch} \geq m_{H^*} + 0.3 \text{ GeV}/c^2$ the chain decay occurs, where m_{H^*} is the mass of the hadron resonance defined by the quantum numbers of the initial quarks of the chain (vector meson or spin $3/2$ baryon).
  - (ii) For $m_{H^*} \leq m_{ch} < m_{H^*} + 0.3 \text{ GeV}/c^2$ we correct the x-fraction of one of the initial quarks of the chain in such a way, that the resonance H^* will be directly

created. The x-fraction of the second valence constituent of the considered nucleon is corrected correspondingly to keep energy conservation.

- (iii) For $m_H \leq m_{ch} < m_{H^*}$ we also correct the x-fractions in order to create directly the stable hadron H (pseudoscalar meson or spin 1/2 baryon).
- (iv) It remains the case of $m_{ch} < m_H$. If we have a sea-sea chain we drop the corresponding pair of sea-sea chains and add its energy to the next sea quarks. This correction corresponds to a decrease of the number n of collisions. If we have a valence-sea chain of the type $\bar{q}_p^s - q_T^v$ or $q_p^s - (qq)_T^v$, we proceed in the same way. Dropping valence quarks or diquarks of nucleons of the target nucleus means that the number n_B of interacting nucleons of the target nucleus B decreases. In case of $q_p^v - \bar{q}_T^s$ or $(qq)_p^v - q_T^s$ chains we do not drop the chains because we decided not to change the number n_A of interacting nucleons of the projectile nucleus A in our model. (This was motivated by considering the collisions in the target nucleus rest frame.) We resolve the conflict by rejecting the event sampled so far and sampling all x-fractions again from the beginning. The same procedure is followed for chains containing only valence constituents $q_p^v - (qq)_T^v$ or $(qq)_p^v - q_T^v$.

4. Comparison to other models and to cosmic ray data

Here we want to discuss results of our nucleus-nucleus Monte-Carlo model on the energy- and A -dependence of average multiplicities as well as rapidity densities and compare them to ISR data /19/, cosmic ray data /18/ and to calculations /9,11/.

In Fig. 2 and 3 we show our model predictions for the energy dependence and for the A -dependence of average charged and average negative multiplicities in case of Oxygen-nucleus collisions.

In Fig. 4 we plot rapidity densities in the central region normalized to the nucleon-nucleon rapidity density for $A+B$ colli-

sions in dependence of the mass number B of the target nucleus. Our model results for different projectile nuclei A are inbetween the results given in Ref. /6/ and Ref. /9/.

Fig. 5 contains the average negative particle multiplicity $\langle n_- \rangle = N_{AB}^{(-)}$ produced in $A+B$ collisions at $\sqrt{s} = 31$ GeV as function of the target nucleus mass number B . $\sqrt{s}$ is the centre of mass energy of a nucleon-nucleon collision, which corresponds to $E_{\text{lab/nucleon}} \approx 511$ GeV. Our model results also agree well with the predictions given in Refs. /6,11/.

In Fig. 6 the same quantity is shown as in Fig. 5 but for central collisions, following Ref. /6/ we put $n_A = A$, which means that all nucleons of the projectile nucleus A take part at the interaction, see also Appendix.

The principal reason for the differences of our results to the results of the same model as formulated by Capella et al. /6/ is the form of our chain rapidity distributions which differs from that one given by Capella et al. /6/. This is due to the fact that we identify all particles in our calculations, which influences the results especially for contributions from light chains. Furthermore we use kinematical corrections different from Ref. /6/ in order to describe the threshold behaviour. The differences between our model predictions and results from Ref. /6/ give an impression of the dependence of such models on several parametrizations. Since these deviations are of the same order as deviations to results from other calculations /9,11/, we conclude that the differences presently obtained between such models are not significant.

Pseudo rapidity distributions are plotted in Fig. 7 a, b at $E_{\text{lab/nucleon}} = 300$ GeV for $B + \text{Ag}$ and $\text{Ca} + \text{Pb}$ collisions and in Fig. 7 c, d at $E_{\text{lab/nucleon}} = 70$ GeV for $\text{N} + \text{Ag}$ and $\text{Mg} + \text{Ag}$ collisions. Our model results for central collisions are compared to cosmic ray data /18/ and to model results from Ref. /6/. In general we have a reasonably well agreement to the data. Differences might be due to the fact, that the procedure to define central collisions in our model differs from that one used in the experiment. For this reason we always show additional our model results for unbiased (normal) collisions, which are clearly lower compared to central collisions.

Furthermore we compare in Fig. 8 our model results for pseudo-

rapidity distributions in case of Si + Ag collisions at $E_{\text{lab/nucleon}} = 3.6$ TeV to cosmic ray data /18/ and to model results from Ref. /6/. The fact that our pseudorapidity distributions are always somewhat above the results given in Ref. /6/ is in correspondence with Fig. 5, where we also have larger negative average multiplicities than in Ref. /6/.

In Fig. 9 and 10 we show our model predictions for the energy and A -dependence (at $E_{\text{Lab/nucleon}} = 1000$ GeV) of pseudorapidity distributions in case of Oxygen-nucleus interactions. Finally we plot in Fig. 11 the KNO-multiplicity distribution for α - α collisions at $\sqrt{s} = 31$ GeV. Our model results for negative multiplicities $n_- \gtrsim 4$ agree well with the data /19/. However, for $n_- \lesssim 4$ the Monte-Carlo points are below the data.

5. Conclusions

Our model for nucleus-nucleus interactions is based on the dual parton model. Using a Monte-Carlo method allows to calculate beside inclusive distributions also exclusive quantities. In this sense the model is well suited to generate complete exclusive events conserving energy-momentum and all additive quantum numbers.

Even for the high multiplicities in nucleus-nucleus collisions our Monte-Carlo event generator is relatively fast. We need approximately one minute CPU time on a IBM-3081 to generate 250 Carbon-Copper interactions at an energy of 500 GeV per nucleon. The accuracy of energy-momentum conservation is better than one permille also for events with more than 1000 particles in the final state.

First results of the model on average multiplicities and rapidity densities for normal and central collisions agree reasonably well with cosmic ray data and results of other models. The differences between our calculations and these alternative calculations are not significant.

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Appendix

For sampling the total number of nucleon-nucleon interactions n and the numbers of interacting nucleons n_A and n_B from the nuclei A and B , resp., we start from the Glauber formalism extended to nucleus-nucleus collisions. These methods, developed by several authors, have been summarized and extensively discussed in Ref. /20/. The cross sections are calculated according to Ref. /6/ :

$$\sigma_{AB}^{n_A, n_B, n} = \binom{A}{n_A} \binom{B}{n_B} [\sigma \cdot T_{AB}(b)]^n [1 - \sigma \cdot T_{AB}(b)]^{A \cdot B - n} \times \sum_{i=1}^{n_A} \sum_{j=1}^{n_B} \binom{n_A}{i} \binom{n_B}{j} \binom{i \cdot j}{n} \cdot (-1)^{n_A + n_B - i - j} \quad (A1)$$

$T_{AB}(b)$ is obtained from the profile functions of nuclei A and B , - $T_A(b)$ and $T_B(b)$ - by

$$T_{AB}(b) = \int d^2s \cdot T_A(\vec{s}) \cdot T_B(\vec{b} - \vec{s}) \quad (A2)$$

with

$$T_A(b) = \int_{-\infty}^{+\infty} \rho_A(b, z) dz. \quad (A3)$$

The nuclear density is parametrized as in Refs. /6, 21/

$$\rho_A(r) = \begin{cases} \frac{\rho_0}{1 + \exp[(r-R)/\alpha]} & \text{for } A \geq 12 \\ \left(\frac{1}{\pi R^2}\right)^{3/2} \exp\left(-\frac{r^2}{R^2}\right), R = 1.37 \text{ fm} & \text{for } A = 4 \end{cases} \quad (A4)$$

with $R = r_0 \cdot A^{1/3}$, $r_0 = 1.14$ fm
 $\alpha = 0.545$ fm .

In this formulation the densities have to be normalized to one, e.g.

$$\int \rho_A(r) d^3r = 1 .$$

The inelastic non-diffractive nucleon-nucleon cross section in Eq. (A1) is taken to be $\sigma = 28$ mb. For our present estimates no energy dependence of σ has been included.

We follow Ref. /6/ in defining central collisions as events with all nucleons of the incident nucleus A interacting, e.g. $n_A \equiv A$ in eq. (A1).

In practical computations it is not feasible, however, to calculate probability distributions for sampling from Eq. (A1): The evaluation of the Glauber series is very time consuming and additionally meets serious problems with the numerical accuracy because of the alternating sign in (A1). For these reasons we mostly sample n_A , n_B and n from Gaussians subjected to the following constraints:

$$\begin{aligned} 1 &\leq n_A \leq A \\ 1 &\leq n_B \leq B \\ \max(n_A, n_B) &\leq n \leq A \cdot B . \end{aligned}$$

Averages and widths of these Gaussians are taken from parametrizations. To establish these parametrizations we calculated averages and dispersions $D = [\langle n^2 \rangle - \langle n \rangle^2]^{1/2}$ for some light and medium nuclei from Eq. (A1) for unbiased as well as for central collisions. The results are represented in Tables 1 and 2 and compare reasonably with average numbers given in /6/.

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Tables

Tab. 1: Average number of inelastic collisions $\langle n \rangle$, average
number of interacting nucleons of nucleus A : $\langle n_A \rangle$
and of nucleus B : $\langle n_B \rangle$ and the corresponding dis-
persions D , D_A , D_B for different nuclei A , B
and for normal collisions. D is defined as $[\langle n^2 \rangle - \langle n \rangle^2]^{1/2}$.
 D_A , D_B are defined in the same way.

unbiased collisions							
A	B	$\langle n_A \rangle$	D_A	$\langle n_B \rangle$	D_B	$\langle n \rangle$	D_n
4	12	1.89	0.98	2.36	1.58	2.60	1.91
4	27	2.25	1.12	3.51	2.64	3.77	3.00
12	12	3.15	2.28	3.15	2.28	3.88	3.34
12	27	4.24	3.10	5.20	4.40	6.19	5.90
12	64	4.61	3.28	6.46	5.68	7.09	6.64

Tab. 2: Average number of inelastic collisions : $\langle n \rangle^c$, average number of interacting nucleons of nucleus B : $\langle n_B \rangle^c$ and the dispersions D^c , D_B^c for different nuclei A , B and for central collisions.

central collisions					
A	B	$\langle n_B \rangle^c$	D_B^c	$\langle n \rangle^c$	D^c
12	12	9.4	1.22	17.4	2.67
12	27	15.8	2.42	22.9	4.19
12	64	24.5	4.74	30.5	6.68
12	108	32.4	6.60	38.8	8.80
27	27	23.0	1.80	49.8	5.90

Figure captions

- Fig. 1: Example for a nucleus-nucleus scattering process with $n = 5$ interactions and $n_A = 2$ contributing nucleons from nucleus A and $n_B = 3$ contributing nucleons from nucleus B . This gives rise to 4 valence-valence chains (v-v), 2 valence-sea chains (v-s) and 4 sea-sea chains (s-s).
- Fig. 2: Our model predictions for average charged multiplicities and average negative multiplicities versus $E_{\text{Lab/nucleon}}$ for $O + A$ collisions.
- Fig. 3: Our model predictions for average charged multiplicities and average negative multiplicities versus the mass number A for $O + A$ collisions at different energies.
- Fig. 4: Rapidity densities in the central region normalized to the nucleon-nucleon rapidity density. Our Monte-Carlo results are compared to predictions from Refs. /6/ and /9/.

- Fig. 5: Average negative particle multiplicity $\langle n_- \rangle = N_{AB}^{(-)}$. Our Monte-Carlo results are compared to predictions from Refs. /6/ and /11/.
- Fig. 6: Average negative particle multiplicity $\langle n_- \rangle = N_{AB}^{(-)}$ for central collisions. Our Monte-Carlo results are compared to predictions from Refs. /6/ and /11/.
- Fig. 7: Rapidity distributions for
 (a) B + Ag
 (b) Ca + Pb
 collisions at $E_{\text{Lab/nucleon}} \approx 300 \text{ GeV}$ and for
 (c) N + Ag
 (d) Mg + Ag
 collisions at $E_{\text{Lab/nucleon}} \approx 70 \text{ GeV}$.
 Our Monte-Carlo results for normal and central collisions are compared to cosmic ray data /18/ (central collisions) and predictions from Ref. /6/ (central collisions). The data and M.-C. results are plotted in pseudorapidity and the results from Ref. /6/ in rapidity.
- Fig. 8: Rapidity distributions for Si + Ag collisions. Our Monte-Carlo results at $E_{\text{Lab/nucleon}} = 3.6 \text{ TeV}$ for normal and central collisions are compared to cosmic ray data /18/ (central collisions) and predictions from Ref. /6/.
- Fig. 9: Model predictions for the energy dependence of pseudorapidity distributions for O + Al collisions.
- Fig. 10: Model predictions for the A -dependence of pseudorapidity distributions for O + A collisions at $E_{\text{Lab/nucleon}} = 1000 \text{ GeV}$.
- Fig. 11: KNO-distribution for negative particles in $\alpha - \alpha$ collisions at $\sqrt{s} = 31 \text{ GeV}$. Our Monte-Carlo results are compared to data from Ref. /19/.

Fig. 1

Fig. 2

Fig. 3

normal collisions

$\sqrt{s} = 31 \text{ GeV}$

Fig. 4

Fig. 5

Fig. 6

Fig. 7a

Ca + Pb

$E_{\text{lab}}/\text{Nucleon} \approx 300 \text{ GeV}$

Fig. 7b

Fig. 7c

Fig. 7d

Fig. 8

Fig. 9

Fig. 10