Two-particle rapidity correlations in C+Ta interactions at 4.2*A* GeV/*c*

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Two-particle rapidity correlations for pp, $p\pi^-$, and $\pi^-\pi^-$ pairs in C+Ta interactions at 4.2 GeV/c per nucleon are presented. The experimental data are obtained with a 2 m propane bubble chamber exposed on the JINR, Dubna, synchrophasotron. It is found that the strength of the correlations does not depend on particle combination, but strongly depends on the rapidity and collision centrality. The quark-gluon-string model describes these features of the correlations well, but needs to be tuned in the target fragmentation region. Since the quark-gluon-string model simulates the nucleus-nucleus collisions by the superposition of hadron-hadron collisions, we conclude that there is no evidence of a collective behavior in our data. This conclusion is additionally supported by the intermittency analysis. [S0556-2813(96)05810-4]

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I. INTRODUCTION

The study of dynamics of multiparticle production in high energy nucleus-nucleus collisions has important role in the search for the new state of nuclear matter, the quark-gluon plasma, and other collective phenomena. The usual way for the search of these phenomena is comparison of hadron-hadron (hh) and nucleus-nucleus (AA) collisions or comparison of AA collisions with phenomenological models that assume independent superposition of nucleon-nucleon collisions. An investigation of correlations is important in such approach since it provides detailed information on hadronic production dynamics beyond that obtained from the single particle spectra.

Particle correlations in longitudinal direction have usually been analyzed in terms of the rapidity variable, $y=(1/2)\ln[(E+p_z)/(E-p_z)]$, and with the help of the normalized correlation function:

$$R(y_1,y_2)=\frac{\rho^{(2)}(y_1,y_2)}{\rho^{(1)}(y_1)\cdot\rho^{(1)}(y_2)}-1$$

where $\rho^{(1)}(y)=\sigma_{\mathrm{in}}^{-1}d\sigma/dy$, and $\rho^{(2)}(y_1,y_2)=\sigma_{\mathrm{in}}^{-1}d^2\sigma/dy_1dy_2$, are the one- and two-particle densities, respectively, σ_{in} is the inelastic cross section, and y_1 and y_2 are rapidities of hadrons h_1 and h_2. If these two hadrons are emitted independently, $\rho^{(2)}(y_1,y_2)$ is simply the product of the two one-particle distribution functions $\rho^{(1)}(y_1)\cdot\rho^{(2)}(y_2)$, and $R(y_1,y_2)$ is zero. The values of $R(y_1,y_2)$ different from zero indicate the existence of correlations between hadrons. Up to now, the two-particle rapidity correlations have been extensively studied in hh [1–6], hA [7,8], and e^+e^- [9] collisions. However, very few experimental results are available on rapidity correlations in nucleus-nucleus collisions [10–13]. In all these experiments, apparent short-range ($\Delta y\approx 1$–2) correlations have been observed although a clear concept of the origin and the character of the rapidity correlations is still lacking. This is related to the main problems encountered in the study of rapidity correlations such as significant pseudocorrelations arising from the mixture of events with different total multiplicities, the effect of energy-momentum conservation, the influence of resonance formation, and the influence of Bose-Einstein correlations. The analysis of these problems will provide an answer to the question whether it is necessary to introduce clusters as specific physical objects, arising in particle production, and what parameters are needed to describe them.

In a previous paper [12], we analyzed the two-particle rapidity correlations in C+C interactions, at 4.2 GeV/c per nucleon. In this paper we present the two-particle rapidity correlations in C+Ta collisions with data obtained at the same energy and using the same experimental technique. We discuss the correlations for pp, $p\pi^-$, and $\pi^-\pi^-$ pairs. The experimental data are compared with the events generated according to the quark-gluon-string model (QGSM) [14,15]. This model was developed to describe hadron-nucleus and nucleus-nucleus interactions at intermediate and relativistic energies. The model includes hadronic rescattering as well as resonance formation, interaction and decay. The single particle inclusive spectra of protons and π^- mesons from QGSM have been shown to agree well with our experimental data for both C+C and C+Ta interactions [16].

II. EXPERIMENTAL DATA

The present study is based on a sample of 2000 inelastic events collected with the 2-m propane bubble chamber, with three 1 mm thick tantalum plates placed inside. The chamber was exposed to a beam of light nuclei at the JINR, Dubna, synchrophasotron. The characteristics of the chamber allow precise determination of the charge multiplicity, measurement of all tracks, as well as identification of negative particles and positive particles with momenta less than 0.5 GeV/c. All tracks are reconstructed in space using standard three-view geometry program. Because of difficulties in determination of the interaction point in the tantalum target, the coordinates of this point had to be determined by extrapolating tracks of the secondary particles. The estimated errors of this procedure are $\sigma_x=0.024$ cm, $\sigma_y=0.033$ cm, and $\sigma_z=0.090$ cm. The outgoing tracks are satisfactorily measured with average error of the momentum $\langle\Delta p/p\rangle=11.5\%$, and the average error of emission angle $\langle\Delta\theta\rangle=0.5^0$.

All negative particles, except identified electrons are considered to be π^- mesons. Among the accepted π^- mesons remains admixture of unidentified fast electrons ($p>0.1$ GeV/c) from γ conversion in the target. This admixture is estimated to be 5% of all negative particles, by a Monte Carlo calculation under the assumpions of equal multiplicities and equal angular and momentum spectra of π^0 and π^- mesons [17,18]. The threshold for π^- meson registration is 0.08 GeV/c. Below this threshold the negative pions are often absorbed in the tantalum plates. If the momentum spectrum is continued smoothly down to zero momentum, the fraction of pions with $p<0.08$ GeV/c constitutes approximately 10% of the total number. This correction is not introduced in our results and affects somewhat the rapidity distributions in the region $|y|<0.54$.

All positive particles with momenta less than 0.5 GeV/c are classified either as protons or π^+ mesons according to their ionization density and range. The π^+ mesons with momenta larger than 0.5 GeV/c cannot be reliably distinguished from protons according to the ionization density, and on data summary tape (DST) are recorded as protons. The admixture of π^+ mesons (less than 15%) is subtracted from the protons statistically, using the number of π^- mesons with momenta larger than 0.5 GeV/c, as follows: $n_p = n_+ - n_{\pi^+}(p<0.5\ \mathrm{GeV}/c) - 0.82\cdot n_{\pi^-}(p>0.5\ \mathrm{GeV}/c)$. Here n_+ denotes the number of single positively charged particles and $n_{\pi^+}(p<0.5\ \mathrm{GeV}/c)$ number of π^+ mesons with $p<0.5$ GeV/c, where they are reliably identified. For pions with $p<0.5$ GeV/c the value of the ratio $\langle\pi^+\rangle/\langle\pi^-\rangle$ is 0.82. Taking into account that according to the QGSM the value of the ratio $\langle\pi^+\rangle/\langle\pi^-\rangle$ is practically the same for pions with $p<0.5$ GeV/c as well as for pions with $p>0.5$ GeV/c, the number of π^+ mesons with $p>0.5$ GeV/c is taken to be $0.82\cdot n_{\pi^-}(p>0.5\ \mathrm{GeV}/c)$. From the n_p protons we further subtract the spectator protons, i.e., the protons with momenta $p>3$ GeV/c and emission angle $\theta<4°$ (projectile spectators) and protons with momenta $p<0.3$ GeV/c (target spectators). In this way, the selected protons still contain admixture ($\approx$17%) of deuterons with $p>0.48$ GeV/c, and tritons with $p>0.65$ GeV/c which cannot be eliminated.

The experimental data are also corrected to the loss of particles emitted at small angles relative to the optical axes of chamber and to the loss of particles absorbed by the tantalum plates. The aim of these corrections is to obtain isotropic distribution in azimuthal angle φ, and smooth distribution in emission angle θ (both measured with respect to the direction of the incoming projectile). As the result of these corrections, the multiplicity of π^- mesons is increased by 7%, and the multiplicity of protons by 11%. Other minor corrections related to the tantalum plate are discussed in more detail in [18]. There, the estimates of the corrections due to the loss of π^- mesons and protons related to their secondary interactions in the tantalum plate are described. These amount to less than 1% and 3%, respectively. In the secondary interactions of the projectile spectator protons with the tantalum, additional 0.5% π^- mesons and less than 2.5% protons are produced. The corrections due to the loss and gain have opposite sign and have, when combined, negligible effect. After taking into account all these corrections, the resulting relevant average multiplicities are 15.2 ± 0.3 for protons, and 3.4 ± 0.1 for negative pions. Also, the average

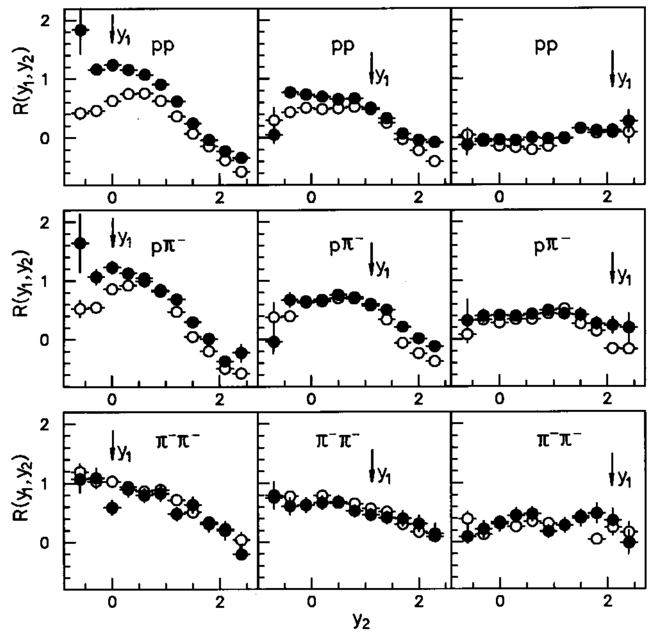

FIG. 1. The inclusive correlation function $R(y_1,y_2)$, for $y_1=0$, $y_1=1.1$, and $y_1=2.1$ (as indicated by arrows on the graphs), for pp, $p\pi^-$, and $\pi^-\pi^-$ pairs. Full circles represent experimental data and open circles represent QGSM calculations.

multiplicities of Λ hyperons and K_s^0 mesons are 0.063 ± 0.010 and 0.025 ± 0.005, respectively [19]. Thus, even if the daughters of a lambda and kaon decays were all misreconstructed as a primary vertex tracks, their contribution would nevertheless be minor.

For comparison with experimental data, the QGSM is used here to generate 3000 inelastic minimum bias events. In order to simulate real experimental conditions, the QGSM events are further passed through a filter to exclude all slow particles absorbed in the tantalum plates.

III. RESULTS

A. Two-particle rapidity correlations

Figure 1 shows the correlation function $R(y_1,y_2)$ vs y_2, for different rapidity intervals y_1, and for various pairs: pp, $p\pi^-$, and $\pi^-\pi^-$. Rapidity intervals for y_1 are selected in such a way to represent target fragmentation region ($y_1=0.\pm0.15$), central rapidity region ($y_1=1.1\pm0.15$), and projectile fragmentation region ($y_1=2.1\pm0.15$). At incident momentum of 4.2 GeV/c, the midrapidity is 1.1 and projectile rapidity is 2.2. It is seen from Fig. 1 that no significant difference is observed in the magnitude and shape of the $R(y_1,y_2)$ function for pp, $p\pi^-$, and $\pi^-\pi^-$ pairs. The strongest positive correlations between particles are observed in the target fragmentation region. Their values decrease when rapidity approaches the projectile fragmentation region, where correlations among particles practically disappear. In the central rapidity region, in contrast to the hadron-hadron [1–6] or symmetric nucleus-nucleus collisions [11,12], the correlation function $R(1.1,y_2)$ is not symmetric with respect to $y_2=1.1$ [or equivalently $y_2=0$ for rapidities y_1, y_2, defined in nucleon-nucleon center of mass (c.m.) system]. This function is larger in the backward c.m. hemisphere as the

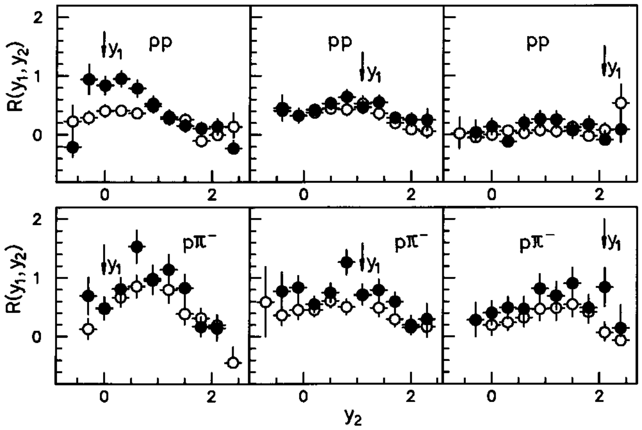

FIG. 2. The correlation function $R(y_1,y_2)$, for $y_1=0$, $y_1=1.1$, and $y_1=2.1$ (as indicated by arrows on the graphs), for pp, and $p\pi^-$ pairs, in the case of peripheral collisions. Full circles represent experimental data and open circles represent QGSM calculations.

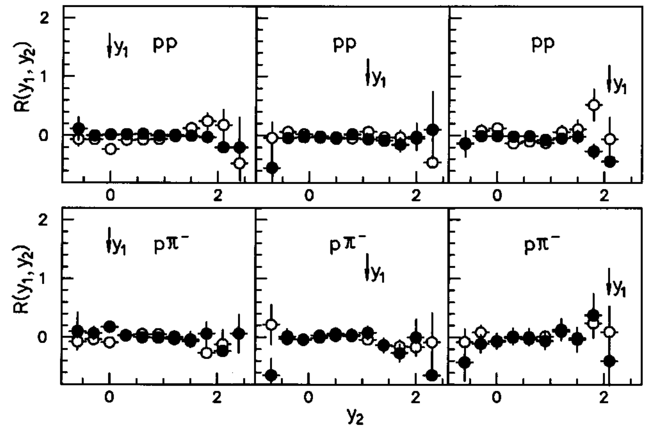

FIG. 3. The correlation function $R(y_1,y_2)$, for $y_1=0$, $y_1=1.1$, and $y_1=2.1$ (as indicated by arrows on the graphs), for pp, and $p\pi^-$ pairs, in the case of central collisions. Full circles represent experimental data and open circles represent QGSM calculations.

result of multiple interactions and its shape is similar to the case of hadron-nucleus interactions [7,8].

It is well known [1–3] that a mixture of events with different total multiplicities causes large and positive pseudocorrelations. Consequently, the inclusive two-particle correlation function can be large and positive even if no dynamical correlations exist. In most papers in which the hadron-hadron interactions are analyzed, this effect is avoided by the use of the semi-inclusive correlation functions calculated for events with fixed total multiplicity. The situation is different in the hA and AA collisions since, in the data sample that contains events with fixed multiplicity, the number of interacting nucleons varies, and particles can be produced in the same collision or in distinct collisions. Therefore, in the hA and AA interactions it is customary to categorize events according to the number of interacting protons, n_p. This number can be conveniently considered as a measure of the collision centrality. In this paper, we divide C+Ta events into three subgroups: $n_p<\langle n_p\rangle$, $\langle n_p\rangle \leq n_p \leq 2\langle n_p\rangle$, and $n_p>2\langle n_p\rangle$. The subgroup with $n_p<\langle n_p\rangle$ (i.e., $n_p<14$) corresponds to the peripheral collisions and represents $\approx$60% of the total inelastic cross section, σ_{in}, while the subgroup with $n_p>2\langle n_p\rangle$ (i.e., $n_p>28$) corresponds to the central collisions and represents $\approx 0.1\sigma_{\mathrm{in}}$.

Figures 2 and 3 depict $R(y_1,y_2)$ function, at fixed rapidity intervals y_1, in peripheral and central collisions. The correlation function is shown only for pp and $p\pi^-$ pairs. (For $\pi^-\pi^-$ pairs figure is omitted because of insufficient statistics in peripheral collisions.) It is seen that in peripheral collisions the correlations are large and positive. They depend on the rapidity intervals y_1 in the same way as for inclusive correlations. In the case of central collisions the correlations are either close to zero or negative. In comparison to the C+C interactions, the only difference found is for pp pairs, for which correlations are close to zero in both central and peripheral collisions. The absence of correlations in the peripheral C+C collisions was in [12] explained by the small number of participating protons (in average 2.1), entailing small probability that they are produced with similar rapidities. The absence of correlations in central collisions is characteristic for both C+Ta and C+C interactions as well as for pp and $p\pi^-$ pairs. It points to the incoherence of processes during the collision and supports the assumption that rescattering processes in nucleus give negative contribution to the short-range correlations [20].

Another way to recognize genuine correlations from pseudocorrelations, and trivial kinematical correlations arising from the conservation laws, is comparison of experimental data with predictions of the QGSM. In this way all nondynamical effects are taken into account and any enhancement of the experimental values of $R(y_1,y_2)$ over QGSM results may be considered as a manifestation of dynamical correlations. The values of $R(y_1,y_2)$ function calculated according to QGSM are also represented on Figs. 1, 2, and 3. It is seen that QGSM underestimates the values of inclusive correlations in the target fragmentation region for pp and $p\pi^-$ pairs. This discrepancy between model and the experimental data also appears in the same way in the peripheral collisions alone. In the case of central collisions, the values of $R(y_1,y_2)$ are close to zero according both to the model and the experimental data. The QGSM reproduces rather well the inclusive correlation function for $\pi^-\pi^-$ pairs (Fig. 1). Figure 4 shows the QGSM results for $R(y_1,y_2)$ function for pp and $p\pi^-$ pairs with constituents originating from decay of Δ, ρ, ω, η, and η' resonances (RES pairs), and with constituents originating from direct reactions (DIR pairs). Direct reactions include $NN\rightarrow NN\pi$, $\Delta N\rightarrow NN\pi$, and similar processes. It is seen from Fig. 4 that the correlation functions for RES and DIR pairs are similar in shape, except that, for $y_1,y_2<1$, the correlations for RES pairs are larger than the corresponding correlations for DIR pairs. This is the same rapidity region where the QGSM fails to reproduce the experimental data (Fig. 1) suggesting that the resonance production included in the model is not sufficient to reproduce the data.

B. Intermittency

Intermittency analysis has been recently introduced as a probe of reaction dynamics (for a review see Refs. [20–23]). There is a close connection between diagonal values of the

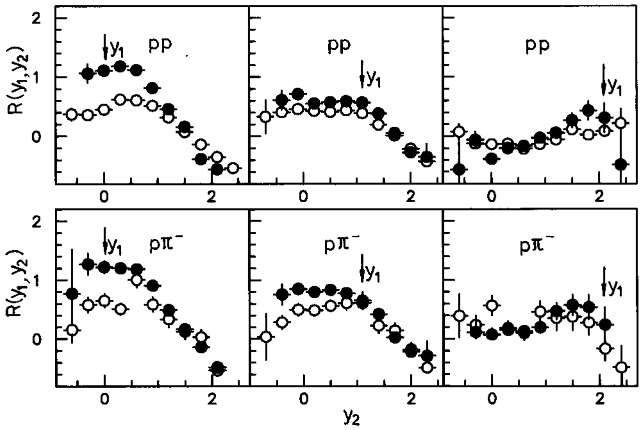

FIG. 4. The QGSM results for $R(y_1,y_2)$ function, for $y_1=0$, $y_1=1.1$, and $y_1=2.1$ (as indicated by arrows on the graphs), for pp and $p\pi^-$ pairs with constituents originating from decay of resonances (full circles), and with constituents originating from direct reactions (open circles).

two-particle correlation function, $R(y_1,y_2=y_1)$, and the average second order factorial moment, $F_2(\delta y)$, obtained in the intermittency analysis, to wit:

$$F_2(\delta y)=1+\overline{R(\delta y)},$$

with

$$F_2(\delta y)=\frac{1}{M}\sum_{m=1}^{M}\frac{\langle(n_m(n_m-1)\rangle}{\langle n_m\rangle^2}$$

and

$$\overline{R(\delta y)}=\frac{1}{M}\sum_{m=1}^{M}R(y_1^{(m)},y_2^{(m)}=y_1^{(m)}).$$

Here the rapidity interval Y is subdivided in M equal subintervals, each of size $\delta y=Y/M$, and centered at the rapidities $y_1^{(m)}$ with $m=1,2,\ldots,M$. n_m is multiplicity in bin m, and the averages $\langle\cdots\rangle$ are taken over all events in the sample.

Calculated average factorial moments of rank 2, 3, and 4, for participant protons (for example) in the rapidity interval Y from -0.15 to 1.35 (around the maximum of rapidity distribution) are presented in Fig. 5. For comparison, the corresponding QGSM values are also shown. One can see that the factorial moments do not increase significantly with decreasing δy, as would be expected if the intermittency were present. This implies that decrease in the value of the rapidity interval δy does not reveal any additional structure in the corresponding two-particle correlation function. Comparison with the QGSM indicates that there is no correlated particle emission beyond that predicted by this model, confirming the results of the two-particle correlation analysis. Analogous conclusions can be reached by considering the factorial moments calculated for π^- mesons only, and also calculated for charged particles.

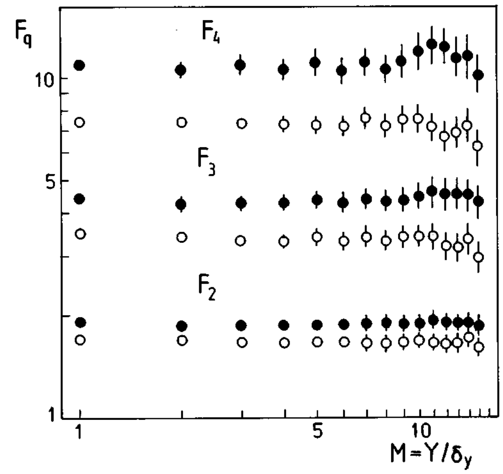

FIG. 5. Dependence of the average factorial moments of rank 2, 3, and 4, for participant protons, on the number M of subdivisions of the rapidity interval. Full circles represent experimental data and open circles represent QGSM calculations.

IV. CONCLUSION

In conclusion, we have analyzed two-particle rapidity correlations for pp, $p\pi^-$, and $\pi^-\pi^-$ pairs in C+ Ta interactions at 4.2 GeV/c per nucleon. We have found that the strength of the correlations is independent of particle combination, but strongly depends on the rapidity region and on the collision centrality. The large and positive correlations are observed in the target fragmentation region and are close to zero in the projectile fragmentation region. The dependence of correlations on the collision centrality indicates significant correlations in the peripheral collisions, and no correlations in the central collisions. The QGSM describes dependence of the two particle correlations on the rapidity range and collision centrality well, but underestimates the magnitude of the correlations in the target fragmentation region. From the observed features of the two-particle rapidity correlations we conclude that rescattering of secondary particles and resonance production both play an important role in determining the shape and magnitude of the correlation function. With the present level of statistical accuracy (in average 7% for pp, 10% for $p\pi^-$, and 15% for $\pi^-\pi^-$ pairs) we find no evidence for collective phenomena, although it is conceivable that the correlations originating from the processes with very small cross sections are perhaps suppressed with the background arising from dominant processes. As an alternative method for analyzing correlated particle production, the intermittency leads us to the same general conclusion.

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