

Research Article

Search for Long-Range Correlations in Relativistic Heavy-Ion Collisions at SPS Energies

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Long-range correlations are searched for by analysing the experimental data on ¹⁶O-AgBr and ³²S-AgBr collisions at 200 A GeV/c and the results are compared with the predictions of a multi phase transport (AMPT) model. The findings reveal that the observed forward-backward (F-B) multiplicity correlations are mainly of short range in nature. The range of F-B correlations are observed to extend with increasing projectile mass. The observed extended range of F-B correlations might be due to overall multiplicity fluctuations arising because of nuclear geometry. The findings are not sufficient for making any definite conclusions regarding the presence of long-range correlations.

1. Introduction

One of the main goals of studying nucleus-nucleus collisions at relativistic energies is to study the properties of strongly interacting matter under extreme conditions of initial energy density and temperature, where formation of quark-gluon plasma (QGP) is envisaged to take place [1–3]. Correlations among the relativistic charged particles produced in different pseudorapidity, η bins, are considered as a powerful tool for understanding the underlying mechanism of multiparticle production in hadron-hadron (hh), hadron-nucleus (hA), and nucleus-nucleus (A-A) collisions [4–6]. Both short- and long-range correlations have been observed in hadronic and heavy-ion collisions at SPS and RHIC energies [5–10]. These observed correlations have been interpreted in terms of the concept of clustering [11]; that is, the particle production takes place via the formation of some intermediate states, referred to as “clusters” which finally decay isotropically in their centre-of-mass (c.m.) frame to real hadrons. Useful information regarding the properties of clusters, for example, size of clusters, number of clusters produced on event-by-event (ebe) basis and the “width,” the extent of phase space occupied, and so forth, can be extracted by studying the two

particle angular correlations [3, 12, 13]. It has been suggested [4, 5, 14, 15] that inclusive two particle correlations have two components: the short-range correlations (SRC) and the long-range correlations (LRC). The SRC have been observed to remain confined to a region, $\eta \sim \pm 1$ unit around mid rapidity, while the LRC, which arise due to ebe fluctuations of overall particle multiplicity, extend to a rather longer range [14–16] (>2 units of η). LRC have been observed at relatively higher incident energies [6, 14–18], while the magnitude of LRC, in the case of hh collisions, has been reported to increase with increasing beam energies as the nonsingly diffractive inelastic cross-section increases significantly with incident energy for hh collisions at $\sqrt{s} > 100$ GeV [19]. These effects have been successfully explained in terms of multiparton interactions [18]. For AA collisions, the multiparton interactions are expected to give rise to LRC, which would extend to rather longer range as compared to those observed in hh collision at the same incident energy [6, 15, 20, 21]. The color glass condensate picture of particle productions and the multiple scattering model also predict presence of LRC in AA collisions [6, 8, 15, 20, 22, 23].

After the availability of the data from relativistic heavy-ion collider (RHIC) and then from large hadron collider

(LHC), interest in the studies involving particle correlations has considerably increased. It is because of the idea that modifications of the cluster characteristics and (or) shortening in the correlation length in the pseudorapidity space, if observed particularly at these energies, may be taken as a signal of transition to quark-gluon plasma formation [4, 15, 24]. A number of attempts have been made by theoretical and experimental physicists [5, 6, 13, 25–35] to study forward-backward (F-B) correlations at RHIC and LHC energies. It is, however, essential to identify some baseline contributions to the experimentally observed correlations which do not depend on new physics, for example, formation of some exotic states like DCC or QGP. It is, therefore, considered worthwhile to carry out a systematic study of F-B correlations at lower energies, BNL, and SPS because of the fact that only a few attempts have been made to study F-B correlations at these energies [9, 14–16, 36]. Such studies would help understand systematically the underlying physics at energies from SPS to RHIC, like dependence of correlation strength and correlation length on beam energy and system size. Once such dependence is understood, modification in the cluster characteristics or shortening of correlation length may be looked into to search for QGP formation.

2. Formalism

F-B correlations are generally investigated by examining the following type of linear dependence of mean charged particle multiplicity in the backward (B) hemisphere, $\langle n_b \rangle$, or the multiplicity of the particles emitted in the forward (F) hemisphere, n_f :

$$\langle n_b \rangle = a + bn_f, \quad (1)$$

where a is intercept and b represents the slope. For symmetric F and B regions, b is often termed as the correlation strength and is expressed in terms of expectation value [6, 15, 28, 37]:

$$b = \frac{\langle n_f n_b \rangle - \langle n_b \rangle \langle n_f \rangle}{\langle n_f^2 \rangle - \langle n_f \rangle^2} = \frac{D_{bf}^2}{D_{ff}^2}, \quad (2)$$

where D_{ff} and D_{bf} denote the forward-forward and backward-forward dispersions, respectively.

3. Details of the Data

Two samples of events, produced in the interactions of ^{16}O and ^{32}S ions with AgBr group of nuclei in emulsion at 200 A GeV/c, are used in the present study; the number of events produced in ^{16}O -AgBr and ^{32}S -AgBr interactions are 223 and 452, respectively. These events are taken from the collection of emulsion experiments performed by EMU01 collaboration [38]. The other relevant details of the data, like criteria for selection of events, classification of tracks, selection of AgBr group of events, and so forth, may be found elsewhere [4, 38–40]. The emission angle, θ of the relativistic charged particle with respect to beam axis, was measured by the coordinate method. The values of x , y , z coordinates at the vertex and at two points one on shower and the other on beam tracks were measured and the pseudorapidity variable, η ,

was calculated using the relation, $\eta = -\ln \tan(\theta/2)$. It should be emphasized that the conventional emulsion technique has two main advantages over the other detectors: (i) its 4π solid angle coverage and (ii) emulsion data are free from biases due to full phase space coverage. In the case of other detectors, only a fraction of charged particles are recorded due to the limited acceptance cone. This not only reduces the charged particle multiplicity but may also distort some of the events characteristics, such as particle density fluctuations [4, 41]. In order to compare the findings of the present work with a multiphase transport model, AMPT [42], two samples of events corresponding to ^{16}O -AgBr and ^{32}S -AgBr collisions at 200 A GeV/c are simulated using the Monte Carlo code, ampt-v1.21-V2.21; the number of events in each sample is equal to that in the experimental data sample. The events are simulated by taking into account the percentage of interactions which occur in the collisions of projectile with various target nuclei in emulsion [43, 44]. The values of impact parameter for each data set are so set that the mean multiplicities of relativistic charged particles become nearly equal to those obtained for the experimental data sets.

The AMPT model is a mixed model based on both hadronic and partonic phases [44]. There are four subprocesses in this model [44, 45]: phase space initialization, the parton-parton interactions, the conversion from partonic to the hadronic matter, and the late hadronic interactions. The initialization takes the HIJING model [46] as event generator which included minijet production and soft string excitation. Scattering among the partons follows Zhang's parton cascade (ZPC) model [47]. The hadronization process is described by quark coalescence model [44] in which two nearest partons combine to become a meson and three nearest partons combine to form a baryon. Finally the rescattering and resonance decay of partons are described by ART (a relativistic transport) model [48].

Pseudorapidity distribution of relativistic charged particles for the experimental and AMPT event samples at the two incident energies considered is displayed in Figure 1. It is interesting to note in the figure that the distributions corresponding to experimental and AMPT events acquire almost similar shapes.

4. Results and Discussion

Pseudorapidity, η distribution of relativistic charged particles, is divided into two parts with respect to its centre of symmetry, η_c . The region with values $\eta < \eta_c$ is referred to as the backward (B) region while the region having values $\eta > \eta_c$ is termed as the forward (F) region. The number of relativistic charged particles emitted in F and B regions is counted on event-by-event (ebe) basis and hence the mean multiplicities in the two regions, $\langle n_f \rangle$ and $\langle n_b \rangle$, and dispersions D_{ff} and D_{bf} are estimated. Dependence of $\langle n_b \rangle$ on n_f for various data sets considered is displayed in Figure 2. The straight lines in the figure represent the best fit to data obtained using (1). The values of slope parameter b obtained from the linear fits are listed in Table 1. Values of b for various data sets are also calculated using (2) and are listed in Table 1. It may be noted from the table that values of b obtained from the linear

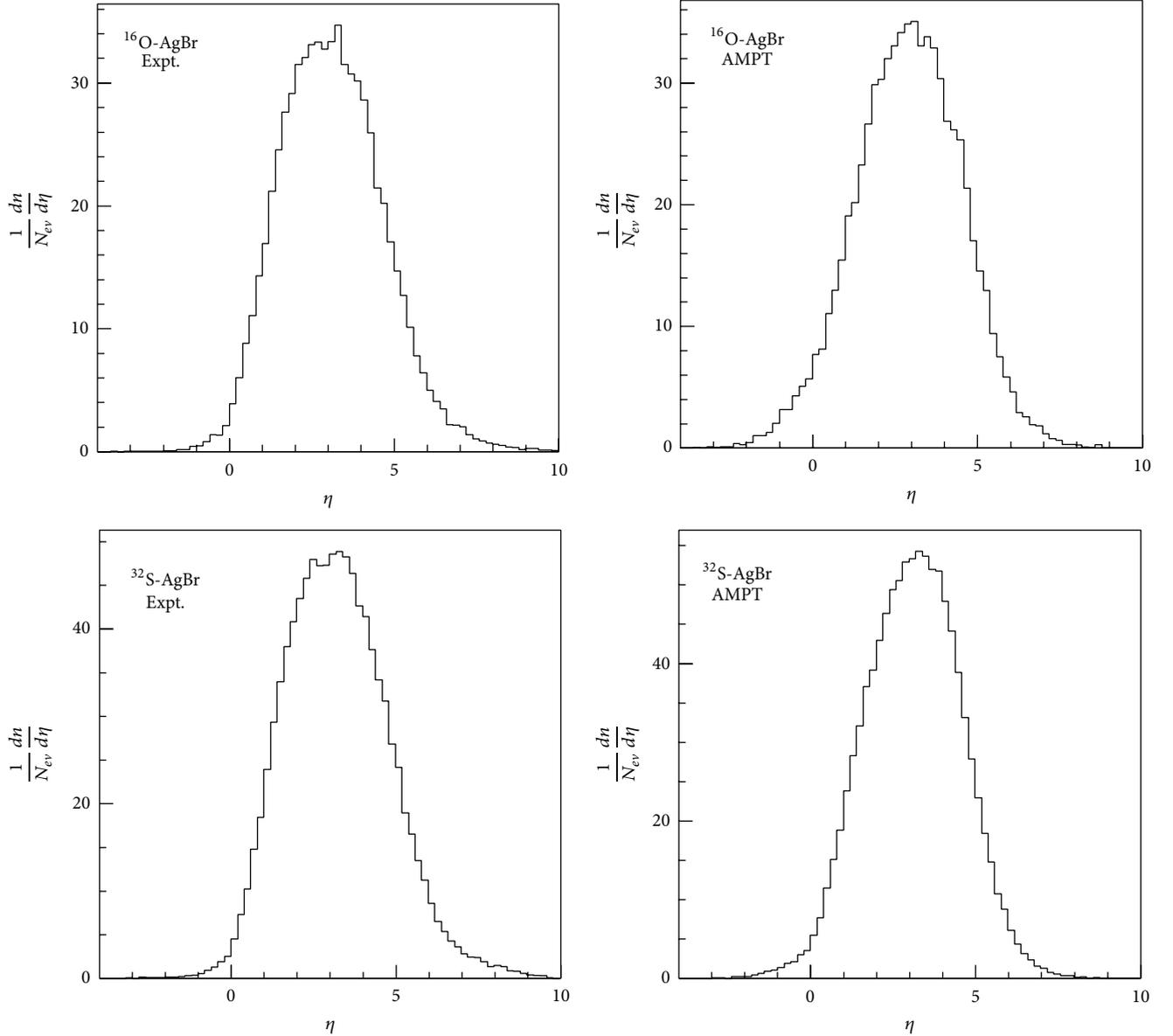


FIGURE 1: Pseudorapidity distributions of relativistic charged particles produced in ^{16}O - and ^{32}S -AgBr collisions compared with AMPT predictions.

fits are nearly equal to the corresponding values estimated using (2). F-B correlation strength, thus estimated from either (1) or (2), indicates the presence of F-B correlations in both experimental and simulated data sample. It may also be noted from Table 1 that the values of correlation strength b are nearly the same for ^{16}O and ^{32}S -AgBr collisions. However, for ^{16}O -AgBr collisions at 14.5, 60, and 200 A GeV/c values of b have been observed [15] to decrease with increasing beam energy. This indicates that correlation strength in the case of AA collisions decreases with increasing incident energy but remains nearly constant with increasing projectile mass. The larger values of b at lower energies observed in ^{16}O -AgBr collisions might be due to the dominance of uncorrelated production for which F-B correlations depend on the mean

TABLE 1: Values of correlation strength, b , and $\chi^2/\text{D.F.}$ for the experimental and AMPT event samples at different projectile energies.

Energy (GeV)	b (linear fit)		$b(= D_{\text{bf}}^2/D_{\text{ff}}^2)$	
	Expt.	AMPT	Expt.	AMPT
^{16}O -AgBr	1.21 ± 0.06	1.08 ± 0.06	1.20 ± 0.03	1.07 ± 0.05
^{32}S -AgBr	1.19 ± 0.03	1.03 ± 0.02	1.18 ± 0.02	1.03 ± 0.03

multiplicity and multiplicity fluctuations in the combined F-B regions [14–16, 34].

Strong F-B correlations are observed when F and B regions are selected such that there is no separation gap between the two regions. This may be attributed mainly to

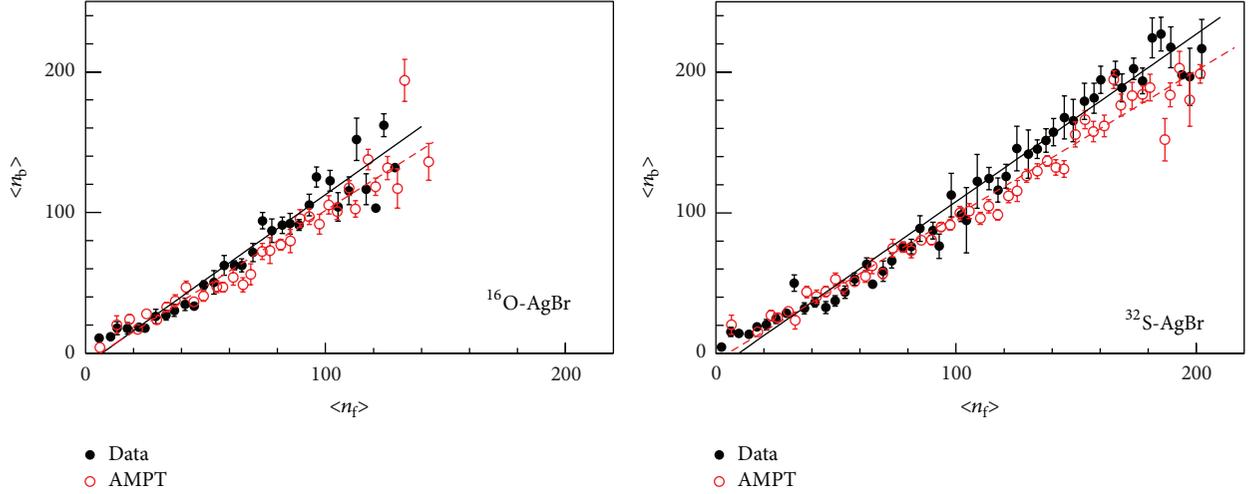


FIGURE 2: Variations of $\langle n_b \rangle$ with n_f for ^{16}O - and ^{32}S -AgBr collisions. The straight lines represent the best fit to the data obtained using (1).

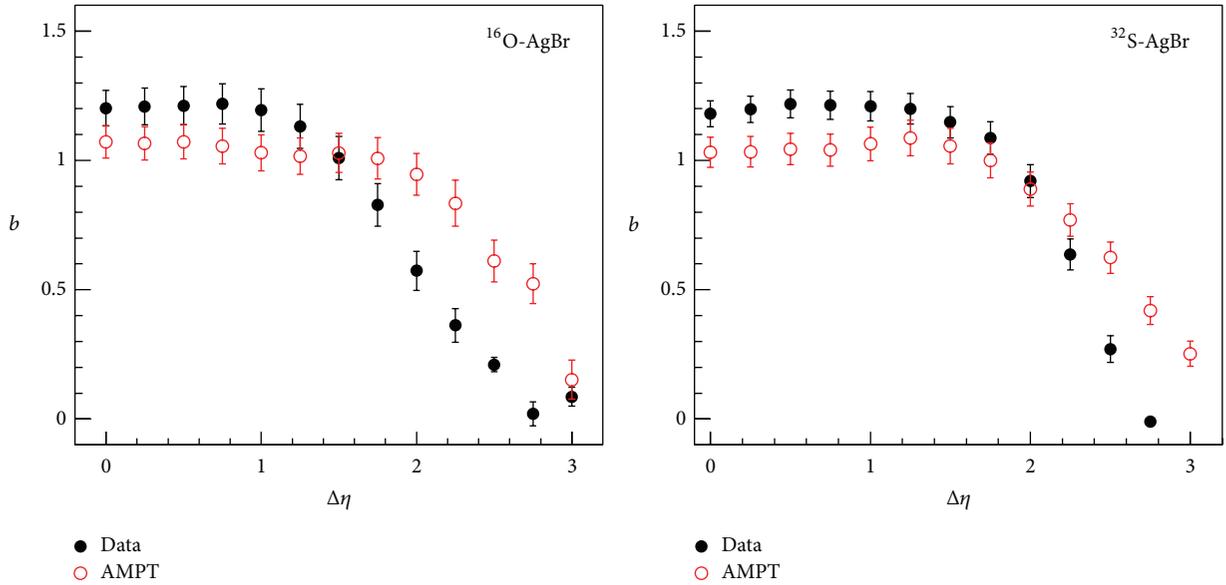
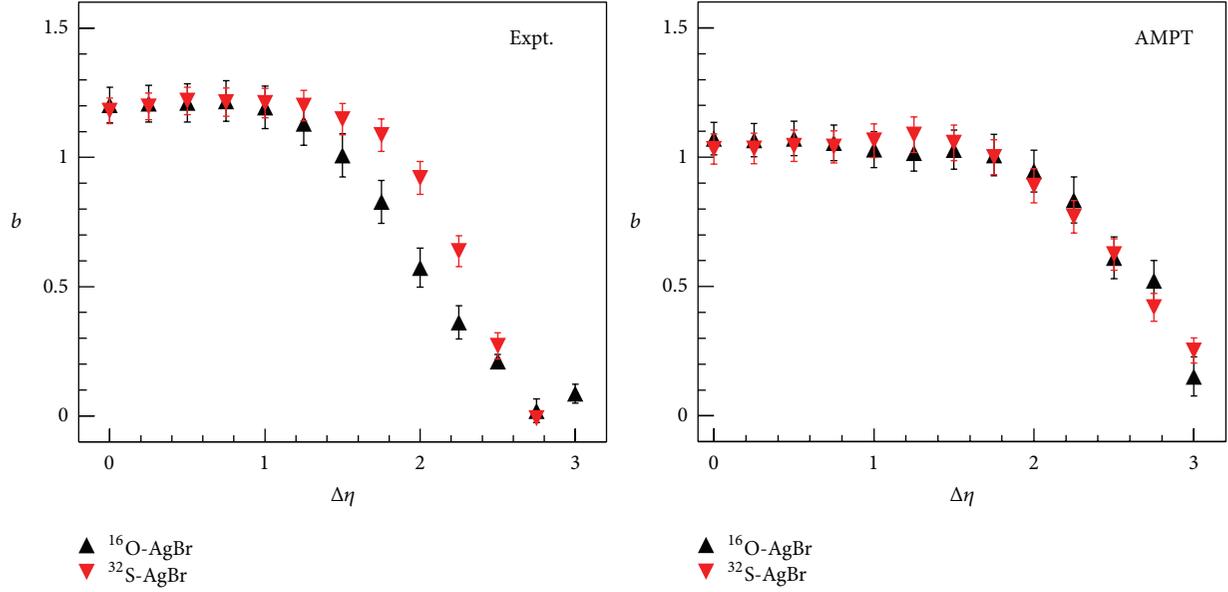
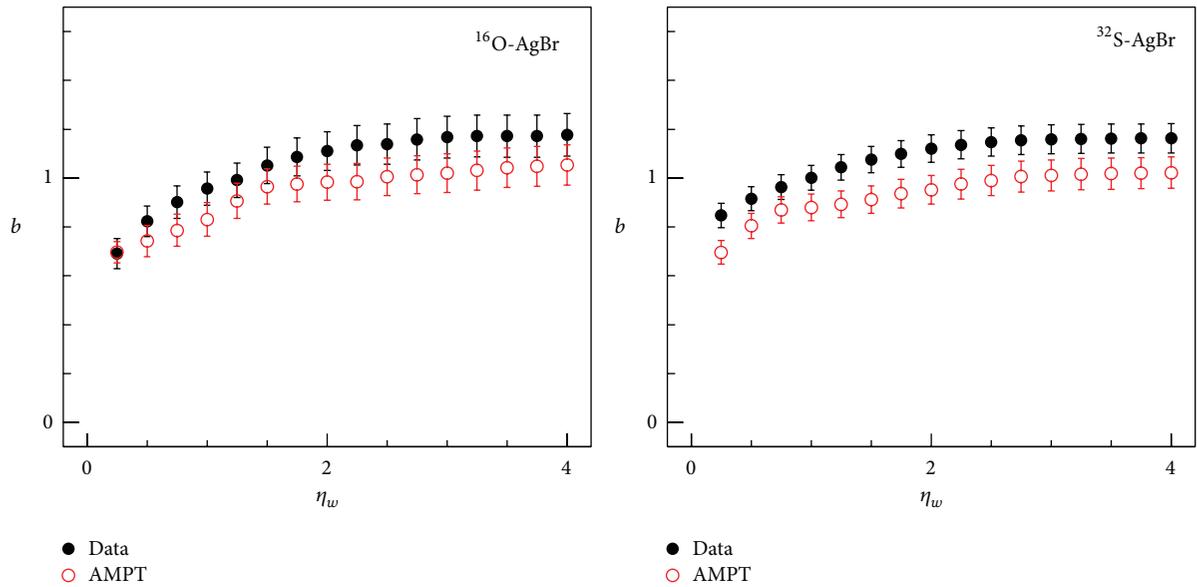


FIGURE 3: Variations of correlation strength b with pseudorapidity window width, $\Delta\eta$ for ^{16}O - and ^{32}S -AgBr collisions.

the clusters produced around η_c whose decay product would go to both F- and B-regions, giving rise to strong SRC. The SRC are envisaged to be confined to a region of $\pm 1\eta$ units around η_c [14–16, 34]. In order to minimize the contributions from SRC, a gap of $\Delta\eta$ from the center of symmetry is introduced in both F- and B-regions such that the particles having η values $\eta_c - \Delta\eta < \eta < \eta_c + \Delta\eta$ in F-region and $\eta_c > \eta > \eta_c - \Delta\eta$ in B-region are not considered while evaluating n_f and n_b . The values of correlation strength b are then calculated by estimating D_{ff}^2 and D_{bf}^2 (using (2)) by taking $\Delta\eta = 0.25$ and then increasing its value in step of 0.25. The variation of b , with $\Delta\eta$ thus obtained for the experimental and AMPT data sets, is plotted in Figure 3. It is observed that values of b , for both ^{16}O -AgBr and ^{32}S -AgBr collisions, remain essentially constant up to $\Delta\eta \approx 1.0$ and thereafter gradually decrease to 0 with increasing $\Delta\eta$. AMPT data, too, exhibit a similar

trend of variations of b with $\Delta\eta$. It may however be noted that AMPT predicts somewhat smaller values of b in the region of smaller $\Delta\eta$ ($\Delta\eta < 1.25$) and relatively larger values of b in the region of $\Delta\eta \geq 1.5$. The smaller values of b observed for AMPT data as compared to the corresponding experimental data in the region $\Delta\eta \leq 1.25$ might be due to the dominance of uncorrelated production in the AMPT model; the exact cause of uncorrelated production in the AMPT model could not be ascertained. Beyond this region, that is, $\Delta\eta \geq 1.5$, values of b are noticed to be larger for AMPT events as compared to those obtained from the experimental data. AMPT thus gives a slower decrease in the values of b with $\Delta\eta$ in comparison to that observed with experimental data. Thus, in the case of AMPT events F-B correlations are observed to characteristically extend to rather longer range as compared to those observed with the experimental

FIGURE 4: Variations of b with $\Delta\eta$ for ^{16}O - and ^{32}S -AgBr collisions.FIGURE 5: Dependence of b on separation gap, η_w for ^{16}O - and ^{32}S -AgBr collisions.

data. Furthermore, almost similar values of b , for both ^{16}O and ^{32}S projectiles, as is evident from Figure 4, indicate that the correlation strength is independent of the mass of the colliding beam. This observation is well supported by the AMPT model. Some difference in the b values for ^{16}O -AgBr and ^{32}S -AgBr experimental events in the region $\Delta\eta \sim 2.0$ might be because of the fluctuations arising due to limited statistics.

It has been reported [15, 34] that multiplicity distributions have different shapes in different pseudorapidity regions and exhibit large fluctuations in wider η -windows. In order to examine the F-B correlation strength in η windows of different widths, two small windows each of width $\eta_w = 0.25$

are placed adjacent to each other with respect to η_c such that the charged particles having η values in the range $\eta_c \leq \eta < \eta_c + \eta_w$ are counted as n_f while those having their η values lying in the interval $\eta_c > \eta \geq \eta_c - \eta_w$ are counted as n_b and the value of correlation strength b is computed. The width, η_w is then increased in step of 0.25 until almost entire η region is covered. Variations of b with η_w for the experimental and AMPT data are shown in Figure 5. It may be noted from the figure that the values of b first increase slowly with increasing η_w (up to $\eta_w \sim 2.0$) and thereafter acquire nearly constant values. Similar trends of variations of b with η_w have also been observed earlier for 14.5 A, 60 A, and 200 A GeV/c ^{16}O -AgBr collisions [9, 15]. It may also be noted from the figure that

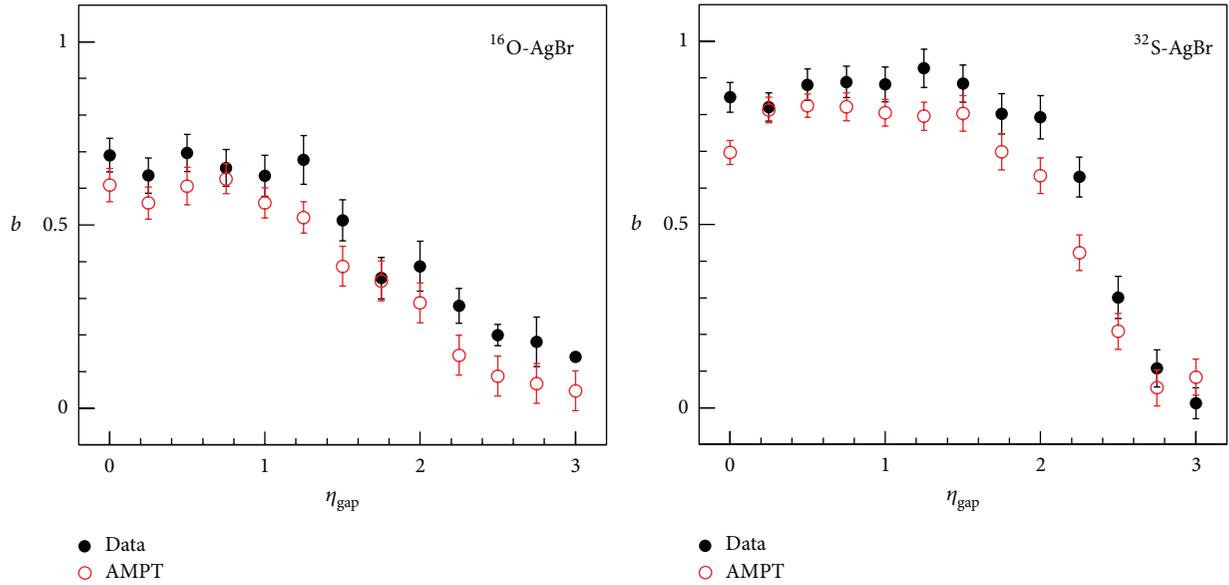


FIGURE 6: Dependence of correlation strength, b on separation gap between two symmetric pseudorapidity windows, η_{gap} for various data sets.

although AMPT predicts the similar trends of variations of b with η_w for both the data sets yet it is evidently clear that AMPT predicted values are somewhat smaller as compared to those observed for the experimental data in the entire range of η_w considered. Furthermore, it is also clear from Figure 5 that the values of b for any given η_w are nearly the same for both the data sets. This suggests that the values of b are independent of the mass of the colliding nuclei. It should be mentioned here that, in the saturation region, that is, the region ($\eta_w > 1.5$), values of b , for the experimental data, have been reported [15] to decrease with increasing projectile energy. Such a decrease in the values of b has been observed due to the increase in the ratio $\langle n_f \rangle / \langle n_s \rangle$ even in the limited phase space [15]; $\langle n_f \rangle$ denotes the average number of charged particles in the F region while $\langle n_s \rangle$ is the mean charged particle multiplicity in the considered phase space.

In order to examine the presence of LRC, if any, contribution from SRC is to be eliminated. For this purpose F-B correlations are studied by adopting the method which has frequently been used, particularly at RHIC and LHC energies [5, 6, 25, 27–32, 34]. According to this method, η windows of small but equal widths, η_w , are placed in F and B regions in such a way that they are separated by equal distances (in η units), η_{gap} , with respect to centre of symmetry η_c . Thus, all the charged particles having their η values in the interval $\eta_c + \eta_{\text{gap}} \leq \eta < \eta_c + \eta_{\text{gap}} + \eta_w$ are counted as n_f , whereas those having their η values in the range $\eta_c - \eta_{\text{gap}} \leq \eta < \eta_c - \eta_{\text{gap}} - \eta_w$ are counted as n_b . By changing the value of η_{gap} from 0 to 3.0 on each side of η_c , n_f and n_b are estimated to evaluate the values of b . Variations of b with η_{gap} for various data sets considered are displayed in Figure 6. It may be noted in the figure that the values of b acquire almost constant value of ~ 0.7 up to $\eta_{\text{gap}} \sim 1.25$ for ^{16}O -beam and thereafter suddenly decrease to zero with increasing η_{gap} values. For ^{32}S -beam the values of b are observed to remain constant up

to $\eta_{\text{gap}} \sim 1.75$ and then decrease to zero. This indicates that with increasing projectile mass the F-B correlations extend to rather longer range. AMPT data, too, exhibit similar trends of variations of b with η_{gap} except that the values of b are somewhat smaller in comparison to the one obtained for the experimental data. These observed correlations are envisaged to be due to formation of resonance or clusters in the central rapidity region, the decay products of which would be emitted in both F and B regions [11, 14, 16, 17]. This observation is not sufficient to consider it as an indication of the presence of some LRC but it does suggest that the range of F-B correlations extends with increasing mass of the projectile. The range of F-B correlations has also been observed to increase with increasing beam energy in $^{16}\text{O-AgBr}$ collisions in the energy range from 14.5 A to 200 A GeV/c [15]. It has been argued [34] that the extended range of F-B correlations may be explained from simple statistical considerations of uncorrelated production of charged particles. Correlations in this range, if observed at higher beam energy or with heavier projectile, arise due to overall multiplicity fluctuations [6, 14, 16, 17, 34]; such fluctuations in AA collisions may show up because of fluctuations in nuclear geometry [34]. It has also been pointed out [34] that, before drawing up any conclusions regarding the presence of dynamical LRC, it should be confirmed that the observed F-B correlations are not arising due to overall multiplicity fluctuations by studying the multiplicity distributions and F-B correlations simultaneously in the same experiment.

5. Summary

On the basis of the findings of the present work, the following conclusions may be arrived at.

- (1) The observed F-B correlations are mainly of short range in nature. However, the range of F-B correlations are

observed to increase with increasing projectile mass and beam energy. This extended range of correlations at higher beam energy or larger projectile mass may be due to overall multiplicity fluctuations arising because of nuclear geometry.

- (2) The study of F-B correlations dependence on the pseudorapidity bin-width and position indicates that the correlation strength b remains independent of the projectile mass.
- (3) The Monte Carlo model, AMPT, is observed to reproduce the data nicely.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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