Two-particle azimuthal correlations in light nuclei collisions at 4.2 GeV/c per nucleon

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(Received 29 July 1991)

Two-particle azimuthal correlations are studied in 4.2 GeV/c per nucleon dC, αC, and CC collisions with a propane bubble chamber at JINR Dubna Synchrophasotron. It is found that the azimuthal correlations are different for different pairs of secondary particles, and that they also depend on the mass of the projectiles and the collision centrality. The majority of the observed characteristics can be accounted for by the kinematic correlations calculated from the model of independent nucleon-nucleon collisions. The only exception is the effect of close pairing of like particles considered to be due to the identical particle effect for pion pairs and to short-range strong interactions for proton pairs.

PACS number(s): 25.70.−z

The purpose of this work is to study the correlations between the vectors of transverse momenta of secondary particles in elastic nucleus-nucleus collisions at energies of 4.2 GeV/c obtained at JINR Dubna Synchrophasotron. The azimuthal correlations are of particular interest since they are free of correlations induced by mixing events with different multiplicities. This has been found to be very important in the rapidity correlations [1,2].

The studies of two-particle azimuthal correlations in hadron-hadron collisions, in a wide energy range, have established the existence of short-range dynamical correlations [3–6]. The established difference in characteristics for the unlike and like particles suggests different production mechanisms. The like-particle correlations are considered to be due to a final-state phenomenon such as Goldhaber-Goldhaber-Lee-Pais effect, while correlations for unlike particles are considered to be a consequence of resonance formation and decay.

The application of the two-particle correlation analysis in the azimuthal plane, to complex processes such as inelastic nucleus-nucleus collisions at relativistic energies, has started recently. Since the important factor in these measurements is the ability to detect and identify most of the charged particles in each event, the majority of the data, on two-particle azimuthal correlations, have been obtained from emulsion experiments [7–12].

The experimental data considered in this paper are obtained from the 2 m JINR Dubna bubble chamber. The data cover 7327 CC, 4852 αC, and 6734 dC inelastic interactions. The transverse momentum correlations between two hadrons are investigated for the following reactions:

$$A+\mathrm{C}\rightarrow\pi^-\pi^-+X\ ,$$

$$A+\mathrm{C}\rightarrow\pi^-p+X\ ,$$

$$A+\mathrm{C}\rightarrow pp+X\ ,$$

($A=d,\alpha,$C). All π^- mesons with momenta $p>70$ MeV/c ($l<3$ cm) are unambiguously identified. Because of the contamination with π^+ mesons ($<10\%$), the protons are selected by a statistical method applied to all positive particles with momentum $p>500$ MeV/c. The protons considered in this work are only the participant protons, i.e., the protons with momenta $0.3<p<3$ GeV/c, and with $p>3$ GeV/c and $\vartheta>4°$, which interact strongly during the collisions. The remaining protons, i.e., protons with $p>3$ GeV/c and $\theta<4°$ and protons with $p<0.3$ GeV/c, are called projectile spectators and target spectators, respectively. In a geometrical picture, spectators originate from the nonoverlapping parts of the colliding nuclei and are not actively involved in the interaction. Their azimuthal correlations will be studied in a separate paper.

In order to show that experimental biases have no effect on the correlation analysis in the azimuthal plane, we present inclusive azimuthal distributions $dN/d\varphi$, for protons [Figs. 1(a) and 1(c)] and π^- mesons [Figs. 1(b) and 1(d)] in dC and CC interactions. It is apparent that the distributions are isotropic.

To investigate correlations in the transverse (azimuthal) plane of the interaction we use the angle $\Delta\varphi_{ij}\equiv\Delta\varphi$,

$$\Delta\varphi\equiv\cos^{-1}\frac{\mathbf{p}_{T_i}\cdot\mathbf{p}_{T_j}}{(|\mathbf{p}_{T_i}|\cdot|\mathbf{p}_{T_j}|)}$$

between the transverse momenta of the ith and jth particles in a given collision ($0\leq\Delta\varphi\leq\pi$). The degree of anisotropy of the distribution $d\sigma/d(\Delta\varphi)$ is described via the parameter of the azimuthal asymmetry defined as

$$B=\frac{\int_{\pi/2}^{\pi}[d\sigma/d(\Delta\varphi)]d(\Delta\varphi)-\int_{0}^{\pi/2}[d\sigma/d(\Delta\varphi)]d(\Delta\varphi)}{\int_{0}^{\pi}[d\sigma/d(\Delta\varphi)]d(\Delta\varphi)} .$$

For statistically independent particle emission, the mathematical expectation of the quantity B is zero because the distribution over $\Delta\varphi$ is uniform in the interval $[0,\pi]$. In the processes studied here there are several reasons to expect $B\neq 0$. The overall conservation of transverse momenta in the final state leads to a value of B which is positive. The formation of clusters (resonances or minifireballs) with $p_T\neq 0$ leads to $B<0$ for the small rapidity gap, $|y_1-y_2|\leq 2\delta\approx 1-2$. The bounceoff of the projectile from the target gives $B<0$.

The main difficulty in the analysis of the correlation effects is to take into account quantitatively trivial (mainly kinematical) effects which violate the statistical independence of the secondary particles. Primarily, they concern the four-momentum conservation which is particularly significant at low energies and at low multiplicities. The effects arising from other conservation laws and from empirically established facts such as the limited transverse momentum, leading particle effect, etc., can also be considered to be trivial. Therefore, the comparison with a theoretical model which specifies the mechanism responsible for the particle emission allows one to sort out the kinematical correlations and makes more certain the interpretation of the experimental data.

In this work, we use the Monte Carlo version of the quark-gluon string (QGS) model for nucleus-nucleus interactions [13,14] for comparison with the experimental data. In this model inelastic nucleus-nucleus interactions are treated as successive two-particle collisions described by the relativistic Boltzmann equation. Each hadron-hadron collision is described using the dual parton model and its interpretation in terms of quark-gluon strings. Space-time dynamics of the string decay and the string interactions are taken into account in an approximation of additive valence quarks, being at the ends of an excited string. Processes like intranuclear rescatterings of hadrons and short-lived resonances are also included. Some modifications in the model are introduced in order to describe interactions of hadrons at intermediate energies ($\sqrt{s}<4$ GeV). Therefore, reactions of the type $\pi+N\rightarrow\Delta(1232)$, $\pi+\pi\rightarrow\rho$, as well as pion absorption by NN quasideuteron pairs are taken into account. The results of the calculation [14] at 4.2 GeV/c per nucleon showed that the model reproduces the experimental data in this energy domain. In fact, the model is developed from the Dubna version of the intranuclear cascade model [15]. In this work, the QGS model was used to generate 15 000 events for dC, αC, and CC interactions each.

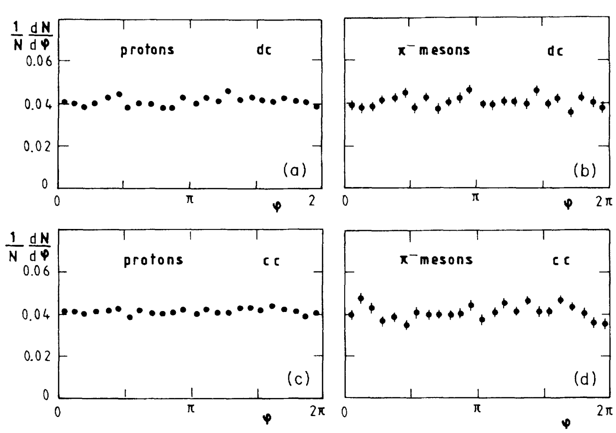

FIG. 1. (a)–(d) The azimuthal angle distributions of protons and π^- mesons in dC and CC interactions.

In Table I, the experimental B values for pairs of particles of a given type in dC, αC, and CC interactions are given. For comparison, the results of calculations from the Monte Carlo code of the QGS model are also given in brackets. Among the considered pairs, the strongest azimuthal correlations are observed between the proton pairs (pp pairs) and somewhat weaker for proton-pion ($p\pi^-$) pairs. For all types of interactions, the B value for pion pairs ($\pi^-\pi^-$ pairs) is within the experimental error, close to zero. For pp and $p\pi^-$ pairs, the parameter B has a positive value as required by the conservation of the transverse momentum. For these pairs, azimuthal asymmetry decreases with increasing mass of the projectile nucleus. Also, the azimuthal asymmetry decreases with increasing collision centrality, i.e., the number of interacting protons. This is shown in Table II for the CC interaction. The number of interacting protons is defined via the net charge $Q=n_+-n_--n_{fr}$, where n_{fr} is the number of spectators from the projectile and target, and n_+ (n_-) is the number of positive (negative) charged particles [16,17]. A strong correlation between the average impact parameter and Q is observed in [17].

The experimental results, Tables I and II, agree with the predictions of the QGS model. In this model, and similar models which consider the nucleus-nucleus interactions as the incoherent sum of hadron-nucleus collisions, particles from one collision are correlated, as required by conservation of momentum, while the particles from different collisions are uncorrelated. Since the number of hadron-nucleon collisions increases with increasing Q and/or A_p, it follows from the superposition models

TABLE I. B values for pp, $p\pi^-$, and $\pi^-\pi^-$ pairs for dC, αC, and CC interactions. The QGS model calculations are given in parentheses.

	dC	αC	CC
pp	0.23±0.01	0.14±0.01	0.087±0.004
	(0.20±0.01)	(0.14±0.01)	(0.083±0.003)
$p\pi^-$	0.10±0.01	0.048±0.008	0.030±0.004
	(0.093±0.007)	(0.052±0.004)	(0.027±0.003)
$\pi^-\pi^-$	−0.018±0.030	0.007±0.020	0.001±0.011
	(−0.009±0.022)	(0.012±0.011)	(0.017±0.006)

that B decreases with increasing Q. In the framework of these models, we can also explain the uncorrelated production of $\pi^-\pi^-$ pairs. At energies of a few GeV per nucleon there is a very small probability that two π^- mesons are produced in one nucleon-nucleon collision. Therefore, π^- mesons are most probably produced in various NN collisions and, as such, they are uncorrelated in the transverse plane.

In order to clarify the various effects that influence the characteristics of azimuthal distributions of two particles, it is important to investigate the dependence of B on the longitudinal variable. Specifically, the study of the dependence of B vs the difference of the rapidities of two particles ($\Delta y = y_1 - y_2$) allows one to separate the long-range and short-range correlations. In the latter case the magnitude of the correlation depends on the relative rapidity difference between particles.

Figures 2(a)–2(d) show the parameter of azimuthal asymmetry B as a function of the rapidity difference Δy for the pp and $\pi^- p$ pairs in dC and CC interactions. Because of the small probability of events with $2\pi^-$, in dC interactions, $B(\Delta y)$ is analyzed only in CC interactions [Fig. 2(e)]. The shape of $B(\Delta y)$ is different for various pair combinations.

For the pp pairs, the parameter B increases with increasing Δy in both dC and CC interactions [Figs. 2(a) and 2(b)]. The QGS model also predicts the increase of B with increasing Δy, although this increase, in the case of CC interactions, is somewhat smaller than in the experiment. The corresponding distributions of proton pairs on the azimuthal angle $\Delta\varphi$ are asymmetric with respect to $\Delta\varphi = 90°$ peaking at $\Delta\varphi = 180°$, for all rapidity gaps, except for the smallest one. This behavior is mainly due to transverse momentum conservation which requires that a particle is produced predominantly in the direction opposite to the others. With decreasing Δy, only the slope of the $dN/d(\Delta\varphi)$ distribution decreases. However, the distribution $dN/d(\Delta\varphi)$, for pairs of protons emitted close to one another in rapidity $\Delta y < 0.1$, shows besides the peak from the kinematic correlations, a significant peak at $\Delta\varphi < 20°$ [Figs. 3(a) and 3(d)]. The peak at $\Delta\varphi < 20°$ disappears if particles are produced with larger rapidity difference, as can be seen in Figs. 3(b) and 3(c) and 3(e) and 3(f). The statistical error does not allow one to check how further narrowing of the binning interval, either below $\Delta y = 0.1$ or $\Delta\varphi = 20°$, influences the peak height. The excess of close pairs appears in both dC and CC interactions. The QGS model does not reproduce such a peak.

TABLE II. B values for CC interaction for different collision centrality, defined via the net charge Q. The QGS model calculations are given in parentheses.

	$Q=0$–2	$Q=3$–6	$Q\geq 7$
pp	0.33±0.02	0.129±0.006	0.052±0.004
	(0.36±0.02)	(0.114±0.004)	(0.062±0.003)
$p\pi^-$	0.096±0.019	0.034±0.007	0.023±0.005
	(0.105±0.016)	(0.041±0.005)	(0.017±0.003)
$\pi^-\pi^-$	0.062±0.042	−0.010±0.019	0.000±0.013
	(0.101±0.046)	(0.034±0.012)	(0.009±0.007)

Figure 2(e) shows B vs Δy for $\pi^-\pi^-$ pairs. For $\Delta y < 0.2$, the parameter of azimuthal asymmetry is negative, while for a larger rapidity difference B has values close to zero within error bars. For $\Delta y < 0.2$, where B is negative, two pions are emitted on average with $\Delta\varphi < 90°$ and the distribution $dN/d(\Delta\varphi)$ has a peak at $\Delta\varphi < 20°$ [Fig. 3(g)]. The distributions $dN/d(\Delta\varphi)$ of two pions with the rapidity difference $0.2 < \Delta y < 0.4$ and $0.4 < \Delta y < 0.8$ are isotropic [Figs. 3(h) and 3(i)]. As in the case of the proton pairs, the QGS model does not reproduce close pairing of π^- mesons.

In previously published papers [8,9,12] in which the two-particle azimuthal correlations in nucleus-nucleus collisions have been investigated, the close pairing of secondaries was also observed. The data analyzed in these papers have been obtained mainly from emulsion

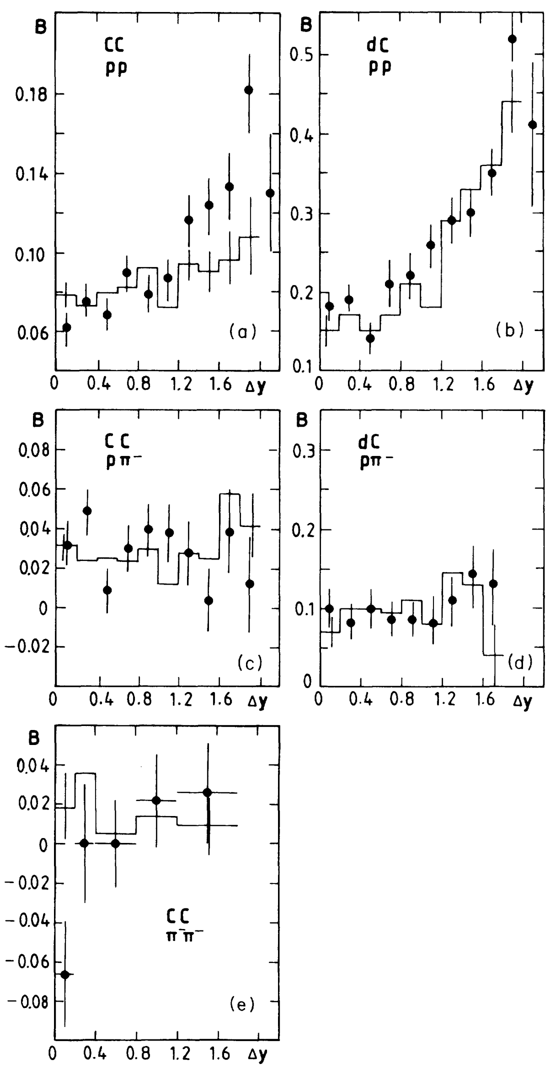

FIG. 2. The azimuthal asymmetry B as a function of the rapidity separation Δy for (a),(b), pp pairs; (c),(d), $p\pi^-$ pairs; and (e) $\pi^-\pi^-$ pairs. Solid lines are the predictions of the QGS model.

experiments in which the identification of the secondary particles is not possible. To our best knowledge, this paper presents the first independent confirmation of close pairing of secondaries obtained with a different experimental technique and including particle identification. The most probable explanation for the presence of highly collimated pion pairs is the identical particle effect.

The small-angle correlations of identical particles have been investigated in relativistic nucleus-nucleus collisions [18–25] using the normalized correlation function $R(q)=\mathrm{norm}\times N_{\mathrm{true}}(q)/N_{\mathrm{backgr}}(q)$ defined as a ratio of the numbers of correlated and uncorrelated (background) pairs with the same relative momenta $q=|\mathbf{p}_1-\mathbf{p}_2|/2$. By comparing the measured correlation function with the theoretical one, in which the radius r_0 and the source lifetime τ_0 appear as the free parameters, the space-time characteristics of the emission region can be determined. In contrast to the pions, for which the shape of the correlation function is determined by the quantum statics only [26–28], the shape of the correlation function of protons reflects the combined effects of the Pauli exclusion principle and the proton-proton interactions [29,30]. Therefore, the resulting p-p correlation curve has a minimum at relative momenta $q\approx 0$ and a broad peak at $q\approx 20$ MeV/c. The $\pi^-\pi^-$ correlation curve has a maximum at small relative momenta only.

In order to show that, in the analysis that we use, the peaks at $\Delta\varphi<20°$ in $dN/d(\Delta\varphi)$ distributions in Figs. 3(a), 3(d), and 3(g) are really caused by low relative momenta, we eliminated in Figs. 4(a), 4(c), and 4(e) all pairs

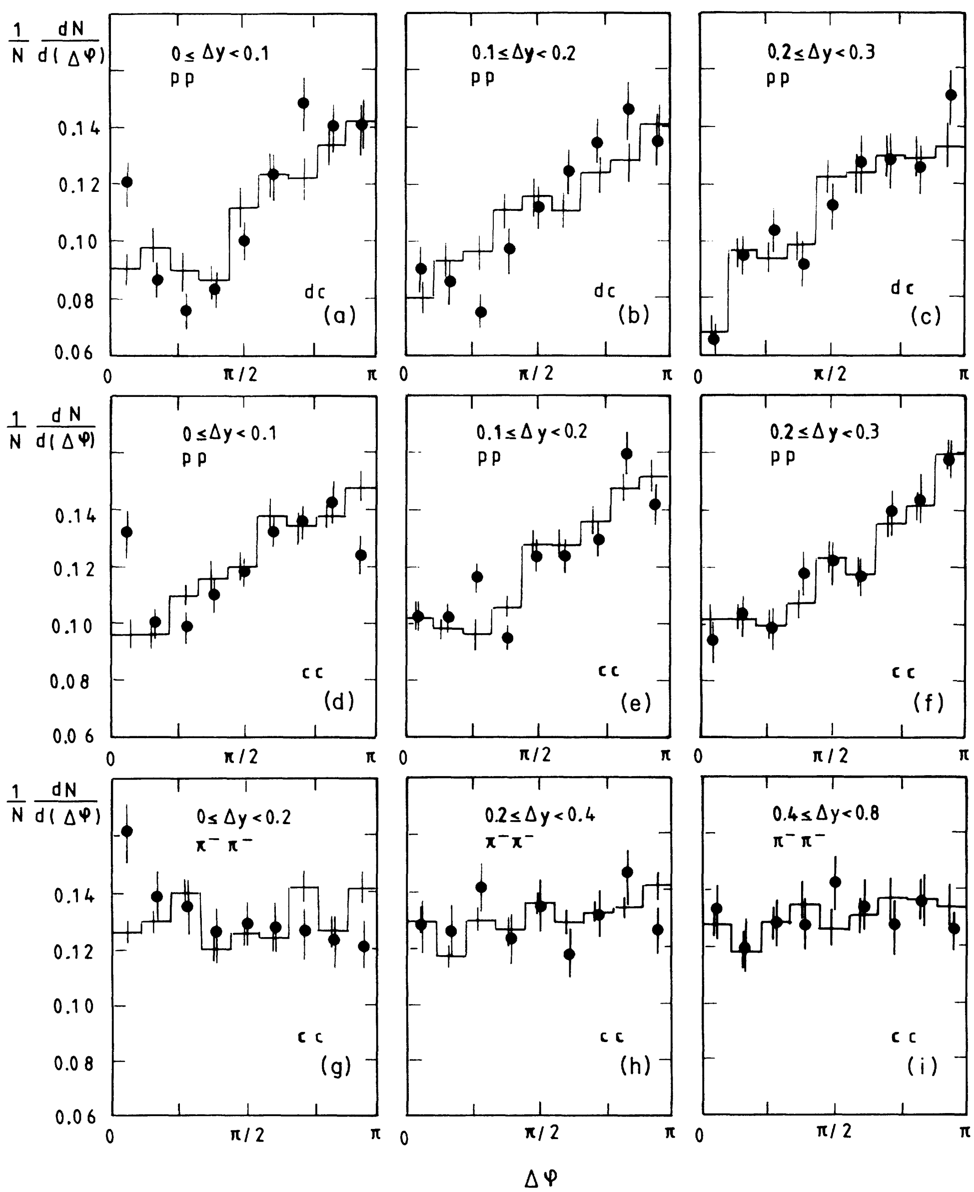

FIG. 3. Normalized $\Delta\varphi$ distributions for (a)–(f) proton pairs and (g)–(i) pion pairs with various Δy. Solid lines are the predictions of the QGS model.

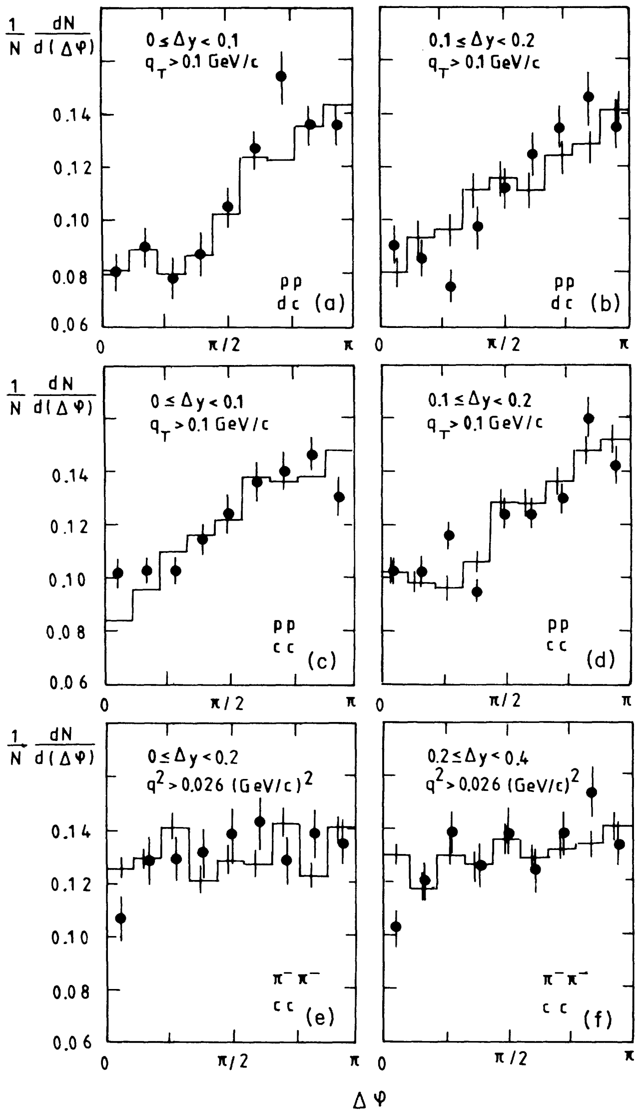

FIG. 4. Normalized $\Delta\varphi$ distributions for (a)–(d) proton pairs and (e),(f) pion pairs with various Δy after elimination of pairs which contribute to the interference effect. Solid lines are the predictions of the QGS model.

of pions with $q^2 < 0.026$ $(\mathrm{GeV}/c)^2$ and all pairs of protons[1] with $q_T < 0.1$ GeV/c ($\mathbf{q} = \mathbf{p}_1 - \mathbf{p}_2$, q_T is the component of $\mathbf{q}$ in the direction perpendicular to $\mathbf{p}_1 + \mathbf{p}_2$). This elimination was done according to Ref. [21], where the two-particle momentum correlations between protons and pions in CC interactions were analyzed using the same body of experimental data. The same criterion was used for the elimination of the protons emitted in dC interactions since the two-particle momentum correlations do not depend on the mass of the projectile nucleus [24]. Comparing Figs. 3(a), 3(d), and 3(g) and Figs. 4(a), 4(c), and 4(e), we see that the peaks at $\Delta\varphi < 20°$ disappear. We also see that the distributions $dN/d(\Delta\varphi)$ for proton pairs with larger rapidity difference remain unchanged [Figs. 4(b) and 4(d)]. The theoretically predicted minimum at $q_T < 15$ MeV/c in the pp correlation function $R(q_T)$ is not observed, probably because of the contamination of the proton sample by misidentified positive pions [21]. This explains why in our analysis we do not see the difference between $\pi^-\pi^-$ and pp short-range correlations.

The possible influence of the Δ^0-resonance decay on the azimuthal correlations can be explored through the dependence of B vs Δy for $p\pi^-$ pairs. The experimental results show that azimuthal correlations among protons and π^- mesons do not depend on the rapidity difference in both dC and CC interactions [Figs. 2(c) and 2(d)]. The QGS model also predicts the independence of B on Δy. Although it follows from the QGS model that $B = -0.18 \pm 0.02$ in CC interactions for $p\pi^-$ pairs from the Δ^0 decay, only 2.1% from the total number of $\pi\pi^-$ pairs originate from the Δ^0 decay. Therefore, a strong combinatorial background suppresses the influence of the Δ^0 decay on the azimuthal correlations.

In conclusion, in this paper the two-particle azimuthal correlations are investigated among the pp, $p\pi^-$, and $\pi^-\pi^-$ pairs in dC, αC, and CC interactions at 4.2 GeV/c per nucleon. The correlation properties for inclusive events can be accounted for by kinematical correlations calculated from the quark-gluon string model as a representation of the model of independent nucleon-nucleon collisions. It is found that the short-range correlations exist only for like particles emitted at small rapidity ($\Delta y < 0.2$) and at small azimuthal separations ($\Delta\varphi < 20°$). These correlations are not reproduced by the QGS model and they can be attributed to the identical particle effect for $\pi^-\pi^-$ pairs and barionic interactions for pp pairs. At small rapidity separation there is no significant effect of the decay of Δ^0 resonance on the azimuthal correlations.

The authors are grateful to their colleagues at the collaborating institutions for assistance in film taking and data processing. We also thank I. Mendaš for valuable suggestions during the manuscript preparation.

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