УДК 539.17.015

A STUDY OF MULTIPARTICLE AZIMUTHAL CORRELATIONS IN HIGH ENERGY INTERACTIONS

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Genuine multiparticle azimuthal correlations between secondary charged particles produced in hadron-nucleon and hadron-nucleus collisions at p_0 = 200–400 GeV/c and in nucleus-nucleus collisions at p_0 = (2.5–4.5)A GeV/c have been studied using a new formalism. These correlations are observed for all types of charged secondaries and in all types of interactions. The meaning of obtained results and capabilities of suggested technique are also discussed at a semi-quantitative level.

The investigation has been performed at the Laboratory of High Energies, JINR.

Изучение многочастичных азимутальных корреляций в соударениях с большой энергией

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С помощью нового формализма изучались истинные многочастичные азимутальные корреляции между вторичными заряженными частицами в адрон-нуклонных и адрон-ядерных соударениях при p_0 = 200–400 ГэВ/с и в ядро-ядерных соударениях при p_0 = (2,5–4,5)A ГэВ/с. Такие корреляции обнаружены для всех типов вторичных заряженных частиц и всех типов взаимодействий. На полуколичественном уровне обсуждены значимость полученных результатов и возможности предложенной техники анализа.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

1. Introduction

The necessity of studying the correlation and fluctuation properties of secondary particles created in multiple particle production reactions at high energies arises from the fact that their simplest characteristics, such as multiplicities or one-particle distributions, reveal a low sensitivity to the choice between various theoretical approaches to the theory of strong interactions. This topic has become very popular, mainly due to the advances that have recently been made in understanding the internal dynamics of multiparticle processes. This has come about with the analysis of various kinds of correlations and fluctuations [1] and also because of its obvious relation with the very important problem of the search for and study of the new hypothetical collective phenomena in particle and nuclear physics.

Correlations between «longitudinal» characteristics (such as rapidities, pseudorapidities, etc.) of secondary particles are considered most often in theoretical and experimental works devoted to this problem. At the same time, the study of azimuthal correlations has a great advantage in that they do not depend on strong pseudocorrelation effects caused by nonuniformity of the events forming the inclusive or semi-inclusive sets under study [2].

Strictly speaking, at present, only the production of resonances, quantum effects associated with the identity of particle, and jets arising in hard QCD processes are well-established dynamic factors that lead to correlations among particles produced in multiple processes. At the same time, although a number of additional interesting physical phenomena have long been discussed in the literature, the questions concerning the existence and properties of these effects remain unanswered. Among them, for instance, «heavy» unstable intermediate objects (that cannot be reduced to known resonances), effects of a «collective flow» type and some other collective properties of quark-gluon, hadron or nuclear matter may be mentioned. One of the reasons behind this situation is that the number of works devoted to the search for genuine multiparticle correlations is obviously unsufficient.

In this report, we present the first results obtained by applying some general methods for analyzing genuine multiparticle azimuthal correlations between secondary particles from hadron-nucleon (*hN*), hadron-nucleus (*hA*) and nucleus-nucleus (*AA*) collisions at high energies. We will not be concerned with the usual two-particle azimuthal correlations based on the relative azimuthal angles

$$\varepsilon_{ij} = \arccos\,(\mathbf{p}_{T_i}\mathbf{p}_{T_j}/p_{T_i}p_{T_j}) = \arccos\,(\varphi_i - \varphi_j)$$

(here $\mathbf{p}_T$ and φ are the transverse momentum and azimuthal angle of the particle, respectively) and their characteristics, nor with the so-called global variables of the events (such as sphericity, coplanarity, directivity, etc.) that give only indirect information on the character of azimuthal correlations between the particles. Tests of the above-mentioned methods show that they may turn out to be an efficient tool for studying final multiparticle states of multiple production reactions and nuclear multifragmentation at high energies.

2. Methodological Aspects

Recently, the following random variables characterizing the azimuthal correlations of arbitrary order were suggested:

(i) the minimum length of the azimuthal interval containing an arbitrary number $k(2 \leq k \leq n)$ of ordered azimuthal angles, i.e., the differences (or «spacings») [3,4]

$$\psi_{k-1}^{(n)} = \begin{cases} \varphi_{i+k-1} - \varphi_i, & 1 \leq i \leq n-k+1, \\ 2\pi + \varphi_{i+k-1-n} - \varphi_i, & n-k+1 < i \leq n \end{cases} \tag{2}$$

of the order $(k - 1)$;

(ii) the dispersion of the φ-distribution of the same subgroups of charged particles [5,4]

$$\sigma_k^{(n)^2} = \begin{cases} \sum\limits_{l=i}^{i+k-1} (\varphi_l - \overline{\varphi}_k^{(n)})^2/(k-1), & 1 \le i \le n-k+1, \\ [\sum\limits_{l=i}^{n} (\varphi_l - \overline{\varphi}_k^{(n)})^2 + \\ + \sum\limits_{l=1}^{i+k-1-n} (2\pi + \varphi_l - \overline{\varphi}_k^{(n)})^2]/(k-1), & n-k+1 < i \le n \end{cases} \quad (3)$$

where $\overline{\varphi}_k^{(n)} = \sum\limits_{l=i}^{i+k-1} \varphi_l/k,$ etc. The second terms in Eq.(2) and Eq.(3) are introduced for symmetrization over the full azimuthal circle;

(iii) the geometric average of the relative angles (Eq.(1)) for the subgroups containing k nonordered particles [6,7]

$$\varepsilon_k^{(n)} = \left(\prod_{i<j}^{M} \varepsilon_{ij} \right)^{1/M}, \quad M = k(k-1)/2. \quad (4)$$

All the statistical characteristics of the mentioned variables can be found for independent emission of the particles (or in zero approximation, when all correlations are absent). For instance, for the first of them, $\psi_{k-1}^{(n)}$ [3]: the distribution density is

$$f(\psi_{k-1}^{(n)}) = (2\pi)^{1-n} \frac{(n-1)!}{(k-1)!\,(n-k-1)!} \psi^{k-1}(2\pi - \psi)^{n-k-1},$$

the moment generating function is

$$m(t) = \Phi(k, n, 2\pi t)$$

(where Φ is the hypergeometric function), and the moments of arbitrary order r are

$$\nu_r = \left.\frac{d^r m(t)}{dt^r}\right|_{t=0} = (2\pi)^r \frac{(k+r-1)!\,(n-1)!}{(k-1)!\,(n+r-1)!}.$$

The simplest of the moments are: a) the expectation value

$$\langle \psi_{k-1}^{(n)} \rangle = \nu_1 = 2\pi(k-1)/n \quad (5)$$

and b) the standard deviation of the $\psi_{k-1}^{(n)}$-distribution

$$\sigma_0(\psi_{k-1}^{(n)}) \equiv (\nu_2 - \nu_1^2)^{1/2} = (2\pi/n)\left[\frac{k(n-k)}{n+1}\right]^{1/2}. \quad (6)$$

Eq.(5) is trivial because we have $\sum (\psi_{k-1}^{(n)}) = 2(k-1)\pi$ in any case. $\sigma(\psi_{k-1}^{(n)})$ can be used, however, as a measure of multiparticle azimuthal correlations since any deviation from the value given by Eq.(6) means that the statistical independence of the angles φ has been violated, i.e., there are correlations between them. The zero approximation expectation value and standard deviation of the second variable, $\sigma_k^{(n)^2}$, are equal to

$$\langle \sigma_k^{(n)^2} \rangle = \pi^2(k+1)(k+2)/[3n(n+1)] \quad (7)$$

and

$$\sigma_0(\sigma_k^{(n)^2}) = (\pi^2/3)\left[\frac{(k+1)(k+2)}{k(k-1)\,n(n+1)} \times \right.$$

$$\left. \times \left(\frac{(k+3)(k+4)(5k^2-k+6)}{5(n+2)(n+3)} - \frac{(k-1)k(k+1)(k+2)}{n(n+1)}\right)\right]^{1/2}, \quad (8)$$

respectively [5], etc.

The formulas presented above are written for fixed n. They can be easily generalized for inclusive sets of events by using normalized quantities. For example, instead of $\psi_{k-1}^{(n)}$, we considered

$$\Phi_{k-1}^{(n)} = (\psi_{k-1}^{(n)} - \langle \psi_{k-1}^{(n)} \rangle)/\sigma(\psi_{k-1}^{(n)}). \quad (9)$$

The expectation value and standard deviation of $\Phi_{k-1}^{(n)}$ are exactly equal to 0 and 1, respectively, in the case of the independent emission of the particles under study. Therefore, any deviations from these values mean the existence of some kind of correlation.

3. Experimental Data and Results

As a first approbation of the above methodology, we carried out a search for multiparticle azimuthal correlations in six inlcusive sets of hadron-nucleon (hN) and hadron-nucleus (hA) collisions at primary momenta of 200 and 400 GeV/c and in four sets of nucleus-nucleus interactions at primary momenta of 2.5—4.5 GeV/c per nucleon. All the experiments were carried out under identical conditions with the help of the emulsion technique. The data on the statistics of the events in these sets are presented in the Table below, which also gives references to the papers containing detailed information on the

Table

Projectile	Target	p_0/A, GeV/c	Accelerator	Numb. of events	Refs.
p	N	200	Fermilab.	1293	[8]
p	Em	200	Fermilab.	1626	[8]
π^-	N	200	Fermilab.	1397	[9]
π^-	Em	200	Fermilab.	5116	[9]
p	N	400	Fermilab.	1061	[10]
p	Em	400	Fermilab.	3484	[11]
^{12}C	Em	4.4	JINR	1717	[12]
^{14}N	Em	2.9	LBNL	1027	[13]
^{22}Ne	Em	4.1	JINR	4070	[14]
^{56}Fe	Em	2.5	LBNL	1890	[15]

experimental conditions and various general characteristics of the events (multiplicities, single-particle distributions, etc.).

A search for multiparticle correlations was carried out for relativistic charged (s) particles from hN and hA collisions and for all types of charged secondaries — shower (s), «gray» (g) and «black» (b) particles from nucleus-nucleus interactions. Division of the charged particles into mentioned types was made according to usual emulsion criteria.

3.1. hN and hA Collisions at p_0 = 200–400 *GeV/c*. Figure 1 shows, as an example, the values of the standard deviation $\sigma(\psi^{(n)}_{k-1})$ of the distribution in the normalized minimum length of the interval containing k neighbouring (with respect to the azimuth) secondary relativistic charged particles produced in hN and hA collisions at 200 and 400 GeV/c. Here and below we only use the first of above methods, because the application of others gives the same results.

The next necessary step in the correlation analysis is to quantitatively take into account trivial kinematic correlations that are due to the effects of conservation laws. For this purpose we generated inclusive ensembles of random events following the phasespace (PS) model, taking into account the presence of neutral secondary particles. Their number, n_0, was simulated for each n = 2, 4,... in accordance with the available experimental data on neutral particle production (including strange ones) in pp collisions at E_0 = 200–400 GeV.

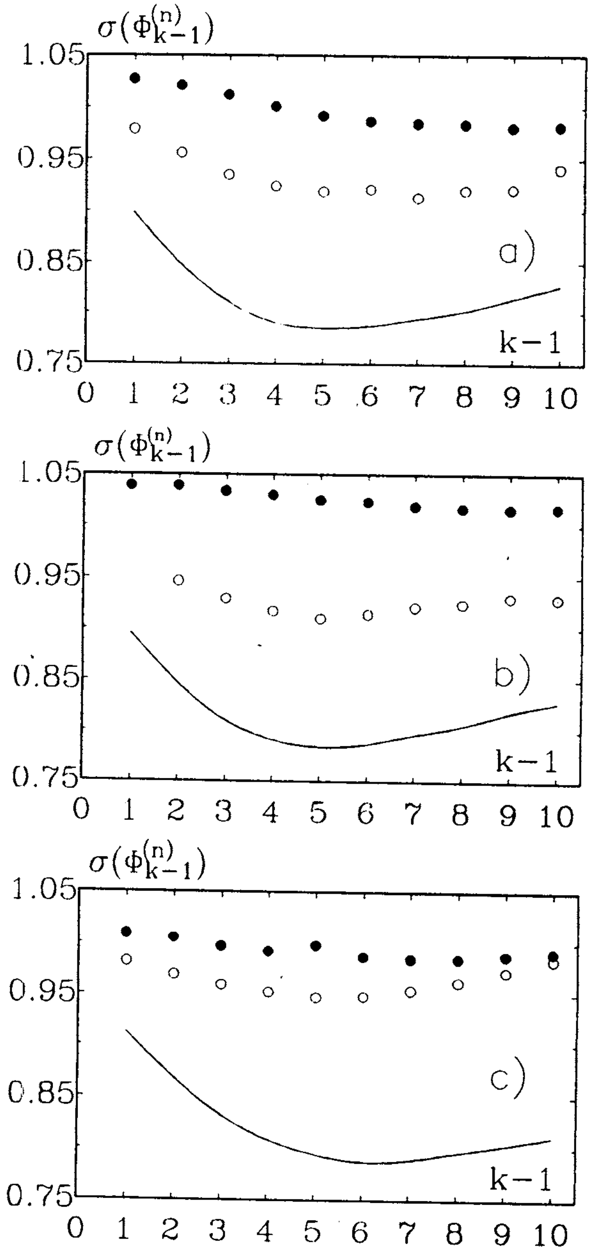


Fig.1. The $\sigma(\Phi^{(n)}_{k-1})$ *vs.* k for hN (open circles) and hA (full circles) collisions: a) pN and pA at 200 GeV/c, b) π^-N and π^-A at 200 GeV/c, c) pN and pA at 400 GeV/c. The curves are calculated for hN collisions according to the phasespace model

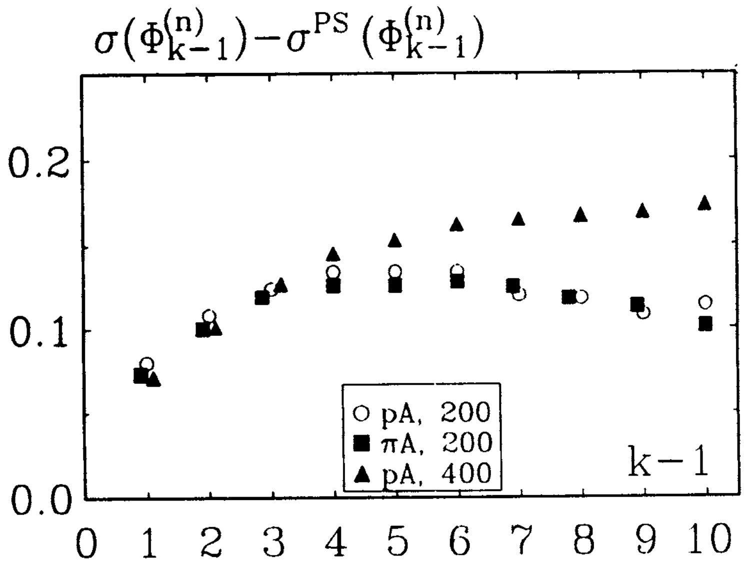


Fig.2. The differences of $\sigma(\Phi_{k-1}^{(n)}) - \sigma^{PS}(\Phi_{k-1}^{(n)})$ *vs.* k for hN collisions at 200—400 GeV/c

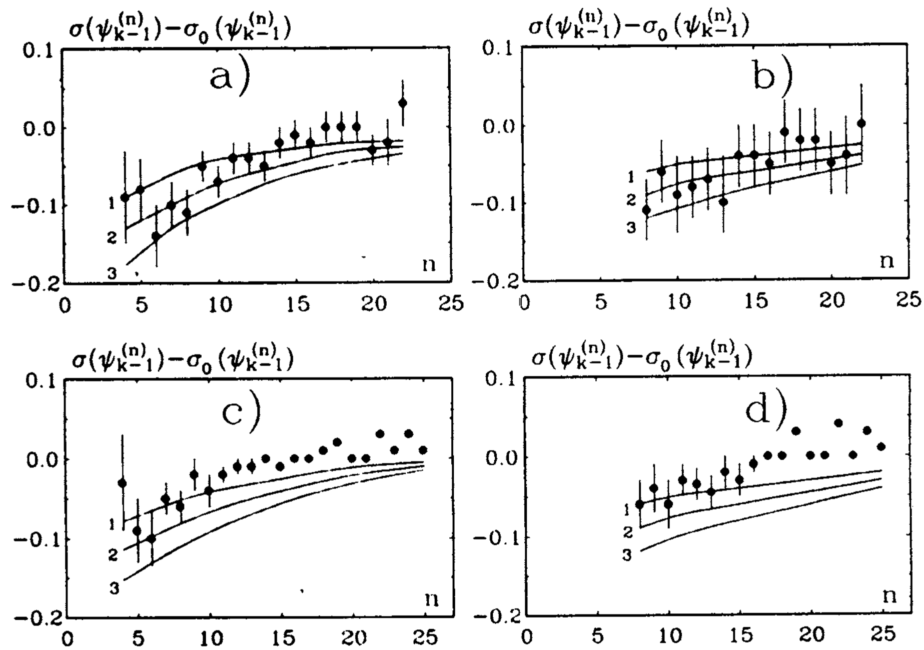
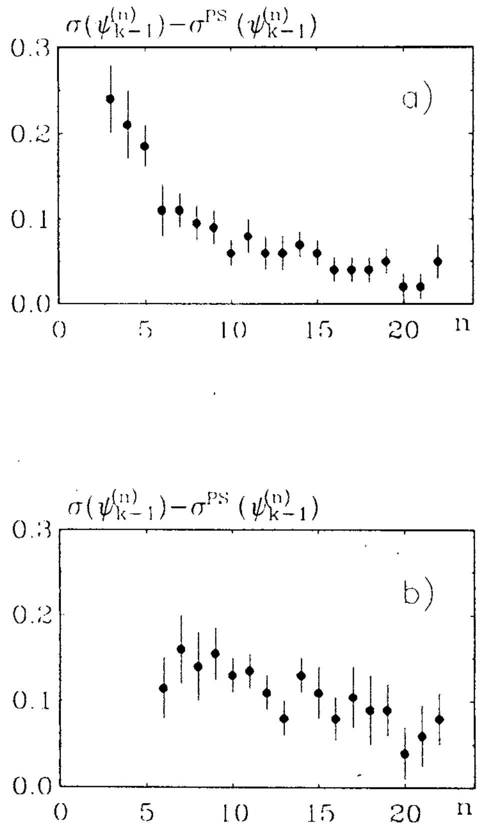


Fig.3. The differences of $\sigma(\psi_{k-1}^{(n)}) - \sigma_0(\psi_{k-1}^{(n)})$ *vs.* n in comparison with the results (curves) of calculations according to the model with two-particle resonances for the fraction (1) 50, (2) 75, and (3) 100% of secondaries produced in their decays. The examples are given: for hN collisions at $k = 4$ (a) and 6 (b); and for hA collisions at $k = 4$ (c) and 6 (d)

Fig.4. The differences of $(\psi^{(n)}_{k-1}) - \sigma^{PS}(\psi^{(n)}_{k-1})$ *vs.* n at $k = 3$ (a) and $k = 5$ (b) for pN collisions at 200—400 GeV/c



The charged particle multiplicity spectra for the real and simulated ensembles were exactly the same. The values of $\sigma(\Phi^{(n)}_{k-1})$ calculated in the *PS* model for *hN* collisions are shown by solid curves in Fig.1. Figure 2 presents the differences between $\sigma(\Phi^{(n)}_{k-1})$ in real and Monte Carlo ensembles of *hN* collisions *vs.* k of the correlations. The following conclusions can be drawn from the inclusive data displayed in Figs.1, 2:

(i) There are genuine multiparticle azimuthal correlations of non-kinematic origin in *hN* collisions at 200—400 GeV/c;

(ii) These correlations are different for *hN* and *hA* interactions;

(iii) They do not depend on the type of primary hadron but depend on the primary momentum;

(iv) The «strength» of the correlations increases at first with increasing k and then reaches a maximum value at a value of k which depends on primary momentum.

Let us consider the semi-inclusive data. For simplicity, we combined events with fixed n from all the ensembles of *hN* collisions (*pN*, 200 GeV/c + $\pi^- N$, 200 GeV/c + *pN*, 400 GeV/c) as well as from the ensembles of *hA* collisions. All the results of our analysis turned out to be a *posteriori* independent of this unification. Examples of these data are presented in Fig.3; it should be noted that we used non-normalized quantities of $\psi^{(n)}_{k-1}$ in the semi-inclusive case.

Finally, Fig.4 shows the differences $\sigma(\psi^{(n)}_{k-1}) - \sigma^{PS}(\psi^{(n)}_{k-1})$ for *hN* collisions at $k = 3$ and 5. One can see that the correlations in actual events differ from those caused by kinematic law for all values of n up to the maximum values. We note that, at large n, the existence of the dynamical correlations is manifested only for high-order correlations and, apparently, was never observed before. It is important to note, also, that the correlations for the same n are different for *hN* and *hA* collisions. This makes it possible to conclude that purely collective models of particle production in *hA* collisions are inadequate in the energy range under consideration.

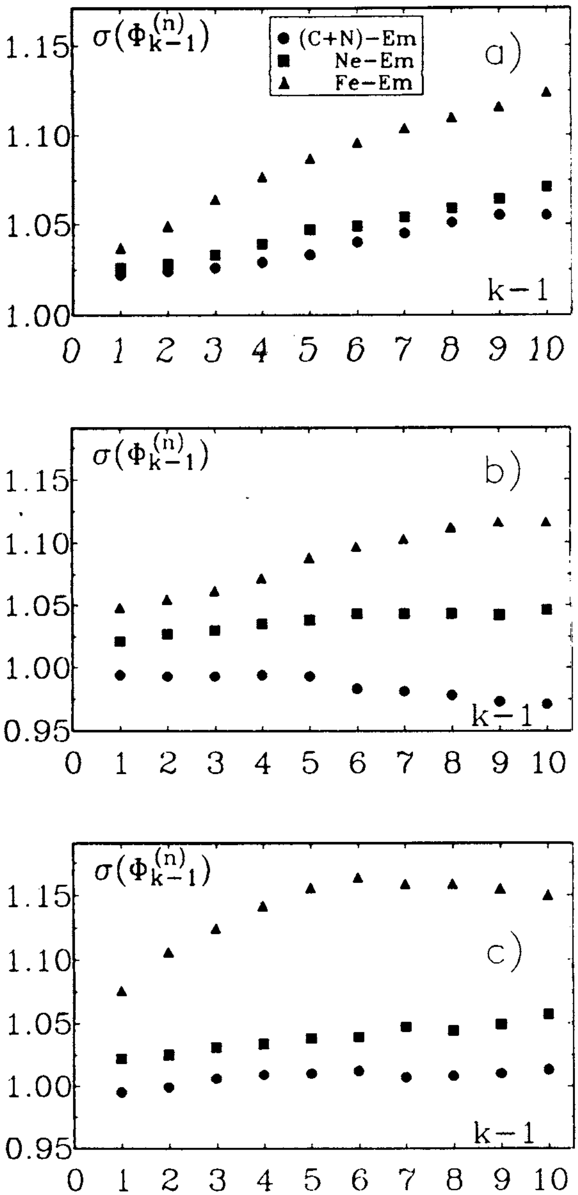


Fig.5. The $\sigma(\Phi_{k-1}^{(n)})$ *vs.* k for s-particles (a), g-particles (b) and b-particles (c) from *nucleus-nucleus collisions*. The spectator fragments of projectile nuclei are excluded from relativistic secondaries

The production of a large *number of resonances* (ρ, Δ, f, *etc.*) is a well-established fact and it is one of the widely discussed physical mechanisms that can generate correlations between secondaries. According to various estimates, the number of particles produced in the decays of these resonances can be as large as 50—90% of their total number.

We considered the behaviour of the suggested characteristics of multiparticle correlations in the production of particles via the decays of two-particle resonances. It was shown that, for all k, these characteristics are sensitive to this phenomenon; so, the study of multiparticle correlations is a direct way to obtain answers to the questions concerning the existence of «heavy» intermediate objects that cannot be reduced to known resonances. It should be emphasized that preference should be given to the study of high-order correlations. An example of such analysis of the experimental data is shown in Fig.3.

We can state that the model with resonances can qualitatively describe the data for $n_s \leq 15$ if the fraction of the resonances is taken to be 50—75% for hN collisions and $\leq 50\%$ for hA collisions. This model cannot, however, describe the data for larger n_s and the inclusive data of Fig.2, especially the difference between the 200 and 400 GeV data.

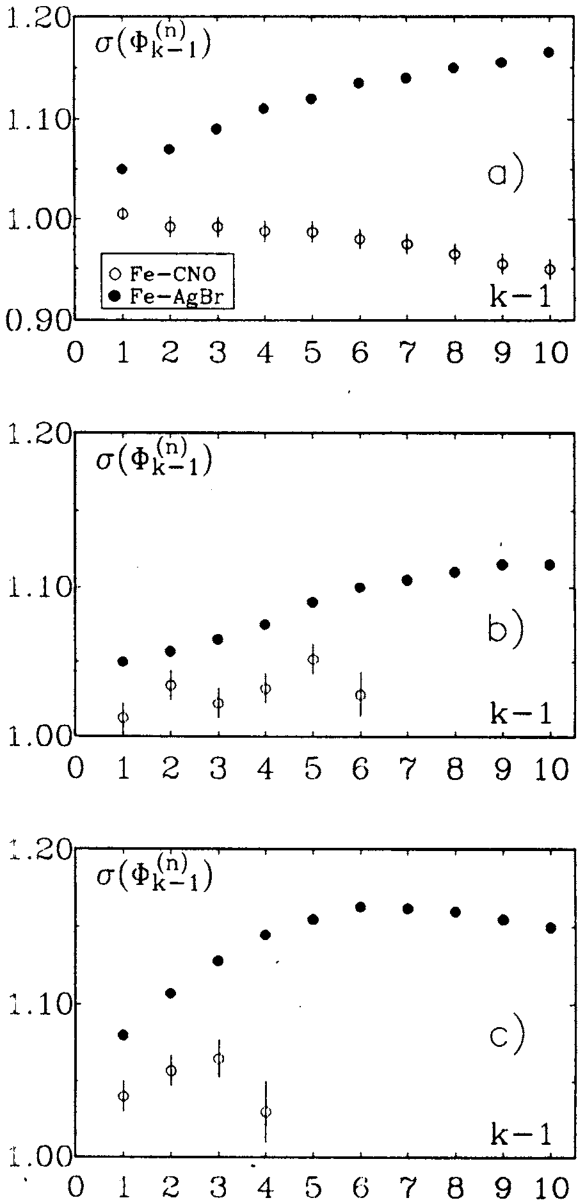


Fig.6. The same as in Fig.5 for Fe—CNO (open circles) and Fe—AgBr (full circles) collisions at 2.5 GeV/c per nucleon

Of course, we should not attach much importance to our conclusions at this point, because we only want to illustrate the capabilities of this new technique, based on the analysis of multiparticle correlations, and to present some qualitative estimates. We hope that we succeeded in doing this to a certain extent.

3.2. Nucleus-Nucleus Collisions at p_0 = (2.5–4.5)*A GeV/c*. Finally, we would like to present briefly a preliminary analysis of the data on multiparticle azimuthal correlations in the nucleus-nucleus interactions at the energies realized at the Dubna and Bevalac accelerators (see the Table above). Typical examples of the dependences of $\sigma(\Phi^{(n)}_{k-1})$ on *k* for all types of charged secondaries are presented in Fig.5. The data for ^{12}C and ^{14}N projectiles were combined; this unification is justified both a *priori* and a *posteriori*.

The following conclusions can be drawn:

(i) There are genuine multiparticle azimuthal correlations among all the types of charged secondaries from nucleus-nucleus collisions (except, may be, for target fragments from the collisions of light projectiles);

(ii) The «strength» of the correlations increases with increasing *k*, although this effect depends on the type of secondary particles and on some characteristics of nucleus-nucleus collisions;

(iii) The observed correlations depend on the atomic numbers of the projectile (see Fig.5) and target nuclei (see Fig.6): the larger the A_{proj} (or A_{target}), the stronger the correlations;

(iv) They also depend on the impact parameter of the nucleus-nucleus collisions (not illustrated): the larger the «centrality», the stronger the correlations;

(v) There is evidence of prompt connections between the observed multiparticle azimuthal correlations and the widely discussed effects of collective flow («bounce off», «splash-side», «squeeze-out», etc.) in nucleus-nucleus collisions. Therefore, the suggested and discussed methodology is of great interest in the search for and study of such phenomena;

(vi) The semi-inclusive analysis showed, in addition, that the data are in agreement with the picture of independent emission of *s*-particles at $n_s \geq 6$—8. Besides, for any fixed n_s

$$\text{correlations}\,(AA) < \text{correlations}\,(hA) < \text{correlations}\,(hN).$$

Therefore, all the purely collective mechanisms of particle production (the simplest versions of hydrodynamical theory, the so-called «collective tube» model, etc.) in nuclear collisions are inconsistent with the experimental data at the energies under study.

In conclusion, the most general result of this work can be stated as follows: the study of multiparticle azimuthal correlations is a very powerful tool for investigations in high-energy and nuclear physics.

It will be reasonable to make a remark: in the case of very high multiplicities, it is useful to apply the above-mentioned methods to particles from different bins of rapidity. In this way very interesting possibilities are opened, but that is a topic for another paper.

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Received on November 23, 1995.