CORRELATIONS OF PARTICLES IN INTERACTIONS OF RELATIVISTIC HADRONS AND NUCLEI WITH PHOTOEMULSION NUCLEI

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Introduction

The interest to hard hadron-hadron interactions at high energies (momentum transferred $q \gg 1$ GeV/c) is due to the fact that the jet character of multiple processes manifests itself clearly in these interactions. Hadron jets, which arise in the scattering of quarks and gluons constituting a hadron, carry the information about dynamics of production and fragmentation of quarks and gluons which are not available in a free state. These jets can shed light on the enigmatic mechanism of the confinement. There is no evidence of the existence of dynamical clusters (clusterization of particles) in soft hadron-hadron ($q < 1$ GeV/c), as well as in hadron-nucleus interactions. New experimental data and new data processing methods are required in both cases.

The same methods and approaches can be used in nucleus-nucleus interactions at high energies where the conditions for appearance of collective flows of nuclear matter, which are not reduced to ordinary superposition of nucleon-nucleon interactions, can occur.

At the PNPI High Energy Physics Division the investigation of relativistic nucleus interaction with nuclei of photoemulsion is carried out in the Collaborations [1,2], where emulsions were exposed to deuterons and α-particles at the energy about 4 GeV per nucleon. The goal of this study was to obtain new experimental data and to search peculiarities connected with correlated emission of secondary particles.

The list of experiments

Experimental data for the analysis have been obtained in the framework of several collaborations and by the photoemulsion group itself. Exposure to the beams of protons and π^- mesons has been carried out at the FNAL accelerator (Batavia, USA). Nuclear emulsion stacks of BR-2 type with the size 10×20 cm^2 and $\simeq 600$ μm thick have been used, the exposure density was $\simeq (2\text{–}4) \cdot 10^4$ particles/cm^2 parallel to the stack plane. The angular dispersion was $\simeq 10^{-4}$ rad. The grains density (photoemulsion sensitivity) is $\simeq$ 25–30 blobs per 100 μm on a projectile track. We shall list briefly sets of events used later on for the analysis.

a) p–N interactions at 200 GeV (1620 quasinucleon interactions in the Collaboration [3]).

p–A interactions at 200 GeV (1709 inelastic interactions in the Collaboration [4]).

b) π^-–A interactions at 200 GeV (4853 inelastic interactions in the Collaboration [5]).

c) p–N interactions at 400 GeV (1322 inelastic quasinucleon events in the Collaboration [6]).

d) p–A interactions at 400 GeV (3353 inelastic proton-nucleus interactions in the Collaboration [7]).

e) Interactions of ^{22}Ne nuclei with photoemulsion nuclei at the momentum of 4.1 GeV/c per nucleon in the Collaboration [8] (4309 events were used for analysis in this experiment).

In addition, we have obtained the data on ^{6}Li nuclei interactions at the momentum of 4.5 GeV/c per nucleon (934 inelastic interactions containing 1425 single- and two-charged projectile fragments of ^{6}Li [9,10]).

Nuclear photoemulsion layers exposed by the beam of ^{208}Pb nuclei at the momentum of 160 GeV/c per nucleon were also obtained from CERN. 127 inelastic events were found by the area scanning. There were light fragments with $Z < 6$–8 among products of the projectile fragmentation. Out of these fragments we selected 302 fragments with $Z = 2$. The plane angles of these fragments were measured [11]. The interactions with free and quasifree nucleons were selected. A separation of projectile fragments and nuclear target fragments was made on the basis of standard criteria.

Emission angles of a secondary particle – polar angle θ and azimuthal angle ψ, or plane angle φ and deep angle α – are measured. The particle charge Z is also determined from the ionization and the counting of δ-electrons located along the particle track.

Dynamical correlations in p–N and hadron-nucleus interactions

An angular correlation of secondary particles can be determined as a probability to observe some small angle between particles in an experiment to be higher than it comes out from angular distributions of single particles in their independent emission. The group of particles with anomalously small angles between them forms the jet. This is just a ground of the method proposed by the authors to investigate the statistical dependence of secondary particles emission (of the space "sticking together" type) and to identify the compact isolated groups of these particles-jets, clusters emitted in the interaction of particles or high energy atomic nuclei with nuclei [12,16]. The basis for proposed method is the determination of a probability **P** that several particles in a collision are close in space. Small value of **P** indicates an unrandom character of particles disposition.

A group of s particles in an event with the production probability **P** less than its critical value of $\mathbf{P_c} = 10^{-8}$ will be considered as a jet. A search for such jets was done in events recorded by Collaborations [3,6] in the photoemulsion as well as events generated in accordance with the Independent Emission Model (IEM) and the quark Resonance Model of Multiparticle Production (RMMP) of Anisovich–Shekhter. It occurred that the number of jets with two or three particles emitted at angles of $\simeq 3°$–$4°$ in the laboratory frame with the probability $\mathbf{P} < 10^{-5}$ was always much higher in an experiment than in a Monte Carlo simulation. An example of one such event is shown in Fig. 1.

The location of the jet is shown by a dotted line. The expected place of its "companion" is shaded. There were no particles in this area but seven particles were found, in addition to the jet, near the beam-jet plane with rather small interval of angles θ. No events of such type was observed in the IEM sample with statistics 100 times larger and in the RMMP on statistics 5 times larger. Thus, we have space dynamical correlations of particles which are jets or narrow groups of particles. The appearance frequency of such jets is much higher in the experiment than in IEM or in RMMP (which include also resonances production). However the total number of jets is still small at the energy of 200–400 GeV.

The clustering can be considered as one of possible reasons of secondary particles correlations in p–A and π^-–A interactions. The concept of clustering is not determined so clear as the correlation, and the degree of clustering has no certain measure. The clustering is being understood usually as the process of formation of some groups, clusters, lumps having the probability less than that of their random formation. These lumps have no certain mass or quantum numbers and are not identified with known resonances.

We used the method to prove the existence of secondary particles clustering effect [12]. The events were selected with shower particles multiplicity higher than 5. The minimum angle r_s to the s neighbour was determined for each event (where $s = 1, 2, 3, 4$), and distributions of the value $x = 1/r_s^2$ were plotted; x is proportional to the density of particles on a sphere with radius r_s . The same procedure was applied to the events generated by the Monte Carlo method. These distributions are shown in Fig. 2 for $s = 1$ and $s = 3$. It is seen that Monte Carlo events for all s have sharp maximum at small x whereas the experiment gives more events with the larger densities. This difference is too contrast to tolerate any explanation other than the clearly expressed aspiration of particles for "sticking together" in the space [13].

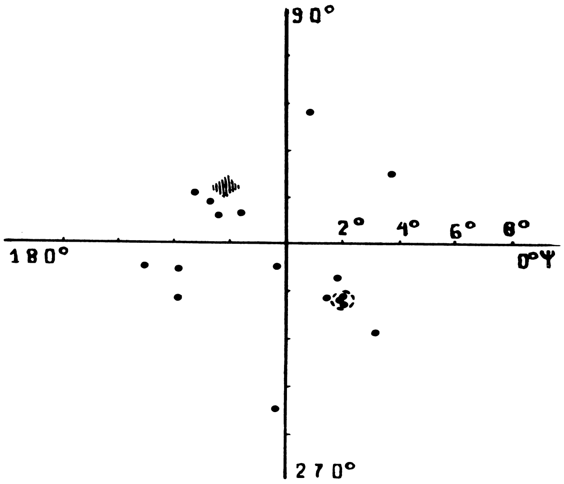

Fig. 1. The angles θ and ψ for one event containing the jet of three particles (are traced by dotted line) among p–N 400 GeV interactions.

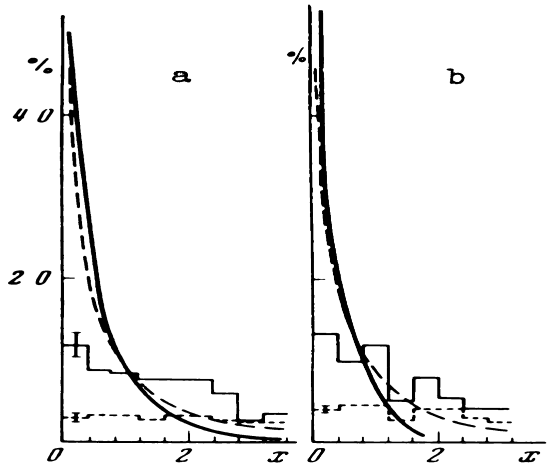

Fig. 2. The distribution of the values $x = 1/r_s^2$ for $s = 1$ (dotted) and $s = 3$ (solid). Experimental results are shown by histograms, Monte Carlo simulation – by curves. a) p–nucleus 200 GeV, b) π^-–nucleus 200 GeV.

Exited pre-fragments

In accordance with the existing physical foundations, the transverse momenta projection on the emulsion plane $P_{\perp\varphi} = A_F{\cdot}P_0 \cdot \sin\varphi$ for fragments with the mass number A_F produced in the fragmentation of relativistic nucleus with the mass number A and projectile momentum per nucleon P_0 should have the gaussian distribution with the dispersion:

$$\sigma_F^2(Z) = \sigma_0^2 \cdot \frac{A_F \cdot (A - A_F)}{A - 1}. \tag{1}$$

The value $\sigma_0 = P_F/\sqrt{5}$ is the standard deviation of the projectile nucleons momenta projection on a random direction (it is assumed that the nucleus was in the ground state before collision). An estimation of σ_0 can be found from the nucleus radius R or from the Fermi momentum P_F known from electron scattering on nuclei.

Fig. 3 shows that the experimental data [14] are in reasonably good agreement with the parabolic law (1). The experiment gives $\sigma_0 = 102.5 \pm 2.5$ MeV/c for the fragments of ^{22}Ne nuclei. This result agrees with known Fermi momentum of nucleons in ^{22}Ne nucleus. The distribution of the fragment transverse momenta projection is a normal one with zero mean and the dispersion σ_0^2 (Fig. 4) [14].

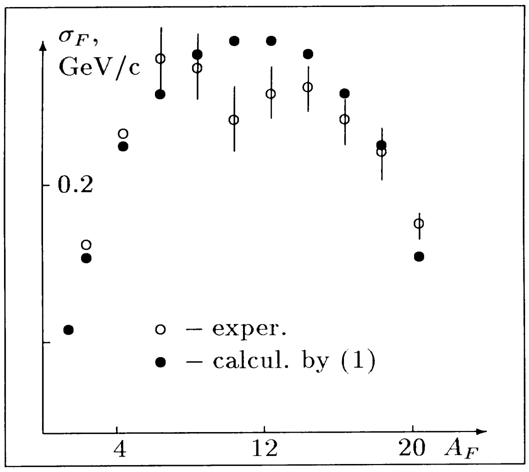

Fig. 3. The A_F-dependence of $\sigma(Z)$ for ^{22}Ne fragments with the momentum 4.1 GeV/c per nucleon.

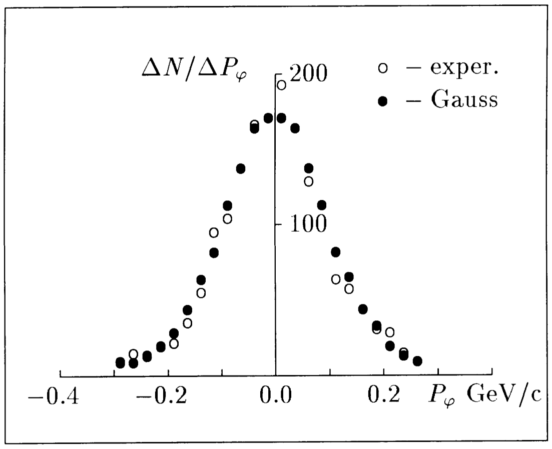

Fig. 4. The P_φ distribution for ^{22}Ne fragments with the momentum 4.1 GeV/c per nucleon.

In the fragmentation of relativistic nuclei, the fragments observed experimentally can be the decay products of residual nuclei, i.e. of pre-fragments. No experimental information is available practically on the properties of pre-fragments. We propose new method for an estimate of the fragment transverse momenta in the c.m. frame of the pre-fragment on the basis of quantities observable experimentally [15]. Here it should be mentioned that our consideration is restricted by the pre-fragments which decay only into two fragments. The transverse part of the invariant mass of the two particles can be calculated as

$$M_{12\perp}^2 = m_U^2 \cdot (A_1 + A_2)^2 + 4 \cdot A_1 \cdot A_2 \cdot P_0^2 \cdot \sin^2(\theta_{12}/2). \tag{2}$$

Here A_1, A_2 are the mass numbers of fragments 1 and 2, P_0 is the momentum per nucleon of the projectile particle, $m_U = 0.931$ GeV is the mass unit and θ_{12} is the angle between tracks of fragments 1 and 2 in the emulsion. We assume the mass of the fragments to be $A_F \cdot m_U$ and its momentum to be $P_0 \cdot A_F$. The latter assumption means that the longitudinal component of the velocity is almost the same for all fragments. Accordingly, the fragments are in motion with respect to each other only in the direction perpendicular to the direction of the c.m. frame motion. However the transverse plane of the c.m. frame can be not the same as the transverse plane of the laboratory frame. The transverse momentum in the c.m. frame of the two fragments is

$$P_\perp^\star = P_0 \cdot \sin(\theta_{12}/2) \cdot \sqrt{A_1 \cdot A_2 \cdot [1 - \frac{m_U^2 \cdot (A_1 - A_2)^2}{M_{12\perp}^2}]}. \tag{3}$$

Since the transverse momentum of the fragment observed in the lab. frame and in the c.m. frame of two fragments has the Rayleigh distribution, we find for particles (fragments) of equal mass $\eta = < P_{\perp exp} > / < P_{\perp}^{*} > = \sqrt{2}$. To test the last relation, we selected 1004 events containing only two fragments from an experimental set of inelastic interactions of ^{22}Ne nuclei with emulsion nuclei at the momentum 4.1 GeV/c per nucleon. For particles with $Z = 1$ the momentum was determined on the basis of the multiple scattering formula. It was possible to separate the hydrogen isotopes. The mass numbers of the fragments with $Z > 1$ were taken to be $A_F = 2Z$.

The Monte Carlo simulation yielded a value of $\eta = 1.461 \pm 0.003$. If the difference between this value and $\eta = \sqrt{2}$ is assumed to be significant, it should be attributed to the approximate estimation of the expected value itself. Experimentally this ratio is $\eta = 1.32 \pm 0.01$, much smaller than both the prediction and the Monte Carlo estimation. Consequently, the experimental value of $< P_{\perp}^{*} > = 0.197 \pm 0.006$ GeV/c is larger than the expected value of this quantity for an independent emission of fragments (0.150 ± 0.003 GeV/c) and the experimental transverse part of the invariant mass of the two fragments is larger than for the independent emission of fragments. This circumstance should be viewed as an indication that the pre-fragments decaying into two fragments in our experiment were excited.

Some peculiarities of angular distributions of secondary particles in inelastic interactions of 4.1 A GeV/c ^{22}Ne ions with emulsion nuclei

1. The following results [12,16] have been obtained in analysis of shower particles in the set [8]. We recognized 177 events each contains jet of 2 particles, 21 events with 3 particles and 11 events with 4 particles. Each of these groups are not a constituent of the higher-order groups, i.e. found pairs do not enter into picked out three, four particles etc. 10 ensembles of events were produced in the Monte Carlo simulation, in each ensemble the distribution of multiplicities n_s is identical to the experimental one. The number of events with 2-, 3-, and 4-particles jet was 87.5, 5.3 and 2.0, respectively, per one simulated ensemble. The difference between the experimental ensemble and the simulated one for events containing jets of 2, 3 and 4 particles is statistically significant.

2. Using the modified Cuiper statistics V^* we have tested the uniformity of the azimuthal distribution in individual events for relativistic single-charged s-type particles with the multiplicity $n_s > 7$. The hypothesis of uniformity of the angular distribution is rejected at the 1% confidence level for $V^* > 2.001$. 40 events satisfying this criterion have been found among 1959 events. The number of such events evaluated by the Monte Carlo simulation is equal to 20. Thus the probability to observe 40 events for a mean value of 20 events is $3{\cdot}10^{-5}$. As an example, one chosen event is shown in Fig. 5. Observed events have been interpreted as events with the side-splash of s-particles. According to our data, the ratio of the numbers of events, in which the collective flow of relativistic particles is observed, to the total number of inelastic interactions is not less than 0.5% . In the case of slower particles connected with the disintegration of the target nucleus such effects are not observed.

3. The events defined as peculiar ones have been observed during the analysis of central interactions. No emission of s-particles is observed in these events at angles less than 6°–12° (events with an "empty middle") in the direction of the primary neon beam for high multiplicities of these particles ($\simeq 40$). The production probability of "empty middle" in event was estimated by the method described in the previous section.

A peculiar event is shown in Fig. 6. 20 peculiar events out of 214 central collisions have been selected according to the criterion $\theta_{min} > 7°$. The cascade evaporation model gives 9.83 events. Assuming that 9.83 and 20 are elements of one and the same Poisson distribution with a mean value of 9.83, we obtain that the probability of registration of 20 does not exceed 10^{-3}.

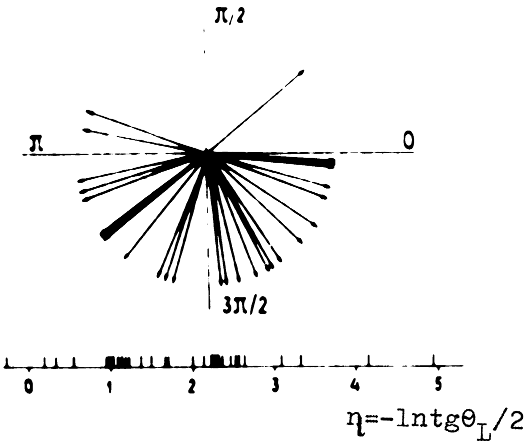

Fig. 5. The scheme of an azimuthal asymmetrical event for s-particles.

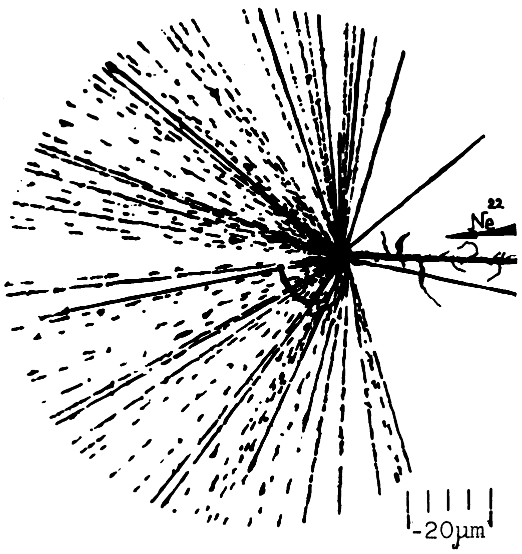

Fig. 6. The scheme of a peculiar event.

For comparison let us turn to hadron-nucleus interactions. 6636 events were recognized with $n_s > 7$ from 3628 proton-nucleus interactions at the energy of 400 GeV and 5353 π^--nucleus interactions at the energy of 200 GeV. The events with nonuniform distribution of azimuthal angle were looked for by the same method as in nucleus-nucleus interactions. 73 such events were found with the expected number 66.3. From this it follows that there is no any evidence for the effect clearly observed in nucleus-nucleus interactions.

Fragmentation of ^{6}Li nuclei with the momentum of 4.5 A GeV/c

The main results on the fragmentation of ^{6}Li nuclei with the momentum of 4.5 GeV/c per nucleon in photoemulsion [9,10] are as follows.

1. Of single-charged fragments, about 50% are protons, 42% are deuterons, and 8% are tritons. These estimates are accurate within 3–4%. The fractions of all double-charged fragments due to ^{3}He and ^{4}He are nearly equal (48–49%). The fraction of the ^{6}He isotope is $\simeq$ 2–3% (Fig. 7).

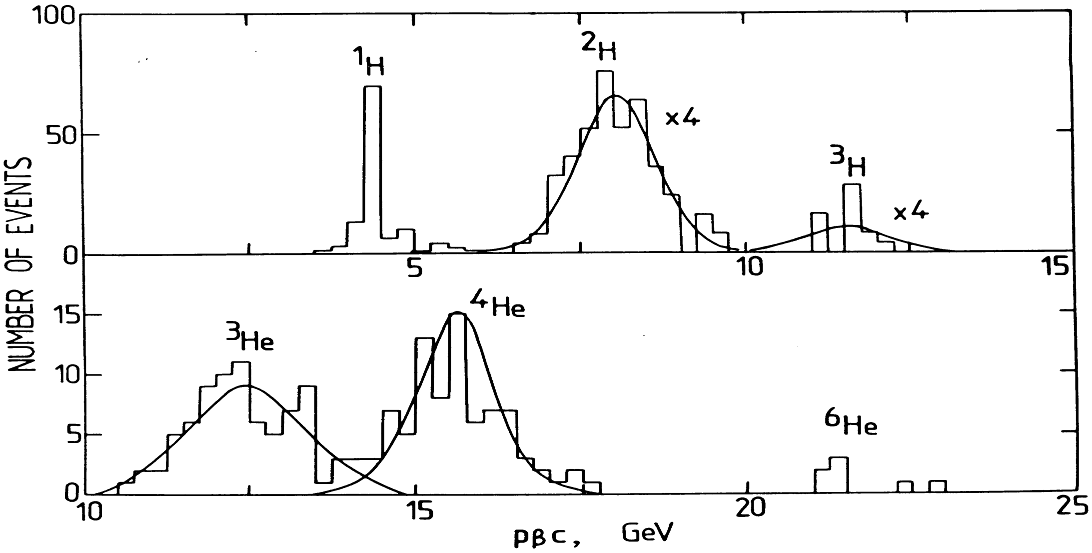

Fig. 7. Separation of hydrogen and helium isotopes (upper and lower plots, respectively) using $p\beta c$ measurements. The data are shown by histograms. The normal distributions shown by curves represent least-squares fits.

2. The detection of ^{6}He among double-charged fragments of ^{6}Li nucleus has led to the prediction and the subsequent observation of events which must occur if nucleon exchange between the projectile and target nuclei has the sufficiently high cross section. The latter was found to be 12 ± 3 mb. Of special interest is our observation of the "pure" fragmentation of ^{6}Li in photoemulsion into two double-charged particles (^{3}He and ^{4}He) with no secondaries or slow particles from the target disintegration.

3. The distributions of the transverse momentum projection onto the emulsion plane for protons and α-particles are used to estimate the Fermi momentum of nucleons in the ^{6}Li nucleus. This value is found to be equal 129 ± 6 MeV/c. A high momentum component with $\sigma_1 = 40.0$ MeV/c and fraction $c = 0.257$ is observed in the transverse momenta distributions for ^{3}He and ^{4}He isotopes. Its existence is coupled with the nucleus structure in the ground state and is due to the stratification of nuclear matter in ^{6}Li-formation of double-charged fragments not only in the centre of nucleus but in its periphery, in stratosphere as well.

4. The value η obtained in the experiment is consistent with $\sqrt{2}$. The fragmentation of ^{6}Li does not involve pre-fragment production.

Conclusion

The present investigation of interactions of high energy hadrons and nuclei with photoemulsion nuclei allows to point at the jet mechanism of multiparticle processes and the collective character of nucleus-nucleus interactions.

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3. SOLID STATE PHYSICS