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MANY PARTICLE CORRELATIONS IN THE MULTIPLE
PRODUCTION ON NUCLEI

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ABSTRACT

In the framework of the multiple scattering models we derive the relations between the many particle rapidity correlations on nuclei and on nucleons.

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1. INTRODUCTION

The main interest in particle-nucleus interactions stems from the fact that, due to their large sizes, nuclei can provide one with valuable information on the space-time development of the multiproduction process. The latter became of great interest in view of the recent developments in QCD. Little is known, as yet, how to apply QCD quantitatively to soft hadronic interactions. However, QCD should, supposedly, be quite different from the usual soft parton models due to the fundamental role played in the former by vector particles.

Keeping this possibility in mind, the best thing to do is to formulate the most characteristic consequences of the soft parton models and wait for experimental data. The variances between such predictions and the data, if any, will presumably point out the proper direction for the development of the microscopic theory of strong interactions.

This paper is devoted to the solution, in the framework of soft parton model^{1),2)}, of two problems. First, we relate the multiparticle-correlation functions for multiple production on nuclei to those for production on nucleons. Second, we demonstrate how, by measuring the rapidity and azimuthal correlations, one can distinguish between the different models for the parton structure of hadrons.

In the parton model the wee partons, emitted by hadrons well before the target, rather than hadrons by themselves, are supposed to interact with the target. Different models differ mainly in their predictions for the wee parton number distributions. Below we shall consider in more detail a few typical possibilities exemplified by the following models:

i) A simple one-ladder parton model (SPM). Here the fast hadron is viewed as a single multiperipheral ladder (MPL) (Fig. 1a). Implications of the SPM for particle-nucleus interactions were analysed first by Kancheli and Matinyan³⁾ and, in more detail, in Ref. 4).

ii) The quasieikonal model (QEM). In the QEM the hadron can contain any number of wee partons and/or MPL's (one wee parton is assigned to each MPL). The distribution in the number ν of interacting ladders is supposed to coincide with that given by the eikonal model (Fig. 1b). To put it more exactly, the planar diagrams of the eikonal model, which correspond to the successive interactions of the projectile with m nucleons of the nucleus, are substituted for by the non-planar diagrams for the interaction of the m constituent state of the parton Fock-space decomposition of the projectile. The $\nu \sim A^{1/3}$ ladder components are projected onto the final state in the collision with the nucleus.

The most comprehensive description of hadron-nucleus interactions, including total cross-sections, multiplicity distributions, inclusive spectra, etc., was given by Shabelski⁵⁾, Capella and Krzywicki⁶⁾.

iii) The additive-quark model (AQM). In the additive quark model the mesons and baryons are viewed as composed of two or three spatially separated constituent quarks. The parton structure of each constituent is described by the SPM^{7),8)} (Fig. 1c). Such an approach has been widely used for more than a decade and has proved to be very successful in explaining many features of hadron-hadron interactions⁸⁾. The AQM was first applied to particle-nucleus inelastic interactions by Anisovich⁹⁾, and developed in more detail in a series of recent papers^{10),11),12)}.

All the models cited are oversimplified to a certain extent. For example, triple-pomeron effects, resulting in a free-like structure of the ladders, are neglected. We also neglect the cascading inside the nucleus. These problems will be treated in more detail in subsequent publications. They are irrelevant for the purpose of this paper, since we shall discuss only the pionization plateau region. The energies are supposed to be high enough, so that we can neglect finite energy corrections, though these corrections are small for the correlations in the central region.

The further presentation is organized as follows. In Section 2 we derive the general equations for two and three particle rapidity correlation functions. In Section 3 we comment on the multiplicity distributions. Section 4 is devoted to the discussion of azimuthal correlations. In Section 5 we discuss the mean number of interactions - the quantity of most importance in the calculations of all the correlations. In the concluding section we summarize our results.

2. MANY PARTICLE RAPIDITY CORRELATIONS

The quantities of interest are the two and three particle rapidity correlation functions:

$$R_2(y_1, y_2) = \frac{(1, 2) - (1)(2)}{(1)(2)} \quad (1a)$$

$$R_3(y_1, y_2, y_3) = \frac{(1, 2, 3) - (1, 2)(3) - (1, 3)(2) - (2, 3)(1) + 2(1)(2)(3)}{(1)(2)(3)} \quad (2b)$$

The notations are self-explanatory:

$$(i) = \frac{d\sigma}{\sigma_{in} dy_i}, \quad (i, k) = \frac{d^2\sigma}{\sigma_{in} dy_i dy_k}, \quad (i, k, l) = \frac{d^3\sigma}{\sigma_{in} dy_i dy_k dy_l}$$

The following equations relate the correlation functions R_n^A and R_n^N for the production on nuclei and nucleons, respectively:

$$R_2^A(y_1, y_2) = \frac{\langle v^2 \rangle - \langle v \rangle^2}{\langle v \rangle^2} + \frac{R_2^N(y_1, y_2)}{\langle v \rangle} \quad (2a)$$

$$R_3^A(y_1, y_2, y_3) = \frac{\langle v^3 \rangle - 3\langle v^2 \rangle \langle v \rangle + 2\langle v \rangle^3}{\langle v \rangle^3} + \quad (2b)$$

$$+ \frac{R_3^N(y_1, y_2, y_3)}{\langle v \rangle^2} + \frac{\langle v^2 \rangle - \langle v \rangle^2}{\langle v \rangle^3} (R_2^N(y_1, y_2) + R_2^N(y_2, y_3) + R_2^N(y_1, y_3))$$

Here v stands for the number of inelastic collisions of the incident fast hadron with the nucleons of the nucleus (see Fig. 1b for a demonstration). These equations can easily be derived following Ref. 13). Indeed, the single particle inclusive spectrum is, evidently, proportional to $\langle v \rangle$, while the two particle spectrum is proportional to $\langle v^2 \rangle$. One has also to account for the correlations R_2^N when both particles are produced in the same collision. Thus one obtains

$$\frac{d^2\sigma_v}{dy_1 dy_2} = (v^2 + v R_2^N(y_1, y_2)) C^2 \sigma_v$$

Here

$$C = \frac{d\sigma^N}{\sigma_{in}^N dy}$$

is the height of the pionization plateau^{*)}. This results in

^{*)} Hereafter, we consider only the pionization region.

$$\sigma_{in} = \sum_v \sigma_v$$

$$(i) = \frac{d\sigma}{\sigma_{in} dy_i} = \frac{C \sum_v \sigma_v}{\sum_v \sigma_v} = C \langle v \rangle$$

$$(i,k) = \frac{d^2\sigma}{\sigma_{in} dy_i dy_k} = \frac{C^2 \sum_v (v^2 \sigma_v + v R_2^N(y_1, y_2) \sigma_v)}{\sum_v \sigma_v} = \quad (3)$$

$$= C^2 (\langle v \rangle^2 + \langle v \rangle R_2^N(y_1, y_2))$$

Substituting these relations into Eq. (1a) one gets Eq. (2a).

The most interesting quantity is the long range piece;

$$\Delta R_2 = \frac{\langle v^2 \rangle - \langle v \rangle^2}{\langle v \rangle^2} = \text{const}(y_i, y_k)$$

of the correlation function. It is sensitive to the v distribution and, consequently to the parton structure of the projectile. The different models differ drastically in their consequences for ΔR_2 .

i) SPM. Here one has $v = 1$ and $\Delta R_2 = 0$. Indeed, the single ladder initial state corresponds, in the reggeon field theory language, to the dominance of the diagrams of Fig. 2c with the rapidity y_c independent of the energy: $y_c - y_A \sim 1/3 \ln A$ ¹³⁾. As a result, the projectile fragmentation, the pionization spectra and the corresponding correlations as well, should be target independent.

ii) QEM. It is convenient to use an impact parameter representation. Then one has:

$$\sigma_{in} = \int d^2\vec{b} (1 - \exp(-\sigma_{hN}^{in} T(\vec{b}))) \quad (4)$$

and

$$\langle v \rangle = \frac{1}{\sigma_{in}} \int d^2\vec{b} \sigma_{hN}^{in} T(\vec{b}) \quad (5)$$

$$\langle v^2 \rangle = \frac{1}{\sigma_{in}} \int d^2 \vec{b} \left\{ [\sigma_{hN}^{in} T(\vec{b})]^2 + \sigma_{hN}^{in} T(\vec{b}) \right\} \quad (5)$$

Here

$$T(\vec{b}) = \int dz \frac{d^2 \vec{b}'}{2\pi B} \rho(z, \vec{b}') \exp \left[-(\vec{b} - \vec{b}')^2 / 2B \right]$$

where B is the slope of the diffraction slope, $d\sigma_{hN}^{el}/dt \sim \exp[Bt]$, and $\rho(z, \vec{b})$ is density of the nuclear matter,

$$\int dz d^2 \vec{b} \rho(z, \vec{b}) = A$$

A few explanatory notes are in order. Equation (4) implies that, at the fixed impact parameter $\vec{b}$, the v distribution obeys the Poisson law with $\langle v(\vec{b}) \rangle = \sigma_{hN}^{in} T(\vec{b})$. This results in

$$\langle v(\vec{b})^2 \rangle = \langle v(\vec{b}) \rangle^2 + \langle v(\vec{b}) \rangle = [\sigma_{hN}^{in} T(\vec{b})]^2 + \sigma_{hN}^{in} T(\vec{b})$$

The same results follow from the AGK cutting rules¹⁴⁾ when applied to the non-enhanced diagrams of Fig. 2a: the $[\sigma_{hN}^{in} T(\vec{b})]^2$ and $\sigma_{hN}^{in} T(\vec{b})$ terms correspond to the contributions of the diagrams of Fig. 2b and Fig. 2c, respectively.

The expected A dependence of ΔR_2 is as follows. For the light nuclei one can use the Gaussian parametrization, $\rho(r) \approx \exp(-r^2/R_A^2)$, where $R_A = r_0 A^{1/3}$. In this case $T(b) \sim A^{1/3} \exp[-r^2/R_A^2]$ and vanishes only at $b \geq A^{1/3} (\ln A)^{1/2}$. This results in $\sigma_{in} \sim A^{2/3} \ln A$, while $d\sigma/dy \sim A$ and $d\sigma/dy, dy_2 \sim A^{4/3}$, so that $\Delta R_2 \sim \ln A$. For the heavy nuclei the sharp edged black disk model is the more appropriate one. Here one gets $\Delta R_2 = 1/8 = \text{const}(A)$.

The numerical results for the realistic nuclei, obtained using the parametrization^{15),*)}

$$\rho(r) = \rho_0 / (ch(R_A/d) + ch(r/d)) \quad (6)$$

*) More sophisticated parametrizations for a specific nuclei result, within an accuracy of 0.01 or better, in the same values of ΔR_2 and ΔR_3 .

where $d = 0.6 F$, $R_A = 1.1 \cdot A^{1/3} F$, are presented in Fig. 3. For the light and intermediate, $A \leq 30$, nuclei ΔR_2 follows the $\ln(A)$ dependence, then flattens at $\Delta R_2 \approx 0.4$ and even starts to decrease for the heaviest nuclei, like Sn - Pb (see Fig. 3). As regards $\langle v \rangle$, it has practically linear dependence on $A^{1/3}$.

iii) AQM. For the meson-nucleus collisions cross-sections of one or two MPL production processes are given by equations:

$$\begin{aligned} \sigma_1 &= \int d^2 \vec{b} \ 2 \{ 1 - \exp[-\sigma_{qN}^{\text{in}} T(\vec{b})] \} \exp[-\sigma_{qN}^{\text{in}} T(\vec{b})] \\ \sigma_2 &= \int d^2 \vec{b} \ \{ 1 - \exp[-\sigma_{qN}^{\text{in}} T(\vec{b})] \}^2 \end{aligned} \quad (7)$$

Here the factor $\exp[-\sigma_{qN}^{\text{in}} T(b)]$ corresponds to the probability for quarks to cross the nucleus without absorption, while the factor $\{1 - \exp[-\sigma_{qN}^{\text{in}} T(b)]\}$ describes the probability of interaction with the production of MPL. The values of $\langle v \rangle$ and ΔR_2 can easily be calculated:

$$\langle v \rangle = \frac{\sigma_1 + 2\sigma_2}{\sigma_1 + \sigma_2} \quad ; \quad \Delta R_2 = \frac{\sigma_1 \sigma_2}{(\sigma_1 + 2\sigma_2)^2} \quad (8)$$

The values of $\langle v \rangle$ and ΔR_2 for the proton-nucleus collisions can be calculated in a similar way. It turns out that in the AQM ΔR_2 has only weak A dependence: $\Delta R_2^{\pi A} \approx 0.1$; $\Delta R_2^{pA} \approx 0.18$.

Different models result in drastically different predictions for ΔR_2 . However, this quantity can not be measured directly. For a comparison with the data one has to include the term $\Delta R_2^N(y_1, y_2)/\langle v \rangle$ in Eq. (2a). Charged-charged rapidity correlations, $R_N^{\text{ch, ch}}(y_1, y_2)$, are rather strong: $R_N^{\text{ch, ch}}(y_1, y_2) \approx 0.6$ for all hN interactions¹⁶⁾. As a consequence, A dependent variations in ΔR_2 and $R_N^{\text{ch, ch}}(y_1, y_2)/\langle v \rangle$ tend to cancel each other, thus bringing the predictions of the QEM and the AQM closer to each other. Influence of the R_2^N dependent term can be diminished, choosing "plus-plus" and/or "minus-minus" combinations. The corresponding correlations are weaker, $R_N^{++}(y_1, y_2) \approx 0.23$, $R_N^{--}(y_1, y_2) \approx 0.35$ ¹⁶⁾, and the differences between the AQM and the QEM predictions for the corresponding correlation turn out to be much larger (see Fig. 3). We recall that the ΔR_2 term is universal for all the charge combinations.

Unfortunately, as yet there have been no high statistics experiments to measure the correlations for the nuclear targets. The only data available are those from emulsion experiments [see review in Ref. 17)]. The values of $R_{\pi\text{Em}}^{\text{ch, ch}}(0,0)$ ¹⁸⁾ and of $R_{p\text{Em}}^{\text{ch, ch}}(0,0)$ ¹⁹⁾ are plotted in Fig. 3. They agree better with the AQM predictions, but still this agreement cannot be taken as conclusive.

Let us turn now to a consideration of the three particle correlation function $R_2^A(0,0,0)$. Equation (2b) can be rewritten as follows:

$$\begin{aligned} R_3^A(0,0,0) &= \Delta R_3 + 3 \frac{\Delta R_2}{\langle v \rangle} R_2^N(0,0) + \frac{R_3^N(0,0,0)}{\langle v \rangle^2} = \\ &= \Delta R_3 + K_{23} R_2^N(0,0) + K_{33} R_3^N(0,0,0) \end{aligned} \quad (9)$$

The AQM and QEM predictions for ΔR_3 and K_{23} are presented in Fig. 4.

The only experimental data on three particle correlations available so far are those of Ref. 20) for π^-p interactions at 200 GeV. The measured correlations were found to be rather weak: $R_{\pi^-N}^{+-}(0,0,0) = 0.26 \pm 0.07$, $R_{\pi^-N}^{--}(0,0,0) = 0.01 \pm 0.06$. If so, the $R_3^N(0,0,0)/\langle v \rangle^2$ term is small compared to other contributions in Eq. (9). In Fig. 5 we display predicted values of $R_A^{+-}(0,0,0)$ and $R_A^{--}(0,0,0)$, using for π^-A interactions as an input, the above values of $R_{\pi^-N}^{+-}(0,0,0)$ and $R_{\pi^-N}^{--}(0,0,0)$, and neglecting, in the case of pA interactions, the $R_3^{pN}(0,0,0)/\langle v \rangle^2$ terms altogether. It turns out that three particle correlations are much more sensitive to the production model than two particle correlations are. The QEM leads to $R_3^A(0,0,0)$ which is approximately 0.4 larger than the AQM. According to the preliminary results of the recent analysis of π^-C interactions at 40 GeV (Alma-Ata et al. collaboration, private communication of G.V. Grishin), $R_C^{--}(0,0,0)$ is consistent with zero within ± 0.08 error bars. This is another piece of evidence for the AQM.

To conclude this section, we emphasize that the finite energy effects are important only in the projectile fragmentation region, and do not influence the correlation functions in the central region.

3. NUCLEUS SIZE DEPENDENCE OF THE MULTIPLICITY DISTRIBUTIONS

For ν independent production processes one has, in obvious notations,

$$\begin{aligned} \langle N(\nu) \rangle &= \nu \langle N(1) \rangle \\ D^2(\nu) &= \langle N(\nu)^2 \rangle - \langle N(\nu) \rangle^2 = \nu D^2(1) \end{aligned} \quad (10a)$$

Once allowance is made for the fluctuations of ν , one obtains:

$$\begin{aligned} \langle N \rangle &= \langle \nu \rangle \langle N(1) \rangle \\ D^2 &= (\langle \nu \rangle^2 - \langle \nu \rangle^2) \langle N(1) \rangle^2 + \langle \nu \rangle D^2(1) \end{aligned} \quad (10b)$$

This results in the relation [compare with Eq. (2a)]

$$\left(\frac{D}{\langle N \rangle} \right)_A^2 = \frac{\langle \nu \rangle^2 - \langle \nu \rangle^2}{\langle \nu \rangle^2} + \frac{1}{\langle \nu \rangle} \left(\frac{D}{\langle N \rangle} \right)_N^2 \quad (11)$$

between the Wroblewski's ratios $D/\langle N \rangle$ for the production on nuclei and nucleons. An alternative derivation of Eq. (11), based on considerations of the relationship between the $D/\langle N \rangle$ and long range correlations, is given in Ref. 21).

The resulting predictions for the A dependence of $(D/\langle N \rangle)_A$, taking as an input $(D/\langle N \rangle)_N = 0.5$, are presented in Fig. 6. The data on 37.5 GeV π^-A interactions are also shown for a comparison²²⁾. They are in better agreement with the AQM. Weak A dependence of $D/\langle N \rangle$ was observed also in earlier emulsion experiments¹⁷⁾ and in Ref. 23).

We would like to emphasize, that for $\nu > 1$ the reduction of the multiplicity in the projectile fragmentation region owing to finite energy effects is compensated for by the cascading. Therefore, the finite energy effects in $(D/\langle N \rangle)_A^2$ are expected to be negligible. Indeed, the data of Refs 22) and 23) taken together with the emulsion data¹⁷⁾, show no energy dependence of $(D/\langle N \rangle)_A^2$ in the energy range from 20 GeV to 400 GeV.

4. AZIMUTHAL CORRELATIONS

Azimuthal correlations are of particular interest since they are free of correlations induced by the production of particles in different collisions, which we have found to be very important in the rapidity correlations. For the production processes described by diagrams of Fig. 2b the azimuthal correlations are very weak, of the order of $1/\langle \vec{q}_t^2 \rangle R_A^2$, where $\langle \vec{q}_t^2 \rangle$ is the mean of the square of the transverse momentum of the secondary particles, and R_A is the radius of the nucleus. To demonstrate this one should simply repeat the general arguments of Ref. 24). The dependence on the relative angle ϕ between $\vec{q}_{1t}$ and $\vec{q}_{2t}$ can result only after the integration over the loop momentum $\vec{k}$ of terms like $((\vec{q}_{1t} \vec{k})/\vec{q}_1^2) \cdot ((\vec{q}_{2t} \vec{k})/\vec{q}_2^2)$. Here each factor corresponds to the emission of the particle by the respective pomeron. Taking into account that $(k_t) \leq 1/R_A$, we arrive at the small azimuthal correlation of the order of $1/\langle \vec{q}_t^2 \rangle R_A^2$, if any. Neglecting this small contribution, we obtain

$$R_\varphi^A = R_\varphi^N / \langle \nu \rangle \quad (12)$$

Moreover, in Ref. 24) the contribution of the processes of Fig. 2b to the integral azimuthal asymmetry,

$$A_\varphi = \frac{N(\varphi > 90^\circ) - N(\varphi < 90^\circ)}{N(\varphi > 90^\circ) + N(\varphi < 90^\circ)}$$

was proven to vanish altogether, so that the integral version of Eq. (12),

$$A_\varphi^A = A_\varphi^N / \langle \nu \rangle \quad (12a)$$

should hold rigorously in all the production models incorporating short range order in rapidities inside the MPL's.

Once A_φ^N is known, one can easily compute A_φ^A using $\langle \nu \rangle$ from Fig. 3. These simple relations would allow one to determine $\langle \nu \rangle$ in the most direct way, and, thus to test different production models.

5. TARGET NUCLEUS EXCITATION DEPENDENCE OF CORRELATIONS

The primary aim of using nuclear targets was to test ν dependence of the production process. One of the possibilities for controlling the moments of ν , considered above, is to change the size of the nucleus. One can control ν distribution for the fixed target as well. To do so one has to select events

with some fixed degree of the excitation of the target nucleus. A convenient quantity is a number n_g of the so-called grey tracks, accompanying the production process. A detailed analysis of n_g distributions and of the $v - n_g$ relationship will be presented in Ref. 21). Here, for the sake of completeness, we quote some of the results which are independent of the exact $v - n_g$ relationship. First, low multiplicities of grey tracks obviously correspond to the peripheral interactions. The relevant correlation functions should be similar to those for light nuclei and for nucleons. Second, the very large values of n_g correspond to the maximum possible values of v . A specific feature of the AQM is that possible values of v are bounded from above: $v \leq v_{\max}$, where for pions $v_{\max} = 2$, and for protons $v_{\max} = 3$. In the very large n_g events $v \approx v_{\max}$, so that $\langle v^2 \rangle \approx \langle v \rangle^2$. Therefore,

$$R_2^A(y_1, y_2) = R_2^N(y_1, y_2) / v_{\max} \quad (13)$$

and we predict the limiting value of the correlation function. In the QEM the values of v can be infinitely high, so that there should be no such limiting value of $R_2^A(y_1, y_2)$. The typical example of the expected n_g dependence of the correlation function is presented in Fig. 7 (see Ref. 21) for more details).

A few comments are in order. First, fixed values of n_g do not imply the fixed values of v as sometimes is supposed: ΔR_2 is quite sizable at low values of n_g . Second, $R_2^{\pi N}(y_1, y_2)$ and $R_2^{pN}(y_1, y_2)$ are very close to each other. As a consequence, one expects that at large values of n_g

$$R_2^{PA}(y_1, y_2) < R_2^{\pi A}(y_1, y_2) \quad (14)$$

The emulsion data¹⁷⁾⁻¹⁹⁾ plotted in Fig. 7 give firm evidence for the decrease of correlations as n_g decreases. A reasonably good, quantitative agreement is found with the AQM predictions (see Fig. 7),

CONCLUSIONS

We conclude that the measurements of two and, in particular, three particle rapidity correlations would allow one to make a crucial test of the current models for multiple production on nuclei and for the parton structure of hadrons. High accuracy counter experiments on correlations on nuclei are eagerly awaited.

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FIGURE CAPTIONS

- Fig. 1 : The particle-nucleus interactions: a) in the SPM, b) in the QEM and, c) in the AQM.
- Fig. 2 : The reggeon field theory diagrams for the particle-nucleus interactions. See text for an explanation.
- Fig. 3 : The AQM and the QEM predictions for the two particle correlations functions $R_2^A(0,0)$ in the pA and πA collisions. The data points shown are from emulsion experiments¹⁷⁾⁻¹⁹⁾.
- Fig. 4 : The AQM and the QEM predictions for the A dependence of ΔR_3 and K_{23} . See Eq. (9) for a definition.
- Fig. 5 : The AQM and the QEM predictions for the three particle correlation function $R_3^A(0,0,0)$ in pA and πA collisions as a function of $A^{1/3}$.
- Fig. 6 : The AQM and the QEM predictions for A dependence of Wroblewski ratio $(D/\langle N \rangle)_A$ versus the data of Ref. 22).
- Fig. 7 : The AQM predictions for the N_g dependence of the two particle correlation function $R_2^A(0,0)$ versus the data from emulsion experiments¹⁷⁾⁻¹⁹⁾. Also shown are N_g dependences of ΔR_2 and $\langle v \rangle$

FIG.1

FIG.2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7